Visual Abstract

Damage and restoration of historical urban walls: literature review and case of studies

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ABSTRACT. Within this work, the causes of collapses and damages occurred in masonry artefacts have been evaluated to properly identify suitable monitoring and restoration methods. In this regard, a comprehensive literature review has been performed. Based on the results, moisture has been found to be a critical parameter, that affects the structural health of masonry artefacts. Various non-destructive methods were employed to measure moisture and monitor the materials involved, including Infrared Thermography, Electrical Resistivity Tomography, Ground Penetrating Radar, Laser Scanning and Digital Terrestrial Photogrammetry, Global Navigation Satellite Systems, Unilateral Nuclear Magnetic Resonance, Laser-Induced Fluorescence technique, Acoustic Imaging and Acoustic Tomography, Geographic Information System, on-site survey process and computer modeling of the structure with specific FEM software. Finally, the implementation of tie-beams, Fiber Reinforced Polymers layers, ventilation, draining systems, and high-quality materials are proposed as solutions for controlling the moisture effect and retrofitting.

KEYWORDS. Historical urban walls collapse, Masonry degradation, Masonry vulnerability, Preservation of historical heritage.

OPEN ACCESS

Citation: Puppio, M. L., Sassu, M., Safabkhsh, A., Damage and restoration of historical urban walls: literature review and case of studies, Frattura ed Integrità Strutturale, 65 (2023) 194-207

Received: 05.04.2023
Accepted: 24.05.2023
Online first: 05.06.2023
Published: 01.07.2023

INTRODUCTION

Historical urban walls and other cultural heritage artworks represent a lighthouse in the history of construction, and their preservation is of great importance for the community [1]. Previous research have analyzed the influence of different parameters responsible for the degradation of masonry structures, finding theoretical tools able to estimate the vulnerability together with several conservation methods [2], [3]. Natural hazards play a key role in the deterioration of historic buildings. Therefore, recognizing the critical aspects that affect the decay of the cultural heritage under the various harsh environmental situation is a paramount concern [4]–[6]. Moreover, structural conservation is keenly required to protect from environmental risks that threaten civil infrastructure and cultural heritage such as earthquakes, floods, intense rainfall, hurricanes, changes in ground water levels, humidity and droughts cycles, extension in moisture period, wind-driven rains, ice storms, winds and freeze-thaw cycles. A comprehensive and accurate study of the criteria for selecting test set ups for building vulnerability assessment is performed in [selection criteria], joined with a practical application on a real case of study [Dynamic identification]. Indeed, a precautionary and proper retrofitting of old buildings has a strong effect on avoiding collapse and reducing damage [7], [8]. In this regard, the existing technical codes, such as Eurocodes, international guidelines, provide useful tools to estimate actions caused by wind, earthquakes, temperature. The applied methods for vulnerability assessment could vary according to the type of structures, materials involved, existing damages and their causes, and the available information related to the structure [9].

The stability of cultural heritage can be severely affected by earthquake [10], [11]: leading to heavy crack patterns and structural damages that may result in partial or total collapse However, floods are the most frequent cause of natural disaster, which can destroy masonry buildings, infrastructure, and cultural landscapes [12], [13]. The damage results from static loads (water pressure, water flow, uplift forces) and dynamic loads (which are influenced by floating objects), wetting of construction materials, influences on soluble salts, chemical contaminates and biological pollution .

Evidence of collapse and damaging of small and medium-span bridges[14]–[16], HUW [17]–[19], and landslides [20] in case of extreme rainstorms or extreme climate scenarios, becoming more and more frequents because of climate changes [21], [22], should be carefully considered..

The retrofit interventions against the presence of moisture need to be properly designed to prevent subsequent drying interventions. As a matter of fact, the traditional drains or other draining strategies can be time-consuming and ineffective over time. Hydraulic drains, non-woven fabrics, drained plasters undergo to appreciable aging and their time-effectiveness should be monitored periodically and with great care, especially when the presence of water can threaten the stability of the artworks as in HUW or in structure with relevant soil interaction [23]–[27]. Moisture plays a key role in affecting the strength and potentially can lead to severe structural damage, which can occur when groundwater penetrates into the foundation, or when heavy rain and moisture vapor occurrences [4]. Tensile strength is a significant parameter to identify the residual performance of existing masonry artefacts, and in some cases, failure scenarios are useful to identify the residual strength of the material [28]. Repetitive freeze-thaw cycles are another phenomena which can affect the mechanical properties (stiffness and strength) and consequently it can lead to deterioration of structure and its surface. The porosity and notably the pore-size arrangement are known as key parameters affecting this process [29] in case of heavy rain, condensation, and moisture.

