Monitoring as strategy for planned conservation: the case of Sant'Andrea in Mantova (Mantua)

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Received: 8 January 2018 / Accepted: 22 August 2018 / Published online: 29 September 2018

Abstract
The synergy between Mantua Diocese, Direzione Regionale per i beni culturali e paesaggistici della Lombardia and Politecnico di Milano enabled the elaboration of a strategic conservation plan for some Mantova buildings of great significance to the city and to the owners: the planning of monitoring activities necessary to the conservation has experienced a further development as regards the structural aspects, after the earthquake, to improve performances vis-à-vis the updated seismic risk level. The collaboration between stakeholder bodies made it possible to systematise the resources needed to access available funds for scheduled conservation and innovative diagnostics over the last decade. The aim is to bring about the necessary conditions for an in depth examination of case studies pretty much representative of local building materials and techniques, for which to identify the best practices for conservation. The networks the bodies belong to permit the dissemination of the results achieved to a vast number of observers, stakeholders, owners, and other local bodies. The paper relates to the diagnostics part, including the innovative techniques employed alongside the more traditional and standardised ones, with a view to drawing up a program of checks and a plan of preventive actions, despite of a limited number of interventions. The monitoring measures and the inspections aim to mitigate some risk factors, among them the (up to now) advanced state of decay of some elements in the oldest buildings, whose maintenance would aggravate the conservation conditions, especially as regards decorated surfaces. Out of the analysed buildings, the case study herein described concerns the Basilica Concattedrale di Sant'Andrea Apostolo in Mantova, a mankind architectural heritage and, obviously, a city monument.

Keywords Preventive and planned conservation · Built cultural heritage · Innovative diagnostics · Structural monitoring · Microclimate · Rising damp

Introduction

The research project arises from the need of the Mantova Diocese to identify an innovative approach to manage the architectural heritage, in the sense of an activity aimed both at the conservation and at the enhancement of the buildings. The buildings involved (Mantova's Museo Diocesano, Palazzo Vescovile, Seminario Vescovile and Basilica Concattedrale di Sant'Andrea Apostolo (in the further Basilica di Sant'Andrea or Sant'Andrea or Basilica)) host various functions and thus demand a different approach as regards maintenance and management of interventions.

Lying at the root of the strategy for conservation of a building is in fact the need for a use compatible with the characteristics of the asset, in the knowledge that if it is essential to physically conserve the artefact, it is likewise fundamental that it will be utilised in such a manner that constant use entails an ongoing care as well, thereby triggering continuous checks instrumental to maintenance and continuous enhancement (Della Torre 2014). All of that starts from an analytical and in-depth knowledge of the asset all the way up to a project of managing future transformations; it does not however take on the form of a punctual event, but rather that an ongoing path.

The earthquake that, in May 2012, struck Emilia Romagna and Lombardy has clearly highlighted the fact that, in the conservation process, we need to view the seismic risk as a

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This is a post-peer-review, pre-copyedit version of an article published in Applied Geomatics, 2018, 10: 441-451. The final authenticated version is available online at: https://doi.org/10.1007/s12518-018-0240-4

looming problem disruptively superimposed on the conservation of monumental assets (Fratus de Balestrini et al. 2013). We can further note that this earthquake is the first one to have been tackled through a new well-defined legislative "corpus" targeting the cultural heritage. We are referring to the "Technical Building Regulations" (NTC) and to the "Guidelines for the assessment and reduction of seismic risk to the cultural heritage brought in line with the new Technical Regulations" (LLGG) of February 2011. One of the first remarks is associated with the fact that the guidelines stipulate a "premium-awarding" mechanism based on the degree of knowledge of the building: if, for the building, a "high" level of knowledge is available, the actions to be taken into account for seismic inspection are fewer (reliability principle). This entails less invasive and less costly interventions.

Innovative strategies and methodologies for the preventive and planned conservation of the built cultural heritage

What is meant by preventive and planned conservation is the totality of activities capable of limiting the risk situations associated with the cultural asset within its context (Della Torre 2003). It is implemented through the introduction of prevention practices and "control and response" procedures, suitably monitored and recorded. It is then enshrined in a conservation plan that stipulates activities of asset management, structural (within a seismic context as well) and geometrical knowledge, planning of maintenance and preventive interventions, and interventions to systematise data collection and management. Moving from the premise that the evolution and transformations of a cultural asset are strictly related to the context, the starting point is identified with the position whereby prevention is achieved through the implementation of interventions aimed at modifying the ambient conditions capable of generating the appearance of decay phenomena. From that point, it is then possible, passing through the idea that the best care is a prevention attained thanks to a periodical maintenance, to reach a wider meaning of prevention in the sense of an integral part of the conservation process.

Preventive conservation operates at different levels. The first level concerns the interventions on the context aimed at avoiding the onset of decay phenomena. The second relates to management and orientation of the control and maintenance operations. The third operational level also concerns the design of possible specific interventions, based on their preventive effectiveness.

The envisaged methodology contemplates the use of technologies suited to the conservation of cultural assets through the creation of a virtuous process for preventive and planned conservation. What is in fact proposed is the use of methods and tools proving to be minimally or not invasive at all, yet capable of yielding results serving to identify the problematic areas relating to the detected decay phenomena. For example, in the field of knowledge, the survey conducted through a 3D laser scanning instrumentation ensures excellent results without damaging or even touching the structures; the characterisation investigations boast the fact that they demand the removal of a limited quantity of matter, besides being partly implemented through portable instruments.

Based on these observations, the Mantova Diocese has tasked Politecnico di Milano with designing a series of asset knowledge activities we might group under two major classes.

The first involves knowledge of the artefacts through the surveys and monitoring checks carried out through topographic, laser scanning and photogrammetric methods. On the one hand, it enables us to fix the initial state of health of the asset, identifying its geometrical characteristics. It further allows us, through the monitoring activity, to check the state of health of the work, especially with regard to the aspects proving to be the most critical (with Sant'Andrea, the response to the seismic stresses of the earthquake and the triggering of possible structural damage mechanisms).

