Documentation strategies for a non-invasive structural and decay analysis of medieval civil towers: an application on the Clock Tower in Pavia

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Abstract
The civil towers in Pavia are a distinctive element of the city's architectural heritage, dating back to the Medieval Age as a statement of the lordship's power and wealth. They constitute singularities in the urban landscape, with out-of-scale vertical development, whether in the original morphology or altered by subsequent actions. Furthermore, they are embedded in a dense urban fabric and therefore they are naturally associated with local risks for the safety of the urban setting and of its users. These peculiarities require accurate and complex documentation practices, and they foster monitoring and morpho-material mapping as preliminary actions to their conservation. The knowledge analysis that has been developed on the case study of the Clock Tower aims to systematize a documentation strategy for delivering an accurate and updated conservation status of the wall surfaces. Digital survey outputs are then developed as diagnosis tools to support intervention procedures, by highlighting deformations and deteriorations that could cause structural instability.

Parole chiave
Non-invasive digital survey, conservative monitoring, out-of-scale buildings, medieval towers, Pavia.

The architectural relationship between towers and urban aggregates in Pavia

The system of medieval towers represents one of the main widespread built heritages of the city of Pavia. These monuments have experienced an evolution of functional characteristics and resilience in the urban architectural context, passing from the original function of control and defense to a symbolic role of noble prestige. In this way, they underwent attacks and targeted demolitions, between the 11th and 13th centuries, during the clashes among local families until the decay of the feudal system (Fig. 1).
The integration of the civil towers into the built assets constitutes a character common to many Italian historic centers, among which the most similar are Mantua, Lucca and S. Gimignano, but also Siena and Volterra (Parenti, 1996, Fiumi, 1951). These architectural artifacts, singular for their morphological configuration, constitute an urban building

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level which is super-ordered over the entire system of aggregates in the settlement[1]. In the specific context of Pavia, the civil towers have arisen densely in the city from the year 1000, with the end of the Longobard rule and the strict affirmation of the power of noble families. In addition to the symbolic role, these towers defined an urban structure that was still essentially military: placed angularly in aggregate blocks and built jointly with a masonry vault, *voltone*, which closed the minor street protecting the internal area, they were used to barricade the city in sectors in case of invasion (Vaccari, 1986, p. 100).

These towers have a square base, tapering upwards with slight corrections of the constructive out-of-plane. They consist of rubble masonry, in double brick facing with a conglomerate of pebbles and lime in the middle. Often, with the interventions of adaptation, a thinning of the internal masonry has been applied, leaving the conglomerate exposed or preserving only the external layer. The structural masses, set on reduced resistant sections, are mainly subjected to compression and they present damages and instabilities due to the flattening. The cracks appear with a rapid propagation along the vertical walls, where documentation and monitoring actions are more difficult to be conducted due to the high levels of development.

The census of the towered heritage in the city center of Pavia has been founded since the late Middle Ages, with various written memories and numerous representations that testify the building phenomenon. In 1330, the mapping of churches and monasteries within the urban walls included the census of more than 50 towers (De Canistris, 1330). In the fresco by Bernardino Lanzani, conserved in the Church of S. Teodoro as a representation of the urban configuration of Pavia between 1522 and 1525, the civil towers entirely preserved in height are reduced to 15, distinct from others more contained in development and from those belonging to the defensive walls. In 1585, Giovan Battista Claricio's historical map generically indicates 22 towers, present as distinct structural blocks within the dense aggregates of the historic center. Finally,

Fig. 1
The city of Pavia: the Romanesque historical centre from Roman centuriation and Longobard architectural development, with the civil medieval tower characterizing the urban skyline (Photo R. De Marco, 2020).

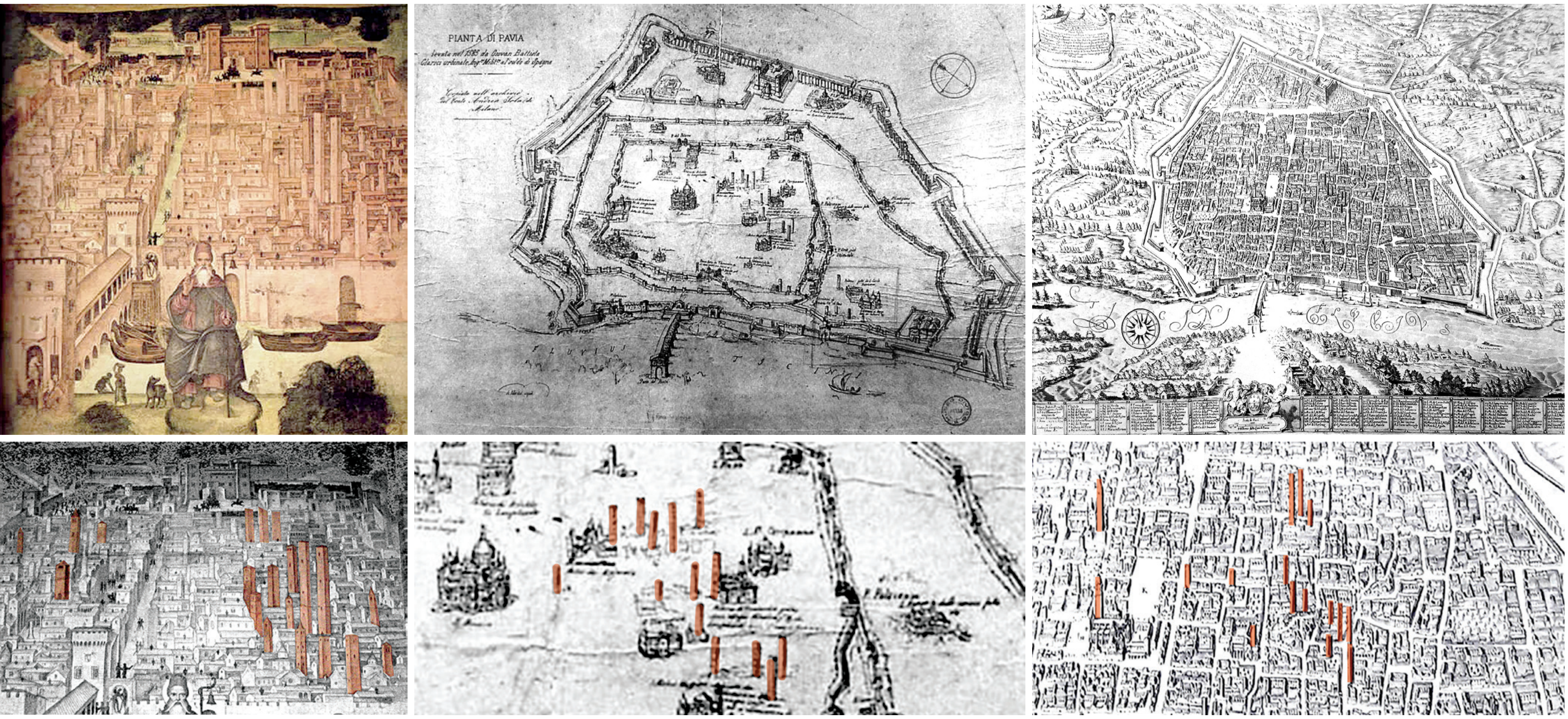

Fig. 2
Historical representations that testify the resilience of civil tower in the historical center of Pavia: from the left, Bernardino Lanzani's fresco in S. Teodoro Church (1522-1525), Claricio's map (1585) and Ballada's map (1684). The localization of the three towers in Piazza Leonardo da Vinci is always well recognizable. (Credits Photographic Archive Guglielmo Chiolini, conserved at Musei Civici del Castello Visconteo in Pavia).

Ottavio Ballada's map of 1654 highlights about 30 towers inside the city, however unifying the representation between the monuments that were still intact and the cutted blocks incorporated within the urban units.
The increasing decimation of the civic towers began as a safety measure considering their high states of degradation. Over the centuries, their structural blocks have often been demolished or recovered after being shortened or behaded, *capitozzati*. A large part, abandoned to the state of ruin, was included in the walls of houses and complexes built later in the historic center. Over half of the sites, on the other hand, have been adapted to functions compatible with the urban context, lowering the structures to safely adapt them to new civic and religious functions[2]. The exposed masonry surface in bricks has often been standardized with homogeneous openings and coatings to the continuous fronts of the residential aggregates (Fig. 2).

Critical building interventions date back to the 14th century during the lordships' conflicts, and again between 1786 and 1860 when 8 towers were destroyed and another one transformed and reduced to domestic use (Vaccari, 1986). In recent centuries, the production of catalogs has provided a more structured method of mapping and census for the recognizance of the tower blocks. Among the most updated reports, Professor Elia Giardini (1830) has listed 14 towers still intact, 1 converted into a residential block, 11 ruins and 36 "localizable memories of towers" (Giardini, 1830), (interpretable as masonry remains incorporated into the urban agglomerations), for a total of 62 examples. In 1888 the catalog of Dr. Cisanto Zuradelli reported 17 more or less intact towers, 8 reduced, 13 ruins and 39 remains, in total 77. In 1986 a typological research highlighted the presence of 10 towers still preserved in height, 10 beheaded but distinguishable, 17

incorporated in the buildings, 2 adjacent to units and other 60 in ruin, for a total of 99 (Cabiati et al., 1986; Vaccari, 1986).
These historical documentations show a wide freedom of typological recognition descriptive method assumed by the authors. In this sense, it returns an irregular mapping of the towers in the historic center of Pavia, which is still far from achieving a complete and truthful recognition of the resilience conditions of the individual monuments (Fig. 3). It is clear that the diversity of the results surveyed among the different sources is a consequence of the indefinite architectural classification code, which often led to confuse or standardize the towers with the surrounding aggregates. On the other hand, their distinction as singular building structures is highlighted, each one with its own characterization of static-mechanical system and material conservation that influence the integrity assessment for the safety of the urban context.
In these terms, the ability to evaluate the experience of structural stress of the tower block, starting from the investigation of its masonry structural surface, can support a specific process of diagnosis of the monument. The analysis of interventions and transformations undergone over time directs the correct calibration of monitoring and stability control indicators, to favor the resilience of the towers in the dynamics of urban administration. Since 1985 there is no longer any evidence of towers demolished or beheaded in the city of Pavia. However, from the following years, numerous episodes of instability of the structures have been experienced by citizens. They reported detachments and expulsions of brick blocks, as a sign of mechanical variations of the towers' structures. These observations belong to a local alert framework particularly focused on the risk of structural instability of the masonry elements, sensitized by the tragic collapse of the Civic Tower of the Cathedral of Pavia in 1989[3] (Fig. 4, p. 6).