Therefore, due to the importance of moisture effect on the cultural heritage, this paper presents some cases of degradation induced by moisture effects and proposes methods by evaluating the most representative case studies founded in literature and analyzed by the Authors in other researches. Knowing how this parameter affects the structures allows us to understand its behavior, slow down the degradation process and prevent collapse.

MATERIAL AND METHOD

The aforementioned arguments push toward a systematic approach to the problem. This section introduces the elements that, in the authors' opinion, most influence the problem and stigmatizes the weaknesses of the masonry systems at the present state. Then these elements are discussed through some case studies in the literature.

- The first step in evaluating a masonry artefact usually involves the mechanical characterization of the base material. This activity can be carried out directly or indirectly [32]. In the authors' judgment, there are other crucial factors in the safety evaluation of masonry artefacts. These factors include: [30]Box behavior and the degree of connection between masonry panels and slabs [30], [31];
- Masonry texture, also considering the local construction technology and the building practice gained from past events (first earthquakes), restraint level, and slenderness [32], [33]
- Effect of settlements, earth-soil interaction, degradation induced by aging, moisture or other chemical or physical agents, as also summarized in [34] by Dodman et all..

So, material properties (tensile and compressive strength, young modulus and so on) can be, in practical cases, less influent in the determination of the stability of a masonry systems with respect to other characteristics, as overall geometry and connection effectiveness. Water penetration from the ground can lead to damp phenomenon in a structure without causing collapse. However, if a damaged structure is not controlled and properly monitored, collapses may occur in the long term.

Moisture and degradation are found to be recurrent factors in cases of damage and restoration of historical masonry, as discussed in the following paragraph [38].[36]The diagnosis of the health condition of a masonry structure is undoubtedly a multidisciplinary and articulated procedure in which Non Destructive Technique (NDT) of investigations offers a relevant contribution. In any case, engineering judgment as a synthetic procedure for assessing venerability requires a cultural and background knowledge that cannot be summarized in a textbook or a publication. This paper, collecting some international case studies through a review of the technical literature, aims to highlight some aspects of this process showing some modern tools and procedures used for the diagnosis process and the consolidation technique.

Masonry vulnerability

Exposure to damaging factors has affected the existing heritage artifacts worldwide. Natural hazards can impact heritage in various forms. Moreover, their consequence can be defined according to the aim of the study, which is, in civil engineering, the direct, indirect and intangible losses related to infrastructure, environment and society (Figure 1) [35]–[39].

Figure 1: An example of infrastructure deterioration.

Heritage characteristics can be affected by climate change, presenting significant risks [44]. Water is considered a critical factor in the damage to heritage caused by natural events such as rainfalls, floods, and wind-driven rains. Heritage managers have also identified the presence of water and moisture as the most critical recurring factor [45].[42][43]The water (or moisture) content is the weight of the water contained in a certain volume of material. It is usually indicated with the letter '*e*' in Soil Mechanics and expressed as a percentage of weight of water with respect to the weight of dry material. Moisture content is usually indicated as a ratio and may range from zero (0) to the value of the porosity to the material at saturation. Several expressions are presented into literature and can be extended from the Geotechnics field to all the kinds of granular or porose material. According to the feature of the considered material (porosity, cohesion, internal friction) water can penetrate inside determining variation in physical and mechanical property of the material and increasing external action (hydraulic thrust, uplift, overpressure).

Aging and durability of materials in historic buildings are significantly affected by moisture content. Any increase in moisture content and soil moisture can escalate their vulnerability to natural hazards, leading to catastrophic consequences [46]. The voids in masonry materials consist of capillary pores and small cracks, which normally contain a mixture of water, air, and water vapor. However, they can become completely occupied by either water or air, accelerating the deterioration process. [44]In fact, shear behavior, which greatly depends on the moisture content, the porosity, and the mortar strength, can decrease considerably. Moreover, since water is inherently incompressible, extra pressure on the pore walls occur, with consequent acceleration of the propagation of microcracks up to the failure of the specimens [40].

