MANAGEMENT OF MESH FEATURES IN 3D REALITY-BASED POLYGONAL MODELS TO SUPPORT NON-INVASIVE STRUCTURAL DIAGNOSIS AND EMERGENCY ANALYSIS IN THE CONTEXT OF EARTHQUAKE HERITAGE IN ITALY

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KEY WORDS: Reality-based modeling, 3D mesh models, structural survey, LiDAR, earthquake, endangered heritage, Italy.

ABSTRACT:

In the context of non-invasive documentation for the prevention of built heritage, digital surveying and the development of 3D models are widely applied. They have highlighted, with increasing reliability, the opportunities for knowledge and mapping on emerging damages related to safety and structural integrity. However, these processes can reach high-quality results on morphological structural detail, useful as source data for static analysis on the built structures. In this way, 3D models serve as source data for preliminary diagnostics on the causes of drift and deformation mechanisms.

The research aims to validate the proposed strategy on the case study of a masonry historical building damaged by the 2016 earthquake in Central Italy, to configure the mesh modeling strategy as a scientific example capable of orienting 3D modeling practices for structural non-invasive diagnosis, also in emergency requirements of intervention. The analysis of the damage mechanisms was performed by exploiting the morphological detail of the virtual surfaces to operate a direct segmentation, automated through the recognition of Feature Regions entities. It was based on the collaboration among professionals and technicians of the Emergency Support Department of EUCENTRE and DAda-LAB researchers of University of Pavia, to evaluate appropriate procedures of digital documentation for on-site survey in sites affected by emergency conditions of post-earthquake damage.

1. INTRODUCTION

In the context of non-invasive documentation for the prevention of built heritage, digital surveying and the development of 3D models are widely applied. They have highlighted, with increasing reliability, the opportunities for knowledge and mapping on emerging damages related to safety and structural integrity (Chiabrando et al., 2017; Colucci et al., 2021).

The development of reality-based high-poly mesh modeling can configure detailed 3D models for reliable simulation, but it also introduces complex and time-consuming management processes. However, these processes can reach high-quality results on morphological structural detail, useful as source data for static analysis on the built structures. In this way, 3D models serve as source data for preliminary diagnostics on the causes of drift and deformation mechanisms(Parrinello, De Marco, 2018).

The purpose for the structural application of a continuous mesh modeling protocol, enriched with reality-based qualities from an on-site 3D digital survey, achieves the development of research on non-invasive diagnostics through digital replicas and virtual structures. These geometric entities, controlled and certified within their envelope limit of the structural domain, necessarily introduce the need to manage polygonal geometric mesh models. The practice involves more time-consuming phases, but it also reaches an higher morphological detail, such as to constitute the same models as a source for diagnostic reflections on the mechanisms of analysis systems.

The obtained 3D models are intended not only to pursue the necessary deviation analysis, but they consolidate a certified practice that defines them both as technical documentation results, directly applicable for static monitoring maps, and as input data for further implementations, both formal and computational. In this way, a digital survey data process is established. It leads exponentially to the exploitation of the potential of the three-dimensional product, from the source, the discrete database, to the model, in terms of metadata for implementation opportunities. The further applications, from FEM platforms to information management, can involve 3D mesh models through common languages, adapting them appropriately. The support of vector drawings and signal datasets (deriving from measurement devices applied in the structural field) highlights evident format discrepancies in the case of joint applications. This strategy is compared with the possibility of direct derivation of 3D data, both in terms of timing (gradually reduced as the experimentation proceeds) and in terms of potential descriptivity (progressively increased according to the more complex and detailed cognitive needs).

The opportunity to develop a certified digital version of the building artifact, considering a controlled monitoring environment, makes it possible to develop an intensive digital documentation procedure that is difficult to achieve in another real context, such as in after damages frameworks. This is intended both in terms of extended calibration of the instrumental acquisition and for the control of the data quality in the influencing factors of the context.

The research developed allows to accurately delineate the complexities of a structural survey on emergency sites in the acquisition, reference, and triangulation processes of morpho-metric data, validating the compatibility and correspondence of

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the resulting models with the multi-instrumental comparison of measurement practices normally applied in the structural field.

The requirement for frameworks of survey and non-invasive documentation of historic architectural structures has established an emergent strength and growth in recent decades, as a good practice of knowledge on built heritage for the safety of buildings and their rehabilitation. The instabilities affecting an architectural structural system, linked to the lability of the building by mechanical phenomena developed after critical events and natural hazards, as seismic events, direct the attention to the establishment of fast planned monitoring practice, as a prevention rather than an implementation service. However, today these opportunities are marginal to the actions on the management of architectural heritage, due to the considerable time and costs for its implementation, even if they can guarantee useful levels of reliability for a correct diagnosis. Within this framework of requirements, digital survey practices have faced in recent years an emerging request for methodological expeditiousness, acquisition, and management of documentable data to produce information useful for safety and intervention operations.

