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Article

Monitoring Environmental and Structural Parameters in Historical Masonry Buildings Using IoT LoRaWAN-Based Wireless Sensors

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Abstract: This study investigates the impact of environmental conditions on the structural integrity and energy dynamics of historical masonry buildings using an IoT (Internet of Things) LoRaWAN-based (Long Range Wide Area Network) wireless sensor system. Over a six-month period, sensors were used to monitor wall temperature, wall humidity, air temperature, air humidity, crack width, and crack displacement. The data revealed significant correlations between environmental parameters and structural changes. Higher temperatures were associated with increased crack width, while elevated humidity levels correlated with greater crack displacement, showing the potential weakening of the masonry structure. Seasonal variations highlighted the cyclical nature of these changes, emphasizing the need for seasonal maintenance. Additionally, the findings suggest that managing temperature and humidity levels can optimize the building's energy efficiency by reducing the need for additional heating or cooling. The use of LoRaWAN sensors provided real-time, remote monitoring capabilities, offering a cost-effective and scalable solution for preserving historical buildings. This study underscores the importance of continuous environmental and structural monitoring for the preservation of heritage sites. It also highlights the potential for integrating proactive maintenance strategies and energy optimization, ensuring long-term sustainability. By leveraging this IoT-based approach, this research contributes to the broader field of heritage conservation, offering a universal framework that can be applied to historical buildings worldwide, enhancing both their structural integrity and energy performance.

Keywords: environmental monitoring; structural integrity; historical masonry buildings; IoT; LoRaWAN sensors; heritage preservation; real-time data collection; wireless sensor networks; energy efficiency; energy management; sustainable preservation

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1. Introduction

Historical masonry buildings are invaluable cultural heritage assets that embody the architectural creativity and historical narratives of past civilizations. These structures, often centuries old, face various environmental stressors that can compromise their structural integrity. Factors such as temperature fluctuations, humidity variations, and humidity ingress play critical roles in the deterioration processes of masonry materials. Understanding these factors is essential for developing effective preservation strategies that ensure the longevity and stability of these irreplaceable assets.

The preservation of historical buildings is not only a matter of cultural importance but also a matter of scientific and engineering interest. The complex interactions between environmental conditions and building materials need a multidisciplinary approach, combining insights from materials science, structural engineering, and environmental monitoring. Recent advancements in sensor technology have offered new opportunities for the detailed and continuous monitoring of these interactions, offering valuable data that can inform preservation efforts [1–9].

Recent studies have highlighted the significant impact of environmental conditions on the structural health of masonry buildings [10,11]. For instance, research has shown that temperature fluctuations can cause thermal expansion and contraction in masonry materials, leading to the development of cracks and other structural defects [12,13]. Similarly, high humidity levels and humidity ingress have been proven to influence the deterioration of masonry through processes such as freeze–thaw cycles and salt crystallization [10]. These environmental stressors not only compromise structural integrity but can also affect the energy efficiency of buildings [14–17], as cracks and material degradation lead to increased heat transfer and reduced thermal insulation capacity. Moreover, parameters like wind speed, solar radiation, and lightning danger have been shown to further exacerbate the vulnerabilities of heritage structures, particularly when combined with other environmental factors [18–21]. These findings underscore the need for continuous monitoring to detect and mitigate the effects of environmental stressors on historical buildings [22–26].

Despite the advancements in understanding the effects of environmental conditions on masonry structures, there is still a gap in the application of real-time monitoring technologies. Traditional methods of structural assessment often involve periodic inspections and manual data collection, which can be labor-intensive and may not capture the dynamic nature of environmental interactions. The integration of wireless sensor networks [1,27,28], particularly those based on Long Range Wide Area Network (LoRaWAN) technology [29–31], offers a promising solution to this challenge by enabling the continuous, real-time monitoring of environmental and structural parameters. The integration of Internet of Things (IoT) data with Building Information Modeling (BIM) and Heritage Building Information Modeling (HBIM) enables a holistic approach, allowing for better visualization, analysis, and decision-making in the management of historical masonry structures [31–35].

LoRaWAN-Based Monitoring

The subject of this study is a four-story tenement house located in a city center of southern Poland, built at the end of the 19th century. This building, part of a row of tenement houses, is a masonry structure without insulation. Sensors placed in this building monitored various parameters, analyzing displacements and humidity–temperature conditions using a system based on LoRaWAN wireless IoT technology. Some sensors measured a single parameter (e.g., displacement), while others measured multiple parameters simultaneously, such as both temperature and humidity. The building exhibits damages that, if further developed, could potentially compromise its safety. Additionally, there are signs of moisture in the structural elements and cracks that show irregularities in the structural system.

Based on the technical condition inspection, the most concerning damage in the analyzed building is the presence of cracks, which are primarily concentrated in the load-bearing walls. These cracks extend along the side walls and around the window openings and are also visible on the external walls. Given the unsatisfactory condition of both the internal and external walls, a detailed static analysis led to the decision to install a monitoring system in the building. This system focuses on monitoring crack width and the temperature and humidity of the indoor air.

The primary goal of this study is to investigate the impact of environmental conditions on the structural integrity of historical masonry buildings. This research uses a LoRaWAN-based wireless sensor system to collect comprehensive data on key environmental and structural parameters over a six-month period. Specifically, this study monitors wall temperature, wall humidity, air temperature, air humidity, crack width, and crack displacement. By analyzing the correlations between these parameters, the study seeks to elucidate the mechanisms by which environmental factors influence the structural health of masonry buildings.

The significance of this study lies in its potential to enhance the preservation of historical masonry buildings through the application of advanced sensor technology. LoRaWAN-based wireless sensors offer several advantages for environmental and structural monitoring [36,37]. These sensors enable real-time data collection and remote access, allowing for continuous monitoring without the need for frequent on-site visits. This capability is particularly valuable for historical buildings, which often require careful and minimally invasive monitoring techniques. Figure 1 shows a general overview of wireless technologies split by their range of transmission.

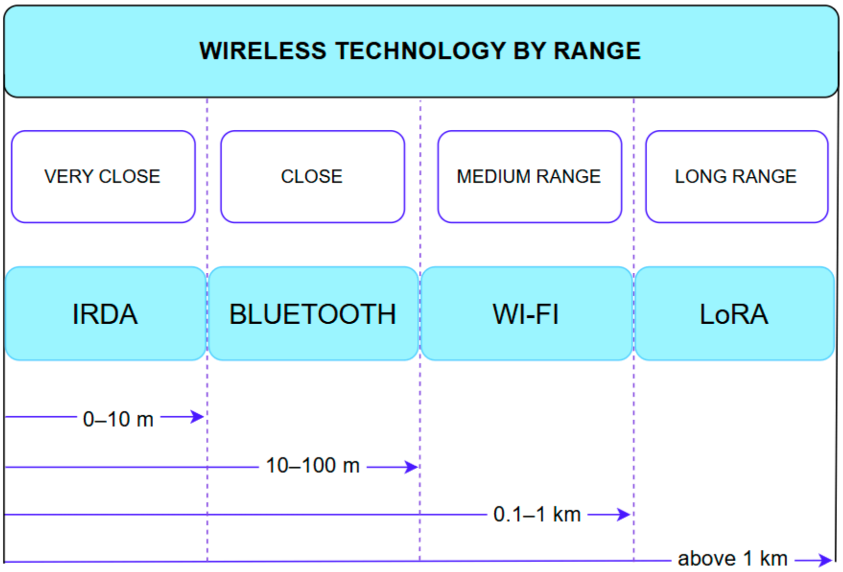

Figure 1. Signal propagation range in data transmission using IoT technology.

Moreover, the use of a wireless sensor network eases the collection of high-resolution data across multiple locations within a building. This spatially distributed data can reveal localized variations in environmental conditions and structural responses, providing a more comprehensive understanding of the building's behavior. The cost-effectiveness and scalability of LoRaWAN sensors make them an attractive possibility for large-scale monitoring projects [38–41], enabling the deployment of extensive sensor networks across multiple heritage sites.

In the field of heritage conservation, there are ongoing debates about the most effective methods for the monitoring and preservation of historical buildings. Some researchers advocate for the use of traditional, manual inspection techniques, arguing that these methods provide a more nuanced understanding of structural conditions [10]. Others support the adoption of advanced sensor technologies, emphasizing the benefits of continuous, real-time data collection and the ability to detect subtle changes that might be overlooked during periodic inspections [1,3,42]. This study contributes to this debate by showing the practical applications and benefits of LoRaWAN-based monitoring systems in the context of historical masonry buildings.

The main aim of this study is to provide a detailed analysis of the impact of environmental conditions on the structural integrity of historical masonry buildings using a LoRaWAN-based wireless sensor system. The principal conclusions of this research will highlight the correlations between environmental parameters and structural changes, offering insights into the mechanisms driving the deterioration of masonry structures. These findings will inform the development of targeted maintenance and preservation strategies, contributing to the sustainable preservation of historical buildings.

The findings of this study will have practical implications for the field of heritage conservation. By showing the effectiveness of LoRaWAN-based monitoring systems, this research will encourage the adoption of similar technologies in other preservation projects. Additionally, the data collected will inform the development of predictive maintenance models, allowing for proactive interventions that mitigate the risk of structural failure. Ultimately, this study aims to contribute to the sustainable preservation of historical masonry buildings, ensuring that these cultural treasures are safeguarded for future generations.

2. Materials and Methods

This section outlines the methodologies employed to investigate the impact of environmental conditions on the structural integrity of historical masonry buildings. This study used a network of LoRaWAN-based wireless sensors to gather comprehensive data on various environmental and structural parameters. The following subsections detail the deployment of sensors, the data collection process, the methods used for data processing and synchronization, and the statistical analyses conducted to derive meaningful insights from the collected data.

