Experimental Assessment of Climate-Induced Impacts on Heritage Materials: Application of the Damage Index Methodology in the Case Study of Bova

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Climatic and Structural Safety in Multi-Hazard Regime of Cultural and Natural Heritage

Methodological Advances and Case Study Applications

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Consuelo Nava · Aurora Angela Pisano ·
Giuseppe Mangano · Francesca Giglio
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Preface

The protection of a Country's cultural heritage, both architectural and environmental, is a highly relevant political and scientific concern, given its profound implications for the social and cultural fabric of societies.

Safety assessment requires a comprehensive understanding of the various sources of risk (climatic, geomorphological, structural, etc.), demanding interdisciplinary approach to the problem. The topics involved are of considerable interest for the scientific community and constitute a knowledge base for any planning strategy, both for preventive actions (maintenance, building and site safety) and reactive interventions (emergency management, evacuation plans).

This book addresses the issue of climatic and structural safety in multi-hazard regime of cultural and natural heritage, drawing on the outcomes of a three-year technology transfer project, funded by the Italian National Recovery and Resilience Plan -PNRR T4Y PP 4.7.1. In particular, the project is entitled Open Platform *phigital space* (physical and digital) of the type *user-profiling* for the advanced and dynamic codesign of interventions on the built and ex novo.

The book is organized into two main parts collecting peer-reviewed papers from approximately twenty involved researchers and begins with a chapter detailing the methodologies adopted and the final goals of the project.

The first part of the book aims to deepen theoretical knowledge related to cultural heritage analysis, proposing advanced models for damage assessment on structures and their surrounding environments. These models also incorporate uncertainties related to material properties and consider different environmental stressors under three projected climate scenarios for the years 2030, 2050, and 2085.

The second part of the book features some chapters with a more applied focus. Thanks to some large-scale case studies, it proposes a digital platform to support all the meta-files relating to the security data collected. This platform, along with the creation of a Living Lab (physical platform), will provide a methodology for the transfer of digitalized data to different stakeholders: including institutions, professionals, and local communities.

The Editors sincerely thank all the senior and the young researches who have contributed by their outstanding contributions to the quality of this book.

October 2025

Consuelo Nava
Aurora Angela Pisano
Giuseppe Mangano
Francesca Giglio

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Theoretical and Methodological Approaches

Experimental Assessment of Climate-Induced Impacts on Heritage Materials: Application of the Damage Index Methodology in the Case Study of Bova

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Abstract. This paper presents an advanced methodology for defining a Damage Index to assess the climate vulnerability of material cultural heritage. The Index is based on three core factors: environmental conditions (F_{env}), material properties (F_{mat}), and external drivers (F_{ext}), each represented by specific indicators, weighted and normalized on a 0–3 scale using the Analytic Hierarchy Process (AHP), allowing for structured risk evaluation. This contribution focuses specifically on the experimental assessment of material factors (F_{mat}), aimed at determining the physical and chemical properties of heritage materials through a replicable site-specific approach. The study is structured in three sections: the first outlines the overall framework of the Index; the second details the experimental and simulation procedures for assessing material properties; the third presents its application to the case study of Palazzo Mesiani in Bova (Reggio Calabria). These analyses were conducted by the MATeRICs Interdepartmental Laboratory at Mediterranea University of Reggio Calabria, using non-destructive techniques such as X-Ray Fluorescence (XRF), Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX), and X-Ray Diffraction (XRD). The data were processed via a dedicated spreadsheet enabling step-by-step calculation of the Index. The case study confirms the methodology's applicability and potential for integration within Living Labs and digital platforms, offering a scalable tool to support adaptive conservation strategies for heritage exposed to evolving climate-related risks.

Keywords: Damage Index · climate vulnerability · cultural heritage · experimental analysis · simulation methodologies

1 Introduction

Climate change is the fastest-growing global threat to the world's natural and cultural heritage. The conservation of built heritage requires complex studies concerning their Global Vulnerability (Day et al., 2020; Smith, 2013). These studies must consider the

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current condition of the building, particularly its degree of degradation, as well as the main factors contributing to deterioration. These factors extend beyond the building's structure and include its location and surrounding environmental conditions. Therefore, the assessment of built heritage vulnerability should encompass not only the building itself but also the broader site and environmental context. (Damas Mollá et al., 2022).

Cultural heritage is increasingly threatened by climate-related risks, including erosion, corrosion, thermal stress, and freeze-thaw cycles, posing significant challenges for preservation (Mavrakou et al., 2025; Sesana et al., 2019). The literature review highlights that climate risks often compound other pressures, such as urbanization, overtourism and lack of adaptation policies and methodologies (Georgiadis, 2019; Boeri et al., 2023).

Possible resolution strategies focus on the built environment, advanced, ecological, and regenerative design (Nava, 2023) capable of strengthening the levels of preparedness of the contexts involved and, at the same time, increasing resilience to climate risk. Intervening in this direction requires the experimentation of integrated tools that consider the multiple fragility conditions inherent to the analyzed heritage contexts. Measurement of multiple risk factors and the calculation of site-specific damage indices represent priority tools for identifying risk conditions in the considered heritage contexts.

