

Computational Hygrothermal Analysis of External Wall Behavior in Naturally Ventilated and Air-conditioned Historical Buildings in Thailand

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ABSTRACT

Moisture in historical buildings has long been a significant problem in Thailand, causing damage to structural elements, wall materials, and indoor air quality. While some issues are attributed to inherited structural systems, many result from changes in space use, particularly the introduction of air-conditioning, which alters hygrothermal performance. This study examines heat and moisture transfer in historical buildings using computational hygrothermal analysis (WUFI), comparing air-conditioned and naturally ventilated cases, with and without wall-cutting interventions, in Thailand's hot-humid climate. The results present the average water content (kg/m^3) in exterior walls across three upper sections and one lower section under both conditions. The findings indicate that in air-conditioned historical buildings, water content in the middle and bottom sections of the upper exterior wall is influenced by dry, lower-temperature indoor conditions. The reduced relative humidity of conditioned air promotes higher evaporation, lowering the damp rise height and reducing water content by 2.83 and 5.13 kg/m^3 in the middle and bottom sections of the upper wall, respectively, compared with naturally ventilated cases. The air-conditioning system has only a slight effect on the hygrothermal behavior of retrofitted walls after wall-cutting interventions, with an approximately 2 kg/m^3 higher water content across all upper sections in the conditioned case compared with the naturally ventilated case. Meanwhile, wall cutting has a greater effect in unconditioned spaces, with larger reductions in water content above the cut but increased moisture below due to redistribution.

Keywords: naturally ventilated and air-conditioned historical buildings, hot and humid climate, heat and moisture transfer behaviors, computational hygrothermal analysis (WUFI), rising damp

INTRODUCTION

Conservation of Thailand's historical buildings, valued not only for their physical and architectural characteristics but also for their cultural and social significance within local communities (Madhury & Sarker, 2024), involves challenges related to material deterioration, environmental conditions, and the selection of appropriate intervention strategies (Tienthavorn, 2024). The first, material deterioration, extending from the presence of moisture, such as rising damp, negatively impacts structural integrity and, therefore, requires interventions that should be carefully evaluated for technical performance and heritage value. It includes deterioration of wall materials, which affects both durability and surface appearance, thereby influencing the building's exterior aesthetics. Moisture can reduce the load-bearing capacity of structural materials. It can also promote mold growth on surfaces or within the voids of building components, which subsequently affects indoor air quality.

Moisture in buildings may originate from various sources, including rain leakage through joints or cracks in the building envelope, condensation forming water droplets, capillary suction drawing moisture from the ground through porous materials, and diffusion caused by differences in air pressure (Jareemit, 2018). Initial moisture embedded in construction materials can also contribute to moisture accumulation. Among these causes, capillary suction, which leads to rising damp, the process of drawing water from the ground through the pores of building materials (Künzel, 1995), is considered the most significant factor in traditional and historical buildings. It takes place when the adhesive forces between water and pore surfaces exceed the cohesive forces within the water (Franzoni, 2014).

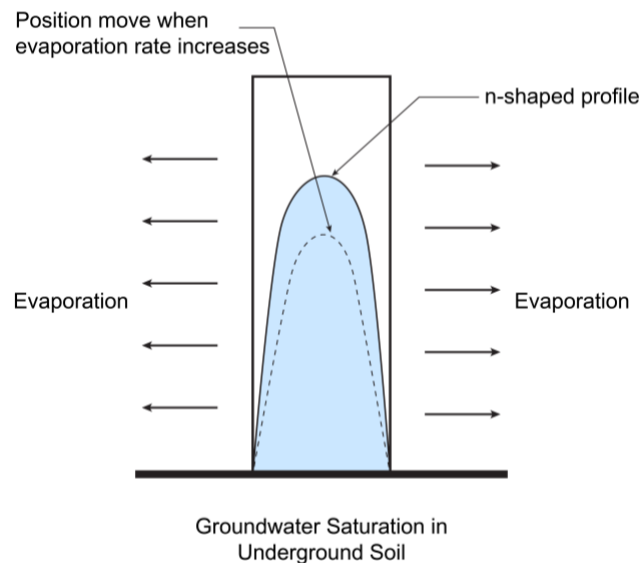
The height and distribution of moisture within walls are governed by the balance between capillary absorption and evaporation, forming a dynamic equilibrium (Falchi et al., 2018; Franzoni, 2014; Guimaraes et al., 2012a). This equilibrium is influenced by factors such as

material porosity, pore structure, evaporation rate, and ground moisture availability (Falchi et al., 2018; Franzoni, 2014; Guimaraes et al., 2012a). Among these factors, evaporation rate plays a particularly important role, as it is affected by temperature, humidity, air movement, and wall surface conditions. Higher evaporation rates generally reduce the height of moisture rise by increasing moisture loss from wall surfaces Rirsch and Zhang (2010). In this way, wall thickness and capillary structure are similarly key factors influencing rising damp behavior. Here, the interaction between capillary rise and evaporation was further conceptualized by Mason (1974), who proposed an n-shaped moisture distribution profile of equilibrium conditions within a wall. Figure 1 illustrates this equilibrium between capillary rise and surface evaporation. These mechanisms are particularly relevant to historical buildings, where porous masonry materials and the absence of effective damp-proof systems often increase susceptibility to rising damp.

Crucially, historical buildings, including those found in Thailand (Jungsiriarrak, 1997), often feature load-bearing walls that extend continuously from the ground to above-ground levels. These walls are constructed from porous masonry materials and lack moisture prevention techniques in their original construction (Emerisda, 2014). Materials such as highly porous fired bricks (Issarathumnoon, 2018; Jungsiriarrak, 1997; Pinich & Mahdavi, 2020) facilitate the absorption and upward movement of ground moisture through their pore structure, and given their long period of exposure, increase the likelihood of moisture-related deterioration. Rising damp occurs in materials that are both hygroscopic and capillary-active, such as brick, plaster, mortar, and stone, whereas materials such as fiberglass and mineral wool do not exhibit this behavior (Künzel, 1995). Additionally, above-ground wall sections are influenced by both external and internal environmental conditions, including temperature variations, humidity levels, rainfall on exterior surfaces, and solar radiation, which can increase the evaporation rate of moisture within the walls (Guimaraes et al., 2012b; Rirsch & Zhang, 2010).

Figure 1

Schematic Diagram of a Brick Wall Illustrating the Equilibrium Between Capillary Rise and Surface Evaporation, Showing the N-Shaped Moisture Distribution



Note. Profile adapted from “Rising damp in masonry walls and the importance of mortar properties,” by E. Rirsch & Z. Zhang, 2010, *Construction and Building Materials*, 24(10), p. 1816 (<https://doi.org/10.1016/j.conbuildmat.2010.04.024>). Copyright 2010 by Eric Rirsch and Zhongyi Zhang.

Among these factors, changes in air humidity play a key role in determining the moisture content within building walls, with air-conditioning systems playing a primary role in influencing indoor air humidity levels. At present, air conditioning is widely used in Thailand, including in retrofitted historical buildings. Split-type air-conditioning systems are among the most commonly used in renovated buildings due to their relatively low installation cost, compact size, and ease of integration into existing structures without requiring significant alterations to the original architectural character. In addition to improving thermal comfort for occupants and visitors, particularly in buildings repurposed as museums, libraries, or religious facilities, these systems can also influence moisture behavior. Air-conditioning systems operate by removing heat from indoor air and releasing it outdoors, resulting in a reduction in both temperature and indoor humidity levels (Greens Energy, 2024).

