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A Pathological Diagnostic Method for Traditional Brick-Masonry Dwellings: A Case Study in Guangfu Ancient City

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Abstract: Many regions of the world have traditional dwellings, which not only represent the main form of residential architecture, but also carry the local vernacular culture, display the region's unique architectural style, materials and technology, and have important historical and cultural value. Due to environmental factors, traditional dwellings often suffer from architectural damage that threatens the stability of their structure and affects their esthetics value, resulting in a significant number of abandoned and demolished houses. In order to scientifically and effectively solve the damage problems of traditional dwellings, based on the theory of architectural pathology, the following diagnostic method for damage manifestation and the characteristics of traditional houses is proposed: "Architectural Pathology Appraisal–Pathological Environment Analysis–Mechanical Properties Testings". The traditional dwellings in the ancient city of Guangfu were used as a case study for the practical application of the methodology for analyzing the main types and causes of the damage of the dwellings by examining the damage information of the dwellings, collecting the environmental data of the damaged walls, and testing the mechanical properties of the damaged walls. The results show that the main damage type in the ancient city dwellings of Guangfu is dampness damage, with corrosion deterioration, wall alkali flooding, and the moisture infiltration phenomenon as the manifested symptoms, and the damage is mainly concentrated in the lower part of the wall. In addition, the humidity and moisture content in the lower part of the wall is higher than that in the upper part of the wall, and the compressive strength of the damaged part of the wall is lower than that of the undamaged part. The humid environment of the old town contributed significantly to the destruction of the dwellings, and water intrusion led to a reduction in the strength of the dwellings' bricks. Through the diagnostic method of building pathology, the causes of Guangfu dwellings' damage are identified, and scientific and targeted damage intervention suggestions are made. This is expected to provide guidance for the treatment and prevention of building pathology in the ancient city of Guangfu and serve as a reference for the diagnosis and treatment of pathology in traditional dwellings in other areas.

Keywords: building pathologies; traditional dwellings; diagnosis; brick walls

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1. Introduction

Vernacular architecture is prevalent globally, yet economic and social progress have prompted population migration from rural to urban areas, leading to the extensive abandonment or renovation of rural houses. This has created a dilemma whereby vernacular architecture faces numerous contradictions between its long-term use and conservation and development efforts [1,2]. Vernacular architecture is not only the embodiment of local traditional ways of life, but also carries deep history and culture. To preserve vernacular architecture, it is essential to restore missing or defective components. Due to factors such as natural and anthropogenic influences, damage and decay are prevalent in local architecture [3–5]. There is no point in restoring and converting a few buildings into a complex. Addressing their deterioration fundamentally requires thorough building examinations to assess their value and issues, along with a comprehensive evaluation of local conditions to formulate precise repair recommendations [6]. Brick-masonry dwellings are the most common form of vernacular architecture in Northern China [7], suffering from inadequate research methodologies and diagnostic approaches for their damage. Thus, developing scientific diagnostic methods is of great research importance for effectively treating building pathology.

The city of Handan, located at the junction of four provinces in China's Hebei Province, has a history spanning over 3000 years. According to the Handan City Government, there are 18 villages in the city with more than 4000 traditional dwellings [8]. Among them, the ancient city of Guangfu in Yongnian County is a famous historical and cultural city in China and the best-preserved of the 11 prefectural cities in Zhili during the Qing Dynasty. At the same time, most residential buildings in the city adopt the brick construction form, preserving the architectural characteristics of traditional residential buildings in Northern China [9]. Therefore, Guangfu dwellings can be viewed as typical representatives of traditional dwellings in the northern region of China. In 2011, the Yongnian District government of Handan City, China, conducted a survey on the ancient city of Guangfu, documenting 173 historical and traditional dwellings. However, field research reveals that many traditional houses have been abandoned or even demolished and rebuilt due to architectural defects. There are now only 63 relatively well-preserved and inhabited traditional dwellings left, and those that remain generally have architectural deficiencies [10]. Building pathologies not only harm the ancient city's historical appearance but also compromise the mechanical properties of building structures and the health of the living environment. However, preserving traditional homes is more difficult than preserving listed buildings [11]. Although some people ultimately continue to live in these dwellings, they can only be roughly repaired using contemporary materials and methods due to a lack of scientific guidance. This type of restoration, rather than addressing the building's underlying problems, results in material and structural incompatibility [12]. Hidden threats to building safety persist, and they exacerbate damage to the appearance of traditional dwellings. Failing to implement maintenance measures and lacking conservation knowledge can lead to severe building pathologies [13], causing the number of traditional dwellings to continue to decline. Therefore, developing science-based, practical solutions to combat building damage is of utmost urgency.

Since the 1950s, scholars in China have been actively studying traditional dwellings [14]. Amid rural revitalization and cultural heritage preservation efforts, traditional dwelling conservation and renewal have yielded substantial outcomes. However, these have primarily focused on interior renewal and style studies, with insufficient research on traditional dwelling pathology [15–18]. Building pathology is in particular caused by poor construction technology, human use, changing environmental conditions at the building's location, and other factors that lead to varying degrees of building damage. Studies on building damage aim not only to repair damaged buildings but also to prevent their occurrence and enhance durability and sustainability. With regard to the investigation of building pathologies, Groak, an expert in the field, first pointed out the importance of preventing building pathologies during planning and construction [19]. With the preservation of historic buildings and urban renewal projects, scientists have gradually placed emphasis on studying building pathologies. When discussing assessment and inspection strategies for older urban buildings, experts underscored the importance of addressing building blight [20]. By examining cracks in building thermal insulation, researchers demonstrate the importance of understanding the causes of building pathologies for effective damage recovery [21]. Experts specializing in specific building diseases employ sub-wall ventilation technology to tackle moisture transfer issues in historic buildings, underscoring the value of targeted interventions [22]. Furthermore, experts researching damaged buildings have found issues related to moisture, mold, and other pathologies within the structures [23]. Chinese researchers have determined that architectural damage correlates with climatic conditions, building materials, shapes, and other factors during the study of cultural artifact and building preservation [24]. To classify and study building pathologies in various types of heritage buildings, scientists have developed tailored assessment systems and treatment methods [25–27]. Work on field research and testing of the building environment [28,29], and building laboratories or using software to simulate the process of building damage development have been used to further analyze the causes of building damage [30–32]. In order to increase the efficiency and accuracy of diagnosing building damage, some scientists have tried to incorporate machine learning algorithms and laser scanning technology into their research in recent years [33,34]. Scholars have achieved extensive results in the study of architectural pathologies, especially the non-destructive testing methods of architectural pathologies and the actual measurement methods of historical architectural environments, which provide the basis for this paper.

Given the complexity of architectural pathologies, a thorough understanding of the condition of residential buildings and an analysis of the underlying causes of the damage are critical to making decisions about remediation efforts [35]. This study aims to propose and implement a methodology for diagnosing the pathological manifestations of traditional dwellings to assist in identifying conservation solutions. The work encompasses damage investigation, non-destructive testing of mechanical properties, and environmental data analysis. By combining pathological examination with environmental detection, this paper investigates traditional dwellings in Guangfu Ancient City, detects their damage status, and collects pathology environment data. It also proposes appropriate interventions based on specific damage causes, offering guidance for the study of pathologies in traditional housing in other regions.

2. Methods

2.1. Research Framework

The aim of this study is to assess the methods of examining and diagnosing pathological manifestations of traditional dwellings. The following figure shows the contents and steps of this study (Figure 1):

- Collection of basic information: Collect relevant literature and organize information on the number, distribution, types, and construction materials of traditional dwellings.
- Pathological examination of traditional dwellings: The study must use non-destructive tests, which are inspection methods that do not affect or manipulate the physical-mechanical properties of the building, in the context of preserving traditional dwellings. Visual inspection [36], infrared thermography [37], ultrasonic propagation velocity [38], acoustic emission [39], and resistivity [40] are the most commonly used non-destructive testing techniques used to examine historic buildings. Given the large and widespread inventory of traditional Chinese dwellings and the low economic level of the people who primarily use them, low-cost inspection methods that can be used on a large scale should be selected. The research used visual inspections to map damage information and assess the damage status in traditional dwellings [41]. Information includes the type of wall damage, the location of the wall damage, and the extent of damage to the wall.
- Environmental data testing of traditional dwellings: Among the numerous factors that lead to building damage, the influence of the natural environment cannot be overlooked. The study of the effects of the natural environment on damage has become a central issue in the preservation of cultural heritage [42]. In this study, we collected typical annual meteorological data of the region and analyzed the meteorological data to make a preliminary conjecture about the relationship between the architectural pathology of residential buildings and the climatic environment. A sample of residential buildings was then selected for testing building microenvironmental data. The tests

measure relative humidity, temperature, wind speed, thermal radiation on the surface of the building walls, and the water content inside the bricks. These parameters are used to draw preliminary conclusions about the pathological environmental properties of the houses, which are then confirmed by macroclimatic environmental data.

- Mechanical performance testing of traditional dwellings and recommendations for intervention: A selection of specific testing tools for testing the mechanical properties of damaged residential buildings and analyzing the causes and severity of residential building damage by combining the results of pathological inspections and pathological environmental tests is carried out. This also produces recommendations for the appropriate damage management measures and interventions based on the pathology.

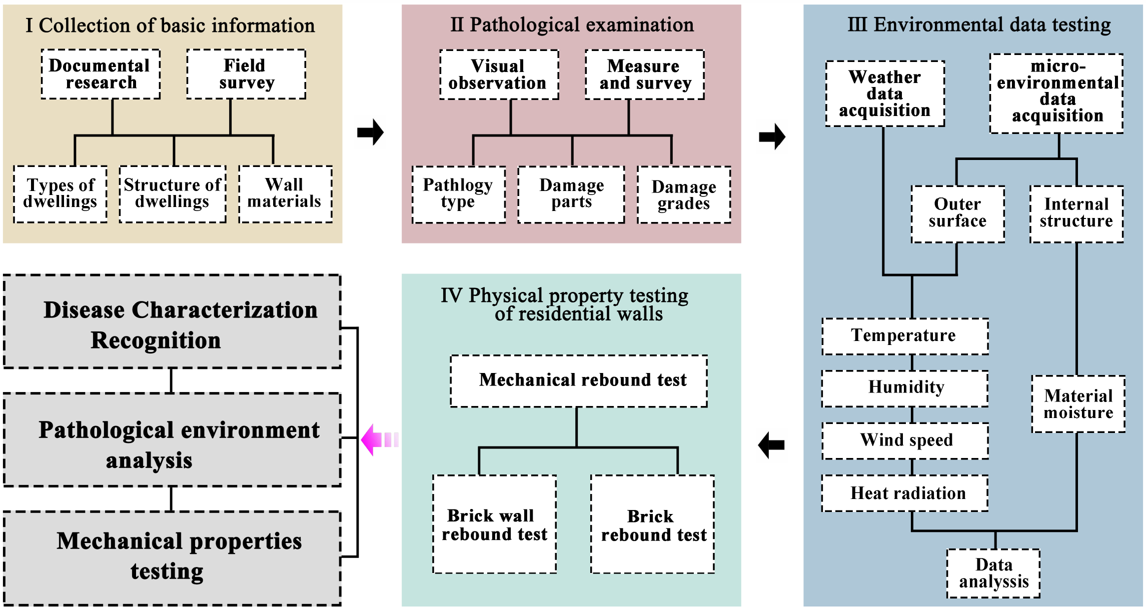

Figure 1. Workflow of holistic approach.

2.2. Current Condition of the Case

The ancient city of Guangfu is located in the southern part of the North China Plain and is surrounded by the Yongnian Depression, a water-rich area. It is located in Yongnian District, Handan City, Hebei Province, China. The ancient city was originally a dryland earth city that was rebuilt as a brick city in the Ming Dynasty [43]. The old town preserves a large number of traditional dwellings. The traditional houses have the characteristic features of courtyard buildings in Northern China, including south-facing courtyards with clearly defined axes. The existing traditional houses in the city are mainly brick houses, with red and blue bricks being the main building materials [44,45]. The main structures within Guangfu Ancient City are single-story brick-masonry buildings. The construction of these buildings can be divided into three parts from bottom to top as follows: the foundation, the walls, and the roof. The predominant types of foundations for residential buildings in the ancient city are rammed earth and brick masonry foundations. The common material used for wall construction within the city is blue brick, with the standard dimensions of 240 × 120 × 55 mm. The roof is typically composed of three layers as follows: the first layer consists of wooden planks or thatch, the second layer is a layer of yellow mud mixed with reed stalks laid over the wooden planks, and the final layer is composed of tiles. In the ancient city of Guangfu, there are primarily two types of architectural structures, namely brick-concrete structures and brick-wood structures. The brick-concrete structures are predominantly utilized in ordinary residential buildings, whereas brick-wood structures are more common in public buildings and the residences of the nobility. The brick-concrete structures bear load through masonry constructed from bricks or stones, while the brick-wood structures carry loads through a combination of wooden columns and brick walls.

Buildings with brick-concrete structures generally have a longer service life compared to those with brick-wood structures, which are more challenging to maintain. Consequently, a greater number of traditional residences with brick-concrete structures are preserved within the city. The investigation found that the damage to traditional houses in the old town is mainly manifested in the walls. Based on the observation and documentation of the brick wall damage phenomena, the following primary building damage problems of the brick wall were identified (Figure 2): moisture infiltration, plastering bulge and rupture, cracks, corrosion and deterioration, wall alkali flooding, plant parasitism, and mold formation.

