Innovation Scenarios in Digital Documentation of Complex Heritage Buildings for Seismic Risk Mitigation

Martina Suppa[1], Federica Maietti[1], Luca Rossato[1], Marida Paternò[2]

[1] University of Ferrara, Department of Architecture, Italy - (sppmtn, mttfrc, rsslcu)@unife.it
[2] Zenith Ingegneria, Ferrara, Italy - mariapaterno@zening.it

Keywords: Digital Documentation, Integrated Workflow, Seismic Damage, Historic Theatres, Risk Mitigation.

Abstract

The research started after the earthquake that hit the Emilia area (part of the Emilia-Romagna region, in the north-east of Italy) in 2012. The significant damage suffered by the historical-architectural buildings, has led the regional administration and the public bodies responsible for heritage conservation to trigger different actions aimed at the reconstruction, conservation and management of cultural heritage, developed in the following years. Among these, the establishment of a regional body focused on the overall coordination of reconstruction (the Emilia-Romagna Reconstruction Agency - Sisma 2012), and the financing of specific research that could propose advancements in documentation, recovery, and risk mitigation. This research is part of the actions undertaken, and it's focused on the improvement of systems traditionally used for seismic damage survey (a sheet-based damage recording) by connecting these analog procedures to 3D digital environments for multi-layer analyses. The aim is to develop an integrated and extended documentation of architectural assets within an optimised workflow, combining sheets with currently used digital survey tools and methodologies. The developed multi-level information framework includes different levels of investigation, which were applied on different case studies. The research is focused on a specific architectural typology, namely the historical theatres, and the paper presents in particular the methodological approach and main outcomes from the assessment of the Teatro Nuovo di Mirandola, in the province of Modena.

1. Introduction

1.1 Research background

Following the 2012 earthquake in the Emilia region, around 80% of protected historic buildings run into severe damage, highlighting both the fragility of cultural heritage and the urgent need for improved monitoring systems. The event also exposed several shortcomings in the current procedures used to assess seismic damage (Suppa et al., 2025). The evaluation of the affected heritage sites relied on a sheet-based damage assessment method originally developed after the 1997 earthquake in Umbria and Marche.

The sheets, set by «Ministerial Decree 23/2006, can be classified into three types: the A-DC model for surveying damage to churches; the B-DP model for buildings; and the C-BM model for movable assets » (Suppa et al., 2023).

A thorough review of the damage assessment sheets provided insight into the effectiveness of this survey method, revealing the need for a significant update to integrate the sheets with modern digital survey tools and techniques.

Research allowed to outline paths of innovation toward the change from analog datasheets to 3D digital environments for multi-layer analyses aimed at the integrated and extended documentation of the architectural asset.

The research has been developed in cooperation with the Agenzia Regionale per la Ricostruzione - Sisma 2012 (Emilia-Romagna Reconstruction Agency - Sisma 2012), established just after the 2012 earthquake to coordinate the reconstruction and still an active regional organisation, and it is focused on a specific architectural typology: historical theatres (Bordoni, 1982).

After the earthquake, and in general due to increasingly frequent and devastating natural disasters, targeted and aware surveying of cultural heritage has become more and more crucial for preserving tangible and intangible assets.

Concepts and strategies related to heritage at risk have been extensively explored in recent years, due to the impact of extreme climate change events and human actions, as well as disasters in consequence of natural hazards (such as hydro-meteorological events for exceptional rainfalls, windstorms, heat waves, etc.), putting enormous additional pressures on heritage sites (Bonazza et al., 2018).

In this context, digitization is nowadays recognised as a key tool for documentation and conservation of heritage, for its ability to quickly capture tangible assets and to provide different tools to support monitoring and recovery actions. Anyway, there is still plenty of room for improvement in systematising interdisciplinary knowledge and experiences, going beyond the mere use of technological tools and adopting a critical approach, while at the same time seeking procedures that can serve as guidelines (Bonazza and Sardella, 2023).

In this direction, a very current gap lies in the increasingly amount of data to be managed and critically assessed in the framework or 3D digital models (Salonia, 2023), finding new approaches to make these data really useful in terms of documentation for risk mitigation.

The applied methodology developed under this research is grounded on these premises, and tailored to the creation of an optimized workflow merging sheet-based data recording to current digital supports. The main aim is to provide a multi-criteria tool able to prioritizing data and information related to damaged historic buildings.

As the core focus of the research are historical theatres in the Emilia-Romagna region affected by the 2012 earthquake, the very first step regarded the mapping of these building all over the regional provinces, and an in-depth typological study in order to understand all relevant historical, cultural, and structural features to be considered to improve survey procedures for damage assessments and seismic risk mitigation (Fig. 1).

The significant damage to cultural heritage that was immediately apparent after the seismic events, and the extensive work for managing the reconstruction (in the broadest sense) in the years that follow, highlighted, on the one hand, the urgency for public and private bodies responsible for heritage sites management and conservation to improve available tools, policies, and strategies for safeguarding assets. On the other hand, the scientific community has been widely urged to propose advances in deploying technological and methodological innovations. Integrated documentation, that can be defined as the act of surveying, assessing, and interpreting, proved to be an essential tool for understanding, raising awareness, and preserving cultural heritage.