Figure 2 presents a block scheme that illustrates the entire process, from sensor deployment to the development of preservation strategies. This visual representation provides a clear and structured overview of the steps involved in this study, highlighting the flow of data and the key stages of analysis.

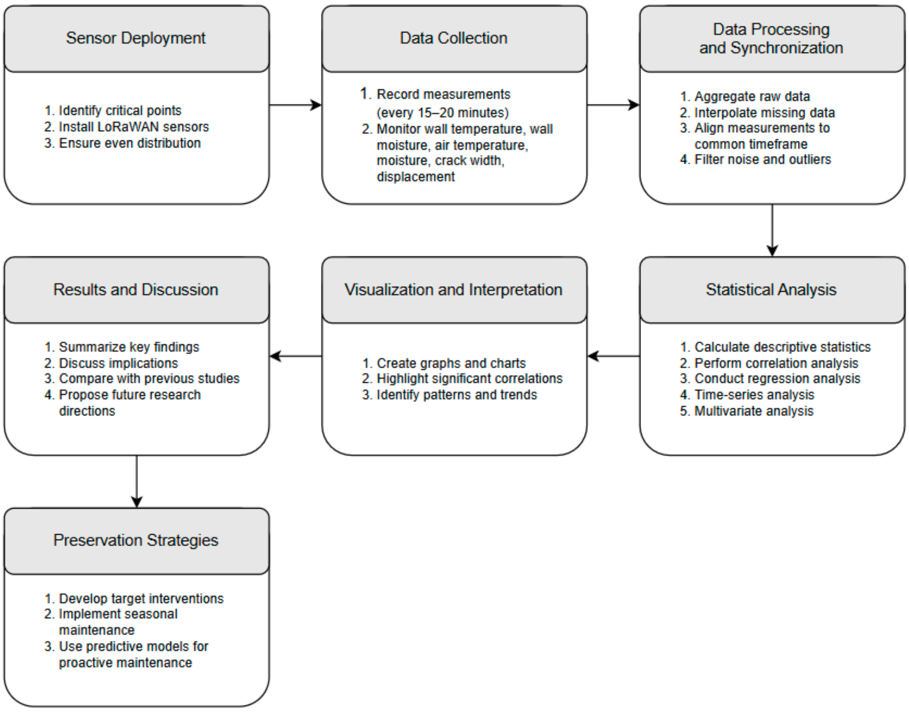

Figure 2. Block scheme illustrating the entire research process.

2.1. Sensor Deployment and Data Collection

To investigate the impact of environmental conditions on the structural integrity of historical masonry buildings, we deployed a network of LoRaWAN-based wireless sensors. These sensors were strategically placed at various heights and locations within the building to ensure comprehensive coverage and even distribution. The placement strategy was developed based on a thorough assessment of the building's structural layout and environmental exposure. Sensors were installed in the areas most susceptible to environmental stressors, such as exterior walls, corners, and regions with visible signs of deterioration. The layout and placement of the sensors are illustrated in Figure 3, and Figure 4 shows one of the installed sensors.

Figure 3. The layout and placement of the used sensors within the building.

Figure 4. One of the LoRaWAN sensors used during the research.

The calibration of the sensors is crucial to ensure accurate data collection. The sensors were calibrated by a dedicated team of technicians before installation and required recalibration at intervals appropriate for each sensor type to maintain their accuracy. The team was responsible for regular maintenance and calibration checks, ensuring that the sensors continued to provide reliable data throughout the study.

The sensors were designed to monitor key environmental and structural parameters, including wall temperature, wall humidity, air temperature, air humidity, crack width, and crack displacement. Wall temperature sensors were placed at different heights to capture vertical temperature gradients, while wall humidity sensors were positioned in areas prone to water ingress. Air temperature and humidity sensors were distributed throughout the building to monitor the internal climate conditions. Crack width and displacement sensors were installed at known structural weaknesses or areas with existing cracks to track changes over time.

The data collection period spanned six months, from 1 April 2024 to 30 September 2024. During this period, the sensors recorded measurements at intervals of 15 to 20 min. This high-frequency data collection allowed for the capture of detailed temporal variations in the monitored parameters. The frequent sampling intervals were chosen to ensure that transient environmental changes and their immediate effects on the building's structure were accurately recorded.

The sensors transmitted data wirelessly to a central database using the LoRaWAN communication protocol. This protocol was selected for its ability to provide long-range, low-power communication, which is particularly advantageous in the context of historical buildings where wiring can be intrusive and impractical. The use of LoRaWAN technology ensured reliable data transmission even in the challenging environment of a historical building, characterized by thick walls and complex architectural features.

To ensure data integrity and minimize the risk of data loss, the sensor network was equipped with redundancy features, including backup power supplies and multiple data transmission pathways. Additionally, a synchronization system was implemented to ensure that data from all sensors were accurately time-stamped and aligned. This system periodically synchronized the internal clocks of the sensors with a central time server, ensuring that all data collected were consistent and could be accurately correlated.

The central database was regularly backed up, and data integrity checks were performed to detect and correct any anomalies. This comprehensive approach ensured that the data collected were reliable and could be used effectively for analysis and decision-making.

In addition to the primary environmental and structural parameters, the sensor network also monitored auxiliary parameters such as ambient light levels and vibration. These additional data points provided context for interpreting the primary measurements and helped identify potential sources of environmental stress, such as nearby construction activities or changes in building usage.

The comprehensive dataset generated by this sensor network provided a rich source of information for analyzing the interactions between environmental conditions and structural integrity. The high-resolution temporal data enabled the identification of short-term fluctuations and long-term trends, offering valuable insights into the dynamic behavior of the building under varying environmental conditions.

Overall, the deployment of the LoRaWAN-based wireless sensor network and the subsequent data collection process were critical components of this study, providing the foundation for the detailed analysis and interpretation of the environmental and structural interactions in historical masonry buildings.

2.2. Data Processing and Synchronization

Given the varying intervals at which the sensors recorded data, it was necessary to synchronize the datasets to create a common timeframe. This synchronization process was crucial for ensuring that the data from different sensors could be accurately compared and analyzed. The first step in this process involved aggregating the raw data from all sensors into a central database. Each sensor's data were time-stamped, allowing for the precise tracking of when each measurement was taken.

To align the measurements from different sensors, we employed interpolation techniques. Linear interpolation was primarily used to estimate the values of missing data points, providing a continuous dataset. This method involves calculating intermediate values based on the linear progression between known data points, ensuring a smooth transition and minimizing the introduction of errors. In cases where data gaps were larger or more complex patterns were observed, more advanced interpolation methods, such as spline interpolation, were applied to maintain data integrity.

The synchronized dataset enabled the establishment of relationships between the various environmental and structural parameters over time. To achieve this, we first standardized the time intervals across all datasets. This involved resampling the data to a common time grid, typically set to the most frequent sampling interval (15 min). By doing so, we ensured that each time point in the dataset had corresponding measurements from all sensors, facilitating direct comparisons and correlation analyses.

Data preprocessing also included filtering out noise and outliers. Noise in the data, often caused by transient environmental factors or sensor malfunctions, was identified and removed using statistical techniques such as moving averages and median filters. Outliers, which could skew the analysis, were detected using methods like the interquartile range (IQR) and Z-score analysis. These steps were essential for enhancing the accuracy and reliability of the subsequent analyses.

Once the data were cleaned and synchronized, they were organized into a structured format suitable for analysis. This involved creating a multi-dimensional dataset where each dimension represented a different parameter (e.g., wall temperature, air humidity) and each entry corresponded to a specific time point. This structured dataset allowed for efficient querying and manipulation, enabling complex analyses to be performed with ease.

To facilitate the visualization and exploration of the data, we developed a series of interactive dashboards using data visualization tools such as Power BI and various Python libraries. These dashboards provided dynamic views of the data, allowing the exploration of temporal trends, the identification of patterns, and the detection of anomalies. Key visualizations included time-series plots, heatmaps, and scatter plots, which highlighted the relationships between different parameters and their variations over time.

In addition to visual exploration, the synchronized dataset was subjected to statistical analysis to identify correlations and trends. Descriptive statistics were calculated to summarize the central tendencies and variability of the data. Measures such as the mean, median, standard deviation, and range provided an overview of the data distribution, while correlation coefficients quantified the strength and direction of relationships between environmental conditions and structural responses.

Data processing was completed using self-written Python scripts, which ensured a high degree of customization and flexibility in managing the dataset. These scripts automated the synchronization, cleaning, and analysis processes, making it possible to efficiently manage large volumes of data and derive meaningful insights. Examples of data visualizations created using the script are presented in Figures 5 and 6.

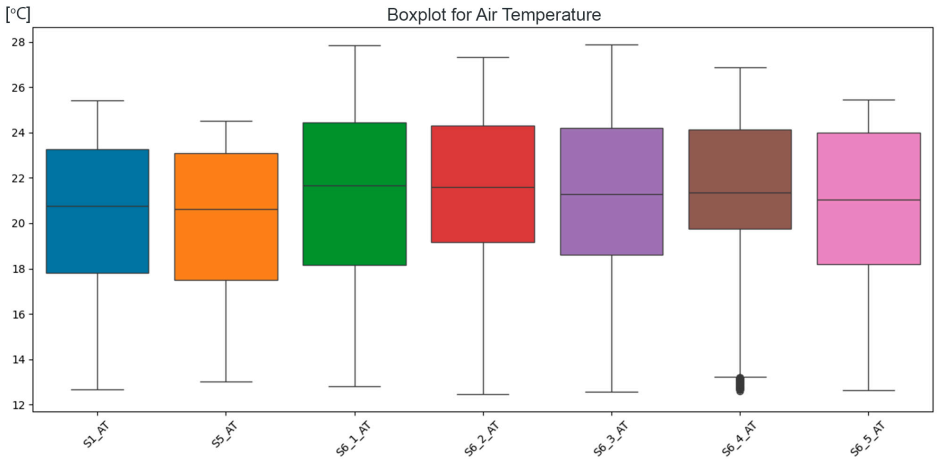

Figure 5. Boxplot chart for all air temperature measurements.