Figure 2 shows an example of degradation in masonry due to moisture. This can be easily detected because of the vegetation and the variation of the color of the external face of the walls. This is evidenced by the well-known case of the collapse of *Lungrano Torrigiani* in Florence in 2016 (

Figure 3). The abundant presence of vegetation along the embankment denotes a copious presence of moisture in the period before the collapse.

Excess moisture leads to a reduction in mechanical behavior of masonry due to inappropriate internal situations and weak thermal insulation effectiveness of walls [41]. Internal moisture act causing chemic and physical degradation phenomena. Vogel et all. in [48] presented a numerical approach based on the mass conservation and Darcian flow of capillary water.

This consent to express the presence of moisture by numerical parameters but further relevant steps should be done relating these parameters with the decay in time of the mechanical strength of masonry structures. This kind of weakening effect is not effectively considered in technical standards and further development is expected in scientific literature. The majority of damage in masonry structures have been in-plane shear failure, out-of-plane failure, corner collapse and also roof collapse. Generally, the failures have been caused due to the exposure of walls to compressive forces, in-plane and out-of-plane forces. Unfortunately, exposed bricks have a higher porosity and poor compressive strength, it is therefore preferred to use stronger materials for bed joints. Moreover, high rate of humidity inside of the building increases the risk of mold especially on cold surface where condensation occurs (i.e. surface temperature is lower than the dew point temperature) on walls [41], [42].

Figure 2: Examples of degradation due to moisture

Figure 3: Collapse of Lungarno Torrigiani in Florence (25th May 2016) as an example of moisture related failure.

Certainly, the material type and the location of the artifact have a significant effect on preservation. Therefore, the proposed strategies, reviewed from the literature, require to be tailored and specified accordingly. Some materials may perform worse while others may perform better under certain climate conditions, such as lower freeze-thaw cycles. Freeze thaw cycles act detrimentally on masonry buildings with the same disaggregating effects whereby ice acts on the shattering of parents rock. In practice, water penetrates the capillary cavities of the masonry, and when it freezes and expands, it progressively damages the material through differential distortion. This element is really difficult to numerically estimate and is joined to the effects of the chemical reaction on masonry elements. However, warmer temperatures may cause more biological attacks by insects or fungi. With regards to the climate prediction, Peter Brimblecombe explored the probable modifications in the climate humidity in England by 2100. His research highlights that improvements of preservation strategies of historical buildings are undelayable. Meteorological information and climate prediction were considered in this study (source: Met Office). The paper evaluated how changes in dampness and rainfall influence the internal and the external parts of a wall. [45]

Settlement represents another hazard which can occur as a consequence of hazardous phenomena, such as flood, which can damage historical infrastructures, specifically the masonry bridges. In these cases, the bearing capacity of arch bridges could be affected significantly, causing damage and collapse [34], [43]. Annually, several historic masonry [49]

Literature reviewed case studies

Several methods exist to evaluate the moisture content in a historical masonry building (Figure 4). Generally, they fall into two major categories: destructive techniques, which demand material specimen to be tested, and non-destructive techniques that do not need any (or very low) structural disturbance. Because of the value of cultural heritage, some restrictions regarding performing destructive tests on historical buildings, allow only application of the non-destructive techniques. Although, one of the most reliable methods is the destructive direct gravimetric method which includes the in-situ testing of the material samples. Quantitative assessment of moisture content is not possible with (relative) non-destructive methods, which offers in general a qualitative response [44], [45]. Quantitative assessment of moisture content can be achieved through a non-destructive technique (chemical method), where the rate of moisture content is calculated based on the modification in color of indicator papers in contact with the moist material surface. In turn, there are no restrictions regarding the number of tests since there is no interference with the structure [46].
A common approach for monitoring humidity consists in embedding the probes within constructions on long-term-basis for measuring relative humidity. This method could indicate the exact assessment of the humid area, but this is not entirely non-destructive because these probes need to be fixed within the construction process. [47].

Figure 4: Examples of visible moisture effect on the wall surface.

