Numerical damage assessment of a medieval masonry castle under differential settlements

C. Ferrero[1], G. L. S. Sacco[2], and C. Calderini[3]

[1]Postdoctoral researcher, Delft University of Technology, Delft, The Netherlands, email: C.Ferrero@tudelft.nl

[2]Postdoctoral researcher, University of Genoa, Genoa, Italy, email: giulioluciosergio.sacco@edu.unige.it

[3]Professor, University of Genoa, Genoa, Italy, email: chiara.calderini@unige.it

ABSTRACT

Historic masonry buildings are often affected by complex damage patterns resulting from multiple interacting actions, including differential settlements. This study presents the numerical damage assessment of the Doria Malaspina Castle, a medieval masonry structure located atop a hill in the village of Calice al Cornoviglio, Italy. The building exhibits crack patterns that, according to previous studies, may be associated with differential settlements, among other contributing factors. To accurately identify the causes of the existing damage, a three-dimensional finite element (FE) model of the entire castle was developed, and nonlinear static analyses were conducted to evaluate its structural response under three differential settlement scenarios, defined based on soil stratigraphy and observed damage patterns. Comparison of the damage predicted numerically with the crack patterns surveyed on-site provided insight into the settlement scenario most consistent with the observed damage.

Keywords: structural damage assessment, historic masonry buildings, finite element modelling, nonlinear static analyses, differential settlements.

INTRODUCTION

Understanding the causes of damage in historic masonry buildings represents a challenging task. These structures typically have life spans of several centuries and may have been subjected over time to various actions, including earthquakes, landslides, settlements, subsidence, and material degradation, among others. Consequently, damage often results from the combined effects of multiple interacting actions. In addition, architectural and structural alterations carried out over the centuries may have modified the original fabric and static equilibrium of the buildings, leading to further damage (Roca et al., 2010).

Structural analysis using advanced numerical methods, such as the finite element (FE) method, represents a powerful tool for investigating damage and deformations in historic masonry structures. These methods allow the simulation of different actions and damage scenarios and are particularly suitable for historic masonry buildings, as they can accurately reproduce complex geometries (D'Altri et al., 2020).

This paper presents the application of advanced numerical methods to analyse the damage patterns observed in a historic masonry building and to identify their potential causes. The case study is the Doria Malaspina Castle, a historic masonry structure located in the village of Calice al Cornoviglio, Italy. The building exhibits a complex crack pattern affecting both vertical and horizontal structural elements. Preliminary numerical analyses, combined with historical research, suggested that differential settlements may be responsible for part of the observed damage (Ferrero et al., 2025). Since no direct information on ground movements in the area of the castle is available, several differential settlement scenarios were formulated as hypotheses in this study. These scenarios were defined by considering the soil stratigraphy, geological setting, and the crack patterns observed in the building.

A three-dimensional finite element model of the entire castle was then developed, and numerical analyses were carried out to evaluate the building response under the proposed differential settlement scenarios, with the aim of improving the understanding of the mechanisms responsible for the observed damage.

DORIA-MALASPINA CASTLE

Description of the structure

The Doria Malaspina Castle is a standalone structure located in the village of Calice al Cornoviglio, Italy (Figure 1). The building has a trapezoidal plan and is arranged over four level, one of which is partially underground. Two circular towers, hereafter referred to as the north and east towers, are located at the northern and eastern corners of the structure, respectively. An external staircase runs along the southwest façade, while a terrace supported by buttressing arches is positioned along the south-east façade.

The current geometry of the building was shaped by successive construction phases identified through historical research (Boato et al., 2023):

1. Phase 1 (13th–15th centuries): construction of the east tower and the perimeter walls at the ground and first levels, excluding the southwest façade.
2. Phase 2 (16th–17th centuries): construction of the internal walls at all levels, the two lower levels of the north tower and the southwest façade, the external walls of the upper two levels, the vaulted diaphragms, and the roof.
3. Phase 3 (18th–19th centuries): addition of a terrace on the south-east side.
4. Phase 4 (20th century): reconstruction of the two upper levels of the north tower following their collapse caused by an earthquake that struck the area in 1920.

The structural system of the castle is entirely composed of masonry. Load-bearing masonry walls extend over the full height of the building, while masonry vaults of various types (cross, barrel, and pavilion) cover the rooms at all levels. The only exception occurs in the north tower, where the original upper masonry vault was replaced by a reinforced concrete slab.