Fig. 3
Medieval civil towers still present in the historical center of Pavia. Different transformations have occurred during centuries, and they have been reduced in height, integrated into aggregates or preserved as urban monuments. From the left, towers in Corso Garibaldi, Aquila family's tower in Strada Nuova, Dalmazio and Porta towers (Photo R. De Marco, 2020).

Fig. 4
The medieval Civic Tower of Pavia: before (on the left) and after the collapse in 1989 which also damaged the urban aggregates of the area (Stabile, 1992), until the present ruins near the Cathedral of Pavia (on the right) (Photo Panorama, 17 March 2015).

This context has prompted public and administrative interest among the need for a specific knowledge strategy dedicated to the civil towers of Pavia. The monitoring of their overall state of conservation aims to be concentrated on the phenomena of material alteration, oscillation and structural deformation. The goal is to highlight the instability mechanisms already affecting the buildings to guide intervention operations and to reduce the conditions of potential risk within the dense area of the city.

The case study of the medieval Clock Tower of the University of Pavia

The three towers in Piazza Leonardo Da Vinci represent the example of the best conserved towered heritage in Pavia's historic center: Torre Fraccaro and Torre del Maino belonged to the corresponding noble palaces, nowadays hosting university spaces, and the third one is the Clock Tower (Fig. 5).

The construction of the Tower dates back to the 11th-12th century and its location, with an incongruous orientation in the alignments of the urban fabric and isolated between the houses and the close wall system, makes it recognizable as one of the oldest of the city. The Tower has a square base, measuring approximately 5.2 meters, it is built in brick masonry more than 2 meters thick, featuring regular courses of putlog holes, and has no stone basement.

The location of setbacks, usually found at half of the height in similar buildings, is at three-quarters of the current height of 37 meters. This circumstance suggests that the original tower was at least 50 or 60 meters high (like the close Torre del Maino) and it has been cut off to remove the oscillation and to secure the structure without dedicated interventions and maintenance operations. The obelisk-shaped roof is thought to be subsequent to the original construction, following the lowering of the Tower.

The monument is named after the addition of the two-sided rendered clock, built between 1775 and 1792 and still functioning. The Tower has a limited number of openings, ranging from one to two windows on each front and three doors on the ground level (an older one on the North front, now walled, other two more recent on the East front, now walled, and one on the West front, still accessible).
The Tower is nowadays located in the middle of the square, according to the original project. This location followed several architectural transformations that affected the surrounding urban aggregate and, as their result, the tower was incorporated in a portion of the former Ospedale San Matteo, when the university complex was converted into the military station of Caserma Menabrea in 1933.

Fig. 5
Piazza Leonardo da Vinci with the three main medieval towers: Torre Fraccaro, Torre del Maino and the Clock Tower inside the urban complex of the University of Pavia (Photo R. De Marco, 2020).

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above
Fig. 6 group
Photographs from historical archives that show the past inclusion of the Clock Tower inside the architectural complex of Caserma Menabrea until 1959. (Credits Photographic Archive Guglielmo Chiolini, conserved at Musei Civici del Castello Visconteo in Pavia).
below
Fig. 7 group
Clock Tower conditions in its assets after the damage of 2019: security structures have been installed under the clock fresco portion and at the ground level around the perimeter, to prevent the risk of detachments for citizens (Photo R. De Marco, 2020).

In 1943 the station was dismissed and, in 1945, once its activities definitively finished, it hosted citizens who remained homeless after the bombing in Pavia. The demolition of the south wing was started in 1959 by the Rector prof. Plinio Fraccaro, who promoted the valorisation and restoration of the medieval towers present in the square (Bossaglia, 1959) (Fig. 6).

Starting from 1989, after the falling of the Civic Tower, the towers in Leonardo Da Vinci Square have been subjected to a program of structural analysis, which highlighted urgent interventions to be conducted on Torre Fraccaro, Torre San Dalmazio and Torre del Maino[4] (Ballio, 1993; Jurina, 2016). Therefore, the Clock Tower has been put under constant monitoring with dynamic sensors in order to control possible movements and settling of the building (Pavese, 1991a; Pavese, 1991b; Resta, Brunamonti, 1998)[5].
In December 2019, following an intense rainfall, portions of the render and fragments of bricks fell from the Clock Tower, thus determining a risk for the citizens and prompting fears about the state of conservation of its structure and covering elements[6]. As primary intervention, bulkheads have been installed under the rendered portions. Although avoiding the risk of further falling debris, this intervention has prevented the feasibility of a deep examination of the upper surfaces, because of the limited accessibility and maneuverability and high costs of renting a lifting platform. The office of Technical Informative and Safety Area of the University of Pavia, the responsible for the monument to the Superintendency, acknowledged the necessity of a large-scale risk control and monitoring action on the Tower and commissioned the laboratories DAda Lab and PLAY of the Department of Civil Engineering and Architecture to elaborate a campaign of documentation and analysis of the masonry structure. The work was required to be non-invasive, expeditious (acquisition and output production in two months, between January and February 2020), reliable, particularly for the higher portions, and with a low impact on the activities of the surrounding urban compartment (Fig. 7).

The attention raised by the event on the Clock Tower reconnects to the extended purpose of widespread conservation of medieval civil towers in the historic center of Pavia. The collapse of the Civic Tower witnessed a structural failure due to a “bowing” mechanism located on a single front of the building, which generated the subsequent collapse. The hypotheses on the extrinsic and intrinsic causes of the collapse (Stabile, 1992) assimilate the specific case to other typological monuments in Pavia, which are also qualitatively affected by phenomena of directional deformation of the block and infiltration of rainwater, of acidic composition, in the interstitial cracks. Among the major towers preserved in height, such as Torre S. Dalmazio and Torre Belcredi, there is a similar framework, in different proportions, of grafting interventions, masonry cross-cutting and discontinuities by stratifications, which could jeopardize the correct tightness and compactness of similar types of brick masonry. In such cases, moreover, there is not a repertoire of historical documentation that testifies in-depth the construction technique and consolidation solutions active on the monumental structure, as it can be reconstructed for the Clock Tower (Resta, Brunamonti, 1998). Thus, this situation defines each activity of rapid documentation as a fundamental preliminary contribution to the risk monitoring and assessment process.

The specialization of digital survey strategy to support reliability and resolution of detail for high elevation surfaces

The need for a morpho-material documentation of the Clock Tower aims at fulfilling a specific accomplishment: the ability to conduct the process of mapping of the conservation status and degradation phenomena with a proper accuracy in terms of their identification and quantification. In addition, there is the need of a support to considerations and diagnosis hypotheses on on-going structural issues. These objectives required to be carefully adapted on the basis of the singular proportions and dimensions of the object, refining the terms of resolution and detail of the expected output.
The singularity of the Tower's elevation affected the actions of planning and calibration of the survey throughout the entire process of development and integration between range-based and image-based survey methods.

The acquisition of spatial and geometrical information has been conducted by Terrestrial Laser Scanner (TLS). The survey campaign was oriented in particular to the control of metric reliability, focusing on one side on the single scans on the Tower block, and, on the other side, on the overall spatial reference. The acquisition was carried out following two polygonal paths, the first as the fundamental one for a first recognition of the main geometries of the surrounding context, the other closer to the Tower in order to obtain a densification of collected data. For both the trajectory paths, each scan location (34 in total) included two acquisitions with different settings: the first one was a complete acquisition (360° visual angle) with medium quality (resolution 1:8), while the second one was conducted with an increase in density (resolution 1:1) and limited scan angles (ranging from 90° and 120°). These settings allowed to obtain a point cloud specifically calibrated for high morpho-metrical quality even for altitudes higher than 20 m (laser spot range under 5mm); the point cloud has been then referenced firstly considering the Tower block, with homologous targets and, subsequently, with the surrounding context by cloud-to-cloud visual alignment (figg. 8-9).

In parallel, the campaign of photographic documentation has been critical for the mapping of the higher portions of masonry. The peculiar context of the Tower, in the middle of the square, influenced the choice of aerial camera used for the campaign, resulting in the use of ultra-light UAVs[7].

The on-site acquisition followed a specific calibration of the camera, developed in the university laboratory. This phase has been critical to plan the acquisition in terms of distance and hovering of the UAV, in order to take into account all the critical aspects: an adequate image quality, mapping trajectories and overlapping ranges to facilitate the photogrammetric processing and the critical aspects of the site in regards to flight trajectories and time slots (De Marco, 2020). The correction of the distortion parameters allowed to process data through the Structure from Motion software, thus obtaining a dense point cloud and a high-polymesh. The collected data have been referenced taking advantage of the reliable orientation of the TLS point cloud (during which the high resolution of both the datasets facilitated the matching process) and they were used to complete the morphological detail of the wall texture, preserving its well conserved portions and damaged ones even in the upper portion of the Tower (Fig. 10, p. 12).