As stated in Giglio F., et al., 2024, an all-encompassing approach should be employed when evaluating the vulnerability to climate change of cultural heritage buildings and structures. This approach should consider various aspects, such as the long-term and sudden impacts of climate change, non-climatic factors, the capacity to adapt, and the cultural significance to the local community. The calculation of these indices should rely on comprehensive vulnerability assessments, utilization of extended monitoring methods, and execution of policies to overcome barriers to adaptation.

In this context it's proposed a methodology for assessing the vulnerability of cultural heritage materials and structures to climate change (Damage Index) that offers a systematic approach to understanding how climate change affects cultural heritage materials.

The paper is structured in three parts: the first provides an overview that briefly outlines the general methodology for calculating the Damage Index, identifying its main steps; the second describes in detail the methodologies used to assess one of the three components of the index, specifically focusing on material properties (F_{mat}) through the different experimental analyses applied; the third part presents the application of the experimental methodology to the case study of Palazzo Mesiani in Bova (RC), with a specific focus on the description of the in-situ material analyses carried out.

2 The Damage Index: An Endpoint Index for Assessing the Combined Effect of Environmental, Material and External Factors of Climate Change on Cultural Heritage

A vulnerability assessment includes an analysis of the scope and severity of the potential impacts of climate change. The study of risk reduction requires a perception of the hazards, and a representation of the system's response when subjected to the hazards (Esposito et al., 2017). Over the past decade, efforts to assess vulnerability to climate change triggered a process of theory development and assessment practice, which is also reflected in the recent reports of the IPCC (Füsse and Klein 2006).

In this context, vulnerability plays a crucial role in assessing the level of risk and developing measures to reduce risk and adapt to climate change. Vulnerability can be defined as the extent to which a system, subsystem, or component is susceptible to damage when exposed to a risk, such as a disturbance or stressor (Turner et al. 2003). Vulnerability, within the realm of climate change adaptation research, is described as the propensity or predisposition to experience adverse effects (IPCC, 2018). Within the framework of the IPCC, vulnerability encompasses various concepts and elements, including sensitivity or susceptibility to harm, as well as the lack of capacity to cope and adapt (IPCC, 2023).

In Vulnerability Assessment Framework, experimented by Ravan, M., et al. 2023, the primary variable is “susceptibility”, which pertains to the inherent vulnerability of the elements exposed to hazards and is function of “sensitivity” that means “an attribute of the system, existing prior to the perturbation, and separate from exposure”. The secondary variable is the “lack of resilience”, which is characterized by limited access to and mobilization of resources to effectively respond to and recover from the adverse consequences of hazards, therefore a lack of adaptive capacity, that is “the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences” (Ravan et al., 2023), even for slow onset events in a long-term perspective.

Following those definitions, the literature review suggested for this study the development of an endpoint index, that consider the comprehensive and combined effect of various midpoint indicators. The Damage Index has been chosen to this purpose, being one of the most representative endpoint indicators. Therefore, it has been considered as a function of the three primary factors:

$$DAMAGE\ INDEX = f\,(F_{env}, F_{mat}, F_{ext})$$

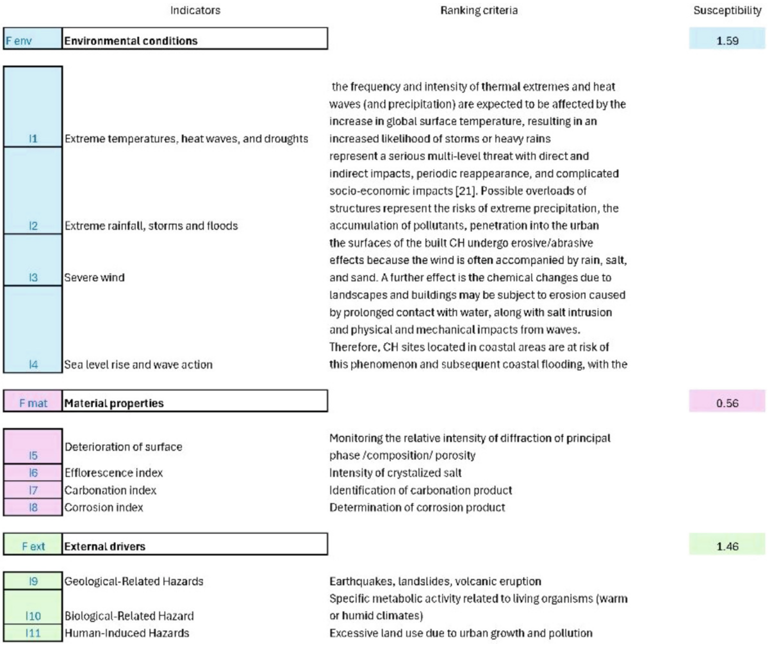
About what has been established so far, the identification, definition, and quantification of the Damage Index is closely tied to three fundamental components:

- Environmental conditions (F_{env}),
- Material properties (F_{mat}),
- External factors (F_{ext}).

These components collectively form the Damage Index definition (Fig. 1).