The walls are made of two types of stone masonry. Barely cut stone masonry (M1) is found in walls dating from phases 1 and 2, while roughly cut stone masonry with good texture (M2) characterizes walls from phases 3 and 4. This latter type of masonry also forms the vaults of the ground and first floors, while the vaults of the second floor are built in brick masonry.

The pitched roof has a timber structure that has undergone substantial modifications over time (Boato et al., 2023). Originally, purlins rested on the internal walls, except in the corner rooms, where horizontal beams and struts provided support. The purlins carry timber rafters, wooden planks, and a slate covering.

Geological settings

The castle is situated on the crest of a steep hill overlooking the village of Calice al Cornoviglio. The geological setting of the site is characterized by the presence of three main lithostratigraphic layers (see Figure 1b). The uppermost layer consists of an incoherent to semi-coherent detrital deposit derived from progressive weathering, fracturing, and disaggregation of the underlying rock mass. This layer extends from the ground surface to depths ranging approximately between 1.8 and 4.0 m below the ground level. Beneath this, a highly weathered and fractured rocky substratum is present, which can be assimilated to a coarse detrital deposit with moderate compaction. This layer extends from approximately 4 to 7 m below ground level and represents the transition between the superficial detrital cover and the deeper, more competent bedrock. The bedrock consists of a moderately to slightly weathered and fractured rock mass (Angiolini, 2023). In some areas, the bedrock locally crops out at the surface, while in others it is concealed beneath the detrital cover.

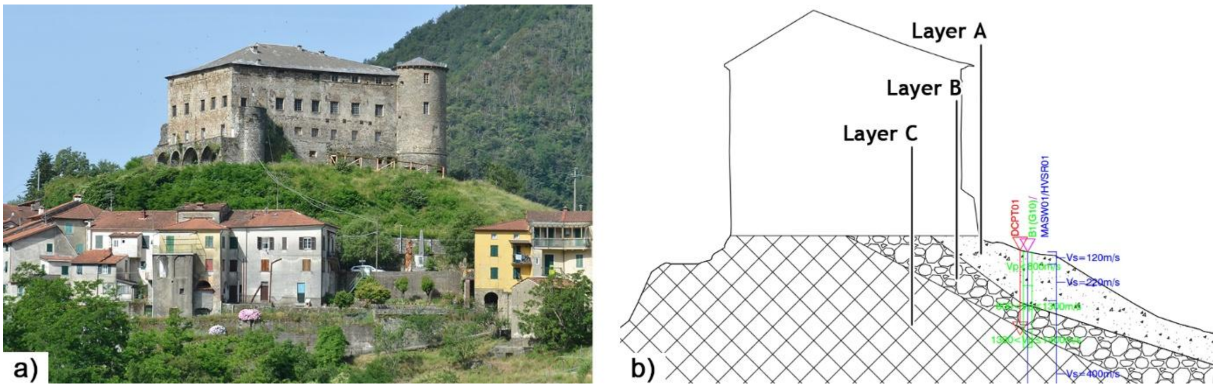

Figure 1. The Doria-Malaspina Castle: a) external view; b) stratigraphic section of the soil (Angiolini, 2023)

Damage and deformation

On-site inspections were conducted in 2023 in the Doria-Malaspina castle to survey the existing damage. Figure 2 presents the crack patterns observed in walls and vaults at the different levels of the building. Cracks are classified as thin, medium, and large according to their width (Ferrero et al., 2021).

Figure 2. Crack patterns survey: a) ground floor; b) first floor; c) second floor; d) attic.

The vaults exhibit widespread cracking throughout the building. The most significant damage pattern is observed in the rooms adjacent to the north-east façade, where the vaults at the ground, first, and second floors present cracks predominantly oriented parallel to that façade. In the eastern corner room, cracks encircling the east tower are observed at the first floor (Figure 2b), whereas diagonal cracks affect the vault at the second floor (Figure 2c). In addition, a large longitudinal crack is visible at the intrados of the vault in the corridor along the west façade at the ground floor (Figure 2a).Thin to medium radial cracks are also present in the vaults of the north tower at the ground and first floors (Figure 2a-b).

Cracking is also observed in the vertical structural elements, particularly in the walls orthogonal to the north-east façade at different levels. At the first and second floors, vertical and diagonal cracks are present in the walls above door openings, aligning with the cracks observed in the adjacent vaults. At the attic level, large subvertical cracks affect the walls orthogonal to the north-east façade. Additional diagonal cracks are observed below the attic windows of the north-east façade and between the windows at the first and second floors of the south-east façade.