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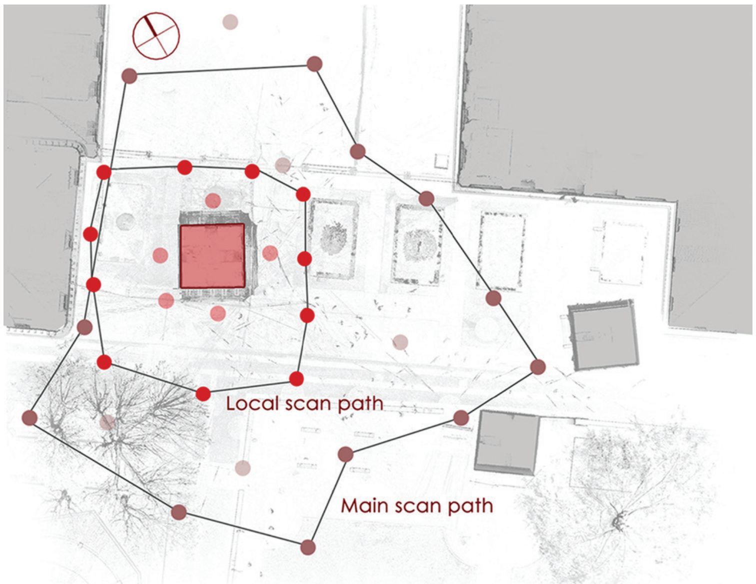
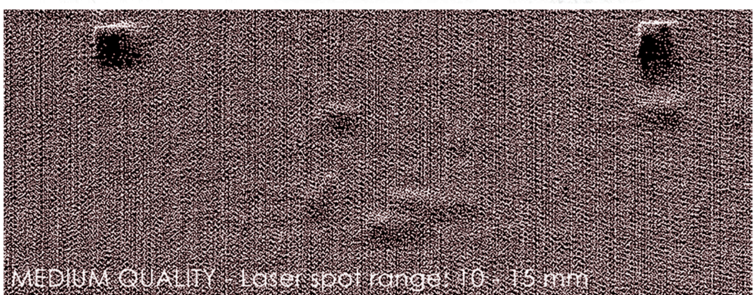
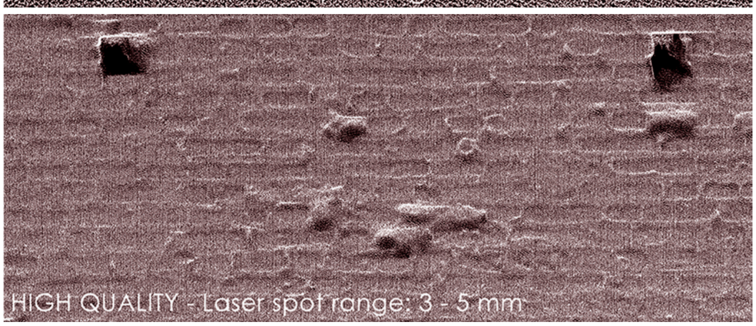
Fig. 8 group
Terrestrial Laser Scanner campaign for the on-site survey, through the set of controlled scan paths and the increase of measurement density on the tower's surfaces (graphic elaboration S. Parrinello, R. De Marco, A. Miceli, 2020).
right column
Fig. 9 group
Double strategy of scan data reference, with local target reference and global cloud-to-cloud alignment, obtaining the final TLS point cloud with high morphological detail also in elevation levels (above 20 meters) (graphic elaboration S. Parrinello, R. De Marco, A. Miceli, 2020).

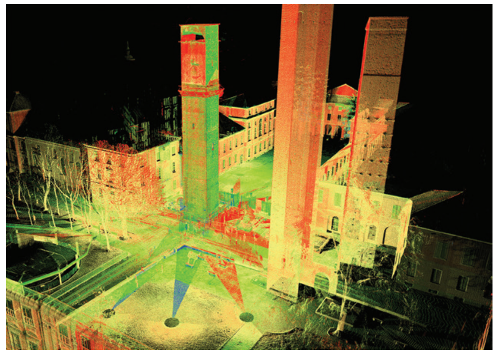
The application of a digital drawing protocol, as consolidated support of the geometrical characters of conservation and damage on the wall surface, has been conducted with the experimentation of semi-automatic techniques of vectorization of the material pattern, based on the high resolution of photo planes obtained from the photographic campaign (Parrinello, La Placa, 2019).

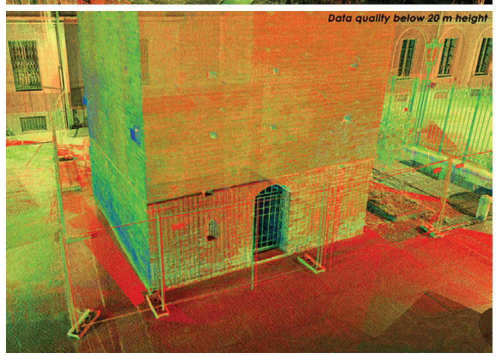
With the support of tablets and pencils, the ortho-mosaic of each front has been critically selected by distinguishing the outline of the components of the wall and of the mortar joints. This processing allowed for the automatic generation of vectorial paths for each brick, which have been subsequently imported and referenced in CAD to complete the drawing of more than 800 m² of total surface area. The experimentation to refine the info-graphic quality and efficiency of the post-production operations implied shorter elaboration times and a shift in the operator's attention from the data processing - now automatic and facilitated for frequent monitoring - to the critical analysis of data, which is the core of the knowledge process (Fig. 11, p. 13).

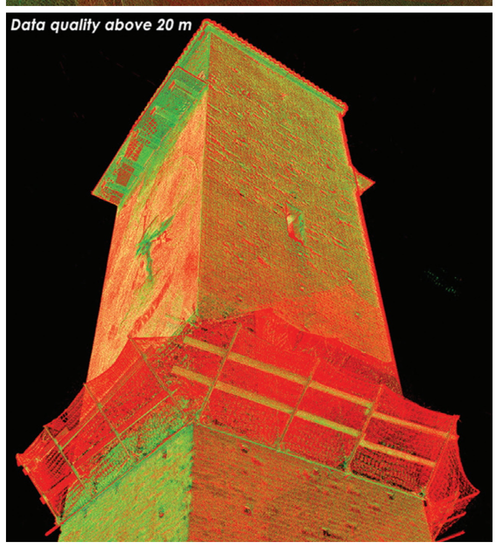

Local scan path
Main scan path


MEDIUM QUALITY - Laser spot range: 10 - 15 mm


HIGH QUALITY - Laser spot range: 3 - 5 mm




Data quality below 20 m height


Data quality above 20 m

above
Fig. 10 group
Strategy for UAV mapping and the reference of photographic data. 2D photographs have been processed through Structure from Motion alignment to obtain 3D meshes of high polygonal shape and texture (graphic elaboration S. Parrinello, R. De Marco, A. Miceli, 2020).

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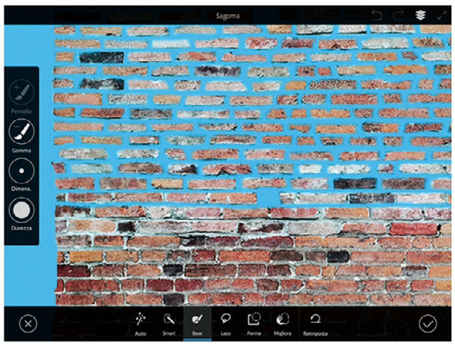
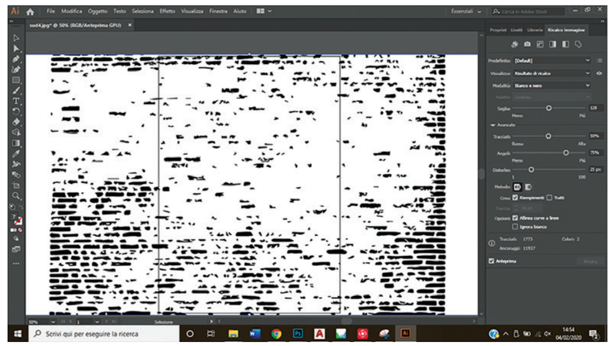
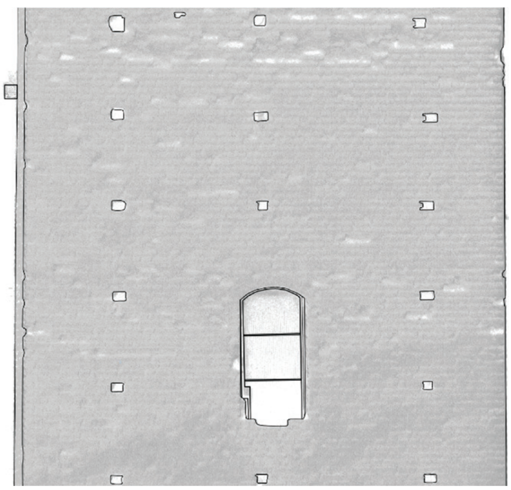
Fig. 11 group
Semi-automatic procedure for the vectorialization of the tower external surfaces, till to reach the high detail of masonry shape and decay both in CAD and ortho-materic elaborates (graphic elaboration S. Parrinello, R. De Marco, A. Miceli, 2020).

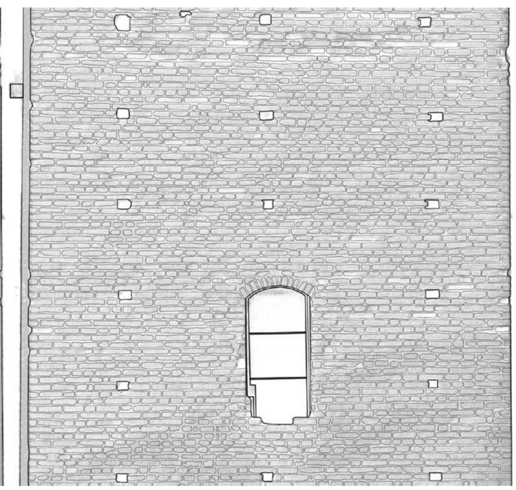


MANUAL PHASE_ ORTHOMOSAIC MASK SELECTION



SEMI-AUTHOMATIC PHASE_ VECTORIALIZATION OF THE IMAGE





The completed database integrated the geometrical peculiarities of the exterior[8] structural masonry of the Tower to the material and texture characteristics of the elevations, defining a comprehensive base on which to conduct the conservative and structural analyses.
In order to evaluate the eccentricity conditions developed along the structure, the action of sectioning of the point cloud allowed to obtain the corresponding slices at a range of 1m between the multiple levels, with the aim of interpolating and highlighting possible alterations in drift and surface integrity of the tower due to unstable conditions.
Alongside with the possibilities of two-dimensional representation of material and construction characters about surface deterioration and crack maps, the high surface density of the 3D dataset allowed a qualitative mapping of the distribution of discrete surfaces and their local deviation from the average reference planes of the fronts. Taking into account the intrinsic constructive tapering, the reference system has been oriented according to the fronts (also with z axis) allowing to calibrate a mapping of the surface according to specific morphological variations observable on the point cloud, including both plastic deformations and surface alterations of the conservation layers. The deviation has been interpreted both when positive, as detachment, and negative, as depression, with the representation of a color map ranging from red to blue (with a 3mm of range). This output has supported the reading of deteriorations and the interpretation of the detected phenomena, when superficial-material, as in the case of erosion, detachment and patina, and when macroscopical affecting the structure, as rotations and torsion (figg. 12-13).