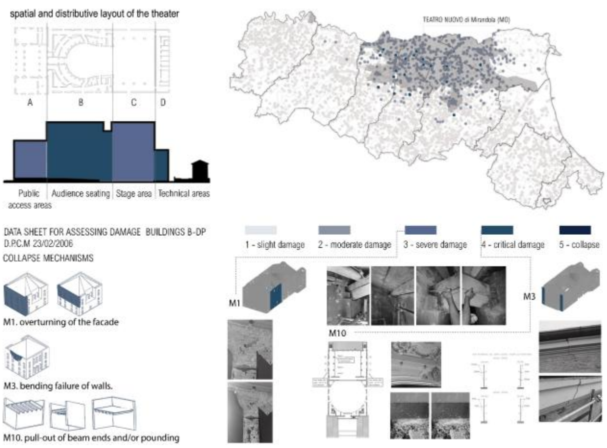

Figure 1. The overall methodological framework, including a macro-schematisation approach for structural behaviour analysis, applied to the Teatro Nuovo in Mirandola (graphic elaboration by the authors).

1.2 Research framework

The research was grounded in existing procedures, standards, and tools conventionally employed in seismic damage surveys, with the objective of formulating an integrated workflow for the documentation and assessment of seismic impacts on historic theatres. The investigation led to the development of a novel workflow comprising integrated procedures aimed at the prevention and mitigation of risks associated with potential emergency scenarios, whether of natural or anthropogenic origin, through the adoption of a comprehensive methodological framework validated across a set of case studies (Suppa et al., 2025).

The 2012 earthquake affected 31 theatres out of 105 located between Bologna, Modena, Reggio Emilia and Ferrara provinces. A sample of 25 sheets drawn up and available for consultation in the Regional archive were included in the data assessment. A critical-comparative analysis of MIC (Ministry of Culture) forms has been undertaken, also considering main architectural features of theatres (morpho-typological analysis), including heritage and cultural values, and significances. In order to understand the spatial and volumetric peculiarities of the historic theatres, the comparative critical analysis of morphological and geometrical features was essential.

The integrated methodological system was conceived to facilitate the analysis, interpretation, and two-dimensional and three-dimensional representation of theatres: morphology, geometry, metric-dimensional aspects, and material-constructive stratigraphy. The identification of these elements enabled the definition of a multi-criteria classification matrix, upon which the morpho-typological study was first developed, followed by a comparative analysis of data collected from post-seismic survey procedures. These included already mentioned forms and technical analyses elaborated by multidisciplinary expert groups responsible for restoration and conservation projects.

The results of the morpho-typological and analytical-comparative study facilitated the development of an optimised workflow for integrated survey procedures, structured as a multi-level information framework interconnecting three levels of investigation, which were applied on different case studies. The paper presents in particular the methodological approach and main outcomes from the assessment of the Teatro Nuovo di Mirandola, in the province of Modena.

2. Related works

The research analysed an extended scenario, delving into the State of the Art on existing risk management databases at the international, national, and regional level; survey procedures applied during the emergency phase for the quick damage assessment; existing digital integrated survey procedures applied to heritage documentation and management of large amounts of acquired data (Matrone et al. 2020). The typological characteristics of historical theatres, and standards and protocols of integrated documentation at national and international level have been analysed as well. Several research actions and ongoing or completed projects have been examined in order to ground the research on a sound basis of pre-existing knowledge.

2.1 State of the Art and background projects

The basis for updating a workflow able of advancing damage assessment to obtain essential knowledge for conservation, lies in the analysis of digital technologies currently available. The research therefore carried out a preliminary examination of the State of the Art in terms of survey tools, in order to provide a clear framework on which grounding the critical approach to the development of 3D models to collect data and information related to seismic vulnerability. The analysis included survey technologies for documenting complex architectures (terrestrial and aerial laser scanners, digital photogrammetry, integrated survey, etc.), up to the most current 3D modelling procedures. As far as concerns data modelling, the most dynamic scenarios involve new methods of database exploration and segmentation, and new frontiers in BIM (Building Information Modelling) applied to cultural heritage (HBIM). While in the field of survey technologies, research is focusing more on issues related to the systematisation of acquired data (Teruggi et al., 2021; Codiglione et al., 2024), in the field of modeling procedures innovation avenues are targeted on data integration by exploiting semantic enrichment or parametric modeling (Croce et al., 2023; Grilli and Remondino, 2020).

As the research focused on heritage at risk survey and digital innovation, the analysis of reference projects that have moved in this direction has been particularly relevant.

The initiative ResCult – *Reinforcing the Resilience of Cultural Heritage: a Decision-Support Tool for Safeguarding Cultural Assets*, completed in 2018, sought to strengthen the ability of Civil Protection authorities to anticipate and reduce the effects of natural and human-induced hazards on heritage locations. This was pursued through the creation of a pan-European Interoperable Cultural Heritage Database, designed as a unified framework accessible to public administrations and regional

stakeholders. Its central objective was to establish a risk reduction strategy, outlining specific measures to bolster both preventive efforts and adaptive resilience. The project emphasized the dual need for stronger collaboration among institutions and the use of digital innovations for heritage safeguarding, encompassing data exchange, interoperability standards, protocols, best practices, and alignment with EU frameworks. Within its scope, ResCult carried out three pilot studies examining diverse categories of heritage exposed to threats such as flooding, wildfires, and seismic activity. These studies generated datasets feeding into the interoperable European Cultural Heritage Database (Datola et al., 2024). Furthermore, the project delivered a standardized 3D Geographic Information System (GIS) integrating cultural asset data with hazard and risk layers, which was subsequently verified and tested through the pilot cases (Colucci et al., 2024).
Several Horizon 2020 projects, now completed, addressed cultural heritage resilience through data-driven approaches and digital platforms. *Shelter* (Sustainable Historic Environments holistic reconstruction through Technological Enhancement and community-based Resilience) and *Heracles* (Heritage Resilience Against Climate Events on Site) developed ICT systems to integrate diverse information sources, offering real-time awareness and supporting innovative strategies for safeguarding heritage.
The *Arch* project (Advancing Resilience of Historic Areas against Climate-related and other Hazards) created a risk management framework and practical tools to help municipalities, citizens, and expert communities strengthen the resilience of historic districts against climate and natural threats. Meanwhile, *Hyperion* (Development of a Decision Support System for Improved Resilience & Sustainable Reconstruction of Historic Areas) combined existing solutions with advanced technologies such as sensors and modeling tools, producing an integrated platform to enhance multi-hazard risk knowledge, preparedness, response capacity, and sustainable recovery.
Within the current Horizon Europe initiatives, the *Triquetra* project (Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage) is developing a knowledge-based assessment system capable of detailed risk categorization. It also compiles a repository of mitigation options and recovery strategies, functioning as a Decision Support Tool to enhance risk management and heritage site restoration. The project employs cutting-edge surveying and monitoring methods, including hydrographic mapping, multi-beam sonar, UAVs equipped with optical, multispectral, and LiDAR sensors, underwater photogrammetry, laser spectroscopy, and advanced simulation modeling (Ioannidis et al., 2024).
In this broader framework, there is a pressing need to strengthen cultural heritage documentation and surveying methods – both to build comprehensive data inventories for disaster risk reduction and to improve the capacity to digitally simulate and analyze the behavior of heritage assets through state-of-the-art technologies (Romao & Bertolin, 2022).

