When and how reducing moisture content for the conservation of historic building. A problem solving view or monitoring approach?

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The conservation of historic buildings requires to face the technical issue for preserving the historic building materials, as stated in the recent Code for protection of Cultural Heritage, in Italy (2004).

Rising damp is a recurrent cause of damage, and the climatic changes are going toward the increase of humidity in the historic masonry: at 40/50° latitudes, at continental/Mediterranean climatic conditions, the alternance of dry seasons and almost monsonic seasons dramatically affects the distribution of rising damp in porous materials, as well as the water content. The evaporation of rising damp from the wet surface due to occasional or seasonal change of air temperature, causes the major damage due to salts crystallization. The evaluation of the increase of water inside the masonry is a critical issue for preventing the damages, because the presence of the water can sharply, naturally decrease in the dry seasons, as well as rapidly increases one month or more after the beginning of heavy and constant rain.

The interventions against water intruding the masonry due to water table or rainfalls that are not properly taken away from the structure are totally different, although the damages caused by both these causes are the same.

Monitoring the presence and distribution of the water is useful to support the choice of the most appropriate intervention, reducing the risk to apply not effective and expensive products and preventing an oversize intervention.

Keywords: Moisture, Historic masonry, Diagnostics, Monitoring, Humidity, Decay, Intervention

1. Introduction

The conservation of historic buildings requires to gather a wide, always updating, data crossing knowledge of the building and its environment. The recent change of perspective from the intervention after the damages occurred, into the prevention of damage itself, required also to update the perspective of the diagnostics objective and the strategy for obtaining the required knowledge to decide any further step of maintenance or repair [1–3].

Although in the last decades procedures to a preliminary knowledge for restoration were defined, at present the requirement is to face the knowledge management, and to reorganize the verified testing techniques and innovative ones as well, according to effective and convenient procedures for monitoring in the field.

Information in the preliminary phase of the project is crucial to define a compatible reuse of the building and to improve the residual performance of the building. The limited cost and invasivity of tests allow to apply them on the widespread built environment, and to support all the planned conservation activities [4].

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In such a way, diagnostics with increasing levels of accuracy and effectiveness are successfully applied in most of historic buildings non monumental too, where economic issue is a fundamental criterion for planning intervention and cares.

As a common cause of decay, rising damp is a recurrent cause of damage due to the exchange between water/porous materials; the climatic changes are going towards the increase of exchanges at 40–50° latitudes, at continental/Mediterranean climatic conditions, due to the alternance of prolonged dry seasons and heavy rainfalls and storms [5,6].

Therefore, only through monitoring water distribution is possible to explore causes and support the choice of the most appropriate intervention, reducing the risk to apply not effective and expensive products and preventing an oversize intervention, according with the “minimum” (least) intervention criterion [7].

The higher is the variability of the environmental change, the higher is the time of monitoring, that necessarily requires to record the data representative of the recurrent changes of the parameters under analysis during one or more years.

Without a midterm monitoring, before and after any intervention or application of devices, it is not possible to determine the effectiveness for reducing or eliminating the water intrusion in the structure.

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2. Climate has changed in the last six decades

As well known, in the last years [8,9] scientists have been recording a general increase of temperature (European Alps and higher mountain regions in the world), drought and extreme high temperature (Spain, Australia, etc.), extreme heavy rainfalls (hurricanes on the Atlantic ocean, summer monsoon in Asia, flood in New Zeeland, etc.). At the poles, melting of ice has local and global consequences, as well as the reduction of glaciers at any latitude, at a speed that never was recorded in the past. The increased rains at high elevation causes thicker ice layers; their melting causes risk of collapse for structures of dams and riverbeds due to the increased amount of melted ice. The database International Disaster shows an increase of prolonged and powerful floods and fires since the 1960s, as well as an increase of global warming [10].