As moisture distribution within masonry walls is strongly affected by indoor environmental conditions, particularly in air-conditioned buildings, appropriate remedial strategies for rising damp become increasingly important in historical building conservation. Addressing rising damp in historical masonry façades has long

posed a significant challenge in building conservation, leading to the development of various remedial approaches. Emerisda (2014) classified these remedial methods into two main categories. The first category includes approaches that prevent or restrict moisture rise, such as damp-proof courses achieved through mechanical interruption, chemical injection, evaporation enhancement, and electrokinetic systems. The second category consists of methods that mitigate visible effects, including special plaster applications, veneer walls, and drainage measures. Franzoni (2014) further refined this classification into four repair systems based on the key factors governing rising damp height, namely water supply, evaporation rate, and wall materials or structure. These approaches aim to reduce moisture accumulation by controlling groundwater supply, enhancing evaporation, modifying wall materials or structures, and redirecting moisture through electro-osmotic techniques. Among these approaches, mechanical interruption, or wall cutting, remains one of the most established and widely used techniques. It involves inserting impermeable or low-absorption layers, such as bituminous membranes, steel plates, or plastic sheets, into masonry joints to block upward

moisture movement (Emerisda, 2014; Freitas & Torres, 2003).

When properly executed, wall cutting can effectively interrupt capillary action above the insertion level (Franzoni, 2014). However, its performance depends heavily on careful construction, particularly at joint overlaps and during mortar repair. In heritage contexts, improper execution of wall cutting may lead to localized cracking or require sensitive detailing to preserve façade authenticity. Moreover, even when concealed, new moisture pathways may form, affecting long-term durability (Emerisda, 2014; Franzoni, 2014). Despite these considerations, wall cutting continues to be widely adopted, particularly in cases of severe and persistent rising damp. In Thailand, it is recognized as one of the most common and effective methods due to the availability of local expertise and its suitability for conditions of high groundwater levels and a hot-humid climate. Accordingly, the study presented in this paper aims to evaluate the performance of wall cutting under controlled conditions using hygrothermal analysis to examine transient heat and moisture behavior within masonry wall assemblies.

To achieve this, hygrothermal analysis was employed to examine the transfer of heat and moisture through building components, including floors, roofs, and walls, as well as their capacity to store thermal and moisture loads (Fraunhofer Institute for Building Physics, 2025a). Such simulations are widely used to evaluate building assembly performance and to assess risks related to durability under varying environmental conditions (Franzoni, 2014; Holm & Künzle, 2003). Numerical approaches are particularly valuable for analyzing historical building façades and identifying viable retrofit strategies (e.g., Mundt-Petersen & Harderup, 2013; Othmen et al., 2014). In this study, WUFI 2D-3.4 was employed to investigate the hygrothermal performance of building components. Developed by the Fraunhofer Institute for Building Physics (IBP), the software conforms to BS EN 15026:2007 and has been validated through comparisons with laboratory measurements and outdoor field data. Its reliability is further supported by previous studies (Alev et al., 2014; Hägerstedt & Arfvidsson, 2010; Mundt-Petersen & Harderup, 2013). Therefore, WUFI is

considered an appropriate tool for hygrothermal analysis.

In WUFI, a comprehensive set of input data is required, including the design of the building component, material properties, climatic boundary conditions, and surface transfer conditions. Based on these inputs, the software calculates the transient distributions of temperature, relative humidity, and water content within the material. In WUFI, water content represents the amount of liquid water within the material and is defined through the moisture storage function (Fraunhofer Institute for Building Physics, 2025b), while relative humidity refers to the moisture condition of the pore air and significantly influences the moisture behavior of porous materials (Fraunhofer Institute for Building Physics, 2025c).

Complementing these simulation approaches, previous studies on historical buildings in Thailand provide valuable empirical insights into moisture behavior under real climatic conditions. Early work examined condensation problems in religious buildings, such as the study of the ordination hall at Wat Kamphaeng (Sirithummapiti, 1999), which demonstrated that moisture problems in churches and temples are not solely caused by rising damp but also by condensation at the lower wall near the ground and the upper wall close to the roof. Condensation on the inner roof tiles was found to occur during nighttime and early morning when surface temperatures dropped below the dew point, with additional influences from occupancy, air leakage, and rapid outdoor temperature changes.

Subsequent studies investigated the variability of moisture accumulation in historic structures. Popradit (2011) found that outdoor temperature and relative humidity strongly influenced indoor thermal and humidity conditions. While indoor conditions remained relatively stable, outdoor variations, particularly in the north and south orientations, significantly affected wall moisture behavior. The study also found that moisture accumulation varied with wall height, with the highest levels occurring at approximately 1.0 meter above ground level, highlighting the combined effects of climate and building geometry. In a related study, Pinich and Sreshtaputra (2015) explored the relationship between wall moisture and surface deterioration

at Wat Niwet Thammaprawat. The study found that areas with higher moisture levels exhibited more severe surface deterioration, including blistering and peeling paint, while orientation-related differences suggested that additional environmental factors contributed to the progression of surface deterioration.

More recent research has applied computational approaches to investigate hygrothermal behavior in tropical climates. Pinich and Mahdavi (2020) employed computational modeling and sensitivity analysis to evaluate post-retrofit moisture behavior in temple brick walls and demonstrated the potential of simulation-based approaches for supporting retrofit strategies in hot-humid climates. Research has also examined moisture-related problems in air-conditioned buildings, particularly condensation risk and moisture penetration through wall assemblies. In this context, Benjaporn (2001) evaluated several common wall types and found that lightweight concrete walls were the least effective in resisting moisture penetration, whereas EIFS systems performed best by maintaining wall surface temperatures above the dew point and reducing condensation risk. The study also highlighted exterior wall insulation as an effective strategy for preventing moisture ingress and condensation. Further addressing moisture-related issues in historical buildings, Leerungruangpan and Sreshthaputra (2018) analyzed thermal comfort in repurposed historical buildings, including the National Museum Bangkok, O.P. Place, and the Ministry of Interior. By combining occupant surveys with environmental measurements, the study proposed mechanical dehumidification as a practical strategy for reducing moisture accumulation.

Collectively, previous research on moisture behavior and environmental performance in Thailand's historical buildings demonstrates the complex interactions between climate, building materials, and use patterns. These studies provide both diagnostic insights and practical strategies that support conservation and moisture management within the context of environmental change. However, studies employing in-depth hygrothermal simulations to observe moisture behavior within historical walls under conditioned indoor environments in tropical climates remain limited. Addressing this gap would provide valuable insights for understanding hygrothermal

behaviors and supporting effective conservation strategies.

Within this contextual framework, the research presented in this paper employs computational hygrothermal analysis to investigate heat and moisture transfer behaviors in a case-study historical building in Thailand. The analysis compares naturally ventilated and air-conditioned conditions and further evaluates two wall scenarios: the original wall assembly and a refurbished case incorporating wall cutting through the insertion of an impermeable layer. By examining these conditions, the research aims to provide a deeper understanding of moisture accumulation in air-conditioned historical buildings and to inform appropriate maintenance strategies for historical walls. Specifically, the following research questions are addressed: (1) How do heat and moisture transfer behaviors in the exterior walls of a historical building differ between naturally ventilated and air-conditioned conditions? (2) To what extent does the wall-cutting intervention affect moisture accumulation in these walls under both environmental conditions? The findings are expected to support the prevention of moisture-related deterioration and contribute to conservation practices for historical buildings in Thailand.

METHODOLOGY

The methodology begins with a review of theoretical and empirical insights into moisture phenomena in historical building materials, focusing on moisture generation, accumulation, and coupled heat–moisture transfer mechanisms. Material attributes such as moisture storage capacity, liquid transport coefficient, and water vapor diffusion resistance are considered alongside construction characteristics and the influence of air conditioning systems on indoor humidity. For the computational analysis, this study employs WUFI 2D-3.4, a two-dimensional hygrothermal simulation tool developed by the Fraunhofer Institute for Building Physics. WUFI performs dynamic coupled heat and moisture transfer simulations under realistic climate boundary conditions and has been extensively validated through laboratory and full-scale experiments, making it an appropriate tool for

analyzing historical wall performance. The case study examines a historical building in Thailand under two indoor environmental scenarios: an air-conditioned condition and a naturally ventilated condition. Two wall construction conditions are evaluated: the original assembly without refurbishment and a variant incorporating refurbishment through wall cutting or the insertion of impermeable material. This setup enables a detailed assessment of moisture accumulation patterns and provides insights into the maintenance and preservation of historical walls, contributing to the prevention of deterioration in Thailand's cultural heritage.