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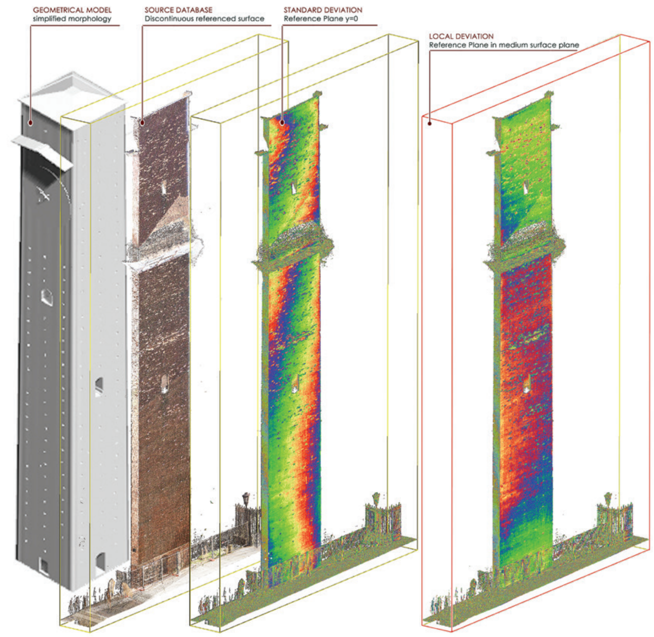
Fig. 12
Calibration and interpretation of the elevation maps for structural and conservation analysis. Considering the constructive tapering of the tower, coordinates settings have been conducted to reference the fronts analysis specifically to the masonry surfaces (graphic elaboration S. Parrinello, R. De Marco, A. Miceli, 2020).
below
Fig. 13
Eccentricity analysis developed from the TLS/UAV survey, with the slice extraction from point clouds (on the left). The survey has provided both a local report on the inclination of fronts and a global consideration on the deviation of the center of eccentricity of the entire tower (graphic elaboration S. Parrinello, R. De Marco, A. Miceli, 2020).

Integrated strategies for material and surface degradation mapping in the alteration frame

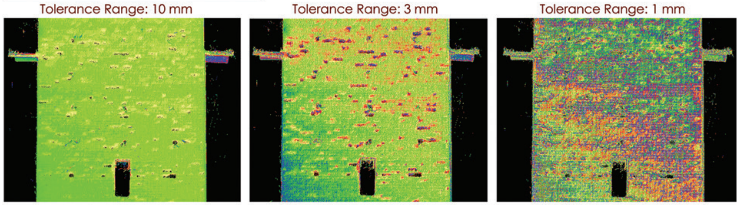
The aforementioned documentation provided for a useful tool to support preliminary but expeditious evaluations to be used in the following stages of a conservation project. The exposed evaluations derived from a comparison strategy between the photogrammetric data and the morpho-metrical database, providing qualitative and quantitative information about the envelope of the Clock Tower, to address a first critical evaluation on the conservation status of the surfaces. Further support has been obtained through researching historical-constructive studies, diagnostic tests and monitoring interventions occurred over time (Resta F. et al., 1998, Pavese A., 1991a and 1991b, Rossi P.P. et al., 1992).
It is important to acknowledge that the conservation project for any historical building requires a thoroughly reasoned critical process, that consist of the necessary instrumental analysis to support the anamnesis and diagnosis phases (Sanpaolesi, 1973).
The metrical and photographic database, although extremely reliable, provided a representation of the surface envelope of the Clock Tower: therefore, preliminary evaluations have been produced, in accordance with the objectives of the research. The knowledge framework that derived is significant, but not exhaustive in regards to the whole structural consistency of the object: in this sense it is crucial to validate the constructive features of the Tower by means of specific instrumental analyses, in order to develop the conservation project.
When approaching the diagnosis phase of any building, it is important to consider and observe intrinsic and extrinsic causes. In the presented case study, the description of

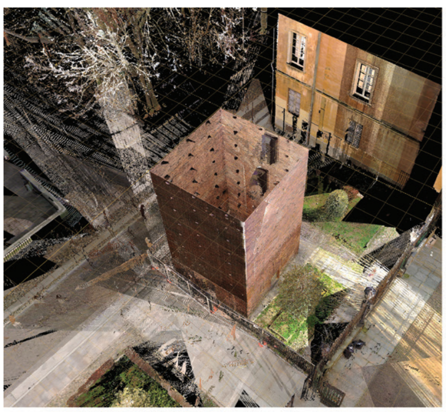
ELEVATION MAPS - CALIBRATION

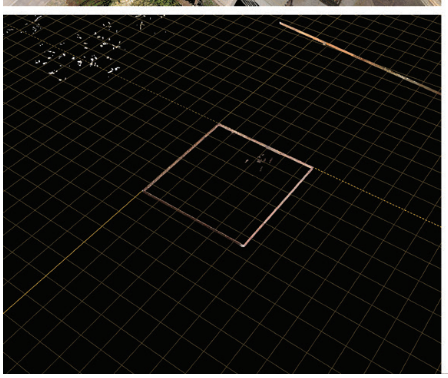


PARAMETERS FOR DEFORMATION ANALYSIS

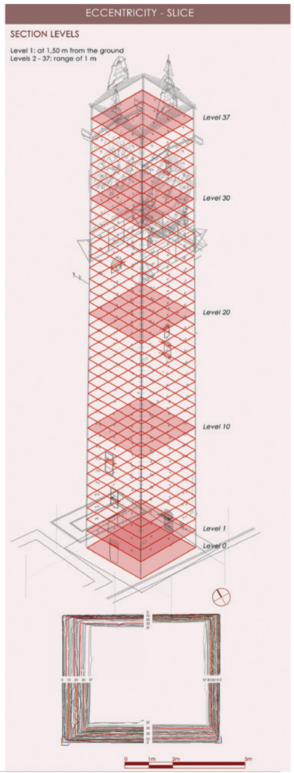
Tolerance Range: 10 mm — Tolerance Range: 3 mm — Tolerance Range: 1 mm

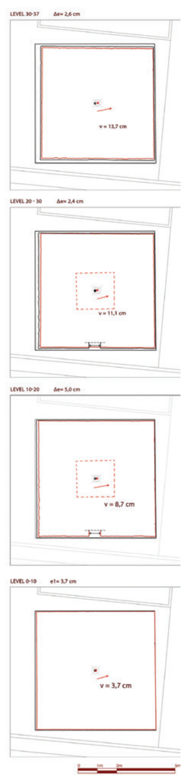






ECCENTRICITY - SLICE





the surface conservation status required reflection on the possible cause factors, which are supposed to be related mainly to the physical and chemical characteristics of materials and their exposition to atmospheric agents and rising damp. Moreover, a general lack of maintenance is certainly considered in addition to the abovementioned causes.
The wall texture, observed from the outside, suggests an overall uniformity in the constructive technique and in the adopted surface materials, except for the rendered areas of the two-sided clock. Past stratigraphic analyses seem to confirm this hypothesis (Resta F., Brunamonti B., 1998).
In addition, differences in the surrounding environmental conditions are expected, namely solar exposure, temperature, action of rain and wind, action of pollutants. It is common that these conditions vary based on the considered front (with major intensity in the West and South-West exposition). This is supposedly due to the location of the tower in the urban context – with one front very close to the University's buildings – and the height variation in the built tissue along the Tower – which, starting from 15m height, is more exposed than the surrounding buildings.
These considerations suggested to shift between close-range and medium-range observations to identify the different phenomena, according to their characteristics and extension.
In the basement area, a large diffusion of phenomena supposedly due to rising damp can be observed: the masonry appears darker and more saturated and shows colours and surface morphologies referable to biological colonization, alveolarization and weathering, the latter both affecting the mortar joints and the bricks (Fig. 14).
The hypothesis deriving from a visual survey should be validated by means of instrumental analysis, such as thermo-hygrometric measurements, in order to punctually confirm and quantify the presence of water in the masonry.
In these portions the masonry has been patched, supposedly to fill the material loss in the texture or to reintegrate grafts of previous buildings once adjacent to the tower. These patches are immediately distinguishable because of the different construction materials and texture, often involving small cracks and fractures along the contact bourder between the two portions of masonry.
In these cases, stratigraphic analyses and physical-chemical studies are advised and could provide useful information to quantify the depth of the patches in the wall thickness and to evaluate the age of the interventions and the materials used.
At high altitudes, brick discolouration becomes widely observable. The colour variation seems to be related to erosion and disintegration of the bricks surface. The lighter-coloured areas visible in the photographs match with good approximation to the local deviation areas highlighted by the elevation maps, which show a depression (up to 36mm) calculated according to the chromatic variation along the colour scale (Fig. 15, p. 19).
These alterations are significantly more diffused starting from an altitude ranging between 16 and 18 meters. The study of historical events noted that below the aforementioned altitude, the tower was once embedded in the San Matteo Hospital building, and thus less exposed to weathering.
In the upper portion, visible effects presumably due to the presence of water in the masonry are once again prevalent, with bricks weathering and diffuse biological colonization widely observable. The visual inspection of the tower's roof represented a crucial objective fostering the documentation project. With this purpose, the UAV survey allowed for close-range and non-invasive observation of the hip roof. The results