The risk of hurricanes and big waves/flood will increase [11–15], menacing the large amount of the coastal population along the ocean sides for an extensive band towards inner region. In Italy, the climatic change will cause an increase of temperatures, intense rainfalls but a decrease of the amount (5–40% in the Alps region), the increase of the risk of desertification (decrease of the total amount 20% of the national territory) due to aridity and erosion risk. As a consequence of the risk for human/animal/vegetal beings, *Cultural Heritage*, especially the tangible and immovable items, are under risks for many factors.

2.1. The consequences of climatic changes on historic buildings

With respect to the European heritage "The Noah's Ark Project – Global Climate Change Impact on Built Heritage and Cultural Landscapes" produces a map of climate, the built heritage, its damages and risks and comparison of past conditions (1961–1990), next future (2010–2039) and far future (2070–2099). [10]

Among many changes affecting inorganic and organic materials/structures, the final table shows (Fig. 2) that in the European region the change of humidity will increase water content in soil.

The alternance of dry seasons (with high temperature and no rain for months) and almost monsonic seasons (at mild temperature with heavy and prolonged rains), dramatically affects the distribution of rising damp in porous materials of masonry, as well as the water content in time [13–16].

In addition, the evaporation of rising damp from the wet surface due to occasional or seasonal change of air temperature, causes the major damage due to salts crystallization and condensation [17–26].

The evaluation of the increase of water inside the masonry is a critical issue for preventing the damages, because the presence of the water can sharply, naturally decrease in the dry seasons, as well as rapidly increases one month or more after the beginning of heavy and constant rain.

In some cases, the draining nature of the soil prevents any swelling due to the foreseen variation of the water content and could prevent the damage of structures. The nature of soil can be different in close regions, at it happens in the Po Valley. In the southern part of Lombardy, the clay component is higher than in the northern part with a variability of the distribution that is influenced by the presence of past/preset riverbeds, the use of the soil (agriculture, animal stock, industry, urban life, etc.) and the stratification of the debris for natural geological cycles of rocks (Fig. 1).

Therefore, the amount of humidity could affect the same structure based building (same materials and building techniques) with different consequences according to the location. This introduces another parameter to observe for an adequate time before determine all the data for design the proper intervention.

The higher is the variability of the environment change the higher is the time of monitoring, that necessarily requires to record the data representative of the recurrent changes of the parameters under analysis during one or more years.

Fig. 1. Geological map of Lombardy: the different colors refer to different formations. The green color shows the debris component of soil, the white indicates the presence of clay.

The water content, its distribution, the temperature of the surface, of the air and air humidity are the commonly accepted variables under monitoring, together with their change outside the buildings.

These parameters are also the same those, after the application of the devices against rising damp, or the intervention on the masonry, can determine if the water inside the masonry is effectively reducing or not.

3. Methods for diagnostic moisture presence and distribution in the present scenario

The scenario of climate changing and its consequences on the built heritage constitutes a challenge for the current standard methods for humidity measurements. In fact, despite of the not destructiveness, the water content measurement is seldom an absolute quantity (other parameters resulting from the measurement), especially if the measures are related to the interior layers of masonry. For in depth measurements, techniques are dramatically reduced to a very few, most of them related to microwaves, radar and including the steady standard of gravimetric method, that implies the related drill and collection of samples from the masonry.

The need of monitoring for prolonged time (2–3 years and more) the humidity distribution, its spreading, the exchange toward the environment and the building interiors, the effects of any intervention, requires to adopt non destructive methods. In fact, the possibility to repeat the test without loss of material, or selecting the least waste of material (in the terms of a few grams) is extremely beneficial. The repetition of tests and their validation require to use fast, low cost, analysis to apply both extensively in the preliminary phase, for a preliminary localization of the anomalies, and in the second phase of the advanced diagnostic, on some specific area and time [27].