It is important to highlight that Damage Index evaluation is just referred to the degradation processes of building materials, such as physical and chemical damages, excluding static and dynamic alterations of structures.

The Damage Index, previously outlined in Giglio et al. 2024, and in Lucanto et al. 2024, adopts a comprehensive approach to assessing the climate change vulnerability of cultural heritage buildings and structures by integrating various types of data, including environmental data, experimental ex-post findings, and non-climatic factors. The Index is calculated by the normalization of experimental data and their weighting through Analytic Hierarchy Process (AHP), to weigh the different indicators, from 0 (low risk) to 3 (high risk) (Fig. 2). The AHP, initially formulated by Saaty and Kearns in 1985,



Indicators		Ranking criteria	Susceptibility
F env	**Environmental conditions**		1.59
I1	Extreme temperatures, heat waves, and droughts	the frequency and intensity of thermal extremes and heat waves (and precipitation) are expected to be affected by the increase in global surface temperature, resulting in an increased likelihood of storms or heavy rains	
I2	Extreme rainfall, storms and floods	represent a serious multi-level threat with direct and indirect impacts, periodic reappearance, and complicated socio-economic impacts [21]. Possible overloads of structures represent the risks of extreme precipitation, the accumulation of pollutants, penetration into the urban	
I3	Severe wind	the surfaces of the built CH undergo erosive/abrasive effects because the wind is often accompanied by rain, salt, and sand. A further effect is the chemical changes due to	
I4	Sea level rise and wave action	landscapes and buildings may be subject to erosion caused by prolonged contact with water, along with salt intrusion and physical and mechanical impacts from waves. Therefore, CH sites located in coastal areas are at risk of this phenomenon and subsequent coastal flooding, with the	
F mat	**Material properties**		0.56
I5	Deterioration of surface	Monitoring the relative intensity of diffraction of principal phase /composition/ porosity	
I6	Efflorescence index	Intensity of crystalized salt	
I7	Carbonation index	Identification of carbonation product	
I8	Corrosion index	Determination of corrosion product	
F ext	**External drivers**		1.46
I9	Geological-Related Hazards	Earthquakes, landslides, volcanic eruption	
I10	Biological-Related Hazard	Specific metabolic activity related to living organisms (warm or humid climates)	
I11	Human-Induced Hazards	Excessive land use due to urban growth and pollution	

Fig. 1. Excel table for Environmental, Materials and External factors, indicators and ranking criteria.

is a technique used to assign relative importance to different evaluation criteria in a decision-making procedure.

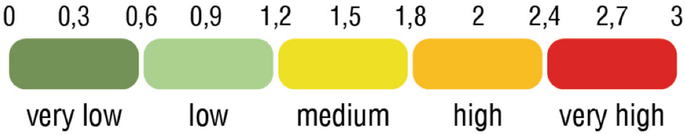


Fig. 2. Numerical score system referred to specific standard of reference

or these reasons, a procedural methodology has been developed for the quantitative definition of the index, based on the variables acquired from the experiments conducted by Ravan et al. (2023), through the application of appropriate calculation methods developed by the authors[1]. The methodology employs:

- Vulnerability, calculated as a function of susceptibility and adaptive capacity:

$$Vulnerability\ (sub - index) = \sqrt{Susceptibility\ x\ Lack\ of Adaptability}$$

---

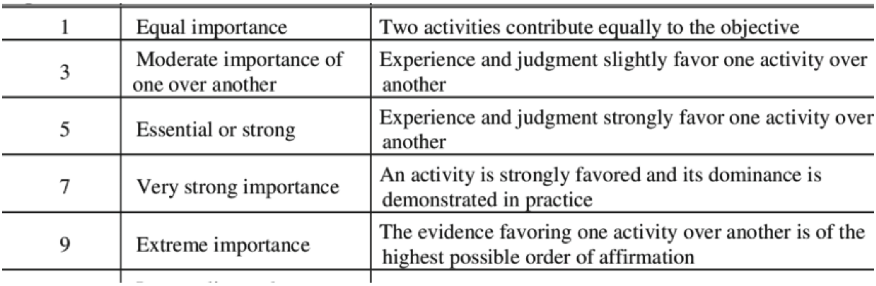
[1] The experimental development of the Damage Index was carried out at the MATeRICs Interdepartmental Laboratory in collaboration with the MATEES Laboratory, involving Prof. P. Frontera and Eng. RtdB A. Malara, together with the authors, Prof. F. Giglio and Arch. PhD F. Armocida.

- Sensitivity, determined through risk classification and weighting criteria:

$$Susceptibility\ I_X = \frac{\left(Sensitivity_n\ x\ Weight_n + Sensitivity_m\ x\ Weight_m\right)}{\left(Weight_n + Weight_m\right)}$$

- Adaptive capacity, which includes human and financial resources and operational plans.

As regards the weighting procedure, the ranking scales used for the pairwise evaluation of criteria/indicators in AHP are based on a standardized five-point scale of ‘intensity of importance’: 1, 3, 5, 7, and 9 (Fig. 3). The Analytic Hierarchy Process (AHP), originally formulated by Saaty and Kearns in 1985, is a method designed to assign relative importance to different evaluation criteria within decision-making procedures (Saaty & Kearns, 1985; Ravan et al., 2023).

