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Hygrothermal Behavior of Thin-Walled CLT Folded Plate Envelopes under Intermittent Heating Regimes

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Abstract

Current building physics regulations, such as TS 825, prescribe heavy insulation based on continuous-heating assumptions. Yet, the hygrothermal consequences of the fluctuating regimes of periodically used buildings remain insufficiently characterized, particularly for thin-walled Cross-Laminated Timber (CLT) envelopes. This study evaluates the hygrothermal performance of the "Barkat Folded Plate" CLT system under a measured periodic-use scenario by triangulating exploratory field observations, steady-state digital calculation (Ubakus, Glaser method), and 1/1 scale dynamic testing. Observations in periodically heated mosques of Istanbul's Fatih district showed indoor temperatures of 14–17°C rather than the regulatory 20–22°C; these data defined the boundary conditions for Simplified Hot Box experiments (15-hour night cycle, ΔT ≈ 17°C) on three stratification strategies. The diffusion-open Type-1 released moisture (−12 g), acting as a hygroscopic buffer; the bitumen-sealed Type-2 gained +15 g, confirming vapor-trap behavior while remaining far below the 20% fiber-saturation threshold associated with biological degradation; the hybrid Type-3 buffered +14 g within the timber without interstitial condensation. Within this single-cycle experimental scope, the findings indicate that diffusion-open and vapor-retarded timber sections manage periodic moisture loads more adaptively than heavily insulated, diffusion-closed assemblies, suggesting that envelope requirements for periodic-use functions may merit differentiation rather than uniform prescription.

Keywords: Cross Laminated Timber (CLT), Folded Plate, Building Physics, Barkat Prototype, Wooden Structures.

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1. Introduction

Indoor thermal comfort and climatic adaptability are as fundamental to architectural design as the functional organization of space. In the varied climate regions of Türkiye, traditional log and timber-frame buildings held their own climatic balance for centuries through the thermal mass and natural breathability of wood; Cross-Laminated Timber (CLT) is the engineered continuation of that massive timber logic, and folded plate systems built from CLT panels have introduced a new tectonic and structural language to architecture (Buri & Weinand, 2008; Robeller & Weinand, 2015). The hygroscopic nature of the material, however, leaves moisture sensitivity and condensation under thermal fluctuation as critical design problems for these systems. The prevailing answer is a multi-layered climatic shell: vapor barrier, thick insulation, air cavity, and exterior cladding added behind the load-bearing timber panel. This “heavy insulation” strategy is sound in building-physics terms for severe winters ranging from −5°C to −10°C, or for functions held continuously at 20–22°C such as libraries and hospitals. Imposing it on periodically used spaces in temperate zones such as Istanbul mosques, covered marketplaces, and temporary exhibition halls leads to significant material and energy waste. In this context, in-situ field observations conducted in mosques built with various structural materials (reinforced concrete, stone masonry, timber) in the Fatih district, the historical center of Istanbul, have shown that the thermal reality of periodically used buildings differs significantly from regulatory assumptions. On a winter day with an outdoor temperature of 8°C, simultaneous measurements taken between the noon and evening prayer periods revealed that indoor temperatures could not be maintained at 20°C continuously; due to localized and temporary heating systems, the temperature fluctuated and averaged within the 14-15°C range.

Given this field reality, applying standard residential/office insulation rules and absolute vapor barriers to buildings with periodic use leads to unnecessary initial investment costs and disrupts the natural diffusion (breathing) cycle of the material. The "Barkat" model (Figure 1), where the topological layout of Mimar Sinan's mosques is reinterpreted with contemporary timber systems (Akyürek, 2024; Köymen and Akyürek, 2026), sits precisely at the center of this debate. Despite its structural slenderness, Barkat's thin-walled timber configuration is thermally competitive with traditional thick-walled masonry structures. Referring to the TS 825 standard, while the calculated thermal conductivity value of timber is around 0.12 W/mK, this value ranges between 1.40 and 1.65 W/mK for traditional masonry materials like reinforced concrete and brick. Although thick stone or composite masonry walls (80–100 cm) typically yield comparable or higher steady-state R-values, their high effective thermal mass requires extended pre-heating periods to reach occupant comfort. In contrast, thin-walled CLT enclosures (4–6 cm) can respond rapidly to intermittent heating cycles, an advantage that aligns with the periodic-use profile examined in this study.

Figure 1. Architectural rendering illustrating the application of the Barkat timber folded plate system as a mosque, emphasizing its reinterpretation of historical Islamic architecture for a periodic use scenario.

In current building physics research, computer-based simulation tools offer practical methods for analyzing heat transfer and condensation risks. However, the core algorithms of these software programs are generally based on norms (e.g., DIN) designed for continuous cold climate conditions and uninterrupted heating regimes. Considering the conditions of Istanbul, where the average outdoor temperature in winter is around 5-8°C, and focusing on a non-continuously heated mosque function, these standard tools fail to accurately model the dynamic hygrothermal behavior of the structure and tend to deviate from the actual service conditions. The inadequacy of digital tools under these complex boundary conditions makes it imperative to validate theoretical data with physical tests (empirical methods).

The energy performance and user comfort of the built environment depend on the accurate characterization of the material's thermal behavior. In this context, the "Hot Box" method is a well-established experimental tool that measures the steady-state or dynamic thermal properties of building components through a specimen placed between two climate-controlled chambers (ASTM C1363; Shen et al., 2021). Framed by the ISO 8990 and ASTM C1363 standards, this method has become a global benchmark for evaluating the performance of building envelope systems. The methodological foundation of the literature is formed by the "curve-fitting" and "fast-ramp" approaches developed by Burch et al. (1990) at NIST, and the dynamic calibration techniques derived by Brown and Stephenson (1993) at NRC Canada. These studies laid the groundwork for the transition from steady-state focused tests to "dynamic tests" that reflect the periodic thermal loads of actual building use, serving as the direct reference point for the 15-hour thermal shock and night cycle approach in the present study.

High installation costs and space constraints in certified laboratories have directed researchers toward low-cost, portable and reduced-scale apparatuses (Alqahtani et al., 2023): CFD-dimensioned portable boxes held within the uncertainty limits of international standards (Barbaresi et al., 2020), rigs tightening the fluctuation criterion of those standards (Alhawari & Mukhopadhyaya, 2022), and compact systems measuring 15–60 cm specimens to better than 4% (Zhao et al., 2019; Sánchez-Calderón et al., 2026). Taken together, these precedents establish that a simplified apparatus can yield defensible comparative data, which is the premise of the Simplified Hot Box adopted here.

Timber-specific dynamic testing sharpens the point. Trgala, Pavelek and Wimmer (2019) tested four timber envelope systems in a Guarded Hot Box under +6°C / −13°C weekly cycles and measured performance substantially better than the declared static values for both an 84 mm CLT panel and a 200 mm laminated log wall. That deviation, engaged analytically against the present results in Section 4.2, indicates that the thermal mass and hygroscopic capacity mobilised under dynamic conditions allow thin-walled massive timber elements to outperform standard λ-table predictions.

In light of these data, the condensation risk created by periodic comfort expectations in the Barkat project is sought to be managed through the natural "hygroscopic buffer" capability and tectonic honesty of timber, rather than encapsulating the structure in heavy insulation packages. Accordingly, the present study addresses the following research question: how do diffusion-open (Bare/Breathable), diffusion-closed (Protected/Bituminous), and hybrid (Vapor Retarded/Insulated) stratification strategies affect the hygrothermal behavior of thin-walled CLT folded plate envelopes under the periodic heating regimes observed in actual religious buildings, rather than under the continuous-heating assumptions embedded in current regulations? It is hypothesized that, under short-cycle heating, diffusion-open and moisture-buffering configurations have the potential to maintain condensation-safe conditions without the heavy insulation packages prescribed for continuously heated functions.