In addition to the damage described above, the castle experienced severe damage during the earthquake that struck the surrounding area in 1920 (Boato et al., 2023). The exact location of the cracks associated with this event is unknown today, as they were not documented and were subsequently repaired (Ferrero et al., 2025).

The crack patterns observed in the building suggest that it may have experienced differential settlement over time, particularly affecting the north-east façade (excluding the north tower). This hypothesis is supported by the series of cracks observed in the vaults of the ground, first, and second floors, which are oriented parallel to the north-east façade, as well as by cracks in the internal walls orthogonal to that façade. The diagonal cracks affecting the vault of the eastern corner room on the second floor (see Figure 2c) indicate that this differential settlement may have also affected the south-east façade, which was constructed during the same phase as the north-east façade. To verify this hypothesis, the actual geometry of the south-east façade was analysed using a laser scanner survey to identify potential deformations. To this end, the profiles of horizontal elements (i.e., window sills and lintels, the top of the buttressing arches, and the eaves line) were compared with horizontal reference lines, as done in Sacco et al. (2023). This comparison, reported in Figure 3, suggests an increasing vertical settlement of the façade from left to right, in the direction of the east tower.

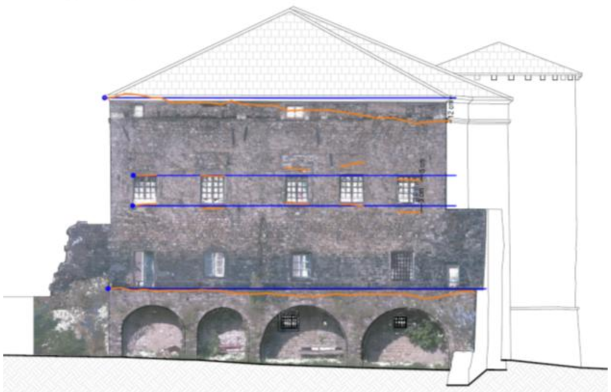

Figure 3. *Deformation analysis of the south-east façade. In blue: reference horizontal lines; in orange: amplified deformations of the architectural elements relative to the horizontal plane.*

STRUCTURAL ANALYSIS

Numerical model

The finite element (FE) model of Doria Malaspina Castle was created using ANSYS Mechanical 2021 (Ansys Inc. 2021). The geometry of the castle was derived from a 3D point cloud obtained through a laser scanner survey. Due to the number and complexity of the vaulted masonry diaphragms present at all levels of the building, the geometry of the vaults was generated using a semi-automatic parametric approach, implemented through a custom script developed in Grasshopper for Rhinoceros 7 (Sacco & Battini, 2025). Each vault was modelled as a combination of a structural cross-section and a non-structural part (infill). The thickness of the structural cross-section was determined based on endoscopy tests (Calderini & Boato, 2023).

The geometric model of the castle included the entire building, except for non-load-bearing interior walls, the exterior staircase, and the roof. Loads transmitted by the roof were applied as distributed masses on top of the attic walls.

A macro-modelling approach was adopted to represent masonry, which was assumed to behave as a continuous and homogeneous material (Lourenço, 1996). Both walls and vaults were modelled using four-node linear tetrahedral elements. Material nonlinearity was applied to the stone and brick masonry, as well as to the vault infills, while reinforced concrete elements (e.g., the north tower slab, and window lintels) were modelled as linear elastic. The nonlinear behaviour of masonry was simulated using the Drucker-Prager Concrete model available in ANSYS, combined with a Fracture Energy model to capture both softening and hardening. Due to the lack of experimental data, material properties were derived from the Italian Building Code (MIT, 2018) and relevant literature (Angelillo et al., 2014). The main material properties adopted in the numerical model are reported in Table 1.

