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Dynamic Thermal Performance Degradation of Building Envelopes Under Wind-Driven Rain: A Cross-Climatic Comparative Analysis

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Abstract

Conventional building codes rely on standard dry-state conditions, systematically underestimating thermal degradation induced by wind-driven rain. To address this, this study establishes a dynamic evaluation framework to quantify moisture-induced deviations and re-rank the hygrothermal adaptability of representative wall assemblies. Transient hygrothermal simulations were conducted on 68 cases, encompassing five wall configurations across four diverse Chinese thermal design zones. Results demonstrate significant thermal degradation under long-term rain exposure, with actual annual average dynamic U -values reaching a mean of $1.25 \text{ W}/(\text{m}^2 \cdot \text{K})$ and exceeding design baselines for 6.15 months. Results show that this degradation follows a geographical gradient, escalating from minor deviations in Severe Cold zones to systemic failure in Hot Summer and Cold Winter zones, where the mean dynamic U -value surges to $2.20 \text{ W}/\text{m}^2 \cdot \text{K}$. Deterioration is episodic, with peak monthly U -values reaching $16.21 \text{ W}/(\text{m}^2 \cdot \text{K})$ during transitional months like June and October, often accompanied by heat flow reversals. The dynamic evaluation shatters normative compliance parity, refining uniform applicability into a definitive performance hierarchy ranging from resilient wall assembly of Type 2 to vulnerable Type 4. Findings highlight that future envelope design must pivot from binary normative compliance toward comprehensive dynamic hygrothermal assessments to ensure genuine climate resilience in practice.

Keywords: wind driven rain; hygrothermal performance; thermal degradation

1. Introduction

Buildings account for approximately 40% of global energy consumption and greenhouse gas (GHG) emissions, making them a significant contributor to global climate change [1]. In addressing the environmental challenges in the building sector, the promotion of near-zero energy buildings (nZEBs) and high-efficiency buildings has become a global consensus and is widely recognized as a critical strategy for combating climate change and achieving energy efficiency in the building sector [2].

1.1. Moisture-Induced Thermal Degradation in Porous Materials

As the physical boundary separating indoor micro-environments from outdoor macro-climates, the thermal performance of building envelopes directly determines the overall operational energy consumption of a building. Porous materials like autoclaved aerated concrete (AAC) and cellular concrete exhibit high thermal resistance due to their low density and high porosity, which trap air and reduce heat transfer [3].



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Consequently, maintaining the low thermal resistance of porous building materials is a fundamental prerequisite in contemporary architectural design. However, porous materials are inherently hygroscopic and highly susceptible to external environmental moisture, and moisture significantly impacts thermal resistance, as water conducts heat more effectively than air [4]. The accumulation of moisture within a porous matrix physically displaces the trapped air with liquid water, and increased moisture content in materials like masonry walls reduces their overall thermal resistance [5]. Recent hygrothermal studies demonstrate that capillary saturation of materials leads to a significant increase in thermal conductivity compared to dry samples, highlighting the role of moisture in degrading thermal performance [6]. For example, in AAC, thermal conductivity and moisture diffusivity can vary by up to two orders of magnitude depending on the moisture content and temperature [7]. Similarly, hemp composites exhibit low thermal conductivity in dry conditions but are affected by excess moisture due to their porous structure [8]. The coupling of heat and moisture transfer exacerbates thermal degradation, especially in multilayered or porous materials, where phase changes in water further degrade insulation properties [9].

Moisture-induced thermal degradation is a critical factor that can severely compromise the energy efficiency of building envelopes, as it leads to higher-than-expected heat transmission losses that are far higher than theoretically designed values [10,11] and underestimation of cooling and heating loads [12], necessitating careful consideration of moisture effects in building design, insulation strategies, and long-term performance modeling [13]. Therefore, preventing moisture accumulation through design and material selection is critical to maintaining consistent thermal resistance [14]. However, in real-world environments, the thermal transmittance of building envelopes exhibits highly transient characteristics and is significantly influenced by external environmental moisture loads. Several studies have empirically quantified the impact of moisture loads on thermal performance. Specifically, studies indicate that increased moisture content can significantly degrade the thermal properties of building materials, affecting energy balance and overall performance [15,16]. The transient pulse technique has been used to measure thermal conductivity across various moisture levels, revealing that moisture can increase thermal conductivity by over 100% in some materials [17]. In particular, environmental factors like wind-driven rain and longwave radiation significantly impact moisture distribution and, consequently, thermal transmittance [18].

1.2. Wind-Driven Rain (WDR) and Climatic Interplay

Among external moisture loads, WDR is widely recognized as one of the most destructive and mechanically complex sources of moisture affecting building facades. Its impact is multifaceted, influencing the durability, thermal resistance, and hygrothermal performance of building envelopes [19,20]. When raindrops, driven by the horizontal velocity component of the turbulent wind field, strike and penetrate the building envelope at a certain angle, they trigger a series of complex coupled heat, air, and moisture transfer processes [19]. Since the thermal conductivity of liquid water is nearly 24 times that of sealed static air, when the pores within building porous materials become filled with water, the highly efficient insulation mechanism originally dependent on the air layer is completely compromised, leading to significant dynamic thermal performance degradation [21]. Furthermore, WDR penetration not only leads to instantaneous and long-term degradation of thermal performance, but the long-term retained moisture also triggers a variety of secondary building defects. These include mold colonization and massive proliferation under high-humidity conditions, freeze-thaw damage in severe cold climates, surface salt efflorescence, propagation of structural microcracks, and deterioration of indoor environmental quality [22,23]. To further elucidate this climatic interplay, our preliminary

study [24] systematically investigated the hygrothermal performance of five typical exterior wall assemblies under long-term WDR exposure across 21 locations in four major climate zones in China. The findings revealed that WDR induces significant climatic disparities in moisture accumulation. For instance, the drying rates of wall assemblies drastically decreased from Severe Cold to Hot Summer and Warm Winter zones. Furthermore, specific configurations, such as external EPS insulation systems, exhibited high sensitivity to WDR, posing persistent mold growth risks. However, while this prior work successfully mapped the cross-climatic moisture transport and durability risks driven by WDR, the corresponding transient degradation of thermal performance, specifically the dynamic fluctuations in real-world thermal transmittance, was not quantitatively addressed.