The research aims to validate the proposed strategy on the case study of a masonry historical building damaged by the earthquake, to configure the mesh modeling strategy as a scientific example capable of orienting 3D modeling practices for structural non-invasive diagnosis, also in emergency requirements of intervention. (De Marco, Parrinello, 2021)

In this way, a perspective for non-invasive diagnostics and preventive monitoring, with fast procedures of survey validated for structural purposes, is presented. The optimization of the 3D digital survey, for facilitating the alignment and triangulation operations of modeling, is combined with the attention of morphological features of the model, accentuated on a large scale for the segmentation and isolation of 3D components with volumetric potential. The methodological strategy wants to configure a scientific example as a guide for the readaptation of survey parameters, constituting a documentary scheme for the application in other similar contexts of damage and emergency.

2. THE STUDY CASE: AN EARTHQUAKE CHURCH IN CENTRAL ITALY

The context of Central Italy has been the scene of notable collapses and instability events of its historical built heritage after the seismic sequence of 2016-2017, which developed in the Apennine area between the regions of Lazio, Umbria, Marche, and Abruzzo (Penna et al, 2019).

In these damaged areas, the masonry structures constitute a significant percentage among the existing buildings. They consist of stone or mixed stone-brick masonries, adopted mainly for residential typologies of the widespread settlement area but also declined within religious complexes and churches, in a territorial heritage extended for over 30,000 sq. Km.

The structures of these complexes are usually less stratified than the surrounding urban aggregates, and they provide the presence of more ancient masonries and constructive systems, rarely affected by recent interventions of consolidation. The typological design of the churches consists of a single large double-height nave without intermediate walls or horizontal floor slabs. The lack of internal diaphragms in the overall structure enhances the drift behavior of the masonry walls, and the possible presence of arches or vaults can cause the development of un-balanced thrusts and out-of-plane stresses. In this way, the façades of the building are more vulnerable in case of out-of-plane characteristic mechanisms induced by seismic events. This situation can result in higher damage effects on the patrimony of rural churches, characterized from a rich variety of materials, types, and structural sizes, with even serious probabilities of total or partial collapse.

The Church of St. John the Baptist in Castelnuovo, among the Municipality of Campli, is one of the rural religious sites of the area. It was built in the 14th century as part of the fortified border of the rural village, and it was severely damaged by the earthquake in 2016. The church, established in 1123 and expanded as “Rettoria” in 1370, was renovated within the design of the present building at the end of the 15th century. It was built closer to the fortified gate of “Porta Angioina” belonging to the perimeter of ancient walls (12th century), and it was adjunct to the watchtower later converted into a bell tower. The structure of the church has a gabled roof, the simple main façade presents a medieval portal with a decentralized pointed arch (14th century) and two oculus windows. It was documented that the plan consisted of three transverse naves with multiple spans, modified in the 15th century to the actual layout. Today the structure of the interiors consists of a single nave divided by a longitudinal double-arched masonry wall, added in a subsequent project phase to divide the two spaces, without apses. At the entrance, there are two aedicules with cross vaults, supported on one side by stone columns and bearing on the façade wall on the other side. Opposite, the apse portion was built at the end of the 15th century and it has been adjunct to the fortified gate with the construction of the bell tower. The roof structure consists of visible wooden trusses, without a false ceiling, and it directly bears on the masonries of the wall perimeter and the intermediate longitudinal wall. It includes plate bricks decorated with a rich array of polychrome geometric motifs. The interiors of the church are enriched with frescoes from the 15th century, and wooden altars from the second half of the 16th century.

Figure 1. The complex of St. John the Baptist in Campli (2019)

3. OBJECTIVE: THE CONSTRUCTION OF AN INTEGRATED DATASET FOR THE DEVELOPMENT OF A MESH RELIABLE 3D MODEL

The effects of the seismic sequence in 2016 in Italy, and in particular in the area of Teramo, have affected the widespread heritage belonging to a large number of municipalities in the local area. In this way, a new discipline for the regulation of the intervention and reconstruction process in the affected urban areas was established, and it required the preliminary documentation of damages and vulnerability assessments present on historical buildings. Because of the lack of an adequate action of monitoring and damage mapping, the reconstruction programs for rehabilitation have been mainly related to private buildings, while the intervention on monuments and churches has been delayed for safety measures and uncertain damage of masonries structures. The case of built heritage in the administrative area of the municipality of Campli has been particularly relevant: in addition to the seismic damages, geological instabilities of the area have characterized between 2016-2019 frequent events of massive landslides, close to the ravine of St. John the Baptiste church site.

Preliminary inspections on the structure of the religious complex have revealed both superficial and cross cracks on the internal and external wall façades and the masonries arches, as well as localized damage in the joints between masonry walls and wooden trusses. Thus, it has been possible to hypothesize the seismic direction of the earthquake, longitudinally to the church structure. However, it has not been possible to advance further assessments on the characteristics of quality and quantity of mechanical damage on the structure of the complex. The existing documentation consisted of photographic archives on visible cracks, with the report of post-earthquake emergency recognition disposed within the Italian Civil Protection and MIBACT census card "A-DC Survey of damage on Cultural Heritage - Churches". This information highlighted the lack of extensive reality-based data to ensure a unified and referenced mapping of the existing structural damage, to enable adequate consolidation projects on the rehabilitation of the church.