Hot Box testing, Glaser-based calculation, and field monitoring are each well-established methods. The contribution of this study lies in their triangulation around a boundary condition derived from measured periodic use: exploratory field observations define the thermal regime (14–15°C), steady-state digital calculations (Ubakus, DIN 4108-3) provide the theoretical baseline, and 1/1 scale dynamic Simplified Hot Box experiments test where and why that baseline breaks down. To the authors' knowledge, this combination has not previously been applied to timber folded plate envelopes under periodic-use scenarios; it allows the discrepancies between steady-state predictions and dynamic hygroscopic behavior to be identified empirically rather than assumed. This article is a substantially expanded and revised version of an abstract paper previously published (Akyürek and Taştemir, 2026) in the ICCAUA 2026 conference proceedings.

2. Materials and Methods

In this study, to analyze the thermal and moisture performance of Barkat timber folded plate systems intended for periodic use (mosques, marketplaces, etc.), a triangulation methodology consisting of "Field Observation," "Digital Calculation," and "Experimental Measurement" phases was followed. The research was conducted during a timeframe when outdoor conditions reflected spring night conditions.

Figure 2: Interior and exterior views of selected mosques from the field study, representing varying structural typologies, volumetric scales, and heating strategies: (a) [Gazi Ahmet Paşa Cami], (b) [Nişancı Mehmet Paşa Cami], (c) [Bali Paşa Cami], (d) [Mesih Ali Paşa Cami], (e) [Mehmet Ağa Cami], and (f) [Parmakkapı Kadıasker Mehmet Efendi Cami], (g) [Kaptan Sinan Paşa Mescidi], (h) [Arpa Emini Mescidi], (i) [Fındıkzade Mescidi], *(All photographs by the author, except (f) retrieved from [Wikimedia Commons / Arild Vågen Archive]).*

2.1. Phase 1: In-situ Field Observations

The first phase consisted of exploratory in-situ field observations (Figure 2) in the Fatih district, the historical center of Istanbul, conducted to characterize the actual thermal behavior of periodically used spaces and to derive realistic boundary conditions for the subsequent building physics calculations, rather than to constitute a statistically representative survey of periodic-use buildings. In this context, rather than a random selection, a typological and volumetric sampling strategy was followed, identifying 9 different mosques built with various structural materials (stone masonry, reinforced concrete, and traditional timber) and employing different heating strategies. The vast majority of the masonry and reinforced concrete domed structures subject to the field study have square or near-square plan layouts, representing small-to-medium scale volumes with space widths and dome crest heights ranging from 15 to 25 meters. Traditional timber-roofed (non-domed) mosques represent more compact and rapidly heatable volumes, with widths of 6–10 meters and ceiling heights of 4–8 meters.

Measurements were carried out during a typical winter/spring period when the outdoor temperature was in the 7–9°C range, specifically in the time interval between the noon and evening prayer periods, which reflects the active use scenario of the building. During this specified timeframe, consecutive readings were taken from the human breathing zone of the congregation space (congregation level) of the spaces by sequentially visiting the structures along the route. With these data, spanning a wide volumetric spectrum from monumental structures to neighborhood mosques, the "actual periodic thermal regimes" exhibited by the buildings were recorded and contrasted against their thermal inertia and the 18–26°C comfort standard assumed by the regulations, establishing a rational foundation for the calculation phases. As a result of these readings, it was determined that the indoor temperatures in the vast majority of periodically heated mosques stabilized in the 14–17°C range. This "fluctuating/temperate" thermal reality, which differs significantly from the static expectations of the regulations, was integrated into the experiment as the primary boundary condition for the subsequent digital calculation and physical (Hot Box) tests. These observations are treated throughout this study as boundary-condition inputs specific to the observed context; their generalization to periodic-use buildings at large is addressed among the limitations in Section 4.3.

2.2. Phase 2: Stratification Design and Preliminary Calculation with Ubakus

In light of the "periodic temperate zone" reality (average 14–17°C indoor environment) obtained from field observations, three different envelope/roof typologies were designed to guide the physical tests (Hot Box) of the Barkat folded plate system. In this phase, considering not only thermal insulation but also the architectural tectonics of the material, regional standards, and applicability criteria, the following stratification scenarios were developed (Figure 3):

- **Type 1 (Bare / Reference Solution):** This is the uninsulated (40 mm CLT) solution that reflects the internal-external material and structural honesty of classical Ottoman architecture, while also serving as a modern engineering interpretation of traditional timber masonry/log (çantı) systems. This bare detail, breathable to the exterior, was designed to reference the natural "hygroscopic buffer" effect of timber in periodic heating scenarios.
- **Type 2 (Sealed / Protected Solution):** This is a vapor-closed scenario specifically aimed at radically preventing leaks against rain and snow water that may accumulate on the roof surfaces of the folded plate form. In practice, considering cost and ease of labor, a bituminous membrane (BTM) was used; thermodynamically, this layer represents the "blind/vapor-impermeable" surface that would be created by shingle, aluminum, or seamed metal roof claddings. No additional measures for thermal insulation were taken in this typology; only the potential "vapor trap" risk caused by water impermeability was investigated.
- **Type 3 (Insulated and Vapor-Retarded Solution):** This is a hybrid (diffusion-open) model designed to meet the U-value expectations of Türkiye's temperate climate zone. In the system, a 5 cm thick XPS insulation board was used to block the cold from the outside, and a vapor retarder (Sd=5m) membrane was utilized to balance the vapor load coming from the indoors (allowing the timber to breathe). In order not to disrupt the material tectonics in the architecture, the outermost layer was finished with an 18 mm thick, breathable, varnished (Hickson Decor Aqua) timber cladding, representing a standard cladding dimension.

Note: Although the flammability risk of XPS boards in actual outdoor applications is known, XPS was preferred over rockwool for the sake of convenience application at the laboratory scale, as the focus of this study is strictly on thermodynamic and hygrothermal (heat-moisture) behavior.