Fig. 1 The orthophoto of the counter-facade of the Basilica with vector drawing overlay and crack detection

The second activity is linked to diagnostics, the aim of which is to investigate the behaviour of the structure vis-à-vis its context. It will find shape in some types of investigation: monitoring measures to assess the micro-environmental conditions and their variations, and ground-penetrating radar investigations.

The diagnostics plan for the basilica di Sant'Andrea

At the behest of the Mantova Diocese, the authors have elaborated a specific diagnostics plan for each of the four afore-listed buildings. In the specific case of the Albertian Basilica di Sant'Andrea, it should be borne in mind that it has been the target of an important conservation intervention on the façade and on the pronaos. Significant critical issues still linger, however, with regard to the inner parts. To that end, suitable diagnostics campaigns have been identified with a view to determining the most urgent and least invasive interventions. In this instance, a direct commitment has manifested from the regional MiBAC (Ministry of Cultural Heritage and Activities) management, which is offering itself as co-financer for the diagnostic intervention on the inner parts of the Basilica.

Survey and monitoring

The increasingly greater importance conferred on the historical-cultural heritage has facilitated the development of

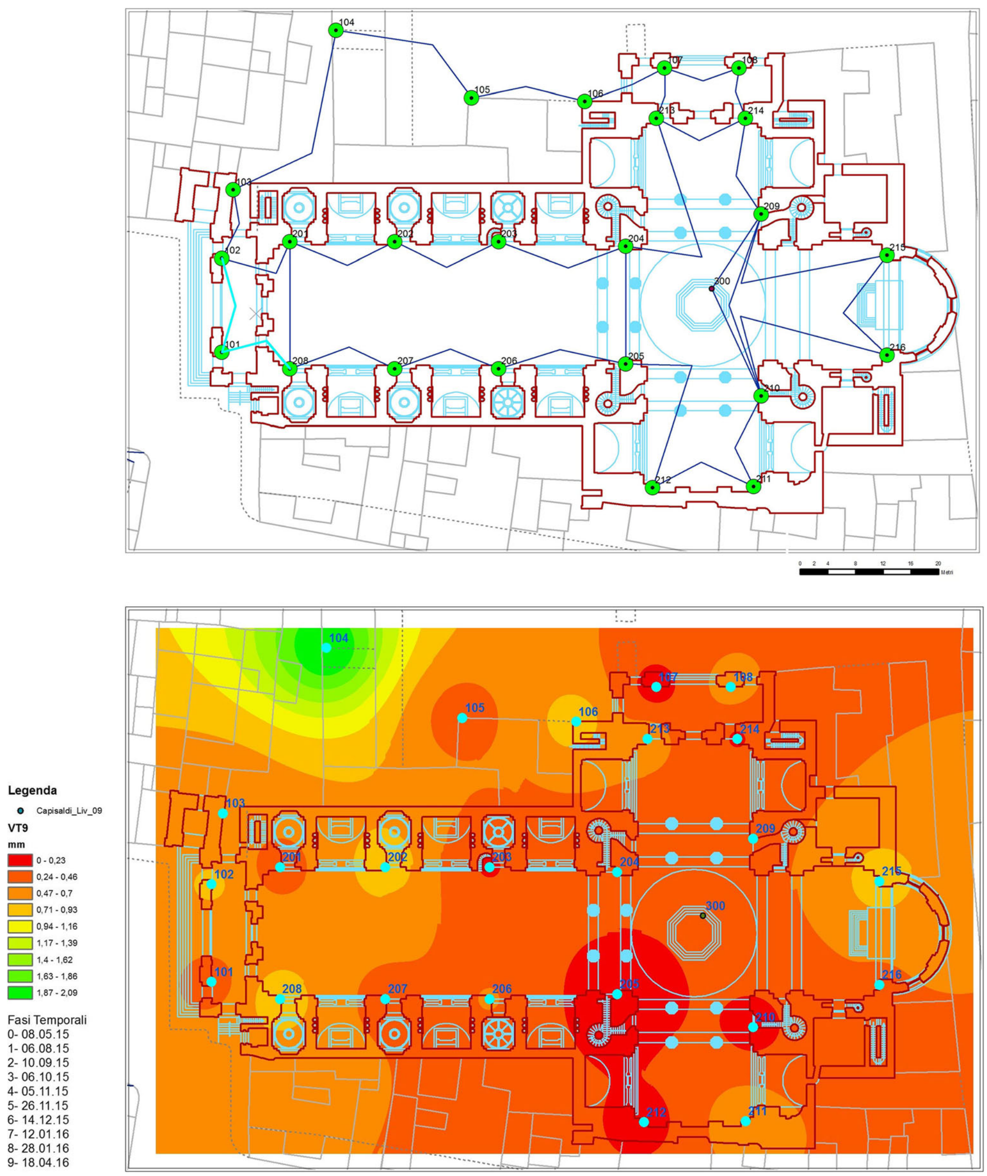

Fig. 2 The monitoring of cornerstones internal to the Basilica, arranged in accordance with the diagram attached in the top

ever more specific and targeted legislative enactments aimed at its protection. Precisely from the starting premise of these enactments, it emerges that, for the sake of an aware conservation, it is essential that the analysis of the structural behaviour of the buildings is conducted through the integration of the most innovative Geomatics techniques and tools (Fregonese Fregonese et al. 2013). In particular, it is increasingly clear that arranging a precise geometrical survey is important to comprehensively detail the examined structures, more specifically the importance of painstakingly surveying the map cracking and deformative scenarios for purposes of a subsequent careful and thorough structural analysis. Thereafter, drawing up a targeted monitoring program, defined in the light of knowledge of the disruptions underway, enables the investigation and ascertainment of the real behaviour of the buildings (Costanzo et al. 2017).

The contribution of monitoring techniques, applied at the diagnostics level, has involved more than one building of the Diocese: this work illustrates, given its singularity and complexity, what has been organised for the Basilica di Sant'Andrea.

The geometrical study in support of the structural analysis of the Basilica has been limited to the complex of the monumental façade, in particular to the internal counter-façade. Range-based acquisitions have been realised through a high-density TLS (Terrestrial Laser Scanning) sensor, by now well-structured and defined (Cignoni Cignoni and Scopigno 2008). Afterwards, for the sake of comparison and completeness, an image-based photogrammetric survey was conducted, one where an automatic image-matching technique enabled the development of a dense cloud of points from which, at a later stage, the continuous three-dimensional mesh representation surface was extracted.