1.3. Limitations of Normative Thermal Transmittance

In conventional building energy modeling and thermal design codes, the thermal transmittance of building envelopes is typically assumed as a constant parameter, with its value primarily derived from laboratory test data of materials under standard dry conditions. As a result, heat transfer calculation is inherently insufficient for capturing the highly transient thermal behavior of building envelopes under real dynamic environmental loads [25].

Numerous studies have confirmed that nominal U-values fail to account for time-dependent dynamic thermal behaviors, such as periodic thermal storage and release properties of building materials, which are critical for optimizing building energy demand under varying climatic conditions. For instance, in warm and humid climates, relying solely on nominal U-values cannot accurately predict actual building energy performance, leading to deviations of up to 4000 kWh in annual operational energy demand even for envelope systems designed with identical nominal U-values [26]. Moreover, most nominal U-value calculation methods do not consider the dynamic redistribution of moisture within porous wall assemblies, an oversight that can lead to unforeseen localized thermal bridging and hidden condensation risks in actual operation [27]. In particular, heat and moisture transfer processes in porous building materials are strongly coupled, and neglecting this bidirectional interaction can lead to significant underestimations of envelope heat loss, especially in regions with high ambient humidity or frequent precipitation [28]. To address these well-documented limitations, metrics such as daily mean dynamic thermal transmittance and dynamic thermal resistance have been proposed in recent research to better reflect real-world fluctuations in envelope heat transfer under coupled hygrothermal loads [29].

While previous studies have quantified moisture-induced thermal conductivity increases, there is a lack of comparative research exploring how these dynamic degradations vary across distinct climatic zones under long-term WDR exposure.

To bridge this gap, this study develops a numerical framework to evaluate the dynamic thermal degradation of diverse wall assemblies. By conducting a cross-climatic comparative analysis, this research elucidates the transient fluctuations and recovery duration of envelope thermal performance under WDR conditions. Furthermore, it identifies the optimal wall configurations for different thermal design zones, thereby providing a scientific basis for the development of climate-adaptive building energy codes.

The remainder of this paper is organized as follows: Section 2 describes the modeling framework for coupled HAMT and the WDR load calculation, further outlines the selected climatic zones and wall assemblies; Section 3 presents a comparative analysis of thermal transmittance fluctuations; and Sections 4 and 5 discuss the implications and conclusions.

2. Methodology

2.1. Numerical Modeling Framework

The numerical simulations in this study were conducted using a coupled Heat, Air, and Moisture Transfer (HAMT) framework. The governing equations, spatial discretization, and specific boundary layer parameters employed have been detailed and validated in our prior study. Therefore, this paper only briefly outlines the core simulation settings. For a comprehensive description of the numerical validation process, readers are referred to [24]. Fundamentally, this study employs the transient HAMT model developed by Künzeli, solved via WUFI Pro (V 6.8) in accordance with the DIN EN 15026 assessment framework [30,31]. The governing equations are as follows:

Heat Transport Equation

$$\frac{dH}{d\vartheta} \cdot \frac{\partial \vartheta}{\partial t} = \nabla \cdot (\lambda \nabla \vartheta) + h_v \nabla \cdot (\delta_p \nabla (\varphi \rho_{sat})) \quad (1)$$

Moisture Transport Equation

$$\frac{dw}{d\varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot (D_\varphi \nabla \varphi + \delta_p \nabla (\varphi p_{sat})) \quad (2)$$

where

$\frac{dH}{d\vartheta}$ [J/m³·K]: heat storage capacity of the moist building material.

$\frac{dw}{d\varphi}$ [kg/m³]: moisture storage capacity of the building material.

λ [W/m·K]: thermal conductivity of the moist building material.

ϑ [K]: temperature

φ [%]: relative humidity

D_φ [kg/m·s]: liquid conduction coefficient.

δ_p [kg/m·s·Pa]: water vapor permeability of the building material.

h_v [J/kg]: evaporation enthalpy of the water.

ρ_{sat} [kg/m³]: density of saturated water vapor

p_{sat} [Pa]: water vapor saturation pressure

∇ [m⁻¹]: nabla operator (gradient/divergence)

Based on the theory of porous media, the model captures the dynamic evolution of temperature and moisture fields driven by hourly weather data under the coupled framework of mass and energy conservation [31]. Overcoming the inherent limitations of the steady-state Glaser method [32], this transient model incorporates WDR as a dynamic liquid water source term at the exterior boundary [33]. This capability enables the accurate characterization of transient hygrothermal responses under real-world precipitation.

To focus on macroscopic performance variations among different wall configurations, a one-dimensional transfer model is adopted. Consistent with the baseline configurations established in our prior work [24], the material layers are assumed to be homogeneous continuous media, neglecting complex two-dimensional thermal bridging, localized construction defects, and anomalous extreme climate scenarios [34]. The spatial domain relies on a refined grid generation strategy with dynamic time-stepping to capture steep hygrothermal gradients accurately [35]. These assumptions ensure that the cross-climatic transient thermal fluctuations are evaluated under strictly unified and comparable conditions.

2.2. Climate Boundary Conditions and WDR Loads

Building upon this numerical framework, the next step involves defining the climatic boundary conditions that drive the transient simulations. According to the Code for Thermal Design of Civil Buildings (GB 50176-2016) [36], China is divided into five thermal design zones. This study focuses on four primary zones, which are Severe Cold (SC), Cold

(C), Hot Summer and Cold Winter (HSCW), and Hot Summer and Warm Winter (HSWW). These regions represent the highest demand for building insulation and exhibit significant variations in wind, rain, and humidity loads. The Mild zone was excluded because the thermal performance of conventional insulated wall assemblies in this region is less critical and lacks representative significance for climate-adaptive optimization.

While the GB 50176-2016 framework is primarily temperature-based, it provides a standardized spatial framework for cross-regional comparative analysis. Building upon this framework, representative locations within the distinct thermal design zones were further selected by incorporating local-scale precipitation, relative humidity, and WDR exposure characteristics. This approach establishes a comprehensive evaluation matrix that seamlessly integrates normative thermal design requirements with actual WDR load variations. Based on the WDR-induced infiltration risk classification across China's building thermal design zones [37], the selected locations systematically encompass high, medium, and low-risk environments within each of the four primary thermal zones. Consequently, this multi-tiered selection fully accounts for local hygrothermal disparities, enabling the subsequent analyses to accurately isolate variations in the dynamic thermal responses of walls driven by localized moisture loads, even within the exact same thermal design zone.