2.2 Typological analysis: the regional theatres

Italian historical theatres traced back their theoretical origins to the Humanistic era. In the 16th century, architects such as Baldassarre Peruzzi and Sebastiano Serlio redefined scenic space, blending Greco-Roman traditions with courtly demands, which led to the development of the modern theatre. Key innovations included perspective wings and frontal viewing, with fixed Renaissance stages evolving into three-dimensional structures featuring inclined floors to enhance the illusion (Amoruso et al., 2016). Significant examples include Palladio's Teatro Olimpico (Vicenza, 1580) and Scamozzi's Teatro Ducale (Sabbioneta, 1588-1590), the first permanent court theatre.
The Teatro Farnese in Parma (1616–1618), designed by Giovan Battista Aleotti, exemplifies the transition from Renaissance to Baroque theatre, with its U-shaped hall and deep proscenium. While early Baroque theatres often faced acoustic and visibility issues, the Neoclassical period brought refinement and codification, as seen in Bologna's and Ferrara's Teatro Comunale. In Emilia-Romagna, 18th- and 19th-century theatres commonly featured horseshoe, elliptical, or U-shaped auditoria with tiered boxes, while the early 20th century introduced continuous galleries and Art Nouveau influences.
The development of stage and auditorium design established the Italian-style theatre as a distinct typology, optimising sightlines and stage use. The replacement of terraces with box seating introduced the "hive" structure, first devised by Alfonso Rivarola (1639) and refined by Andrea Seghizzi (1641), which increased capacity while mirroring the era's social stratification. Despite ongoing acoustic and visibility issues in lateral boxes, the horseshoe auditorium with tiered boxes became the dominant model. By the late 18th century, monumental civic and royal theatres proliferated in urban centres, and in the 19th century the typology reached its definitive form, shaped by the ascendancy of the bourgeoisie. In the early 20th century, new layouts for prose and circus performances appeared, incorporating continuous galleries and Art Nouveau influences.
The evolution of stage and auditorium transformed the Italian-style theatre into a defined icon (Fig. 2), with a layout optimising sightlines and stage area.

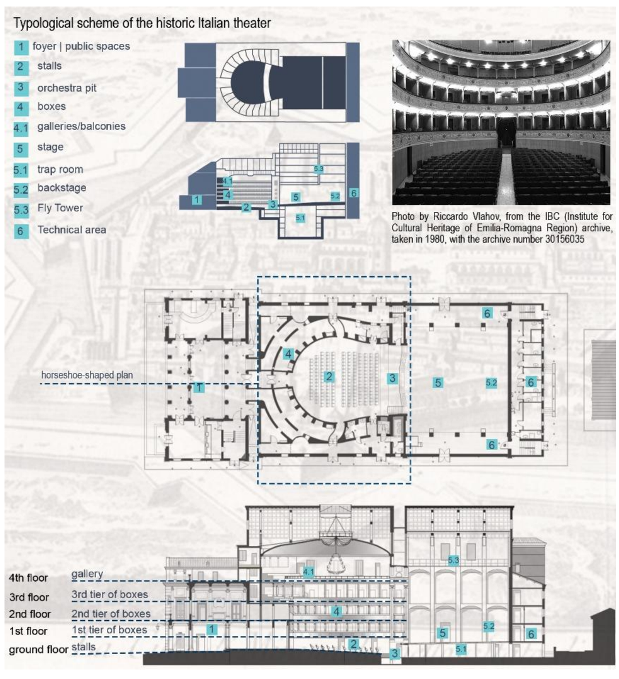

Figure 2. The Teatro Nuovo in Mirandola analysed according the typological schema of Italian historical theatres (graphic elaboration by the authors).

With regard to the historical theatres of Emilia-Romagna, the first systematic mapping was undertaken in 1982 by the IBC (formerly the Regional Institute for Cultural Heritage, now the Cultural Heritage Sector) (Bondoni, 1982). That report identified seventy-two Italian-style theatres in the region, compared with the one hundred and thirty recorded in the first census of 1868. According to the IBC's findings, the substantial reduction in the number of theatres was primarily attributable to the bombings of the Second World War. Additional losses stemmed from theatres designated for demolition due to severe degradation and abandonment, as well as from irreversible alterations that had deeply compromised their original architectural features.

In the mid-1990s, regional administrations and the Cultural Heritage Authority launched an extensive preservation programme aimed at enhancing and promoting the use of historic theatres. A new survey developed in 1995 registered eighty-seven theatres, 30% of which were closed either because of structural decay or ongoing restoration. As part of this initiative, the IBC digitised the data collected in the 1982 survey for the first time. A subsequent study in 2002 documented the interventions undertaken since the mid-1990s, recording the reopening of numerous restored theatres to the public.