Out of the totality of these first elaborations, the orthophoto of the counter-façade of the Basilica was produced (Fig. 1)

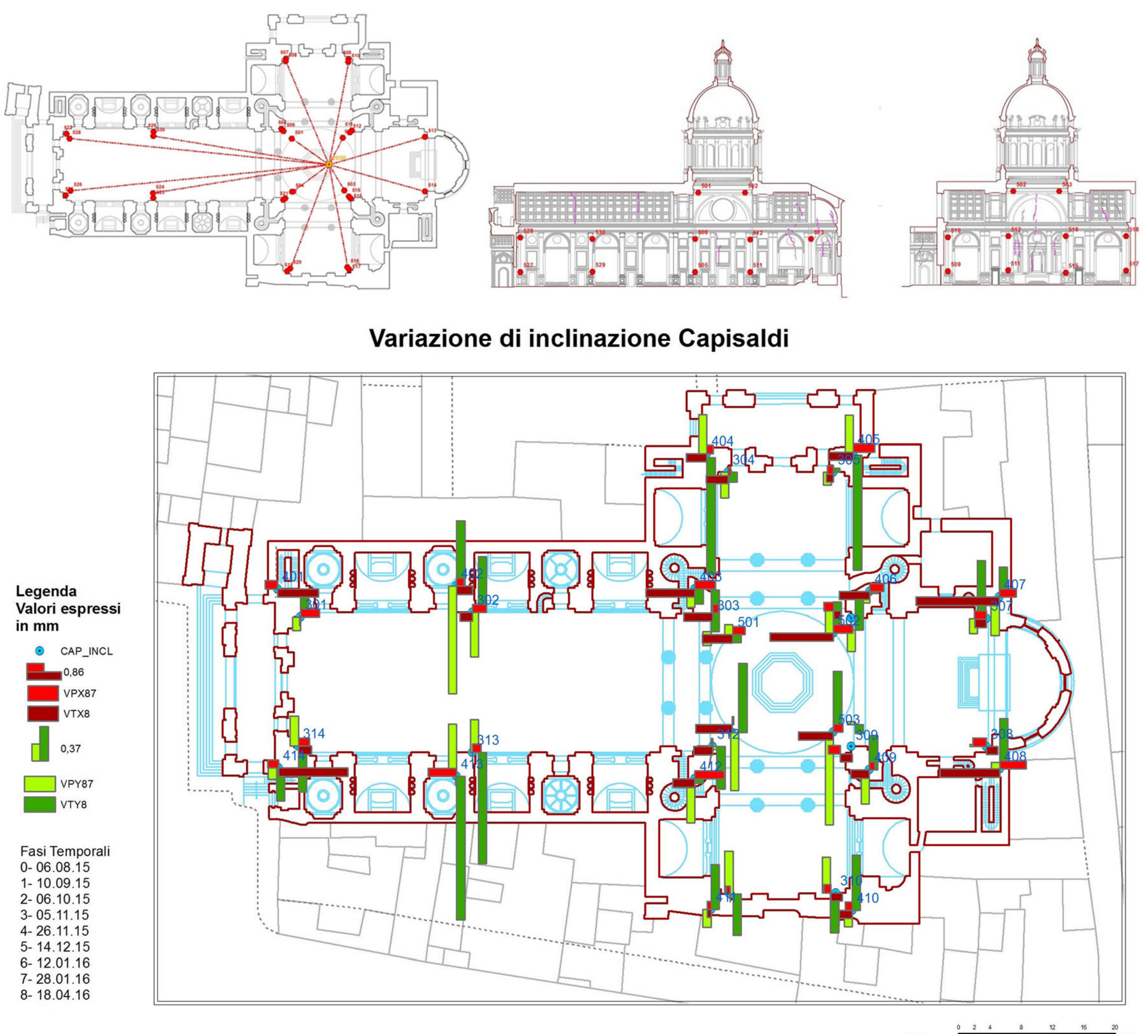

Fig. 3 The positional scheme of the prisms in plan and elevation on the top

enabling us to read the complexity and gravity of the map cracking underway (Chiarini et al. 2014). Thereafter, a careful analysis of the structural picture began with targeted interventions.

At the end of this phase, to ascertain the dynamism of the phenomena underway, a monitoring activity has been considered, one divided in accordance with a hierarchical dimensional approach into:

- *altimetric monitoring* to check the upward variations of the structure and the Basilica complex, carried out via precision levelling;

- *three-dimensional monitoring* to analyse the deformations of the Basilica in the three-dimensional field, so as to identify any kinematic motions giving rise to displacements or slants of the structures;

- *monitoring of the map cracking*: study and control of the map cracking through a reading of the ambient parameters, in order to correlate the local deformations to the global ones of the structure.

Micro-climatic monitoring and thermo-hygrometric surveys

The purpose behind the diagnostic investigations is to obtain a map of the distribution of humidity in the masonry, the conditions of balance with the ambient of the finishes on site, the variations caused by the daily and seasonal ranges, and identification of the micro-climatic factors that might represent a risk to the conservation of the surfaces on site. More specifically, the aim of the micro-climatic monitoring, which lasted a number of years, is to assess the imbalances occurring naturally inside the building, so as to be able to define the threshold values of ambient temperature (T in °C) and relative humidity (UR) enabling the optimal conservation of the historical surfaces. The thermo-hygrometric investigations allow us to locate the presence of liquid water in the surfaces thanks to a mapping of surface temperatures: in some points that proved to be the most significant ones, the water content was inspected through gravimetric tests and through innovative