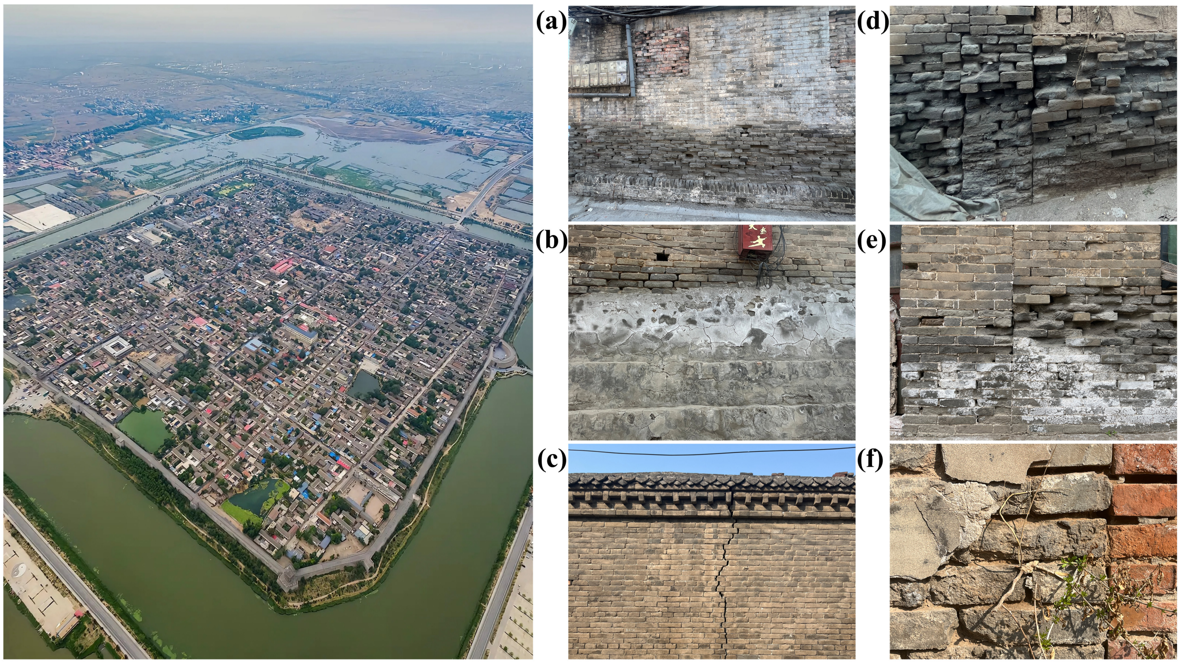

Figure 2. Status of Guangfu Ancient City and damage images of residential dwellings: (**a**) Moisture infiltration; (**b**) Plastering bulge and rupture; (**c**) Cracks; (**d**) Corrosion and deterioration; (**e**) Wall alkali flooding; (**f**) Plant parasitism.

To elucidate the pathology of residential structures, a pre-evaluation of the common damage problems is conducted. For instance, the genesis of cracks in residential brick masonry walls is typically attributed to material properties and environmental factors [46]. Temperature-induced thermal expansion and contraction can initiate the formation of masonry cracks. Additionally, drying shrinkage of brick masonry materials, particularly following the evaporation of water from cement mortar, can precipitate cracking. Environmental factors, such as fluctuations in the water table, uneven foundation settlement, and the influence of corrosive agents, can also induce wall cracks. Cracks can be categorized as structural or non-structural; structural cracks potentially compromise the safety and stability of the building, whereas non-structural cracks primarily impact esthetics and durability [47]. The cracks observed in the old city houses examined in this study are predominantly non-structural. Brick wall efflorescence is primarily associated with brick quality and environmental factors. A humid environment expedites the dissolution and migration of soluble salts, precipitating alkalization [48]. Soluble inorganic salts from groundwater or surface water can infiltrate the brick wall with moisture, leading to alkalization. Variations in environmental water content or temperature fluctuations induce the crystallization and dissolution of salts, resulting in a loose masonry structure, which is also a major cause of alkalization [49]. Therefore, this study aims to clarify the environmental analysis of the pathological conditions affecting the dwellings.

2.3. Descriptors Used

This study includes numerous parameters. The relevant parameters of the study are defined and explained to make the research content clearer (Table 1). These three "descriptors", essential for the study of the damage, include the following basic parameters: location, type, and degree of wall damage caused by damage [50].

Table 1. Codification and relation of the descriptors used in the research.

Descriptor	Code	Concept	Description
Descriptor 1: Construction units	W1	Upper part of the wall	
	W2	Central part of the wall	
	W3	Lower part of the wall	
	W4	Wall footing	
	W5	Gable wall	
Descriptor 2: Pathology type	P1	Corrosion deterioration	Chipping on the wall surface, damage to the bricks, missing bricks, and chalking.
	P2	Wall alkali flooding	White crystals precipitate inside the wall and adhere to the outside surface of the wall material.
	P3	Moisture infiltration	Water damage to walls, color changes to the material, severe wetting.
	P4	Plastering bulge and rupture	Cracks and bulges in the outer layer of the wall.
	P5	Cracks	Structural cracks in walls with misalignment.
	P6	Mold formation	Parasitic fungi cling to the wall surfaces.
	P7	Plant parasitism	Plants grow up the wall and cause damage to the wall surface.
Descriptor 3: Damage grades		Light damage Moderate damage Severe damage Destruction	

Descriptor 1 is the name of the different parts of the residential wall. Different parts of the wall have different damage states, and to ensure the accuracy and specificity of the study, different parts of the brick walls of the dwellings were defined based on traditional architectural features and divided into five different units (Figure 3). Descriptor 2 refers to the manifestation symptoms of the damage in the dwellings of the ancient city. The seven types of manifestation symptoms of architectural pathology were explained accordingly. Descriptor 3 refers to the extent of the damage. In March 2011, the local government conducted a status quo study on the historical houses in Guangfu Ancient City. The study assessed the current state of building preservation and classified buildings into the following four main categories: better preserved, in need of minor repairs, in need of major repairs, and beyond repair [51]. This study follows the damage classifications of residential buildings according to the classification in the government research report and defines the degree of damage as light damage, moderate damage, severe damage, and destruction.

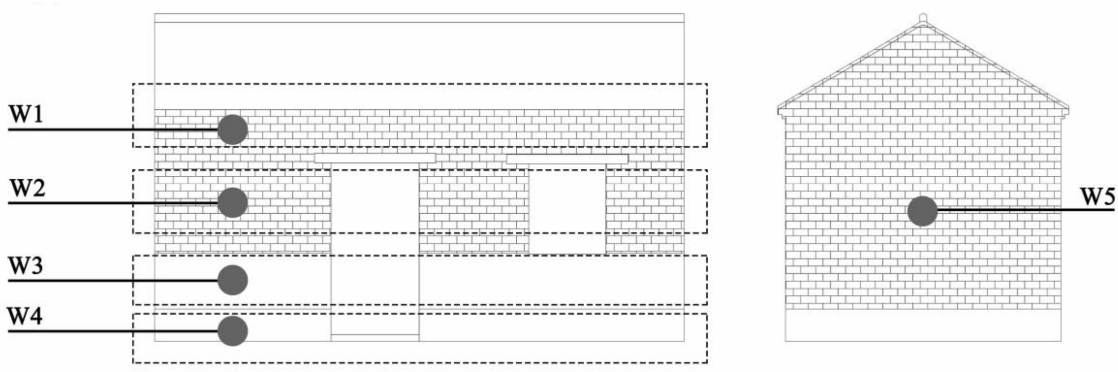

Figure 3. Schematic diagram of the codes for each part of the building wall.

2.4. Field Measurement and Investigation

2.4.1. Methods of Pathological Examination of Traditional Dwellings

In the context of preserving traditional dwellings, this study uses an investigative approach to architectural pathology questions [52]. Exploring the damage information of traditional houses through visual inspection and measurement and mapping the damage and damage information. The damage and damage information map is a graphical tool used for recording the detailed damage and damage status of a building or structure, which typically contains information on the following aspects: the types of damage on living walls, such as cracks and erosion, differentiated according to different symbols or colors on the map (Table 2); the parts of the living wall damage, clearly identifying the specific locations of the damage on the wall, e.g., around the window frames of the wall and in the middle part of the wall; and the extent of the damage to the residential wall. The degree of wall damage is assessed using quantitative indicators such as crack length and damage area, as well as qualitative descriptions such as mild and moderate.

Table 2. Differentiation of surface pathology in residential wall.

Pathology	Identification	Pathology	Identification
P1		P5	
P2		P6	
P3		P7	
P4			

The procedure for image acquisition to capture the current situation of the wall facade of residential buildings is as follows: First, we survey and map the facade of traditional residential buildings to obtain the basic image of the wall frame. Second, we measure and record the contour and location of the damage and take photos to facilitate the positioning of the damage map during the drawing process [53,54]. Using software, we draw pictures of the wall facade of traditional residential buildings (Figure 4). Finally, the image information and associated data are systematically numbered and recorded for each housing unit to facilitate the subsequent quantitative analysis of damage information in traditional dwellings.

2.4.2. Environmental Data Testing Methods for Traditional Dwellings

(1) Climate environment data collection

The environmental climatic data used in this study are TMY (Typical Meteorological Year) data in the Chinese Standard Weather Data (CSWD) format. The data source is the Special Meteorological Dataset for Analysis of the Thermal Environment of Buildings in China, which was developed and published by the Meteorological Data Office of the China

Meteorological Information Center and the Department of Architectural Technology and Science of Tsinghua University [55]. Handan's meteorological data were analyzed using Climate Consultant software and then analyzed and discussed.

(2) Microenvironmental detection methods

From the dwellings where damage symptoms are clearly manifested, three sample groups, each consisting of two sample homes from the same neighborhood, were selected to collect microclimate environmental data. Three groups of building samples or a total of six residential buildings made of brick and concrete were selected for the experiment. The sample groups were, as the figure shows, dispersed as widely as possible, with groups a and b, c and d, and e and f located in different locations within the ancient city and facing different directions. The samples were mainly selected from traditional dwellings of blue brick masonry. The test sites are chosen from the neighborhoods of Yingchun Street, Vulcan Temple Street, and Fuhou Street in the ancient city (Figure 5). The residential data testing will take place between 11 and 15 March 2024. Examination of microclimate data includes examination of relative humidity, wind speed, temperature, and radiation values.

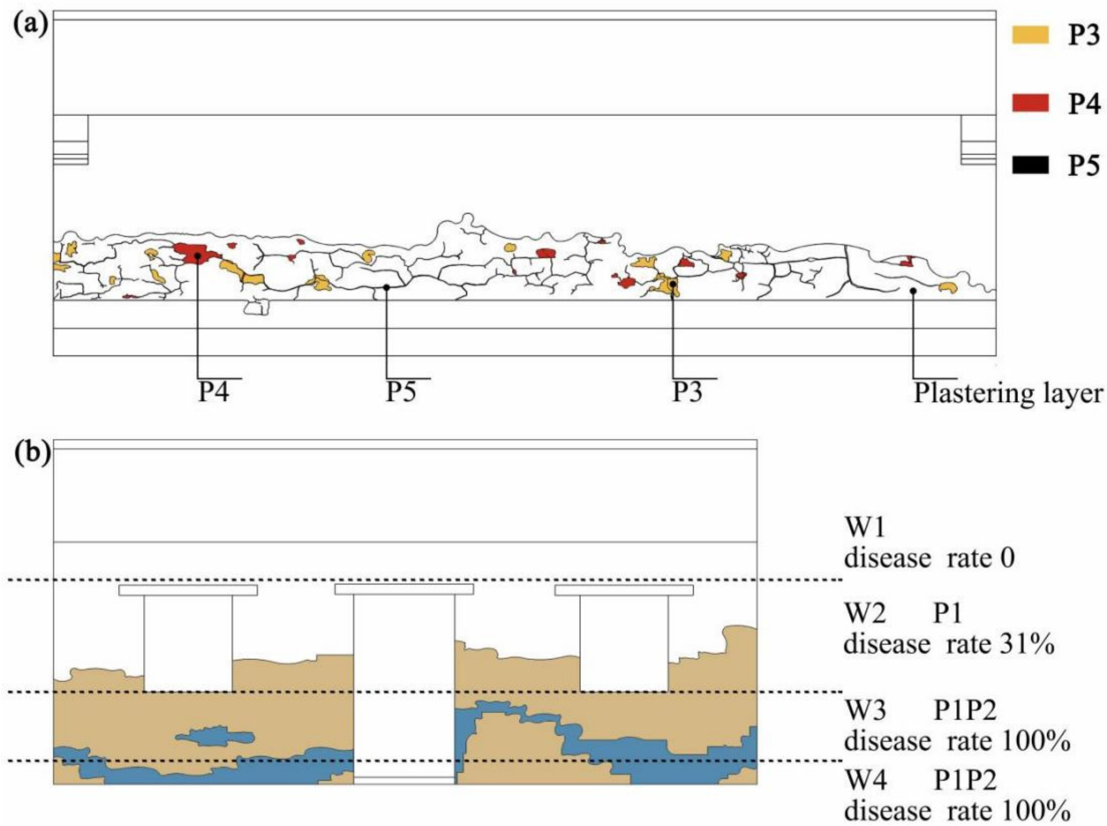

Figure 4. The damage and damage information map. (**a**) Infographic of damage types; (**b**) Infographic on the percentage of damaged area.