Case Study

The selected case study building is the Holy Rosary Church of so-called the Kalawar Church, a Roman Catholic church with Gothic architecture, located in Samphanthawong District, Bangkok. The church is situated on the eastern bank of the Chao Phraya River. Designed by architect Joachim Grassi, the Holy Rosary Church was built between 1891 and 1897 in the Gothic Revival style (Pinich et al., 2018). It is situated within the settlement of Portuguese Catholics who migrated to the area after the fall of Ayutthaya, the former capital of Thailand (Issarathumnoon, 2018). The most recent renovations to the church were completed in 1989. Figure 2 presents architectural drawings of the Holy Rosary Church, depicting the west and south elevations, while Figure 3 illustrates the frontal view of the church together with the deterioration of its walls.

The church's exterior walls, which are typical of 19th-century Thai traditional temples (Bunjerdskul, 2014; Issarathumnoon, 2018; Watsantachad, 2006), were chosen for this study. The three primary layers of the wall construction are, in order from outermost to innermost: (i) lime plaster (stucco) (0.005 m), representing a thin lime-based surface coating; (ii) lime plaster (0.045 m); and (iii) solid clay brick (0.60 m for the exterior walls) (see Figure 4). The outermost layer was modeled using lime plaster properties, as traditional wall finishes in this period were primarily composed of lime-based materials rather than modern paint systems (Bunjerdskul, 2014; Watsantachad, 2006). The

foundation, estimated to extend approximately 2 meters below ground level (Sacho, 2008), was constructed using load-bearing brick masonry with a thickness of 0.60 meter to support the exterior walls (Issarathumnoon, 2018; Jungsiriarrak, 1997). Terracotta was employed for both the exterior and interior floor tiles.

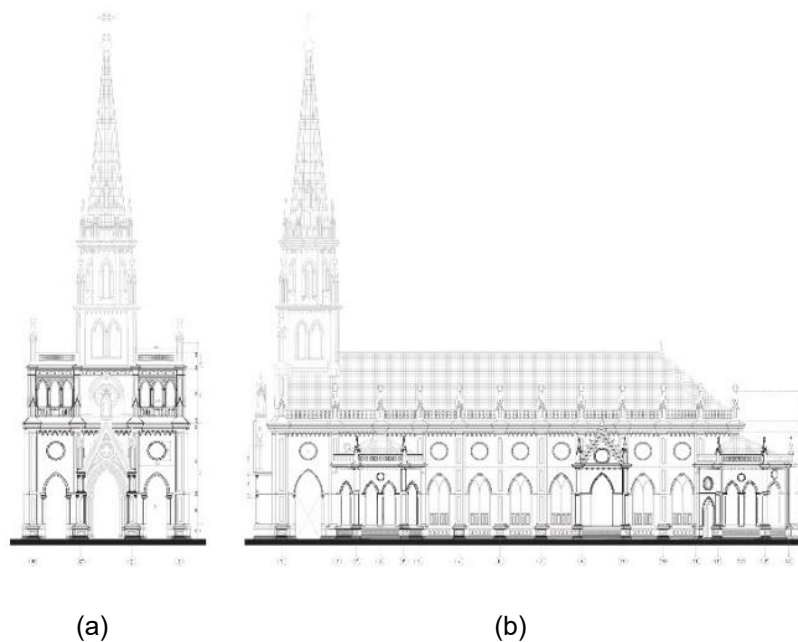
Simulation Inputs and Settings

WUFI software was utilized to simulate moisture accumulation, transport, and distribution within the walls of the selected case study building. Developed by the Fraunhofer Institute for Building Physics in Germany, WUFI employs two-dimensional computational hygrothermal analysis to model the transfer of heat and moisture through building materials (Fraunhofer Institute for Building Physics, 2025a). To achieve a numerical solution, WUFI employs a fully implicit approach for temporal discretization and the finite volume technique for spatial discretization of the transport equations (Ibrahim et al., 2014; Künzle, 1995). This computational tool enables researchers to forecast and analyze the dynamic interactions of heat and moisture within building components (Fraunhofer Institute for Building Physics, 2025b). Such analyses are crucial for evaluating and addressing moisture-related challenges in historical buildings like the Holy Rosary Church. Figure 5 shows the graphical interface and functionalities of the WUFI 2D program.

The design of the building model requires multiple software configurations and input parameters. WUFI 2D can compute the external heat transfer coefficient as a function of wind speed. An interior heat transfer coefficient of 8 W/m²K was applied (Fraunhofer Institute for Building Physics, 2025c; Guimaraes et al., 2012b), corresponding to an equivalent surface thermal resistance (R) of 0.125 m²K/W. The absorptivity of short-wave radiation was set at 0.4, which is equivalent to a standard stucco surface. It was assumed that the emissivity of long-wave radiation was 0.9. The external floor surface (function of the wall inclination) had a value of 0 and the adhering fraction of rain of the outside wall surface was set at 0.7. Table 1 details the input data and program settings utilized for the simulation.

Figure 2

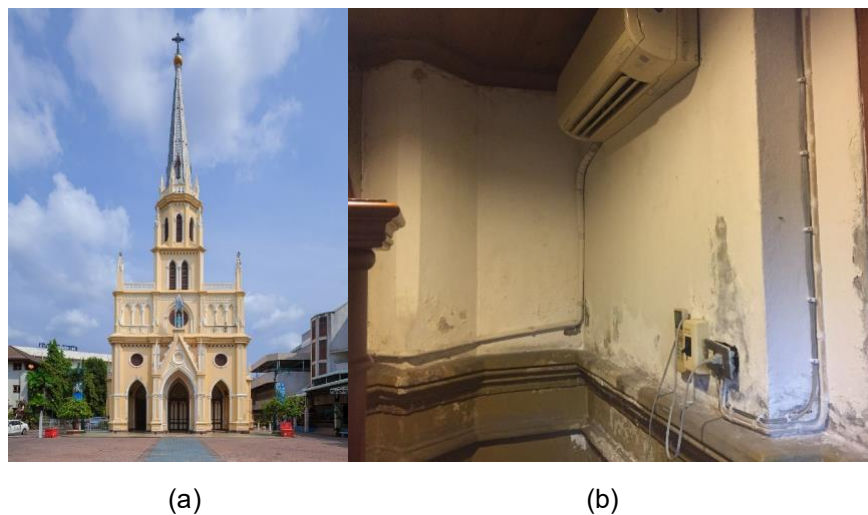
Architectural Drawings of the Holy Rosary Church Illustrating the West and South Elevations



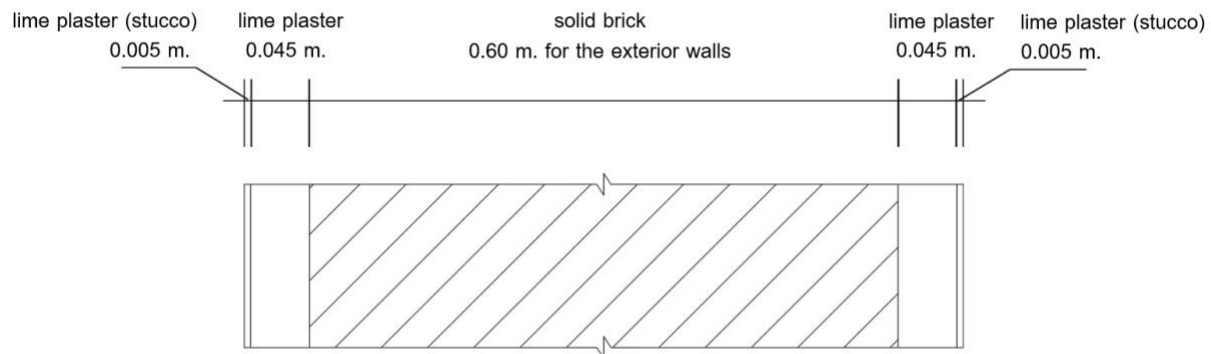
Note. (a) west elevation and (b) south elevation. Adapted from *Initial and planning stages in preservation process: Contributions to recommendation for appropriate conservation treatments: A case of conservation of the Our Lady of the Rosary Church project* (p. 5-17), by Department of Architecture, Faculty of Architecture, Chulalongkorn University, 2017. Copyright 2017 by Chulalongkorn University.