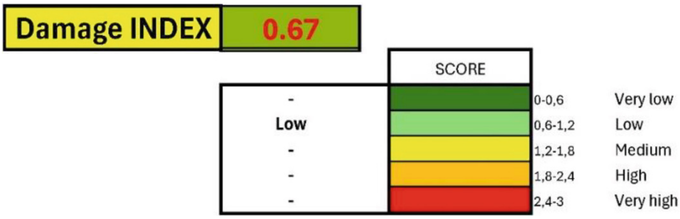


1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Fig. 3. Saaty’s scale of relative importance (graphical elaboration by Stanic et al., 2017, based on the methodology of Saaty and Kearns, 1985)

The final index is a weighted average of the “vulnerability” sub-indices. The calculation relies on a spreadsheet that classifies and weighs sensitivity, adaptive capacity, and their relative importance, drawing on experimental data for the materials examined. The outcome is a quantitative framework for assessing climate-related risk to building materials, which in turn informs conservation and adaptation strategies.

Finally, the Damage Index is calculated as the average of the three weighted vulnerability indexes (Fig. 4).



Damage INDEX	0.67		
	SCORE		
-	🟩	0-0,6	Very low
Low	🟩	0,6-1,2	Low
-	🟨	1,2-1,8	Medium
-	🟧	1,8-2,4	High
-	🟥	2,4-3	Very high

Fig. 4. Excel table indicating an example of the final comprehensive Damage Index

This framework provides a systematic approach to understanding the impacts of climate change on cultural heritage materials by integrating environmental data, material properties, and adaptive capacities into a unified numerical model, it enables accurate vulnerability assessments that reflect the complexity and interdependence of multiple influencing factors.

3 The Methodology of Damage Index for Assessing Material Properties (F_{mat}) Through Experimental Analysis

With reference to the Damage Index calculation methodology outlined in the previous sections, this part delves into the specific procedures related to one of the three components of the index: material properties (F_{mat}). These properties form the basis for both the experimental assessment and the methodological transfer through in-situ analyses conducted on the selected case study.

These experimental analyses (described in paragraph 3) involve the implementation of non-invasive investigations on Palazzo Mesiani, Bova (RC), using advanced instrumentation aimed at determining the chemical-physical properties of the materials entity that constitute the fabric of the case study (XRD, XRF evaluation, Carbonation Test, etc.).

3.1 Material properties (F_{mat})

The F_{mat} factor specifically refers to the degradation processes affecting construction materials, including physical and chemical damage. Drawing on scientific literature, midpoint indices have been identified; these typically represent the average impact of a stressor across different spatial or temporal scales and contribute to calculating the Damage Index. The selected indices (Fig. 5) include:

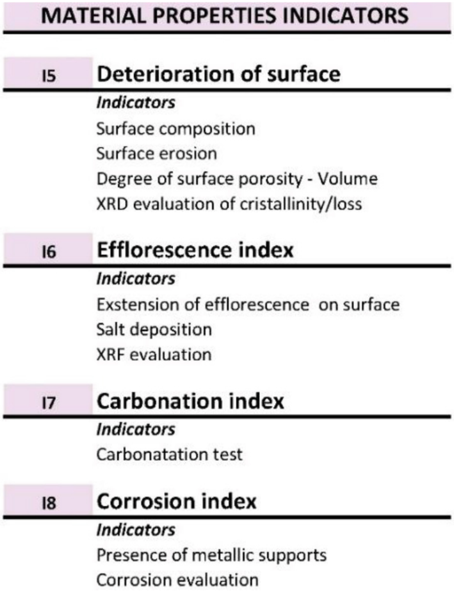
- Surface deterioration
- Carbonation (relative to the reference substrate)
- Efflorescence
- Corrosion of metallic elements

Each index is linked to specific ranking criteria, which are subsequently used in the calculation of the Damage Index (Table 1).

The methodology for material properties (Fig. 6), starts from the preliminary definition of the midpoint indicators and their respective benchmarks, it was necessary to divide each of them into specific sub-indicators based on the experimental analyses to be carried out in situ or with the support of laboratory tools (see paragraph 2.2.2).

These sub-indicators contribute to their respective definitions:

- The surface deterioration index is a function of surface composition, surface erosion, degree of surface porosity, and the state of surface crystallinity.
- The efflorescence index is a function of extent of efflorescence on the surface, salt deposits, and XRF evaluation.
- The carbonation index is based on carbonation testing.



MATERIAL PROPERTIES INDICATORS

I5 **Deterioration of surface**

Indicators

Surface composition

Surface erosion

Degree of surface porosity - Volume

XRD evaluation of cristallinity/loss

I6 **Efflorescence index**

Indicators

Exstension of efflorescence on surface

Salt deposition

XRF evaluation

I7 **Carbonation index**

Indicators

Carbonatation test

I8 **Corrosion index**

Indicators

Presence of metallic supports

Corrosion evaluation

Fig. 5. Sensitivity Factor: Indicators of Material properties

Table 1. Midpoint Indices and Corresponding Ranking Criteria Used for Damage Index Calculation

Indicators (Midpoint Indices)	Ranking criteria
Surface Deterioration	Monitoring the relative intensity of diffraction of the primary phase
Efflorescence Index	Intensity of crystallized salts
Carbonation Index	Identification of carbonation products
Corrosion Index	Determination of corrosion products

- The corrosion index is a function of presence of metallic elements and corrosion evaluation (%).