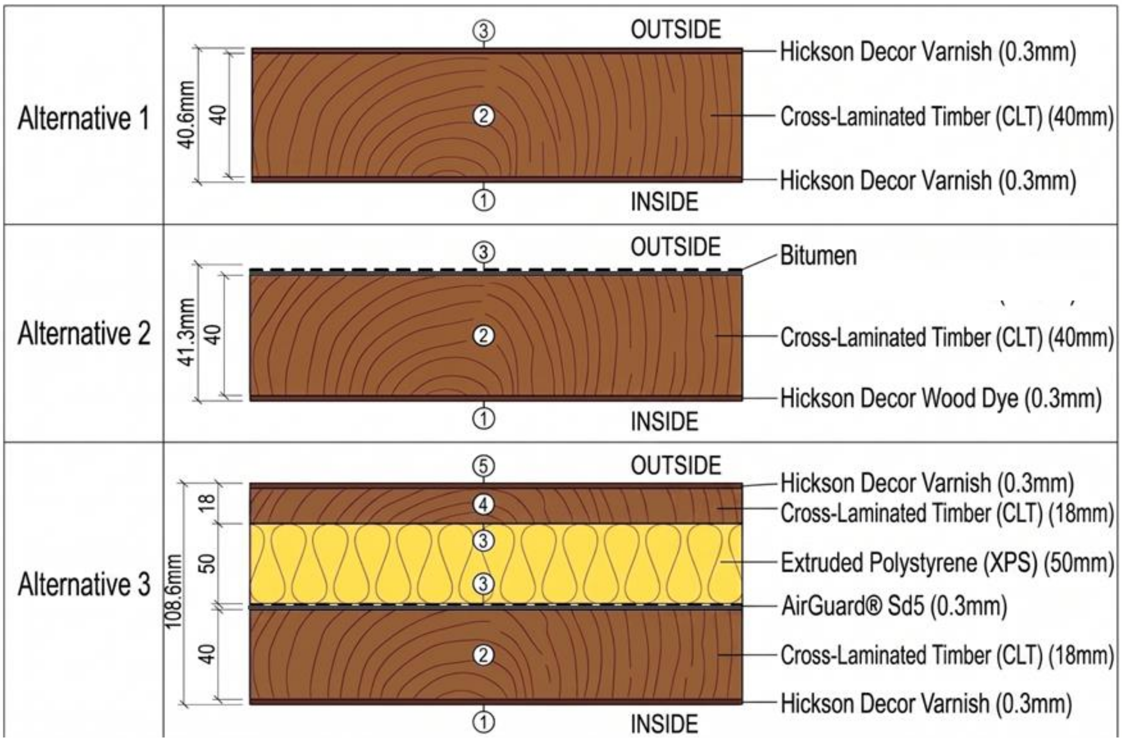


Figure 3: Cross-sectional configurations and theoretical thermal gradients of the three stratification typologies, simulated via Ubakus (DIN 4108-3).

The theoretical performance of these three developed typologies was analyzed using Ubakus (DIN 4108-3) software prior to the physical tests. The main objective of these analyses was to theoretically examine the risk of interstitial condensation (Glaser Diagram mass water accumulation) of different envelope strategies while minimizing heat loss in periodic use, and to provide analytical pre-screening/validation for the production of the 1/1 scale physical mock-ups (Figure 4).

2.3. Phase 3: Experimental Setup and Mock-up Matrix

To test the physical performance of the theoretically optimized envelope details, increase measurement sensitivity, and minimize edge effects to ensure 1D heat flow at the center of the specimen, the test mock-ups were produced at a 1/1 scale with dimensions of 60x60 cm. The experimental setup was constructed from 10 cm thick high-density XPS boards to direct heat and moisture transfer solely to the specimen surface. The internal volume of the Simplified Hot Box was dimensioned to have a net width-length of 50x50 cm and a depth of 55 cm. While the outer walls were constructed with a 10 cm thickness, a 5 cm rebate/step detail was created on the front surface frame so that the 60x60 cm timber mock-up could fit perfectly and overlap the box opening. Additionally, to ensure the design integrity of the box interior and to more realistically simulate the indoor surface dynamics of timber structures, the inward-facing surfaces of the XPS boards were clad with 3 mm thick plywood sheets.

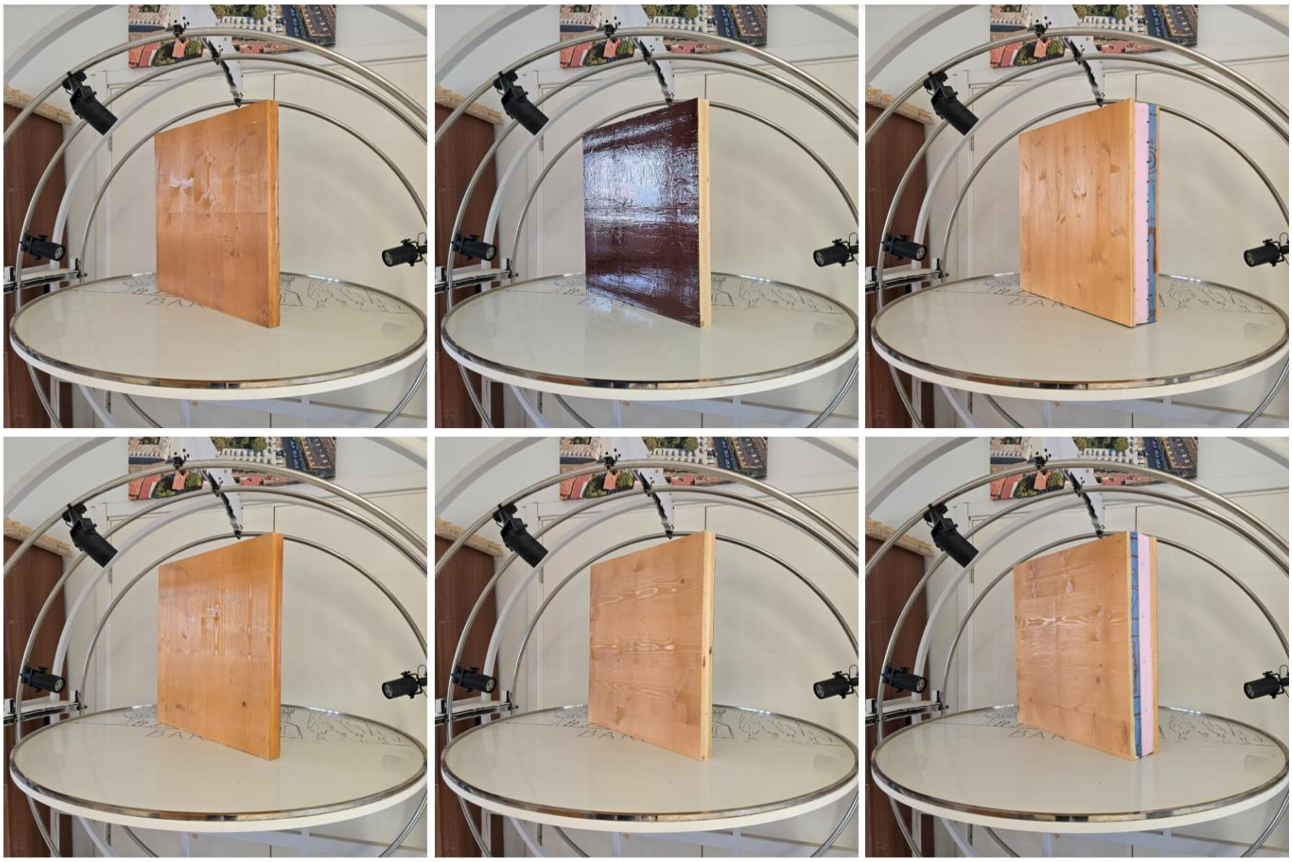


Figure 4: External (top row) and internal (bottom row) faces of the 1/1 scale (60x60 cm) mock-ups prepared for the Hot Box tests. From left to right: Type 1 (Reference/Bare CLT), Type 2 (Bitumen-sealed CLT), and Type 3 (Vapor-retarded with XPS and external wood cladding).

To ensure the overall airtightness of the system, XPS joints were sealed with polyurethane foam and aluminum foil tapes. The front platform where the specimen is seated was designed with a depth of 25 cm, providing flexibility to test thicker insulated envelope typologies of the Barkat system in future studies. Once the specimen is placed on this platform, it is secured with a specially developed retractable compression mechanism. This mechanism forcefully compresses the specimen against three rows of rubber gaskets in the inner frame, completely preventing any heat and moisture leakage from the edges during the experiment.

