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Effect of slow-moving landslides on a vaulted masonry building: The case of San Carlo Borromeo church in Cassingheno (Genova)

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ABSTRACT: This paper presents the structural analysis of San Carlo Borromeo church, a masonry building located in Cassingheno (Genoa, Italy) in an area affected by a slow-moving landslide. A deep knowledge of the building in terms of geometry, structural configuration, history and construction phases was acquired by means of on-site surveys and archival research. The crack patterns were surveyed in detail and the deformations were studied through a point cloud obtained from a LIDAR survey. The comparison between the landslide direction and the damage observed showed discrepancies and suggested the presence of foundation settlements due to other phenomena. To identify the actual causes of damage, a finite element model (FEM) of the building in its hypothetical undeformed configuration was created. The geometry of such configuration was reconstructed starting from the point cloud obtained from the LIDAR survey and removing geometrical defects such as leaning of walls, deformation of vaults and inclination of tie-rods. To simulate the effects produced by the landslide and the foundation settlements on the building over time, nonlinear analyses were performed by imposing different displacement fields at the foundation plane in multiple steps. The damage predicted numerically was then compared with the one experienced by the building, showing good agreement.

1 INTRODUCTION

The study of the effects of slow-moving landslides on cultural heritage buildings is in its early stage. Therefore, in contrast to seismic threats, a standardized diagnostic procedure to easily assess this risk is still lacking. A first contribution to the topic was given by a large-scale study of several churches in the Liguria region (Ferrero et al. 2021a), which led to the identification of some recurrent damage mechanics associated with slow-moving landslides. Further investigations at a smaller scale showed the need to ensure a detailed knowledge of each single building and separate the effects of the landslide from the effects of other types of actions (subsidence, local foundations settlements, load changes, etc.).

This paper presents the structural analysis of San Carlo Borromeo church in Cassingheno (Genova). The church is located on a medium slope area affected by a slow-moving landslide and presented a complex damage distribution (crack patterns and deformations) not completely compatible with the landslide direction. The damage and deformations identified in San Carlo Borromeo church were critically analyzed with the aim of assessing whether they could be entirely attributed to the landslide acting in the area or not.

A detailed survey of the building, including laser scanning and photogrammetry, was performed to gather information about geometry, distortions, and crack patterns (Section 2). A

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historical research was also carried out to obtain a deep knowledge of history, architectural alterations, and construction phases. In addition, information about landslides and geotechnical soil characterization in the surrounding areas was collected (Section 3).

With the aim of assessing the causes of the damage observed in the church, a finite element model of the entire building in its initial hypothetical undeformed configuration was created. Nonlinear static analyses were then performed by imposing different foundation displacement fields at the base of the structure (Section 4). These displacement fields were defined based on the deformations and foundation settlements experienced by the church over time, which were in turn identified thanks to the laser scanner survey and the analysis of the building construction phases. This represents the main novelty of the work, since detailed information about the displacements underwent by a historic building during its entire life is not usually available. In the case of the church under consideration, the identification of displacements fields based on the actual displacements experienced also made up for the lack of data regarding magnitude and rate of the landslide movement (see Ferrero et al. 2021b). The effectiveness of adopting this strategy was verified by comparing the damage predicted by the numerical simulations with the crack patterns and deformations surveyed on site.

2 DESCRIPTION OF THE CASE STUDY

San Carlo Borromeo church is located in Cassingheno, a small village part of the municipality of Fascia (Genoa metropolitan area). The church and the village of Cassingheno are situated on a medium-low inclined slope (about 20°), which is likely to be the accumulation zone of a relict deep slide. In the area of interest, the soil consists of a thick layer (10–15 m) of very heterogeneous blanket (sand with clasts, clayey silts) separated from the bedrock (shales) by a transition zone (1–3 m) of weathered rock. The ground water table, which oscillates according to the seasonality, is located inside the blanket (Cambiaggi et al. 2021).

As shown in Figure 1, the entire village of Cassingheno lies on an active slow-moving landslide, which has an area of about 0.17 km^2 (Arpal 2020) and is classified as complex according to the *Atlante dei Centri Instabili della Liguria* (hereafter called Atalante et al. 2004). Within the framework of the REMOVER monitoring project of the Liguria Region, the landslide was monitored by means of inclinometers. All the instruments showed small movements of the blanket at variable depths along the slope and indicated a possible failure surface at a depth of about 9–12 m from the ground surface (Cambiaggi 2020).