A third methodological phase involved identifying specific measurement criteria for each sub-indicator, as well as determining the experimental results (Table 2).

The indicators are expressed as percentages instead of absolute units to allow a uniform comparison of different parameters. Using percentages enables:

1. Comparability: It normalizes diverse data like porosity, erosion, and crystallinity, making them directly comparable despite different measurement scales.
2. Relative assessment: Percentages reflect changes or degradation relative to an ideal or original material state, rather than absolute values.

Fig. 6. Schematic representation of methodological phases for the normalization of F_{mat}

Table 2. Correlation between Indicators, Sub-indicators, and Measurement Criteria

Indicators	Sub-indicators	Measurement criteria
Surface Deterioration	Surface Composition	Composition (N compounds)
	Surface Erosion	Percentage of erosion
	Degree of Surface Porosity	Percentage of porosity
	Surface Crystallinity	Percentage of crystallinity
Efflorescence	Extent of Efflorescence	Percentage of coverage
	Salt Deposits	Percentage quantification
	XRF Evaluation	Peak area ratio
Corrosion	Carbonation Test	Percentage of surface area extension
Corrosion	Presence of Metallic Elements	Percentage of metallic supports present
	Corrosion Evaluation	Percentage of corrosion

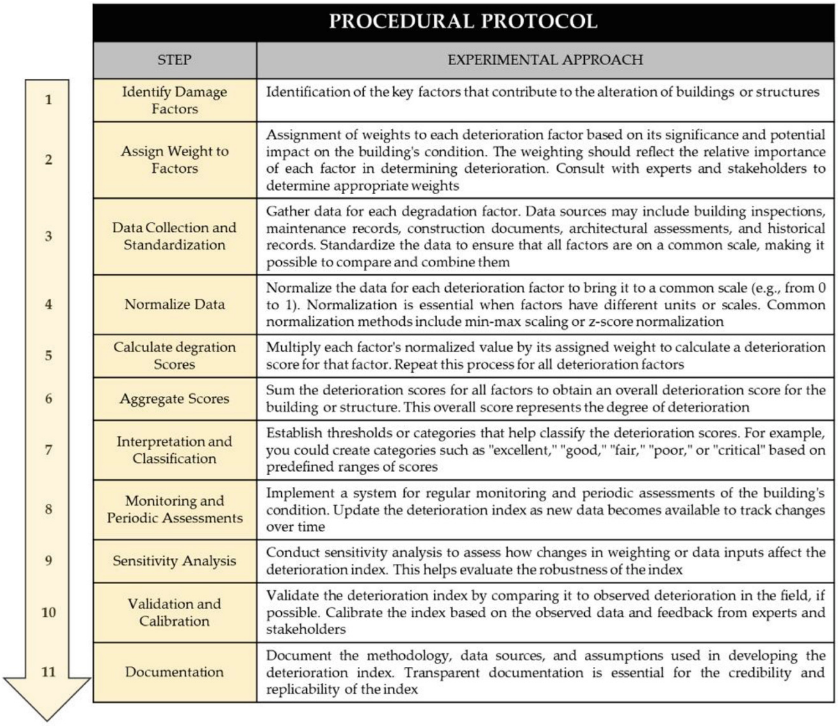
3. Extent of degradation: They quantify how much damage has occurred compared to the original, undamaged material, which is key for conservation.
4. Spatial distribution: Percentages capture how phenomena like crystallinity and carbonation vary across a surface, showing material heterogeneity and localized degradation.

Thus, the use of percentages allows for uniform comparison across different parameters, represents the severity of degradation relative to an original state, and facilitates the communication of results.

The final phase involved normalizing the results by transposing the experimentally obtained values into the Damage Index.

3.1.1 F_{mat}: Procedural Protocol Through Experimental Instrumental Analysis for the Quantitative Definition of the Indices

A procedural protocol has been implemented for the quantitative definition of the sub-indicators constituting the indices, as illustrated in the following diagram (Fig. 7).