The limit of achieved information was related both to a synthetic report from expeditious examination, in terms of “time issue”, and to detail of available knowledge, in terms of “data issue”. The poorness of documentation reports has resulted from the reduced time spent on post-damage sites by the emergency teams of technicians: in compliance with the law for safety conditions of operators inside damaged built structures, the average time allowed for direct inspections cannot exceed 40'. This limit is intended within the critical buffer area of the site, even with the provision of standard personal safety devices, and it prevents human operators to actuate an extensive and detailed documentation action. In particular, more detailed knowledge would be relevant in terms of both localization and quantification of the damage mechanisms developed by the masonry structures after the seismic event. The availability of evaluation maps for plastic and kinematic frameworks under progress, even if in a preliminary level of reliability, would be useful to influence the diagnosis of building damage. In particular, it would assess a triple level of awareness on the building preservation considering the incremental damage of structures, the safety for surrounding users and assets, and the planning of resources for consolidation and restoration actions.

The presented research has been developed among the collaboration experience between EUCENTRE - European Centre for Training and Research in Earthquake Engineering (Italy) and the Department of Civil Engineering and Architecture of the University of Pavia. The research was conducted through the facilities of DAda-LAB (Drawing Architecture Document-Action Laboratory) and PLAY (Photography and 3D Laser for visual Architecture Laboratory). It was based on the collaboration among professionals and technicians of the Emergency Support Department of EUCENTRE and DAda-LAB researchers, to evaluate appropriate procedures for an exhaustive digital documentation protocol for on-site survey in sites affected by emergency conditions of post-earthquake damage.

In the experimentation conducted on the site of St. John the Baptist church in Campli, attention was paid to assess the levels of detail, reliability, and completeness in the acquisition and accuracy of post-production information through the different methodological practices of digital documentation. Short times of on-site data acquisition have been calibrated to ensure the quality of digital data, required for the development of preliminary diagnostic maps of damage.

Figure 2. University of Pavia and EUCENTRE researchers during on-site activities of survey and documentation in 2019

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4. FAST SURVEY FLOWCHART FOR ON-SITE DIGITAL DOCUMENTATION

The research consisted in the qualification of an efficient pipeline for non-invasive mapping on masonry structures damaged by seismic events. The aim was to deepen the standard analysis from post-earthquake emergency instructions (Civil Protection guidelines of "Survey of damage on Cultural Heritage - Churches") towards more detailed and reliable monitoring actions of quantification and reference of damages. In this way, the collaboration with the Emergency Support group by EUCENTRE was focused on fast survey procedures to calibrate the quality and adequacy of digital morphometric databases for the development of surface diagnostics on the masonry volumes. (D’Altri et al., 2018)

The digital documentation campaign was applied with a joint strategy of close-range metric morphological acquisition tools, with both terrestrial LiDAR, RGB sensors, and photographic, aerial, and terrestrial sensors planned according to a joint protocol. (Guarnieri et al., 2005) On the one hand, it was developed a global mapping of St John the Baptist complex within time slots of max 40’ for on-site acquisition, as fast survey experimentation. On the other hand, it was guaranteed a standard prototype of a digitized archive for the collection of geometric survey data, on which to develop the certification procedures.

4.1 UAV aerial photogrammetric survey

Aerial camera acquisition campaign was focused on the church complex and the bell tower. Considering the high elevation of the main walls (9.5 meters for the nave, 19 meters for the bell tower), acquisition campaign from the ground has not provided sufficient photographic sharpness. In this way, two different drones for 3D photogrammetry have been applied for the on-site survey: DJI Phantom 4 Pro, with semi-automated flight options, and DJI Spark, with manual flight and shooting options.

Total photographic shots, limited to 35' from the on-site survey with adequate detail, included 4 flight plans. The first, performed with DJI Phantom 4 Pro for 5' flight, was focused on zenith and radial shots on the complex, framed automatically within the "Point of Interest" mode. The camera mode was ensured by an automatic control tool of the Remote-Control device, and it was set according to a center point and a distance radius gradually calibrated for width and height, to define a spiral shooting trajectory around the building. The second flight plan was performed manually with DJI Spark for 10' manual flight, ensuring the full coverage of the bell tower.