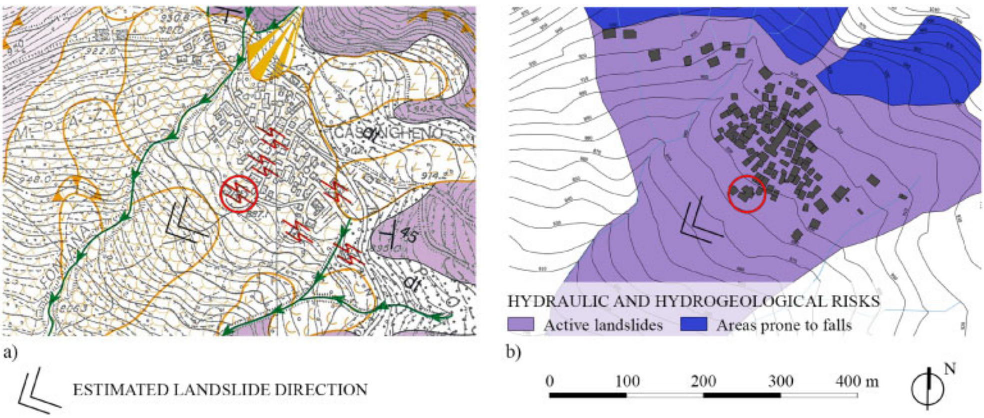

Figure 1. Landslide maps for the landslide affecting Cassingheno village and San Carlo Borromeo church (indicated with a red circle): a) *Atlante dei Centri Instabili della Liguria* (Federici et al. 2004), b) *Atlante dei Rischi Idraulici e Idrogeologici* (Autorità di bacino distrettuale del fiume Po 2017).

The landslide direction, indicated with an arrow in Figure 1, was found to be almost parallel to the longitudinal axis of the church. Following the same approach adopted in Ferrero et al. (2021a), the landslide direction was estimated on the basis of the orientation of the symbols used in the maps of the Atlante to represent landslide phenomena (Figure 1(b)).

San Carlo Borromeo church (Figure 2) has a single nave, a presbytery, a semicircular apse, two lateral chapels and a belltower. Including the apse, the church is about 20 m long and 6 m wide. The nave and the presbytery are covered with barrel vaults, while the apse has a hemispherical dome. The entire building (both walls and vaults) is made of stone masonry and is covered by a recently built wooden roof. A clergy house and a sacristy, respectively made of stone and brick masonry, are also present on the north-western side of the church.

No information about the foundation system of the church is available. However, since the church dates back (at least) to the end of the XVI century (see the following paragraph), it is reasonable to assume that the foundations are shallow and consist in an enlargement of the perimeter walls.

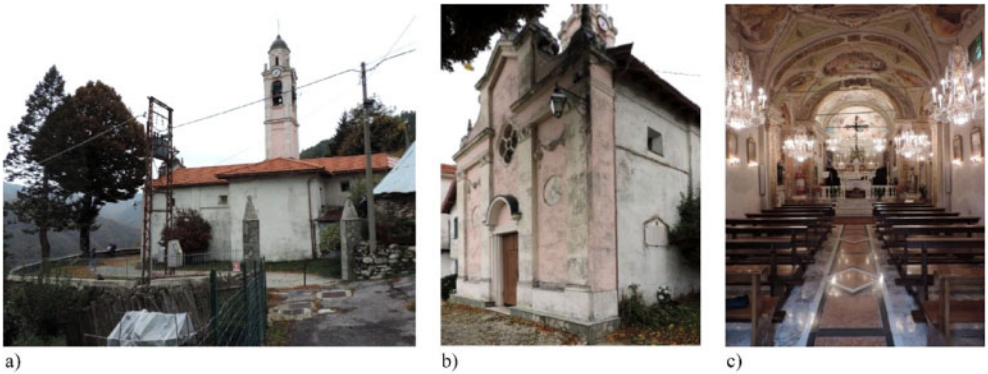

Figure 2. (a and b) Exterior. (c) Interior.

The building as it appears today is the result of significant transformations undergone over time. Although the historical information about the church is limited, different construction phases were identified through archeological and stratigraphical analysis (Cabella & Sacco 2020). The first document attesting the existence of the building as an oratory dates back to 1595 (Cazzulo et al. 1998). However, it is likely that the original core was built in late Middle Ages, since documents (Sanguigliani 1892) confirm the presence of the village of Cassingheno in the twelfth century. The original building was probably similar in shape to the current one but smaller and with a shorter belltower (Figure 3(a)). The apse and the base of the belltower are the only remaining