PROCEDURAL PROTOCOL

	STEP	EXPERIMENTAL APPROACH
1	Identify Damage Factors	Identification of the key factors that contribute to the alteration of buildings or structures
2	Assign Weight to Factors	Assignment of weights to each deterioration factor based on its significance and potential impact on the building's condition. The weighting should reflect the relative importance of each factor in determining deterioration. Consult with experts and stakeholders to determine appropriate weights
3	Data Collection and Standardization	Gather data for each degradation factor. Data sources may include building inspections, maintenance records, construction documents, architectural assessments, and historical records. Standardize the data to ensure that all factors are on a common scale, making it possible to compare and combine them
4	Normalize Data	Normalize the data for each deterioration factor to bring it to a common scale (e.g., from 0 to 1). Normalization is essential when factors have different units or scales. Common normalization methods include min-max scaling or z-score normalization
5	Calculate degration Scores	Multiply each factor's normalized value by its assigned weight to calculate a deterioration score for that factor. Repeat this process for all deterioration factors
6	Aggregate Scores	Sum the deterioration scores for all factors to obtain an overall deterioration score for the building or structure. This overall score represents the degree of deterioration
7	Interpretation and Classification	Establish thresholds or categories that help classify the deterioration scores. For example, you could create categories such as "excellent," "good," "fair," "poor," or "critical" based on predefined ranges of scores
8	Monitoring and Periodic Assessments	Implement a system for regular monitoring and periodic assessments of the building's condition. Update the deterioration index as new data becomes available to track changes over time
9	Sensitivity Analysis	Conduct sensitivity analysis to assess how changes in weighting or data inputs affect the deterioration index. This helps evaluate the robustness of the index
10	Validation and Calibration	Validate the deterioration index by comparing it to observed deterioration in the field, if possible. Calibrate the index based on the observed data and feedback from experts and stakeholders
11	Documentation	Document the methodology, data sources, and assumptions used in developing the deterioration index. Transparent documentation is essential for the credibility and replicability of the index

Fig. 7 Schematization of the procedural protocol (Graphic elaboration from Giglio, F.; Frontera, P.; Malara, A.; Armocida, F. Materials and Climate Change: A Set of Indices as the Benchmark for Climate Vulnerability and Risk Assessment for Tangible Cultural Heritage in Europe. Sustainability 2024, 16, 2067.)

To this end, experimental investigation techniques such as X-ray diffraction (XRD) for the identification of material structures and scanning electron microscopy (SEM) combined with energy dispersive X-ray analysis (EDX) for morphological and chemical characterization were used. The protocol includes both in situ and laboratory investigations. Specifically:

- In situ: X-ray fluorescence (XRF) spectrometry was applied to non-destructively determine the chemical composition of masonry materials at selected planar points, followed by sample collection for further analysis.

- Laboratory investigations: SEM-EDX and XRD analyses were performed to investigate the morphological, chemical, and structural properties of the collected samples. The analysis was conducted by the MATeRICs Interdepartmental Laboratory in collaboration with the MATEES Laboratory, both at the Mediterranea University of Reggio Calabria.[2]

4 Application of Experimental Diagnostic Analyses and Simulation Tools in the Case Study of Palazzo Mesiani, Bova (RC)

Macroscopically, it is possible to observe the presence of heterogeneous materials in this building, due to the combined use of different types of original materials, as well as more recent materials likely introduced during reconstruction and/or maintenance work.

Indeed, from an initial visual inspection, the main materials constituting the structure are evident: local stone, identified as limestone or sandstone, already studied in other buildings in nearby areas and typical of many historic buildings in Calabria; bricks made of local clay, which are significantly present in this structure; mortar used to bind bricks and stones; and cement, found in some areas, likely due to restoration or adaptation work. The experimental analyses and simulation methodologies were first carried out in-situ (Fig. 8) and then processed in the laboratory.[3]

Fig. 8 Representative images of Palazzo Mesiani (Bova, Reggio Calabria)

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[2] MATeRICs Interdepartmental Laboratory (resp. scient. prof. F. Giglio), MATEES Laboratory (resp. scient. prof. P. Frontera)

[3] The experimental analyses on Palazzo Mesiani were conducted by MATeRICs Interdepartmental Laboratory in collaboration with the MATEES Laboratory, involving Prof. P. Frontera and Eng. RtdB A. Malara, alongside the authors, Prof. F. Giglio and arch. PhD's F. Armocida.

4.1 In-Situ Investigations

Experimental analyses were conducted on various points of the masonry by means of X-ray Fluorescence Spectroscopy (XRF) to determine the chemical composition of materials. The microstructural and chemical characteristics were directly identified on-site using XRF analysis (X-ray fluorescence). Given the building's large dimensions, the most representative points of the entire structure were analyzed, and the results obtained were appropriately averaged (Fig. 9).

Fig. 9. Application of spectroscopy and analysis sampling, Palazzo Mesiani, Bova (RC)

The most representative XRF spectra are reported below (Fig. 10), from which relevant information regarding chemical composition, potential crystalline structures, and alterations experienced by the structure over time were extracted.

As evidenced by the XRF spectra, the main elements identified are calcium, silicon, iron, chlorine, and, in smaller percentages, aluminum and potassium. The main crystalline structures were identified as belonging to limestone matrices (tufa), various types of silicates (calcium and iron), quartz, aragonite, and calcite, which are compatible with the structures of mortars. Additionally, the high percentage of iron (iron oxide) was attributed to bricks, which are mainly characterized by high concentrations of iron oxide, calcium oxide, and low levels of silica.

4.2 Laboratory experimental investigations

Regarding the implementation of the Damage Index, the material characterization analyses include various experimental techniques and methodologies:

- ImageJ Software Analysis on Representative Areas: The ImageJ software is used for quantitative evaluations of visual and structural characteristics of surfaces. Specifically, in the described analyses, the software measures parameters such as porosity and surface erosion (Fig. 11).