Figure 5: Collapsed portion of the wall, Pistoia

Collapse of City Walls of Pistoia (Italy)

This example illustrates the collapse of a structure with very modest masonry texture weakened by water. A portion of the medieval City Walls of Pistoia (Tuscany, Italy) collapsed in September 2011 (Figure 5). The wall was long 3.2 meters and it

was damaged due to poor quality of the materials. As a matter of fact, the wall was constructed using river pebbles (limestone rocks, from the Brana river) and filled without proper connection between internal and external wythes. The thickness of the collapsed portion was about 1.6 meters, and 11 meters high (which is significant relative to the thickness). The results showed that significant height-to-thickness ratio and inappropriate materials were the effective factors in this collapse. Moreover, the existence of a previous riverbed and the extreme rainfalls contributed to the collapse.
In this study, qualitative investigation was performed by means of visual inspection, Geographic Information System (GIS) and on-site survey. For the restoration, two series of tie-beams were created by stainless steel wire ropes, with different lengths, in which pre-stressing was imposed between turnbuckles. The beams were placed at 2 meters spacing to prevent the outward rotation of the wall. A sequence of circular hollow section braces prevented toppling of walls inward according to Figure 6 [48].

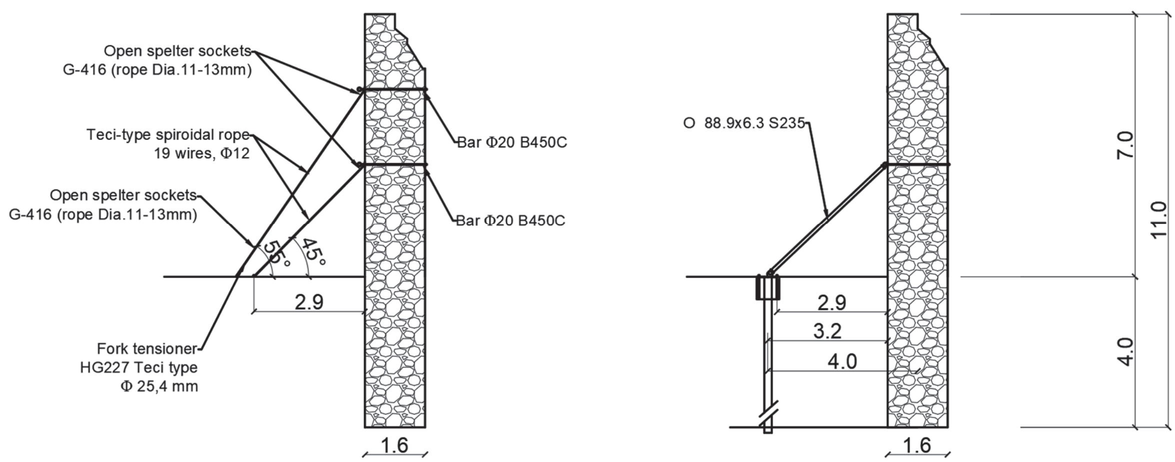

Figure 6: Proposal of restoration of a historic wall with steel tie-rod 5 [48].

Walls of Amelia (Italy)

In January 2006, a large part of the walls of Amelia collapsed. The width of the damaged part was around 25 meters, and the height was about 15 meters.
A few non-destructive methods like Ground Penetrating Radar (GPR) and Resistivity Tomography (ERT) were used for geophysical investigations and controlling of the internal features of the walls. Moreover, Laser Scanning (LS), Digital Terrestrial Photogrammetry (DTP), Global Navigation Satellite Systems in static mode (GNSS) and 3D local network measurements techniques were adopted for monitoring the exact position and the probable transition of the exterior wall surface.
In addition to the evaluation of the reasons of degradation and probable conservation treatments, the crack pattern and the classification of the stones were also investigated. The collapse was attributed to the very rainy winter and the history of Amelia in the last 25 centuries. Another cause of collapse was the landfill behind the walls which was not originally present, and likely causes additional passive stresses in the walls. Moreover, the construction of new buildings, placed upstream to the retaining wall, increased the overload threatening the overall stability and modifying the natural runoff and absorption of stormwater. Finally, using imperfect drainage system led to an increase in the horizontal active stress of groundwater [49].

Figure 7: Migration of calcium sulphate in the wall, Ghiassieh school, Iran.

Ghiassieh school (Iran)

Ghiassieh School, a historical Timurid school founded in the 9th century, is located in northeastern Iran. The walls were constructed of rising masonry bricks and gypsum mortar. A typical feature is the presence of decorative tiles. The analysis showed that material deterioration was caused by salt crystallization, as well as stresses caused by moisture, wind erosion and thermal effects (Figure 7): this phenomenon is shown throughout the variation of colors of the façade, joined with measurement of ettringite contains.