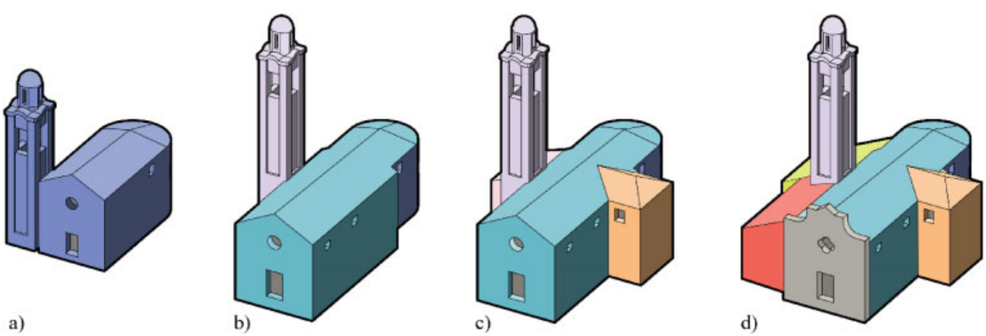

Figure 3. a) Original building - late Middle Ages. b) Church – before 1595. c) Right chapel – before 1879 d) Current configuration – early 19th sec.

parts of the original building, while the current nave, whose walls are not perfectly aligned with those of the apse, was constructed later with a size larger than the original one (before 1595). The current belfry was added at the same time of the enlargement of the nave or just after, leading to the configuration shown in Figure 3(b). Subsequently, before 1879, a sacristy and a chapel were built on the left and right sides of the church, respectively (Figure 3(c)). Between the end of the eighteenth century and the first half of the nineteenth century, San Carlo Borromeo church underwent further transformations, including the construction of the clergy house (colored in red in Figure 3(d)) and the reconstruction of the original sacristy, which brought the building to its present form (Figure 3(d)). An intervention to straighten the belltower was also carried out after the Second World War, hiding most of the rotation experienced by this structure over the centuries.

3 DAMAGE AND DEFORMATIONS

3.1 *Damage survey*

3.1.1 *Crack pattern*

Figure 4 shows the crack pattern of San Carlo Borromeo church. Since in 2019 the church underwent a restoration that partially hided the damage on the exteriors, the crack pattern surveyed by the authors in 2020 was integrated with the one reported in Memme (2019) and Ferrero et al. (2021a).

Extensive and severe damage is observed in the walls, in particular in the second bay behind the façade. In this bay, both the longitudinal walls are affected by a series of large diagonal cracks that originate from the level of the floor and propagate upwards towards the apse. In addition to these cracks, large diagonal cracks are observed in the longitudinal walls of the first bay of the nave and the presbytery. Both cracks progress upwards towards the façade of the church (Figure 4(b)).

Unlike walls, arches and vaults do not show severe cracking. A thin to medium longitudinal crack, oriented in same direction as the landslide, cuts the barrel vaults of nave and presbytery approximately at mid-span. Thin cracks with a slight concentric pattern around the belltower can also be observed.

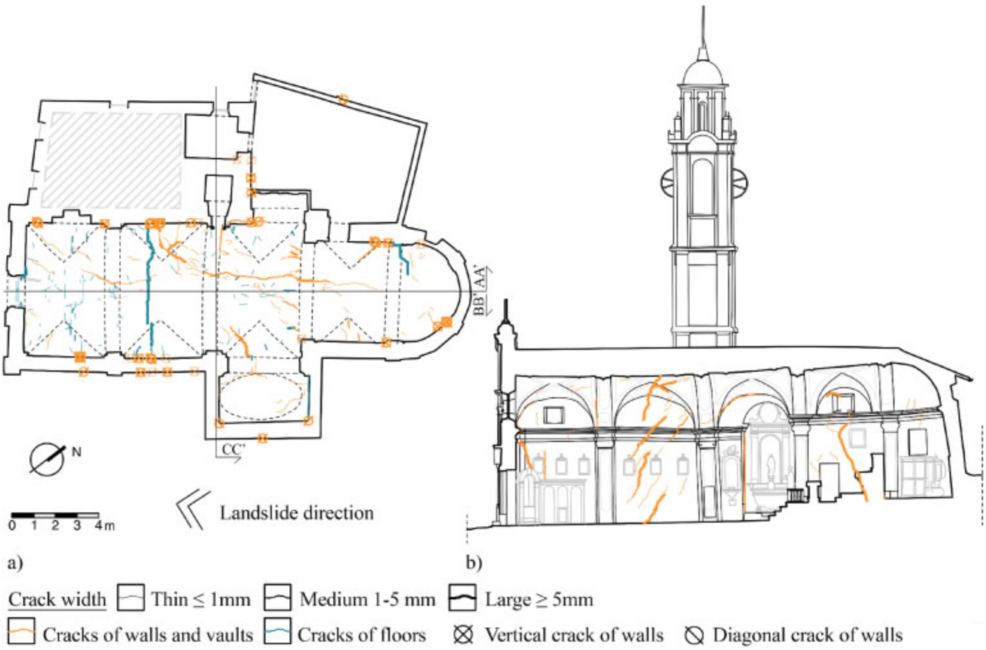

Figure 4. Crack pattern of San Carlo Borromeo church: a) plan, b) section AA'.