According to the perspective of planned conservation (PPC), in the last decades the development of diagnostics focused on the need of procedures for the preliminary analysis of the building

Climate Parameter	Climate change risk	Physical, Social and Cultural Impacts on Cultural Heritage
Atmospheric moisture change	- ground water changes - changes in humidity cycles - increase in time of wetness - sea salt chlorides	- physical changes to porous building materials and finishes due to rising damp - damage due to faulty or inadequate water disposal systems; historic rainwater goods not capable of handling heavy rain and often difficult to access, maintain, and adjust - crystallisation and dissolution of soluble salts caused by wetting and drying affecting standing structures, archaeology, wall paintings, frescos and other decorated surfaces - erosion of inorganic and organic materials due to flood waters - biological attack of organic materials by insects, moulds, fungi, invasive species such as termites - subsoli instability, ground heave and subsidence - relative humidity cycles/shock causing splitting, cracking, flaking and dusting of materials - corrosion of metals
Temperature change	- diurnal, seasonal, extreme events (heat waves, snow loading) - changes in freeze-thaw and ice storms, and increase in wet frost	- deterioration of facades due to thermal stress - freeze-thaw/frost damage - damage inside brick, stone, ceramics that has got wet and frozen within material before drying - biochemical deterioration - changes in 'fitness for purpose' of some structures. For example overheating of the interior of buildings can lead to innapropriate alterations to the historic fabric due to the introduction of engineered solutions - inappropriate adaptation to allow structures to remain in use
Sea level rises	- coastal flooding - sea water incursion	- coastal erosion/loss - intermittent introduction of large masses of 'strange' water to the site, which may disturb the metastable equilibrium between artefacts and soil - permanent submersion of low lying areas
Wind	- wind-driven rain - wind-transported salt - wind-driven sand - winds, gusts and changes in direction	- penetrative moisture into porous cultural heritage materials - static and dynamic loading of historic or archaeological structures - structural damage and collapse - deterioration of surfaces due to erosion
Desertification	- drought - heat waves - fall in water table	- erosion - salt weathering - impact on health of population - abandonment and collapse - loss of cultural memory
Climate and pollution acting together	- pH precipitation - changes in deposition of pollutants	- stone recession by dissolution of carbonates - blackening of materials - corrosion of metals - influence of bio-colonialisation
Climate and biological effects	- proliferation of invasive species - spread of existing and new species of insects (eg. termites) - increase in mould growth - changes to lichen colonies on buildings - decline of original plant materials	- collapse of structural timber and destruction of timber finishes - reduction in availability of native species for repair and maintenance of buildings - changes in the natural heritage values of cultural heritage sites - changes in appearance of landscapes - transformation of communities - changes the livelihood of traditional settlements - changes in family structures as sources of livelihoods become more dispersed and distant

Fig. 2. Processed table of principal climate change risks and impacts on cultural heritage, from the UNESCO World Heritage Report 22, Climate Change and World Heritage (UNESCO World Heritage Center, May 2007, p.25).

and its environment, together with the development of monitoring for years, with the aim to study the effects of environment (and its change) on the historic built fabric. The requirements of PPC mostly meet the needs listed above, and the experiences of the last decades are valuable, basing on which further advancement of the techniques to develop.

The first example is that the early detections methods support conservation/maintenance programs and the evaluation of the range of their costs. Because of reduced time and economic support, the devices have to fast deliver qualitative out put, and to be feasible on wide surfaces.

Fast scan working techniques on wide surfaces have a considerable advantage rather than those techniques that give punctual data back, after a long processing data time. Collection of documentation about the building, damage location, its evolution in time, the use across years is mandatory to work out an effective diagnostic plan, especially for preliminary test. The first step of investigation is the assessment of surface conditions by means of multispectral analysis, performed by instruments that do not require a contact with the surface under inspection. Previous research [4] showed that periodic controls, multispectral analysis aided, allow to early detect initial damage due to non homogeneity and vulnerability of structure at critical environmental conditions.

Therefore, the triage setting of multispectral analysis (IR, visual – including sliding light photos and macrophotos) is a pilaster of surface monitoring, for early detection, as well as for prolonged monitoring, especially if couples with some standardized, less destructive, quantitative methods feasible in the site at low cost [28].

Usually, a widespread method is the weighting test for measuring the water content on samples. Dario Camuffo in [29], describes the EN and ISO standards dealing with this and other quantitative tests.