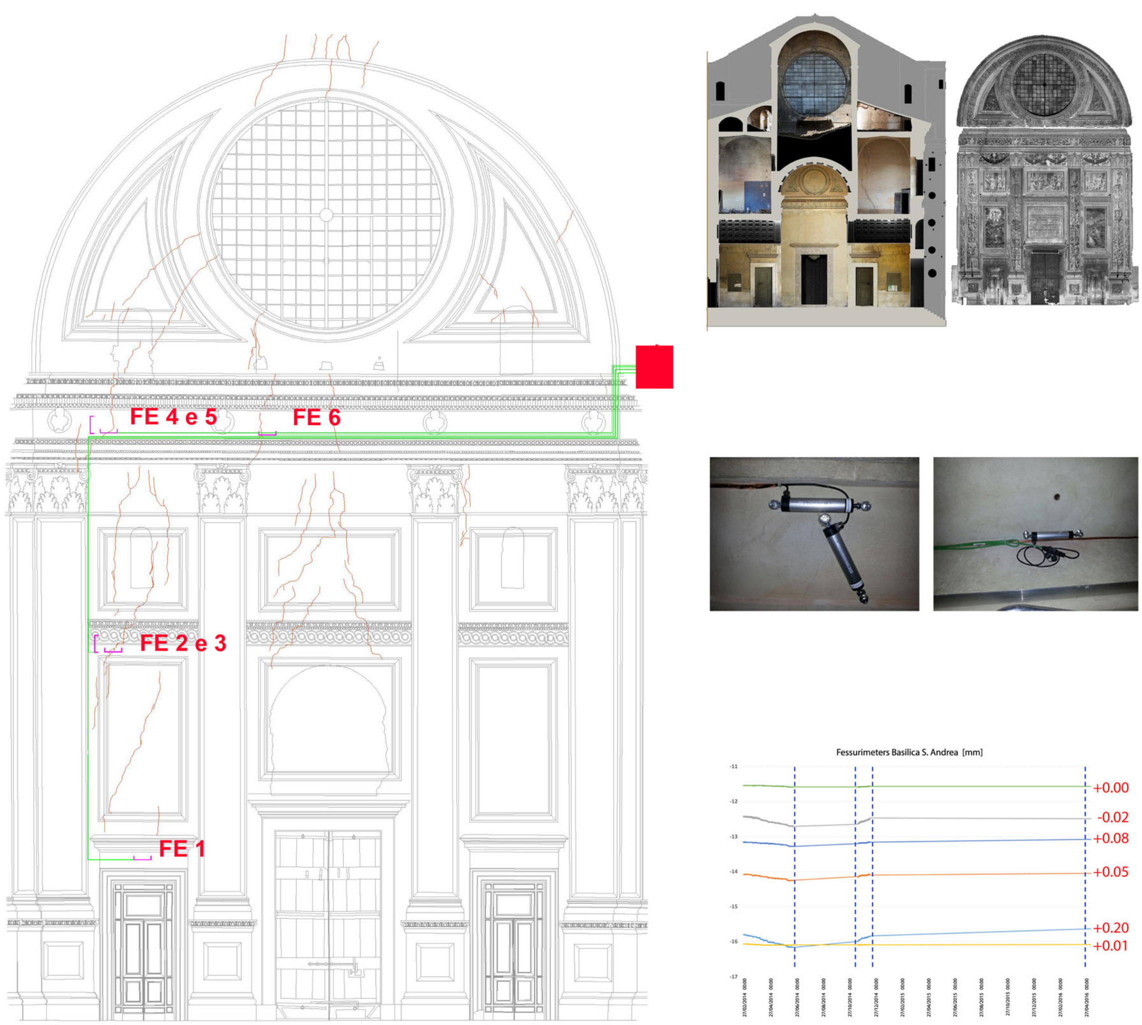

Fig. 4 The façade and counter-façade of the Basilica

techniques. The results expected from the investigations and the monitoring activities are the attainment of a correspondence between decay and presence of water, in liquid and gaseous state, in the different periods of the year, so as to embark upon damage prevention actions as regards both the use of the building and the maintenance practices, as well as any further renovation interventions wherever deemed necessary.

First results

Hereunder set out are the results of the activities as provided by the diagnostics plan, with a detailed description of the procedures used and the results obtained for the Basilica di Sant'Andrea.

Structural monitoring: altimetric monitoring

To be able to check the geodetic–topographic phenomena of the Basilica, a basic control revolving around the fundamental points of the complex has been suggested. The monitoring of cornerstones internal to the Basilica, arranged in accordance with the diagram attached in the top of Fig. 2, has been carried out pursuant to the methodologies of the high precision levelling networks:

-method of double reading measurement per single stroke (backward-forward, forward-backward);

-levelling lines carried out pursuant to ring-type schemes to check the closures;

-tolerances in the closures of the levelling lines have fulfilled the following ratio T (tolerance) $\leq 0.1\sqrt{n}$ (mm), where n stands for the number of strokes of the levelling ring.

These cornerstones have been realised through stainless steel linchpins, thermally treated so as to render the surface opaque and amber-like, fixed onto the wall structures through hole and dowel. The location of the said linchpins has been studied to be the least visible inside the Basilica.

The measurement sessions were carried out monthly for a period of 1 year. In the image (bottom of Fig. 2) we can observe a representation of the absolute altimetric variations compared to the initial T^0 situation (first measurement session). At the end of the observations, it was proposed to extend the monitoring period in order to obtain more significant data. The observations carried out, however, evince clear movements as regards some of the cornerstones (for the cornerstone with the greatest variation, amounting to + 2.09 mm, we assume that the linchpin has been somehow struck and modified in its initial positioning). Altogether, over the winter period the Basilica witnessed an average rise of 0.44 mm.