As can be seen from Figure 4(a), in the second bay behind the façade, the floor presents a large crack (12 mm wide), which crosses the entire nave and propagates transversally between the longitudinal walls. Thin to medium cracks with the same orientation were also observed in the first bay and the northernmost part of the right chapel. These cracks are oriented perpendicular to the direction of the landslide acting in the area.

3.1.2 *Deformations*

To study the deformations of the church a laser scanner survey was performed, and longitudinal and transversal sections were extracted from the point cloud.

From the analysis of the longitudinal section (Figure 5(a)), it can be seen that the whole building exhibits a significant rotation toward the valley, in the direction of the landslide. The more significant rotations were measured in the apse and presbytery. The presbytery vault was rotated by about 4.9°, the apse wall by 6.8°, and the moldings by 3°. In the nave, the floor, moldings, and pilasters show a rotation of only about 1.4°, while the barrel vault exhibits a deflection of about 20 cm in the center of the second bay. No significant rotations were measured in the façade.

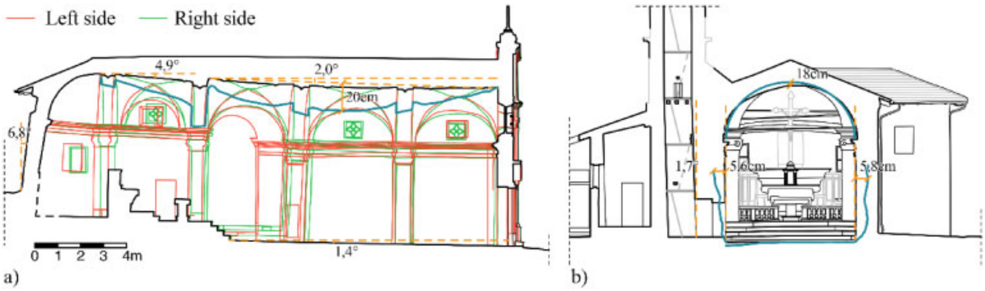

Figure 5. Deformation surveyed. a) Longitudinal section BB', b) transversal section CC' (the sections are indicated in the plan of the church in Figure 4).

From the analysis of the transversal section (Figure 5(b)), the walls of the nave were found to lean outwards. The right wall has the maximum rotation of 1.6° near the first pilaster from the façade, probably due to the thrust of the vault. The left wall, which experienced larger rotations, exhibits the maximum one in correspondence of the belltower, which presented the same rotation of 2.14°.

The deformation of the arches and barrel vaults was also assessed. To this aim, the original undeformed shape of these structural elements was reconstructed under three hypotheses: i) the original profiles were elliptical; ii) the length of the deformed and undeformed profiles remained constant during the deformation; iii) the original clear span of the arch was established when the walls were still vertical and the springings were at the same level. In the reconstruction, the thickness of cracks was also taken into account (for further details the reader is referred to Cabella & Sacco 2020). The first arch and the second arch from the façade were found to be significantly deformed and exhibit a deflection at the crown of about 22 cm and 18 cm with respect to the hypothetical undeformed shape, respectively (Figure 5(b)). Such a deflection is compatible with the deflection measured in the barrel vault.

A distortion of the façade in the horizontal plane was also observed.

Since the church was built in several construction phases, the presence of differential settlements was also verified. In particular, the differential settlement between the left and right parts of the building was assessed comparing the elevations of the floors, windowsills, tie rods, decorations, and moldings. For each pair of points in plan, several pairs of points in elevation were extracted from the point cloud and their heights were compared (Cabella & Sacco 2021).

From this analysis, three phenomena were observed. The left part of the church, from the apse to the belltower, underwent a larger vertical displacement (of about 5 cm) with respect to the right part.

The belltower underwent a localized settlement of about 11 cm, measured by comparing the height of the capitals of the pilasters on the left and right parts of the church. The localized settlement of the belltower can be easily identified in Figure 6, which shows the vertical distance between the points of the floor taken from the point cloud and their best fit plane passing through the floor (Pesci et al. 2011).