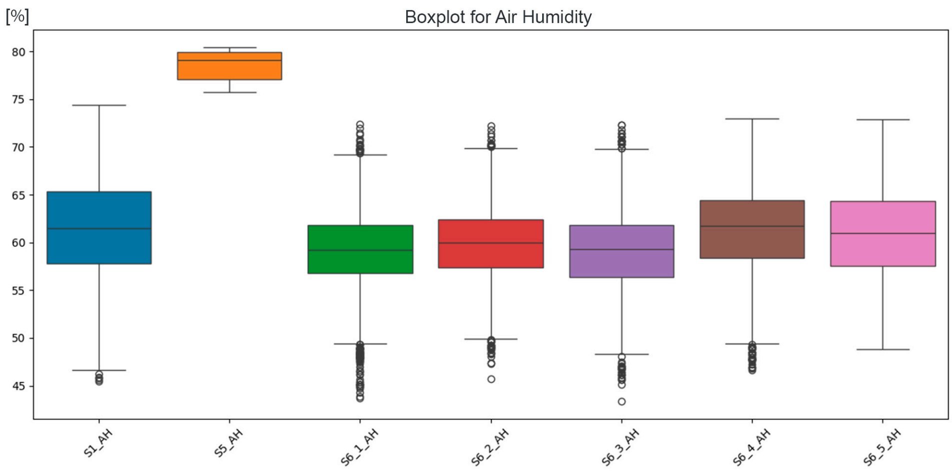

Figure 6. Boxplot chart for all air humidity measurements.

Overall, the data processing and synchronization steps were critical for transforming the raw sensor data into a coherent and analyzable dataset. By ensuring that the data from different sensors were accurately aligned and cleaned, we were able to derive meaningful insights into the impact of environmental conditions on the structural integrity of historical masonry buildings. This comprehensive approach to data management laid the foundation for the detailed statistical analyses and interpretations presented in the subsequent sections of this study.

2.3. Statistical Analysis

The synchronized data were subjected to a comprehensive statistical analysis to identify correlations, trends, and patterns that could provide insights into the impact of environmental conditions on the structural integrity of historical masonry buildings. The analysis was conducted in several stages, each employing different statistical techniques to extract meaningful information from the dataset. Dedicated Python scripts were created to automate and streamline these processes, ensuring accuracy and efficiency.

Descriptive statistics were calculated to summarize the central tendencies and variability of the data. Measures such as the mean, median, mode, standard deviation, variance, range, and interquartile range (IQR) were used to provide a detailed overview of the data distribution for each monitored parameter. These statistics helped in understanding the general behavior of the environmental and structural variables over the monitoring period. For instance, the mean and median values provided insights into the typical conditions experienced by the building, while the standard deviation and variance highlighted the extent of fluctuations around these central values.

Correlation analysis was performed to examine the relationships between environmental conditions (temperature and humidity) and structural responses (crack width and displacement). Pearson correlation coefficients were calculated to quantify the strength and direction of linear relationships between pairs of variables. A positive correlation indicated that as one variable increased, the other tended to increase as well, while a negative correlation suggested an inverse relationship. The significance of these correlations was assessed using p-values, with a threshold of 0.05 used to determine statistical significance. In addition to Pearson correlation, Spearman's rank correlation was also employed to assess the relationships between variables. This non-parametric method is particularly useful for identifying monotonic relationships that may not be strictly linear. By comparing the results of the Pearson and Spearman correlations, we could gain a more nuanced understanding of the interactions between environmental and structural parameters.

To further explore the dependencies between environmental conditions and structural responses, regression analysis was conducted. Linear regression models were developed to predict structural parameters (crack width and displacement) based on environmental variables (temperature and humidity). The coefficients of the regression models provided insights into the magnitude and direction of the effects of environmental conditions on structural integrity. Multiple regression analysis was also performed to account for the combined influence of multiple environmental factors on structural responses.

Time-series analysis was conducted to investigate the temporal patterns and seasonal variations in the data. Techniques such as moving averages, autoregressive integrated moving average (ARIMA) models, and Fourier transforms were used to identify periodic trends and anomalies. Moving averages helped smooth out short-term fluctuations and highlight longer-term trends, while ARIMA models were employed to forecast future values based on past observations. Fourier analysis was used to decompose the time-series data into their constituent frequencies, revealing underlying periodicities that could be linked to seasonal changes. The seasonal decomposition of time series (STL decomposition) was also applied to separate the data into trend, seasonal, and residual components. This decomposition allowed for a clearer understanding of the seasonal effects on the monitored parameters and helped identify any irregular patterns that might indicate structural issues.

Multivariate analysis techniques, such as principal component analysis (PCA) and cluster analysis, were used to explore the relationships between multiple variables simultaneously. PCA was employed to reduce the dimensionality of the dataset, identifying key components that explained most of the variance in the data. This technique helped in visualizing the complex interactions between environmental and structural parameters and in identifying the most influential factors. Cluster analysis was used to group similar observations based on their characteristics. By clustering the data, we could identify distinct patterns and behaviors within the dataset, such as periods of high humidity and temperature that corresponded to significant structural changes. These clusters provided valuable insights into the conditions that posed the greatest risk to the building's integrity.

The results of the statistical analyses were visualized using various graphical techniques, including scatter plots, heatmaps, time-series plots, and correlation matrices. These visualizations facilitated the interpretation of the data and helped communicate the findings effectively. Key insights were highlighted, such as the identification of critical environmental thresholds beyond which significant structural changes occurred. The comprehensive statistical analysis provided a robust framework for understanding the complex interactions between environmental conditions and structural integrity in historical masonry buildings. The findings from this analysis will inform the development of targeted maintenance and preservation strategies, contributing to the sustainable preservation of these cultural heritage assets.

3. Results

The analysis of the data collected from the LoRaWAN-based wireless sensors revealed several significant correlations between environmental conditions and structural parameters in the historical masonry building. These correlations provide insights into how variations in temperature and humidity levels impact the structural integrity of the building.

3.1. *Environmental and Structural Correlations*

The following sections detail the significant correlations identified between environmental conditions and structural parameters. The full correlation heatmap presenting an overview of all correlations is shown in Figure 7. These correlations highlight the complex interactions between temperature, humidity, and structural integrity, providing a deeper understanding of the factors influencing the preservation of historical masonry buildings.

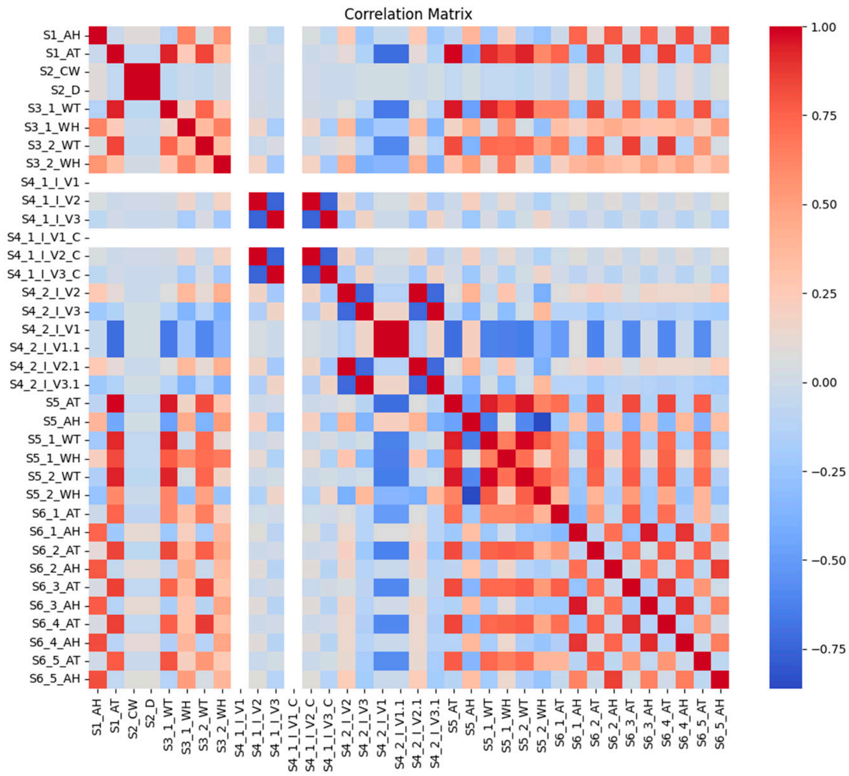

Figure 7. Correlation matrix of all sensor variables.

3.1.1. Air and Wall Humidity Correlations

A strong negative correlation was observed between air humidity (S5_AH) and wall temperature (S5_2_WT) with a correlation coefficient of −0.60. This suggests that higher air humidity levels are associated with lower wall temperatures. This relationship indicates that as the air becomes more humid, the walls tend to cool down, possibly due to the evaporative cooling effect of humidity on wall surfaces.

Similarly, air humidity (S5_AH) showed a significant negative correlation with wall humidity (S5_2_WH) at −0.89, indicating that increased air humidity is linked to decreased wall humidity levels. This inverse relationship could be attributed to the hygroscopic nature of masonry materials, where walls absorb humidity from the air until a saturation point is reached, after which the humidity content in the walls stabilizes or decreases.