An integrated air conditioning system was installed for the automation and monitoring of the thermodynamic conditions inside the box. In order to distribute the indoor air homogeneously and prevent thermal stratification, the electric heater module was integrated with a circulation fan. This heater is controlled by a digital thermostat placed outside the box, which receives real-time data from the temperature probe inside; the indoor temperature is continuously maintained within the 22–24°C range, matching the periodic use target. A free-standing water container was placed inside the box to simulate the relative humidity load caused by humans or usage required by the experiment. The cross-checking of system performance and the monitoring of indoor relative humidity data were ensured by an independent digital thermometer/hygrometer positioned inside the box, securing measurement reliability (Figure 5).

The experiment scope included the three different envelope typologies (Type 1, Type 2, and Type 3) previously detailed in Section 2.2, selected by considering the cost-performance ratio and periodic use dynamics. Before being subjected to tests, all mock-ups were kept in a laboratory environment at 22±1°C temperature and 55±5% relative humidity until they reached equilibrium moisture content (EMC). Their initial weights were recorded with a precision scale.

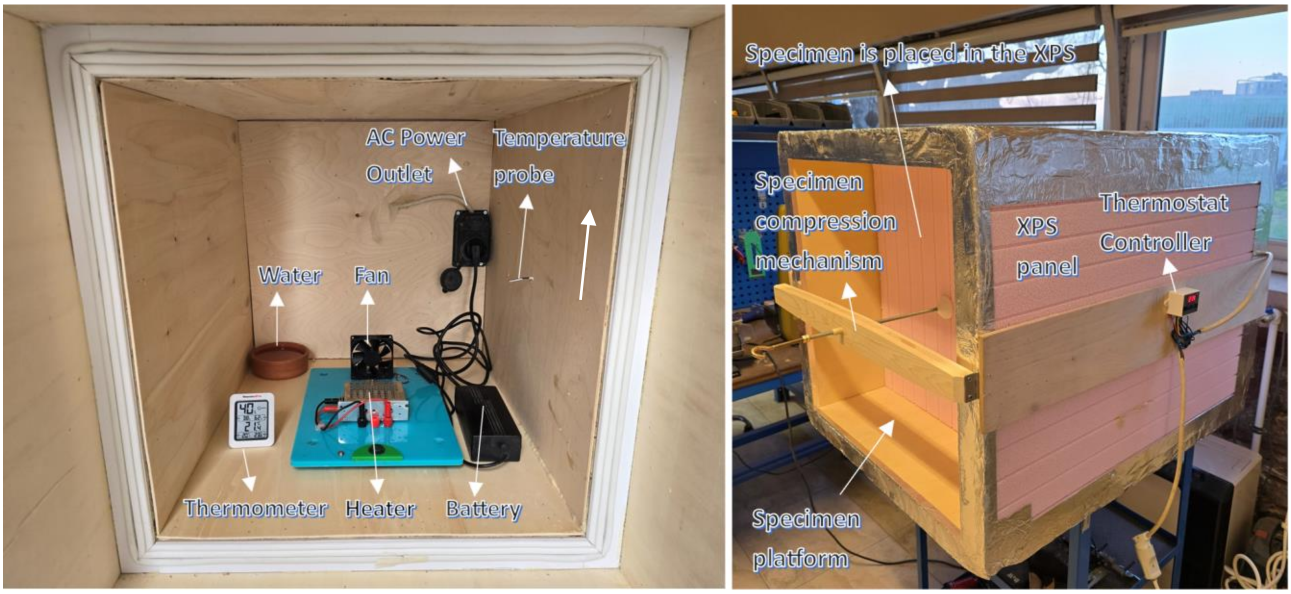


Figure 5. Internal (left) and external (right) components of the custom-built Simplified Hot Box apparatus used for the physical thermal test. The setup ensures 1D heat flow and maintains a controlled internal environment at 23±1°C to test the intermittent condensation risk of 1/1 scale CLT mock-ups.

2.4. Test Protocol and Measurement Techniques

Field observations revealed that on a typical Istanbul winter/spring day when the outdoor environment averaged 8°C, the indoor temperatures of periodically heated mosques remained within the 14–17°C range. However, when designing the experimental protocol, it was a strategic choice to observe the condensation risk under a "worst-case scenario." Accordingly, natural night conditions where the outdoor environment still averaged 8°C were awaited for the experiment days; however, the temperature inside the box (indoor environment) was raised to the 23±1°C level in accordance with standard comfort regulations. Thus, the indoor-outdoor temperature difference (ΔT) increased to approximately 15°C, simulating the most aggressive thermal shock and maximum condensation potential that periodic heating could exert on the building envelope. This deliberate elevation of the indoor set-point above the observed 14–17°C range therefore constitutes a conservative boundary condition rather than a reproduction of average field conditions: any stratification that remains condensation-safe under this amplified ΔT can be expected to remain safe under the milder measured regime.

To measure dynamic behavior under this rigorous scenario, the following test protocol was standardized:

- Thermal Shock and Cycle Duration: To simulate the sudden moisture and heat load (human density and instantaneous heating) in the periodic use scenario, experiments were conducted as 15-hour continuous night cycles (17:30 – 08:30) under spring conditions.
- Indoor Conditioning: Within the highly insulated XPS box having a net internal volume of 50x50x55 cm, the target temperature was stabilized at 23±1°C through the integration of a 12V DC PTC ceramic heater and a circulation fan. To create a realistic condensation threshold, a controlled moisture load (evaporation) was generated with a shallow water source placed inside the box.
- Outdoor Exposure: Real weather conditions were preferred over laboratory-type stationary coolers; the uninsulated outer surfaces of the mock-ups were exposed to actual outdoor conditions where the temperature averaged 6°C, fluctuating between 4°C and 9°C throughout the night.

- Data Collection and Analysis: At the end of the 15-hour periods, the system was shut down, and a rapid measurement phase commenced. The mass water absorption or evaporation in the mock-ups was recorded via gravimetric analysis (precision scale); the surface moisture changes of the timber via a resistance-based moisture meter; and the surface temperature distributions and potential thermal bridges via a thermal camera (Testo 872). These acquired experimental data were analyzed comparatively alongside a digital calculator (Ubakus) and field data.

In the thermal performance analysis of the hot box experimental setups conducted within the scope of the study, the continuity of environmental boundary conditions is of critical importance for the reliability of the obtained data. It was determined that the external weather conditions followed a very close and stable course during the three different experimental periods conducted in this study. In the measurements taken, it was observed that the outdoor air temperatures exhibited similar oscillations between 4°C and 14°C, and particularly during the night cycles, the temperature stabilized in the 4°C to 9°C range across all three periods. Although relative humidity values varied between 45% and 100% across the periods, the rising humidity trend during the night hours in all periods exhibited a common characteristic, and even the temporary saturation point observed in the 2nd period remained consistent with the overall environmental pattern. This thermal and hydrometric stability in the outdoor environment minimized exogenous variability on the hot box test cell, allowing the temperature difference between the indoor and outdoor environments to be kept under control and enabling material-based heat transfer coefficient calculations to be performed with high accuracy (Figure 6).