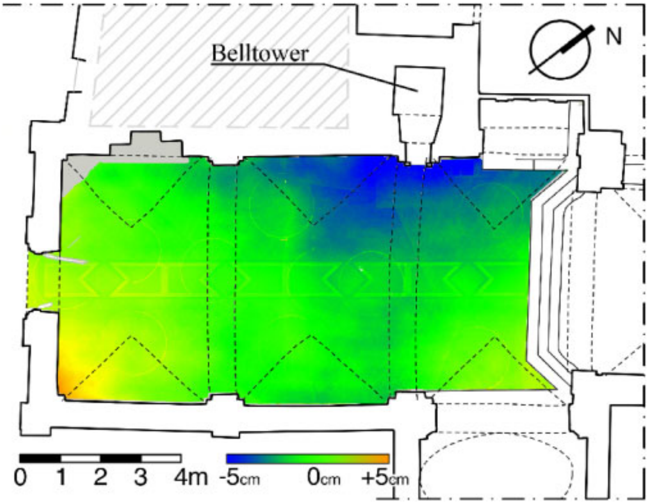

Figure 6. Local settlement of the belltower identified by analyzing the vertical distance between the points of the floor taken from the point cloud and the best fit plane passing through the floor.

In addition to the abovementioned phenomena, in the right chapel, the south-eastern wall (toward valley) was found to have settled 9 cm more with respect to the north-eastern wall.

3.2 *Critical damage assessment and identification of the displacement fields*

The damage and deformations identified in San Carlo Borromeo church were critically analyzed with the aim of assessing whether they could be entirely attributed to the landslide acting in the area or further phenomena could be involved.

As regards the crack pattern, the cracks of the floor oriented perpendicular to the landslide direction can be attributed to the horizontal component of the landslide movement and clearly indicate that the church suffered an extension in the direction of the acting landslide. However, the cracks in the barrel vault of the nave as well as the diagonal cracks in the walls on the left and right sides of the belltower, which progress upwards toward this latter, suggest a local settlement of the belltower. Such a settlement could also be responsible for the deformation of the second arch from the façade.

The analysis of the deformation and foundation settlements indicates that not all the damage suffered by the church was produced by the landslide. Indeed, while the vertical component of the landslide has reasonably caused of the global rotation of building (Ferrero et al. 2021a), it has hardly produced the differential settlement between the left and the right part of the building and the localized settlement of the belltower.

On the basis of the deformation and foundation settlements identified in San Carlo Borromeo church, four displacement fields, representing the displacements experienced by the building over time, were identified: a global displacement, affecting the entire church, and three local displacements. The global displacement is due to the landslide and has both vertical and horizontal components (Figure 7(a–b)), while the local displacements represent the vertical settlements of the left part of the church (Figure 7(c)), the belltower (Figure 7(d)), and the right chapel (Figure 7(e)).

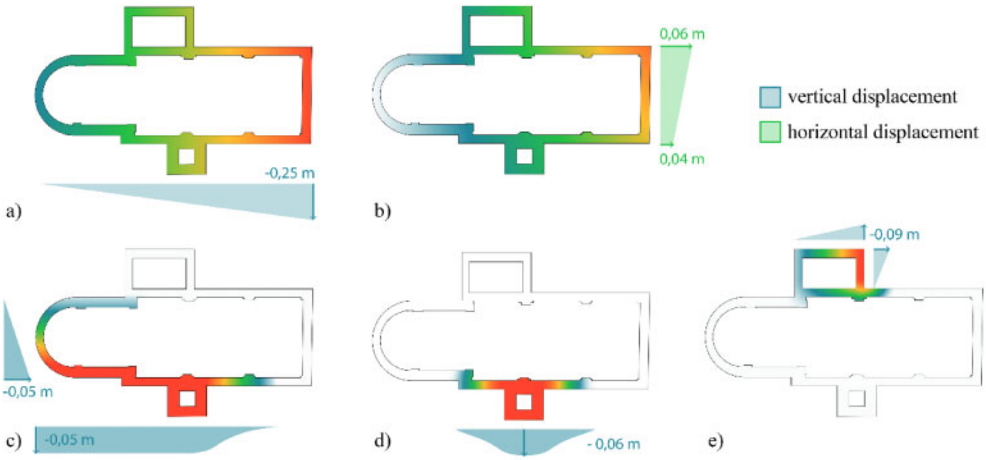

Figure 7. Displacement fields: a) vertical component of global displacement, b) horizontal component of the global displacement, c) left portion of the church, d) belltower, e) right chapel.