The data collection process is essentially divided into two phases; the first involves measuring the physical environmental data of the building at different heights and directions, and the second involves collecting physical environmental data from the damaged areas of the building.The following instruments were selected for microclimate testing. Temperature and humidity are measured with CEM DT-172 temperature and humidity loggers manufactured by Huashengchang Technology Co. Wind speed is detected by Testo 425 anemometer made by German company Testo. Thermal radiation was detected by JTR09 Radiant Thermometer manufactured by Beijing Century Jiantong Technology Co. The moisture content of the bricks was detected by Testo 606-2 Material Moisture Meter made by German company Testo. The test points for microclimate testing were numbered for each sample during the data testing procedure [56]. The facades of the residential buildings were numbered as ESWN for each of the four directions, and the measurement points were selected for each facade based on the requirements of the actual measurement. For each wall, three lines are constructed at different heights at a distance of 2500, 1200, and 200 mm from the floor, respectively, with an even distribution of detection points along each line (Figure 6). When collecting microclimate data, it is necessary to wait until the instrument data have stabilized before reading. Each measuring point must be measured three times, with the average serving as a record of the measurement results. This ensures that errors due to experimental chance are avoided and the data are reliable and accurate.

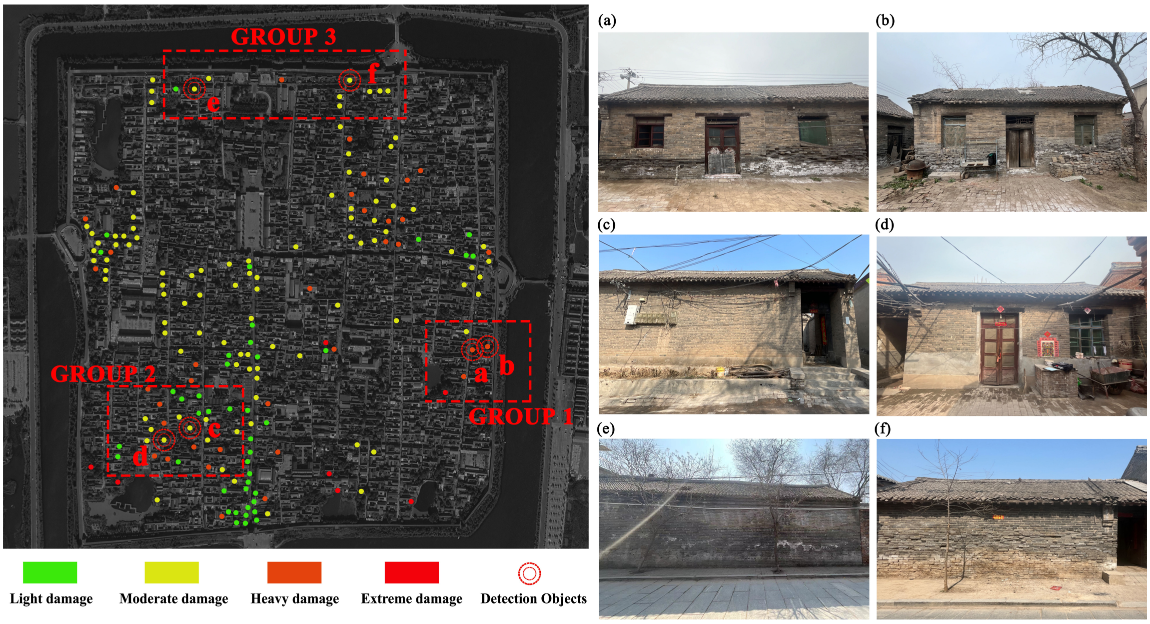

Figure 5. Microenvironmental detection of the current situation of residential houses and their location in the old city. (**a**,**b**) Architectural Status of Selected Residences on Yingchun Street; (**c**,**d**) Architectural Status of Selected Residences on Vulcan Temple Street; (**e**,**f**) Architectural Status of Selected Residences on Fuhou Street.

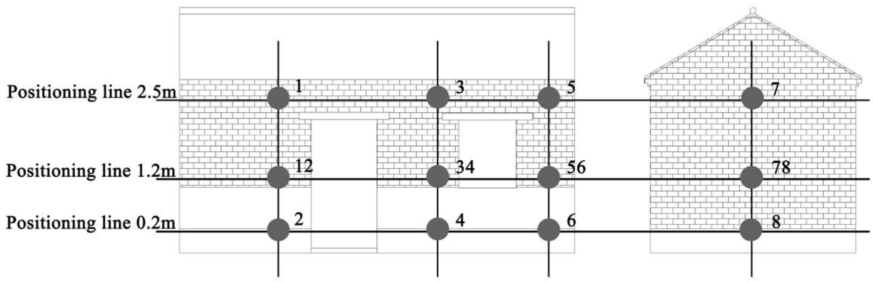

Figure 6. Collection point for microclimate tests.

2.4.3. Mechanical Properties Testing of Residential Brick Walls

(1) Material properties of bricks

Before the invention of concrete, residential buildings were essentially wall structures made of brick materials, which were primarily artificial bricks. Artificial bricks are solid bricks made by firing clay as a raw material [57]. Artificial bricks come in two main varieties, red bricks and blue bricks. Red bricks are created during the firing process when the iron in the clay completely oxidizes, producing iron trioxide red. During the firing process, blue bricks are created when the clay is partially cooled with water. Blue bricks and red bricks have the same raw materials and firing process, only the cooling method after firing is different; red bricks are naturally cooled, and blue bricks are water-cooled. As for the properties of bricks, blue bricks are fired for a longer period of time and have higher resistance to high temperatures and humidity, while red bricks are fired for a shorter period of time and have a higher compressive strength. However, in terms of the manufacturing process, they are all insufficiently fired bricks (Figure 7). Both have the characteristics of a loose structure, high porosity, and high water absorption. In particular, the expansion stress after water absorption increases the looseness of the brick's microstructure, making it brittle and easy to disintegrate, favoring the development of damage [58].

(2) Mechanical rebound experiments on brick walls

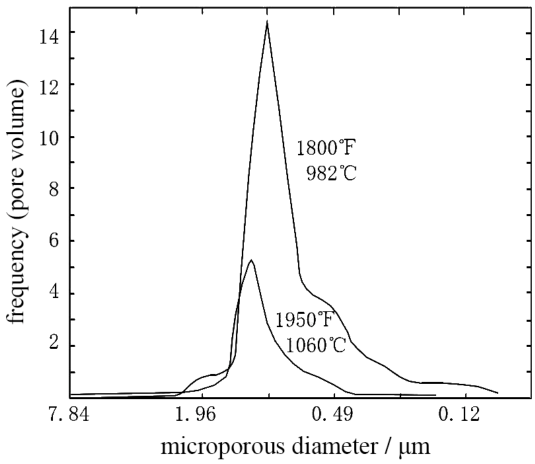

Figure 7. Microporous size distribution of brick products under two temperature conditions: underfiring and normal baking "Adapted with permission from Ref. [59]. 2012, Qingfan Li" [59].

The traditional dwellings in Guangfu Ancient City are brick houses because the brick wall is mainly used to bear pressure. Therefore, the focus of the quality inspection of the wall bricks of the dwellings is on testing their compressive strength, and the index of their strength is directly related to the safety and durability of the structure of the traditional dwellings [60]. The current method for determining the strength of masonry blocks is usually on-site sampling [61]. This provides clear and reliable test results, but it is labor- and time-intensive and can jeopardize the integrity of the masonry itself. This is not suitable for the traditional dwellings in this study, as the appearance of the dwellings needs to be preserved, and the technology can be widely available. Therefore, it is of great importance to study non-destructive testing methods applicable to the strength testing of traditional dwellings. Due to lightweight equipment, easy handling and efficient operation, minimal site requirements, and straightforward data processing, the rebound method is perfect for testing the strength of traditional residential building blocks [62]. In this study, the strength of bricks was determined using the rebound method on residential brick masonry. To indirectly determine the compressive strength of conventional residential bricks, the method relies primarily on the brick rebound value of surface hardness, which is measured using the brick rebound measuring device. Related mechanical parameters such as tensile strength, elastic modulus, and the compressive strength of brick masonry are also calculated, using the correlation of the direct compressive strength of the brick to establish a relationship equation. The parameters of the brick resilience meter are shown in the following table (Table 3).

The tested brick walls were divided into two types of zones, intact and damaged zones. Each type of brick serves as a detection unit and, based on the type of damage present in the brick wall to be tested, the damage zone selects an appropriate number of detection units. In each test unit, 4 measurement areas are randomly selected, the area of each measurement area is no less than 2 square meters, and 20 randomly selected bricks with outward stripes are used as the 20 measurement positions used for rebound testing. The distance between the selected brick and the edge of the brick wall must be more than 250 mm, and the distance between each measuring area cannot be less than 250 mm. Five impact points are evenly arranged on the measuring surface of each stone. When choosing the impact point, we avoided unevenness in the brick surface. The distance between two adjacent impact points should not be less than 20 mm, and the distance between the impact point and the edge of the brick should not be less than 20 mm, and each impact point can only rebound once. The rebound meter must be horizontal during the test and its axis must be perpendicular to the surface of the brick. The rebound value of a single side position is taken as the average of the rebound values of 5 impact points [63]. There are four villages within the old city: North Village, East Village, South Village, and West Village [47]. The buildings in the South and East Villages have been more extensively restored and preserved due to their high commercial and tourist value. In contrast, the structures in the North and West Villages are comparatively older. Architectural conditions vary among the four villages. Consequently, two brick-masonry dwellings from each village were selected for rebound testing (Figure 8). The resilience test was carried out for each dwelling unit, evaluating the resilience values of bricks within the same wall in various locations.

Table 3. Main indicators of the brick rebound tester.

Main Indicators	Parameter Range
Types of rebounders	HT75-A Brick rebounders
Kinetic energy of an impact	0.735 J
Stretching length of sprung tension springs	75 ± 0.3 mm
Friction on the pointer slider	0.5 ± 0.1 N
Working length of sprung tension springs	61.5 ± 0.3 mm
Spherical radius of the end of the striking rod	25 ± 1 mm
Brick compressive strength conversion formula	$f = 2 \times 10^{-2} R^2 - 0.45R + 1.25$ f: Compressive strength of bricks R: Brick resilience value

Figure 8. Distribution of samples for brick wall rebound testing in the Guangfu Ancient City.

3. Case Study

3.1. Pathological Examination of Residential Brick Walls

Using the number of samples of damaged residential buildings as a quantitative criterion for architectural damage, the information on residential damage in Guangfu Ancient City was summarized and analyzed to draw the following preliminary conclusions (Figure 9):

- The percentage of traditional dwellings with different degrees of damage is as follows (Figure 9a): through the summarization and analysis of the degree of damage to traditional dwellings in the ancient city, it was found that traditional residences in the ancient city generally exhibit varying degrees of damage, with more than half exhibiting moderate damage.
- The number of different building pathology types for brick walls is as follows (Figure 9b): upon summarizing and analyzing the quantities of various architectural pathology types in traditional dwellings of the ancient city, it was determined that the primary pathologies affecting the ancient city are P1 and P3.
- The number of building pathology types in different parts of the brick wall are as follows (Figure 9c): through the summarization and analysis of the quantities of various architectural pathology types in different sections of brick walls in traditional dwellings of the ancient city, it has been determined that the primary pathological types affecting the ancient city are W2, W3, and W4. It can be observed that the architectural pathology phenomena in traditional residences are predominantly concentrated in the middle and lower sections of the walls.

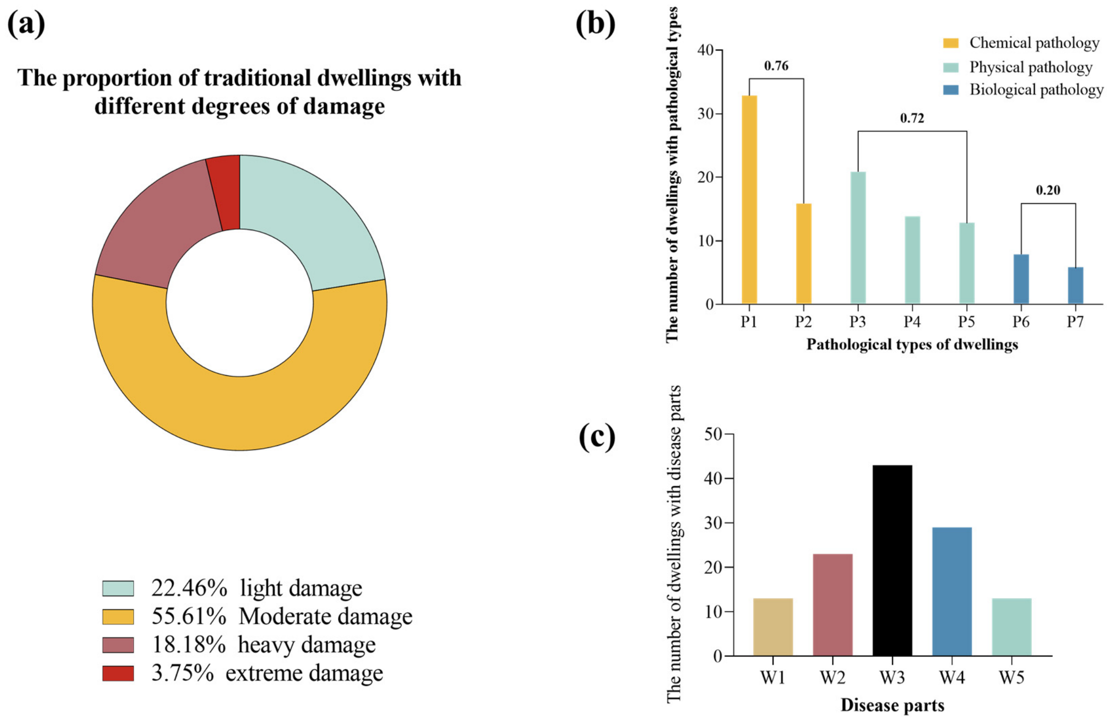

Figure 9. Damage analysis diagram: (**a**) The percentage of traditional dwellings with different degrees of damage; (**b**) The number of different building pathology types for brick walls; (**c**) The number of building pathology types in different parts of the brick wall.