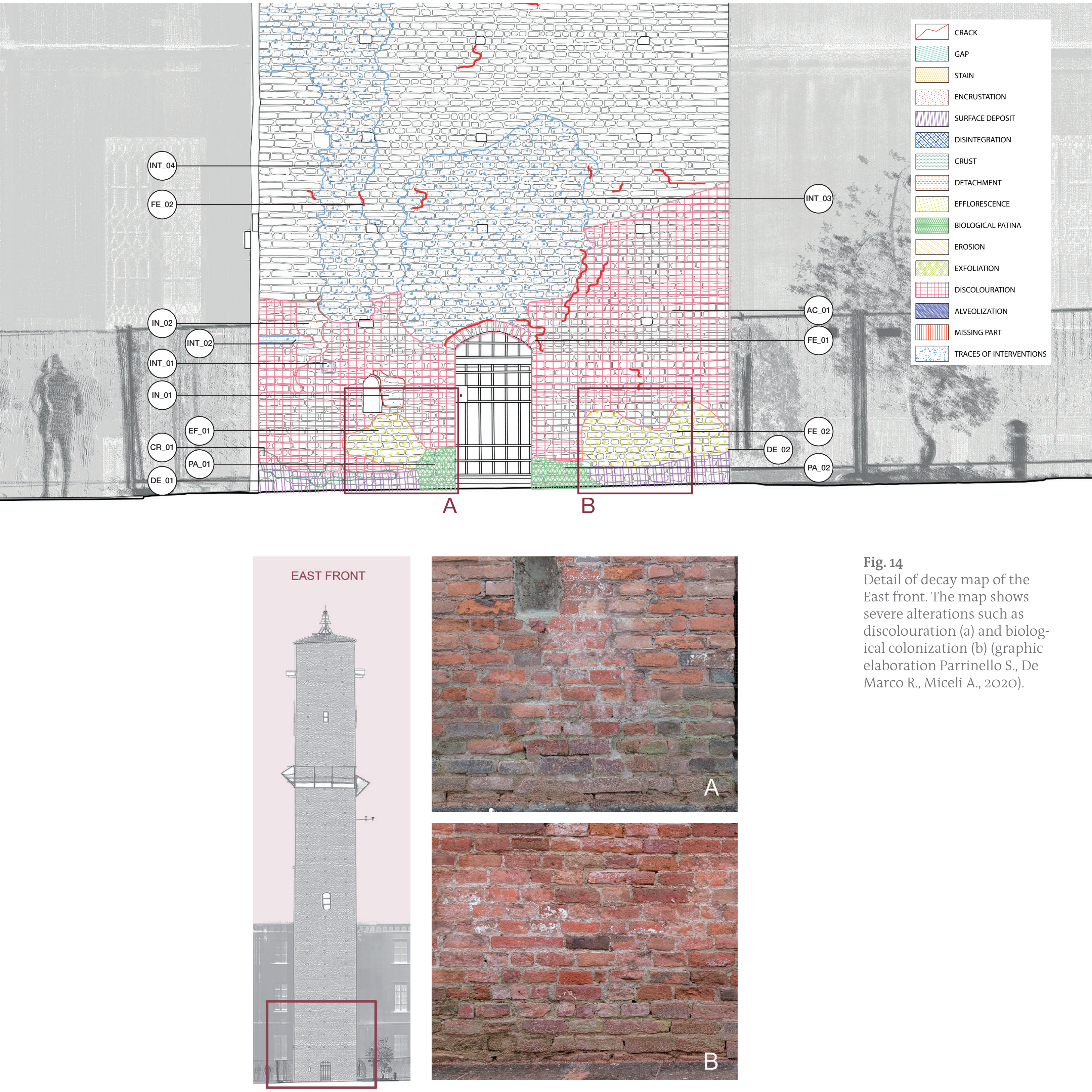


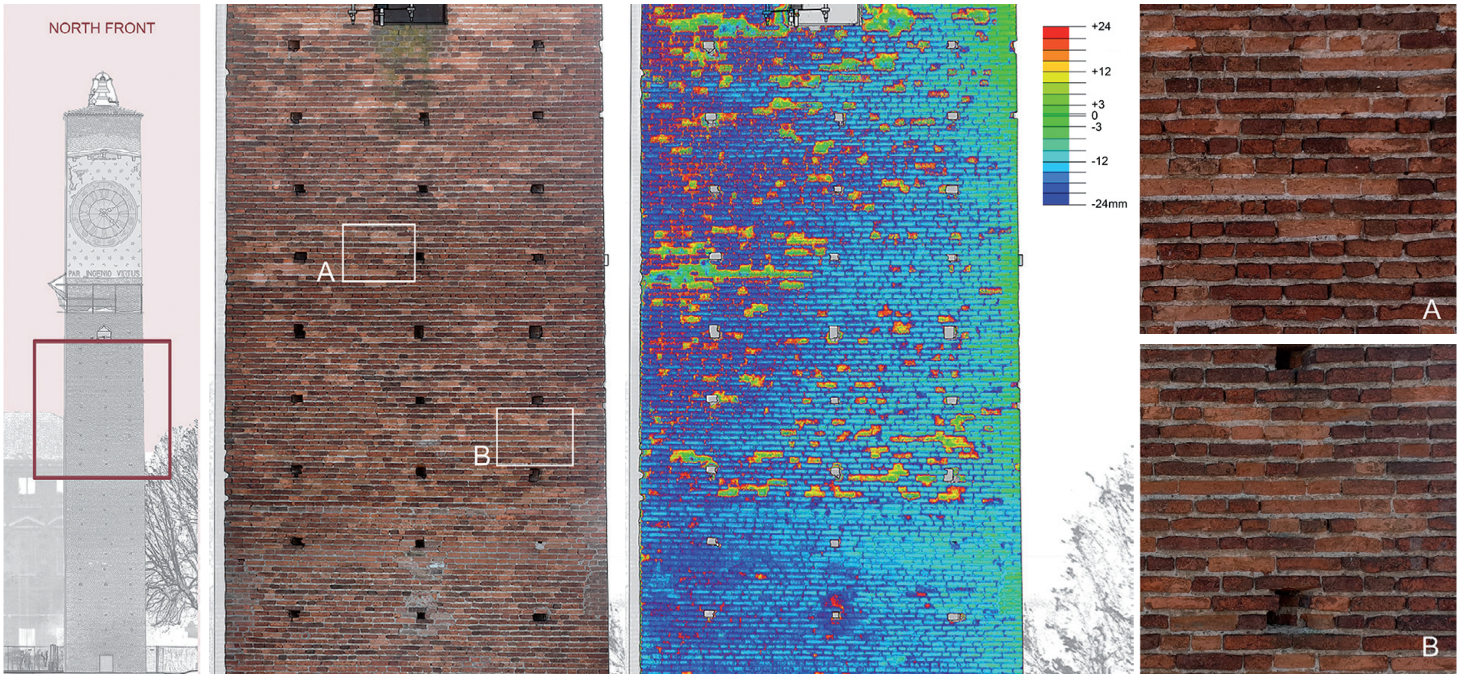
Fig. 14
Detail of decay map of the East front. The map shows severe alterations such as discolouration (a) and biological colonization (b) (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).

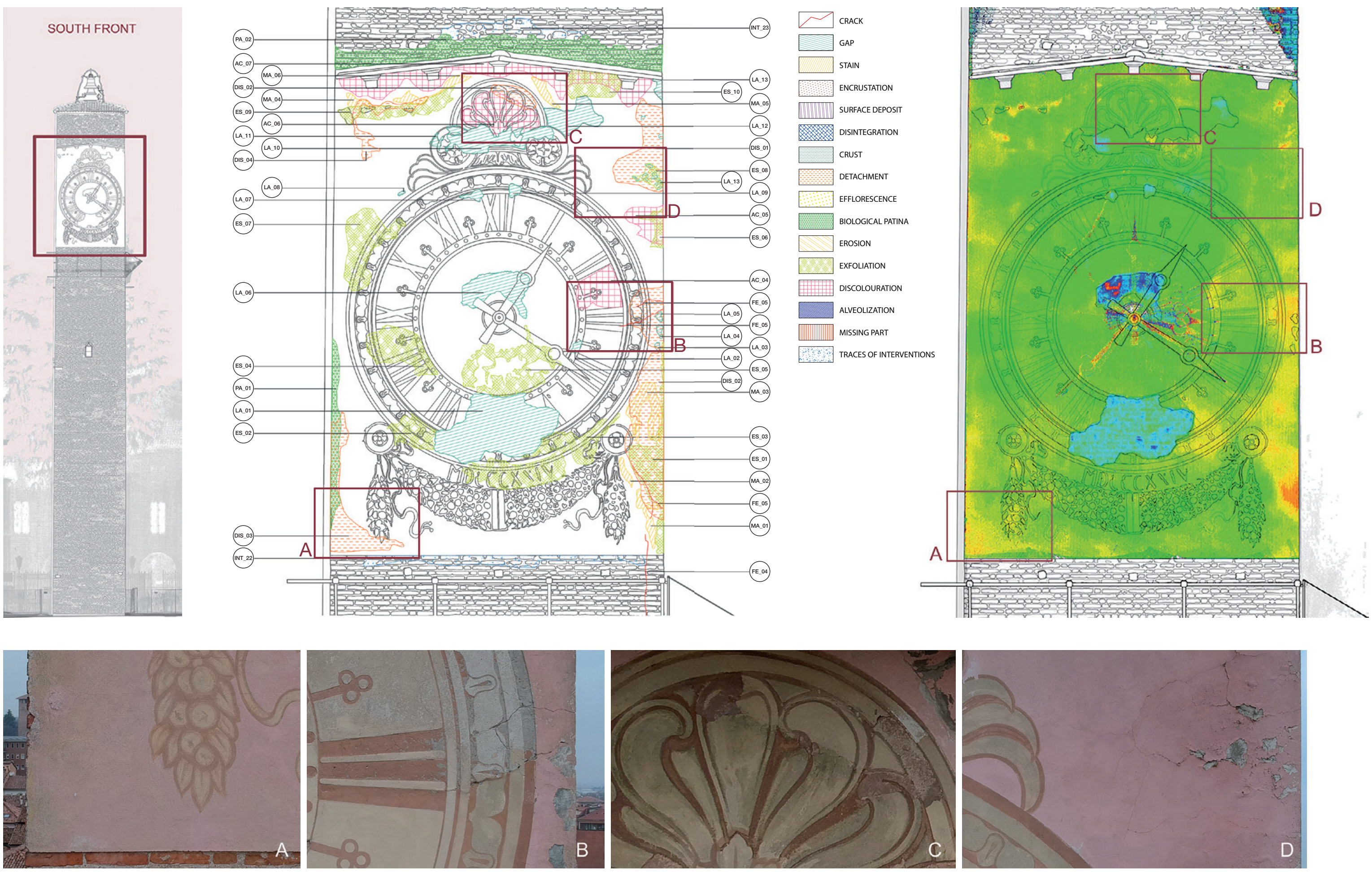
of the survey show outdated rainwater systems and a general lack of maintenance that impacts on the conservation status of the wall surface, as rainwater soaks into the pores of the materials and joints accelerating their disintegration.
Ultimately, the two sides of the clock have been deeply analysed in order to identify and classify the visual alterations affecting the decorated rendering. The recent fall of debris led the documentation project to focus on the rendered area, with the aim of monitoring its conditions and keeping track of portions close to detachment.
While direct observation was used to locate gaps, exfoliation and surface cracks, further support has been found in the comparison with the morpho-metrical data: elevation maps, in fact, highlighted yellow and red areas (with a deviation of 9-24mm), interpretable as positive deviation from the assumed reference plane. These results suggest that the render could be lifted and detached from the support. Since the detachment of render is not immediately visible in the photographic dataset, a closer inspection of the indicated areas is advised, in order to determine whether there is risk of further falling debris (Fig. 16).
The mapping of visible deteriorations has been conducted in parallel with a preliminary classification of the phenomena, corresponding to hatches and photographic abaci, for a quick and reliable consultation of the database depicting the single damage episodes.