Further analysis revealed that air humidity (S1_AH) also had a positive correlation with wall humidity (S3_1_WH) at 0.68. This suggests that in some areas, higher air humidity levels contribute to increased wall humidity, highlighting the variability in humidity absorption and retention across different parts of the building.

The correlation between air humidity (S1_AH) and wall humidity (S6_2_WH) was found to be 0.87, reinforcing the observation that air humidity significantly influences wall humidity levels. This strong positive correlation indicates that monitoring air humidity can provide valuable insights into the humidity dynamics within walls, which is crucial for preventing humidity-related deterioration.

Additionally, the correlation between air humidity (S6_2_AH) and wall humidity (S6_5_WH) was 0.97, suggesting a nearly direct relationship between these parameters. This high correlation underscores the importance of maintaining optimal air humidity levels to protect the structural integrity of walls.

Overall, these findings highlight the critical role of air humidity in influencing wall temperature and humidity levels. The strong correlations observed suggest that effective humidity management strategies, such as controlling indoor humidity and improving ventilation, are essential for preserving the structural integrity of historical masonry buildings. Through the continuous monitoring of air and wall humidity levels, it is possible to implement timely interventions to mitigate the adverse effects of humidity on the building's structure.

3.1.2. Temperature and Humidity Interactions

The interactions between temperature and humidity levels within the historical masonry building revealed several significant correlations, highlighting the complex dynamics between these environmental factors and their impact on the building's structural integrity.

Wall temperature (S5_2_WT) and wall humidity (S5_2_WH) exhibited a positive correlation of 0.76, suggesting that higher wall temperatures are associated with higher wall humidity levels. This relationship indicates that as the temperature of the walls increases, the humidity content within the walls also tends to rise. One possible explanation for this phenomenon is that higher temperatures can enhance the evaporation of humidity from the surrounding environment, which is then absorbed by the porous masonry materials. Additionally, the increased temperature may cause the walls to expand, creating microcracks that allow more humidity to penetrate and be retained within the structure.

Air temperature (S1_AT) and wall humidity (S5_2_WH) also showed a positive correlation of 0.61, indicating that higher air temperatures correspond to increased wall humidity. This correlation suggests that the ambient air temperature plays a significant role in influencing the humidity dynamics within the walls. Warmer air can hold more humidity, leading to higher humidity levels, which in turn can result in greater humidity absorption by the walls. This relationship underscores the importance of monitoring both air and wall temperatures to understand their combined effects on the building's humidity content.

Further analysis revealed that air temperature (S1_AT) and wall temperature (S3_1_WT) had a strong positive correlation of 0.99. This near-perfect correlation indicates that changes in air temperature are closely mirrored by changes in wall temperature. Such a strong relationship suggests that the thermal properties of the building materials allow for efficient heat transfer between the air and the walls, leading to synchronized temperature variations.

The correlation between wall temperature (S3_1_WT) and wall humidity (S5_1_WH) was found to be 0.81, reinforcing the observation that higher wall temperatures are associated with increased humidity levels. This relationship highlights the potential for thermal effects to influence humidity retention within the walls, which can have significant implications for the building's structural health. For instance, higher humidity levels can lead to the growth of mold and mildew, as well as the deterioration of masonry materials, through processes such as freeze–thaw cycles and salt crystallization.

Moreover, the correlation between air temperature (S5_AT) and wall humidity (S5_1_WH) was 0.83, indicating that warmer air temperatures contribute to higher humidity levels within the walls. This finding suggests that managing indoor air temperature and humidity is crucial for controlling the humidity content in the walls and preventing humidity-related damage.

The positive correlation between wall temperature (S5_2_WT) and air temperature (S6_2_AT) at 0.89 further emphasizes the interconnectedness of these environmental factors. As air temperature rises, it directly influences the temperature of the walls, which in turn affects the humidity dynamics within the building. This relationship underscores the need for a holistic approach to environmental monitoring, where both temperature and humidity levels are continuously tracked to ensure the preservation of the building's structural integrity.

Overall, the significant correlations between temperature and humidity levels highlight the importance of maintaining optimal environmental conditions within historical masonry buildings. Through an understanding of the interactions between these factors, it is possible to develop targeted strategies for humidity management and thermal regulation, thereby enhancing preservation efforts for these cultural heritage assets. Continuous monitoring using advanced sensor technologies, such as the LoRaWAN-based wireless sensors employed in this study, provides valuable data that can inform proactive maintenance and intervention measures to protect the structural integrity of historical buildings.

3.1.3. Crack Width and Displacement

The analysis of the relationship between crack width (S2_CW) and displacement (S2_D) revealed a perfect correlation (1.00) between these two parameters. This perfect correlation confirms that changes in crack width are directly proportional to displacement, indicating a strong and consistent relationship between these structural indicators.

This finding is significant as it underscores the reliability of using crack width measurements as a proxy for displacement in structural health monitoring. In historical masonry buildings, cracks are common indicators of structural stress and potential failure. The direct proportionality between crack width and displacement suggests that as the building experiences structural shifts, the cracks widen in a predictable manner. This predictability is crucial for developing effective monitoring and maintenance strategies.

The perfect correlation also highlights the sensitivity of the sensors used in this study. The LoRaWAN-based wireless sensors were able to capture minute changes in crack width and displacement with high precision, providing accurate and reliable data. This level of sensitivity is essential for the early detection of structural issues, allowing for timely interventions to prevent further damage.

Further analysis of the data showed that the relationship between crack width and displacement remained consistent across different environmental conditions. This consistency suggests that the structural behavior of the building, as indicated by crack width and displacement, is primarily driven by internal stresses rather than external environmental factors. However, it is important to note that environmental conditions such as temperature and humidity can still influence the overall structural integrity of the building, as discussed in previous sections.

The strong relationship between crack width and displacement also provides valuable insights into the mechanics of crack propagation in masonry structures. As the building undergoes stress, the cracks not only widen but also exhibit displacement, indicating movement within the masonry materials. This movement can be attributed to factors such as thermal expansion, humidity ingress, and mechanical loading. Understanding these mechanics is crucial for developing targeted repair and reinforcement strategies to address the underlying causes of structural stress.

In practical terms, the perfect correlation between crack width and displacement means that the monitoring of crack width alone can provide a comprehensive understanding of the building's structural health. This simplifies the monitoring process, as it reduces the need for multiple types of sensors and allows for more focused data collection. Through the continuous tracking of crack width, it is possible to detect early signs of structural distress and implement corrective measures before the damage becomes severe.

The findings from this study also have implications for the preservation of other historical masonry buildings. The methodology and sensor technology used in this research can be applied to similar structures to monitor crack width and displacement, providing valuable data for preservation efforts. The ability to accurately measure and analyze these parameters is essential for maintaining the structural integrity and longevity of historical buildings.

Overall, the perfect correlation between crack width and displacement highlights the importance of continuous structural monitoring in historical masonry buildings. Through the leveraging of advanced sensor technologies and data analysis techniques, it is possible to gain a deeper understanding of a building's structural behavior and implement effective preservation strategies. This approach ensures that these cultural heritage assets are protected for future generations, preserving their historical and architectural significance.

3.1.4. Inclination and Structural Shifts

The analysis of inclination measurements and their relationship with structural parameters revealed significant negative correlations, indicating that changes in inclination are inversely related to structural shifts. This finding is crucial for understanding the dynamics of structural movements within the historical masonry building.

One of the notable correlations observed was between inclination V3 (S4_2_I_V3) and V2 (S4_2_I_V2), which had a correlation coefficient of −0.73. This strong negative correlation suggests that as the inclination in one direction increases, the inclination in the other direction decreases. This inverse relationship highlights the complex interplay between different parts of the structure as it responds to various stressors.

Inclination measurements are critical indicators of structural stability, as they reflect the tilting or leaning of building components. In historical masonry buildings, such movements can be caused by a variety of factors, including foundation settlement, thermal expansion and contraction, and humidity-induced swelling and shrinkage. The significant negative correlations observed in this study suggest that these factors are actively influencing the building's structural behavior.

Further analysis revealed additional significant correlations between inclination measurements and other structural parameters. For instance, inclination V1 (S4_2_I_V1) and air temperature (S6_2_AT) had a correlation of −0.68, indicating that changes in inclination are also influenced by temperature variations. This relationship suggests that as temperature fluctuates, it induces thermal stresses within the building materials, leading to changes in inclination. Such thermal effects are particularly pronounced in masonry structures, where differential expansion and contraction can cause significant structural movements.

The correlation between inclination V1 (S4_2_I_V1) and wall temperature (S5_2_WT) was found to be −0.66, further emphasizing the impact of temperature on structural shifts. This finding indicates that higher wall temperatures are associated with a decrease in inclination, suggesting that the thermal expansion of the walls may counteract some of the tilting movements. Understanding these thermal effects is essential for developing strategies to mitigate their impact on the building's structural integrity.

Inclination measurements also showed significant correlations with humidity levels. For example, inclination V1 (S4_2_I_V1) and wall humidity (S5_1_WH) had a correlation of −0.65. This relationship indicates that as the humidity content in the walls increases, the inclination decreases. The humidity-induced swelling and shrinkage of masonry materials can lead to differential movements within the structure, causing changes in inclination. These findings highlight the importance of managing humidity levels to maintain structural stability.

The correlation between inclination V2 (S4_2_I_V2) and structural displacement (S4_2_I_V3) was −0.73, suggesting that changes in inclination are closely linked to displacement within the building. This relationship indicates that as the building tilts or leans, it also experiences horizontal movements, which can exacerbate structural stress and lead to further damage. Monitoring both inclination and displacement is therefore crucial for a comprehensive assessment of the building's structural health.