The value of the vertical component of the global displacement was estimated based on the displacements measured in the nave, while the value of the horizontal component was evaluated by considering the thickness of the cracks of the floor of the nave as well as the distortion of the façade in the horizontal plane. For further details on the definition of the displacement fields, the reader is referred to Cabella and Sacco (2021).

4 STRUCTURAL ANALYSIS

The structural analysis aims at identifying the causes of the damage and deformations observed in San Carlo Borromeo church. For this purpose, a FE model of the entire building was prepared, and nonlinear static analyses were performed considering different scenario of foundation displacements.

4.1 *Numerical model*

4.1.1 *Geometry*

A tridimensional model of the entire church was created in Rhinoceros (Robert McNeel & Associates 2018) and Ansys SpaceClaim (Ansys inc. 2020b) starting from the point cloud (Figure 8(a)) obtained by the laser scanner survey. To transform the surveyed deformed configuration of the building in a reference undeformed configuration (Figure 8(b)), several assumptions were made. In particular, all the deformations that were not consistent neither with the historical building techniques nor with the construction history were removed (Figure 8(b)): (i) the walls were assumed to be straight, vertical, and parallel in pairs; (2) the vaults and arches were modelled with their undeformed profiles defined in Cabella and Sacco (2021) and (3) the tie-rods were assumed to be perfectly horizontal.

The clergy house and the sacristy were not included in the numerical modelling, as they were not accessed during the inspections, and they do not have structural continuity with the walls of the church. The left chapel was not modelled because it was created within the space of the sacristy by adding thin brick walls.

Starting from the geometrical model, a FE model of the church was created in Ansys Mechanical (Ansys inc. 2020a) (Figure 8(c)). A macro-modeling approach was adopted to represent masonry, which was considered as a homogeneous material. The masonry walls and vaults as well as the tie

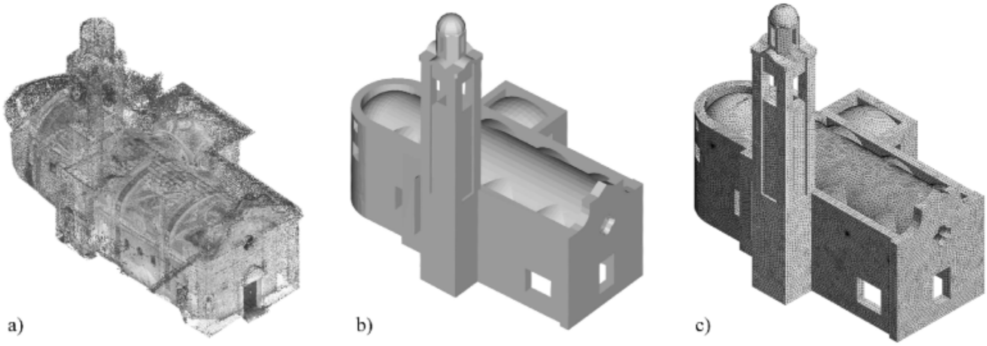

Figure 8. a) Point cloud model, b) geometrical model, c) mesh.

roads were modelled using ten nodes tetrahedrons solid elements (TET10). Mesh sizes of 20 cm and 1 cm were adopted for the solid and beam elements, respectively. The mesh for the solid elements was also refined in correspondence of the contact surface with the tie-roads. In total, the numerical model consists of about 1.1 million nodes and 700 thousand elements. All the degrees of freedom of the nodes at the base of the church were restrained to provide boundary conditions.

4.1.2 *Constitutive model and material properties*

The nonlinear behaviour of masonry was simulated using a perfect elasto-plastic model with a Drucker-Prager yield criterion. Due to the lack of experimental data, the mechanical properties were estimated based on the reference values suggested in the explanatory notes of the Italian building code (Circolare 21 gennaio 2019, n.7, table C.8.5.1 pg. 257) as well as on empirical relations. The Young's modulus E and uniaxial compressive strength f_{uc} were taken equal to the minimum values provided by the Italian Circolare for ashlar stone masonry. The volumetric density ρ suggested for this type of masonry was also adopted. The use of the Drucker-Prager criterion as implemented in Ansys also required to define a biaxial compressive strength f_{bc} and a uniaxial tensile strength f_{ut}, which were evaluated based on the following relations (Jiang & Zhao 2015):

$$f_{bc} = 1,5 f_{uc} \tag{1}$$

$$f_{ut} = 1,4 (f_{uc}/10)^{2/3} \tag{2}$$

The physical and mechanical properties of the stone masonry of walls and vaults are reported in Table 1.

Table 1. Physical and mechanical parameters adopted for stone masonry.