The use of the light UAV has been necessary considering the proximity required between the drone and the wall surfaces (1-2 meters), to guarantee safety conditions both for users and in the maneuverability of the instrument (De Marco, 2020). The choice has affected the time consumption of survey, considering the absence of control automatisms in DJI Spark compared to the DJI Phantom 4 Pro, with longer piloting and shooting times. The safety conditions imposed the use of DJI Spark also for the third and fourth flight plans (10' each one) in the documentation of roofs and high wall portions at the complex premises, with photographic shots and detailed videos. The collected data has been structured in an overall archive of documentation on the complex. It has been applied for the elaboration of 3D Structure from Motion (SfM) models, fundamental for the integration of morpho-metric data in higher-level on façades, in particular in the area of the ravine and within the dense urban aggregate area.

Figure 3. UAV digital survey and SfM point cloud.

4.2 LiDAR Mobile scanning

The experimentation of a fast morpho-metric acquisition campaign included the application of a Mobile LiDAR, directly handled by the operator both internally and externally to the building. A KAARTA LiDAR Stencil instrument was adopted as Mobile Laser Scanner (MLS), with simultaneous SLAM localization and mapping. It was arranged an acquisition trajectory to guarantee a closed-circuit focused on the structural layout of the complex, to compensate the polygonal path for the control of the data deviation. Considering the acquisition of both external and internal spaces, the standard on-site activity provided the entire 3D scan of the environments and wall surfaces in a time slot of 10'. The instrumental limits concerned the shooting angles (360° horizontal FOV, -15°/+15° vertical FOV), with no data in the highest portions of the façades (above 5 meters from the street). The specific conformation of the acquisition paths has also affected the survey procedure, interrupting the trajectory of acquisition in the portion of the apse and with inaccessible areas in the interiors.

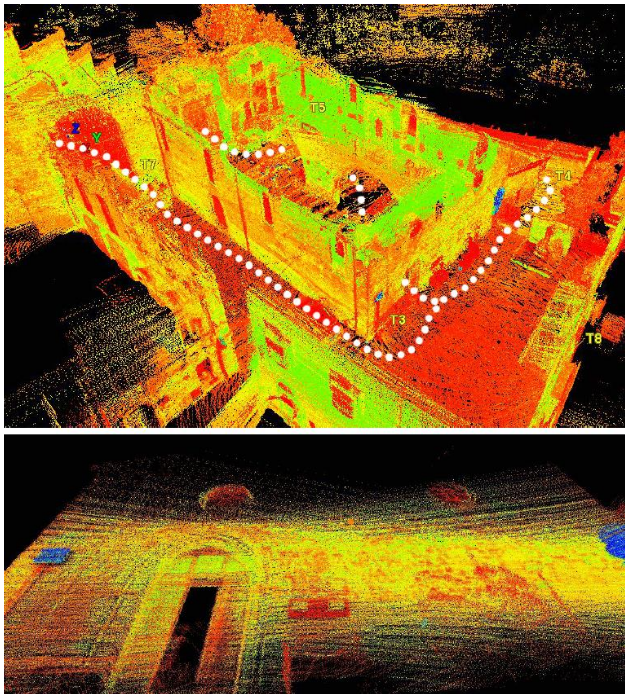

Figure 4. Mobile Laser Scanner survey and 3D point cloud.

4.3 LiDAR Terrestrial static scanning

Static laser scanner survey operations have been recalibrated considering the fast survey requirements. The adopted Terrestrial Laser Scanner (TLS), FARO CAM2 Focus S150, provided multiple options of acquisition times, which can be calibrated taking into consideration a minimum number of scanning positions to (i) complete a polygonal path for alignment control; (ii) ensure sufficient coverage of the geometries and surfaces of the masonry structures to allow sufficient information on their physical domain.

The calibration of the instrument was balanced on 3 features: density of acquired points, the resolution quality of scans, and colorimetric value of point cloud data. The fast acquisition provided 34 scans, divided between external and internal environments. The campaign was developed in 40’ of on-site activity, with an average time of scans of 1.13' at 4x resolution and global range (122,000 points/sec). Subsequently, the acquisition was replicated, according to standard documentation procedures in architectural sites, in 80' of on-site activity (2 slots of 40' each): 30 scans have been acquired, with an average time of 2.54', according to the higher density of each single scan (488,000 points/sec). In addition, a third survey campaign limited to interior environments was carried out by integrating the metric data with combined RGB information: 4 high-density scans have been acquired in an average time of 5.54' plus 4.00' of photographic acquisition (976,000 points/sec), for a total of 40' of on-site activity.