At the beginning of the 2000s, several theatres were again closed for renovation, and a decade later the 2012 Emilia earthquake provided a further test of the conservation state of the recently restored theatres, highlighting the urgency of a new survey (Suppa et al., 2023).

Based on the morpho-typological evolution previously summarized, the research proposes a seven-group classification for historical theatres, defined by urban context, auditorium configuration, and construction date. Synoptic analyses demonstrate how theatre design reflects socio-political and economic contexts, adapting to dramaturgical and scenic demands across historical periods. In this classification, the Teatro Nuovo in Mirandola falls into the first group, including late 17th- to mid-19th-century structures characterised by a horseshoe-shaped plan and tiered boxes.

3. Methodology

The knowledge and methodological framework led to a critical-comparative analysis, divided into two levels: the first involved studying critical issues in the B-DP form, mainly used in the 2012 theatre survey. The second covered the techniques - laser scanning, digital photogrammetry – and integrated survey methodologies applied during the in-depth investigations for repair and restoration works. The critical-comparative analysis and morpho-typological study led to the development of an integrated procedural flow to survey damage in historic theatres, aimed at systematising and optimising the stages of damage documentation. The integrated workflow (Fig. 3) was conceived as a knowledge tool essential for documenting historic theatres according to the specific historical-architectural features related to seismic vulnerability. The workflow, developed during the PhD research (Suppa, 2022), is structured into three levels of investigation:

«• Screening Level (L1): digitised implementation of the MIC damage survey datasheets used in 2012 - and B-PD models - adapted to theatres. The digital tool is called SD-T (Seismic Damage-Theatres), and it is the matrix of a single digital database related to the 106 historic theatres surveyed at regional scale (Suppa et al., 2023; Suppa et al., 2025).

• Survey Level (L2): digital integrated survey by applying a protocol to obtain 3D models to be consulted and implemented over time. The protocol is the one developed within the European Project Inception (Di Giulio et al., 2017) adapted to seismic damage survey.

• HBIM Plus Level (L3): collector of the first and second levels. Information collected, data acquired, and processed are the basis for the HBIM model, linked to semantic platforms (Iadanza et al., 2020). Information layers (LOI) that parametric models can include in representing the damage directly on geometries (Brusaporci et al., 2018) were included» (Suppa et al., 2023).

The third step, related to the HBIM modeling and uploading on semantic platforms, foreseen the opportunity to support management and monitoring in a more efficient way, linking the digital model with additional information and databases (Empler et al., 2021). The HBIM environment provides a crucial framework for documenting, classifying, and archiving key information on theatres, while enabling the updating of metric and geometric surveys and supporting damage assessment and conservation status evaluation in a collaborative setting (Suppa et al., 2025). The three-level workflow was tested and verified on different pilot cases. The paper will focus on the Teatro Nuovo in Mirandola, Modena (Fig. 4), starting from the datasheet filled in after the earthquake and from the 3D point cloud.

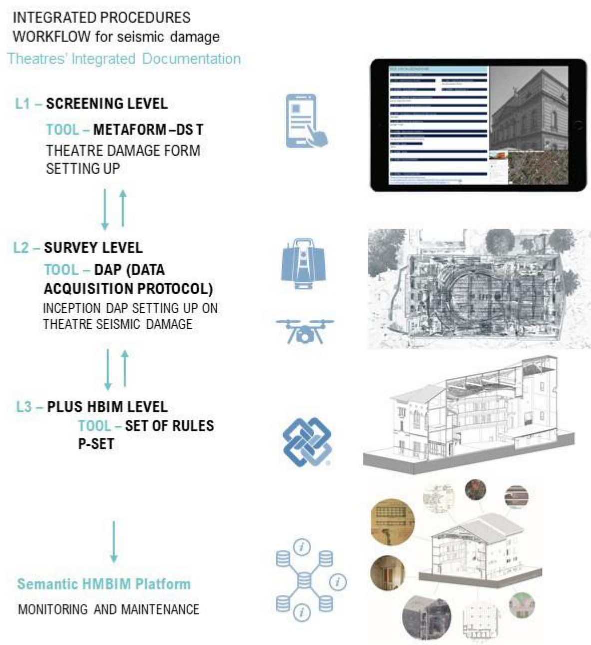

Figure 3. The overall integrated documentation workflow (graphic elaboration by the authors).

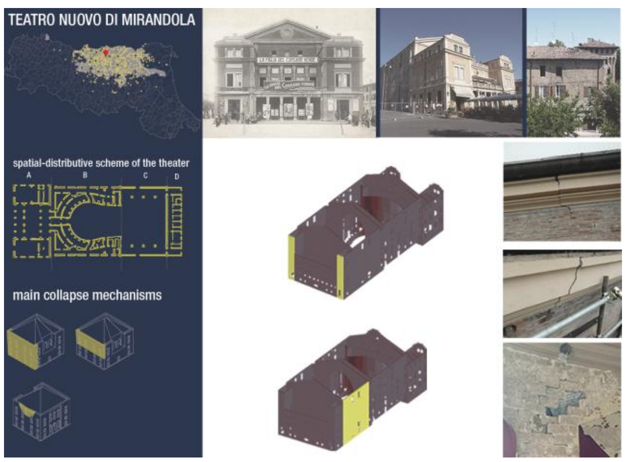

Figure 4. Analysis of the Teatro Nuovo in Mirandola (graphic elaboration by the authors).