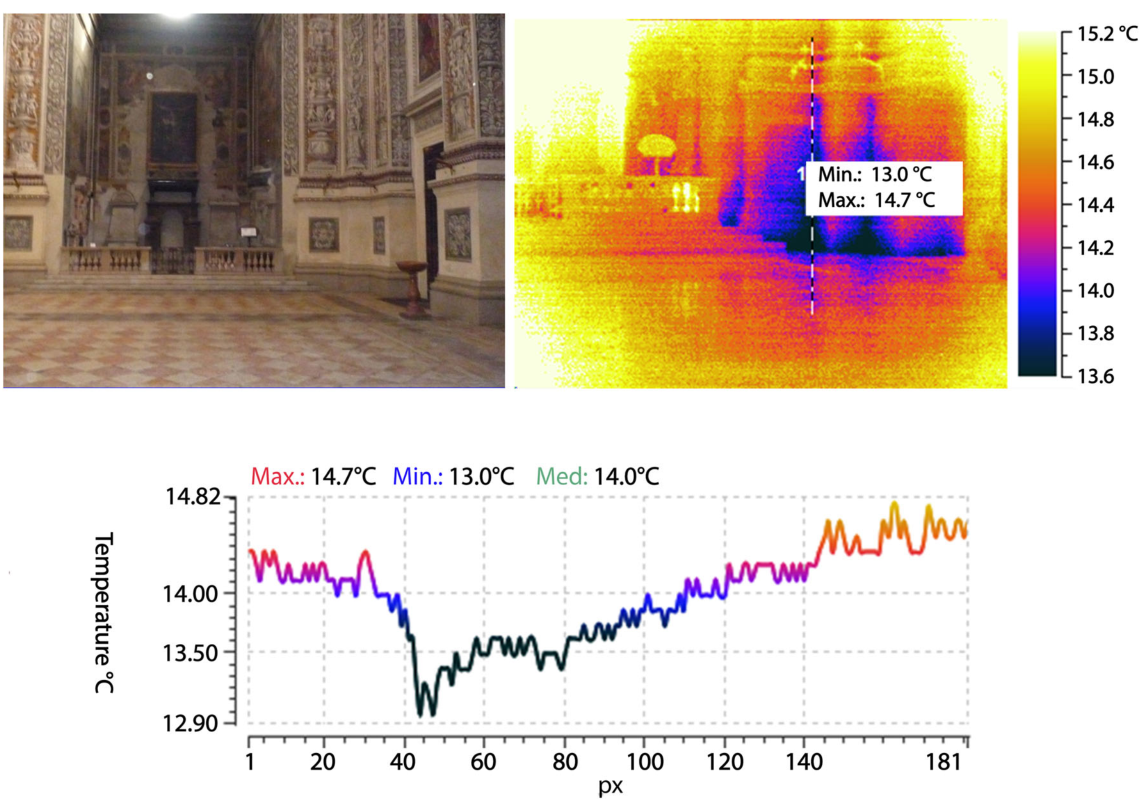

Fig. 5 The base of the masonry

Three-dimensional monitoring

To realise and analyse the deformations of the Basilica in the three-dimensional field, and thereby identify any possible kinematic motions giving rise to displacements or slants of the structures, the project envisaged a study of the behaviour of the complex via determination of the position of mini-prisms placed on the bearing structures and their displacements with millimetric/sub-millimetric precision.

In this instance, we use of a total station for monitoring the latest generation [Leica Ts30] which currently allows an angular resolution $\pm 0.5''$ and distance accuracy, by resorting to precision prisms, of ± 0.6 mm + 1 ppm. The tool used is a motorised station that enabled automatic acquisition of the observations, so as to reduce to a minimum the effect of observation errors caused by the operator.

It follows that, by means of repeated observations from the same station point, suitably materialised, it was possible over time to determine the changes in position of the prisms and the resultant ascertainment of the relative displacements of the structures, recorded within a global, uniform and precise system. You can see the positional scheme of the prisms in plan and elevation on the top of Fig. 3.

In order to define the observation point, stable over time, we chose to use a small pillar specifically realised at the octagonal angle of the Basilica. The structure has been anchored to the pier of the balustrade through four linchpins on pre-existing and documented holes.

Within the same time span and frequency of altimetric monitoring observations, the following components were observed (bottom of Fig. 3):

-the counter-façade has a rotational movement towards the inside of the Basilica;

-the aisle at the centre discloses an opening towards the outside of the upper part;

-the counter-façade of the north transept shows a rotation towards the octagon;

-the dome drum evinces negative variations in the component in X, whereas the movements in Y are more significant in the southerly part.

Monitoring of the crack mapping

The project provided for the study and control of the map cracking through a reading of the environmental parameters in order to correlate the local deformations of the structure to the previously described global ones. The monitoring network was realised through the installation of a 16-channel EDAS (Enhanced Data Acquisition System) control unit with a 512-KB data memory for approximately 1,200.000 observations. The installed sensors are displacement transducers connected in wired mode in the most critical points of the façade. The analysis takes place in single mode (horizontal vertical and horizontal component) in respect of two other observation points by associating two linear transducers.

More specifically, use was made of electrical sensors with potentiometer (50 mm stroke) and centesimal resolution. Measuring range ± 25 mm.

What is in particular suggested is to monitor the façade and counter-façade of the Basilica, along the main