Overall, the significant negative correlations between inclination measurements and structural parameters underscore the importance of continuous monitoring to detect and address structural shifts. Through an understanding of the factors that influence inclination, such as temperature and humidity, it is possible to develop targeted interventions to stabilize the building and prevent further deterioration. The use of advanced sensor technologies, such as the LoRaWAN-based wireless sensors employed in this study, provides valuable data that can inform these preservation efforts.

These findings contribute to a deeper understanding of the structural dynamics within historical masonry buildings, highlighting the need for integrated monitoring approaches that consider multiple environmental and structural factors. Through the leveraging of the insights gained from inclination measurements, it is possible to enhance the preservation and maintenance of these cultural heritage assets, ensuring their longevity and stability for future generations.

3.1.5. Temperature Correlations Across Different Points

Strong positive correlations were found between temperatures measured at different points within the building, indicating a high degree of consistency in temperature variations across various locations. This consistency is crucial for understanding the thermal behavior of the building and its response to environmental changes.

One of the most notable correlations observed was between wall temperature (S3_1_WT) and air temperature (S5_AT), which had a perfect correlation of 1.00. This perfect correlation suggests that changes in air temperature are directly mirrored by changes in wall temperature. Such a strong relationship indicates efficient heat transfer between the air and the walls, likely due to the thermal properties of the masonry materials. This finding underscores the importance of monitoring both air and wall temperatures to gain a comprehensive understanding of the building's thermal dynamics.

Further analysis revealed additional strong correlations between temperatures measured at different points. For example, wall temperature (S3_1_WT) and air temperature (S6_4_AT) also exhibited a high correlation of 0.98. This strong correlation suggests that temperature variations are consistent not only within the same room but also across different areas of the building. Such uniformity in temperature distribution indicates that the building's thermal environment is well regulated, which is essential for maintaining structural stability and preventing thermal stress.

The correlation between wall temperature (S5_2_WT) and air temperature (S6_2_AT) was found to be 0.89, further emphasizing the interconnectedness of these environmental factors. This relationship suggests that as the air temperature rises, it directly influences the temperature of the walls, leading to synchronized thermal responses. Understanding these interactions is crucial for developing strategies to manage the building's thermal environment, such as optimizing ventilation and insulation to maintain stable temperatures.

Moreover, the correlation between wall temperature (S3_1_WT) and wall temperature at another point (S5_2_WT) was 0.96, indicating that temperature variations within the walls are highly consistent. This finding suggests that the walls of the building respond uniformly to external temperature changes, which is important for assessing the overall thermal performance of the structure. Consistent wall temperatures help prevent localized thermal stresses that could lead to cracking and other forms of structural damage.

The strong correlations observed between temperatures at different points also highlight the effectiveness of the LoRaWAN-based wireless sensors used in this study. The sensors were able to capture detailed and accurate temperature data across various locations, providing a comprehensive view of the building's thermal environment. This level of detail is essential for identifying potential thermal anomalies and implementing targeted interventions to address them.

In addition to the correlations between air and wall temperatures, this study also found significant correlations between temperatures measured at different heights within the building. For instance, air temperature (S5_AT) and air temperature at a higher point (S6_3_AT) had a correlation of 0.98. This strong correlation suggests that temperature variations are consistent vertically, indicating effective thermal stratification within the building. Such stratification is important for maintaining a comfortable indoor environment and preventing thermal gradients that could lead to structural stress.

Overall, the strong positive correlations between temperatures measured at different points within the building highlight the importance of continuous thermal monitoring. Through an understanding of the thermal behavior of the building and its response to environmental changes, it is possible to develop strategies to optimize the thermal environment and enhance the preservation of the structure. The use of advanced sensor technologies, such as the LoRaWAN-based wireless sensors employed in this study, provides valuable data that can inform these efforts, ensuring the longevity and stability of historical masonry buildings.

3.1.6. Humidity Correlations Across Different Points

The analysis of humidity levels within the building revealed strong positive correlations between air humidity measurements taken at different points, indicating a high degree of uniformity in humidity distribution. This consistency is crucial for understanding the humidity dynamics within the building and its impact on the structural integrity of the masonry.

One of the most notable correlations observed was between air humidity at S6_2 (S6_2_AH) and S6_5 (S6_5_AH), which had a correlation coefficient of 0.97. This strong correlation suggests that humidity levels in the air are consistently distributed across these points, reflecting a uniform indoor climate. Such uniformity is essential for maintaining the structural health of the building, as it prevents localized areas of high humidity that could lead to differential swelling, shrinkage, and other humidity-related damage.

Further analysis revealed additional strong correlations between air humidity levels at various points within the building. For instance, air humidity at S1 (S1_AH) and S6_1 (S6_1_AH) exhibited a correlation of 0.87. This significant correlation indicates that humidity levels are consistent not only horizontally but also vertically, suggesting effective air circulation and humidity control within the building. Maintaining such consistency in air humidity is crucial for preventing the accumulation of humidity in specific areas, which can lead to mold growth, material degradation, and other structural issues.

The correlation between air humidity at S6_2 (S6_2_AH) and S6_4 (S6_4_AH) was found to be 0.98, further emphasizing the uniform distribution of humidity within the building. This high correlation suggests that the building's ventilation system is effectively managing humidity levels, ensuring that humidity is evenly distributed and preventing the formation of damp spots. Such effective humidity management is vital for preserving the integrity of the masonry and preventing humidity-related deterioration.

Moreover, the correlation between air humidity at S1 (S1_AH) and wall humidity at S_1 (S3_1_WH) was 0.68, indicating that higher air humidity levels are associated with increased wall humidity. This relationship highlights the importance of monitoring both air and wall humidity levels to understand their combined effects on the building's structural health. Through the maintenance of optimal air humidity levels, it is possible to control the humidity content within the walls, thereby preventing humidity-induced damage such as efflorescence, spalling, and freeze–thaw cycles.

This study also found significant correlations between air humidity levels and wall humidity at different points. For example, air humidity at S6_2 (S6_2_AH) and wall humidity at S6_5 (S6_5_WH) had a correlation of 0.97, suggesting a direct relationship between these parameters. This strong correlation indicates that changes in air humidity levels are closely mirrored by changes in wall humidity, underscoring the need for integrated humidity monitoring to protect the building's structural integrity.

Additionally, the correlation between air humidity at S1 (S1_AH) and wall humidity at S6_2 (S6_2_WH) was 0.87, reinforcing the observation that air humidity significantly influences wall humidity levels. This relationship suggests that effective humidity control within the building can help maintain stable humidity levels in the walls, preventing humidity-related damage and enhancing the building's durability.

Overall, the strong positive correlations between humidity levels at different points within the building highlight the importance of continuous humidity monitoring. Through an understanding of the humidity dynamics and their impact on the building's structural health, it is possible to develop targeted strategies for humidity management and preservation. The use of advanced sensor technologies, such as the LoRaWAN-based wireless sensors employed in this study, provides valuable data that can inform these efforts, ensuring the longevity and stability of historical masonry buildings.

3.2. Regression Analysis Results

The regression analysis revealed several significant relationships between environmental and structural parameters, providing insights into the factors influencing the building's structural integrity. These relationships are crucial for understanding how different factors interact and affect the preservation of historical masonry buildings.

One of the key findings was the strong positive correlation between air humidity at different points. For instance, the relationship between air humidity at S6_4 and S1 showed a coefficient of 1.0692, an intercept of −2.9203, and an R^2 score of 0.6695. This indicates that changes in air humidity at S6_4 are significantly predictive of changes in air humidity at S1. Similarly, the correlation between air humidity at S6_5 and S1 had a coefficient of 1.1013, an intercept of −5.7156, and an R^2 score of 0.6659, further highlighting the strong predictive relationship between these points. Figures 1 and 2 illustrate these relationships, showing how increases in air humidity at S6_4 and S6_5 led to corresponding increases at S1.

The analysis also revealed very strong correlations between wall temperature and air temperature. For example, the relationship between wall temperature at S3_1 and air temperature at S1 had a coefficient of 0.9997, an intercept of 0.4661, and an R^2 score of 0.8818.

This near-perfect correlation indicates that wall temperature at S3_1 is almost directly proportional to air temperature at S1, with very little unexplained variance. Another significant finding was the correlation between wall temperature at S5_1 and air temperature at S1, which had a coefficient of 1.3013, an intercept of −3.1695, and an R^2 score of 0.8465. These strong positive relationships suggest that changes in wall temperature at these points are highly predictive of changes in air temperature at S1, as shown in Figures 3 and 4.

The analysis of displacement and crack width revealed perfect correlations, indicating direct proportionality between these parameters. The relationship between displacement at S2 and crack width at S2 had a coefficient of 1.0000, an intercept of −35.8900, and an R^2 score of 1.0000, suggesting that displacement at S2 is directly proportional to crack width at S2, with no unexplained variance.. Figures 5 and 6 illustrate these perfect correlations, showing the direct relationship between displacement and crack width at S2.

The regression analysis also identified significant correlations between air temperature and inclination. For instance, the relationship between inclination at S4_2_I_V1 and air temperature at S1 had a coefficient of −5.5009, an intercept of 499.9971, and an R^2 score of 0.5097. This negative correlation suggests that as the inclination at S4_2_I_V1 increases, the air temperature at S1 decreases. Similarly, the correlation between inclination at S4_2_I_V1 and air temperature at S5 had a coefficient of −5.2442, an intercept of 477.4165, and an R^2 score of 0.4938, indicating a significant inverse relationship. The linear regression of this pair is presented in Figure 8. Similarly, other examples of linear regressions are presented in Figures 9 and 10.