opposite page
above
Fig. 15
Details of photo plane and elevation map of the North front. The process of layering and comparing the two outputs allowed for an accurate mapping of the erosion areas (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).
below
Fig. 16
Detail of decay map of the clock in the South elevation. Gaps and detachments in the rendering create local risks of falling debris and undermine the legibility of the decorative painting (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).

Stratigraphic hypothesis, interpretation of crack patterns and elevation maps for a preliminary structural frame

The observation and mapping of visible alterations highlighted the presence of stratigraphic traces clearly due to different interventions. Although not related to the natural degradation of the constructive materials, these alterations proved relevant and worth being mapped and represented. Therefore they have been classified with a distinct codification - not currently included in the relevant italian regulations[9]. The aim is to offer an overall view of these traces and identify those which require deeper inspections in order to enrich the technological and constructive knowledge of the object.
These alterations, defined as ‘traces of interventions’, present a preliminary value judgement: in fact, some of them are incoherent interventions, with inhomogeneous brick bonds and apparent incompatibility of materials; in other cases they represent evidences of the constructive stratification process occurred on the monument.
In case of uncertainty, the interpretation of the episodes has been supported by a strategic change in the observation distance. At a macroscopic scale, the traces that initially appeared as mere patches revealed to be much more complex episodes, witnesses of pre-existences and buildings once leaned to the tower.
The traces of the military station of Caserma Menabrea are immediately recognizable because of discolourations and patches visible in the wall surfaces: several traces are observable, which, according to the pitched roof, are sloped in the East and Western elevation, and horizontal in the North and South elevation; under these, a number of patches were made, presumably to restore the slots where the wooden beams once connected to the walls.
Moreover, in the West elevation, it is possible to notice horizontal traces where the masonry has a lighter colour compared to the surrounding texture: the marks allegedly point out the two floors of the pre-existing building.

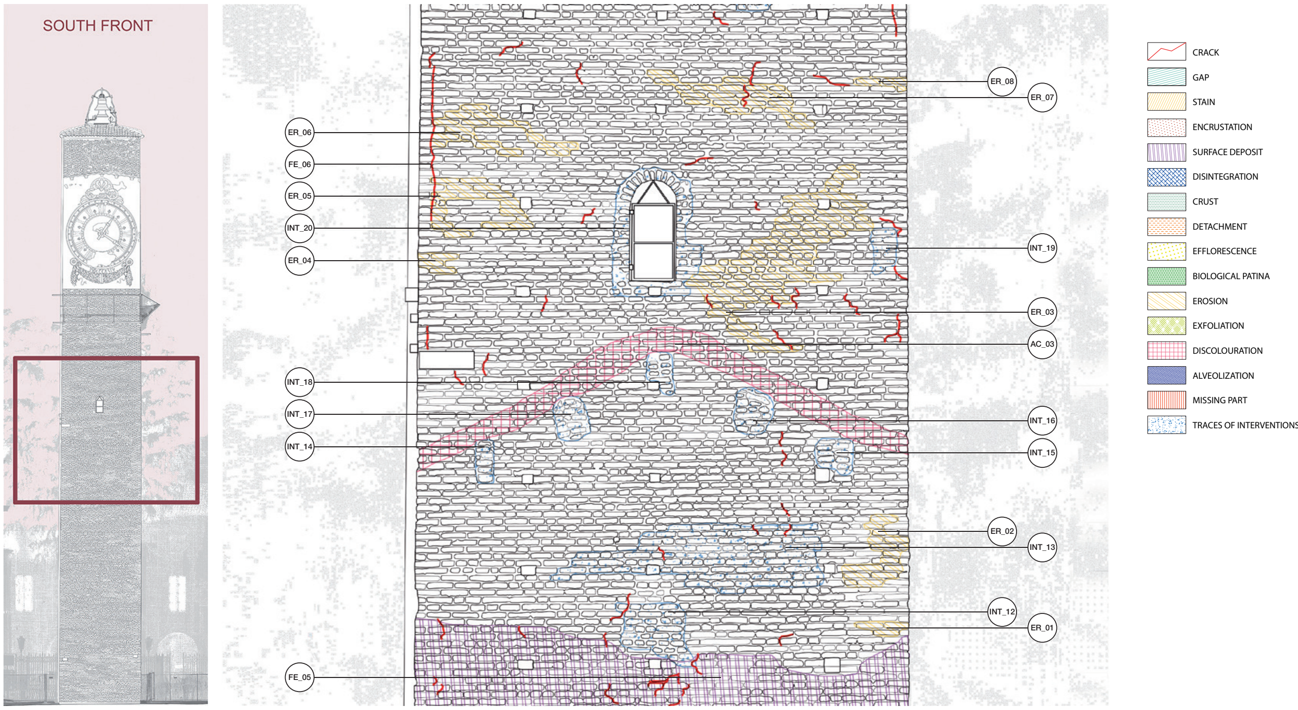

NORTH FRONT
PAR INGENIO VIRTUS
A
B
+24
+12
+3
0
-3
-12
-24mm
A
B

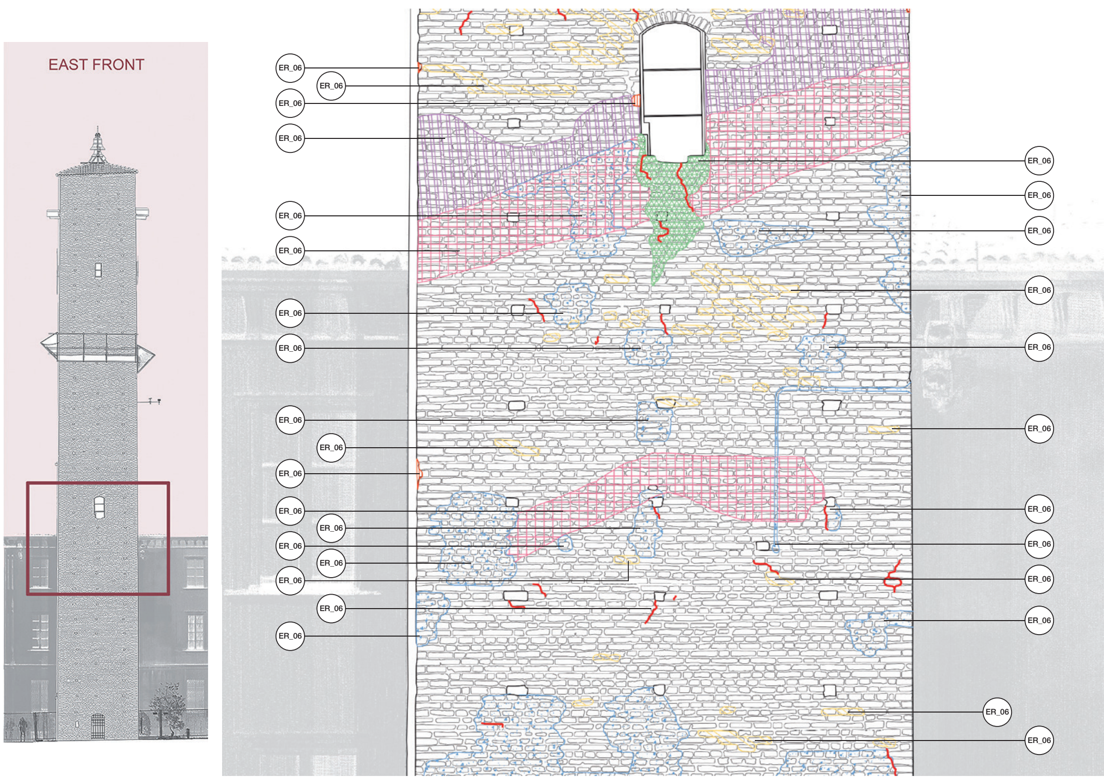

SOUTH FRONT
CRACK
GAP
STAIN
ENCRUSTATION
SURFACE DEPOSIT
DISINTEGRATION
CRUST
DETACHMENT
EFFLORESCENCE
BIOLOGICAL PATINA
EROSION
EXFOLIATION
DISCOLOURATION
ALVEOLIZATION
MISSING PART
TRACES OF INTERVENTIONS
A
B
C
D
A
B
C
D

opposite page
Fig. 17
Detail of alteration maps of South (above) and East (below) elevation. The patches and discolouration of masonry are evidence of buildings once leaned to the tower (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).