Figure 3

Holy Rosary Church



Note. (a) The frontal view of the Holy Rosary Church, from *Holy Rosary Church, Bangkok*, by Wikipedia contributors, 2023 (https://en.wikipedia.org/wiki/Holy_Rosary_Church,_Bangkok). Copyright 2025 by CC BY-SA 4.0, and (b) deterioration of interior walls within the Holy Rosary Church

Figure 4*Detailed View of Wall Construction Used in the Case Study*

Using Meteornorm software version 7.1.5 (Meteotest AG, 2020), the measured data from the Thai Meteorological Department served as the basis for the creation of the outdoor climate file. The data set came from the Thai International Airport weather station in Bangkok (Thai Meteorological Department [TMD], 2020). The simulation ran for six years from 2019 to 2024. For the natural ventilation scenario, the indoor climate file was generated using the WUFI tool *CreateClimateFile.xls*, based on in-situ measurements of indoor temperature and relative humidity collected within the church throughout the year 2016 (Pinich, 2020). For the conditioned scenario, a typical air-conditioned room setpoint of 25 °C was used to define the indoor climate condition. The air-conditioning system was assumed to operate continuously for 24 hours to represent a worst-case scenario. The model's initial parameters were set at 25 °C for the entire construction, except for the underground soil, which was assigned a temperature of 20 °C (Uchida, 2011).

The specific material properties are categorized into two main groups: (1) material basic properties and (2) hygrothermal functions. The basic properties include bulk density (kg/m^3), porosity (m^3/m^3), specific heat capacity (dry) (J/kgK), thermal conductivity (dry) at 10°C (W/mK), and water vapor diffusion resistance factor (dimensionless). These properties are sourced from literature reviews, interviews, and software databases. The hygrothermal functions include moisture storage function, liquid transport coefficient, water vapor diffusion resistance factor

(sorption and redistribution), and thermal conductivity (moisture-dependent and temperature-dependent), primarily sourced from software databases. In the context of the simulation software, the term “hygrothermal function” refers to dynamic material properties that vary with environmental and material conditions, such as moisture state and thermal conditions, and must be input as continuous functions (e.g., curves or line graphs) rather than single static values. These functions are essential for accurately simulating the behavior of hygroscopic, capillary-active materials, particularly the moisture storage function, which relates water content to relative humidity, and the liquid transport coefficients for suction and redistribution, which are defined as functions of water content. Due to their complexity, these properties are typically generated or selected directly from the software's material database. Table 2 outlines the material's basic properties configured within the program, while Table 3 shows data input for the material's hygro-thermal characteristics.

Figure 4 illustrates the three layers of the wall construction: solid clay brick (0.60 m for the exterior walls), lime plaster (0.045 m), and a thin lime-based coating (lime plaster/stucco) (0.005 m). The outermost layer was modeled using lime plaster properties, consistent with traditional lime-based finishes (Bunjerdskul, 2014; Watsantachad, 2006). A model of the foundation was designed based on an assumption of data from a literature review (Jungsiriarrak, 1997; Sacho, 2008). The simulation model of the

building is shown in Figure 6 as an illustration of a traditional 19th-century Thai wall structure. As a case study foundation type, strip foundations from this era could extend as deep as 2.00 meters below the surface (Sacho, 2008).

The initial moisture content of the wall in the simulation was defined based on the converged

results of the pre-retrofitted cases. Initially, the pre-retrofit wall model was simulated using a default relative humidity of 80% until the moisture accumulation reached an equilibrium state. The resulting converged values were then applied as the initial conditions for the subsequent simulations (Pinich, 2020).

Figure 5

Graphical Interface and Functionalities of the WUFI 2D Program

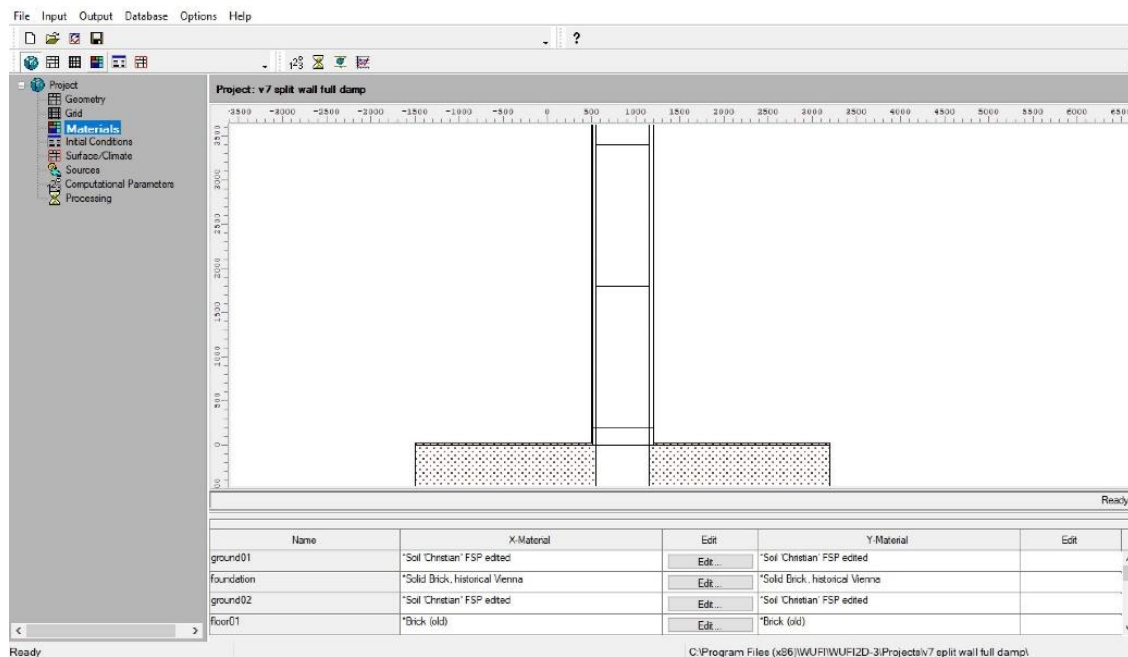


Table 1

WUFI Software Inputs and Settings

Settings and Inputs		Value
Orientation/ Height/ Inclination	Orientation of external surface	South
	Inclination [°]	90
Building height-driven rain coefficient	Rain load	R1 [-] = 0
	=Rain*(R1+R2*Wind velocity)	R2 [s/m] = 0.07
Surface transfer coefficient	Thermal resistance of exterior surface [m²K/W]	Function of wind speed
	Sd-Value of exterior surface [m]	0 (No coating)
	Short wave radiation absorptivity	0.4
	Ground short wave reflectivity	0.9
	Adhering fraction of rain (wall)	0.7
	Adhering fraction of rain (floor)	0
	Thermal resistance of interior surface [m²K/W]	0.125
	Sd-Value of interior surface [m]	0 (No coating)