Table 1. *Material properties used in the FE model (Ferrero et al., 2025).*

Material	$f_{c,u}$ **[MPa]**	$f_{c,b}$ **[MPa]**	f_t **[MPa]**	E **[MPa]**	ν **[-]**	w **[kN/m^3]**
Stone masonry M1	2.67	3.07	0.093	1230	0.2	20
Stone masonry M2	1.93	2.21	0.083	1740	0.2	21
Brick masonry	1.93	2.21	0.074	1500	0.2	18
Vaults infill	0.50	0.58	0.025	25	0.2	12
Reinforced concrete	-	-	-	31500	0.2	25

$f_{c,u}$: uniaxial compressive strength; $f_{c,b}$: biaxial compressive strength; f_t: tensile strength; E: Young's modulus; G: shear modulus; ν: Poisson's ratio; w: unit weight

The nodes at the base of the model were fixed to provide boundary conditions during the application of dead loads and were subsequently used to impose differential displacements when simulating settlement scenarios (see Section below). Additional live loads associated with the building's use (areas prone to crowding) were applied as distributed masses at the extrados of the vault infills.

Nonlinear static analyses under differential settlements

Nonlinear static analyses were performed in ANSYS Mechanical 2021 to investigate the structural response of Doria Malaspina castle to differential settlements and evaluate whether they may be responsible for the observed damage.

Three different settlement scenarios were considered, each associated with a specific displacement field applied at the base of the FE model (Figure 4). The first displacement scenario, hereafter referred to as *Case I* (Figure 4a), consists of a global displacement field involving the entire foundation system. This scenario was derived from the stratigraphic sections of the site reported in Angiolini (2023), one of which is shown in Figure 1b. The profiles of the stratigraphic sections enabled the identification of the overall inclination and depth of the bedrock. Based on this information, an inclined displacement field combining vertical and horizontal components was defined, oriented toward the north-east along the maximum slope and inclined at approximately 27° with respect to the horizontal plane. The maximum displacement was imposed at the eastern corner of the castle, while no or negligible displacement was applied to the portion of the structure resting on the bedrock (i.e., the south-eastern portion).

The other two displacement scenarios, hereafter referred to as *Case II* and *Case III*, were defined based of the observed crack patterns and deformations. *Case II* (Figure 4b) aims to simulate the settlement of the north-east façade and east tower, as suggested by the crack patterns surveyed in the building (see Section *Damage and deformation*). The imposed displacement field consists of a uniform vertical displacement applied beneath the north-east façade and east tower only. To avoid convergence issues, smaller displacements tapering to zero were also applied at the base of the adjacent walls, preventing abrupt deformation discontinuities (Ferrero et al., 2025).

Case III (Figure 4c) aims to simulate a more widespread settlement involving both the north-east and south-east façades of the castle. The displacement field consists of a uniform vertical displacement beneath the north-east façade and east tower, as in *Case II*. In addition, a triangular vertical displacement, increasing toward the eastern corner, is imposed beneath the south-east façade and the buttressing arches. This displacement scenario is compatible with the results of the deformation analysis of the south-east façade. Similarly to *Case II*, smaller displacements tapering to zero were applied at the base of the adjacent walls to ensure numerical stability.

In all three cases, nonlinear static analyses were performed using a staged procedure. First, gravitational and live loads were applied incrementally over ten steps; subsequently, foundation displacements were imposed and gradually increased until the numerical solution failed to converge, which was interpreted as an indicator of loss of structural stability.