Young's modulus	E	1,5 GPa
Poisson's ratio	ν	0,18
Volumetric density	ρ	2050 kg/m^3
Uniaxial compressive strength	f_{uc}	2,6 MPa
Biaxial compressive strength	f_{bc}	3,0 MPa
Uniaxial tensile strength	f_{ut}	0.46 MPa

A bilinear isotropic hardening model was used to describe mechanical behaviour of the steel tie-rods, whose mechanical properties are indicated in Table 2.

4.1.3 *Loads and foundation displacements*

The roof was not included in the FE model due to the lack of a proper survey. Based on the information provided in Varese (2015), the loads transmitted by the roof were calculated and

Table 2. Physical and mechanical parameters adopted for the steel of the tie-rods.

Young's modulus	E	210 GPa
Poisson's ratio	ν	0,3
Volumetric density	ρ	7850 kg/m^3
Yield stress	σ_0	250 MPa
Tangent modulus	E_t	1,45 GPa

applied as distributed loads at the top the walls and as point loads at the extrados of the vaults. No pretension was considered for the tie roads.

Different combinations of vertical and horizontal displacements were applied at the base of the church to simulate the foundation settlements as well as the displacements produced by the landslide. In particular, three displacements scenarios were defined taking into consideration the displacement fields identified in Section 3.2 as well as the history and transformations of the building (Cabella & Sacco 2021). In each scenario, the dead loads were applied first; then, different combinations of global and local foundation displacements were imposed. For the sake of conciseness, since the results of the numerical simulations carried out with the different scenarios are very similar, only one displacement scenario is described in this paper. In this case, the landslide was assumed to be acting for the entire lifespan of the church. The global displacement produced by this phenomenon was divided in three steps. The displacements of the belltower and that of the left portion of the church were imposed in the second step, while the displacement of the right chapel was applied in the third step.

4.2 *Results of nonlinear static analyses*

In this section, the results of the FE simulations are presented in terms of maximum principal plastic strain, which provides an indication of the crack formation.

Figure 9 shows the results obtained in correspondence of each step of the displacement scenario. As shown in Figure 9(a), the application of the dead loads did not cause any plastic deformation, which, in contrast, appeared as soon as foundation displacements were imposed (Figure 9(b)). The application of the global landslide displacement caused a concentration of plastic deformation at mid-span of the arches that separate the nave from the lateral chapels, probably due to the smaller stiffness of this portion of the church (Figure 9(b)). During the survey, cracks were observed at the same locations, and the phenomenon presented a moderate intensity both in the numerical model and in the building.

As shown in Figures 9(c) and 10, the application of the foundation displacements of the belltower and the left part of the building produced the most significant damage and was responsible for most

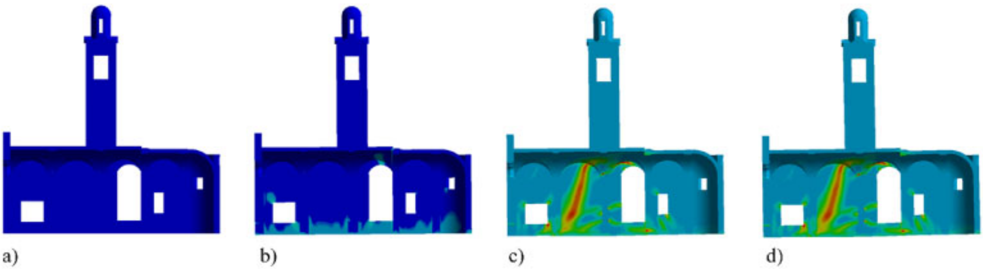

Figure 9. Maximum principal plastic strain produced by: a) dead loads, b) 1/3 global displacements, c) 1/3 global displacement plus displacements of the left portion of the church and belltower d) 1/3 global displacement plus displacement of the right chapel.

of the cracks observed in the vaults and in the walls of the left side of the church. In particular, the occurrence of the large crack detected in the wall of the second bay during on-site inspections was accurately simulated. This can be seen from Figure 10(b), in which the crack pattern surveyed in-situ is overlapped to the results of the numerical simulations. As regards the vaults of the nave (Figure 10(a)), the formation of the cracks due to the application of the foundation displacements of the belltower and the left part of the building proves that these cracks are not produced by the landslide and thus explain why they are oriented parallel to the landslide direction.