Table 2*Material Basic Properties Input Data*

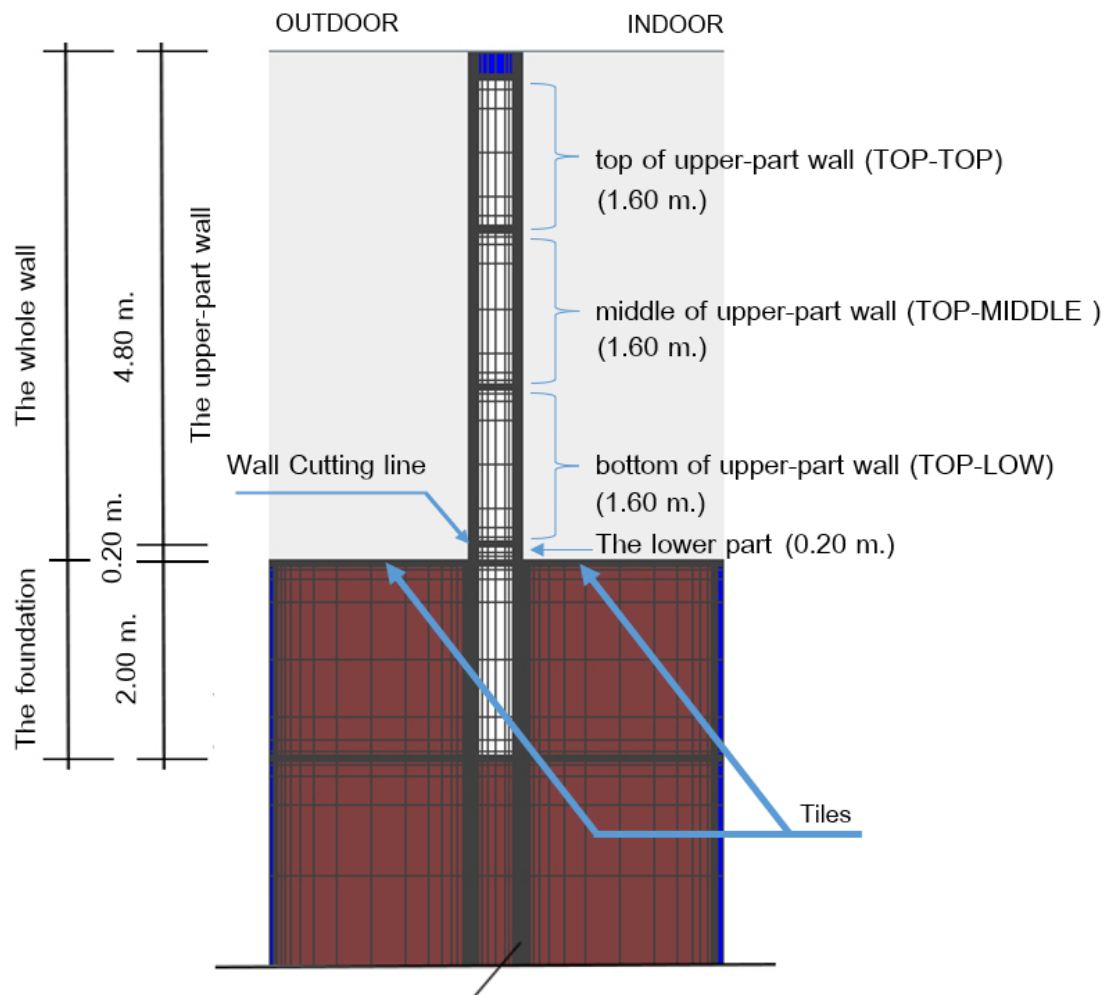
Basic Properties	Lime Plaster	Solid Brick	Terracotta Tiles	Underground Soil
Layer thickness [m]	0.05	0.45	0.02	-
Bulk density [kg/m ³]	1,600	1,560	1,670	1,500
Porosity [m ³ /m ³]	0.3	0.38	0.196	0.5
Specific heat capacity [J/kgK]	850	850	840	1,000
Thermal conductivity (dry material at 10°C) [W/mK]	0.7	0.6	0.4	2.0
Water vapor diffusion resistance factor [-]	7	14.93	16	50

Table 3*Data Input for Material Hygro-Thermal Characteristics*

Hygro-thermal Properties	Lime Plaster	Solid Brick	Terracotta Tiles	Underground Soil
Reference water content (RH 80%) [kg/m ³]	Hygrothermal function	4.5	Hygrothermal function	9.2
Free water saturation (RH 100%) [kg/m ³]	Hygrothermal function	230	Hygrothermal function	370
Water absorption coefficient (A-value) [kg/m ² s ^{0.5}]	Hygrothermal function	0.36	Hygrothermal function	Hygrothermal function
Moisture-dependent thermal conductivity supplement [%/M-%]	8.0	15.0	8.0	Hygrothermal function
Temperature-dependent thermal conductivity [W/mK ²]	0.0002	0.0002	0.0002	Hygrothermal function

Figure 6

Simplified Simulation Model of the Historical Masonry Wall and Foundation Showing the Wall Evaluation Sections



Simulation Cases and Evaluation Indicators

This study employs computational hygrothermal analysis to examine the heat and moisture transfer behaviors in a case-study air-conditioned historical building. The hygrothermal behaviors of a naturally ventilated historical building are compared to the heat and moisture transfer behaviors in an air-conditioned historical building. The simulation is divided into two cases: (1) a case study building without refurbishment, and (2) a case study building with refurbishment. The method of wall cutting or inserting impermeable material was selected and evaluated as a refurbishment alternative for the case study wall. Bitumen was used for the cutting

layer. As shown in Figure 6, the cutting plate is positioned 0.20 meters above the ground. The bitumen layer used in the study has material properties sourced from the database, specifically the Roof Membrane V13 (bitumen felt) from the Generic Material source, with a thickness of 0.005 meters. This is summarized in Table 4 and Table 5, which present the basic input properties and hygrothermal properties of the bitumen layer model used in the simulation, respectively.

Simulation results show a steady accumulation of the whole wall's water content (kg/m^3) over the entire five-year simulation period. The simulation was conducted over a six-year period, as moisture conditions within the materials were found to reach convergence (equilibrium) within

this timeframe. The first year was excluded as an initialization period to allow the model to stabilize. Therefore, the average moisture content was calculated over the subsequent five-year period to ensure the reliability of the results. The average water content (kg/m^3) of the three parts of the exterior walls, comprising the entire wall, the upper part, and the lower part of the solid brick wall, are analyzed (see Figure 6). The upper part wall is also divided into three parts: (1) the top of upper-part wall, (2) the middle of upper-part wall, and (3) the bottom of upper-part wall (see Figure 6). The criteria for dividing the upper-part wall into these three vertical segments were directly based on the height of the capillary moisture rise (the rising damp front) and empirical evidence from on-site visual inspections. Specifically, visual surveys indicated that moisture-related damages reached up to approximately 0.80–2.00 meters (Pinich, 2020). By dividing the wall into these specific segments,

the study can accurately evaluate the extent of the rising damp front. The top segment serves as a reference area unaffected by rising damp, remaining in equilibrium with the ambient environmental humidity, while the middle and bottom segments capture the varying degrees of capillary moisture accumulation from the ground.

RESULTS AND DISCUSSION

The simulation was conducted over a six-year period, with analysis focused on the final five years. The results indicate a steady accumulation of water content in the walls throughout this period. This section presents a comparison of water content in the exterior wall of air-conditioned and naturally ventilated historical buildings, considering conditions both with and without wall cutting.

Table 4

Basic Properties Input Data of Bitumen Layer Model

Basic Properties	Bitumen Layer
Layer thickness [m]	0.05
Bulk density [kg/m^3]	2,400
Porosity [m^3/m^3]	0.001
Specific heat capacity [J/kgK]	1,000
Thermal conductivity (dry material at 10°C) [W/mK]	0.5
Water vapor diffusion resistance factor [-]	100,000

Table 5

Hygro-Thermal Properties Input Data of Bitumen Layer Model

Basic Hygro-thermal Properties	Bitumen Layer
Reference water content (RH 80%) [kg/m^3]	Hygrothermal function
Free water saturation (RH 100%) [kg/m^3]	Hygrothermal function
Water absorption coefficient (A-value) [$\text{kg/m}^2\text{s}^{0.5}$]	Hygrothermal function
Moisture-dependent thermal conductivity supplement [%/M-%]	Hygrothermal function
Temperature-dependent thermal conductivity [W/mK^2]	0.0002

Comparison of Water Content in Exterior Walls of Air-Conditioned and Naturally Ventilated Historical Buildings

The results of this case study indicate that the top section of the upper-part exterior wall accumulates the least moisture compared to other parts of the wall. Specifically, the moisture content at the top of the upper-part wall was similar for both naturally ventilated and air-conditioned cases, with values of 21.48 kg/m^3 , making it the driest area. In the middle of the upper-part wall, the moisture content was higher, with 39.66 kg/m^3 in the naturally ventilated case and 36.83 kg/m^3 in the air-conditioned case. At the bottom of the upper-part wall, the moisture content was higher, with values of 210.76 kg/m^3 in the naturally ventilated case and 205.63 kg/m^3 in the air-conditioned case.