This study adopted the meteorological dataset consisting of 8760 hourly records for the year 2020, synthesized from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis [38]. This dataset provides the temporal resolution and variable coverage required for hygrothermal simulations, including air temperature, relative humidity, global solar radiation, wind direction, wind speed, and precipitation. The ECMWF weather data has undergone rigorous validation and demonstrates high reliability. Furthermore, our prior study [24] quantified the statistical agreement between the monthly average precipitation from the ECMWF 2020 dataset and the 1991–2020 data from the China Surface Climate Normals Database (CSCND), confirming the dataset's suitability for this study.

Initially, 106 meteorological stations spanning the four major thermal zones were preliminarily screened. Weather data consistency was then validated through a regression analysis of the monthly average precipitation between the ECMWF 2020 and CSCND 1991–2020 datasets for each site. A total of 33 stations met the consistency criterion, defined as a coefficient of determination (R^2) threshold of 0.7. This threshold followed the established convention in climate data validation, where $R^2 \geq 0.7$ is widely accepted as indicating sufficient agreement between datasets for subsequent modeling applications [39]. To ensure a uniform spatial distribution across the climate zones and prevent regional over-concentration or sparsity, 21 stations were further selected from these 33 qualified candidates as the final simulation sites, carefully accounting for the geographical boundaries and climatic disparities of each zone (Table 1). While our prior study focused on using this dataset to assess long-term moisture accumulation, the current work repurposes these dynamic climatic loads to specifically drive the transient thermal transmittance fluctuations.

To systematically evaluate the long-term transient hygrothermal performance of the wall assemblies, among the eight directional WDR loads computed, only the one corresponding to the maximum annual cumulative load was used as the exterior boundary condition. The WDR load calculation and orientation selection were conducted through a two-step procedure.

First, the annual WDR loads from eight directions (the four cardinal and four ordinal directions) were estimated using the empirical model developed by the Fraunhofer Institute of Building Physics (Germany). This preliminary calculation integrates horizontal rainfall intensity, wind speed, and empirical coefficients related to building geometry. Based on these directional WDR profiles, annual WDR rose diagrams were generated for each of the 21 selected locations to explicitly identify the predominant WDR direction.

Table 1. The selected locations for simulation.

Thermal Design Zones	Infiltration Risk Level	Location	Goodness of Fit	Annual Rainfall (mm/a)	WDR Direction	AWDR (mm/a)
SC	Low	Qumacai	0.91	824.2	North	96.3
		Yushu	0.90	972.4	Southwest	58.6
		Datong	0.84	431.8	North	44.1
		Ganzi	0.90	1327.1	West	72.8
	Medium	Seda	0.96	1145.9	Northwest	97.0
		Erenhot	0.77	213.3	Southeast	37.7
C	Low	Taiyuan	0.71	531.8	Northeast	82.6
		Shijiazhuang	0.79	621.9	North	105.8
		Xuzhou	0.87	1056.3	East	244.3
		Qingdao	0.81	975.9	East	402.7
	Medium	Daoxu	0.96	1361.5	Southeast	97.9
HSCW	Low	Hefei	0.79	1490.4	East	203.6
		Yibin	0.76	1403.6	Northwest	245.8
	Medium	Nanjing	0.86	1483.1	East	210.7
		Guangchang	0.73	1728.0	South	150.8
	High	Fuding	0.79	1313.1	Northeast	142.9
HSWW	Low	Yuanmou	0.71	804.2	South	61.1
	Medium	Fuzhou	0.66	1167.9	Northeast	98.4
		Guangzhou	0.72	1672.0	Southeast	247.1
	High	Shantou	0.76	1095.5	Southeast	176.3
		Fogang	0.71	1683.8	South	202.9

Subsequently, for the identified dominant direction, the precise hourly WDR deposition was calculated in accordance with the ASHRAE Standard 160 [34]. Consistent with the loading protocols established in our prior study, this standard effectively translates hourly meteorological data into dynamic envelope moisture fluxes, accounting for terrain, building height, and roof geometry. The hourly vertical WDR deposition (r_{bv}) ($\text{kg}/(\text{m}^2 \cdot \text{h})$), is determined by Equation (1):

$$r_{bv} = F_E F_D F_L U \cos(\theta) R_h \quad (3)$$

where r_{bv} is the amount of rainwater deposited on the vertical wall ($\text{kg}/(\text{m}^2 \cdot \text{h})$);

F_E is the rain exposure coefficient, generally taken as 1;

F_D is the rain deposition coefficient, generally taken as 0.5;

F_L is the empirical constant, with a value of $0.2 \text{ kg} \cdot \text{s}/(\text{m}^2 \cdot \text{mm})$;

U is the hourly average wind speed at 10 m height above the ground (m/s);

θ is the angle between the wind direction and the normal to the wall surface;

R_h is the rainfall intensity on the horizontal surface (mm/h).

Finally, the annual cumulative WDR load (AWDR) on the dominant facade is obtained by integrating the hourly r_{bv} over 8760 h of the year, as expressed:

$$AWDR = \sum_{h=1}^{8760} r_{bv,h} \quad (4)$$

By targeting the dominant WDR direction characterized by DR, this methodology ensures that the subsequent dynamic thermal degradation analysis captures the maximum potential moisture accumulation and its corresponding impact on thermal transmittance.

2.3. Boundary Condition Settings

This study defines the outdoor and indoor boundary conditions separately to reflect the response characteristics of exterior wall assemblies under real climatic conditions [30, 31]. The exterior boundary is driven by the hourly meteorological dataset established in Section 2.2, capturing the comprehensive impacts of diurnal, seasonal, and short-term climatic fluctuations. Compared to constant or periodic boundary simplifications, this transient approach is essential for a realistic assessment of long-term hygrothermal behavior under coupled wind and rain loads [38]. Specifically, WDR is integrated as a dynamic liquid water flux on the exterior surface, effectively simulating the wetting process under actual exposure conditions [30,33]. Simultaneously, solar radiation participates in the surface energy balance, regulating the exterior surface temperature and subsequent evaporation potential, which collectively determine the moisture states within the envelope.

The interior thermal environment is derived using the algorithmic framework specified in ASHRAE Standard 160, where indoor conditions are dynamically calculated based on the corresponding outdoor climatic data. To represent typical residential occupancy, the indoor design temperatures and air change rates (ACHs) were standardized according to the operational requirements of China's thermal design zones [40–43], as shown in Table 2.

Table 2. Settings of indoor temperature setpoint and air change rate.