Firstly, the climate-based analysis was performed and the historical records of temperature, relevant humidity, and wind speed from 1951 to 2018 were analyzed. The analysis has shown significant changes, including a sharp rise in wind speed, temperature, and a quick reduction in humidity. These changes could lead to material aging and erosion of exterior wall surfaces.

Subsequently, construction-based analysis such as Wind-Driven Rain (WDR) (by means of the ISO semi-empirical technique) and Heat, Air and Moisture (HAM) simulation have been performed. In terms of HAM approach, documented weather information from 1980 until 2000 were used as the external climate input for HAM modeling.

Temperature and Relative Humidity (RH) sensors were applied in different locations to monitor the indoor climate. According to the analysis, the number of Freeze-Thaw Cycles (FTCs), the moisture index, and the WDR force decreased. For an appropriate numerical simulation, samples of the structure exposed to the principal wind have been selected for testing according to European standards. Moreover, to assess pore size distribution in the samples Mercury intrusion test has been done [50].

Church of San Nicola in Carcere (Italy)

The church is located near the Tiber River in the historical center of Rome. The deterioration in the lower part of the apse and next to the pillars was caused by penetration of water, efflorescence of salt and mould. The church is situated in the swampy area exposed to the floods of Tiber. In particular, the apse is located near the river. Although sewer systems built by Romans are available, the portion of the wall is affected by humidity.

To provide a multidisciplinary point of view and perform experiments using a holistic approach, the moisture distribution and its effects have been identified by using all techniques. To measure and monitor the rising water from the ground due to capillarity, and to map the preliminary moisture, the IRT could be used as non-contact and non-destructive test method. Moreover, this technique is very useful to recognize the areas that need further analysis via other techniques. The distribution and the quantitative assessment of moisture content by a proper calibration can be gained by Unilateral NMR, a non-invasive and non-destructive time-saving technique. The results obtained by LIF technique demonstrate that the water content does not have a significant effect on altering the emission spectrum of investigated artifacts. In AI and AT techniques, potential fluctuation of the elastic characteristics of the constituent materials and assessment of the decay processes are especially prominent due to water absorption [51]. It was pointed out that the presence of piezometer and inclinometer, as a traditional monitoring of the surrounding underground water level and of the displacements, had a strategic role, particularly in situations with a strong soil structure interaction. Especially in the case of very extended infrastructure, such as historic urban walls, monitoring with a satellite constellation, combined with early warning systems, can play a strategic role in preventing collapse [52], [53].

Varamin Friday mosque (Iran)

The mosque is located in Varamin city, closed to the central desert of Iran with rather harsh climate conditions characterized by high day/night and winter/summer temperature differences and also considerable annual precipitation. The mosque, built in 1301 using local materials such as adobe and clay bricks, was retrofitted twice, in 17th and 19th century. To explore structural damage the survey method was applied. The major purpose of this project was to discover a relation between consolidation problems, temperature variation and moisture.

Temperature and humidity of internal and external parts of the masonry structure were measured to investigate structural damage by using computer modeling software, THERM & WUFI. Moisture and thermal performance of masonry walls were evaluated, taking into account internal moisture-producing ratio, external climate situations and modeling software tool. To measure hydrothermal performance of materials in various categories under climatic situations, a sample wall was modeled based on climate information obtained from original materials in two periods.

Firstly, severe moisture damage was surveyed in the pillars and portico of the structure which could cause collapse of ornaments, brick masonry and ceramic tiles, and moisture ingress in bricks. A few critical problems are illustrated in Figure 8.

As the next step, temperature and relevant humidity in internal and external parts of the structure were measured twice, during four days in the coldest and hottest months of year, throughout electronic hydrometer. The indoor/outdoor

temperature fluctuation resulted equal to 7.7 °C, causing humidity and moisture increase which could in turn increase condensation, by the help of a thermometer. Subsequently, computer simulation of a typical wall was carried out by THERM software to investigate the climatic factors.
The wall was modeled using WUFI-ORNL/IBP software, a one-dimensional program for measuring phenomena in structural elements. In particular, the moisture movement analysis was performed according to finite volume techniques, in a 730 thirty day period modeling in hourly measurement, after adding climatic data. Finally, the moisture behavior illustrated in a climatic diagram and the consequences were obtained.
The results underline that the climatic methods, designed to increase thermal comfort in building interior, could increase moisture amount between wall layers. Consequently, condensation problems may occur, leading to critical flaws and devastation. However, in this study, an active ventilation system to reduce indoor/outdoor temperature gradient was suggested to eliminate the condensation problems [54].