Since it is a destructive method, to minimize this damage, samples are generally extracted from less representative parts, e.g. near the borders, in already damaged areas, or their depth is limited to a surface layer. The risk for scarce representativeness cannot be avoided increasing the number and dimension of the test specimens, as discussed in his paper.

Generally speaking, the triage focus for the determination and location of the water source constitute an integration of different methods (qualitative/not destructive and quantitative/least destructive) [30].

Therefore, the recommended set of measurements should aid to monitor in a period of a minimum of 18–24 months and in opposite meteorological conditions (before and after heavy rainfall) to check if the cause of humidity is constant over time. A complimentary technique is mapping the superficial thermohygrometric conditions through the integration of infrared thermography, which indicates the surface temperature of large areas, and precise surface (with contact probes) and depth (with dust extraction through gravimetric tests) analysis.

Taking into consideration the change of rainfalls quantity, frequency, distribution, monitoring for prolonged time will prevent to consider anomalous water content and distribution due to yearly exceptional weather conditions.

It would therefore be useful to be able to calculate the dew point thanks to the data obtained from the monitoring of surface temperatures by contact probes. However, changes in the dew point due to the presence of salts in the material must also be taken into consideration [31,32].

The interventions against water intruding the masonry due to water table or rainfalls that are not properly taken away from the structure are totally different, although the damages caused by both these causes are the same. Therefore, to assess the real cause of damage is mandatory: it always has been a rule of good practice, since now it becomes unavoidable. What could be the consequence in the next future of a wrong intervention, that is not really effective on the causes but only on the present effects?

4. Is moisture content to reduce?

Presence of water in masonry is rarely caused by a single humidity phenomenon because many passages from a state of phase to another occurs several times in a day due to the thermo-hygrometric variations. In fact, when the water invades masonry, due to low air and surface temperatures also condensation phenomena occur, especially on the colder/wet surfaces.

Therefore, the set of monitoring techniques should include monitoring of internal and external environmental variations of UR and T to prevent or protect the building from condensation humidity in case of significant excursions during the days, months and years. Mapping of the surface thermo-hygrometric conditions is recommended as well, based on the integration of infrared thermography, quantitative tests and monitoring of surface temperatures through contact probes. In case of condensation humidity, the results obtained in the different seasons may be extremely variable due to the temporary nature of the phenomenon. The presence of water can cause damage mechanisms further than freezing/thaw cycles [33]. At Italian latitude, and especially under the current changes of climate, the major damage induced by water presence inside porous materials is due to its transport toward the surface and the crystallization of soluble salts. Soluble salts sometimes come also from sewage leakage (in urban areas), agriculture activities, decomposition of organic matters (gardens and natural parks).

The sharp alternances of dry/wet conditions will increase the quantity and spread the diffusion of soluble salts on the surfaces and the consequent damages.

Air temperature and RH are the observables that highly affect the evaporation/dew phenomena. Therefore, the surface and the thin layers underneath are the most affected by these phenomena, because of the high rate of exchanges with the indoor/outdoor air.

For the last two decades the evaporation flux and its quantification [34,35] has been remaining one of the major tool for estimating the damage occurring, together with the visual analysis and the documentation/assessment of the damage and its history, the analytical campaign is the main tool for assessing the water content and distribution.