3.1 Case study: the Teatro Nuovo in Mirandola

The Teatro Nuovo in Mirandola was built to replace the former Teatro Greco-Corbelli, which closed in 1903 due to concerns about public safety. This action triggered a civic initiative in 1904, supported by the municipal administration and private investors, which led to the acquisition of an area previously part of the Castello. The initial design by engineer Lorenzo Coliva, a more modest two-tier structure, was expanded resulting in 65 boxes and a footprint of 1265.62 sqm. Although influenced by the late Neoclassical façade of Modena’s Teatro Storchi, the Teatro Nuovo shows a more pronounced eclecticism and monumentality (Figg. 5-6) (Ziroldi, 2005).

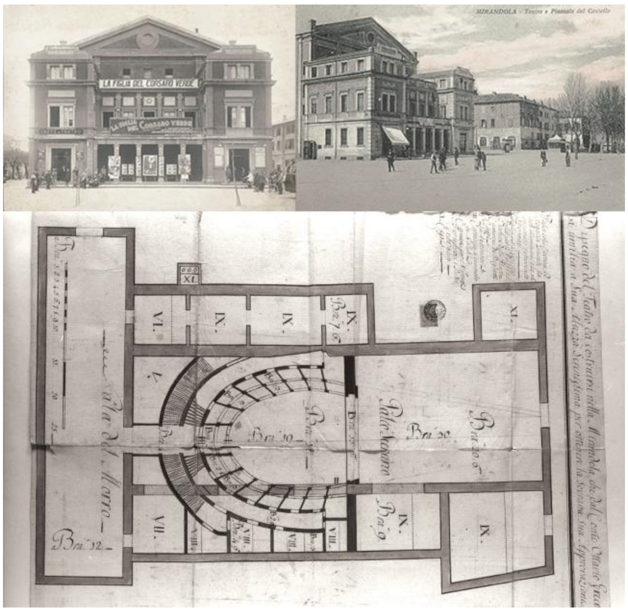

Figure 5. Historical pictures and drawings of the Teatro Nuovo in Mirandola (source Ziroldi, 2005).

Figure 6. Pictures of the main façade and south side of the Teatro Nuovo in Mirandola (Sisma 2012 Agency).

Its facade features a portico with composite capitals, while a tympanum crowns its main auditorium. In the late 1960s, the conversion into a cinema led to a significant change in the building, closing the original openings. Morphologically, the theatre has a classic horseshoe-shaped auditorium with a significant rake, originally seating 224, and includes a recessed orchestra pit with an inverted vaulted “harmonic box” for sound amplification. The current seating arrangement reflects a shift from its original operatic focus. The auditorium features three tiers of boxes and an amphitheatre-style loggia, topped by a broad, shallow vault with a central skylight (now veiled) and rich decorations. Box balconies are adorned with gilded stucco, composers’ insignia, and painted medallions. The proscenium arch displays the construction date in Roman numerals. Throughout its history, the theatre has undergone several significant renovations, including a refurbishment between 1966 and 1969 focused on the stage and plants upgrades, as well as the installation of an additional cinema projection equipment. Further structural upgrades were made in 1989-2000 to ensure its renewed operation and safety.

4. Development and outcomes

In the broader framework of studies on the effects of the 2012 earthquake on historic theatres in Emilia-Romagna, the Teatro Nuovo in Mirandola stands out as an emblematic example of post-seismic vulnerability. Similar to other historic buildings assessed and «classified within the “moderate to severe damage” range, it was assigned “damage state 2” and medium vulnerability, corresponding to operational level E0 for seismic upgrading interventions» (Suppa, 2022). The damage assessment began during the emergency phase, when preliminary inspections documented through the B-DP form revealed significant damage to major structural elements: perimeter walls exhibited overturning (M1) and flexural failure (M3), horizontal structures showed beam-end slippage and/or hammering (M10), and vaults were affected by in-plane deformation (M13) (Suppa et al., 2025).
Within the scope of the research, the theatre was analysed through an integrated three-level investigation workflow aimed at comprehensively understanding the extent and nature of the structural damages.

4.1 The workflow application

The first level (L1) involved the use of SD-T (Seismic Damage–Theatres), an interoperable digital tool integrated with regional databases to support emergency surveys by streamlining data acquisition, organisation, and management. Validated at the Teatro Nuovo in Mirandola, SD-T employs mandatory field categories and subcategories to structure information essential for metric–geometric surveying and diagnostic analyses (L2). The system also introduces seven structural micro-units (USTs): forepart/foyer (UST 1), auditorium (UST 2), proscenium arch (UST 3), stage and backstage (UST 4), service block (UST 5), foundations (UST 6), and stairs (UST 7).
This subdivision facilitated the identification, classification, and documentation of parameters closely linked to seismic behaviour, including materials, construction systems, and degradations influencing the building’s structural response, contributing to the trigger of specific collapse mechanisms. From this information, it is possible to gather a damage index for each structural sub-unit, and then an overall index, optimising initial operations surveying localised damage for each UST.
The second level (L2) advanced the investigation through the application of integrated digital technologies, such as laser scanning, for metric-geometric surveying and advanced diagnostics. In the case of the Teatro Nuovo in Mirandola, a 3D laser scanner survey has been performed, applying Leica C10 and Faro Focus 3D X130 tools (Figg. 7-10).
High-accuracy 3D digital databases generated from point clouds allowed for a reliable verification of the metric and geometric features of the halls and structural elements, identifying angular variations, misalignments, and wall out of lead. These data were then discretised to graphically represent significant profiles, cracking patterns, and seismic deformations, providing an essential support for diagnostic and structural investigations. These analyses included sclerometer tests and investigations on the stage box floors and vault via endoscopic surveys, integrated

by further investigations to identify the type and diameter of reinforcing steel. Macro-structural subdivisions highlighted how the state of damage particularly affects part of the building with greater altimetric development, identified within the auditorium (UST 2), proscenium arch (UST 3), stage and backstage (UST 4). In these areas significant deformation were surveyed, mainly due to specific structural deficiencies such as the lack of stiffening elements in the upper portions of tall and long load-bearing masonry walls, simple beam supports lacking connections, unrestrained masonry vaulted systems, unanchored partition walls, upper portions of masonry walls subjected to roof thrusts, low-resistance floors, and roof coverings/structures lacking adequate connections (Suppa, 2022).