In summary, the damage situation in traditional dwellings in the ancient city is serious, and the number of homes with moderate or higher damage accounts for a relatively large number of homes. There are three types of pathologies that are more pronounced within the walls of ancient city dwellings. Concurrently, the damage information of residential building walls indicates that multiple damage combinations occur on the walls of the same traditional dwelling. For instance, several types of architectural pathologies are observed to co-occur frequently. The types of architectural pathologies that frequently appear also vary across different parts of the building walls. Therefore, there is a certain relationship between the types of architectural pathologies, the wall positions, and among different pathologies themselves. Based on the compilation of residential damage information, this study analyzed the combinations of pathologies in traditional dwellings, the correlations between different pathologies, and the correlations between different parts of the residential walls and various pathologies (Figure 10).

- Pathological combinations of traditional dwellings (Figure 10a): Through the detection and analysis of brick wall damage in 50 dwellings, a total of 23 combinations of housing damage were identified: Among them, there are three groups of individual pathological combinations; there are eight groups with two pathological combinations; three pathological combinations with ten groups; and four pathological combinations with two groups. Therefore, the residential pathological combinations in the ancient city mainly consist of two and three pathological combinations, and the main pathological combinations are P1P2 and P1P3.
- Pathological correlation of traditional dwellings: As depicted in Figure 10b, the heatmap presents the correlation coefficients between various architectural pathology types. The intensity of the colors indicates the strength of the correlations, with hues closer to red signifying stronger correlations. Through the analysis of the heatmap, we identified several significant clusters of correlations. For instance, positive correlations were observed among the pathologies within the combinations P1P2, P1P3, P3P6, and P4P5. Additionally, some pathological combinations showed weak or non-significant correlations, such as the non-significant correlation between P6P7, suggesting that the occurrence of these combinations may be incidental. Furthermore, we noted some unexpected correlations, such as the negative correlations between P1P7 and P3P5, which may indicate the need to consider the interplay of these pathological causes in future strategies for addressing architectural damage.
- Correlations between pathological parts and pathological types of traditional dwellings (Figure 10c): The heatmap utilizes color intensity to denote the strength of correlations, with hues closer to red signifying stronger associations. Our analysis of the heatmaps revealed several notable clusters of significant correlations. Notably, the darkly colored regions between P1 and W2, W3, and W4 suggest a robust positive correlation, indicating a pronounced relationship. Conversely, the correlation between certain pathologies and wall parts was weak or insignificant, such as the negligible link between P3 and W2, W3, and W5. This may suggest that the occurrence of P3 in these wall parts is somewhat incidental or less predictable. The heatmap reveals that W1 is predominantly affected by pathology P3, while the other four sections, W2, W3, W4, and W5, are primarily affected by P1. Additionally, P1 is observed across all wall parts.

In summary, P1P2P3 architectural pathology was found to occur frequently as a combination of pathologies. These architectural pathologies are mainly symptoms of moisture damage to the brickwork. Natural "defects" occur in the physical and chemical properties of building materials. Brick, one of the oldest building materials, has many internal voids because it is made primarily of fired clay and sand. Through the cavities, moisture is stored inside the building and, together with salts, causes damage to the masonry. Wall dampness-related pathologies, including mold growth and moisture retention, significantly impair indoor air quality and pose health risks to occupants [64]. These conditions can emit mold spores and volatile organic compounds (VOCs) into the indoor environment, thereby degrading air quality. Mold metabolites, such as mycotoxins, can trigger respiratory irritation and allergic responses, with chronic exposure potentially leading to severe health issues such as bronchitis, tonsillitis, rhinitis, and asthma. Individuals with weakened immune systems are at an increased risk of experiencing headaches, fever, and skin or mucous membrane inflammation. Additionally, humid environments facilitate the growth of bacteria and viruses, contributing to respiratory and dermatological health problems [65]. Consequently, dampness-induced wall pathologies exert a profound influence on both indoor air quality and human health, underscoring the need for scientific research and effective preventative measures.

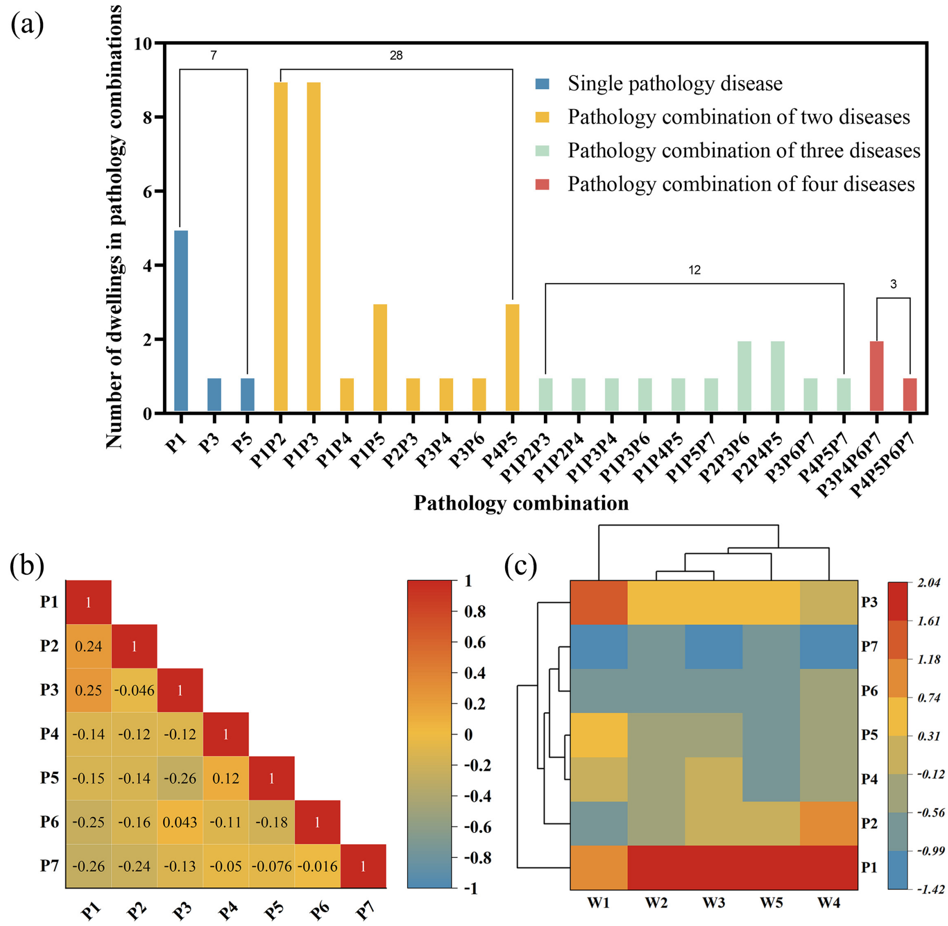

Figure 10. (**a**) Percentage of the number of different pathology combinations of traditional houses in the old city; (**b**) Correlation between the different types of pathologies present in traditional dwellings; (**c**) Heat map of the distribution of different building pathology types in different parts of the wall.

3.2. Analysis of Residential Environment Data

3.2.1. Climatic Environment of Traditional Dwellings

The frequency and severity of extreme weather events has increased dramatically worldwide in recent years, and more extreme weather events are predicted to occur in the future [66]. It is important to study the climatic conditions of traditional dwellings in Guangfu Ancient City because historical structures are particularly susceptible to this unfavorable climate, which leads to the development of architectural pathologies. The findings from the a of the potential impact of macroclimatic environmental factors on masonry wall damage using the Handan climate data (Figure 11) are as follows:

- When the air is saturated with water vapor, the air temperature is equal to the dew point temperature. The difference between dew point and air temperature can therefore indicate how far the water vapor in the air is derived from saturation. From studying Handan's dry bulb and dew point temperatures, buildings that are prone to condensation during the summer months of July and August create a humid environment for the walls.
- When analyzing the wind speeds in Handan, it was found that the maximum wind speeds mainly occur in February, March, and November, and the excessive wind speeds can damage the surface of living walls and cause the phenomenon of wind erosion.

- When analyzing the relative humidity in Handan, it was found that it was significantly above 50%, with the highest relative humidity occurring in July and August in the summer when it was almost 80%. This finding is consistent with the condensation phenomenon discussed in the previous article and can easily occur during these months.
- When analyzing the rainfall in Handan, it was found that July and August are the wettest months in Handan, while rainfall is very uneven throughout the year.

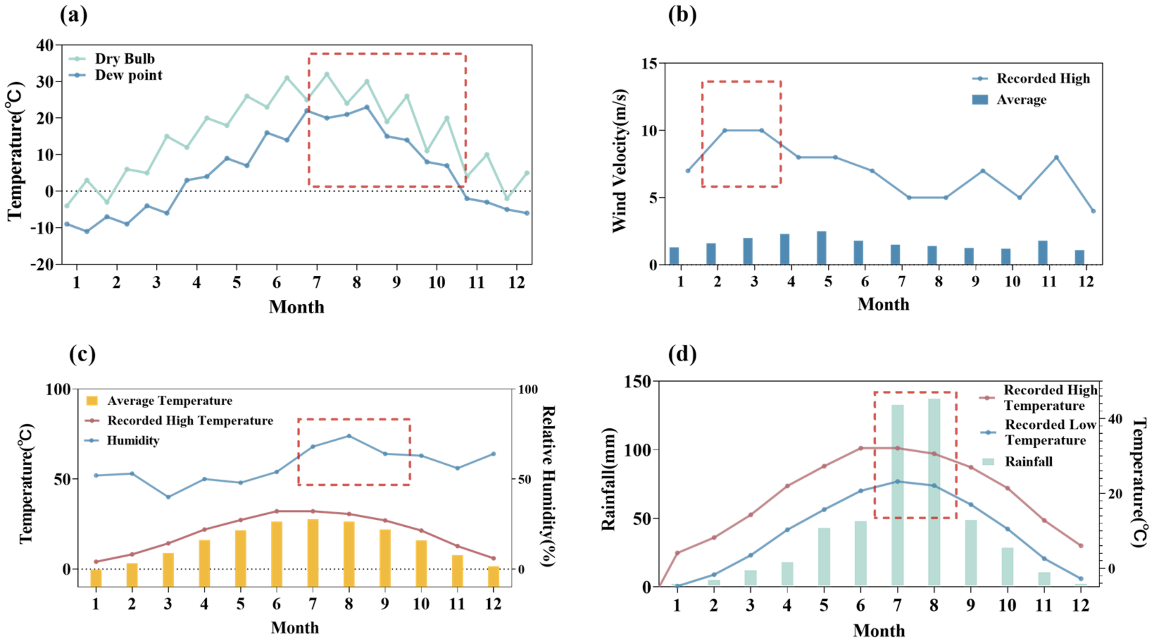

Figure 11. Climate and environmental analysis chart: (**a**) Temperature; (**b**) Wind speed; (**c**) Relative Humidity; (**d**) Precipitation. (The red dotted box shows data for months with significant changes in the climate environment).

In summary, the summer months of July and August are found to be the wettest times of the year in the ancient city of Guangfu. This is also the time when the temperature is closest to the dew point temperature, making buildings vulnerable to condensation. The relative humidity analysis charts also showed that the humidity was higher during this phase, which led to the pathologies. In addition, spring and autumn winds prevailed, exposing the brick walls of the residential buildings to the unfavorable environment of a wet–dry–wet cycle. This resulted in pathologies of varying degrees in the brick residential buildings.

3.2.2. Microenvironmental Analysis of Building Brick Walls

Environmental factors have different effects on building pathology, and buildings and their environments interact and influence each other. The most important climatic elements that make up a building's microclimate are temperature, humidity, wind direction and speed, and solar radiation. These elements also have a significant impact on the overall structure of the building and the comfort of its residents [67,68]. The microclimate data of residential walls were objectively collected in this study, and the test data could accurately reflect the microclimate information on the surface of the brick wall and the degree of environmental influences on it. This allows the investigation of the extent to which microclimate information negatively impacts various brick building components and serves as a basis for further research (Table 4).