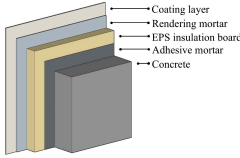
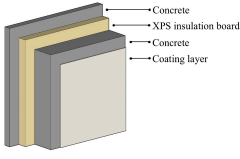
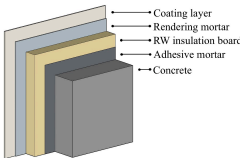
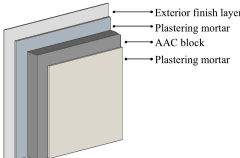
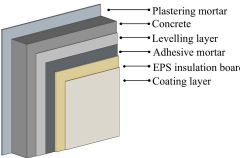
Climate Zone	Heating Setpoint (°C)	Cooling Setpoint (°C)	ACH (h ^{−1})
SC and C	18	—	0.5
HSCW	18	26	0.5
HSWW	—	26	1.0 (during A/C period)

These standardized interior parameters isolate the research focus on the impacts of external climatic stress and assembly configurations on moisture transport. Aside from these normalized boundary conditions, no additional internal heat or moisture sources were introduced, thereby ensuring consistent comparability across different locations and structural scenarios.

2.4. Wall Assemblies and Zone-Specific Adaptations

Five typical exterior wall assemblies (Type 1 to Type 5), representing the mainstream construction practices across the evaluated climatic zones, were selected for the dynamic thermal degradation analysis (Table 3).

Table 3. Thermal parameters for five external wall assemblies.

Wall Assembly	Schematic Plot	U-Value (W/m ² ·K)	Layers	d (mm)	λ (W/m·K)	ρ (kg/m ³)	Cp (J/kg·K)
Type-1		0.4/0.45/1.2	Coating layer	10	0.700	1785	850
			Rendering mortar	20/15/10	0.930	1880	850
			EPS insulation board	91/80/23/18/13	0.040	15	1500
			Adhesive mortar	1.0	0.20	1250	1400
			Concrete	60/200	1.740	2200	850
Type-2		0.4/0.45/1.2	Concrete	60	1.740	2200	850
			XPS insulation board	78/68/30	0.035	40	1500
			Concrete	200	1.740	2200	850
			Coating layer	10	0.700	1785	850
Type-3		0.4/0.45/1.2	Coating layer	10	0.700	1785	850
			Rendering mortar	10	0.930	1880	850
			MW insulation board	101/88/28	0.041	88	850
			Adhesive mortar	1.0	0.20	1250	1400
			Concrete	60/200	1.740	2200	850
Type-4		1.2/1.5	Exterior finish layer	10	0.700	1785	850
			Plastering mortar	20	0.930	1880	850
			AAC block	115/86	0.180	600	850
			Plastering mortar	20	0.930	1880	850
Type-5		1.2/1.5	Plastering mortar	15	0.930	1880	850
			Concrete	200	1.740	2200	850
			Levelling layer	10	0.87	1700	1050
			Adhesive mortar	1.0	0.20	1250	1400
			EPS insulation board	18/13	0.040	15	1500
			Coating layer	10	0.700	1785	850

While the primary insulation materials (EPS, XPS, and MW) share similarly high porosity and low initial thermal conductivity, they exhibit drastic differences in their vapor diffusion resistance factors (μ -values: 30 for EPS, 100 for XPS, and 1.3 for MW). These intrinsic material disparities significantly dictate the moisture accumulation rates

and subsequent drying potentials under WDR exposure. To ensure practical engineering relevance and strict normative compliance with China's General Code for Energy Efficiency and Renewable Energy Application in Buildings (GB 55015-2021) [44], the nominal design U-value of the assemblies must be tailored to the specific requirements of each thermal design zone. For residential buildings of three stories or more, the maximum allowable U-values are 0.40, 0.45, 1.20, and 1.50 W/(m²·K) for the SC, C, HSCW, and HSWW zones, respectively. Consequently, within the same configuration type across different zones, only the thickness of the principal insulation layer (or the AAC block in Type 4) was adjusted to meet these regional thermal thresholds. The material sequence and fundamental insulation mechanisms remained strictly unchanged. This controlled adaptation effectively isolates the variables, ensuring that the cross-climatic disparities in dynamic thermal degradation observed in subsequent analyses stem exclusively from the interplay between assembly configurations and local transient climatic loads, rather than arbitrary changes in wall compositions.

2.5. Calculation Methods for Dynamic Thermal Performance

To quantify the extent of thermal deviation caused by moisture, a comprehensive set of dynamic thermal performance indicators was established. These indicators characterize the magnitude, deviation, and fluctuation of heat transfer performance under moisture-laden conditions, and include the annual average dynamic heat transfer coefficient ($U_{\text{dyn-mean}}$), the annual average deviation rate (DR_{mean}), the maximum and minimum monthly average U-values ($U_{\text{max,m}}/U_{\text{min,m}}$), the maximum monthly deviation rate ($DR_{\text{max,m}}$), the effective fluctuation amplitude (AU), the standard deviation (SD), and the number of months exceeding the design value (N_{ex}).

(1) Annual Mean Dynamic ($U_{\text{dyn-mean}}$)

Let $U_{\text{dyn}, t}$ denote the dynamic U-value at time t during the final statistical year. The annual mean dynamic $U_{\text{dyn-mean}}$ is defined as:

$$U_{\text{dyn-mean}} = \frac{1}{n} \sum_{t=1}^n U_t \quad (5)$$

where n represents the total number of hourly records in a year $n = 8760$.

(2) Annual Mean Deviation Rate (DR_{mean})

The annual mean deviation rate reflects the long-term departure of the actual thermal performance from its normative design baseline. Let U_{design} be the nominal design U-value (U_{design}); DR_{mean} is expressed as:

$$DR_{\text{mean}} = \frac{U_{\text{dyn-mean}} - U_{\text{design}}}{U_{\text{design}}} \quad (6)$$

(3) Monthly dynamic U-value (U_m)

In the WUFI post-processor, the transient U- and R-values are both defined in terms of the ratio (or its inverse, respectively) of the average heat flow density divided by the average temperature difference over the calculation period.

$$U_m = \frac{\bar{q}}{\Delta T} \quad (7)$$

as

$$\bar{q} = \frac{1}{N} \sum_{j=1}^N (q_j)$$

$$\Delta \bar{T} = \frac{1}{N} \sum_{j=1}^N (T_{i,j} - T_{e,j})$$

where q_j is the hourly density of heat flow rate at the interior surface, and $T_{i,j}$ are the concurrent indoor and outdoor environmental temperatures, and N represents the total number of hours in the targeting month.