Overall, the naturally ventilated case showed greater moisture accumulation in both the middle and bottom of the upper-part wall. In the middle section, the annual fluctuation in moisture content in the naturally ventilated case was slightly higher than in the air-conditioned case by 2.83 kg/m^3 . At the bottom of the upper-part wall, where the most pronounced fluctuations occur, the annual fluctuation in the naturally ventilated case was considerably greater than that in the air-conditioned case by 5.13 kg/m^3 . Additionally, the lower part of the wall contained the same amount of water content in both the naturally ventilated and the air-conditioned cases. It can be seen that in air-conditioned historical buildings, water content in the middle and bottom sections of the upper exterior wall is influenced by dry, lower-temperature indoor air, as reduced relative humidity promotes higher evaporation and lowers the damp rise height compared with naturally ventilated cases. These findings are consistent with established building physics principles. The reduced moisture accumulation in the middle and bottom sections of the upper wall under air-conditioned conditions can be explained by evaporation equilibrium, where

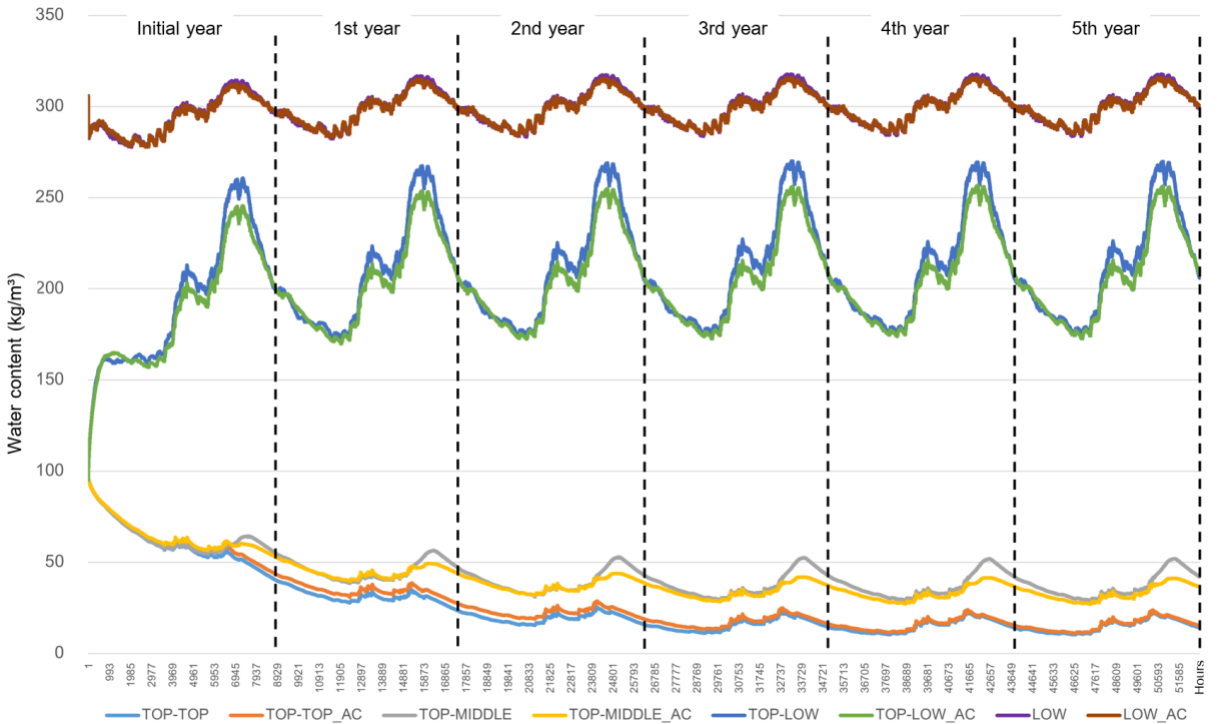
lower indoor relative humidity enhances evaporation and reduces the height of capillary rise (Guimaraes et al., 2012a; Rirsch & Zhang, 2010). This also supports previous recommendations that mechanical dehumidification can be an effective strategy for managing moisture in repurposed Thai heritage buildings (Leerungruangpan & Sreshthaputra, 2018). Table 4 shows the average water content (kg/m^3) in the exterior wall of air-conditioned and naturally ventilated historical buildings, while Figure 7 displays time evolution of the water content (kg/m^3) given for the three sections of the upper part and the lower part of the exterior wall of air-conditioned and naturally ventilated historical buildings.

To further interpret whether these moisture levels represent acceptable or problematic conditions, particularly at the bottom of the upper-part wall where the simulated values reached 210.76 kg/m^3 and 205.63 kg/m^3 , as well as at the lower-part wall where values increased to 299.89 kg/m^3 and 299.49 kg/m^3 , the following criteria are applied. Based on previous empirical observations of similar traditional Thai masonry, severe surface deteriorations, such as severe paint blistering and peeling, are explicitly linked to excessive moisture accumulations, whereas sections with lower moisture content exhibit significantly less damage (Pinich & Sreshthaputra, 2015). In the context of hygrothermal simulation, excessive moisture conditions can be identified when the water content approaches the material's free water saturation (W_f), the state where capillary pores are highly saturated with liquid water at 100% relative humidity (Fraunhofer Institute for Building Physics, 2025b; Künzle, 1995). For the historical solid clay brick modeled in this study, the free water saturation limit was 230 kg/m^3 (Fraunhofer Institute for Building Physics, 2025b). Consequently, simulated water content values nearing this threshold indicate highly problematic moisture conditions prone to deterioration, whereas substantially lower values indicate acceptable equilibrium with the ambient tropical climate.

Table 4
Average Water Content (kg/m³) in Exterior Walls of Air-Conditioned and Naturally Ventilated Historical Buildings

		Average Water Content (kg/m ³) over a 5-year Period			
Exterior Wall		Top of upper-part wall (TOP-TOP)	Middle of upper-part wall (TOP-MIDDLE)	Bottom of upper-part wall (TOP-LOW)	Lower-part wall (LOW)
Naturally ventilated		21.48	39.66	210.76	299.89
	Air-conditioned	21.48	36.83	205.63	299.49

Figure 7
Time Evolution of Water Content (kg/m³) for Three Sections of Upper and Lower Parts of Exterior Walls of Air-Conditioned and Naturally Ventilated Buildings



Comparison of Water Content in Exterior Walls of Air-Conditioned and Naturally Ventilated Historical Buildings With Wall Cutting

With a wall-cutting intervention, the results indicate that in naturally ventilated cases, the top and middle sections of the upper-part wall

accumulate an equal amount of water content, each at 19.11 kg/m³. This value is close to the accumulated water content in the wall at the bottom section of the upper part. A similar behavior was observed in air-conditioned buildings, with a water content of 21.15 kg/m³, also comparable to the accumulated water content in the wall at the bottom section of the upper part. Moreover, in both naturally ventilated and air-conditioned cases, the water content at the lowest section of the wall was identical. The

air conditioning system exerted a slight impact on the hygrothermal behavior of retrofitted walls following a wall-cutting intervention. This was evidenced by a water content difference of 2.04 kg/m^3 between the top and middle sections of the upper part of the exterior wall, and a 2.09 kg/m^3 difference at its bottom section. The water content in every section of the upper exterior wall of the air-conditioning case was approximately 2 kg/m^3 greater. This could be due to the higher vapor pressure on the exterior side of the wall compared to the conditioned interior, which drives a higher rate of water vapor transport through the porous materials of the historical wall, leading to increased moisture accumulation in the wall materials (Hagentoft, 2001). Furthermore, the water content at the base of the wall remained the same in both naturally ventilated and air-conditioned conditions. Table 5 presents the average water content (kg/m^3) in the exterior walls of air-conditioned and naturally ventilated historical buildings with a wall-cutting intervention over the study period. Figure 8 illustrates time evolution of the water content (kg/m^3) given for the three sections of the upper part and the lower part of the exterior wall of air-conditioned and naturally ventilated historical buildings with a wall-cutting intervention. As shown in Figure 8, several curves overlap because some wall sections exhibited nearly identical or identical water content values throughout the simulation period. In particular, the lowest section of the wall showed the same moisture content under both naturally ventilated and air-conditioned conditions, while the top and middle sections of the upper wall displayed very similar trends after the wall-cutting intervention.