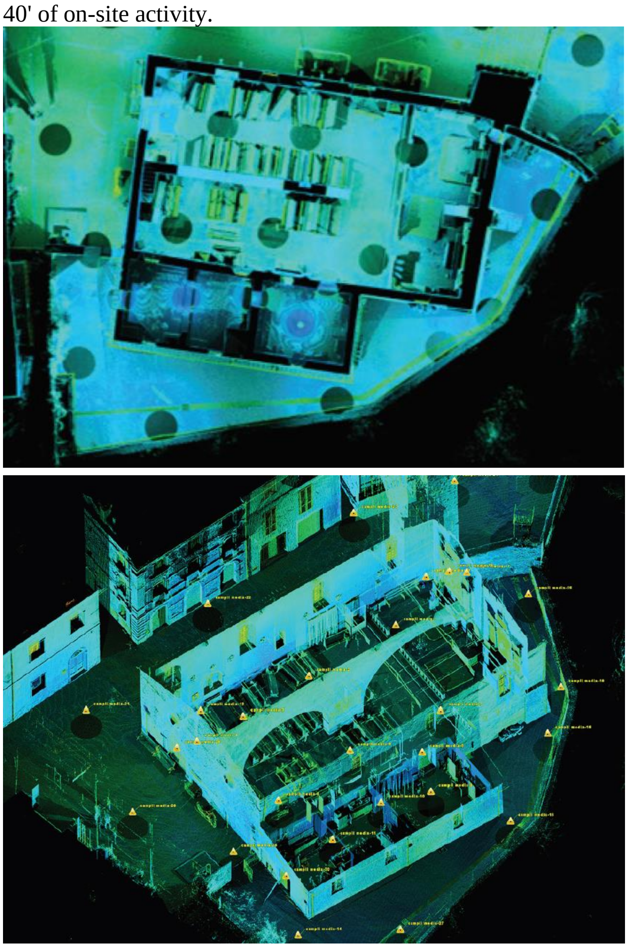

Figure 5. TLS survey and final point cloud.

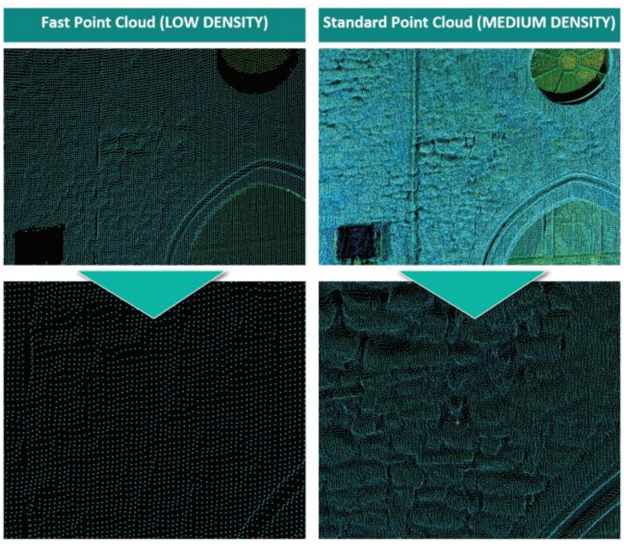

Figure 6. Comparison between fast and standard density point cloud acquired with TLS survey.

4.4 Photographic 2D survey

The photographic campaign for the 2D acquisition was focused on the purpose of reliable mapping cracks and visible damages on the masonry façades. The collected atlas was classified directly during on-site activities: cracks have been classified according to superficial or crossing type, defining a preliminary map to assess the census information within the post-produced digital databases. The acquisition was pursued with a reflex camera CANON EOS 70D as the most expeditious instrument for ground shooting (10"/photo), while a 3D EYE system with telescopic camera APS-C has been applied for integrating the shots elevated heights (3-10 m). In this case, times of acquisition have been extended for the arrangement, framing, and shooting actions of the interested area (30''-1' /photo).

Figure 7. Detailed photographic survey on-site damages.

4.5 Photographic 360° survey

The photographic acquisition activities have been completed with orbital photoshoots acquired with RICOH Theta 360° Panoramic Camera. 360° photos constituted a further global reference for monitoring the mapping and extension of damages. They have also been applied for the design of a virtual tour addressed to educational purposes in training professional teams, useful for representing on-site frameworks of damage through the definition of a dynamic and immersive virtual tour (Dell'Amico, 2019). 30 shots with 360° coverage have been collected, considering a time of 1'/photo for the positioning of camera tripod and shooting. The collected data, processed in a first discrete spatial form, was referenced on a common UCS system and compared to evaluate the effectiveness of localization for morphological damages.

5. INTEGRATION AND COMPARISON OF DATA

The comparison among multi-source data showed that fast survey data quickly performed by the static data from TLS, in low-density quality, satisfy the threshold of density and coverage of morpho-metric points sufficient for the mapping of the out-of-plane damaged surfaces. On the contrary, the data obtained from MLS proved to be ineffective for the continuous identification of damaged portions, both for the incompleteness of the point cloud (particularly extended shadow areas of missing data are present, due to the reduced instrumental maneuvers for acquisition in the dense urban context) and for the excessive instrumental approximation of metric coordinates compared to the scale of dimension of structural damages (medium uncertain deviation between the point cloud and real masonry surface: ± 5 cm). Considering UAV data, the dense cloud generated with SfM processing has ensured greater adherence to the TLS reference data (average deviation ± 1.5

cm), but they have demonstrated a low resolution of morphological detail on the vertical surfaces of the fronts, due to maneuverability and distance limit imposed for safety flight of drones in the urban context. However, the morpho-metric database from SfM data has shown a fundamental contribution to the monitoring of damages on high surfaces and roof portions, even with limited possibilities of global reconstruction of the architectural complex as a single acquisition chunk.