Therefore,

$$U_m = \frac{\frac{1}{N} \sum_{j=1}^N q_j}{\frac{1}{N} \sum_{j=1}^N (T_{i,j} - T_{e,j})} = \frac{\sum_{j=1}^N q_j}{\sum_{j=1}^N (T_{i,j} - T_{e,j})} \quad (8)$$

This is in accordance with the standard Average Method formulated in ISO 9869-1:2014. This equation utilizes a one-month time-averaging window (e.g., 720 or 744 h). Through the integration of the transient heat flux and temperature gradients over a monthly timescale, the net thermal energy storage variations within the thermal mass approach zero, and high-frequency diurnal latent heat fluctuations are effectively attenuated.

(4) Monthly Extremes and Fluctuation Indicators

Based on the monthly average dynamic $U_{m,i}$ ($U_{m,i}$, where $i = 1 \dots 12$), the maximum and minimum monthly average U -values are defined as:

$$U_{\max,m} = \max(U_m), \quad U_{\min,m} = \min(U_m) \quad (9)$$

Correspondingly, the maximum mean deviation rate is:

$$DR_{\max} = \frac{U_{\max,m} - U_{\text{design}}}{U_{\text{design}}} \quad (10)$$

The effective fluctuation amplitude AU , describing the range of dynamic heat transfer coefficient throughout the year, is given by:

$$AU = U_{\max,m} - U_{\min,m} \quad (11)$$

It is crucial to clarify the physical definition of the minimum value and the zero-value truncation in this study. Because the dynamic U -value evaluation focuses on the wall's ability to resist outward heat loss, heat transfer from the indoor to the outdoor environment is defined as positive. When high outdoor temperatures or intense solar radiation during summer cause a reversal in the heat transfer direction (i.e., heat flowing from the exterior to the interior), the raw dynamic U -value manifests as a negative value. To focus the statistical analysis strictly on the degradation risk of forward insulation performance, all negative values (representing the reverse heat transfer phase) are systematically recorded as zero.

Additionally, the standard deviation of monthly U -values is calculated to reflect the dispersion of thermal transmittance on an annual scale. The number of months exceeding the design value quantifies the duration (out of 12 months) in which the monthly mean U -value remains higher than U_{design} .

Together, these indicators constitute a multi-dimensional evaluation matrix for assessing the average level, deviation magnitude, and fluctuation characteristics of wall thermal performance.

2.6. Simulation Reliability and Model Limitations

To verify the computational accuracy of the numerical framework, a validation model of an expanded polystyrene (EPS) internally insulated concrete wall assembly was reconstructed in WUFI Pro based on reference [45]. The comprehensive validation of the transient HAMT simulation framework implemented herein directly refers to the protocols

established in our prior work [24]. Specifically, for the convenience of readers, the brief is introduced as follows: The material layer sequence, structural thicknesses, and hygrothermal properties were strictly aligned with the documented literature. However, as the original study did not specify the exact climate data source, an absolute replication of the historical climate boundary input was unachievable. To overcome this limitation, the outdoor boundary in this validation model was constructed utilizing the hourly meteorological dataset obtained from ECMWF. Consequently, the primary focus of this validation lies not in achieving a point-to-point, day-by-day numerical identity, but rather in evaluating the consistency of the simulated results with the literature data regarding dynamic evolutionary trends, cyclic seasonal fluctuation patterns, and overall numerical magnitudes. The evaluation prioritizes the model's capability to reliably reproduce the underlying hygrothermal response mechanisms of the envelope under ambient forcing.

Figure 1 illustrates that the simulated temporal evolution of the moisture content exhibits a notable degree of correlation and consistency with the reference data across the continuous multi-year exposure period. The two curves demonstrate considerable agreement in overall evolutionary trajectories and phased fluctuation characteristics, proving that the adopted material properties, boundaries, and simulation protocols possess high suitability. To further quantitatively evaluate the goodness-of-fit and predictive accuracy of the model, a linear regression and statistical error analysis were performed. The results demonstrated exceptional predictive fidelity across a continuous multi-year exposure period, achieving a Pearson correlation coefficient (r) of 0.979, a coefficient of determination (R^2) of 0.959, and a Mean Absolute Percentage Error (MAPE) of 23.3%. Given the divergence in the climatic boundary files, a MAPE of this magnitude is considered acceptable for transient multi-year hygrothermal fields and further substantiates the mathematical reliability and fidelity of the established modeling framework.

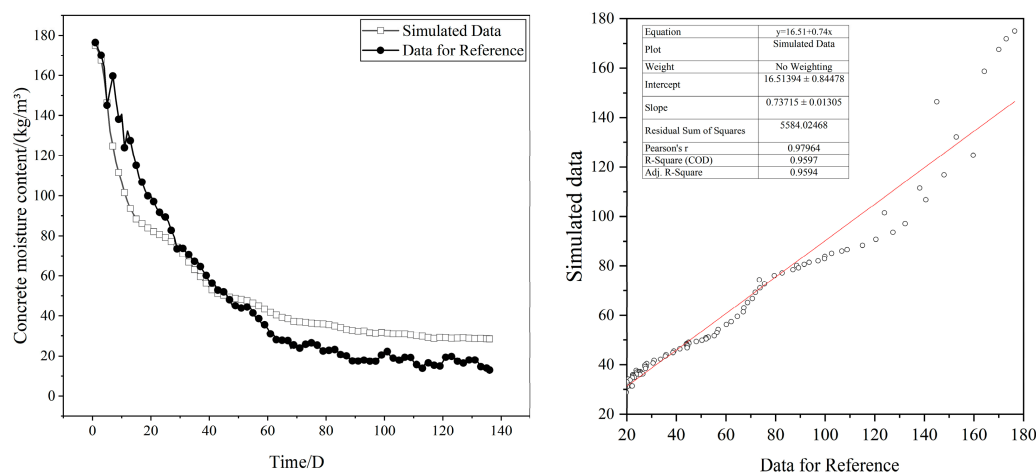


Figure 1. Validation of the numerical model by benchmarking against experimental moisture content data from [45]. Open dots represent individual data points; the red solid line is the linear regression fit.