Comparison of Average Water Content in Exterior Walls of Air-Conditioned and Naturally Ventilated Historical Buildings With and Without Wall Cutting

Figure 9 presents a comparison of average water content in the exterior walls of air-conditioned and naturally ventilated historical buildings, both with and without wall cutting retrofit. In conditioned buildings, the air-conditioning system

primarily affects the upper part of the exterior wall, particularly its middle and bottom sections. The wall adjacent to the conditioned room exhibited lower average water content, with reductions of 2.83 kg/m^3 in the middle of the upper part and 5.13 kg/m^3 at the bottom of the same part, compared with the corresponding wall in the unconditioned room. By contrast, conditioning had no influence on the topmost section, which contained the lowest average water content, or on the lowest section, which contained the highest. This outcome can be attributed to enhanced evaporation driven by the low relative humidity of conditioned indoor air, which reduces the height of capillary water rise and results in lower water content in the middle and bottom of the upper-part wall. Figure 10 illustrates a brick wall in equilibrium between capillary rise and surface evaporation, shown for both the unconditioned case and the conditioned case with the installation of the air-conditioning system. After the wall-cutting intervention in the historical building, the water content in all four wall sections responded similarly under natural ventilation and air-conditioning. This is evident in both the sections above and below the cutting line of the retrofitted wall. In both conditions, the water content in the upper part of the wall remained constant, similar to the lower part beneath the cut. In conclusion, following the intervention, the retrofitted walls were minimally affected by air conditioning, showing an increase of approximately 2 kg/m^3 in water content compared to the unconditioned case.

Another finding from this simulation, presented in Figure 9, is that the wall-cutting intervention significantly influenced water content accumulation in the bottom portion of the upper wall. Following the intervention, the water content decreased by 190.88 kg/m^3 in the naturally ventilated case and by 183.66 kg/m^3 in the air-conditioned case. In the middle portion of the upper wall, reductions of 20.55 kg/m^3 and 15.58 kg/m^3 were observed for the naturally ventilated and air-conditioned cases, respectively. At the very top of the wall, the decreases were smaller, at 2.37 kg/m^3 and 0.33 kg/m^3 . By contrast, in the section below the cutting line, the water content increased by 59 kg/m^3 in both unconditioned and conditioned cases after the retrofit. Overall, the findings suggest that the wall-cutting method exerts a stronger influence on unconditioned

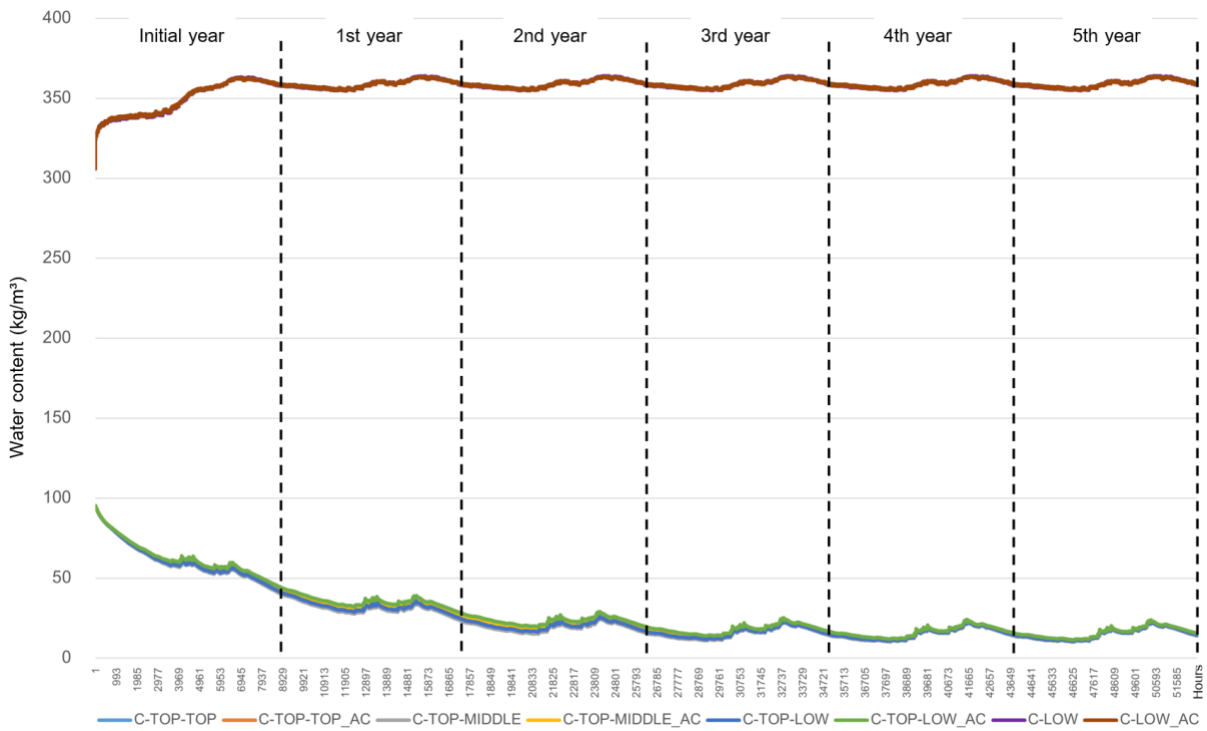
spaces than on conditioned spaces, as the reductions in water content after the intervention were greater across all wall sections in the unconditioned case. While the intervention

substantially improved drying in the wall sections above the cut, it produced an opposite effect by promoting water accumulation below the cut.

Table 5
Average Water Content (kg/m³) in Exterior Walls of Air-Conditioned and Naturally Ventilated Historical Buildings with a Wall-Cutting Intervention over the Study Period

		Average Water Content (kg/m³) over a 5-year Period			
		Top of upper-part wall (TOP-TOP)	Middle of upper-part wall (TOP-MIDDLE)	Bottom of upper-part wall (TOP-LOW)	Lower-part wall (LOW)
Exterior Wall with Wall	Naturally ventilated	19.11	19.11	19.88	259.27
Cutting Retrofit	Air-conditioned	21.15	21.15	21.97	259.28

Figure 8
Time Evolution of Water Content



Note. Time evolution of the water content (kg/m³) given for the three sections of the upper part and the lower part of the exterior wall of air-conditioned and naturally ventilated historical buildings with a wall-cutting intervention. Some plotted lines overlap because certain wall sections have identical or very similar water content values during the simulation period.

Furthermore, comparing the cases with and without wall cutting reveals a shift in the pattern of moisture fluctuations within the upper-part wall. Before the intervention, fluctuations were most pronounced at the bottom section of the upper wall, where the naturally ventilated case showed greater variability than the air-conditioned case due to reduced evaporation under higher indoor humidity conditions. After wall cutting, the capillary moisture supply from the ground was effectively interrupted, resulting in a substantial reduction in overall moisture content. Consequently, moisture fluctuations became less dependent on rising damp and were instead influenced by vapor transport driven by differences between exterior and interior conditions. Under these conditions, the effect of air conditioning became less significant, with only

minor differences observed between the two cases. This indicates that wall cutting not only reduces moisture accumulation but also alters the dominant mechanism governing moisture behavior, shifting from capillary-driven fluctuations to vapor-driven moisture transfer. In contrast, for the wall section below the cutting line, moisture behavior is governed by continued exposure to ground moisture that can no longer migrate upward. As a result, water tends to accumulate in this lower section, leading to consistently high moisture content with relatively limited fluctuation over time. This accumulation reflects a redistribution of moisture within the wall system rather than an overall reduction, highlighting a potential side effect of the intervention in which moisture is effectively trapped below the barrier.