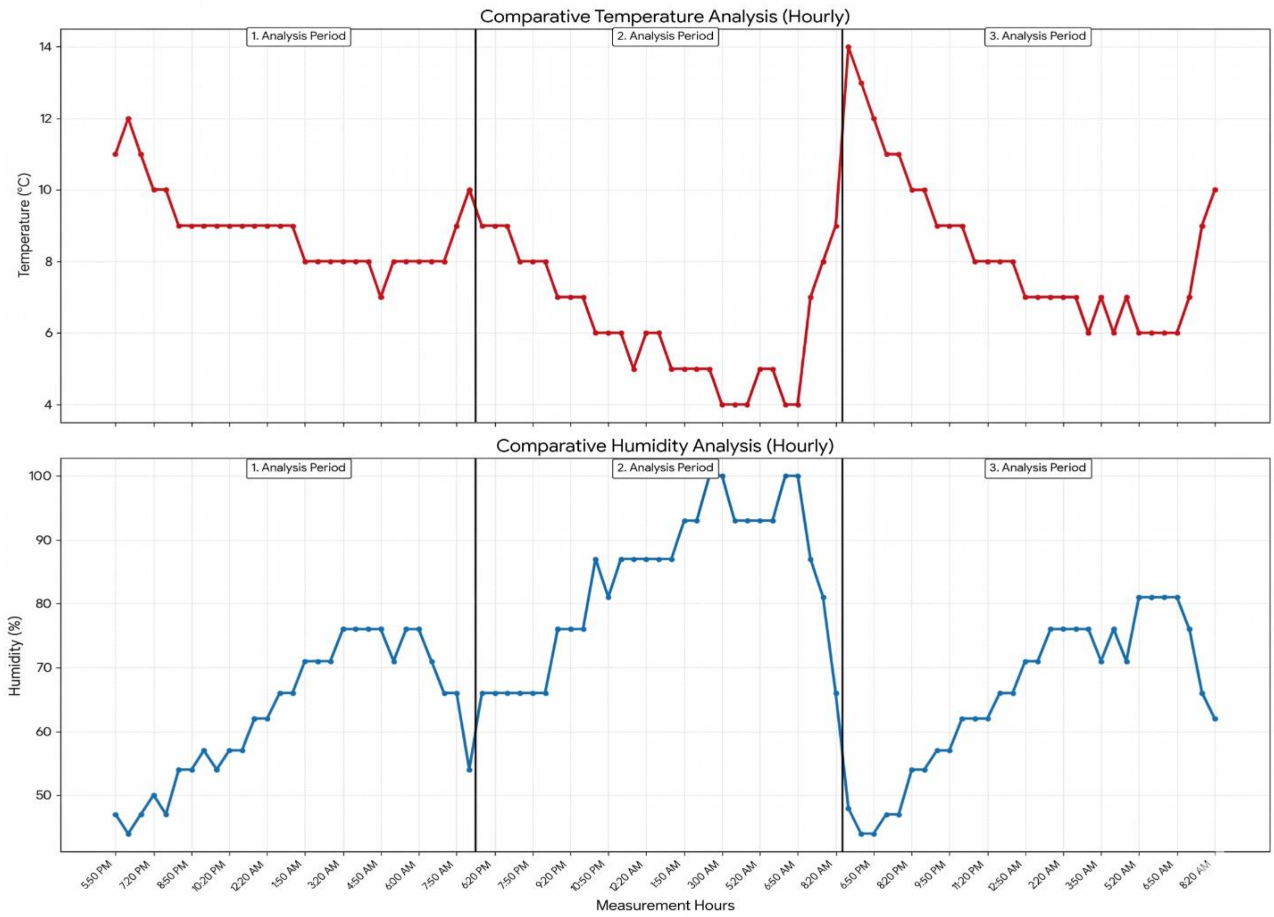


Figure 6: Hourly Variations of External Ambient Temperature and Relative Humidity Levels During Three Distinct Stages of the Hot Box Experiment.

3. Results

Building on the test protocol described above, the following sections present hygrothermal and thermal-imaging results for the three envelope typologies, beginning with a comparative overview of surface temperature distributions. The 1/1 scale Simplified Hot Box experiments, designed in light of the data obtained from field measurements, clearly distinguished the behaviors of three different envelope typologies (Type 1, Type 2, and Type 3) under periodic thermal shock. Before moving on to the specific hygrothermal (moisture and mass change) findings detailed in the subsections, visualizing the general thermal impact of the rigorous 15-hour night cycle on the mock-ups is of great importance to comprehend the insulation and heat retention capacities of the systems.

The thermal imaging (Testo 872) matrix presented in Figure 7 comparatively reveals the temperature distributions formed on the internal and external surfaces of the mock-ups at the end of the experiment (08:30). While the effect of cold air is observed homogeneously on all surfaces facing the outdoor environment (8-12°C); the distinct reactions measured between 17°C and 20°C on the surfaces facing the 23.5°C indoor environment visually reflect the thermal resistance and heat storage capacity exhibited by each typology (bare CLT, bitumen-protected, and XPS-insulated) depending on their material tectonics.

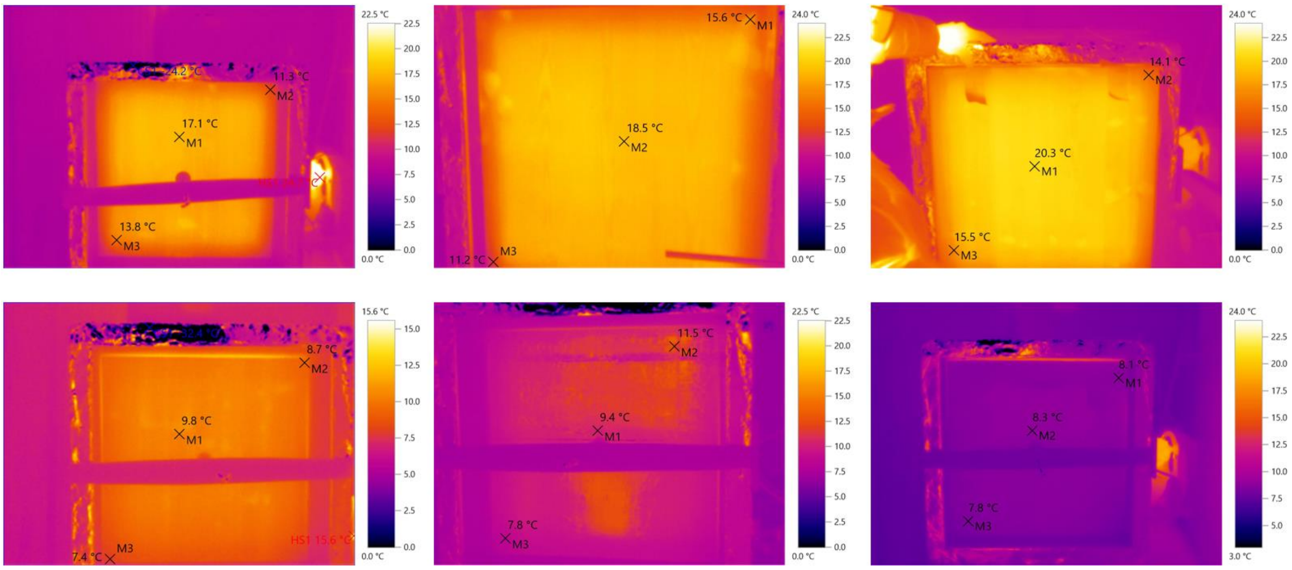


Figure 7: Comparative thermal imaging matrix of the 1/1 scale mock-ups (Type 1, Type 2, and Type 3) recorded at the end of the 15-hour Hot Box periodic heating cycle. The top displays the interior surfaces, while the bottom illustrates the external surface temperatures, reflecting the distinct heat retention and thermal resistance strategies of each stratification scenario.