Table 4. Study of the residential situation.

Code	Position	Construction	Pathology	Damaged Sections	Damage Grades
a	Yingchun Street	Brick and wood structure	P1P2	W2, W3, W4	c
b		Brick and wood structure	P1P2	W3, W4	c
c	Vulcan Temple Street	Brick and wood structure	P4P5	W4, W5	b
d		Brick and wood structure	P1P3	W5	c
e	Backstreet of the government office	Brick and wood structure	P1P2	W5	b
f		Brick and wood structure	P1P2P3	W5	c

For example, in the case of residential house sample d, the four exposed wall facades of the house are used as measurement points, and each one is selected based on the need for monitoring the surrounding microclimate. Measuring points 1, 3, and 5 are located along the horizontal detection line in the upper part of the wall, 2500 mm above the floor. 12, 34, 56 are distributed along the horizontal detection line in the middle of the wall, 1200 mm above the floor; 2, 4, 6 are distributed along the lower part of the wall, 200 mm above the floor (Figure 12).

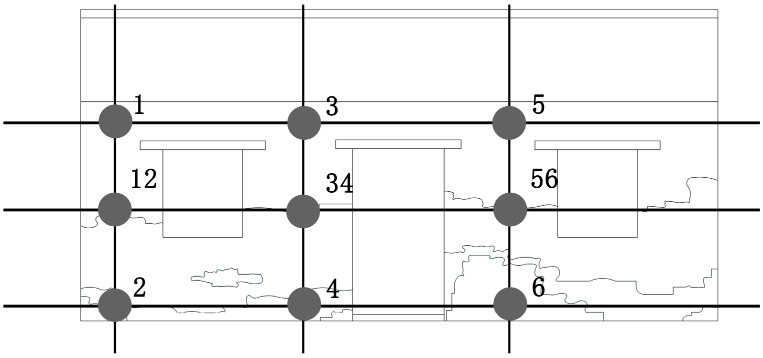

Figure 12. Schematic diagram of microclimate testing points in traditional dwelling d.

As part of the microclimate test, the following variables were measured at each measuring point on the wall surface (Table 5): temperature, humidity, wind speed, solar radiation, and the amount of moisture inside the bricks.

Table 5. Acquisition of microenvironmental data on the north and south walls of sample d.

Detection Point	**N-1**	**N-12**	**N-2**	**N-3**	**N-34**	**N-4**
Temperature (°C)	22	22.1	20.6	20.3	20.2	19.3
Relative humidity (%)	35.6	39.6	40.2	36.4	40.1	40.4
Solar radiation (w\m)	86	142	116	89	130	93
Detection Point	**N-5**	**N-56**	**N-6**	**S-1**	**S-12**	**S-2**
Temperature (°C)	20	19.8	19	18.1	18	18.2
Relative humidity (%)	36.4	37.5	35.2	32.8	33	33.4
Solar radiation (w\m)	134	67	32	43	33	29
Detection Point	**S-3**	**S-34**	**S-4**	**S-5**	**S-56**	**S-6**
Temperature (°C)	18.3	17.9	18.1	20	19	19.2
Relative humidity (%)	33.2	34.4	33.3	32.7	33.5	33.8
Solar radiation (w\m)	46	33	29	49	38	31

The primary physical properties of microenvironmental indicators are temperature, humidity, wind speed, and UV radiation on building surfaces. The damage was mainly caused by the humid environment, according to the research on the pathologies of the walls of ancient houses in Guangfu. This study focused on testing environmental factors, including temperature, wind speed and radiation, as well as the humidity of the wall surface and the moisture content of the bricks. The microenvironments of the walls and different areas of the walls in each orientation of the building vary, influenced by the courtyard-like layout and orientation of the buildings. In this study, the environmental data of differently oriented parts of the sample walls were examined and the following preliminary conclusions were drawn by synthesizing the microenvironmental data of the six samples and analyzing them against the damage data:

- Results from the analysis of the average humidity of the walls in each direction of the sample show that the north and west walls have relatively high humidity, while the south and east walls have relatively low humidity. The north and east walls also experience relatively high temperatures, while the south and east walls experience high temperatures (Figure 13a–c). This suggests that temperature and humidity are correlated; at higher temperatures, water evaporation is easier, and at lower temperatures, humidity increases. Meanwhile, changes in wind speed and radiation intensity have an impact on air humidity, as statistical results from environmental parameter measurements show. The data show that these variables are the highest on the south side of the wall, followed by the east side, and with the lowest values found on the north and west sides of the wall. The data suggest that an increase in wind speed and radiation intensity causes moisture to be more easily removed from the brick material, thereby reducing the humidity within the brick wall.
- There are differences in the microenvironmental parameters in different parts of the wall, and they objectively reflect the physical conditions at the time of damage to the masonry by building pathologies. Therefore, the microenvironmental data from different parts of the brick wall were compared and analyzed with the damage data (Figure 13d–f). The damage and brick moisture comparison of the three sample groups showed that the percentage of damaged wall increased with brick moisture content. According to the measured results, the W4 base area of the wall had a higher probability of damage and a higher moisture content in the brick material.

In summary, in the statistics of the data for all orientations and parts of the brick walls of the residential building, the highest humidity was found on the west side and the highest humidity was found in the base area of the W4 wall. Due to the spatial layout of the ancient urban court residence, the internal wind environment is relatively stable and therefore is more affected by light radiation. It is first concluded that due to the shading of wall foundations and other parts of the wall, these areas are exposed to high humidity, low wind speed, and low intensity of light irradiation, and are in a state of sustained water infiltration and accumulation, making it difficult for water to pass through and reduce the ability of moisture to evaporate evaporation, thus leading to the high and concentrated incidence of the damage.

3.3. Compressive Strength of Residential Brick Walls

Due to the different construction times of the dwellings in the old town, the bricks used were affected by the environment at different periods of time, resulting in different types and severities of damage. As a result, the study was carried out to compare the compressive strengths of different test units in the same dwelling and to analyze the compressive strength results of each dwelling separately. In this study, a total of eight dwellings were tested using the rebound method, with three test units per dwelling, for a total of twenty-four test units. This include eight intact units (640 detection points), six damage units of P1 (480 detection points), one damage unit of P2 (80 detection points), three damage units of P3 (240 detection points), one damage unit of P4 (80 detection points), one damage unit of P5 (80 detection points), two damage units of P6 (160 detection points), and two damage units of P7 (160 detection points). Average rebound and compressive strength values were calculated for each residential test unit.

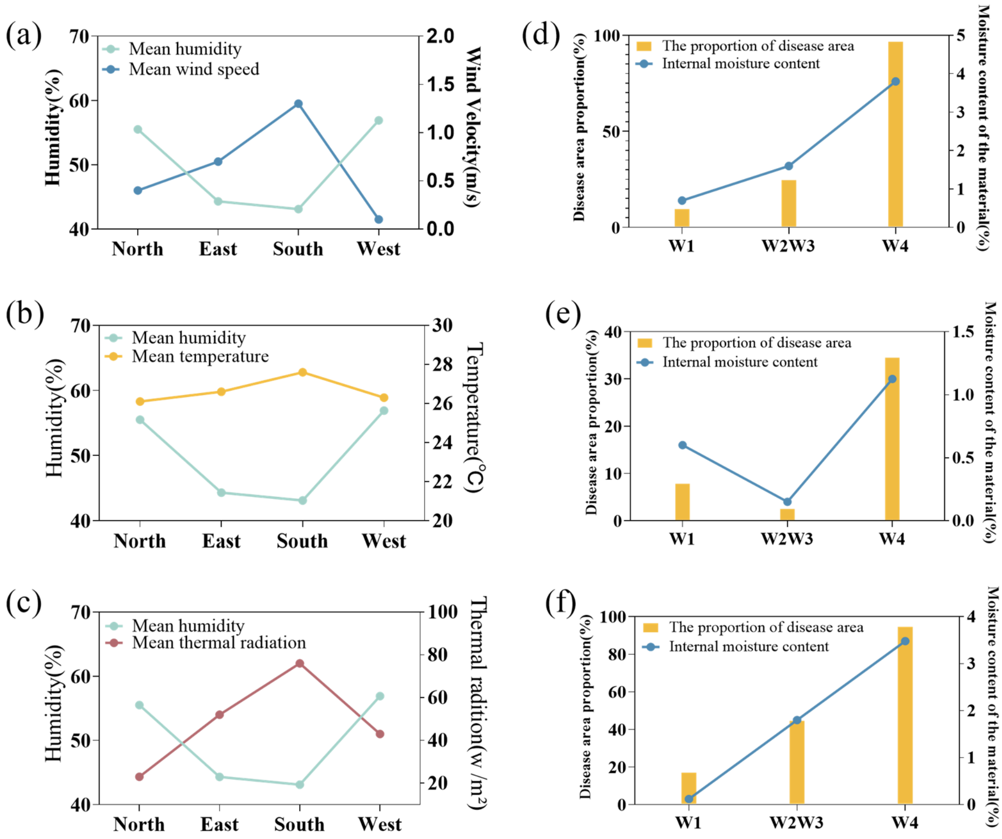

Figure 13. (**a**–**c**) The mean values of humidity, wind speed, temperature, and radiation on the exterior wall surfaces facing various orientations within the same residential structure. (**d**–**f**) The proportion of damage occurrences in various parts of walls and the moisture content of internal materials in different residential buildings.

The findings from the statistics presented in Table 6 are as follows: Within the same dwelling, the compressive strength of the bricks in the damage detection unit was much lower than that of the intact and undamaged detection unit. After combining the eight dwellings for analysis, the bricks of the intact units had an average compressive strength of 13.4 MPa, with the bricks from dwelling no. 2 in the East Village having the highest value at 24.9 MPa and those from dwelling no. 1 in the South Village having the lowest value at 6.1 MPa. The mean value of the compressive strength of the bricks of the damaged units was 5.6 MPa, with the largest compressive strength of the bricks of the P2 unit of the North Village dwelling no. 2 being 11.9 MPa and the smallest of the bricks being 1.6 MPa in the P2 of dwelling no. 2 in the West Village. The 'General Code for Masonry Structures' (GB 55007-2021) stipulates the minimum strength grades for masonry materials [69]. In this study, the urgency of building pathologies is determined by comparing the compressive strength of residential brick materials with the specifications set forth in the code. Meanwhile, the average compressive strength of the housing unit in West Village 2 was the lowest, indicating that the damage posed a major risk to structural safety and there was an urgent need for treatment for the damage.

In summary, the bricks in traditional houses with damaged areas have lower compressive strength than the bricks in the normal, undamaged areas. The compressive strength of bricks is directly related to the structural safety of traditional homes. Therefore, the degree of damage to the structure can be judged by the compressive strength of bricks or brick walls, which determines the method of damage treatment and the degree of urgency for damage treatment.

Table 6. Brick inspection data record sheet.

Detection of Dwellings	Sensor Unit	Average Brick Resilience Value	Brick Compressive Strength/MPa
North Village No. 1	Intact	37.1	12.1
	P1	24.9	2.4
	P3	29.4	5.3
North Village No. 2	Intact	41.8	17.4
	P5	36.9	11.9
	P6	28.2	4.5
East Village No. 1	Intact	34.3	9.3
	P1	26.9	3.6
	P3	27.9	4.3
East Village No. 2	Intact	47.4	24.9
	P1	35.7	10.7
	P7	25.4	2.7
South Village No. 1	Intact	30.4	6.1
	P1	26.7	3.5
	P7	27.6	4.1
South Village No. 2	Intact	35.8	10.8
	P1	28.7	4.8
	P6	34.7	9.7
West Village No. 1	Intact	42.1	17.8
	P1	32.5	7.8
	P4	33.9	9
West Village No. 2	Intact	33.4	8.5
	P3	25.8	3
	P2	23.2	1.6

4. Results and Discussion

4.1. Environmental Influences on the Pathology of Traditional Dwellings

Brick wall dampness damage is influenced by a multitude of factors, leading to variations in the extent of damage manifestation across different environmental samples. In this study, microenvironmental data were collected from six residential buildings within the ancient city. Among them, dwellings a and b were designated as Group 1; dwellings c and d as Group 2; and dwellings e and f as Group 3 (Figure 5). To identify the predominant influencing factors for each sample, we integrated and correlated damage information and environmental data from three groups of residential samples. We then conducted a principal component analysis (PCA) to reduce the dimensionality and compare several variables, utilizing the initial principal components as independent variables in our regression model analysis (Figure 14a). The findings are as follows:

- Figure 14a presents the PCA score plot, illustrating the projection of three groups of residential samples (as shown in Figure 5) onto a new coordinate system defined by the first two principal components. These two principal components account for a combined 62.8% of the total variance in the data, with PC1 explaining 36.8% and PC2 explaining 26.0%. Each point on the score plot represents an individual sample, with its position determined by its scores on PC1 and PC2. The distribution of the sample points reveals their relative positioning along these two principal components, thereby reflecting the similarities and differences among the samples. It is observable from the plot that the samples can be broadly categorized into three distinct clusters, indicating a clear grouping tendency within the data based on the selected principal components. Consequently, there are certain differences between the three sample groups.
- Through principal component analysis (PCA), it has been observed that there are certain distinctions between sample groups. Consequently, an analysis of the principal

component data for humidity and temperature across the three groups of samples has been conducted. The vertical axis of the chart represents relative humidity and wall surface temperature, while the horizontal axis indicates the distance of the wall measurement points from the ground level. Analysis of the temperature and humidity fluctuations depicted in Figure 14b,c reveals a consistent trend across all three sample sets; there is a gradual reduction in wall surface moisture content and a concomitant increase in temperature with increasing height above the ground. This observation suggests that, in addition to climatic and microenvironmental humidity, geographical environmental humidity factors also play a role in the pathology of brick walls in residential structures. For instance, soil moisture can infiltrate the wall through capillary action and then rise along the wall's roots.