Overall, the regression analysis results indicate strong correlations between various environmental and structural parameters. The high R^2 scores for many pairs suggest that the predictor variables are effective in explaining the variance in the response variables. These findings highlight the importance of the continuous monitoring and analysis of environmental conditions to understand their impact on the structural integrity of historical masonry buildings. The use of advanced sensor technologies and data analysis techniques provides valuable insights that can inform targeted preservation strategies. By focusing on the interactions between different parameters, we can develop more effective interventions to maintain the building's structural health.

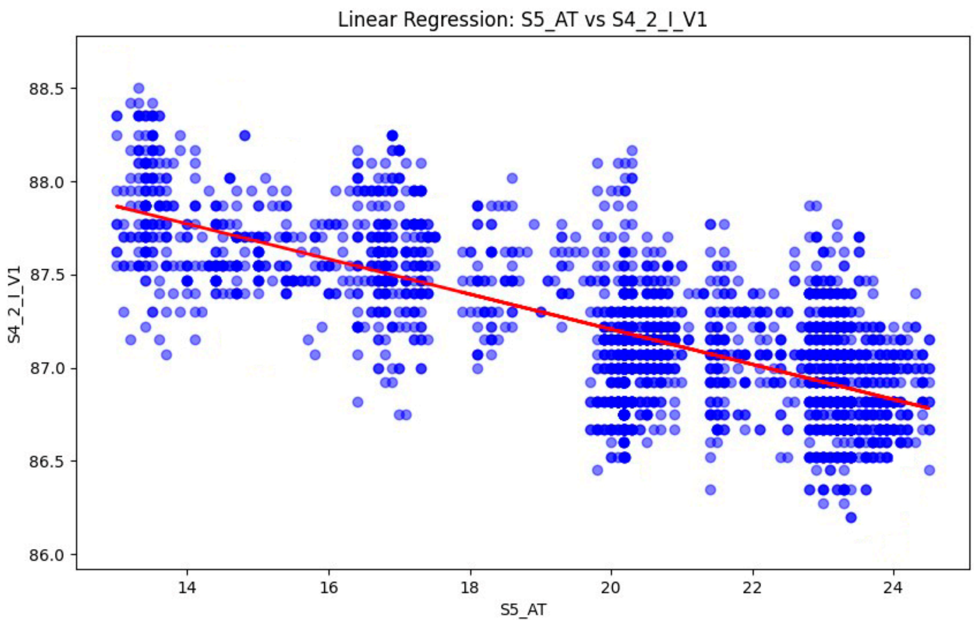

Figure 8. Linear regression between air temperature (sensor 5) and inclination (sensor 4).

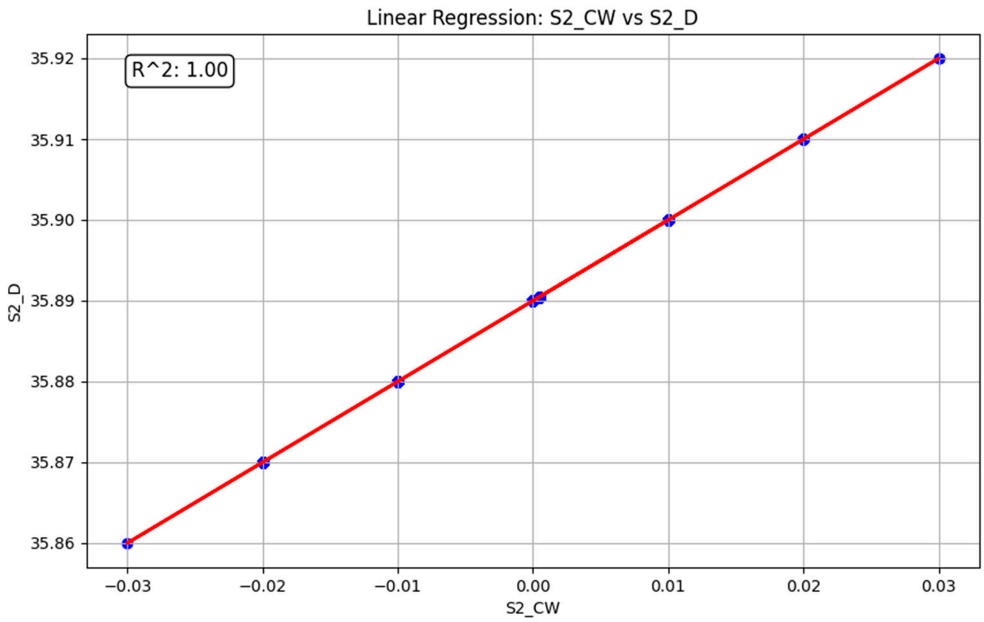

Figure 9. Linear regression between crack width (sensor 2) and displacement (sensor 2).

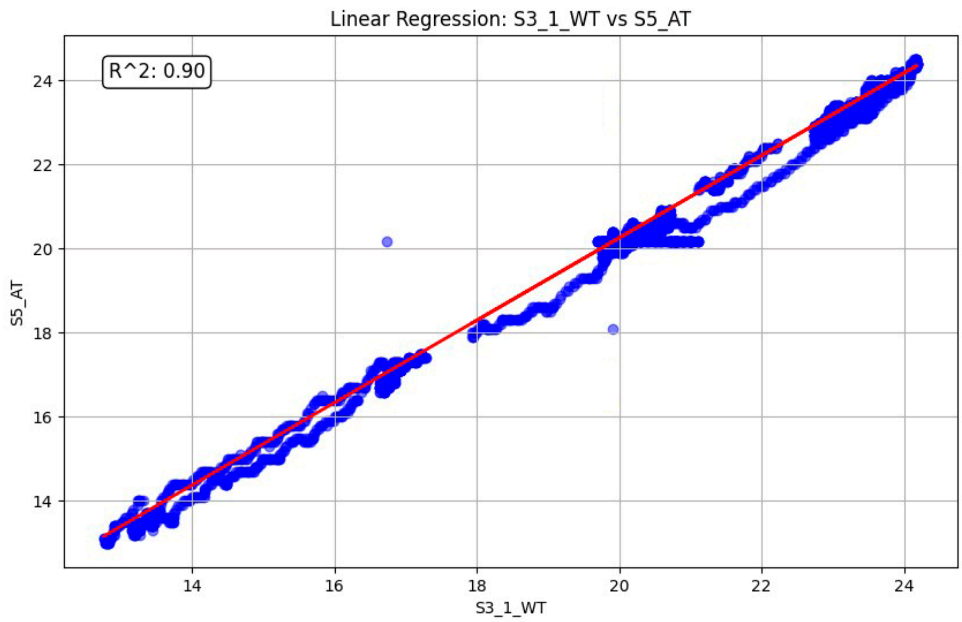

Figure 10. Linear regression between wall temperature (sensor 3) and air temperature (sensor 5).

3.3. Time-Series Analysis and Seasonal Patterns

The time-series analysis provided valuable insights into the trends, seasonal patterns, and residual variations in various environmental and structural parameters. By decomposing the time-series data, we identified the underlying trends and seasonal effects that influence the building's structural integrity.

3.3.1. Overall Time-Series Analysis

For air humidity (S1_AH), the trend mean was 61.4181, indicating a relatively stable humidity level over time. The seasonal mean was 0.0001, and the residual mean was 0.0009, suggesting minimal seasonal fluctuations and residual variations. Similarly, air temperature (S1_AT) had a trend mean of 20.4144, with negligible seasonal and residual variations, indicating stable temperature conditions.

The analysis of crack width (S2_CW) and displacement (S2_D) revealed trend means of 0.0004 and 35.8904, respectively, with no significant seasonal or residual variations. This stability suggests that the structural movements at these points are consistent over time, without notable seasonal influences.

Wall temperature (S3_1_WT) and wall humidity (S3_1_WH) showed trend means of 19.9508 and 3.0841, respectively. The minimal seasonal and residual variations indicate stable conditions for these parameters. Similarly, wall temperature (S3_2_WT) and wall humidity (S3_2_WH) had trend means of 20.2508 and 2.7052, respectively, with negligible seasonal and residual effects.

Inclination measurements (S4_1_I_V1, S4_1_I_V2, and S4_1_I_V3) exhibited stable trends with means of 90.0000, 0.1015, and 179.9566, respectively. Seasonal and residual variations were minimal, indicating consistent inclination levels over time. The corrected inclination measurements (S4_1_I_V1_C, S4_1_I_V2_C, and S4_1_I_V3_C) also showed stable trends with negligible seasonal and residual effects.

For air temperature (S5_AT) and air humidity (S5_AH), the trend means were 20.2100 and 78.3344, respectively. The minimal seasonal and residual variations suggest stable environmental conditions. Wall temperature (S5_1_WT) and wall humidity (S5_1_WH) had trend means of 18.1125 and 7.0787, respectively, with negligible seasonal and residual effects. Similarly, wall temperature (S5_2_WT) and wall humidity (S5_2_WH) showed stable trends with means of 18.5136 and 10.7005, respectively.

The analysis of air temperature (S6_1_AT, S6_2_AT, S6_3_AT, S6_4_AT, S6_5_AT) revealed trend means ranging from 20.3183 to 21.8373, with minimal seasonal and residual variations. Air humidity (S6_1_AH, S6_2_AH, S6_3_AH, S6_4_AH, S6_5_AH) had trend means ranging from 58.5748 to 60.9543, with negligible seasonal and residual effects.

Overall, the time-series analysis results indicate stable trends for most environmental and structural parameters, with minimal seasonal and residual variations. These findings suggest that the building's structural integrity is influenced by consistent environmental conditions over time. The insights gained from this analysis will inform our preservation strategies, ensuring that we address the most critical factors affecting the building's longevity.