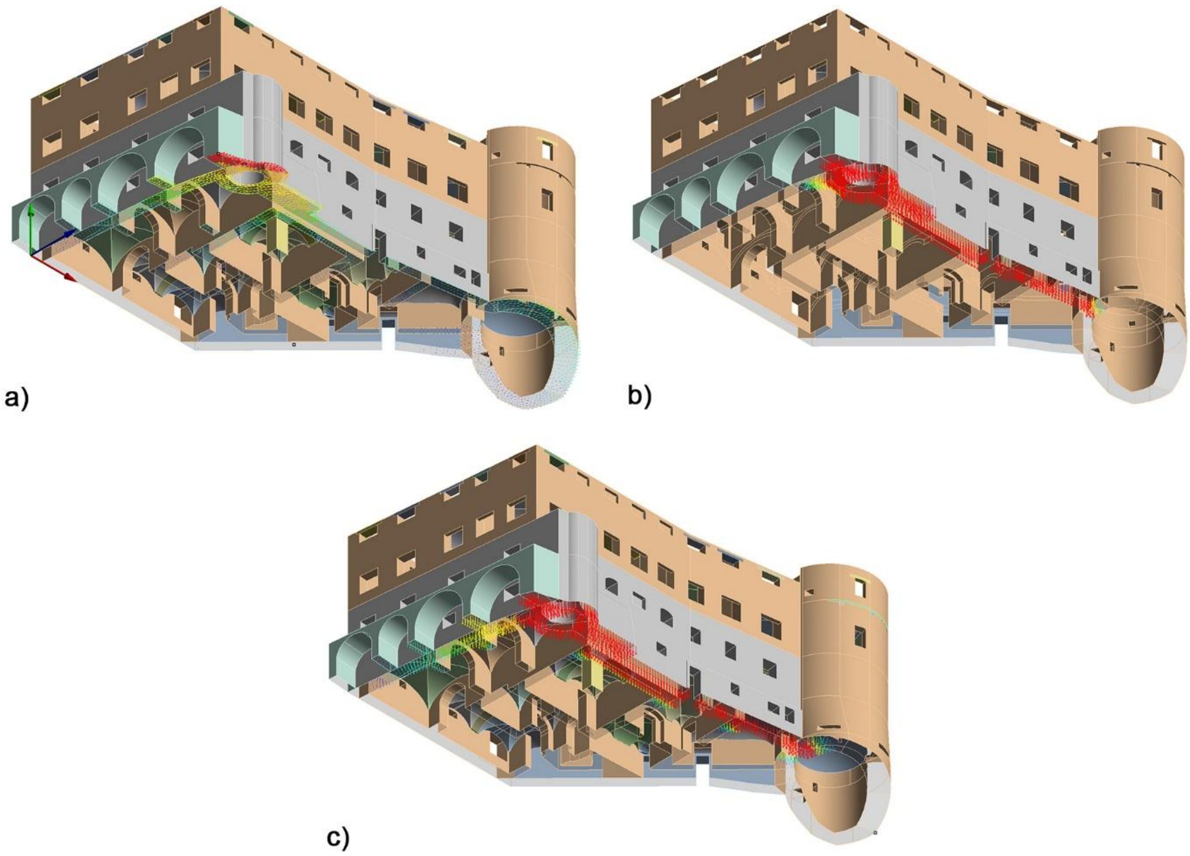

Figure 4. *Differential settlement scenarios considered in the numerical simulations: a) Case I, b) Case II, c) Case III.*

Figure 5 shows the damage patterns obtained at the intrados of the vaults and within the walls for the three differential settlement scenarios considered in the nonlinear static analyses. For each scenario, the damage was obtained at the last convergent step of the simulation, corresponding to the maximum displacement applied. The results are presented in terms of maximum principal plastic strain, which serves as an indicator of damage.

For *Case I* (Figure 5a-b-c), the damage patterns correspond to a maximum vertical displacement of 47 mm and maximum horizontal displacements of 89 mm and 25 mm in directions normal and parallel to the north-east façade, respectively. These values were obtained at the eastern corner of the buttressing arches. The damage is concentrated in the north-eastern and south-eastern portions of the building. Cracks are observed in the buttressing arches at midspan, propagating vertically along the south-eastern façade. Diagonal cracks are present in the vaults of the rooms adjacent to the north-eastern and south-eastern façades at both the ground and first floors. At the first floor, the cracks cut through the entire vaults. Additional cracks are observed on the eastern side of the vault of the noble hall at the second floor.
Figure 5d-e-f show the damage patterns obtained for *Case II* when a maximum vertical displacement of 52 mm is imposed under the north-east façade and east tower. Cracks oriented parallel to the north-

east façade appear in the vaults of rooms adjacent to this façade at the ground, first, and second floors. The vault of the eastern corner room exhibits cracks encircling the east tower on the first floor (Figure 5e) and diagonal cracks on the second floor (Figure 5f). Additionally, cracks are observed in the walls orthogonal to the north-east façade on the first and second floors, as well as in the attic.

Figure 5g-h-i illustrates the damage patterns obtained for *Case III* when a maximum vertical displacement of 60 mm is applied to the north-east façade and east tower. Similarly to *Case II*, cracks oriented parallel to the north-east façade appear in the vaults of rooms adjacent to this façade at the ground and first floors. Differently from *Case II*, where the damage is more concentrated on the north-east side of the building, in *Case III* the damage is also widespread on the south-eastern side of the building.