Figure 7. View of the main façade of the Teatro Nuovo in Mirandola extracted from the point cloud during the data assessment phases (graphic elaboration by the authors).

Figure 8. Point cloud view of the north elevation (graphic elaboration by the authors).

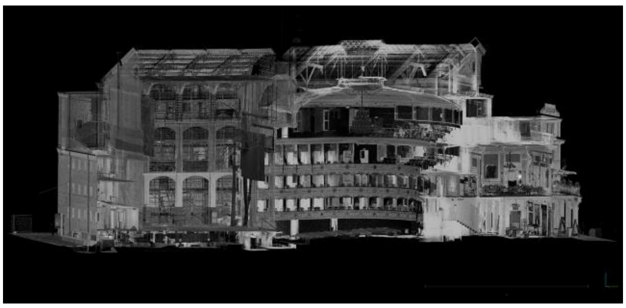

Figure 9. Axonometric section extracted from the point cloud (graphic elaboration by the authors).

In the auditorium (UST 2) and for the proscenium arch (UST 3), severe damage was recorded, most likely due to mechanism 13 (arches) of the A-DC form.

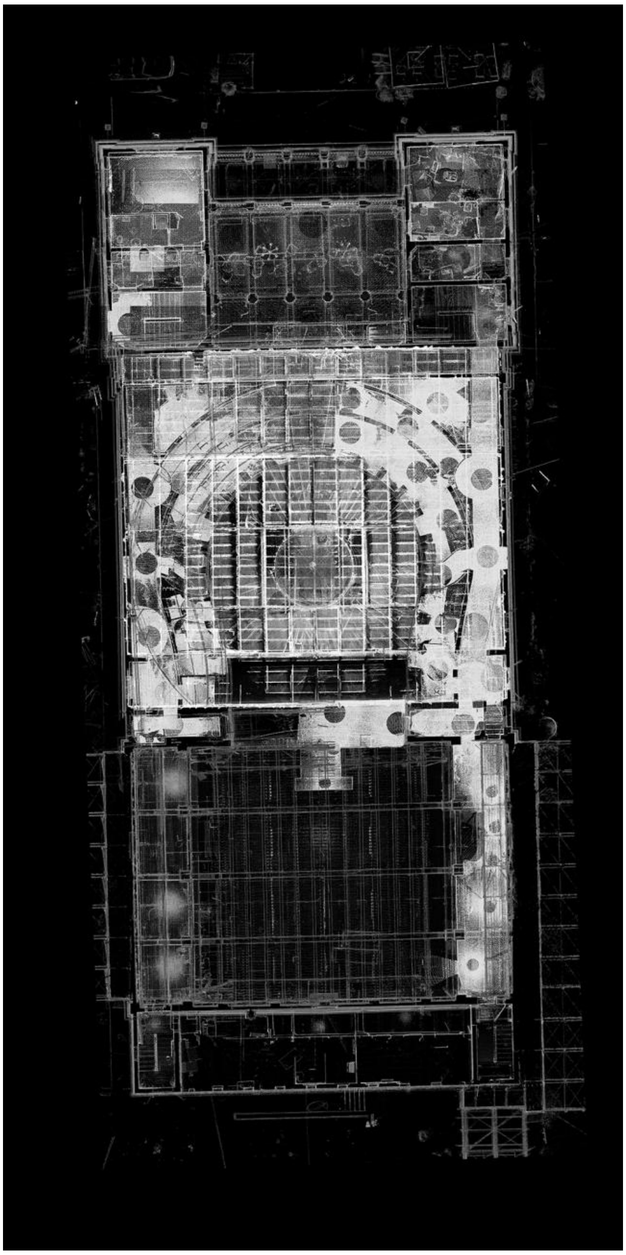

Figure 10. Floor plan of Teatro Nuovo in Mirandola, through the horizontal section of the 3D point cloud at the upper level (graphic elaboration by the authors).

The third level (L3) included advanced analyses using Finite Element Method (FEM) modelling integrated with a BIM framework, enabling detailed assessment of cracking patterns and seismic behaviour. The stalls and stage were identified as the most vulnerable areas, largely due to the absence of seismic-resistant vertical structures beyond the perimeter, which produced significant displacements and stresses in masonry walls and columns. Observed damage included wide cracks (up to 3–4 cm), overturning and sliding at column bases, crushing over 30% of elements, and out-of-lead conditions exceeding 2% along longitudinal walls due to inadequate connections and restraints. Additional cracking was detected in the cantilevered concrete gallery above the proscenium arch, affecting USTs 2 and 3.

Overall, UST 3 (proscenium arch) was classified as severely damaged, with weak masonry and poor mortar conditions predisposing it to local collapse mechanisms under seismic forces. The auditorium (UST 2) also exhibited severe damage to the masonry columns of the upper tier of boxes supporting the stage trusses, requiring urgent reinforcement. The analysis highlighted the prevalence of kinematic mechanisms, delineating vulnerable masonry profiles prone to overturning and flexural failures.