- Surface deterioration

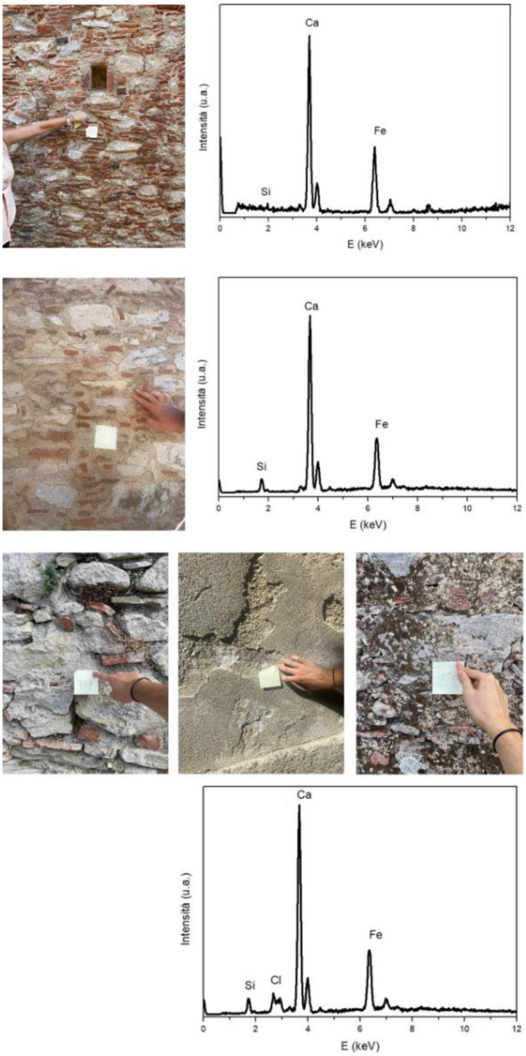

Fig. 10. Representative samples of the structure and corresponding averaged XRF spectra.

- Surface composition: Point-specific XRF analysis identified the chemical composition of surface morphologies, detecting 8 main compounds with a weight percentage >5%. A relative score from 0 to 3 was assigned based on the number of compounds. A low number indicates limited impact, whereas high material heterogeneity can trigger multiple and interconnected degradation processes.
- Degree of surface porosity: Evaluated using ImageJ software by analyzing selected image areas to distinguish voids through contrast and depth calculations. The average porosity measured was 10.7%, significantly influenced by the construction technique involving alternating bricks and stone elements.

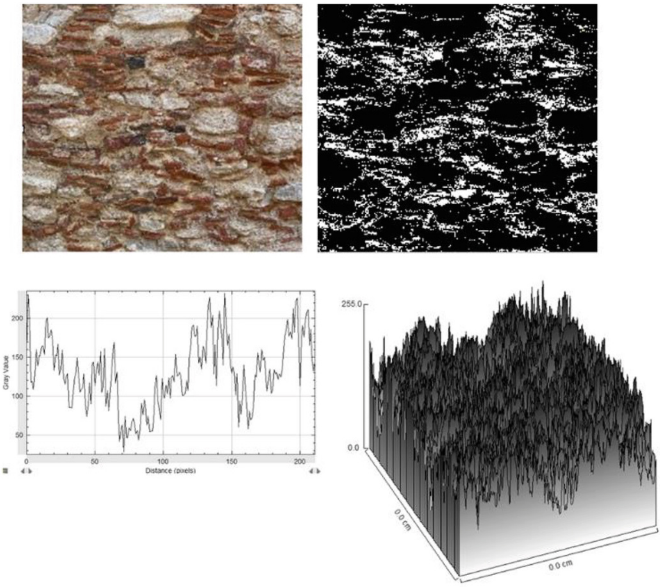

Fig. 11. Analyses obtained using ImageJ software

- Surface erosion: Also analyzed with ImageJ, erosion was quantified as the average depth value across a fixed-width section (50 cm). The surface is generally irregular, and some cavities are due to construction technique rather than erosion. The average erosion percentage was approximately 8.7% (≈4.3 cm per 50 cm at 100%).
- XRD evaluation of crystallinity: Although direct crystallinity evaluation was not possible, the presence of efflorescence and organic deposits (from XRF data) suggests an estimated 10% decrease in surface crystallinity, corresponding to the observed efflorescence extent.

- Efflorescence index

  - Extension of efflorescence on surface: Visual inspections of selected areas identified efflorescence and organic deposits. The surface coverage was estimated at 1.1% of the total analyzed area (in m^2).
  - XRF evaluation: Targeted XRF spectroscopy detected chlorides typically associated with efflorescence. The ratio between fluorescence peak areas related to efflorescence compounds and those from building materials averaged 0.07 (Fig. 12).
  - Salts deposition: XRF analysis confirmed the presence of chloride-based salts indicative of saline efflorescence. These are attributed to moisture-driven salt migration from the subsoil to the wall surface. Although weight % quantification is complex, it is unnecessary for the index calculation given the limited extension observed.