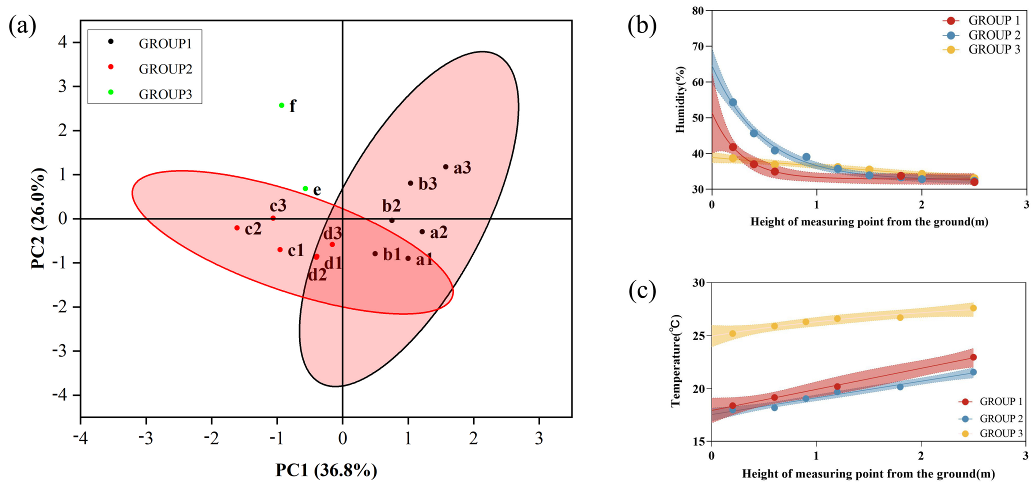

Figure 14. (**a**) Principal component analysis of sample damage environments (In the figure, the letters a, b, . . ., f represent the residences a, b, . . ., f); (**b**) Relationship between sample moisture and distance from the ground; (**c**) Relationship between sample temperature and distance from the ground.

In summary, a variety of factors, including climate, architectural microenvironment, and geographical location, have an impact on residential brick walls. Furthermore, the extent to which these factors influence a given sample varies, suggesting the need for a targeted approach when studying architectural damage [70,71].

4.2. Environmental Effects on the Mechanical Properties of Brick Walls

The primary cause of the damage affecting traditional dwellings in the ancient city of Guangfu is known to be the erosion of the dwellings by water in the surrounding environment, based on an analysis of the pathological environment. In order to schematize the real behavior of the brick in the environmental conditions, quantifying the variability of the performances of building materials in the presence of moisture is essential [72,73]. In this study, the moisture content of brick materials was also tested using a Testo 606-2 material moisture meter during rebound testing of brick walls in traditional dwellings. A correlation analysis was also carried out between the average resilience values and the moisture content of the brick walls. Testing the data for normality revealed that the rebound values followed a normal distribution, but the moisture content did not. Therefore, the choice was made to use Spearman correlation analysis [74].

From the correlation analysis, it can be seen that the correlation coefficient between the rebound value and the moisture content is −0.8017, and the two are negatively correlated with $p < 0.001$, which means that the correlation is statistically significant (Figure 15). Therefore, it is important to analyze the influence of the environment on the mechanical properties of bricks.

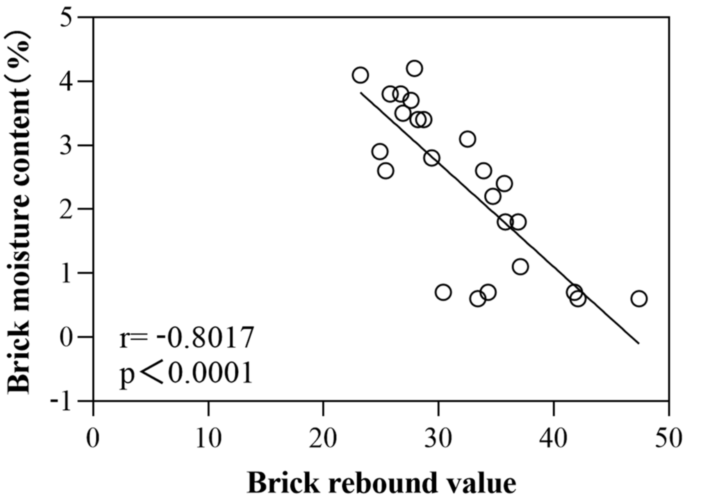

Figure 15. Correlation analysis between resilience values and moisture content of brick walls.

Due to the fact that traditional dwellings are exposed to complex environmental factors over a long period of time, the test results may be subject to some errors. At the same time, the raw material clay used to make bricks varies depending on the local soil composition, resulting in the different properties of the finished bricks. Therefore, in this study, ten traditional residential bricks were selected from the area, including five blue bricks and five red bricks, which were divided into two groups. Each brick was dried and then soaked in a basin so that the bricks had different water content states as follows: dry state, 2% water content, 4% water content, 6% water content, 8% water content, 12% water content and fully saturated. Concurrently, during this process, the moisture content was recorded at hourly intervals to track its variation over time. Brick samples were immediately subjected to a rebound test for each moisture content achieved. After completing the tests, the average of the rebound values at different moisture contents was calculated for each group of brick samples. The influence of moisture content on the elasticity value of brick samples was analyzed by comparing the experimental results of two groups of samples. The test results are listed below (Figure 16a).

From Figure 16a, it can be seen that although the average brick rebound value varies between the two groups of bricks, the values tend to decrease as the moisture content of the bricks increases. At a moisture content from 2% to 6%, the rebound value decreases more significantly, with the maximum decrease being around 3.9. Figure 16b illustrates that the moisture content of the brick material shows an increasing trend during the initial 12 h. Between 12 and 24 h, the moisture content gradually stabilizes, fluctuating within a narrow range. At 21 h, the brick material reaches its peak moisture content. The resilience value of bricks is based on their surface hardness, which is directly impacted by the moisture content of the bricks [75]. Tests have shown that as water erosion of the brick material increases, the mechanical properties of the brick gradually deteriorate. Studies conducted by Lei Z. have reported that moisture infiltration can lead to significant structural damage within a range of specific time periods. Lei Z. conducted an experimental study of moisture in brick masonry in a confined laboratory. The experiment was conducted by placing brick masonry in a pool of water and observing the time of occurrence and distribution of the phenomenon of flooding on the surface of the bricks. During the experiment, the room temperature and humidity were actively regulated by equipment to maintain a stable temperature, humidity, and airflow field. At 168 h, a small number of white crystals began to precipitate on the surface of the brick wall. At 360 h, the alkalized area of the brick wall reached half of the overall area. At 720 h, the brick wall reached the maximum area of alkali [76]. Wall flooding occurs when soluble salts in the water crystallize and precipitate onto the surface of the wall due to evaporation of water inside the wall. When the humidity is high, it dissolves back into the water and returns to the interior of the material. In this process of repeated dissolution and crystallization, the expansion force of salt crystallization continues to expand the original pores, causing damage to the brick masonry structure [77]. Therefore, wet conditions can adversely affect the mechanical properties of traditional residential brick walls, compromising structural integrity and potentially leading to building damage.

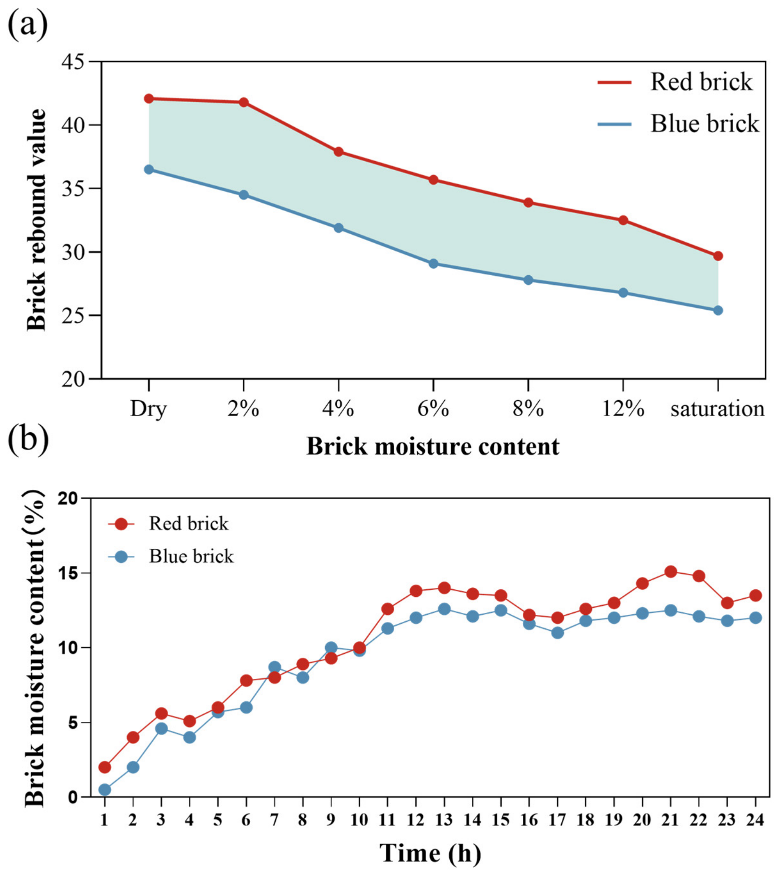

Figure 16. (**a**) Distribution of mean rebound values for each moisture content condition; (**b**) Variation in brick moisture content with time.

4.3. Recommendations for Intervention

The residents of the old city used crude and simple methods to treat the walls of the buildings, such as mixing two types of bricks to fill the missing parts of the walls and applying a layer of veneer directly on the surface of the damaged walls (Figure 17a). The lack of scientific pathological inspection protocols and damage treatment guidance has led residents to take gross measures that not only worsen the damage to the building's historic facade, but also exacerbate the building's ongoing moisture problem [78]. Thus, targeted and scientifically sound strategies need to be developed to address the building's pathologies and extend its service life. On this basis, the following interventions are recommended for the identified construction defects:

(1) Development of an inspection plan

Traditional dwellings should be inspected regularly to maintain their good condition. In addition, scientific pathological investigation methods should be used to deduce causes of damage in traditional residential buildings and identify defects. In this way, data can be obtained to determine preventative measures to preserve these traditional dwellings.

(2) Treatment of building pathologies

Remediation of pathologies should be carried out in such a way that the original appearance of the building is preserved. Suggestions should include targeted repair measures based on the main pathological symptoms of dwellings. If there are signs of wall alkali flooding and corrosion damage to the wall, it is first recommended to clean the wall surface with TiO_2 in order to further assess the extent of the wall damage. Fonseca et al. used a 1% aqueous solution of distilled anatase water to clean facades [79]. The bricks were then categorized and processed according to the mechanical properties of the wall so that the less damaged bricks could be repaired and reused [80]. As for the severely corroded bricks, the bricks were chiseled away and rebuilt according to the type, size, and style of the original bricks. The masonry was removed and replaced at the same time, with a maximum of 60 cm being replaced at once. If there are cracks in the wall, bonding techniques should first be used to restore the entire wall, by applying cement mortar mixed with 107 glue as an adhesive. The width of the crack dictates the consistency of the mortar. Technical reinforcement measures would then be taken. Since the traditional houses in the old town are single-story brick buildings, brick reinforcement hoops can be used to reinforce the walls [81].

(3) Prevention of building pathologies

In the course of studying building pathologies, it was discovered that some of the traditional local houses have a horizontal waterproof layer in the walls, usually made of materials such as reeds or wooden boards (Figure 17b). Based on the original technology, certain measures can be taken to stop the development of building pathologies. For wall surfaces, silicone coatings can be sprayed evenly onto the brick surface to achieve water and weather resistance. Currently, the following two materials are the best ones for achieving that: sodium methylsilanolate and sodium methylsilicate 3‰ aqueous solution [82]. In addition, chemical injections into the wall can be used to address rising humidity levels inside the wall [83].