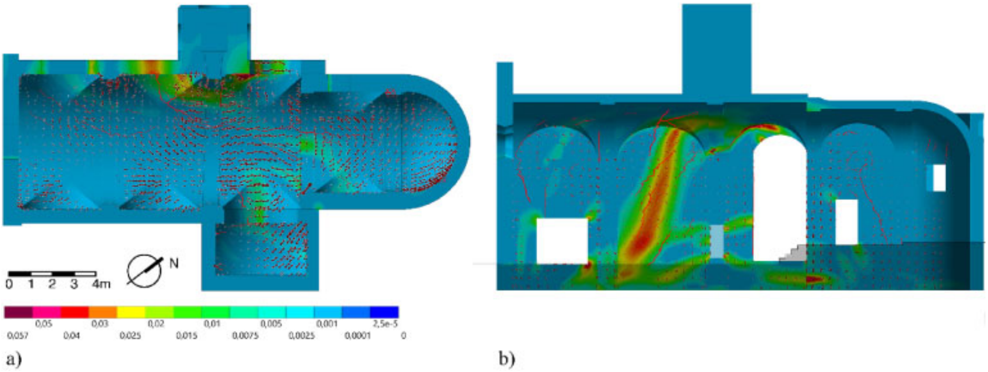

Figure 10. Comparison between FE results (in terms of maximum principal stress σ_1 vectors and maximum principal strain $\varepsilon_{1,pl}$ contours) and crack pattern surveyed on site: a) vaults, b) north-western wall (section AA').

Finally, the settlement of the right chapel caused the crack pattern in its vault as well as the cracks in the right wall of the second bay and the large crack in the presbytery.

In conclusion, a good agreement was obtained between the damage and deformations predicted by the numerical simulations and those observed on-site, even though the actual deformation of the church was underestimated. The complex rotation of the belltower, which leans both downstream and towards the left side of the church, and the deformation of the arch nearby were also accurately simulated (see Figure 11), proving the reliability of the numerical model.

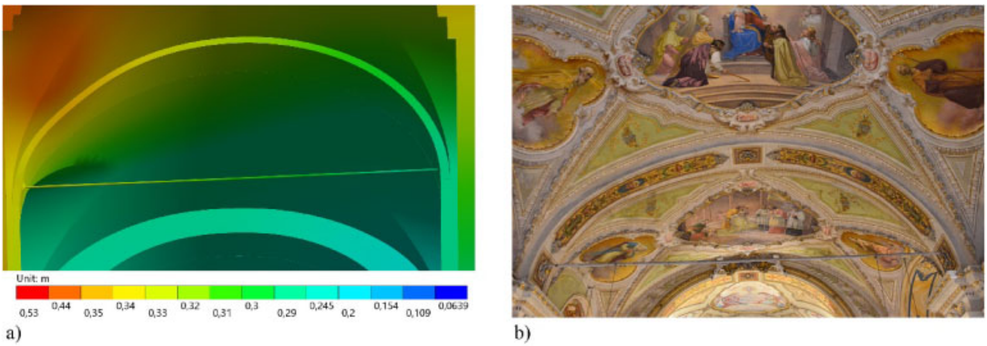

Figure 11. Deformation of the second arch from the façade. a) FE results (total displacement), b) real damage.

5 CONCLUSIONS

In this paper, the structural behavior of San Carlo Borromeo church was investigated under the application of different displacements fields, which simulate the foundation displacements produced by the landslide acting in the area as well as local settlements. Such displacement fields were estimated by means of an in-depth analysis of the deformations and foundation settlements experienced by the church, which were assessed thanks to a laser scanner survey. Using the data collected from historical and geometrical surveys, a three-dimensional FE model of the church was created. The building was modelled in its hypothetical initial undeformed geometry and nonlinear static analyses were performed to evaluate if the assessed displacement fields could be responsible for the current damage state.

The results of the numerical simulations showed that only part of the current damage was produced by the landslide acting in the area. Indeed, some crack patterns and deformations were found to be the consequence of local foundation settlements. More in specific, the settlements of the left portion of the church and the belltower proved to have produced both the longitudinal cracks in the vault of the nave and the deformation of the arch between the second and third bays. Part of these local settlements are likely to be the result of a soil consolidation occurred due to the weight of the belltower and well explain the diagonal cracks in the walls on the left and right sides of this structure. Furthermore, even if the damage in the right chapel were not fully predicted by the FE simulations, the settlement of this part of the church proved to be the cause of the cracks in the presbytery and apse and could also be responsible for part of the cracks observed in the right wall of the nave.

In conclusion, the numerical model proved to be able to simulate the current damage state of the church and, furthermore, helped in the identification of the causes of crack patterns and deformations. Future works will include the use of a constitutive model that takes into account the evolution of the damage and the degradation of the mechanical properties of masonry under plastic deformations.

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