Comparison of the damage predicted by the numerical simulations with the crack patterns surveyed in the building (Figure 2) shows that the best agreement occurs for *Case II*. In this scenario, the numerical simulations accurately replicate the damage observed in the vaults and walls adjacent to the north-east façade. For *Case II*, cracks in vaults oriented parallel to the north-east façade are correctly predicted, but the crack patterns in the eastern and south-eastern corner rooms are not well reproduced. In contrast, the crack pattern predicted for *Case III* differs significantly from that observed on site. These results indicate that part of the existing damage can be attributed to a settlement of the north-east façade of the castle.

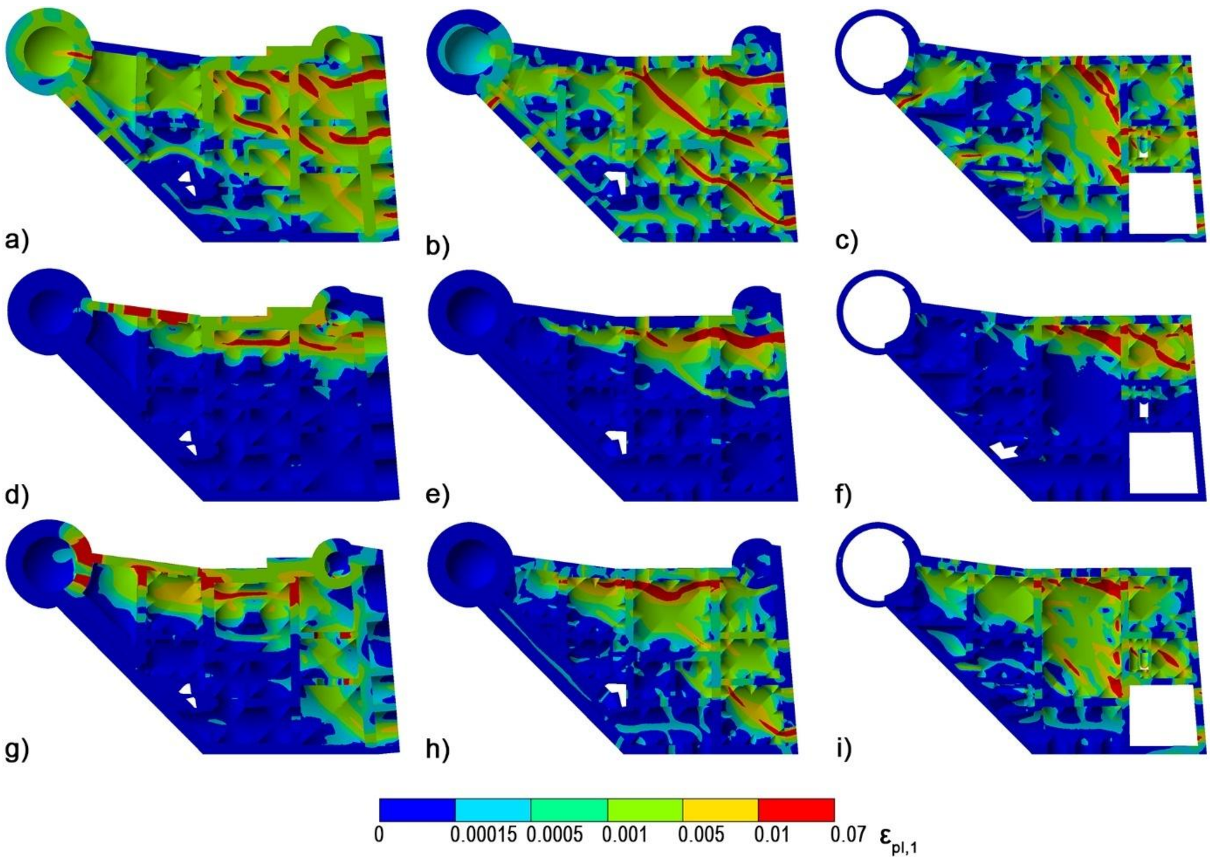

***Figure 5**. Crack patterns in vaults (intrados) and walls from nonlinear static analyses: a-b-c) Case I; d-e-f) Case II; g-h-i) Case III. For all cases, the left, middle, and right images correspond to the ground, first, and second floors, respectively. Results are presented in terms of maximum principal plastic strain.*

CONCLUSIONS

This paper aimed to identify the causes of the crack patterns observed in the Doria Malaspina Castle, a historic masonry building in Calice al Cornoviglio, Italy. Finite element modelling and numerical simulations were employed for this purpose. A three-dimensional FE model of the entire castle was developed based on a laser scanner survey, capturing the detailed geometry of walls and vaults. Three differential settlement scenarios, defined based on soil stratigraphy and observed damage, were simulated through nonlinear static analyses by applying appropriate displacement fields at the base of the model.