Although the adopted Heat and Moisture Transfer (HAMT) numerical model achieves high predictive precision and complies with the international EN 15026 standard, it has inherent limitations at both the material and boundary levels that merit objective consideration. One such limitation is the assumption of idealized layer interfaces, where the mathematical engine presumes perfect hydraulic contact at the boundaries between adjacent material layers. Furthermore, semi-empirical wind-driven rain calculations simplify localized aerodynamic turbulences across complex facades. These material-level simplifications represent a baseline distinct from the spatial constraints of the one-dimensional approach. The specific impacts of omitting multidimensional thermal bridges, lateral

moisture redistribution, and localized construction defects are addressed separately in Section 4.6.

3. Results

3.1. Variations in $U_{\text{dyn-mean}}$ Across Thermal Design Zones

Prior to conducting a cross-sectional comparison across thermal design zones and configurations, an overall statistical analysis of the dynamic thermal performance indicators for all 68 test cases was performed (Table 4).

Table 4. Overall descriptive statistics of dynamic thermal performance for all cases.

Index	Mean [W/(m ² ·K)]	Median [W/(m ² ·K)]	Standard Deviation [W/(m ² ·K)]	Min-Value [W/(m ² ·K)]	Q1 [W/(m ² ·K)]	Q3 [W/(m ² ·K)]	Max-Value [W/(m ² ·K)]
$U_{\text{dyn-mean}}$	1.25	0.85	1.25	0.34	0.39	1.53	7.13
DR_{mean}	0.37	0.01	0.89	−0.18	−0.02	0.27	4.97
$U_{\text{max,m}}$	5.20	1.29	9.44	0.37	0.60	4.52	46.39
$DR_{\text{max,m}}$	5.83	0.53	13.75	−0.65	0.01	3.52	84.86
$U_{\text{min,m}}$	0.50	0.36	0.41	0.00	0.18	0.80	1.98
AU	4.70	0.82	9.25	0.03	0.37	3.55	46.01
SD	1.29	0.19	2.53	0.01	0.14	1.15	12.46
Exceeding months	6.15	6.00	2.73	0.00	4.00	8.25	11.00

The results revealed significant disparities in dynamic thermal performance between the cases. The $U_{\text{dyn-mean}}$ was 1.25 W/(m²·K) and the median was 0.86 W/(m²·K), with a peak value reaching 7.13 W/(m²·K), indicating a pronounced right-skewed distribution. The DR_{mean} was 0.37, while the median was merely 0.01, confirming that a minority of cases experiencing severe thermal degradation significantly elevate the overall average.

Furthermore, the $U_{\text{max,m}}$, AU, and standard deviation all display extensive dispersion, highlighting that certain wall assemblies undergo drastic dynamic thermal fluctuations within the year period (Figure 2). Specifically, $U_{\text{max,m}}$ reaches 1.36 W/(m²·K) in the SC zone, 3.4 times the control limit of 0.40 W/(m²·K); 4.62 W/(m²·K) in the C zone, 10.2 times the limit of 0.45 W/(m²·K); 20.2 W/(m²·K) in the HSCW zone, 16.8 times the limit of 1.2 W/(m²·K); and 29.7 W/(m²·K) in the HSWW zone, 19.8 times the limit of 1.5 W/(m²·K). And the mean duration exceeding the U_{design} is 6.15 months with median of 6 months, implying that under WDR stress, the actual heat transfer capacity of most cases is inferior to the theoretical design baseline for approximately half of the year. Notably, given that transmission heat loss is linearly proportional to the U-value of the building envelope under a specific temperature gradient, the substantial seasonal surges in thermal transmittance induced by moisture will directly cause a proportional increase in dynamic heat loss, which will significantly elevate the actual energy consumption for heating and cooling load during periods with high moisture activity. These aggregate statistics, however, obscure significant inter-zonal disparities, which are disaggregated in the following section.

To reveal the underlying WDR impacts, a zonal statistical analysis was conducted. As illustrated in Figure 3, overall, dynamic thermal performance exhibits pronounced climate-specific degradation profiles. The $U_{\text{dyn-mean}}$ in the SC and C zones was maintained at lower levels, whereas those in the HSWW and HSCW zones display systemic numerical elevation. When contrasted with their respective design baselines, it is evident that the actual heat transfer capacities of walls in warm and humid climates are highly susceptible to severe deviations following moisture absorption.