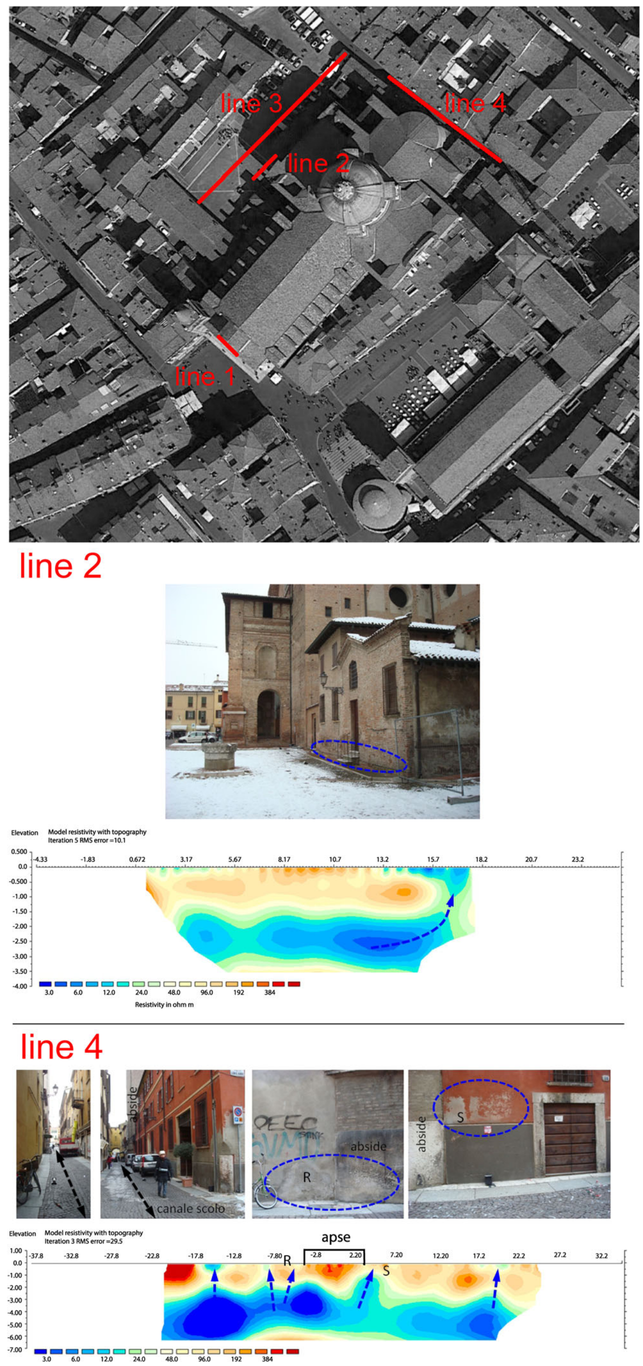

Fig. 6 One of the four profiles detected along the free sides of the building

cracks, envisioning a static acquisition system with six acquisition sensors placed in the most suitable positions (left of Fig. 4) deemed appropriate by the structural technician.

During the 1-year monitoring, the ongoing acquisition of the measurements was suspended twice by reason of an overload caused by lightning that struck the Basilica. From the analysed data, we can notice the following displacements:

-Probe 01: + 0.20 mm enlargement;

-Probe 02: + 0.05 mm enlargement;

-Probe 03: − 0.02 mm narrowing;

-Probe 04: + 0.01 mm enlargement;

-Probe 05: + 0.08 mm enlargement;

-Probe 06: + 0.00 mm (zero) variation.

We noticed a stability of the map cracking with a significant opening as regards the probe placed above the architrave of the entrance door to the Basilica (bottom right of Fig. 4).

Control of the thermo-hygrometric regime of the structures

The thermographic and gravimetric strokes enabled the detection of humidity (Rosina Rosina and Grinzato 2001; Ludwig Ludwig and Rosina 2001) on part of the inner surfaces, just above the stone wainscot covering the base of the masonry.

Moreover, the base of the masonry, in contact with the floor, proves to be colder than the grade plane, likely on account of the lower temperature of the ground and base the Basilica rests upon (Fig. 5). The thermographic stroke realised in the spring of 2013 confirms the results already documented during the previous thermographic strokes carried out by another group of researchers of the Politecnico in May 2008 (Analysis and Diagnostics Laboratory of Built Environment, Prof. A. Grimoldi). The tests ending in 2016 had in fact been preceded by the collection and careful examination of the investigations conducted in the previous years by various operators and research centres.

In the thermographic measurements carried out in May 2013, it was found that the widest thermal disproportions concerned the surfaces of the transept and the chapels on the north side of the aisle. Such a gradient represents a risk factor for conservation of the surfaces on site, due to the possible condensation of the ambient humidity over the lower temperature areas. As a means of checking the frequency of occurrence of the phenomenon, some of the lower temperature areas witnessed the installation of a limited number of contact probes that record the temperature of the surfaces and accordingly memorise the peaks at which dew point is reached. The surveys conducted confirm the subsistence of the humidity conditions of air and surface temperature (of the stone materials) that might

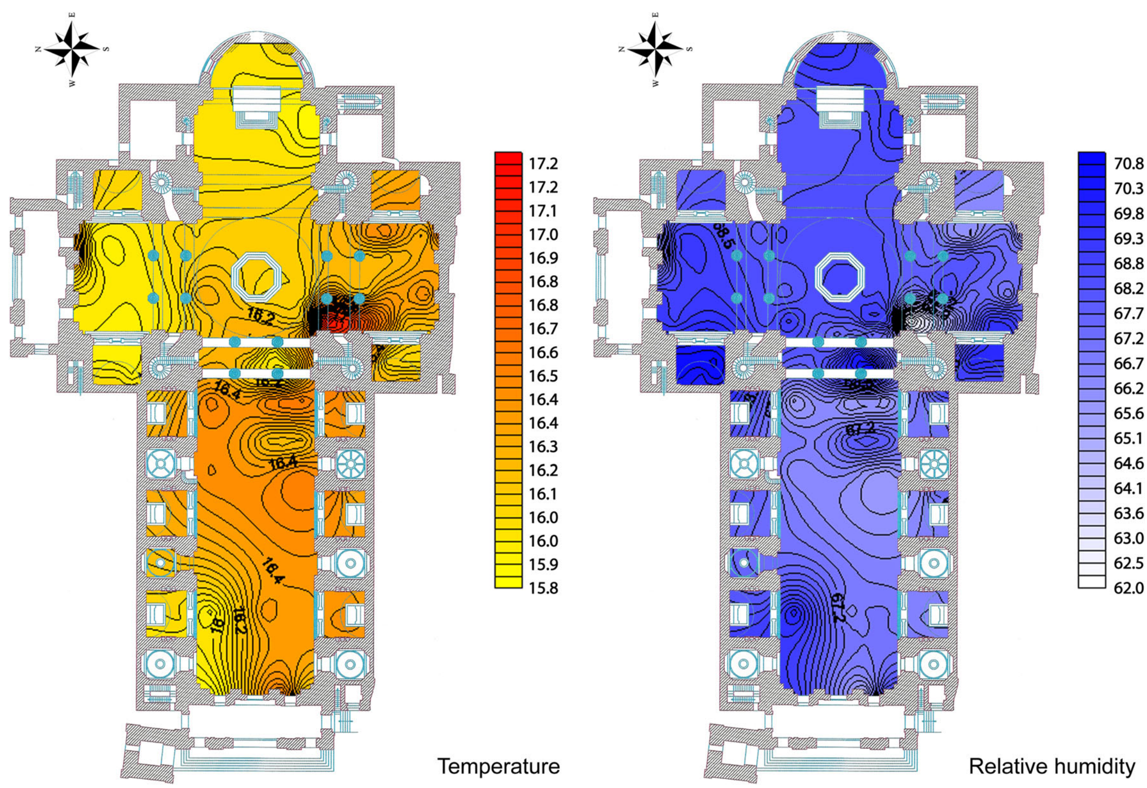

Fig. 7 The distribution of temperature and relative humidity of the air, at a height of 1.10 m above the floor, on 21 May 2013

frequently cause surface condensation phenomena, especially at the beginning of autumn and in spring.