3.1. Type 1: Reference Performance

To establish a baseline for the thermal behavior of the Barkat model in a periodic use scenario (mosque/temporary exhibition), the Type-1 (Bare CLT, 40 mm) section was examined first. In the preliminary calculation conducted with Ubakus software (DIN 4108-3), the thermal transmittance coefficient of the section was calculated as $U = 2.08\ \mathrm{W/(m^2K)}$. When referencing current energy regulations for continuous use functions like residences or libraries (e.g., TS 825: $U < 0.24\ \mathrm{W/(m^2K)}$), this value is classified as “insufficient” for static heating regimes.

However, considering the fluctuating thermal regime (average 14–17°C) obtained from field observations in Fatih mosques, this low thermal capacity ($14.1\ \mathrm{kJ/(m^2K)}$) transforms from a disadvantage into a "periodic adaptation" advantage, allowing the space to react and heat up rapidly when local heating is activated. More importantly, in the Ubakus Glaser diagram analyses, "zero condensation" was predicted for the uninsulated Type-1 section, even under spring/winter night conditions.

This theoretical prediction of "no condensation" was consistent with the outcome of the Simplified Hot Box experiments. Under spring night conditions where the outdoor temperature fluctuated within the 4–9°C band (see Figure 6), a 15-hour (17:30–08:30) thermal shock and condensation cycle was simulated. The indoor temperature of the box was stabilized at 23±1°C , accompanied by a controlled water evaporation. The initial weight of the mock-up, taken from the conditioning room (23±°C / 50% RH) into the test, was recorded as 5691 grams. Despite the vapor load created indoors, at the end of the 15-hour experiment, rather than an increase in weight (water absorption), a mass decrease was detected, with the final weight dropping to 5679 grams (−12 grams). In parallel, the initial timber moisture content of 11.8% was recorded to have decreased to 11.0% on the inner surface and 11.3% on the outer surface by the end of the experiment.

This behavior indicates that cross-laminated timber (CLT) panels, which are breathable to the outside, act as a passive "hygroscopic buffer" against sudden heating and moisture increase trends indoors. The specimen attempted to reach equilibrium moisture content (EMC) by releasing its excess moisture into the environment before the ambient relative humidity exceeded the dew point. In thermal camera measurements, the surface temperature of the specimen facing the 23°C interior was observed to hold steady in the 17–18°C band; thus, no localized condensation or sweating occurred on the surface.

3.2. Type 2: Protected-Closed Performance

The Type-2 section, where the Barkat model is externally sealed against outdoor climatic conditions with a bitumen membrane, is considered in building physics literature as a diffusion-closed (vapor-closed) system carrying a "vapor trap" risk. In Ubakus' digital calculations, due to the high vapor resistance (S_d = 35m) of the bitumen layer on the outer surface, it was theoretically predicted that the vapor penetrating the timber from the interior could not be expelled and would tend to condense (sweat) within the cross-section. In the same calculation scenario, the surface temperature of the mock-up facing the interior was calculated to stabilize around 19°C.

This theoretical framework showed a strong correlation with the physical data obtained from the Hot Box tests. At the end of the 15-hour (17:30 - 08:30) periodic heating and humidification cycle, while the indoor temperature of the conditioned box reached 23.6°C, a controlled evaporation of 29 grams occurred from the water container inside, raising the indoor relative humidity to 69%. In the readings taken with the thermal camera at the end of the experiment, while the outer surface temperature remained in the 10-11°C band, the timber surface temperature facing the interior (warm zone) was measured in the 18-19°C range. This acquired thermal data agreed closely with the theoretical inner surface temperature of 19°C calculated in Ubakus (a deviation of approximately 0.5°C).

Gravimetric analyses and moisture measurements indicated the physical manifestations of the "vapor trap" theory. Unlike the Type-1 mock-up, which became lighter by releasing moisture (-12 grams) during the experiment, the externally bitumen-sealed Type-2 mock-up exhibited a mass increase post-experiment. The pre-test mock-up weight of 5831 grams was found to have increased to 5846 grams (+15 grams of water absorption) under the 15-hour vapor load. In parallel, the initial inner surface timber moisture, recorded as 10.9% in resistance-based measurements, increased to 11.4% (+0.5%) by the end of the experiment.

Although this expected condensation and water absorption physically occurred, the recorded 15-gram mass increase and marginal 0.5% moisture rise are well below the 20% moisture limit (Fiber Saturation Point) that would trigger biological degradation (decay/fungi) in the timber material. This finding demonstrates that in spaces with only "periodic use" (short-term heating scenarios) like mosques, even if the use of a blind exterior cladding (bitumen, etc.) theoretically creates a "vapor trap", it does not cause short-term destructive damage in practice; the cross-section can tolerate this moisture. Nevertheless, the measurements showed that the Type-2 detail falls behind the uninsulated Type-1 in terms of its ability to expel moisture; this finding empirically supports the rationale that motivated the development of Type-3 (Smart Moisture Management with Sd=5m vapor retarder), which combines vapor regulation with thermal insulation and is analyzed in the following section.

3.3. Type 3: Insulated Performance

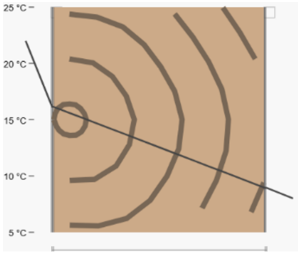
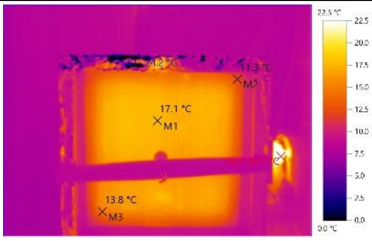
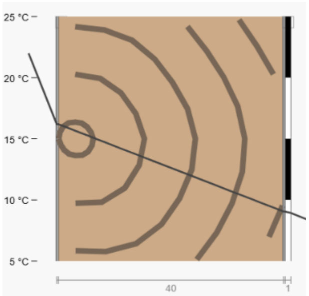
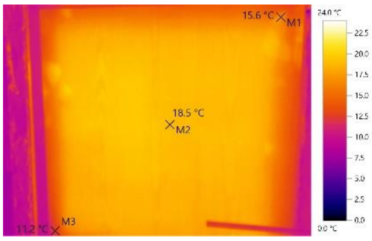
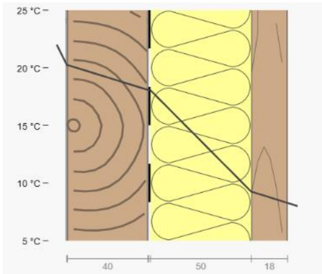
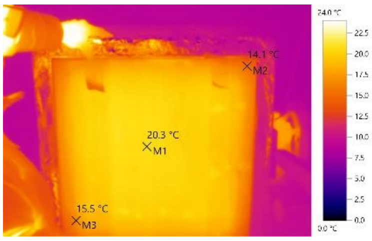
In the final stage of the study, the thermodynamic performance of the Type-3 (CLT + Sd5 Retarder + 5cm XPS + 18mm Timber Cladding) cross-section, designed to meet the U-value standard envisioned for Türkiye's temperate climate zone, was tested. In preliminary calculations conducted with Ubakus (DIN 4108-3), it was calculated that the section met the U-value expectations and no interstitial condensation (Glaser dew point exceedance) would occur between the layers. The calculation predicted that at an indoor temperature of 23.5°C, the inner surface temperature would stabilize at 21.9°C.