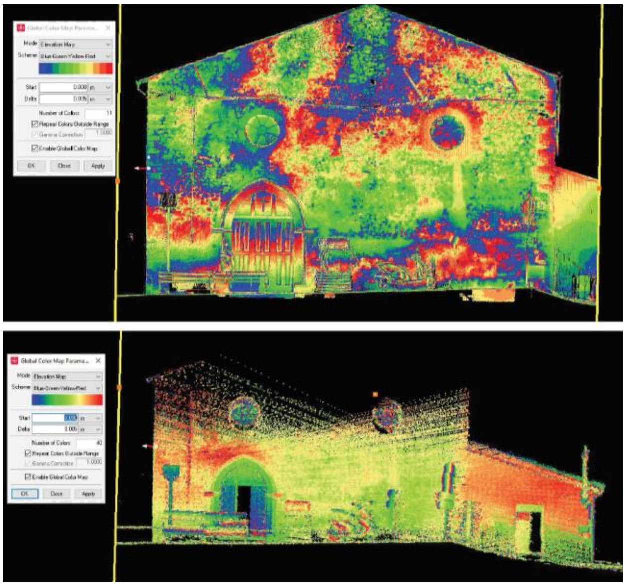

Figure 7. Calibrating elevation maps on TLS (above) and MLS (below) point clouds.

5.1 Migration of data to support knowledge in the development of structural analysis from the digital survey

The non-invasive analysis for structural damages has been performed in the first phase directly from the 3D point cloud.
Through the tool of point clouds management software, it has been possible to set for each façade a Reference Plane, designed as a geometrical average plane for the surface with reference verticality (Y=0). In this way, it was processed to apply a color map to each point of the point cloud, in a scaled grade from blue to red, according to the distance of each point from the Reference Plane. Out-of-plane portions, characterized by drift deformations from the main vertical plane, have been directly highlighted on the point cloud. A tolerance range (corresponding to green color in the map) has been set according to the scale of masonry deformations on ± 5 mm.

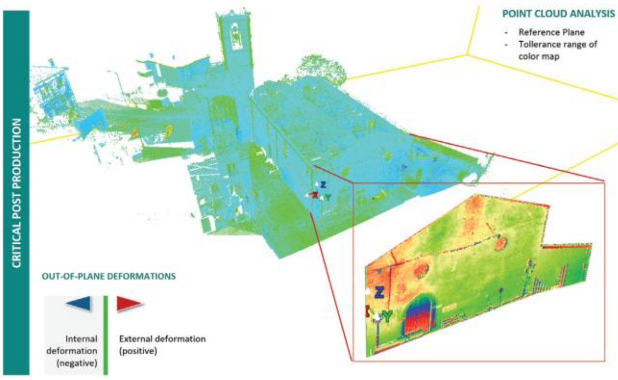

Figure 8. Reference and extraction of 2D elevation maps.

The elevation maps extracted from the point cloud, as a discontinuous database, have ensured the first identification of damaged areas in the masonry walls, localizing the on-course collapse mechanisms.
The main facade showed the presence of localized damaged portions, instead of the drift of the entire fronts. Deformed blocks have been mapped on the left corner of the main façade and at the top of its tympanum, considering the hammering action of the orthogonal wall and the roof as a probable mechanism of damage. At the same time, the longitudinal walls of the nave, even with local episodes of hammering of the roof trusses, did not show the foreseen shear mechanisms but just the presence of localized drift phenomena. The bell tower highlighted an independent mechanical behavior from the main body of the church, without corresponding deformations to the nave block, due to the absence of a structural joint with the main building during its construction phase.
The objective of the documentation research was thus directed towards the quantitative evaluation of the deformed blocks, to verify the existing framework of the collapse mechanisms between the theoretical behavioral predictions and the data resulting from the elevation maps of the survey. In particular, the identification based on the colorimetric elevation map was pursued to advance a semi-automatic method of classification for the deformation blocks, considering their morpho-metric characteristics on the surfaces of the global structure, defining a reliable 3D model for the direct analysis of damages.