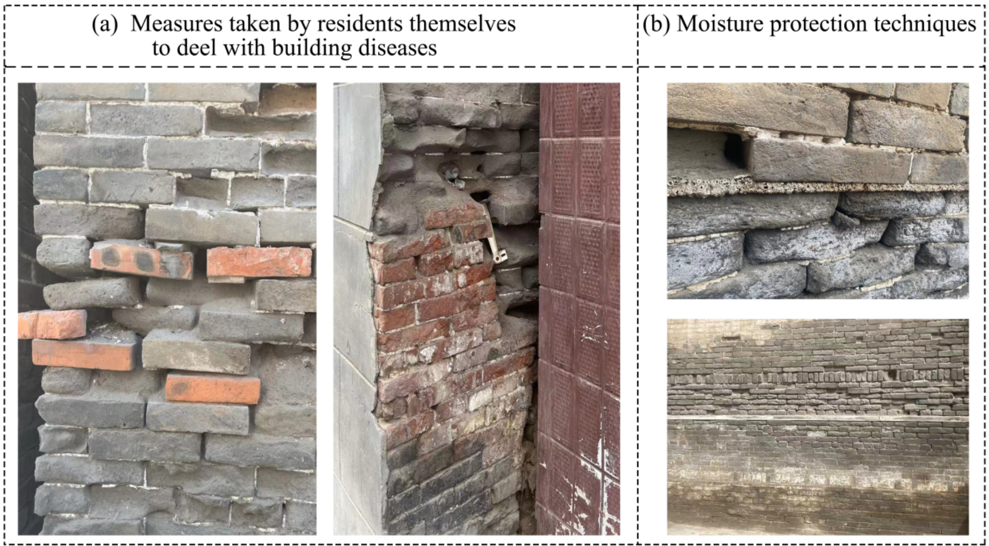

Figure 17. Solutions and preventive measures for existing local construction defects.

5. Conclusions

Traditional brick dwellings are representative vernacular buildings in Northern China, and architectural damage have led to the destruction of their appearance and structure, which has a negative impact on the long-term use and protection of the dwellings. In order to effectively address the damage of dwellings, this article has discussed the process of diagnosing building pathology. The study selected brick houses in the ancient city of Guangfu and examined them using the pathological diagnosis method of "Architectural Pathology Appraisal–Pathological Environment Analysis–Mechanical Properties Testings", proposed in this study. And the symptoms of the ancient city damage, the cause of the damage, and the severity of the damage were derived. The focus of this work is not to identify the causes of damage to the traditional dwellings of Guangfu Ancient City, but to illustrate the rationality and effectiveness of the proposed damage diagnosis method using the example of Guangfu Ancient City. The conclusions reached by the methodology are discussed below as a whole:

- Architectural Pathology Appraisal: Collecting information on damage in traditional dwellings by means of visual inspection and mapping of damage. For example, the damage in Guangfu Ancient City dwellings is concentrated in the lower part of the wall. The damage mostly occurs in the form of pathological combinations, in which the main performance symptoms are corrosion deterioration, wall alkali flooding, and moisture infiltration. By assessing building pathology, the damage types and damaged parts of dwellings are determined to propose targeted cleaning measures for the lower part of the wall and replacement methods for the damaged bricks.
- Pathological Environment Analysis: The regional climatic environment and the microenvironment of the dwellings were collected and tested, respectively, to analyze the causes of damage in traditional dwellings. For example, the climatic environment data of Handan show that there is heavy rainfall in summer in July and August, and this period is prone to condensation phenomena, resulting in the humid environment in brick walls, thus causing dampness damage. Data from microenvironmental testing show that the lowest part of dwelling walls has the highest humidity because this part of the wall is in the shade, where it is difficult for light and wind to reach, and difficult for moisture to escape. At the same time, the moisture content of the bricks gradually decreases from bottom to top, and the lower bricks are in a permanently a wet state, resulting in higher morbidity. Through the analysis of the pathological environment, it is determined that the damage in residential areas is caused by moisture, so targeted measures should be taken for wall surface and internal moisture protection and water blocking.
- Mechanical Properties Testings: A brick rebound tester was used to test the mechanical properties of the brick walls of the dwellings and determine the extent of the damage to the dwellings. For example, the results of the rebound test indicate that the mechanical properties of the damaged parts of the ancient city dwellings are poor. Meanwhile, results of brick rebound tests show that the degree of water infiltration affects the mechanical strength of the bricks. By testing the mechanical properties, the severity of the damage of various dwellings in the ancient city is determined, so as to judge the order of treatment of the damaged dwellings in the ancient city and the type of reinforcement measures to be taken.

In conclusion, given the large quantity and wide distribution of brick houses, this study proposes a low-tech, low-cost pathological diagnostic approach that is universally applicable. And on the basis of past building damage research and environmental analysis, mechanical property testing was added. Through the three steps of the diagnostic method, we analyze the pathologies of dwellings from the surface to the interior to propose effective scientific management measures. This is expected to provide a reference for the identification and treatment of traditional dwelling pathologies in other areas.

6. Limitations and Further Research

This article presents a diagnostic approach to traditional dwelling pathology by starting with solving traditional dwelling damage and combining them with architectural pathology. This approach includes pathological characterization, etiological analysis, and interventions. The method is also applied and verified using the example of the ancient city of Guangfu, showing that it is useful and effective. However, there are differences between the traditional handmade bricks used in the residential buildings of this study and modern bricks. The walls of traditional residences in ancient cities are generally constructed using traditional craftsmanship, where clay bricks are hand-molded and fired to produce blue bricks [62]. In contrast, modern bricks may incorporate modern industrial raw materials, including quartz sand, white clay, and feldspar. The disparate raw materials and manufacturing processes result in different performance characteristics between the two. When calculating compressive strength, this study utilized the strength measurement curve for common modern bricks, which may diverge from the actual compressive strength values. At the same time, the study limited the analysis of the overall performance of the dwellings by focusing only on the bricks of the dwellings after sampling and testing while ignoring the mechanical properties of the mortar. In addition, there is some difficulty in applying the experimental method to simulate the actual environmental conditions and the actual time of occurrence of building damage, and the specific effects of the geographical environment on the residential area are not fully taken into account. For example, the nature of the soil and the water table can influence the level of penetration of wet conditions.

Therefore, subsequent research should involve conducting actual compressive strength tests on local brick materials to verify the accuracy of the rebound method measurements. Additionally, data testing and statistical analysis should be employed to determine the rebound strength curve that aligns with the local brick materials. Moreover, it should investigate and study the soil properties, water table, etc., of the area. Additionally, a multi-parameter, long-time simulation is used to analyze the entire traditional residential house with the aid of simulation software. In our forthcoming research, we will conduct a detailed study on the temporal evolution of various types of structural 'pathologies. We aim to address this issue through the development of models that simulate the moisture force coupling and the migration of moisture and heat within masonry structures, which is crucial for understanding the behavior of brick masonry under different environmental conditions.

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References

1. Tortajada Montalvá, E.; Mileto, C.; Vegas López-Manzanares, F. Assessment Methodology for Physical Vulnerability of Vernacular Architecture in Areas Affected by Depopulation: The Case of Comunidad Valenciana, Spain. *Land* **2024**, *13*, 695. [CrossRef]
2. Rosaleny-Gamón, M.; Cabrera i Fausto, I. Vernacular Architecture Facing a Degrowth Scenario. In *Relevance of Doctoral Research in Architecture*; archiDOCT & Anglia Ruskin University: Cambridge, UK, 2024.
3. Jamil, M.; Shahzad, K.; Mustafa, A. Paradigm Shift of Construction Techniques from Vernacular to Neo—Vernacular in Villages to Sustain Climate Change. *Pak. Soc. Sci. Rev.* **2024**, *8*, 68–81. [CrossRef]
4. Escobar, A.H.; de Miguel, M.L. *Sustainability, Risks and Resilience of Vernacular Heritage*; Taylor & Francis: London, UK, 2024. Available online: https://api.taylorfrancis.com/content/books/mono/download?identifierName=doi&identifierValue=10.4324/9781003475736&type=googlepdf (accessed on 25 June 2024).
5. Xu, H.; Wan, X.; Fan, X. Rethinking the Implementation of Authenticity in Cina's Heritage Conservation—A Case Study of Hongcun Village. *Hum. Geogr.* **2012**, *27*, 107–112. [CrossRef]
6. Korcâk, P. The Goals and Means of Preserving Vernacular Architecture. *ODTÜ Mimar. Fak. Derg.* **1978**, *4*, 139–147. Available online: https://hdl.handle.net/11511/51231 (accessed on 1 July 2024).
7. Wang, D.; Lyu, Q.; Wu, Y.; Fan, Z. The characteristic of regional differentiation and impact mechanism of architecture style of traditional residence. *J. Nat. Resour.* **2019**, *34*, 1864–1885. [CrossRef]
8. Guo, H.; Wang, Y.; Fei, F.; Xu, C. Optimizing and Transforming Measures of Winter Thermal Environment of Guangfu Residence in Handan Guided by Subjective and Objective Evaluation. *J. Tianjin Chengjian Univ.* **2023**, *29*, 108–115. [CrossRef]
9. Li, Q.; Qi, Q. Spatial Form Research of Guangfu Ancient City in Handan. *Archit. Cult.* **2020**, *1*, 242–243. [CrossRef]
10. Xie, K.; Zhao, H.; Yan, J.; Liu, L. Study on the Protection and Utilization of Guangfu Ancient City. *Archit. Cult.* **2021**, 105–106. [CrossRef]

11. Zhu, L. Considerations on Some Questions of Traditional Villages Research. *South Archit.* **2017**, *1*, 4–9. [CrossRef]
12. Mileto, C.; Vegas, F.; García, L.; Pérez, A. Assessment of vulnerability of earthen vernacular architecture in the Iberian Peninsula to natural risks. Generation of an analysis tool. In *Sustainability, Risks and Resilience of Vernacular Heritage*; Taylor & Francis: London, UK, 2024; pp. 69–82.
13. Do Rosário Veiga, M.; Fragata, A.; Velosa, A.L.; Magalhães, A.C.; Margalha, G. Lime-based mortars: Viability for use as substitution renders in historical buildings. *Int. J. Archit. Herit.* **2010**, *4*, 177–195. [CrossRef]
14. Lu, D. 50 Years' Researches on Chinese Folk House. *Archit. J.* **2007**, *11*, 66–69. [CrossRef]
15. Li, Z.; Lv, Y. Several Key Issues in the Study of the Integrity of Southern Vernacular Construction Techniques. *South Archit.* **2018**, *6*, 51–55. [CrossRef]
16. Zhang, D.; Zhang, W.; Chen, D. Analysis and exploration of the concept of traditional settlement protection and development cluster mode in the new period. *Urban Dev. Stud.* **2022**, *29*, 16–21+39. [CrossRef]
17. Porretta, P.; Pallottino, E.; Colafranceschi, E. Minnan and hakka tulou. Functional, typological and construction features of the rammed earth dwellings of Fujian. *Int. J. Archit. Herit.* **2022**, *16*, 899–922. [CrossRef]
18. Lin, Y.; Huang, T.; Yang, W.; Hu, X.; Li, C. A Review on the Impact of Outdoor Environment on Indoor Thermal Environment. *Buildings* **2023**, *13*, 2600. [CrossRef]
19. Groak, S. *The Idea of Building: Thought and Action in the Design and Production of Buildings*; Taylor & Francis: London, UK, 2002.
20. Vicente, R.; Ferreira, T.M.; Da Silva, J.R.M. Supporting urban regeneration and building refurbishment. Strategies for building appraisal and inspection of old building stock in city centres. *J. Cult. Herit.* **2015**, *16*, 1–14. [CrossRef]
21. Freitas, S.S.; de Freitas, V.P. Cracks on ETICS along thermal insulation joints: Case study and a pathology catalogue. *Struct. Surv.* **2016**, *34*, 57–72. [CrossRef]
22. Torres, M.I.M.; de Freitas, V.P. Treatment of rising damp in historical buildings: Wall base ventilation. *Build. Environ.* **2007**, *42*, 424–435. [CrossRef]
23. Singh, J.; Yu, C.W.F.; Kim, J.T. Building pathology, investigation of sick buildings—Toxic moulds. *Indoor Built Environ.* **2010**, *19*, 40–47. [CrossRef]
24. Cheng, S.; Liu, S. Study on the disease characterization and factors of concrete materials of historic architecture in plum rainy climate zone. *Concrete* **2022**, *1*, 79–83+91. [CrossRef]
25. Pan, J.; Lan, J.; Huang, T.; Wang, Y.; Tang, Y. Technical System and Practical Cases of the Plant Disposal on the Top Surface of the Great Wall Heritage Site. *Chin. Landsc. Archit.* **2024**, *40*, 22–27. [CrossRef]
26. Meng, W.; Shang, H.; Gu, L.; Wu, Y.; Hou, G. Study on the Disease Evaluation System of Brick and Wood Structure Historical Buildings in Qingdao Area. *Low Temp. Archit. Technol.* **2024**, *46*, 1–5+11. [CrossRef]
27. Dai, S.; Zhong, Y. Frontier Applied Technologies of Material Pathology Diagnosis, Repair, and Monitor on Historic Building Conservation. *Bull. Chin. Acad. Sci.* **2017**, *32*, 749–756. [CrossRef]
28. Shen, Y.; Liu, S.; Cheng, P. Study on the Pathogenic Environment of Timber Architectural Heritage Along the Southeast Coast of China. *World Archit.* **2023**, *9*, 114–119. [CrossRef]
29. Wang, F. A preliminary survey of the interior temperature and humidity of historic buildings in the Palace Museum. *Sci. Conserv. Archaeol.* **2014**, *26*, 85–93. [CrossRef]
30. Lei, Z.; Zhang, Y.; Wan, L. Forensics, Diagnosis, and Evidence Base: Exploration of the Building Pathology of the Town God's Temple Murals in sTong-vkhor, Qinghai, Under the Influence of Environmental Climate. *South Archit.* **2020**, *5*, 70–77.
31. Sitzia, F.; Lisci, C.; Mirao, J. Building pathology and environment: Weathering and decay of stone construction materials subjected to a Csa mediterranean climate laboratory simulation. *Constr. Build. Mater.* **2021**, *300*, 124311. [CrossRef]
32. Bi, W.; Yan, Z.; Zhang, Z.; Yao, S.; Zhang, J.; Wang, X. Modeling and numerical simulation of heat and mass transfer in the cave wall of the Mogao Grottoes in China. *Build. Environ.* **2021**, *201*, 108003. [CrossRef]
33. Zahs, V.; Anders, K.; Kohns, J.; Stark, A.; Höfle, B. Classification of structural building damage grades from multi-temporal photogrammetric point clouds using a machine learning model trained on virtual laser scanning data. *Int. J. Appl. Earth Obs. Geoinf.* **2023**, *122*, 103406. [CrossRef]
34. Hola, A.; Czarnecki, S. Brick wall moisture evaluation in historic buildings using neural networks. *Autom. Constr.* **2022**, *141*, 104429. [CrossRef]
35. Prieto, A.J.; Silva, A.; De Brito, J.; Macías-Bernal, J.M.; Alejandre, F.J. The Influence of Pathological Situations on Churches' Functionality: An Approach Based on Historical Records. *Int. J. Archit. Herit.* **2017**, *11*, 566–587. [CrossRef]
36. Moropoulou, A.; Labropoulos, K.C.; Delegou, E.T.; Karoglou, M.; Bakolas, A. Non-destructive techniques as a tool for the protection of built cultural heritage. *Constr. Build. Mater.* **2013**, *48*, 1222–1239. [CrossRef]
37. Kordatos, E.Z.; Exarchos, D.A.; Stavrakos, C.; Moropoulou, A.; Matikas, T.E. Infrared thermographic inspection of murals and characterization of degradation in historic monuments. *Constr. Build. Mater.* **2013**, *48*, 1261–1265. [CrossRef]
38. Molero, M.; Segura, I.; Izquierdo MA, G.; Fuente, J.V.; Anaya, J.J. Sand/cement ratio evaluation on mortar using neural networks and ultrasonic transmission inspection. *Ultrasonics* **2009**, *49*, 231–237. [CrossRef]
39. Carpinteri, A.; Lacidogna, G. Damage monitoring of an historical masonry building by the acoustic emission technique. *Mater. Struct.* **2006**, *39*, 161–167. [CrossRef]