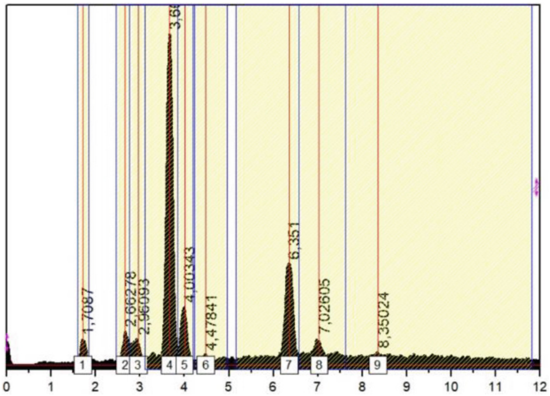

Fig. 12. XRF evaluation elaboration results

- Carbonatation index
  - Carbonatation test: The carbonation test evaluates CO_2 penetration into construction materials and its reaction with calcium hydroxide, forming calcium carbonate. This process reduces pH and may trigger corrosion if metal reinforcements are present. In their absence, carbonation improves durability by increasing hardness and reducing porosity. Although direct measurements of carbonation and surface carbon content were not possible, the presence of calcium compounds indicates that carbonation likely occurred. Given the heterogeneous surface and the estimated distribution of calcium-rich binder mortar (about 50% of the analyzed area, including restored sections), an approximate carbonation score of 50% was assigned.
- Corrosion index
  - Presence of metallic support: No visible metallic elements were found in the analyzed area, and due to the historical period of construction, the presence of internal metal components is unlikely. The score is 0, indicating negligible corrosion risk.
  - Corrosion evaluation: Consistent with the above, no corrosion was observed. The corrosion index is 0, with no measurable impact on degradation.

The data obtained are summarized below (Table 3):

Table 3. Summary of data obtained from experimental analyses

Indicators	Sub-indicators	Measurement	
Surface Deterioration	Surface Composition	Composition (N compounds)	8(>5% by weight)
	Surface Erosion	Percentage of erosion	8.7%
	Degree of Surface Porosity	Percentage of porosity	10.7%
	Surface Crystallinity	Percentage of crystallinity	Not measurable; hypothesized 10% decrease
Efflorescence	Extent of Efflorescence	Percentage of coverage	1.1% of the surface covered
	Salt Deposits	Percentage quantification	Minimal; irrelevant for calculation
	XRF Evaluation	Peak area ratio	XRF peak area ratio: 0.07
Corrosion	Carbonation Test	Percentage of surface area extension	50% of the surface
	Presence of Metallic Elements	Percentage of metallic supports present	0
	Corrosion Evaluation	Percentage of corrosion	0

5 Conclusions

The study, developed within the framework of Pilot Project 4.7.1 T4Y Spoke 4, highlights how climate change poses an increasing challenge to the preservation of tangible cultural heritage, emphasizing the importance of systematic and multidisciplinary approaches for risk assessment and mitigation. The proposed Damage Index, integrating environmental conditions (Fenv), material properties (Fmat), and external drivers (Fext), provides a comprehensive framework for evaluating vulnerabilities and supporting evidence-based conservation strategies. Through quantitative and experimental methodology, this contribution provides practical tools to identify degradation processes and support conservation strategies.

In particular, the application of these tools, tested in heritage contexts characterized by evident formal and structural fragilities, can foster the adoption of climate adaptation strategies calibrated to the criticalities and risk conditions experimentally identified, through a site-specific approach. This makes it possible to outline an integrated and replicable model, capable of supporting decision-makers and the key stakeholders involved in heritage management in defining policies, methodologies, and targeted adaptation actions, with particular attention to historic contexts that are poorly resilient and vulnerable to physical, chemical, and biological degradation processes (e.g., surface erosion, cracking, thermal shocks) induced by climate change.

The case study of Palazzo Mesiani in Bova (RC) demonstrates the methodology's applicability, underscoring the importance of combining on-site analyses, laboratory experimental data, and simulation tools to obtain precise results.

The methodology also shows potential for integration into digital tools and Living Labs for heritage, enabling dynamic and participatory monitoring frameworks. In this perspective, the Damage Index may play a key role in operationalizing climate adaptation at local scale, aligning European and international frameworks such as the IPCC, and promoting knowledge-based, context-specific conservation practices.

Future research will focus on incorporating the remaining factors (Fenv and Fext) trough site-specific climate and socio-imfrastructural data, enabling a full evaluation of the Damage Index and validating its applicability across diverse heritage sites and climatic scenarios.

Ultimately, this work contributes to the ongoing effort of bridging the gap between climate science and conservation practices, offering a scientifically robust, experimentally grounded, and policy-relevant methodology for addressing the increasing vulnerability of built heritage in the face of climate change.

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Author Contributions The study was conducted collaboratively, with both authors contributing to all stages of research and writing. Francesca Giglio led conceptualization, theoretical framing, literature review, (Introduction, Sects. 2 and 3). Francesco Armocida performed experimental analyses, data collection, processing, and application to the case study, including in-situ and laboratory work, simulations, and drafting of methodological and results sections (Sects. 3.1.1, Sect. 4 and Conclusions).

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