However, the Simplified Hot Box tests clearly revealed a "dynamic hygroscopic behavior" unseen by digital software making steady-state calculations. In the 15-hour night cycle (Outdoor: 4-9°C / 40% RH, Indoor: 23.5°C / 71% RH), the controlled moisture load created indoors (13 grams of water evaporated from the container) was absorbed by the system. As a result of thermal camera and gravimetric analyses, the surface temperature of the CLT mock-up facing the interior was measured as 20.2°C (1.7°C lower than the theoretical prediction), and it was determined that the mock-up gained 14 grams in mass. In contrast, the exterior timber cladding exposed to 40% relative humidity was observed to dry out, losing 7 grams (from 2937g to 2930g).

Although "zero condensation" was predicted in the Ubakus calculation, the water absorption (+14g) of the CLT mock-up in the physical test is not a building physics vulnerability; on the contrary, it reflects timber's "hygroscopic buffer" effect. The vapor retarder layer with a value of S_d=5m effectively limited the indoor vapor from passing into the cold XPS layer and condensing. The vapor, unable to pass into the XPS, remained in the interior volume and was safely absorbed by the timber load-bearing panel (CLT). Even though a water uptake of 14 grams by mass occurred (from 5655g to 5669g), the surface moisture of the timber, initially at 12.0%, only rose to the 12.2% level. This marginal increase is well below the 20% moisture limit that would initiate biological degradation (decay/fungi) in timber.

When compared to the mass loss (-12g) in the diffusion-open (breathable) Type-1 mock-up and the vapor trap (+15g) in the diffusion-closed Type-2 mock-up, this finding suggests that, within the tested scope, Type-3 offers the most effective " moisture management " strategy among the tested configurations for temperate climates and periodic use scenarios. The system is able to temporarily store vapor on the inner surface without trapping it within the building envelope (unlike Type-2) and release it back into the environment once the heating period ends. The gravimetric, hygric, and thermal responses of the three typologies are summarized comparatively in Table 1 and Figure 8.

Table 1: Results of the 15-hour (17:30 - 08:30) Hot Box thermal shock and condensation cycle.

Sample Type	Cross-Section (Ubakus.de)	Thermal Image (Interior)	Mass Change (Δm)	Inner Surface Moisture (Initial / Final)	Inner Surface Temp. (Physical / Digital)
Type 1			−12 g (5691 to 5679)	11,8% / 11,0%	17,1 °C / 17,5 °C
Type 2			+15 g (5831 to 5846)	10,9% / 11,4%	18,5 °C / 19,0 °C
Type 3			+14 g (5655 to 5669)	12,0% / 12,2%	20,2 °C / 21,9 °C

4. Discussion

4.1. Interpretation of Key Findings

The holistic analysis of the theoretical and physical findings summarized in Table 1 and Figure 8 indicates that building envelope design in periodically used spaces must be approached with a dynamic perspective, independent of standard "continuous heating" regulations. When the steady-state Glaser calculations forming the basis of Ubakus calculations are compared with the dynamic reality of Hot Box experiments, the dynamic tests showed diffusion-open bare timber (Type 1) to be an effective "hygroscopic buffer" capable of discharging the sudden indoor moisture load without sweating (-12g) and even storing it internally. It was observed that diffusion-closed outer coverings (Type 2) created a vapor trap as expected (+15g), but due to the short-term nature of periodic heating, the timber was able to tolerate this condition without reaching the degradation limit. In the insulated model (Type 3) designed to meet thermal resistance standards, although theoretical analyses did not predict condensation, it was determined that the vapor trapped inside by the Sd5 vapor retarder was absorbed in a controlled manner by the timber panel (+14g), preventing condensation. Consequently, instead of imposing heavy and diffusion-closed insulation packages in periodically heated buildings, "smart stratification" strategies focusing on the natural breathing and moisture storage capacity of timber, as offered by the Barkat system, appear to provide a promising solution in terms of both building physics and material lifespan.

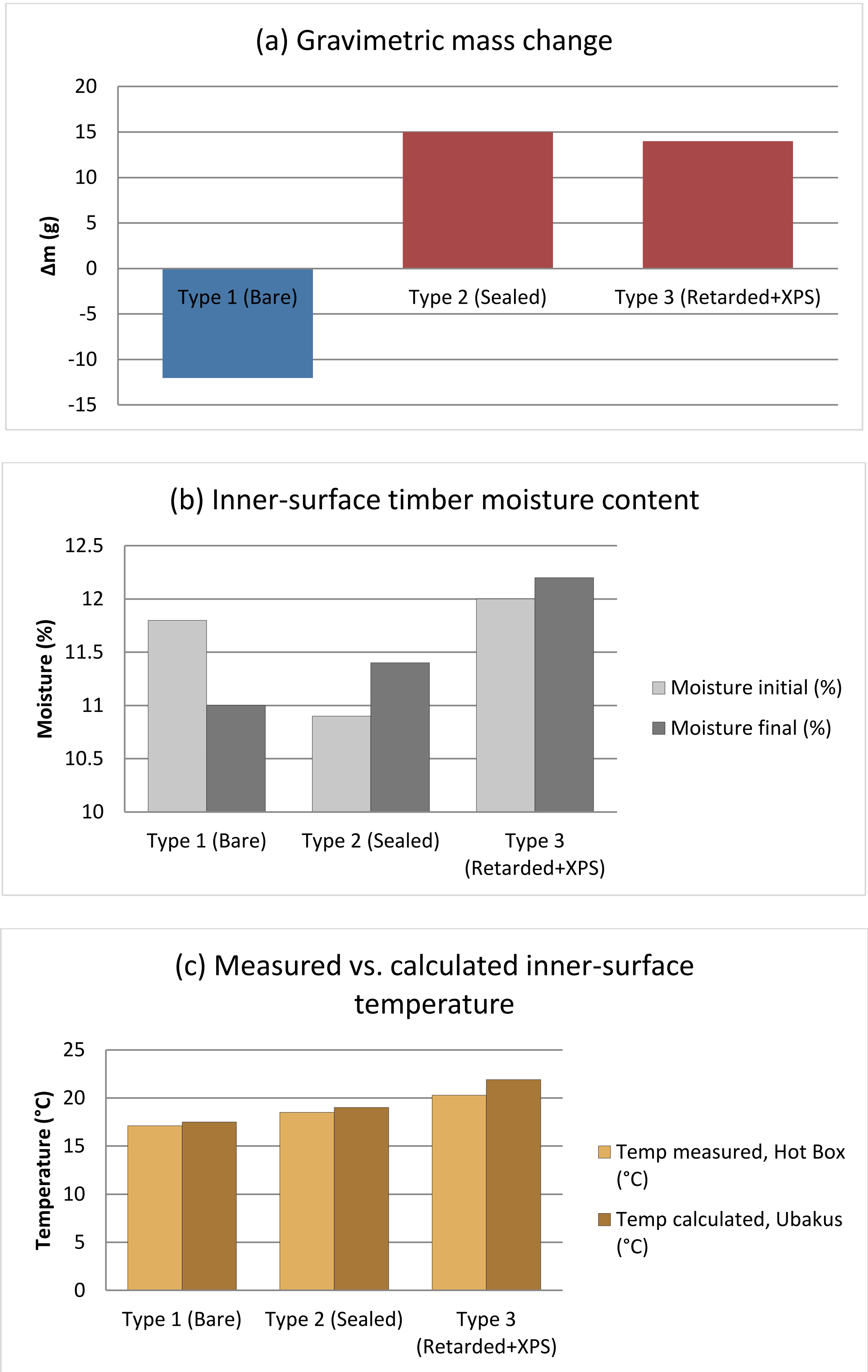


Figure 8: Comparative summary of the 15-hour Hot Box cycle across the three stratification types: (a) gravimetric mass change (Δm); (b) inner-surface timber moisture content before and after the cycle; (c) measured versus calculated (Ubakus) inner-surface temperatures.