3.3.2. Seasonal and Temporal Patterns

The time-series analysis revealed pronounced seasonal variations in both environmental and structural parameters, underscoring the dynamic nature of the building's response to changing climatic conditions. These variations were particularly evident during the summer months, when higher temperatures and increased humidity levels were observed. The analysis demonstrated that these seasonal changes had a significant impact on the building's structural integrity, as evidenced by the correlation between environmental conditions and structural responses.

During the summer months, the building experienced higher ambient temperatures, which were closely mirrored by increases in wall temperatures. This rise in temperature was accompanied by elevated humidity levels in both the air and the walls. The combination of heat and humidity created conditions conducive to thermal expansion and humidity absorption, leading to noticeable structural changes. Specifically, the data showed that higher temperatures and humidity levels were associated with increased crack width and displacement. This relationship suggests that the building materials expanded and contracted in response to the thermal and humidity stress, resulting in the widening of existing cracks and the formation of new ones.

The seasonal patterns observed in the data highlight the importance of understanding the temporal dynamics of environmental stressors. For instance, the correlation between air temperature and crack width was particularly strong during the summer, indicating that thermal expansion played a significant role in the structural shifts observed during this period. Similarly, the increased humidity levels contributed to the swelling of masonry materials, exacerbating the effects of thermal expansion and leading to greater displacement. Examples of visual representations of seasonal decompositions for wall temperature and wall humidity measured using sensor number 5 are presented in Figures 11 and 12. The top plot in each figure shows the raw data measured with sensor 5. Both wall temperature and wall humidity showcase fluctuations, which have been smoothed out in the trend plots. Furthermore, the seasonal plot illustrates the regular, repeating patterns in the data. In these case the plot indicates that the data's behaviorfollows a daily pattern. Lastly, the residual component of the figures addresses all random variations or random noise in the data, which could be explained neither by the trend component nor the seasonal component. Reasons for these random measurements can vary; an example of an influencing factor could be the body temperature of someone adjusting the sensor.

The impact of seasonal changes on the building's structural integrity emphasizes the need for proactive maintenance strategies. Seasonal maintenance can help mitigate the effects of environmental stressors by addressing the specific challenges posed by different climatic conditions. For example, during the summer months, it may be necessary to implement measures to control indoor humidity and temperature, such as improving ventilation and insulation. These interventions can help reduce the thermal and humidity stress on building materials, preventing the formation and propagation of cracks.

In addition to summer-related stressors, the analysis also revealed the effects of other seasonal variations. For instance, during the winter months, lower temperatures and reduced humidity levels were associated with a decrease in crack width and displacement. This contraction of the building materials is likely due to the reduced thermal and humidity stress, which allows the materials to return to their original dimensions. However, the freeze–thaw cycles common in the winter can also pose a risk to the structural integrity of the building. The presence of humidity within the masonry can lead to the formation of ice, which expands and exerts pressure on the materials, potentially causing cracks and other forms of damage.

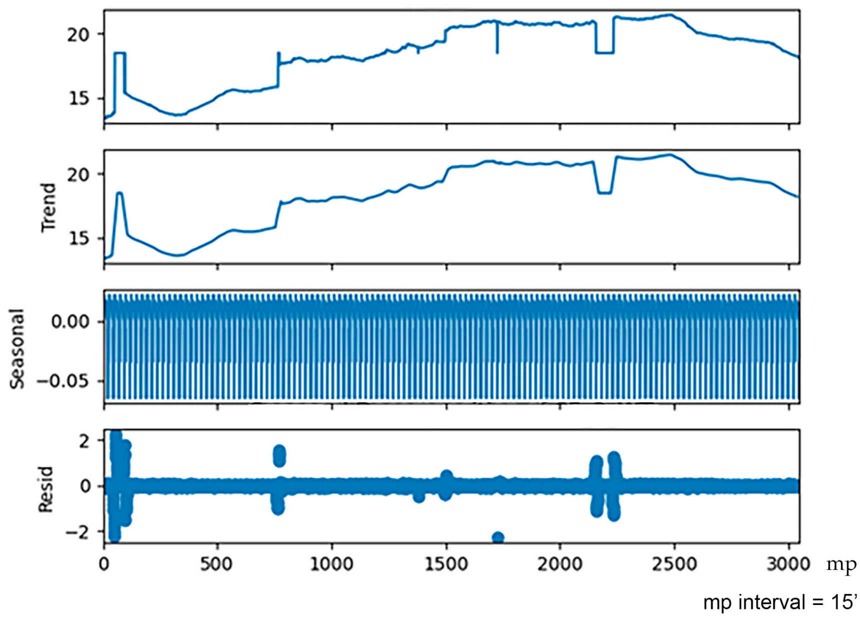

Figure 11. Seasonal decomposition of sensor 5 presenting the change in wall temperature based on all measurement points (mp).

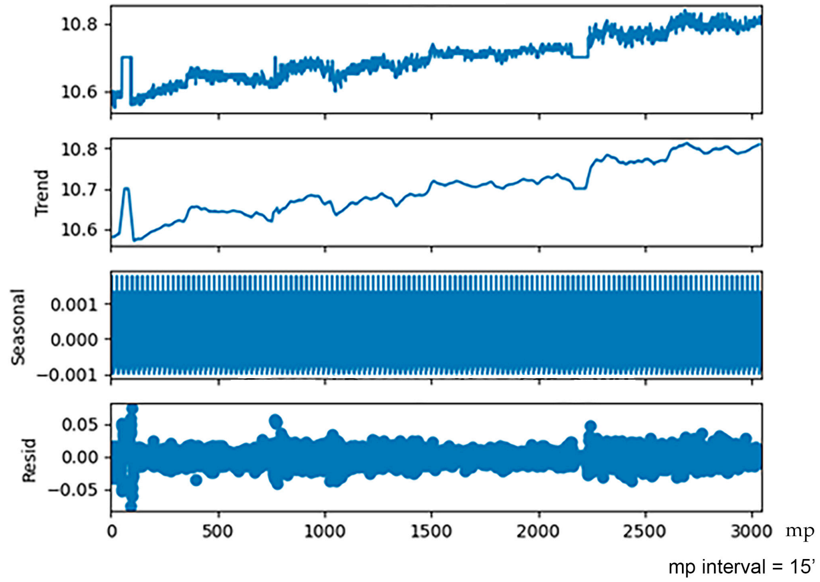

Figure 12. Seasonal decomposition of sensor 5 presenting the change in wall humidity based on all measurement points (mp).

The findings from the time-series analysis underscore the importance of continuous monitoring to capture the full range of seasonal and temporal variations. Through the tracking of environmental and structural parameters throughout the year, it is possible to identify patterns and trends that inform maintenance and preservation strategies. The use of advanced sensor technologies, such as the LoRaWAN-based wireless sensors employed in this study, provides the high-resolution data needed to understand these complex interactions.

Overall, the seasonal and temporal patterns observed in this study highlight the dynamic nature of the building's response to environmental stressors. These findings emphasize the need for a comprehensive approach to preservation that considers the full range of climatic conditions and their impact on structural integrity. Through the implementation of targeted maintenance strategies and the leveraging of continuous monitoring technologies, it is possible to enhance the resilience of historical masonry buildings and ensure their longevity for future generations.

3.4. Principal Component Analysis

The principal component analysis (PCA) conducted on our dataset provided valuable insights into the underlying structure of the environmental and structural parameters. By reducing the complexity of the data, PCA highlighted the most significant patterns and relationships, which are crucial for understanding the factors influencing the preservation of historical masonry buildings.

The first principal component (PC1) explained 33.79% of the total variance, while the second principal component (PC2) accounted for 20.87%. Together, these two components captured 54.66% of the variance in the dataset, indicating that they represent the most critical factors affecting the building's structural integrity.

PC1 reflects a combination of environmental factors such as temperature and humidity, which are highly correlated with structural parameters. The significant variance explained by PC1 suggests that these environmental conditions play a major role in influencing the building's stability. This finding underscores the importance of monitoring and controlling temperature and humidity to prevent structural deterioration.

PC2, while accounting for a smaller portion of the variance, still represents important secondary patterns. This component may capture specific interactions between wall temperature and air temperature or between displacement and crack width. The insights from PC2 highlight the need to consider these interactions when developing preservation strategies.

The PCA results emphasize the need for a comprehensive approach to monitoring and preserving historical masonry buildings. By focusing on the key factors identified by PC1 and PC2, we can develop targeted interventions to address the most influential environmental and structural parameters. For example, efforts to stabilize temperature and humidity levels could significantly enhance the building's structural integrity.

Overall, the PCA results provide a clear framework for understanding the complex interactions between environmental conditions and structural health. These insights will inform our preservation strategies, ensuring that we address the most critical factors affecting the building's longevity. The use of advanced statistical techniques like PCA, combined with continuous monitoring, will help us maintain the structural integrity of historical masonry buildings for future generations [43,44]. Figure 13, illustrating the PCA plot, provides a visual representation of these significant relationships, helping to identify clusters and trends that may not be immediately apparent from the raw data.

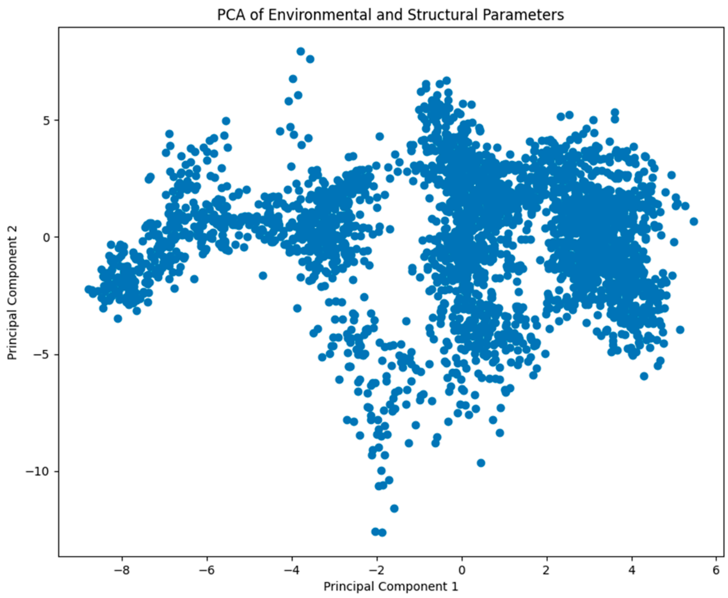

Figure 13. PCA plot.