40. López-González, L.; Gomez-Heras, M.; de Cosca, R.O.O.; Garcia-Morales, S.; Fort, R. Coupling electrical resistivity methods and GIS to evaluate the effect of historic building features on wetting dynamics during wind-driven rain spells. *J. Cult. Herit.* **2022**, *58*, 209–218. [CrossRef]
41. Bersch, J.D.; Verdum, G.; Lamego Guerra, F.; Falcao Socoloski, R.; Giordani, C.; Zucchetti, L.; Borges Masuero, A. Diagnosis of pathological manifestations and characterization of the mortar coating from the facades of historical buildings in Porto Alegre—Brazil: A Case Study of Chateau and Observatorio Astronomico. *Int. J. Archit. Herit.* **2021**, *15*, 1145–1169. [CrossRef]
42. Shen, Y.; Liu, S. Salt Efflorescence Damage of Architectural Heritage along the Southeast Coast of China Based on Micro-environment Parameters. *Archit. J.* **2022**, *S2*, 61–67.
43. Li, Q.; Zhang, S.; Shen, S. The Study on the Development of Guangfu Ancient City Based on the Influence of Water Environment. *Tradit. Chin. Archit. Gard.* **2024**, *1*, 94–97.
44. Guo, H.; Wang, Y.; Fei, F.; Xu, C.; Wang, L. Research on the Indoor Thermal Environment of Traditional Houses in Handan Guangfu Ancient City in Summer. *Build. Sci.* **2023**, *39*, 90–96+192. [CrossRef]
45. Xie, K.; Zhao, H.; Jin, B.; Lin, X. Study on the Streets, Lanes and Dwellings of Guangfu Ancient City. *Urban. Archit.* **2021**, *18*, 80–82+96. [CrossRef]
46. Wang, Z.; Yang, Z. Cracks in Masonry Houses in Rural Areas and Preventive Treatment Measures. *Agric. Technol. Serv.* **2011**, *28*, 385–386+410. [CrossRef]
47. Wu, C.; Cui, Q.; Lu, Z.; Li, J.; Wu, C. Study on the construction technology for masonry structure reinforcement and renovation. *Archit. Technol.* **2023**, *54*, 1483–1486. [CrossRef]
48. Su, S. Study on the Prevention and Treatment Measures of Alkali Flooding on Clear Water Brick Walls. *Jiangxi Build. Mater.* **2017**, *9*, 129+133. [CrossRef]
49. Feng, N.; Wang, H.; Wang, S.; Song, D.; Zhu, H. Study of efflorescence on the city wall of Xi'an. *Sci. Conserv. Archaeol.* **2012**, *24*, 26–30. [CrossRef]
50. Carretero-Ayuso, M.J.; Rodríguez-Jiménez, C.E.; Bienvenido-Huertas, D.; Moyano, J.J. Interrelations between the types of damages and their original causes in the envelope of buildings. *J. Build. Eng.* **2021**, *39*, 102235. [CrossRef]
51. People's Government of Yongnian County. *Famous Towns of Chinese History and Culture: Guangfu Welcome Materials*; General Office of Handan Municipal People's Government: Handan, China, 2011.
52. Wang, L.; Yao, S. *Building Pathology: Diagnosis and Countermeasures for Common Building Diseases*; China Electric Power Press: Beijing, China, 2002. Available online: http://www.shukui.net/book/1372966.html (accessed on 6 May 2024).
53. Lei, Z.; Sun, Z. Salt Study on Field Survey Methods of Dampness Damage in Buildings: Taking the Taoist Classics Library in Wudang Mountains as an Example. *Archit. J.* **2011**, *S2*, 22–27.
54. Lei, Z.; Wan, L.; Zhang, Y. Investigation, Diagnosis, Assessment and Conservation Strategy for a Wall Painting at Wudang Mountain Taoist Temple Using BIM Technology. *Stud. Conserv.* **2018**, *63* (Suppl. S1), 377–380. [CrossRef]
55. Meteorological Data Room, Meteorological Information Center, China Meteorological Administration. *China Building Thermal Environment Analysis Specialized Meteorological Data Set*; China Construction Industry Press: Beijing, China, 2005.
56. Raposo, P.C.; Correia, J.A.; Sousa, D.; Salavessa, M.E.; Reis, C.; Oaliveira, C.; de Jesus, A. Pathological Inspection of Structural Masonry Walls of a Late-Romantic Historical Building. *Procedia Struct. Integr.* **2017**, *5*, 1102–1107. [CrossRef]
57. Xiao, J.; Liu, W.; Tan, X.; Yang, W. Research on Strength Testing Methods for Bricks of Historically Preserved Buildings. *Eng. Mech.* **2010**, *27* (Suppl. S2), 276–279.
58. Liu, S.; Chen, S. The Impact of Meteorological Parameters on Salt Efflorescence Damage of Historic Architecture in Cold Regions. *Archit. J.* **2017**, *2*, 11–15. [CrossRef]
59. Li, Q. Questions and suggestions on the absence of frost resistance indexes for bricks and blocks in GB 13544-2011. *Brick-Tile* **2012**, *11*, 105–115. [CrossRef]
60. Ding, W. Study on the Strong Measurement Technique of Wall Bricks in Ancient Buildings. *Constr. Qual.* **2019**, *37*, 48–51. [CrossRef]
61. Nunes, C.; Skružná, O.; Válek, J. Study of nitrate contaminated samples from a historic building with the hygroscopic moisture content method: Contribution of laboratory data to interpret results practical significance. *J. Cult. Herit.* **2018**, *30*, 57–69. [CrossRef]
62. Ding, W.; Wang, Z.; Liu, B.; Liu, C.; Li, P. Research on rebound detection technology of ancient city wall bricks. *Build. Struct.* **2014**, *44*, 83–86. [CrossRef]
63. Song, X.; Ou, L. Study on construction of brick rebound strength measurement curve in Qing dynasty imperial tomb city. *Brick-Tile* **2023**, *11*, 23–25. [CrossRef]
64. World Health Organization. WHO Guidelines for Indoor Air Quality: Dampness and Mould. 2009. Available online: https://www.who.int/publications/i/item/9789289041683 (accessed on 16 July 2024).
65. Liu, N.; Liu, W.; Deng, F.; Liu, Y.; Gao, X.; Fang, L.; Chen, Z.; Tang, H.; Hong, S.; Pan, M.; et al. The burden of disease attributable to indoor air pollutants in China from 2000 to 2017. *Lancet Planet. Health* **2023**, *7*, e900–e911. [CrossRef]
66. Urso, A.; Evola, G.; Costanzo, V.; Nocera, F. A critical analysis on the use of different weather datasets to assess moisture-related risks in building components for a Mediterranean location. *J. Build. Eng.* **2023**, *76*, 107177. [CrossRef]
67. Zhu, L.; Liu, S.; Zhu, Y. Influence of Comprehensive Physical Environment Parameters on Wet Diseases of Plastered Cultural Relics in Three Southeastern Coastal Provinces. *Archit. J.* **2022**, *S2*, 68–73.

68. Tang, S.; Liu, S.; Zhu, Y. Research on diseases of brick cultural relics in southeast coastal areas based on microenvironment parameter detection. *Contemp. Archit.* **2023**, *7*, 123–128.
69. *GB 55007-2021*; General Code for Masonry Structure. Standardization Administration of the People's Republic of China: Beijing, China, 2021.
70. de Oliveira, L.M.; Mesquita, E.F.; de Oliveira Freire, F.L.; Bertini, A.A. The influence of the bricks and mortar characteristics, paint, and salts on the rising damp of historic masonries through hygrothermal simulation. *J. Cult. Herit.* **2023**, *64*, 92–101. [CrossRef]
71. Panico, S.; Herrera-Avellanosa, D.; Troi, A. Monitoring rising damp in solid masonry walls: An experimental comparison of five different methods. *J. Build. Eng.* **2023**, *75*, 106999. [CrossRef]
72. Vitiello, V.; Castelluccio, R.; Merino, M.D.R. Experimental research to evaluate the percentage change of thermal and mechanical performances of bricks in historical buildings due to moisture. *Constr. Build. Mater.* **2020**, *244*, 118107. [CrossRef]
73. Hoła, A.; Matkowski, Z.; Hoła, J. Analysis of the moisture content of masonry walls in historical buildings using the basement of a medieval town hall as an example. *Procedia Eng.* **2017**, *172*, 363–368. [CrossRef]
74. Fan, R.; Meng, D.; Xu, D. Survey of Research Process on Statistical Correlation Analysis. *Math. Model. Its Appl.* **2014**, *3*, 1–12. [CrossRef]
75. Li, S. Reuse and Restoration of Green Brick Materials in Lingnan Ancient Buildings. *Cult. Ind.* **2018**, *63* (Suppl. S1), 377–380.
76. Lei, Z.K.; Zheng, J.H.; Zhou, L. Experimental Study of the Characteristics of Damp and Efflorescence Mechanism for Building Brick. *Adv. Mater. Res.* **2012**, *535*, 1697–1701. [CrossRef]
77. Kong, Z.; Li, Y.; Hokoi, S.; Hu, S. The rising damp in two traditional clay-brick masonry walls and influence on heat transfer performance. In *MATEC Web of Conferences, Proceedings of the 4th Central European Symposium on Building Physics (CESBP 2019), Prague, Czech Republic, 2–5 September 2019*; EDP Sciences: Ulis, France, 2019; Volume 282, p. 02097. [CrossRef]
78. Yi, S.; Wang, Z.; Zhang, C.; Li, G. The detection technique for compress strength of sintered clay perforated brick by resilience method. *Brick Tile World* **2006**, *4*, 40–42. [CrossRef]
79. Alfano, F.R.A.; Palella, B.I.; Riccio, G. Moisture in historical buildings from causes to the application of specific diagnostic methodologies. *J. Cult. Herit.* **2023**, *61*, 150–159. [CrossRef]
80. Fonseca, A.J.; Pina, F.; Macedo, M.F.; Leal, N.; Romanowska-Deskins, A.; Laiz, L.; Gómez-Bolea, A.; Saiz-Jimenez, C. Anatase as an alternative application for preventing biodeterioration of mortars: Evaluation and comparison with otherbiocides. *Int. Biodeterior. Biodegrad.* **2010**, *64*, 388–396. [CrossRef]
81. Chen, Y. Construction Technology of Structural Reinforcement and Appearance Restoration of Excellent Historical Buildings. *Build. Constr.* **2024**, *4*, 515–518. [CrossRef]
82. Guo, S. *Conservation and Restoration Engineering of Chinese Heritage Buildings*; Peking University Press: Beijing, China, 2014.
83. van Hees, R.P.; Lubelli, B.; Hacquebord, A. CNew test methods to verify the performance of chemical injections to deal with rising damp. *J. Cult. Herit.* **2018**, *31*, S52–S59. [CrossRef]