While these traces are confirmed by the study of historical sources, other evidences of previous actions are present, and not relatable to the aforementioned Caserma: in particular, the patches and discolourations visible on the South and East elevations, at 17 and 11.5m high respectively, made clear the presence of pitched roofs once attached to the tower (Fig. 17).
In the last phase of the research, the close-range high-altitude photographic survey allowed for an accurate visual examination of the walls and highlighted the presence of cracks and microcracks that spread along the mortar joints and, in some cases, cross the surface layer of the brick masonry.
During the processing of collected data, macroscopic observation allowed for a preliminary critical reading, in which the single events have been related to mechanically defined phenomena, such as continuous crack lines and crack "families", thus grouping fractures according to their location in the wall surface (Fig. 18, p. 22).
Then, the information derived from previous constructive analyses[10] and morphological database have been compared to support qualitative reading of the deformation status. Besides, inspections carried out in January 2020 to check the interior wall surfaces, highlighted no fractures matching the ones surveyed in the exterior surfaces.
The deviational analysis allowed to match cracks and cracks families to the specific effects of the same structural mechanism, providing a preliminary mapping of damages (Fig. 19, p. 23). In fact, by comparing the 3D point cloud with an ideal morphological model, it is possible to highlight possible macroscopic on-going kinematic events. For example, at the base of the North front; the wide colour variation suggests the presence of a plastic hinge to which the cracks in the same area could be related. Other fractures in the West front seem to be related to corner failings; additionally, in the East front compression stresses and an extensive corner failing are suggested by the colour variation in the elevation maps, possibly relating with the cracks visible at 7.5 meter height (Fig. 20, p. 23).

Considerations on possible conservation and monitoring strategies
The presented research highlights, starting from the case study, the presence of an intrinsic morphological and constructive complexity in the towered monuments of medieval foundation, as result of a sedimentation of events and building actions that have determined their stratified compartments.
The required conservation operation, including the Clock Tower itself, cannot be separated from consolidated processes of knowledge, tests and investigations. The architectural survey, combined with the study of historical and constructive characteristics, represents only a preliminary tool to the project of intervention and restoration.
The achieved graphic results reveal specific requirements and complexities of diagnosis on the structural block of the tower, amplified in consideration of its specific proportion. The study aims at advancing the documentation practice applicable to these monuments in relation to the acquisition criticalities and the necessary level of detail for a reliable mapping of the surfaces.
The proposed approach aims at facilitating a cyclical monitoring framework on the Clock Tower, useful for guiding the precise definition of a more complex restoration project. In this way, it is possible to avoid or, at least, limit the changes during the restoration phase and at the same time to ensure a more efficient conservation of the materic integrity compared to the extensive application of invasive investigations. According to these purposes, the quality and level of detail of the morpho-materic database have


SOUTH FRONT
ER_06
FE_06
ER_05
INT_20
ER_04
INT_18
INT_17
INT_14
FE_05
ER_08
ER_07
INT_19
ER_03
AC_03
INT_16
INT_15
ER_02
INT_13
INT_12
ER_01
CRACK
GAP
STAIN
ENCRUSTATION
SURFACE DEPOSIT
DISINTEGRATION
CRUST
DETACHMENT
EFFLORESCENCE
BIOLOGICAL PATINA
EROSION
EXFOLIATION
DISCOLOURATION
ALVEOLIZATION
MISSING PART
TRACES OF INTERVENTIONS


EAST FRONT
ER_06

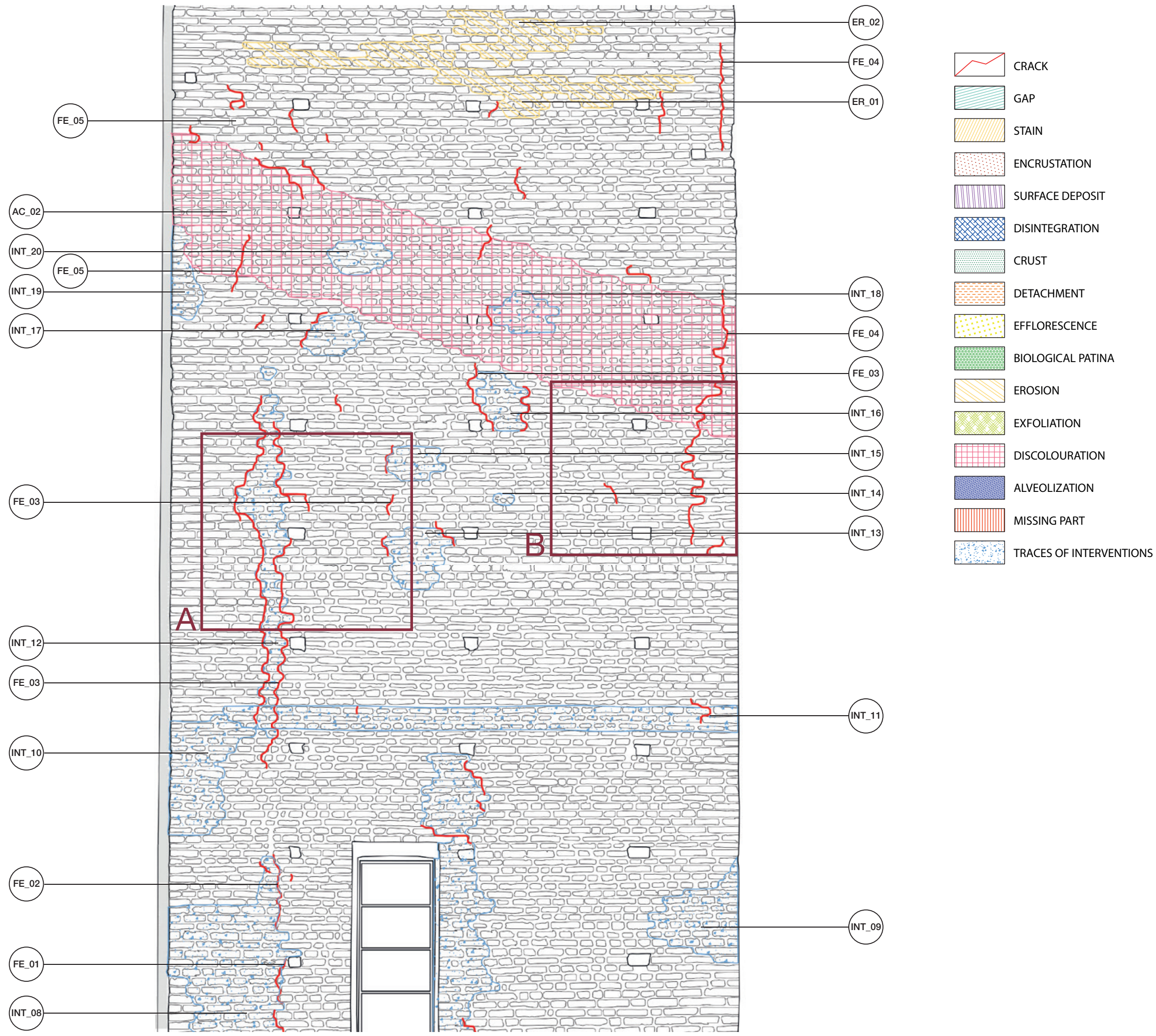
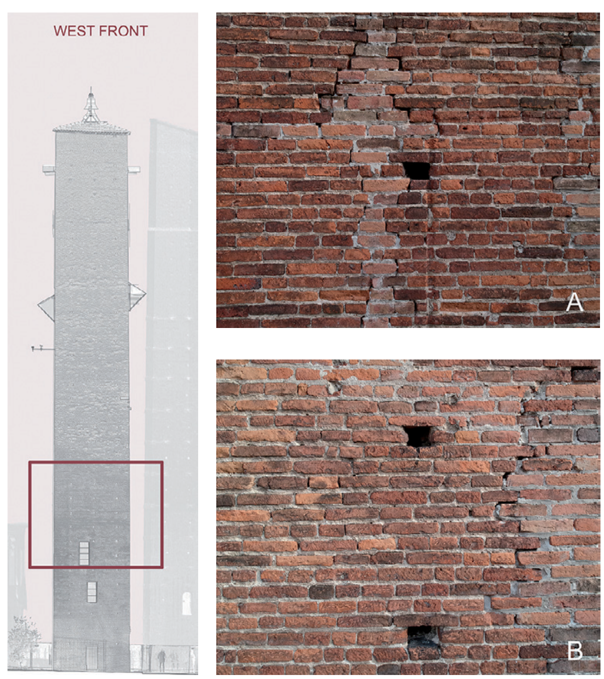
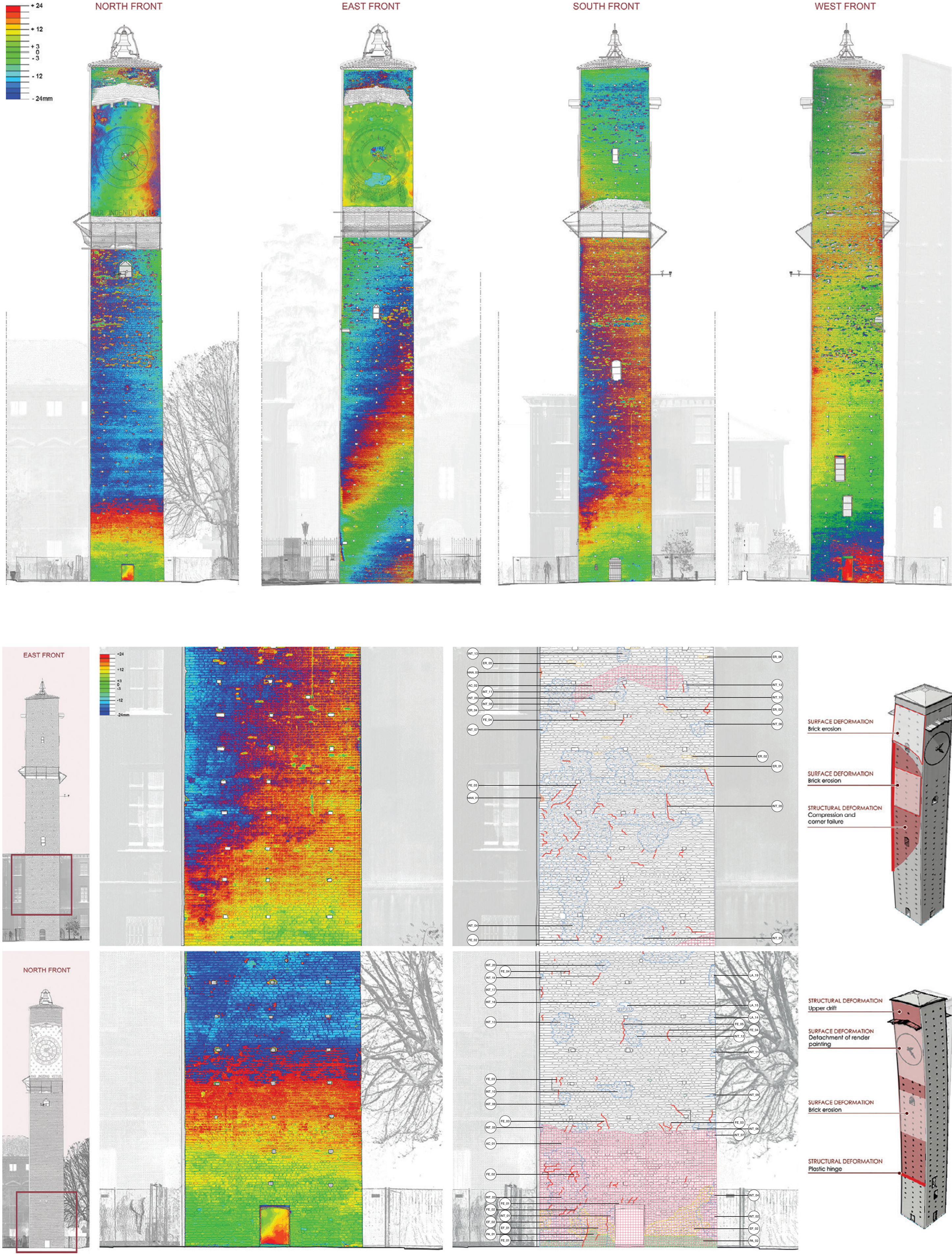