Figure 9

Comparison of Average Water Content in Exterior Walls of Air-Conditioned and Naturally Ventilated Historical Buildings With and Without Wall Cutting

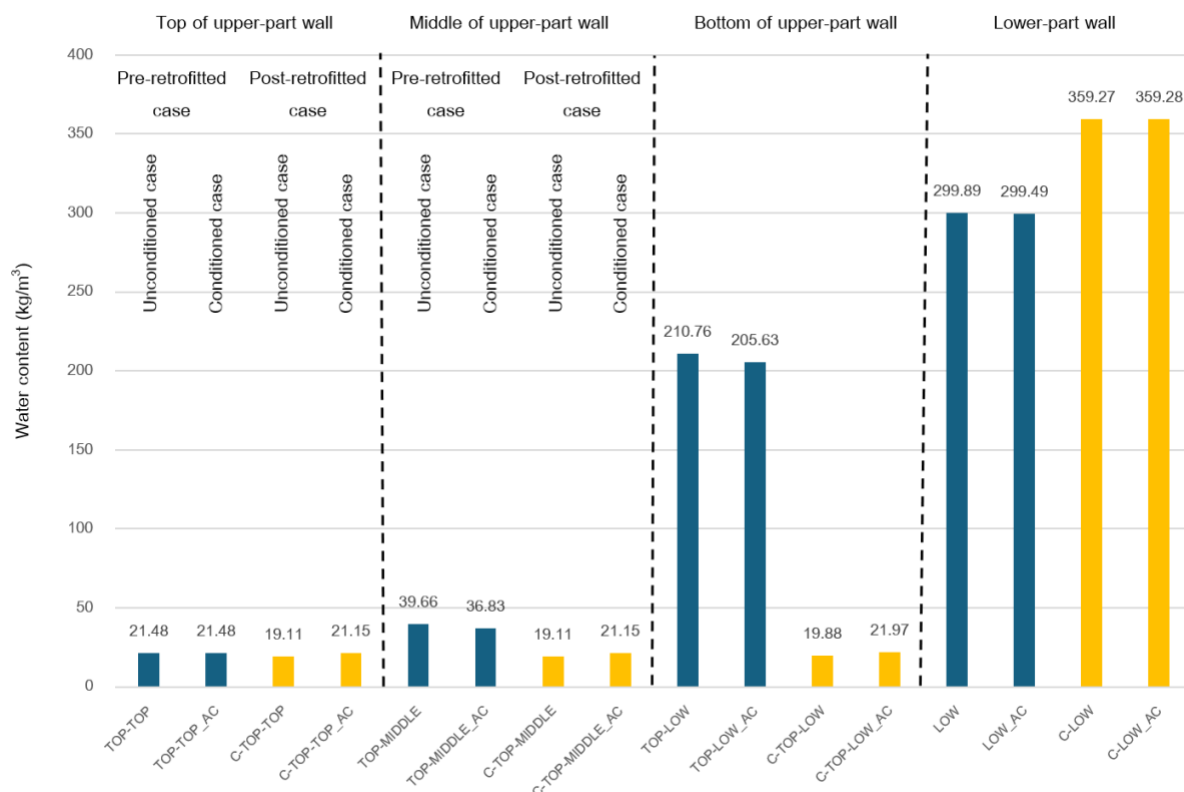
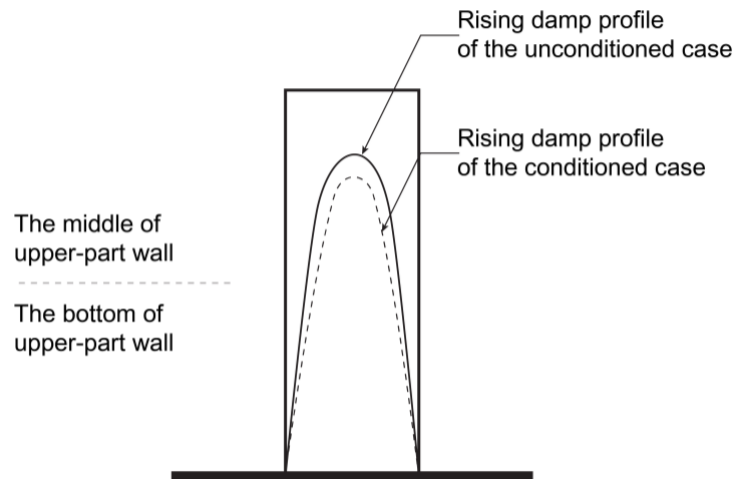


Figure 10

Illustration of a Brick Wall in Equilibrium Between Capillary Rise and Surface Evaporation in Pre-Retrofitted Condition, Shown for Both Unconditioned Case and Conditioned Case With Installation of Air-Conditioning System.



CONCLUSION

In Thailand, moisture is a major concern in historical buildings, as it can cause structural deterioration, wall material degradation, and poor indoor air quality. With the increasing use of air conditioning to enhance occupant comfort, understanding the hygrothermal behavior of these buildings becomes essential for developing effective strategies to control moisture and safeguard both the structure and the indoor environment.

This study involved a simulation-based analysis of the hygrothermal performance of historical brick walls in a tropical climate. The average water content in the exterior walls of air-conditioned and naturally ventilated historical buildings, both with and without wall cutting were examined. Comparisons were made of water content (kg/m^3) across three sections of the upper part and the lower part of the exterior wall under the two conditions (air-conditioned and naturally ventilated). The main findings of the study can be summarized as follows:

- In the pre-retrofitted case, the accumulation of water content in the middle and bottom sections of the upper part of the exterior wall in air-conditioned historical buildings was influenced by the dry, cooled air supplied by the air-conditioning system. By contrast, the top section of the upper wall and the lowest section of the wall remained unaffected, as both exhibited similar water content levels under naturally ventilated and air-conditioned conditions.
- Within the pre-retrofitted scenario, the wall adjacent to the air-conditioned space exhibited lower average water content in both the middle and bottom of the upper-part wall. In the middle portion, the naturally ventilated case showed a modestly greater annual fluctuation of moisture content than the air-conditioned case. At the bottom, where fluctuations were most pronounced, the naturally ventilated case experienced substantially higher seasonal fluctuation. This outcome can be primarily attributed to enhanced evaporation induced by the lower relative humidity of the conditioned indoor air, which reduces the height of capillary water rise and leads to less moisture accumulation in these parts of the wall.
- The air-conditioning system had only a slight effect on the hygrothermal behavior of retrofitted walls after the wall-cutting intervention. This was reflected in an approximately 2 kg/m^3 higher water content across all sections of the upper

part of the exterior wall in the air-conditioned case compared with the naturally ventilated case. This difference may be attributed to the higher vapor pressure on the exterior side of the wall relative to the conditioned interior, which drives a large amount of moisture through the wall and leads to its accumulation within the construction. By contrast, the lowest section of the wall remained unaffected by the air-conditioning system, showing identical water content in both air-conditioned and naturally ventilated cases.

- Compared with conditioned areas, the exterior walls of unconditioned spaces are more strongly affected by the wall-cutting technique, as the differences in water content before and after the intervention were greater in all sections of the unconditioned case than in the conditioned case. While the wall sections above the cut benefited substantially, exhibiting markedly reduced water content, the technique had an adverse effect on the section below the cut, where the wall became saturated with moisture.

Future research on simulation-based hygrothermal performance should encompass exterior walls with orientations toward all four cardinal directions (east, west, north, and south) and consider all wall sections to provide more comprehensive outcomes. In addition, the influence of varying indoor air-conditioning set points, rather than assuming a constant temperature of 25 °C, should be examined to yield broader insights. Further investigations could also include comparisons of different wall materials and retrofit techniques, as well as the integration of experimental validation to support model accuracy.

These findings highlight the need for more comprehensive investigations into the effects of moisture accumulation in air-conditioned historic buildings located in hot-humid climates. For building operators and owners, these findings indicate that relying solely on air-conditioning for moisture control may be insufficient, and integrated strategies should be considered. Such knowledge is crucial for developing strategies to prevent further deterioration of Thailand's historic built heritage.

While this study primarily evaluates the effect of wall cutting under naturally ventilated and air-conditioned conditions, other limitations associated with this technique, such as potential structural impacts and aesthetic considerations in heritage contexts, are beyond the scope of this study. These aspects should be investigated in future research.

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