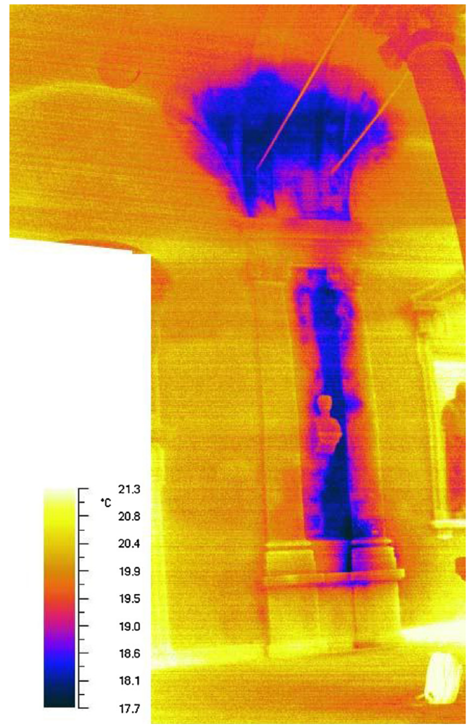
The most recent trend of this applied research in the field of diagnostics for Cultural Heritage [36] is to make the use of instruments on-site that are required to be reliable, feasible and affordable. On-site diagnostic applications depict a broader view of the elements of the building under investigation, as well as allowing researchers to study those parts affected by moisture in comparison to the environment [37].

More than in the past, the diagnostics of what is going on is crucial for the choice of the intervention.

The observation of the last 20 years [38–40] shows that rising damp and water infiltration mostly is due to the rainfalls not properly drained by plants (gutters, downspouts and water canalization for water removal from the foot of masonry). Rain spreading in the soil, toward the depth layers or remaining on the surface ones where clay layers intercept its draining, diffuse also soluble salts inside the masonry materials, due to water sorption.

With the present trend of increasing seasonal rainfalls alternated to dry time, middle term monitoring is a mandatory tool for gathering the necessary data. The aim is to exclude not recurrent behaviors, quantifying the water fluctuations in masonry for identifying the water sources of water intrusion. Only the results of a middle-long term monitoring will give the data to evaluate if intervene and which is the best intervention to apply to reduce humidity, especially with a perspective on the long term result. In fact, the risk to apply a not appropriate intervention ranges between be ineffective, or, even worst, dangerous. For example, the application of not effective devices for reducing rising damp often is not costless: at least, it requires an investment of time (to monitor the effectiveness), that implies further loss of materials due to the prolonged damage. On the other hand, the application of water repellent products or waterproof membranes could increase the level of damp in the wall, up to the free surface where evaporation can occur. The consequences are the extension of the damaged materials according to the new distribution of rising damp. On this edge, also the application of effective methods only on a part of the masonry or with inappropriate materials can worst the damage in parts of the building that have never been affected by rising damp before the intervention, due to the deviation of water infiltration paths to intrude the masonry.

Moisture content remains a risk for the conservation of masonry, especially of the surface, nevertheless the exchanges with air are the real cause of damage, that soon or later will occur although not apparent in the beginning of water infiltration. With the results of monitoring, as previously explained, is possible to evaluate the cause of the infiltration and its behavior in terms of periodically, amount, variation, dependence on the rain or other sources. The screening of the sources and identification of cause/causes will guide also the decision to intervene and the choice of the intervention. A thumb rule could be to avoid the water intrusion anyway, nevertheless it is only the consideration case by case of all the data



Figs. 3 and 4. Brera Palace, Milan, western side of the loggia, second level, mosaic of thermograms, exterior wall of room 24, June 8th, 2011; Emissivity 0.92, air $T = 22\,^{\circ}$C; RH% = 70%.

and identification of risks, at present and in the middle-long time, together to the affordability in term of reachable final advantages too, that should lead the decision. In fact, the application of any device to reduce rising damp can be unsuccessful for many reasons, due to the presence of factors that inhibits the effectiveness of the device. The researches of the last 10 years [41–43] elucidate that if the masonry remains in contacts with stagnant water in the soil, damp has fluctuations due to the amount of the water source, nevertheless the presence of water does not show stable reduction, if the monitoring time is long enough to include yearly weather variations.

5. Learned lessons in Lombardy: how maintenance can prevent damage to heavy rainfalls

This paragraph shows the gathered observation about how to improve the protection of historic building in Lombardy, on the bases of the investigation on many study cases in the last decades. The paper presents the learned lessons without details of the study cases and results of the investigation. The references include further information.