Fig. 18
Detail of alteration map of the West front. The map shows discolouration, traces of inappropriate interventions and fractures (A and B) (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).

opposite page
above
Fig. 19
Elevation maps, obtained by processing the morphological database collected during the on-site survey stage, highlight macroscopic deformations and possible kinematisms affecting the structure (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).
below
Fig. 20
The comparison between crack maps and elevation maps highlighted the possible relationships between surface deteriorations and structural deformations. For example, crushing, corner failure and hinges highlighted by elevation maps usually correspond to cracks and crack groups observable in the photo planes (graphic elaboration Parrinello S., De Marco R., Miceli A., 2020).




+ 24
+ 12
+ 3
0
- 3
- 12
- 24mm
NORTH FRONT
EAST FRONT
SOUTH FRONT
WEST FRONT
EAST FRONT
SURFACE DEFORMATION
Brick erosion
SURFACE DEFORMATION
Brick erosion
STRUCTURAL DEFORMATION
Compression and corner failure
NORTH FRONT
STRUCTURAL DEFORMATION
Upper drift
SURFACE DEFORMATION
Detachment of render painting
SURFACE DEFORMATION
Brick erosion
STRUCTURAL DEFORMATION
Plastic hinge

been increased, also proposing a strategy of multi-instrumental integration. Within it, the comparison between morpho-metric and materic data completely covers the cognitive requests for the mutual relationship between deformation mechanisms and superficial pathologies.

The conservation status found in the Clock Tower requires a double attention to the diagnostic project.

First of all, it is necessary to promptly intervene on the deterioration of materials, especially in the high-altitude surfaces where the fresco of the clock is located. Once the hypotheses of degradation have been confirmed or not, also following more invasive local investigations, it is suggested to intervene on reducing the conditions of material alteration. In particular, for the plaster portions, the consolidation of gaps, detachments and exfoliation is indicated, ensuring safety from possible new detachments as well as preserving the legibility of the pictorial apparatus. A direct inspection of the portions of morphological alteration is also indicated, in particular on the East and West fronts, to verify a possible consolidation action of bowing and corner detachments, and a series of restorative interventions of the portions of masonry presumably affected by humidity phenomena and erosion.

Secondly, a methodological systematization of invasive analysis and monitoring of the emergency frameworks, highlighted by the survey, is suggested, assessing possible guidelines. These guidelines are intended to be focused not only on the intervention procedure, but also on the prevention and scheduled planning of cyclical inspections for the in-progress macroscopic phenomena, both by intrinsic deformations and environmental conditions. The definition of a specific monitoring plan for the Clock Tower, with respect to the categories of supposed pathologies, suggests an annual inspection to check for any increase in deformation and eccentricity, which can also be locally detailed with sonic/ultrasonic tests, georadar measurements or endoscopies. In addition, a six-monthly monitoring is advised for the control of material integrity and infiltrations according to seasonal conditions, concentrated in the base and the top wall portions.

In this aim for safeguarding, the digital database obtained proves to be a valid tool for rapid application and analysis of qualitative assessments on the extension and localization of the alteration phenomena, in order to establish diagnostic strategies and action priorities. Furthermore, it is available for further additions useful to support specific requirements of analysis, such as non-destructive instrumental investigations.

The research proves that a reliable and replicable methodological protocol is strategic for the towered heritage of the historic center of Pavia, as it allows to replicate and extend the survey operations for monitoring specific monuments over time, towards an efficient strategy for long-term conservation.

Credits

Although the authors share the same methodological approach, premises and conclusions, Sandro Parrinello wrote the paragraphs 1 and 2, Raffaella De Marco wrote the paragraphs 3 and 4, Alessia Miceli wrote the paragraphs 5 and 6.

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Note

[1] Even without comparing with the elevation of the noble towers (over 30-40 meters), the limited planimetric development of the medieval city already required the search for solutions oriented towards the vertical development of units, overcoming the building resistance offered by wooden structures, limited to one or two floors, with the use of stone or brick techniques. It was a common practice to insert these wall monuments as stiffening bodies for wooden structures, as in Bologna (with the *buona sponda* constructive system) (Bergonzoni, 1992). Then, the case of real tower-houses (where the housing function was not separated from the defensive-offensive one) has specifically declined the masonry structures such as in Siena and Volterra.

[2] The widespread diffusion of civil towers in urban contexts has forced many Italian municipalities (such as Pisa, Genoa, Verona, Florence, Bologna) to organize a series of regulamentations between the 11th and the 14th centuries to limit their height for residential use, imposing the demolition of those

exceeding the established limit (Bergonzoni, 1992, Bossaglia, 1959, Vaccari, 1986). A conscious awareness of the risk represented by these structural blocks to the unexpected occurrence of instability phenomena was already demonstrated.

[3] The 78 meters high tower, among the most massive in the city and practicable to reach the top until its collapse, was integrated with a bell block from 1330, which was then rebuilt in stone from 1581 with the annexation to the Cathedral complex (Vaccari, 1986, pp. 77-86; Stabile, 1992). The overloading of the bell block generated a phenomenon of crushing and hidden damage to the underlying rubble masonry structures, leading to the sudden collapse of the entire monument on March 17th, 1989. In addition to the victims, 4 dead and 15 injured, significant damage was reported to the structures of the adjacent Cathedral and to the 3 surrounding urban aggregates.

[4] After the tragic event of the Civic Tower, the Minister of Civil Protection constituted a technical commision called to examine its causes, but also the state of conservation of the surrounding monuments. The documentation project focused on Torre San Dalmazio, Torre del Maino, Torre Belcredi, Torre Fraccaro and the Clock Tower, and it comprised of several phases: historical-artistic analysis, archive research, topographic survey, mechanical, physical and stone tests on the materials, dynamic analysis and structural calculations with numerical modelling. Following these studies, the Torre Fraccaro, Torre San Dalmazio and Torre del Maino were subjected to interventions of consolidation, adopting complex structural solutions in the interiors to strengthen the walls, taking advantage of the putlog holes to set the transversal chains.

[5] The monitoring project was based on evaluating the results of the application of dynamic measurements on the Tower, using natural stress caused by wind and ground vibration. The work focused on the comparison with linear analyses of data transmitted by fixed transductors installed to measure the frequencies of oscillation of the structure.

[6] See Ghezzi, A. 2019, *Torre dell'Orologio: allarme per la caduta di pezzi di mattone*, «La Provincia Pavese», 18 December 2019, p. 12.

[7] The research was enforced in a collaboration between DJI Enterprise and the University of Pavia for the development of research activities, and the promotion of different ways of using drones for cultural heritage. This collaboration is based on the 'Agreement for the development of research activities about the digital documentation of cultural heritage and landscape using drones' between the Department of Civil Engineering and Architecture of the University of Pavia and iFlight Technology Company Limited, signed in February 2020, lasting three years.

[8] The documentation campaign focused on the exterior wall surfaces. The extremely limited plan development due to the massive thickness (approximately 2 meters) and the presence of a staircase, not sufficiently stable to allow for an instrumental campaign, brought to opt for a visual examination, respecting the safety protocols for the operators. The inspection showed that the brick masonry shrinks proceeding towards the top of the tower in order to reduce the weight of the walls. Moreover, it shows the signs of the original horizontal partitions.

[9] See UNI 11182:2006, 2006, Cultural heritage. Natural and artificial stone. Description of the alteration. Terminology and definition.

[10] Inspections have been conducted to study the structure of the Tower (Resta, Brunamonti, 1989):, the coring exposed that the masonry consists of three layers: the interior and the exterior layers are brickwork, while the core is filled with pebbles, brick fragments and sand and cement mortar. In addition, the coring revealed the presence of wooden beams embedded in the core which served as reinforcement against the effects of the compression stresses.