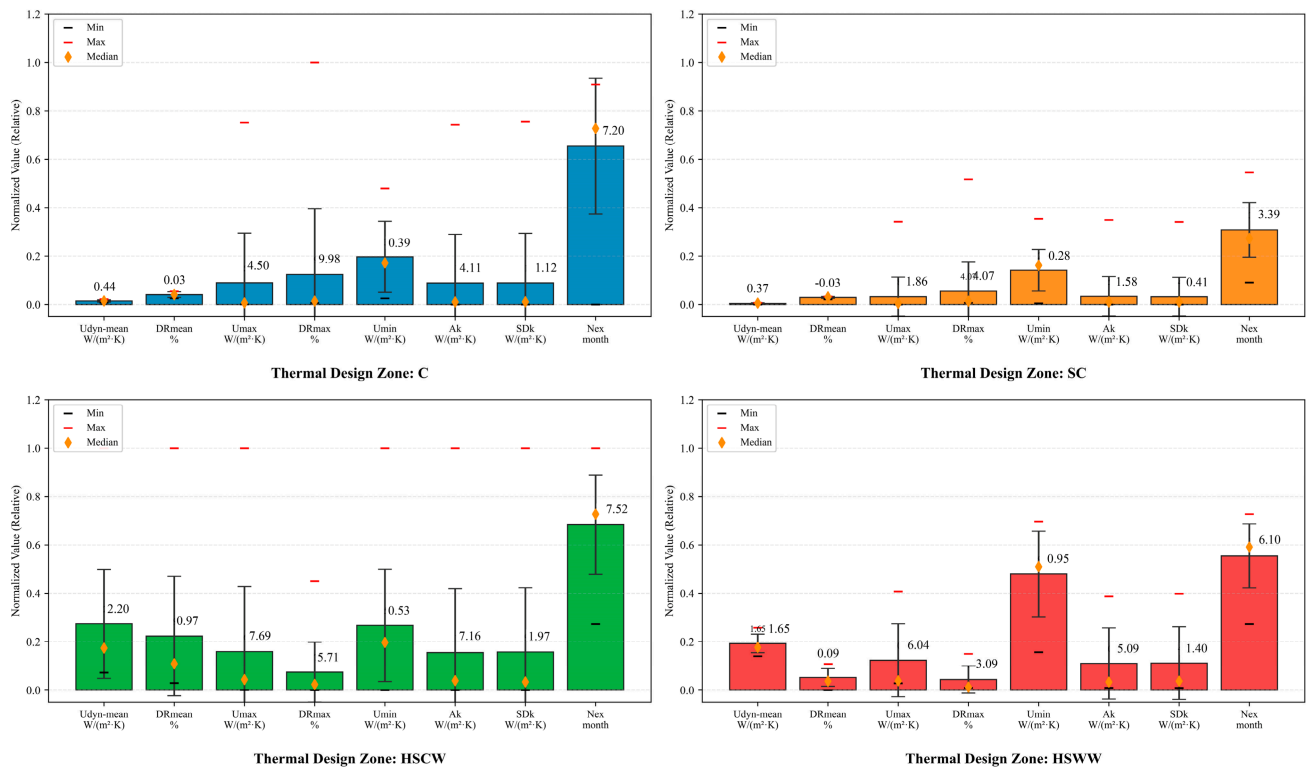


Figure 2. Comparison of eight thermal indicators across four climate zones. Note: The bar charts for each climate zone were normalized using the min–max method (scaling each indicator to 0–1) to eliminate the influence of magnitude discrepancies among the eight thermal indicators, allowing for a direct visual comparison on a unified scale. In these charts, bar height represents the normalized mean; I-shaped error bars denote standard deviation (SD). The bottom and top short horizontal lines on each bar indicate the minimum and maximum values, respectively. Orange diamond markers above each bar represent the median. The numerical values at the top of each bar are the actual means, preserving the original dimensional scale.

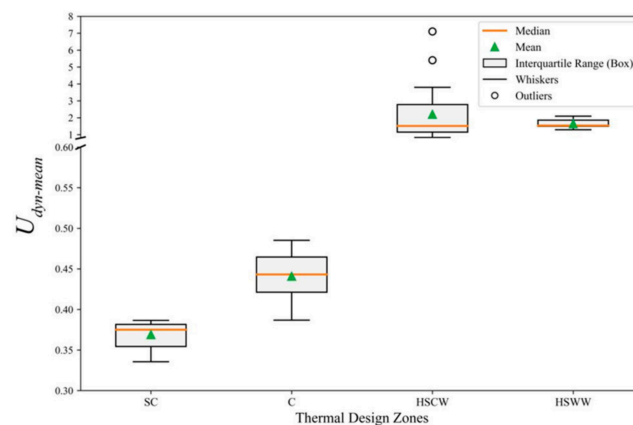


Figure 3. Box plots of annual average dynamic U-value for wall assemblies across different thermal design zones.

Specifically, in the SC zone, both the mean and the median of the annual average dynamic U-value ($U_{\text{dyn-mean}}$) remained strictly below the regional control limit of $0.40 \text{ W}/(\text{m}^2 \cdot \text{K})$. This indicates that the actual heat transfer performance of walls in this zone under moisture-laden conditions generally remains within a safe and controllable range, devoid of macroscopic thermal deterioration. The narrow interquartile range confirms minimal dispersion among cases, reflecting exceptional robustness post-moisture absorption. The mean annual average deviation rate is -0.03 , and the duration exceeding

the design value is merely 3.4 months, substantiating that most configurations can maintain near-design insulation levels year-round. In contrast, while the mean annual average dynamic U -value in the C zone is $0.44 \text{ W}/(\text{m}^2 \cdot \text{K})$, marginally below the nominal design limit of $0.45 \text{ W}/(\text{m}^2 \cdot \text{K})$, the box and whisker spans for this zone are significantly elongated compared to the SC zone, indicating an onset of intensified systemic volatility. More alarmingly, although the annual average deviation rate in the C zone remains moderate with a mean value of 0.03, the mean duration exceeding the design value jumps to 7.2 months. This phenomenon uncovers that the dynamic thermal risk in the C zone manifests not as a drastic increase in the U -value magnitude, but rather as a significantly prolonged duration of deviation.

Compared to the northern cold regions, the dynamic thermal performance in the HSWW and HSCW zones deteriorates sharply. In the HSWW zone, both the mean $1.65 \text{ W}/(\text{m}^2 \cdot \text{K})$ and median $1.54 \text{ W}/(\text{m}^2 \cdot \text{K})$ of $U_{\text{dyn-mean}}$ breached the $1.50 \text{ W}/(\text{m}^2 \cdot \text{K})$ design baseline, suggesting substantial, systemic degradation in heat transfer performance for most cases. The mean DR_{mean} reaches 0.09 with massive internal variance, signifying that the dynamic thermal issue has escalated into a systematic deterioration on an annual scale. Notably, the HSCW zone presents the most adverse dynamic thermal environment. The mean value of $U_{\text{dyn-mean}}$ sharply rises to the maximum of $2.20 \text{ W}/(\text{m}^2 \cdot \text{K})$, with a mean DR_{mean} of 0.97. Additionally, the mean $U_{\text{max,m}}$ in this region reaches $7.69 \text{ W}/(\text{m}^2 \cdot \text{K})$, and the duration exceeding the design value extends to 7.5 months. These extremes confirm that WDR-induced moisture accumulation and subsequent thermal negative feedback loops are most intense in the HSCW zone, causing devastating fluctuations and protracted performance deviations in the actual insulation capacity of the walls.

Beyond mean values, the intra-annual fluctuation characteristics differ significantly across zones (Figure 4). The mean AU for the SC and C zones is 1.58 and 4.11, respectively, whereas they increase to 5.09 and 7.16 in the HSWW and HSCW zones, suggesting a progressive escalation in thermal volatility from cold/dry to warm/humid regions.

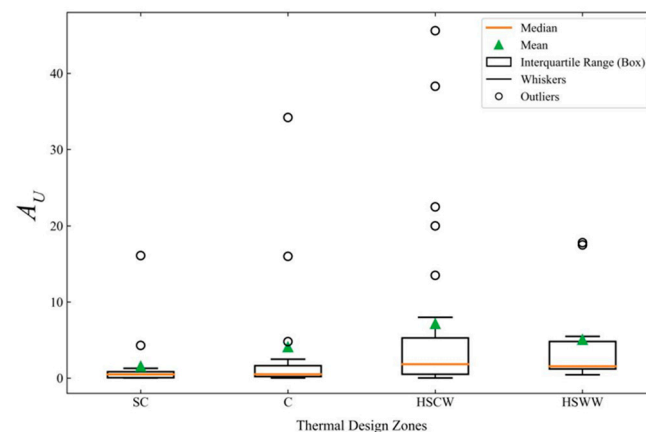


Figure 4. Box plots of the effective fluctuation amplitude of $U_{\text{dyn-mean}}$ for wall assemblies across different thermal design zones.