A crucial point is related to the building features and its technical plants. The increase of rainfalls intensity does require both to reduce the time of contact between foundation/masonry and soaked soil (especially if clay ground), as well as to improve the drainage system from the eaves to the foot of the masonry. In Italy, since early 20° century up to the 1960–1970s a recurrent intervention on historic building was to hide the downspouts inside the masonry, with the aim to avoid disfiguring the aesthetic apparel of the historic buildings with technological plants. The gutters and downspouts had dimensions appropriate for the rain collection at the time of the intervention. At present, these systems are not sufficient anymore, because of exceptional increase of water amount to quickly and effectively gather and convey into the vertical ducts inside the masonry. In addition, also the shape and dimensions of the final gathering basins at the edge of the downspouts are not

Fig. 5. Brera Palace, Milan. The connection of the water duct from the eave gutter to the downspouts. A metal grid protects the obtrusion of big objects.

sufficient to contain and drain the hydrometeors. An example is Brera Palace, Milan (Fig. 3), and the consequences of the exceptional rainfall occurred in the beginning of June 2011. The exceptional storms with wind speed of 40 km/h and more, caused very heavy rains. The partial obstruction of one of the downspout due to leaves and timbers transported by wind in the eaves gutter (Fig. 5), the partial refurbishment of the system due to the new plant of climatization and the fast accumulation of a large amount of water inside the downspout caused its breakage and of the masonry around (see the mosaic of thermograms in Fig. 4; the recapture after few hours shows the large extension of the water infiltration from the vault along the downspout in the masonry, although the surface does not appear damaged yet, apart from the detachment of the decorative pillar that permitted to the accumulated water to flow out of the dead space between the downspout and the masonry).

The maintenance of rain canalization in historic buildings raise of importance, as well as the protection that prominent eaves can provide: increasing the protection of masonry means also to rethinking the typological and philological criteria to avoid any eave ducts or to avoid to reshape the roof slope and ledge although it is not a character of the historic architecture of the zone.

Since the main aim is to protect masonry from water intrusion, it is also under investigation the application of transparent and water repellent protective treatments on vertical structure, especially if the orientation and location can improve the risk for biological attack. An example comes from the research at Lavello convent in Lecco lake area (Northern Italy), that regarded three critical issues correlated with the increase of rainfalls and the historic building features.

The main critical point is the northern elevation, in front of a soccer field and garden, protundes out of the eaves cantilevering, therefore the foot of the masonry is exposed to direct rain. The lack of solar irradiation, the stagnant water in the close garden/soccer field, and the inadequate quality of plaster, in the recent past generated the worst condition for the conservation. The researchers studied both the mixing ratio for a new plaster, based on traditional recipes and natural local materials that ensured the best fit and durability of the historic structure due to the climatic conditions. Moreover, they studied and tested also the effects of chemical water repellent treatments in addition to biocides for preventing algae/fungi growth due to the high humidity and the composition of the plaster substrate [44].

6. Conclusion

As shown in the previous paragraph it is only by monitoring for a prolonged time that decision of intervention can be taken. In fact, in the worst cases it is better to avoid any direct intervention on the masonry if the expected results could not fit the present requirements and any foreseen worsening of climate in the middle long term. An example is the use of waterproof products for the underground insulation of floors (without creating a gap space or expansion layer for further rising of the water from the soil), especially if the waterproof layer intrudes the masonry or it upholsters the structure.

Moreover, the same intervention could be split into steps with increasing invasiveness, suitable of checking along the process to update the intervention step by step. With the aim to privilege the less invasive intervention the first step is to collect and drain the rainfalls alongside the perimeter of the buildings, and after monitoring the effects for 18–24 months and more due to the changed climatic condition. The result of the monitoring will support the decision to proceed to further more invasive step for reducing the rising damp (if yet spread in the masonry) as described in papers of the present issue (Lubelli B., Effectiveness of methods against rising damp in buildings: the EMERISDA project; Vanhellemont Y., Are electrokinetic methods suitable for the treatment of rising damp?; Van Hees R., New test methods to assess potential of chemical injections in case of rising damp; Torres I., New technique for treating rising damp in historical buildings: wall base ventilation).

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