Comparison of the numerical results with the crack patterns observed on site suggests that the differential settlement of the north-east façade is likely responsible for the main damage observed in the building, as the predicted patterns closely match the surveyed ones. Other scenarios involving more global or extensive settlements misrepresented the actual damage distribution. These findings demonstrate that numerical simulations, combined with detailed geometrical modelling, provide valuable insight into the origin of existing damage and support informed strategies for the conservation of historic masonry structures.

ACKNOWLEDGEMENTS

The authors thank Prof. Anna Boato from the University of Genoa for providing information on the history and past damage of the Doria Malaspina Castle. They also gratefully acknowledge Dr. Geol. Matteo Angiolini for providing the geological data used in this study.

REFERENCES

Angelillo, M., Lourenço, P. B., & Milani, G. (2014). Masonry behaviour and modelling. In Mechanics of masonry structures (CISM Series). Springer.

Angiolini, M. (2023). Relazione geologica – Modellazione geologico-sismica dei terreni di fondazione del Castello Doria Malaspina nel Comune di Calice al Cornoviglio con esecuzione di indagini geognostiche [Technical report in Italian].

Ansys Ic. (2021). Ansys software documentation.

Boato, A., Calderini, C., & Ferrero, C. (2023). Archeologia dell’architettura e diagnosi del dissesto per una conoscenza integrata: Il caso del Castello Doria-Malaspina di Calice al Cornoviglio (SP). In Restauro dell’architettura. Per un progetto di qualità, sezione 3: Conoscenza per il progetto (530–538).

Calderini, C. & Boato, A. (2023). Relazione - Analisi della conformazione della struttura e delle sue fasi costruttive e alla diagnosi dei dissesti strutturali [Technical report in Italian].

D’Altri, A. M., Sarhosis, V., Milani, G., Rots, J. G., Cattari, S., Lagomarsino, S., Sacco, E., Tralli, A., Castellazzi, G., & de Miranda, S. (2020). Modeling strategies for the computational analysis of unreinforced masonry structures: Review and classification. Archives of Computational Methods in Engineering, 27(4), 1153–1185. https://doi.org/10.1007/s11831-019-09351-x.

Ferrero, C., Cambiaggi, L., Vecchiattini, R., & Calderini, C. (2021). Damage assessment of historic masonry churches exposed to slow-moving landslides. International Journal of Architectural Heritage, 15(8), 1170–1195. https://doi.org/10.1080/15583058.2020.1799259

Ferrero, C., Sacco, G., & Calderini, C. (2025). Multi-hazard structural damage assessment of historic masonry buildings: The case study of a medieval castle in northern Italy. In F. M. Mazzolani, R. Landolfo, & B. Faggiano (Eds.), Protection of Historical Constructions (Lecture Notes in Civil Engineering). Springer.

Lourenço, P. B. (1996). Computational strategies for masonry structures (PhD thesis). Delft University of Technology, Delft University Press.

MIT – Ministero delle Infrastrutture e dei Trasporti (2018). Norme tecniche per le costruzioni (D.M. 17 gennaio 2018, Suppl. ord. G.U. n. 42 del 20 febbraio 2018). Gazzetta Ufficiale della Repubblica Italiana.

Roca, P., Cervera, M., Gariup, G., & Pelà, L. (2010). Structural analysis of masonry historical constructions: Classical and advanced approaches. Archives of Computational Methods in Engineering, 17(3), 299–325. https://doi.org/10.1007/s11831-010-9047-7

Sacco, G., & Battini, C. (2025). Algorithmic modelling for scan-to-FEM process of a complex vaulted system. In Èkphrasis. Descrizioni nello spazio della rappresentazione / èkphrasis. Descriptions in the space of representation. Proceedings of the 46th International Conference of Representation Disciplines Teachers (3303–3322). FrancoAngeli. https://doi.org/10.3280/oa-1430-c926

Sacco, G., Ferrero, C., Battini, C., & Calderini, C. (2023). Combined use of deformation and structural analysis for the structural damage assessment of heritage buildings: A case study in the Liguria region (Italy). Engineering Failure Analysis, 146, 107154. https://doi.org/10.1016/j.engfailanal.2023.107154.