6. MESH MODELING AND SEMI-AUTOMATED EXTRACTION OF FEATURE REGIONS

The 3D modeling of the St. John the Baptist complex has been developed considering the first phases of optimization and integration of multi-source data from TLS and UAV. The reverse modeling phases have considered the goal of processing a complete and numerical grid model of the wall structure of the complex. In this way, the preservation of structural detail for damaged areas as well as the reality-based localization of deformations have been preserved.
The modeling process has foreseen the triangulation of the integrated 3D point cloud within triangular poly-faces, generating a mesh grid. The surfaces have been elaborated to achieve the main features of (i) regular shape of triangular poly-faces, (ii) watertight option for the entire mesh to identify a volumetric border (Attene et al., 2013).
The pipeline has considered the filtering of the shape deviations created by secondary elements and furniture in interiors. Considering the box-unit conformation of the main structure, the overall morphological system presented a complete data coverage of 70%. The major alteration was represented by "shield holes" in correspondence with the religious furnishings, wooden altars, and terracotta tiles on the internal walls of the nave. A singular case concerned the sacristy rooms, with additional counter-walls and coatings. In this case, the fixing of mesh holes has been evaluated from the surrounding exposed area, with an average interpolation of missing portions, and the thickness of masonry has been carefully considered.
The absence of significant over-hanged volumes or horizontal diaphragms has prevented extensive cases of "corner holes", limited to only external stone shelves, without compromising the reliability of reconstruction of the polygonal surface with automatic fixing processes. Overall, no geometric reconstructions have been required to support the modeling, due to the compactness of the church structural system. Similarly, the evaluation of "bullet holes" did not involve specific triangulation measures for the wall surfaces: the masonry texture consisted of non-squared, superficially eroded stone blocks mixed with bricks, with profiled bedding mortar

maintained which prevented the presence of extended shadow cones within the acquisition of the points data from the ground.
The triangulation process has shown advantageous processing times, mainly dedicated to the cleaning of source data from urban noise and mobile devices, and it has allowed obtaining a model of the masonry structure, preserving the detail of blocks texture on the exposed surfaces. This goal has certified the preservation of reality-based geometrical features and morphological irregularities, otherwise, the misalignment of mechanical blocks of damage would not have been transposed in the 3D modeling process for geometrical NURBS process.
Otherwise, the reconstruction of the wall structure for geometrical partitions of mechanical block, considering the main geometry of the complex, would have ignored the specific morpho-metric detail of the damaged areas. Critical issues in the processing would regard: (i) poly-faces density, simplifying the macro-dimensional modeling, (ii) poly-faces localization, decentring the reference of micro-areas of damages. In the case of the absence of specific information regarding the thickening of masonries, as for the time-consuming extraction of dense slices sections, it is central to preserve the reliability and resolution of digital morpho-metric data on the damaged portions. This aspect involves a critical evaluation considering both the analysis phase of the post-crisis units and the future applications of survey data, such as for the simulation of consolidation and rehabilitation interventions of the structures.

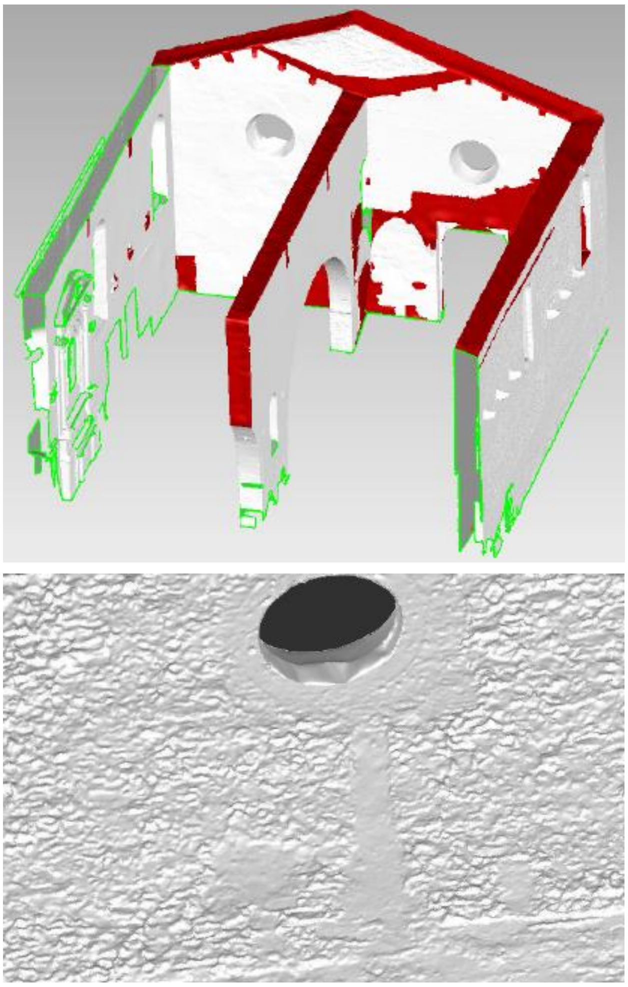

Figure 9. Modeling phases of the 3D poly-face mesh results of the structural complex from the integrated database.