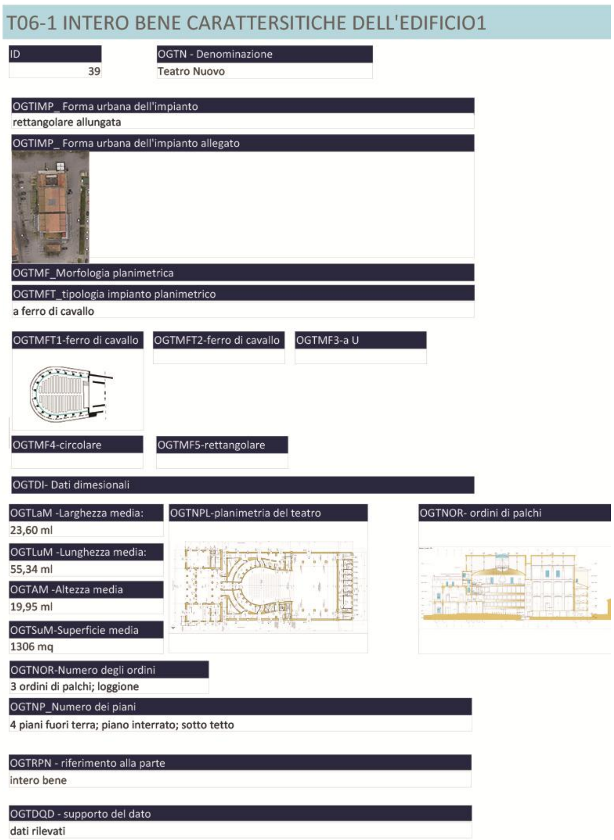

Figure 11. Damage survey sheet of the Teatro Nuovo in Mirandola (graphic elaboration by the authors).

5. Conclusions

The study underscored the value of integrated documentation in the field of cultural heritage as a means to devise strategies for proactive conservation and management, while also emphasizing the significance of systematic data collection for generating advanced knowledge. Information such as historical evolution, morpho-typological, structural, technological, geospatial data, state of conservation, and previous interventions provided the basis for defining preventive maintenance and management actions.
This research was driven by the need to systematically record and manage data from post-earthquake damage assessment forms, using the region's Web GIS digital platform for cultural heritage (Spettu et al., 2023). The primary goal was to establish standardised data analysis and digitisation approaches for effective seismic risk management and mitigation.
The implementation of the integrated survey workflow facilitated the collection of both quantitative and qualitative information within a hierarchical taxonomic matrix.
A preliminary knowledge phase involved a morpho-typological analysis and a critical-comparative study of MIC damage survey forms, while, to better understand Italian-style historical theatres, a detailed morpho-typological study was performed. This analysis was crucial for documenting the "theatre space's syntax", highlighting issues from initial damage assessments and aiding in understanding the complex relationships between architectural features and seismic vulnerability (Suppa et al., 2023). Further collaboration with the Agenzia Regionale per la Ricostruzione - Sisma 2012 resulted in the inspection of 11 sample venues to analyse professional survey and representation techniques for restoration purposes.
The analysis was also extended to the regional extra-crater area of Romagna to gain a comprehensive understanding of historical theatre typology. Findings revealed limitations in the existing MiC models for theatre damage assessment due to their generic nature. This highlighted the need for an *ad hoc* damage sheet (Suppa, 2022; Suppa et al., 2025) specific to theatres (Fig. 11), based on a homogeneous and hierarchical taxonomy derived from national and international standards (De Luca, 2024).
The research allowed opening up some issues and criticalities, to be furtherly investigated (access to complex information, subjective-qualitative data, issues in parametric modelling for geometrically representing deformations).
Future investigations can be focused on explorations on connections between datasheets and different interdisciplinary digital environments, analysing current semantic platforms and their potential central role in supporting the integrated workflow's setting up.

Acknowledgements

The research is part of the PhD thesis "Optimisation of survey procedures and application of integrated digital tools for seismic risk mitigation of cultural heritage: the Emilia-Romagna damaged theatres" developed by Martina Suppa within the International Doctorate in Architecture and Urban Planning, University of Ferrara – Polis University; supervisor Marcello Balzani; external experts Federica Maietti, Fabiana Raco.
The research is funded with European Social Fundings of the Operational Programme 2014/2020 Regione Emilia-Romagna: High Competences for Research, for Technology Transfer and Business / Three-year High Skills Plan for Research, Technology Transfer and Entrepreneurship, under Legislative and Representative Assembly No. 38 of 10/20/2015, thematic objective 10 of the ERDF ESF 2014/2020.

The 3D survey of the Teatro Nuovo in Mirandola has been developed by Zenith Ingegneria, Ferrara, Italy.

Although the paper was written in close collaboration between the authors, the authorship of the paragraphs is as follows:
MS is author of chapters 1.2, 2.2, 3, 4.
FM is author of chapters 1.1, 2.1.
LR is author of chapters 3.1, 5.
MP provided the 3D survey and the database from which graphic representations from the point cloud were extracted.

References

Amoruso, G., Sdegno, A., Riavis, V., 2016. Virtual reconstruction of an illusory space. The relief-perspective by Giovanni Maria da Bitonto in Bologna. In Felip Miralles, F., Gual Ortí, J., Cabeza González, M., García-García, C. (Eds.), *Drawing, building, dreaming. Research on graphic expression applied to building*, 453–465. Tirant Lo Blanch, Valencia.

Bonazza, A., Maxwell, I., Drdácký, M., Vintzileou, E., Hanus, C., 2018. *Safeguarding Cultural Heritage from Natural and Man-Made Disasters. A comparative analysis of risk* *management in the EU*, European Commission, © European Union.

Bonazza, A., Sardella, A., 2023. Climate Change and Cultural Heritage: Methods and Approaches for Damage and Risk Assessment Addressed to a Practical Application. *Heritage*, 6-4, 3578–3589.