Case studies from the literature, presented in this section, are summarized in Table 1 and some pics of NDT's instruments are also showed in Figure 9.

Figure 8: Entrance in the Varamin mosque, Iran

	Damage/structural damage		Main data			Survey/monitoring	Restoration	Ref.
	Year	Cause	Age	Material	Dimension	Instruments	Technique	
City wall of Pistoia (Italy)	2011	Poor quality of materials	From II century b.C.	Limestone river pebbles	Thickness: 160 cm Height: 11 m	Adopted instruments	Proposed techniques	[55]–[57]
Walls of Amelia (Italy)	2006	Heavy rainfalls, additional passive stress, imperfect drainage system	VI - IV century b.C.	Limeston blocks	Width: 25 m Height: 15 m	Visual inspection, GIS, on-site survey	Tie-beams	[64]
Ghiassieh school (Iran)	N.A.	Salt crystallization, moisture, wind erosion, thermal effects	IX century a.C.	Masonry bricks and gypsum mortar	N.A.	GPR, RT, LS, DTP, GNSS, 3D Local network	-	[58]
Church of San Nicola in Carcere (Italy)	N.A.	Penetration of water, efflorescence of sault, mould	1599-1865	-	N.A.	WDR, HAM, temperature and RH sensors	-	[59]
Varamin Friday mosquee (Iran)	N.A.	In/Out temperature and humidity	1301	Adobe bricks	Thickness: 160 cm Height: 11 m	Adopted instruments	-	[62]

N.A. = Not Applicable

Table 1: Summary of the litterary review.

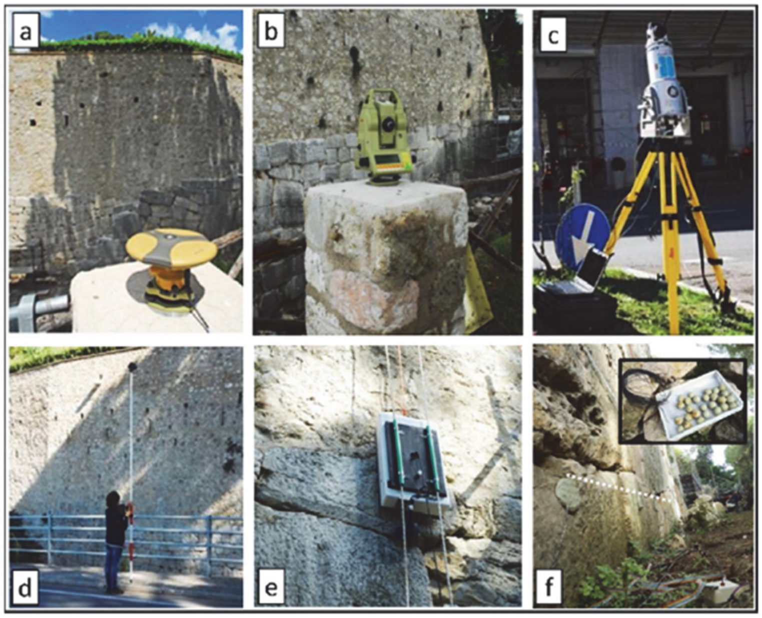

Figure 9: Integrated Survey techniques: a) GNSS survey, b) Total station, c) Laser scanner, d) Digital camera, e) 500MHz GPR antenna with customized frame, f) ERT survey [58].

DISCUSSION AND CONCLUSION

The present study concentrates on the assessment of degradation due to moisture effects and on the vulnerability of masonry artifacts. In this regard, several case studies from Italy, Iran and Romania, including investigation and restoration methods, have been presented in this paper. Practical solutions to prevent and slow down degradation and collapse process are also presented. Porous materials (particularly highly porous and low-strength materials) can be damaged by several FTCs [59]. Such degradation could be attributed especially to material deterioration. Moreover, the pressure produced from the increase of ice crystals on the internal pores produces cracking. Therefore, cracks and delamination occur particularly on the surfaces which are more exposed to freeze-thaw.