4. Discussion

The results of this study provide valuable insights into the interactions between environmental conditions, energy dynamics, and structural integrity in historical masonry buildings. The significant correlations identified between temperature, humidity, and structural parameters underscore the importance of continuous monitoring for effective preservation. These findings align with previous studies that have highlighted the impact of environmental stressors on the structural health of masonry structures.

The strong negative correlation between air humidity and wall temperature suggests that higher humidity levels are associated with lower wall temperatures. This relationship can be interpreted in the context of evaporative cooling, where humidity on wall surfaces absorbs heat and lowers the temperature. Similar findings have been reported in studies examining the thermal behavior of porous materials, where the humidity content significantly influences thermal conductivity and heat transfer. This has direct implications for energy efficiency, as managing humidity levels can help optimize the thermal performance of the building, reducing the need for additional heating or cooling [15–17,45–47].

The positive correlation between wall temperature and wall humidity indicates that higher temperatures are associated with increased humidity levels within the walls. This relationship is consistent with the hygroscopic nature of masonry materials, which absorb humidity from the air. Previous research has shown that temperature fluctuations can enhance humidity absorption and retention in porous materials, leading to an increased humidity content. This finding emphasizes the need for effective temperature and humidity control to prevent humidity-related damage in historical buildings. Additionally, maintaining optimal temperature and humidity levels can improve the building's energy efficiency by minimizing the energy required to manage indoor climate conditions.

The perfect correlation between crack width and displacement confirms that changes in crack width are directly proportional to displacement. This finding is significant as it validates the use of crack width measurements as a reliable indicator of structural movement. Previous studies have demonstrated that crack width is a sensitive measure of structural stress and can be used to monitor the progression of damage in masonry structures. The ability to accurately measure and analyze crack width and displacement is crucial for the early detection of structural issues and timely intervention. From an energy perspective, maintaining structural integrity is essential for ensuring that the building envelope remains effective in regulating indoor temperatures, thereby reducing energy consumption.

The significant negative correlations between inclination measurements and structural parameters highlight the complex dynamics of structural movements within the building. The inverse relationship between inclination and displacement suggests that as the building tilts or leans, it also experiences horizontal movements. This finding aligns with previous research on the structural behavior of masonry buildings, where differential movements due to foundation settlement, thermal expansion, and humidity-induced swelling have been observed. Understanding these dynamics is essential for developing targeted interventions to stabilize the building and prevent further deterioration. Stabilizing the structure can also enhance energy efficiency by preventing gaps and cracks that could lead to heat loss or gain.

The strong positive correlations between temperatures measured at different points within the building show a high degree of consistency in temperature variations. This finding suggests that the building's thermal environment is well regulated, which is important for maintaining structural stability. Previous studies have shown that a consistent temperature distribution helps prevent localized thermal stresses that can lead to cracking and other forms of structural damage. The use of advanced sensor technologies to monitor temperature variations provides valuable data for optimizing the building's thermal environment, thereby improving energy efficiency by ensuring that heating and cooling systems operate more effectively.

The uniform distribution of humidity levels within the building, as shown by the strong positive correlations between air humidity measurements, underscores the effectiveness of the building's ventilation system in managing humidity levels. This finding is consistent with earlier research on humidity dynamics in historical buildings, where effective humidity control has been shown to prevent humidity-related deterioration. The continuous monitoring of humidity levels is crucial for supporting the structural health of masonry buildings and preventing issues such as mold growth, efflorescence, and freeze–thaw cycles. Effective humidity management also contributes to energy efficiency by reducing the need for dehumidification and maintaining a stable indoor climate.

The seasonal and temporal patterns observed in the data highlight the dynamic nature of the building's response to environmental stressors. Higher temperatures and humidity levels during the summer months were associated with increased crack width and displacement, emphasizing the impact of seasonal changes on structural integrity. These findings align with earlier studies that have documented the effects of seasonal variations on the structural behavior of masonry buildings. The need for seasonal maintenance to mitigate the effects of environmental stressors is clear, and proactive measures such as improving ventilation and insulation can help stabilize the building's environment. These measures not only protect structural integrity but also enhance energy efficiency by reducing the load on heating and cooling systems.

The principal component analysis (PCA) results further emphasize the importance of considering multiple dimensions when analyzing the environmental and structural parameters of historical masonry buildings. The first principal component (PC1) explained 33.79% of the total variance, while the second principal component (PC2) accounted for 20.87%. Together, these components captured 54.66% of the variance, highlighting the critical factors affecting the building's structural integrity. PC1 likely reflects a combination of temperature and humidity, while PC2 captures additional interactions between wall temperature, air temperature, displacement, and crack width. These insights will inform our preservation strategies, ensuring that we address the most critical factors affecting the building's longevity and energy efficiency.

Future research should focus on expanding the monitoring period to capture long-term trends and seasonal variations more comprehensively. Additionally, integrating other environmental parameters, such as wind speed and solar radiation, could provide a more holistic understanding of the factors influencing structural integrity and energy dynamics [20,21]. The development of predictive maintenance models based on historical data and machine learning algorithms could further enhance the effectiveness of preservation efforts. By leveraging advanced sensor technologies and continuous monitoring, we can ensure the sustainable preservation of historical masonry buildings for future generations, while also optimizing their energy efficiency.

Implications for Preservation

The correlations identified between environmental conditions and structural integrity emphasize the importance of continuous monitoring for the effective preservation of historical masonry buildings. LoRaWAN-based wireless sensors proved to be an efficient tool for real-time monitoring, enabling timely interventions to prevent damage.

The strong relationship between air humidity and wall temperature highlights the need for precise humidity control, which can mitigate thermal stress and prevent deterioration. Effective humidity management can reduce risks like mold, efflorescence, and freeze–thaw cycles that threaten the integrity of masonry.

The correlations between temperature, humidity, and structural parameters, such as crack width and displacement, underscore the value of integrated environmental and structural monitoring. The detection of early signs of structural stress enables proactive maintenance, preventing minor issues from escalating into significant damage.

LoRaWAN sensors offer several benefits for heritage conservation, including minimally intrusive installations and scalability for large areas. The data collected can inform localized preservation strategies, such as improving drainage or optimizing insulation.

Moreover, the integration of advanced sensor technologies into heritage conservation practices can facilitate predictive maintenance. Through the analysis of historical data and the identification of patterns, it is possible to forecast potential structural issues and address them before they manifest. This predictive capability enhances the efficiency of preservation efforts, reducing the need for reactive repairs and extending the lifespan of the building.

The results of this study also underscore the importance of interdisciplinary collaboration in heritage conservation. The successful implementation of sensor technologies requires expertise in fields such as materials science, structural engineering, and environmental monitoring. Through the fostering of collaboration between these disciplines, it is possible to develop comprehensive preservation strategies that address the multifaceted challenges faced by historical buildings.

Furthermore, the insights gained from this study can be applied to other heritage sites, providing a framework for the preservation of historical masonry buildings worldwide. The methodologies and technologies used in this research can be adapted to different climatic conditions and building types, ensuring that heritage conservation practices are tailored to the specific needs of each site.

Overall, the results of this study underscore the importance of integrating advanced sensor technologies into heritage conservation practices. By providing detailed and continuous data on environmental and structural conditions, these technologies can enhance preservation efforts for historical buildings, ensuring their longevity and stability for future generations. The proactive and data-driven approach to preservation enabled by these technologies represents a significant advancement in the field of heritage conservation.

5. Conclusions

This study underscores the critical role of continuous environmental and structural monitoring in the preservation of historical masonry buildings. The significant correlations identified between temperature, humidity, and structural parameters highlight the importance of maintaining optimal environmental conditions to prevent structural deterioration. The use of IoT LoRaWAN-based wireless sensors proved to be an effective method for real-time monitoring, enabling timely interventions to protect the building's integrity.

The findings emphasize the need for integrated monitoring approaches that consider multiple environmental and structural factors. Through the leveraging of advanced sensor technologies and data analysis techniques, it is possible to gain a deeper understanding of the building's behavior and implement targeted preservation strategies. The insights gained from this study contribute to the broader field of heritage conservation, providing a framework for the preservation of historical masonry buildings worldwide.

These results present broader implications for heritage preservation, highlighting the importance of adopting modern technologies and data-driven approaches in conservation practices. By applying these methods, heritage managers can develop more effective preservation strategies, ensuring that historical sites are maintained in their best possible condition. This approach not only protects the physical structure but also preserves the cultural and historical significance of these sites, allowing future generations to appreciate and learn from them.

Overall, the results of this study underscore the importance of proactive and data-driven preservation efforts. By continuously monitoring environmental and structural conditions, heritage managers can ensure the longevity and stability of historical buildings, safeguarding these cultural treasures for future generations. Additionally, optimizing environmental conditions not only preserves structural integrity but also enhances energy efficiency, contributing to the sustainable management of heritage sites. The integration of advanced monitoring technologies and comprehensive data analysis is essential for the effective preservation and energy management of historical masonry buildings.

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administration, N.D., G.W., and Ł.B.; funding acquisition, N.D., G.W., and Ł.B. All authors have read and agreed to the published version of the manuscript.

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