Bondoni M.S. (Ed), 1982: *Teatri storici in Emilia-Romagna*. Grafis Edizioni, Bologna.

Brunetti, B., 2016. I plafoni lignei dei teatri all'italiana in Emilia: materiali, tecniche costruttive, elementi di vulnerabilità. PhD Thesis, Alma Mater Studiorum Università di Bologna. Dottorato di ricerca in Architettura, 28 Ciclo. 10.6092/unibo/amsdottorato/7672.

Brusaporci, S., Maiezza, A. Tata, A., 2018. A Framework for Architectural Heritage HBIM Semantization and Development. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2, 179–184.

Codiglione, M., Mazzacca, G., & Remondino, F., 2024. Dimensional discoveries: Unveiling the potential of 3d heritage point clouds with a robust ontology framework. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-2/W4-2024, 119-125.

Colucci, E., Matrone, F., Noardo, F., Assumma, V., Datola, G., Appiotti F., Bottero, M., Chiabrando, F., Lombardi, P., Migliorini, M., Rinaldi, E., Spanò, A., Lingua, A., 2024. Documenting cultural heritage in an INSPIRE-based 3D GIS for risk and vulnerability analysis. *Journal of Cultural Heritage Management and Sustainable Development*, Vol. 14 No. 2, 205–234.

Croce, V., Caroti, G., Piemonte, A., De Luca, L., Véron, P., 2023. H-BIM and Artificial Intelligence: Classification of Architectural Heritage for Semi-Automatic Scan-to-BIM Reconstruction. *Sensors*, 23(5), 2497.

Datola, G., Assumma, V., Appiotti, F., Bottero, M., Rinaldi, E., Campostrini, P., Lombardi, P., 2024. The ResCult project: Implementation of the risk analysis interface for the Church of Santa Maria dei Miracoli and the Covent of San Nicola (Italy). *Journal of Cultural Heritage,* 67, 164–182.

De Luca, L., 2024. A digital ecosystem for the multidisciplinary study of Notre-Dame de Paris. *Journal of Cultural Heritage*, 65, 206–209.

Di Giulio, R., Maietti, F., Piaia, E., Medici, M., Ferrari, F., and Turillazzi, B., 2017. Integrated Data Capturing Requirements for 3D Semantic Modelling of Cultural Heritage: the INCEPTION Protocol. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W3, 251–257.

Empler, T., Caldarone, A., Rossi, M.L., 2021. BIM Survey. Critical Reflections on the Built Heritage's Survey. In C. Bolognesi & D. Villa (Eds.), *From Building Information Modelling to Mixed Reality*, 109–122. Springer, Cham.

Grilli, E., Remondino, F., 2020. Machine Learning Generalisation across Different 3D Architectural Heritage. *ISPRS International Journal of Geo-Information*, 9(6), 379.

Iadanza E., Maietti F., Medici M., Ferrari F., Turillazzi B., Di Giulio R. 2020. Bridging the Gap between 3D Navigation and Semantic Search. The INCEPTION platform. *IOP Conf. Ser.: Mater. Sci. Eng*. 949 012079.

Ioannidis, C., Verykokou, S., Soile, S., Istrati, D., Spyrakos, C., Sarris, A., Akritidis, D., Feidas, H., Georgoulias, A.K., Tringa, E., et al. 2024. Safeguarding Our Heritage—The TRIQUETRA Project Approach. *Heritage* 7,2, 758–793.

Libro, A., 2019. Il rilievo del danno al patrimonio storico-artistico e i primi interventi di messa in sicurezza, Paesaggio Urbano, 1/2019, 147–151.

Matrone, F., Lingua, A., Pierdicca, R., Malinverni, E. S., Paolanti, M., Grilli, E., Remondino, F., Murtiyoso, A., Landes, T., 2020. A Benchmark for Large-Scale Heritage Point Cloud Semantic Segmentation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2020, 1419–1426.

Romão, X., Bertolin, C., 2024. Risk protection for cultural heritage and historic centres: Current knowledge and further research needs. *International Journal of Disaster Risk Reduction*, 67, 102652.

Salonia, P., 2023. Cultural Heritage at Risk: Let's Give Intelligence to our Technologies. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2 (2023), 1387–1394.

Spettu, F., Achille, C., Fassi, F., Della Giovampaola, I., 2023. Web Platforms for Cultural Heritage Management: The Parco Archeologico del Colosseo Case Study. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2-2023, 1493–1500.

Suppa, M., 2022. *Optimization of survey procedures and application of integrated digital tools for seismic risk mitigation of cultural heritage: The Emilia-Romagna damaged theatres*. Doctoral thesis, Institutional Archive of the University of Ferrara. https://hdl.handle.net/11392/2501203.

Suppa, M., Maietti, F., Raco, F., 2023. Documenting Theatres as Spaces for 'Transitions'. In Cannella M., Garozzo A., Morena S. (Eds.). *Transitions. Proceedings of the 44th International Conference of Representation Disciplines Teachers*. FrancoAngeli, Milano, 3216–3225.

Suppa, M., Vona, V., Zanazzi, E., 2025. 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. In Balzani, M., Maietti, F., Raco, F. (Eds), *Heritage at Risk. Improving Resilience and Awareness towards Preservation, Risk Mitigation and Governance Strategies*. CRC Press, Boca Raton, 326–337.

Teruggi, S., Grilli, E., Fassi, F., & Remondino, F., 2021. 3D surveying, semantic enrichment and virtual access of large cultural heritage. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, VIII-M-1-2021, 155–162.

Ziroldi, G. (Ed.), 2005: *I cento anni del Teatro Nuovo di Mirandola 1905 – 2005*. Grafiche "Il Dado", Mirandola.