The analysis of the damage mechanisms was performed assuming the morphological detail of the mesh surfaces to operate a direct automated segmentation, through the recognition of Feature Regions. The filter of curvature parameters found on the mesh made it possible to interpret the localization of the deformed portions as a function of the relative curvature between the polygons of the mesh. Suitable scales of parameters have been set, testing from a framework of fragmented reading for masonry blocks (curvature range 80/100) to the approximation in macro-areas (curvature range 65-70/100) until to reach the uniform mapping of the façade (curvature range 60/100). At high levels of curvature range (above 80/100), it was possible to notice the influence of the fixing operations, distinguishing the portions of mesh integration where fixing tools have been applied for the geometric correction of holes. These areas have shown discordant morpho-metric features from the boundary properties of the triangulated surface, demonstrating the reliability limit of the procedure regarding the applied scale of analysis.
Feature Regions, from the automatic segmentation of the continuous mesh surface, made it possible to set a thickness and noise factor regarding their domain limit and to transpose their boundaries into vector entities, directly generated from the 3D model. These curves, evaluated on both the internal and external surfaces of the structure, were joined by extruded units generating 3D solid blocks of intersection with the polygonal mesh of the structure. In this way, they operated as cross-cutting entities for the identification of the mechanical blocks of damage. Their extraction has been compared with elevation maps, verifying the reliability of damaged areas.

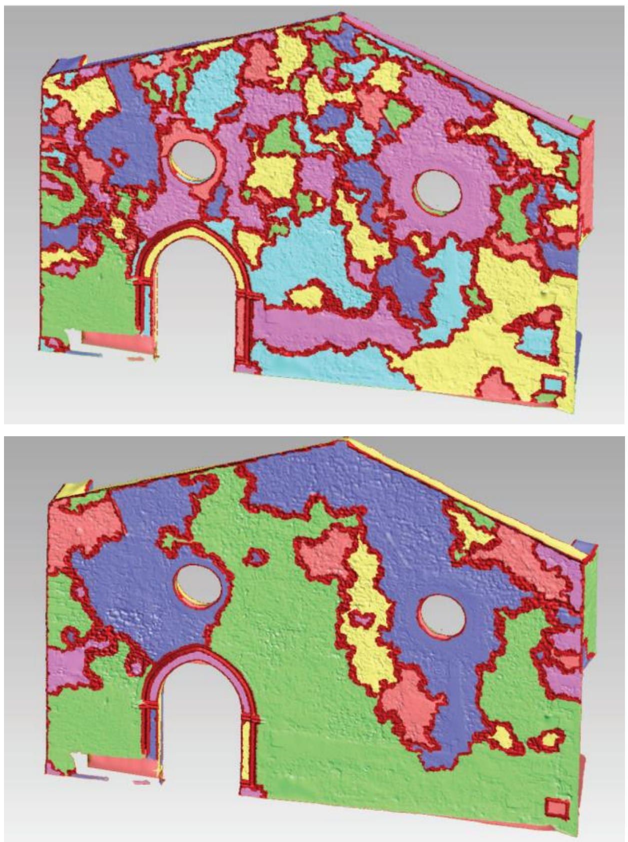

Figure 10. Feature regions automatically extracted by the high-poly reality-based mesh model: from the top, non-optimized mesh, then optimized mesh with high curvature range extraction (80/100) and optimized curvature range extraction (65-70/100).

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7. CONCLUSIONS

Considering the overall acquisition campaign, some instrumental applications have proved to be more functional in terms of achieved digital data for fast survey, in terms of facilitated maneuverability, automated data acquisition, and processing (DeLuca et al., 2006).
TLS survey has been adopted as reference data, constituting the basis for non-invasive diagnostic analysis to extract the elevation map frameworks, subsequently compared with diagnostic maps from other digital acquisition products. UAV aerial cameras, thanks to GPS reference, have also performed fast time slots of on-site surveys with high levels of data resolution and reliability for data integration. Otherwise, MLS has not provided sufficient data quality for structural evaluation. For these instruments, the research application has involved the experimental calibration of parameters set, to check the preservation of sufficient quality of data for analysis and further modeling procedures. The reduction of acquisition times has necessary limited the quality of the collected information, both in terms of density, coverage, and reliability. The evaluation of key measures and minimum calibrations has been favored, to guarantee sufficient detail and morpho-metric reliability on digital replicas of damaged structures.
The choice for a 3D mesh modeling flowchart from the digital survey data optimized and integrated with the alignment and reverse modeling phases, allowed to obtain a useful polygonal model of the wall structures. It was filtered from the shape deviations constituted by the internal secondary structures, ensuring a 70% value coverage. The triangulation process demonstrated advantageous processing times. The analysis of the damage mechanisms was performed by exploiting the morphological detail of the virtual surfaces to operate a direct segmentation, automated through the recognition of Feature Regions entities. The curvature parameters filtered on the mesh allowed to interpret the localization of the deformed portions.
The 3D processing showed a greater extension of the damage areas compared to the data analyzed from the point cloud, replacing a vector quantitative mapping for the previous color map. The reference color values of the elevation map did not guarantee a correct visual reading of the real extent of damage, due to the rough colorimetric interpretation. From the analysis of the extracted Feature Regions, new assessments emerged related to the collapse mechanisms present on the masonry structures of the Church of St. John the Baptist, highlighting the possibility of deriving adequate detailed polygonal models even from expeditious databases achievable during safety timeslots of inspection from the emergency teams.

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