The results from the EFD (Evanescent Field Dielectric) investigations developed by the team of Roberto Olmi, CNR-IFAC Institute of Applied Physics in Florence (Olmi Olmi et al. 2011), confirm the presence of water content slightly higher than what is deemed physiological for the materials of the inner finishes in some areas (transept, north side).

The results achieved have also been cross-checked with those derived from subsoil resistivity measurements (Bottacchi 2010; Groom 2008), with a view to identifying the main water infiltration phenomena within the territorial scope surrounding the structure, which measurements were taken in February 2012 by the Geoarchaeology working group of the CGT SpinOff s.r.l., university spinoff of Siena University owing to funds provided by the Regional Management within the scope of preliminary researches on the structure of the Basilica.

More specifically, the investigation aimed to detect the possible presence of water flow occasioned by problems associated with the poor maintenance of the road network or the underlying infrastructures; identify the presence and development of any sub-surface saturated levels inside the maximum depth investigated; and identify any cavities or areas with high resistivity characteristics traceable to anthropic structures beneath the floor.

The results achieved are visualised through electrical tomographies representing bi-dimensional models of the resistivity of the subsoil. As an example, we illustrate one of the four profiles detected along the free sides of the building, referring readers to Fig. 6 for a view of the results.

A comparison between resistivity models obtained enabled us to state that the area under examination is subject to manifest phenomena of sub-superficial waters climbing back, as the main cause of humidity spots and plaster detachments quite prominent on the outer walls of the Basilica. In particular, the elaborated tomographies corresponding to *Line 2* and to *Line 4* visibly highlight the presence of a low resistivity area of modest depth (centre of Fig. 6) starting at 1.5/2 m from the surface: this area can be interpreted as a sub-surface saturated area, a basin of manifest climbing back of waters. The phenomena of water climbing back is further aggravated by the contribution from the waste water of gutters (bottom of Fig. 6) and the underground drains.

Micro-climatic monitoring

The psychrometric survey (Rosina Rosina and Suardi 2007; Rosina 2008) was undertaken by repeating the measurements at different times of the same day, at least 1 day per season.

The psychrometric tests conducted in spring and late summer enable us to identify modest temperature gradients between the north and south sides of the aisle, apse and presbytery, and in the transept.

See, for instance, the maps in Fig. 7 that illustrate the distribution of temperature and relative humidity of the air, at a height of 1.10 m above the floor, on 21 May 2013. Based on the results achieved, six probes were installed inside the Basilica (Fig. 8), at different heights, in the areas where the greatest imbalances were recorded. The ambient humidity values detected as early as the period from May to September are on average higher than those recommended by the legislation in force, subject to some extensive and rapid variations (in the month of August) caused by the external climatic ranges.

In order to identify the areas where the quickest and most far-reaching variations occur, the measurements recorded by sensors were assessed and compared. We set out, as an example, the analysis conducted on the 2013 summer data as regards the areas recording the most critical discontinuities for the conservation of surfaces.

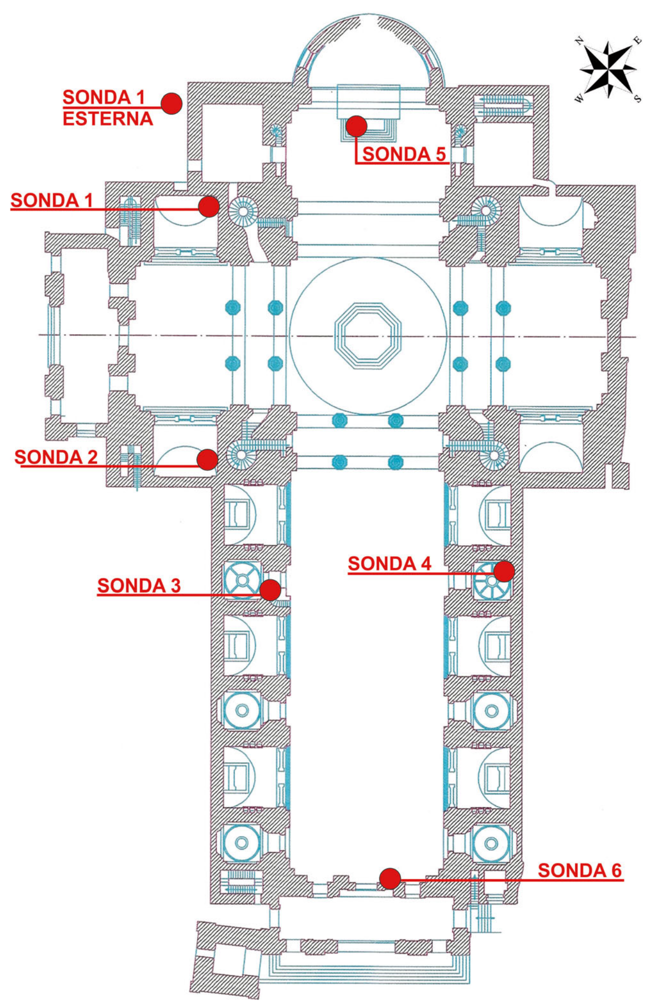

Fig. 8 Six probes installed inside the Basilica, at different heights, in the areas where the greatest imbalances were recorded

Probe no. 1 (installed in the North Chapel)

The values recorded show temperature gradients of approximately 2–3.5 °C for the month of August, whereas less significant are the ranges recorded in June, July and September (top of Fig. 9). The RH (relative humidity) values suffer rapid and extensive variations (up to 30% over 2 days) from the third week of July to the first one in August, and in September (bottom of Fig. 9). The maximum values reach 80% and the minimum ones 50%, hence the measured ranges represent a risk to conservation of the surfaces due to the cycles of deliquescence and crystallisation of soluble salts already present on the surfaces and just below them.