4.2. Comparison with Previous Studies

The observed divergence between steady-state predictions and dynamic measurements is consistent with the pattern reported in the Hot Box literature. Trgala, Pavelek and Wimmer (2019) measured a dynamic thermal performance approximately 34% better than the declared static U-value for an 84 mm CLT specimen, and 56% for a 200 mm laminated log wall, attributing the deviation to thermal mass and hygroscopic effects that steady-state calculation cannot capture. The present results reproduce this pattern at the hygrothermal level: while the Glaser method (DIN 4108-3) predicted zero condensation for the Type-1 and Type-3 sections, it anticipated neither the −12 g moisture release of the diffusion-open section nor the +14 g controlled uptake of the vapor-retarded section, because moisture storage within the timber mass lies outside the steady-state framework. Surface-temperature predictions were more robust: measured interior surface temperatures deviated from the calculated values by approximately 0.4°C for Type-1, 0.5°C for Type-2, and 1.7°C for Type-3, the largest deviation occurring in the most complex multi-layer assembly.

Rather than presenting these comparisons as a blanket validation, they are read here as a mapping of the boundaries of each method. Steady-state tools remain serviceable for interior surface temperatures and for the relative ranking of typologies; dynamic or empirical methods become indispensable for the moisture-mass balance under short heating cycles. This reading aligns with the motivation behind the low-cost dynamic apparatuses reported by Barbaresi et al. (2020), Alhawari and Mukhopadhyaya (2022), Shen et al. (2021) and Sánchez-Calderón et al. (2026): standard steady-state characterization systematically underestimates the adaptive capacity of hygroscopic, massive timber elements, and the present findings extend that evidence base from flat wall assemblies to a folded plate configuration under a periodic-use boundary condition.

4.3. Limitations

Several limitations bound the interpretation of these findings. First, the experimental campaign covered a single 15-hour night cycle per typology in one climatic context (Istanbul, temperate-humid); cumulative multi-season moisture behavior, long-term durability, and fungal-growth dynamics under repeated cycles were not monitored. Second, each stratification type was tested on a single mock-up without replication, so the reported mass and moisture changes should be read as indicative magnitudes rather than statistically validated estimates. Third, the Simplified Hot Box isolates one-dimensional heat and vapor flow; occupancy dynamics, ventilation, solar gains, and three-dimensional thermal bridging at the folded plate joints were deliberately excluded and remain to be examined. Fourth, the field observations were exploratory and limited in temporal scope, serving to define boundary conditions rather than to characterize periodic-use buildings in general. Within these bounds, however, the consistency between the theoretical Glaser predictions and the measured dynamic responses across all three typologies supports the internal validity of the comparative conclusions.

4.4. Implications and Future Directions

Beyond the specific Barkat case, the findings have implications for envelope design in any building with fluctuating occupancy, such as religious buildings, covered marketplaces, exhibition halls or seasonally used community facilities. For such functions, envelope requirements could be differentiated by use profile rather than applied uniformly: where heating is short-cycled, diffusion-open or vapor-retarded stratifications that exploit the hygroscopic storage capacity of timber offer a materially leaner and hygrothermally more forgiving alternative to uniformly prescribed low-U-value packages. For standards development, the results support complementing steady-state Glaser-based verification with dynamic, use-profile-sensitive criteria for periodically heated functions. Future research should extend these single-cycle experiments to repeated seasonal cycles and long-term in-situ monitoring of a full-scale Barkat structure; replace weather-dependent exposure with a controlled cold source, so that a wider family of stratifications can be compared under identical boundary conditions and matched to the differing demands of other periodic-use functions; incorporate replication and uncertainty quantification into the Hot Box protocol; examine three-dimensional thermal-bridge effects at the folded plate joints; and couple the experimental data with transient hygrothermal simulation.

5. Conclusions

This study investigated the thermal and hygrothermal behavior of the Barkat folded plate system, which merges the geometric heritage of historical masonry structures with contemporary timber engineering, thereby presenting a new perspective to the missing templates in the building physics literature regarding periodically used spaces. Considering the triangulated data obtained from in-situ field observations, digital calculations, and 1/1 scale Hot Box experiments, the following main conclusions were reached:

- **The Continuous Heating Assumptions of Regulations:** Field measurements conducted in 9 different mosques in Fatih, Istanbul, showed that buildings with periodic use operate far from the static 20-22°C standard assumed by thermal comfort standards (ASHRAE 55), averaging 14-17°C. For these spaces, over-engineering targets focused solely on lowering the U-value (thermal transmittance) do not align with the functional use and energy rationality of the space.
- **The Hygroscopic Buffer Power of Timber (Type-1):** Thanks to its ability to buffer excess indoor moisture without exceeding the dew point and to release it to the exterior once the heating period ends, bare timber remained condensation-free throughout the tested cycle indicating that, for periodic-use functions in temperate climates, a diffusion-open timber section can be sufficient on its own where condensation safety is the governing criterion.
- **Vapor Trap Risk and Tolerance (Type-2):** Envelopes sealed from the outside with diffusion-closed materials like bitumen (Type-2) prevented the expulsion of moisture from the interior, creating the expected "vapor trap" and causing water absorption (+15g). However, due to the short-term nature of periodic heating, this condensation did not reach the 20% fiber saturation point (FSP) limit that would cause biological decay in the timber. This situation demonstrates that even incorrect material stratification can be tolerated in the short term under periodic use scenarios.
- **Balanced Hybrid Solution for Temperate Climates (Type-3):** Developed to meet both regional energy insulation standards (U-value) and prevent condensation, the Type-3 system exhibited the most successful "smart moisture management". The Sd5 vapor retarder successfully prevented vapor from passing into the cold insulation layer (XPS); the indoor vapor was instead absorbed by the timber load-bearing panel (+14 g) a dynamic storage effect that the steady-state Glaser approach cannot represent. This configuration is the optimum solution that both preserves the architectural/tectonic honesty of the material and satisfies building physics standards.

In summary, innovative and thin-walled timber structures like the Barkat folded plate system should not be unnecessarily enclosed within heavy insulation packages in periodic spaces such as mosques, covered marketplaces, or exhibition halls. Stratification strategies that allow the material to "breathe" and adapt to the dynamic thermal regime will both extend the lifespan of the structure and preserve architectural integrity. Future studies are recommended to extend the analysis of these cross-sections, examined in this paper as 1D heat flow, to the thermal bridge effects at the three-dimensional geometric joints of the folded plate.

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Conflicts of Interest
The authors declare no conflicts of interest.

Data Availability Statement
The raw datasets, thermal imaging records, and Ubakus calculation files generated and analyzed during the current study are not publicly available due to the ongoing intellectual property, design registration, and patent application processes regarding the Barkat timber folded plate structural system. However, summarized data supporting the findings of this study are available within the article, and specific anonymized datasets are available from the corresponding author on reasonable request.

Institutional Review Board Statement
Not applicable. This study did not involve human or animal subjects.

CRediT Author Statement
Muhammed Emin Akyürek: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Project administration, Funding acquisition, Writing - original draft.
İbrahim Agah Taştemir: Investigation, Data curation, Validation, Visualization, Writing - review & editing.
All authors have read and approved the final manuscript.

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