The decay of masonry buildings is exacerbated by repeated frost damage and the physical properties of the materials. In fact, porosity, material strength, water holding-retaining substantially affect masonry degradations. Furthermore, stiffness, energy-dissipation capability and bearing capacity of the structure decreases and the lateral displacement of masonry wall gradually increases. This can be explained by the weakening of bond strength between mortar and bricks [60]. The residual tensile resistance of masonry can be estimated by pull-out tests [61] or other direct or indirect low-disruption techniques.

Monitoring urban walls and structures with different materials like soil, stone and brick, can be performed by means of Infrared thermography (IRT), electrical resistivity tomography (ERT) and Ground Penetrating Radar (GPR). Specifically, these are non-destructive methods for the evaluation of the moisture content in masonry and mortar joints and provide information about the internal properties of the walls. IRT is a routine method to measure the thermal behavior of masonry and could also be used as an indication of moisture near the wall surface. IRT is not very accurate, but it provides an acceptable view of the masonry moisture pattern [47]. In addition, Laser Scanning (which provides geometric properties of the assessed surfaces), Digital Terrestrial Photogrammetry, Total Station and Global Navigation Satellite Systems (GNSS) are used [49].

In some cases, GIS and on-site survey are proposed for integrating visual inspections, as a part of the monitoring process. The GIS application works by using satellite images. The GIS provides information on relative distance, absolute distance from the initial points, altimetry, and topography coordinates, so that, together with in-situ survey, help to obtain geometric information[62] and furnish speedy vulnerability indications.

Additionally, an examination of the climate factors, the climate and construction-based parameters is carried out to analyze the climate change influences on heritage. For analyzing climatic parameters during the time period, significant changes in temperature, wind speed and humidity should be evaluated. Climate-based analysis consists of meteorological parameters analysis, considering annual average temperature and precipitation, relative humidity, wind velocity, annual number of FTCs, annual amount of salt crystallization, and, finally, annual moisture index specific for the studied region. Construction-based

analysis includes calculation of Wind-Driven Rain load and HAM simulation. Wind-driven rain load is related to the investigation of the wind erosion and the annual number of WDR, while HAM simulation provides detailed data regarding the deterioration progress of the structural components [50].
Non-invasive and non-destructive methods such as Unilateral NMR and LIF techniques are used to evaluate and detect moisture content. Potential variation of elastic properties of the wall materials could be determined by using AI and AT [51].
In another case study, a survey method was applied to detect severe damage in the structures and, in the second section of survey, to determine temperature and relative humidity in internal and external parts of structure. Finally, dealing about computer modeling, THERM modeling and WUFI software modeling can be used [54].
It should be noted that measurements obtained by inclinometers and piezometers often provide important insights into the exposure of all soil-interacting artifacts, particularly those made of masonry. The study highlights that although there are numerous tools to predict masonry deterioration, further steps need to be taken to account for degradation due to the presence of water and aging.
Retrofitting method should be chosen depending on the causes of degradation, the type of masonry structure, the materials and the available facilities, the sustainability and the available budget [63]. For instance, in a city wall with a risk of collapsing of tie-beams, practical draining system and high-quality materials should be used for retrofitting. In the case of a bridge, Fiber Reinforced Polymer (FRP) materials could be effective because of the flexibility, low weight, and increasing the strength and ductility and load-bearing capacity of the structure. For existing residential buildings, combined structural and energy retrofit interventions [64] can play a strategic role, particularly in addressing current community performance requirements. When it comes to envelope structures like mosques and churches proper ventilation and drainage system could be a good option to decrease the temperature difference between inside and outside avoiding condense or other moisture related problems.

ACRONYMS AND ABBREVIATION

The acronyms and abbreviations, as presented in the paper, are summarized in the following:

HUW	Historical Urban Walls
GIS	Geographic Information System
GPR	Ground Penetrating Radar
ERT	Electrical Resistivity Tomography
LS	Laser Scanning
DTP	Digital Terrestrial Photogrammetry
GNSS	Global Navigation Satellite System
WDR	Wind-Driven Rain
HAM	Heat, Air and Moisture
RH	Relative Humidity
FTC	Freeze-Thaw Cycle
NDT	Non-destructive technique
IRT	Infrared Thermography
NMR	Nuclear Magnetic Resonance
AT	Acoustic Thermography
AI	Acoustic Imaging
LIF	Laser Induced Fluorescence
FRP	Fiber Reinforced Polymer

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