Probe no. 6 (installed in the counter-façade)

The trend in maximum and minimum values acquired by the probe installed in the counter-façade exhibits the widest oscillations and variations compared to the findings of all the other probes. The difference between minimum and maximum values is approximately 1 °C, until the end of July, then rises in the second part of the examined period to reach peaks of 1.5–2.5 °C (end of August). The maximum temperatures are higher (26.5 °C is in fact reached), whereas the minimum ones are similar to those measured in the other parts of the Basilica. The relative humidity variations are more far-reaching and frequent, and are less than 5% (both the maximum and the minimum ones).

The analysed data show that those parts of the building most affected by the external climatic variations are the counter-façade, due probably to the frequent opening of the entrance door and the inadequate hold of doors and windows, and the north chapel. In this latter area, the variations represent a critical aspect for conservation of the surfaces on site, since here, too, the highest humidity values in the masonry, in addition to the condensation phenomena during seasons when the surfaces reach temperatures around 5–6 °C or lower, have been recorded.

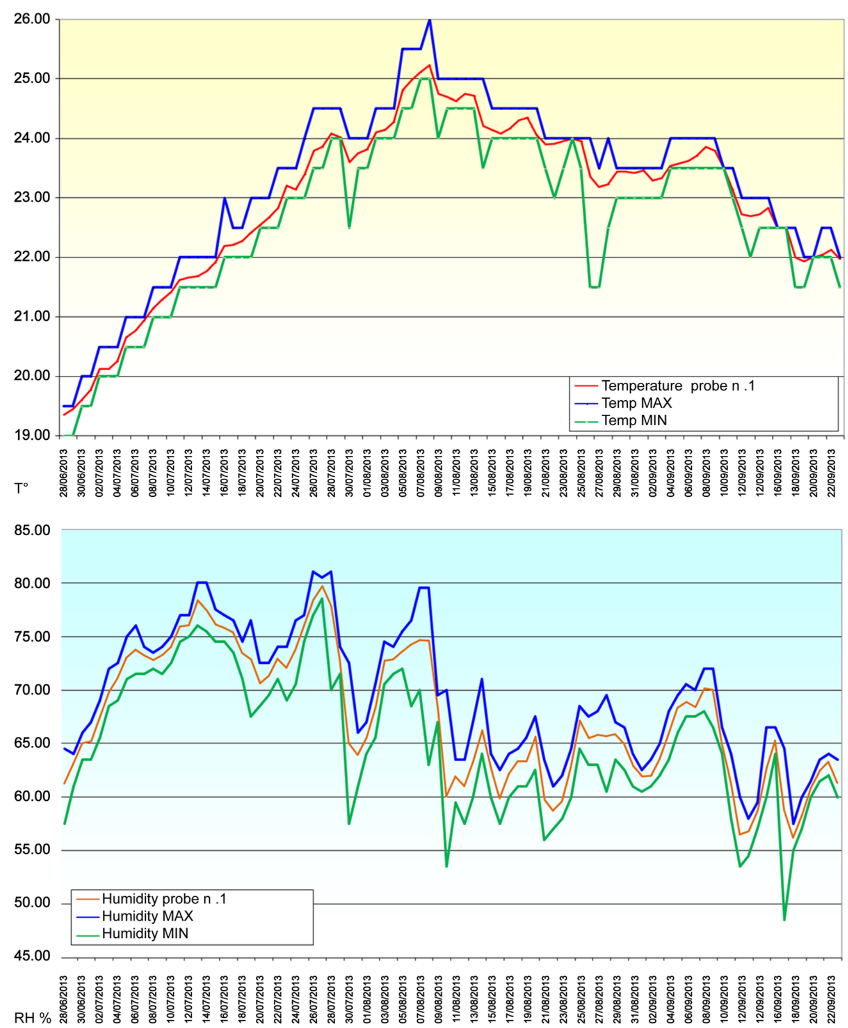

Fig. 9 Recorded temperature and relative humidity values

Conclusive remarks

The monitoring activities carried out on the Basilica di Sant'Andrea have proved their effectiveness both in the description of specific phenomena and in the definition of a general picture of the building for the sake of its planned conservation. The deep knowledge of the sacred building is guaranteed by the integration of the different monitoring techniques: geomatics and thermo-climatic analysis allow to define the behaviour of the technological elements both from the structural (movements in different directions) and material point of view. The innovative aspect of this work shows that the effectiveness of monitoring is amplified when it is carried out in several areas: geodetic monitoring has to be read, in the programmed conservation process, precisely in function and combination of micro-climatic monitoring.

The observations that have accompanied the observation phase chiefly concern the need for a lengthy monitoring phase to be able to keep the identified phenomena in check. That way, we can embark on a path that considered an initial phase capable of defining the basic knowledge of the building and identifying its problems and critical areas, followed by a lengthy monitoring phase, with broader timeframes, for the sake of a constant control of the state of detected problems.

By implementing the dynamics of programmed conservation, the monument's resilience to earthquakes, but also to a whole series of heritage risks, is increased.

The knowledge drawn from the monitoring made it additionally possible to identify well-defined maintenance procedures and practices that currently represent a conservation plan for the building. The Mantova diocese then used all the data from the project, concerning the Basilica di Sant'Andrea and the other three abovementioned buildings, to elaborate a body of generic recommendations addressed to the users and managers of the buildings in question. These recommendations represent the user manual, operating tool of the conservation plan. Therein, we specifically find recommendations pertaining to each part of the building (structural system, covering and water disposal, masonry, vaults-ceilings-bearing structures, coatings and decorative fixtures, doors and windows, floors, electrical systems, microclimate, furnishings and works of art) "day by day"(Bossi 2016). For each element, we find a description, the explanation of signs of decay/damage, the instructions on what to avoid, and what to do (expedients, controls and events on which to call the technicians).

We were thus successful in discharging the difficult task to involve not only the specialist technicians but also the managers and end-users of the building in the planned conservation process. Involvement of the public and the users was likewise achieved through divulgation of the planned conservation activities, such as conferences devoted to sector specialists (architects, engineers and plant engineers) and asset managers (parishes and priests), and a website enabling verification of the outcomes of the project and the resultant input (http://www.diocesidimantova.it/beni-culturali#).

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