The distribution of standard deviations also mirrors this trend. Coupled with the statistics on months exceeding the design value (Figure 5), it suggests that warm and humid regions not only face higher-frequency thermal fluctuations but also suffer from prolonged moisture-laden periods that severely undermine their actual thermal adaptability.

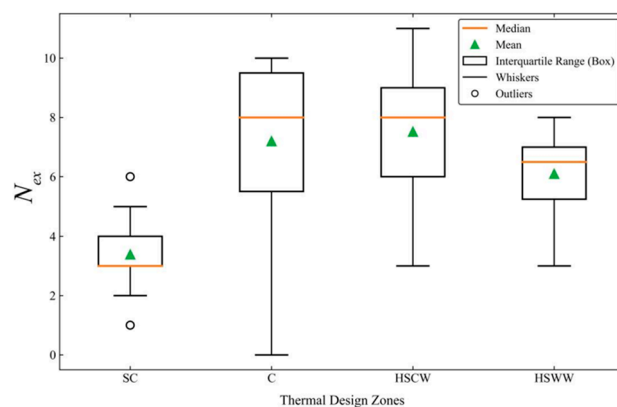


Figure 5. Box plots of the duration (in months) exceeding the design baseline for wall assemblies across different thermal design zones.

In summary, WDR-driven dynamic thermal degradation exhibits high regional dependency. The SC zone demonstrates exceptional thermal stability; the C zone represents a transitional state characterized primarily by a prolonged deviation period; while the HSWW and HSCW zones experience profound degradation, with the HSCW zone being the most serious. Consequently, for warm and humid regions, nominal U-value compliance is inadequate for addressing actual moisture load challenges, making it imperative to comprehensively prioritize the dynamic effects of WDR in wall configuration selection, climate adaptability assessments, and the formulation of protective strategies.

3.2. Variations in Dynamic Thermal Performance Across Wall Assemblies

To systematically compare the dynamic thermal performance of different wall assemblies under WDR, statistical analyses were conducted on key indicators, including the annual average dynamic U-value, annual average deviation rate, maximum monthly average U-value, effective fluctuation amplitude, standard deviation, and the duration (in months) exceeding the design baseline.

3.2.1. Annual Average Performance and Deviation Rates

As shown in Figures 6 and 7, the overall distribution of annual average dynamic U-values reveals significant disparities among the different configurations.

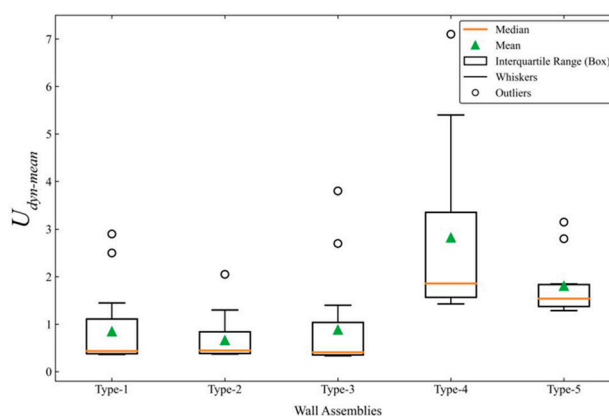


Figure 6. Box plots of annual mean dynamic U-value for different wall assemblies.

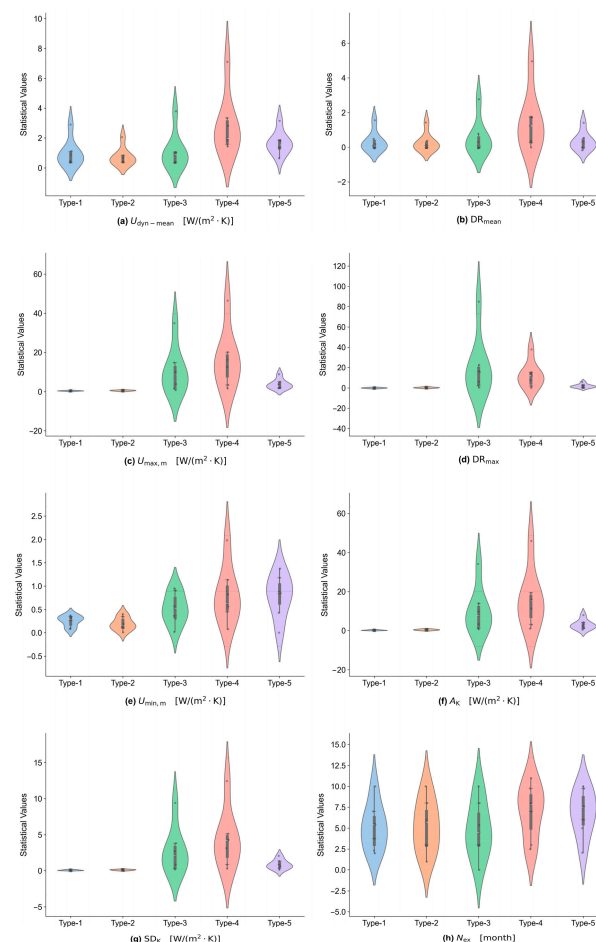


Figure 7. Descriptive statistics of dynamic thermal performance indicators for different wall assemblies.

It is crucial to note that Types 1, 2, and 3 are distributed across the SC, C, and HSCW zones, whereas Types 4 and 5 are evaluated in the HSCW and HSWW zones. Therefore, direct transversal comparisons of mean values between the two cohorts (Types 1–3 vs. Types 4–5) are climatically skewed; a more rigorous approach is to compare the configurations within their shared climatic zones.

Within the colder/transitional cohort (Types 1, 2, and 3), the $U_{\text{dyn-mean}}$ remained generally low, with medians of 0.44, 0.45, and 0.41 $\text{W}/(\text{m}^2 \cdot \text{K})$, respectively. Type 2 exhibits the lowest mean value (0.67 $\text{W}/(\text{m}^2 \cdot \text{K})$), indicating superior dynamic thermal performance compared to Types 1 and 3 (0.85 and 0.89 $\text{W}/(\text{m}^2 \cdot \text{K})$, respectively). By contrast, within the warmer/humid cohort (Types 4 and 5), the median values rise significantly to 1.87 and 1.54 $\text{W}/(\text{m}^2 \cdot \text{K})$. Type 4 is particularly disadvantaged, with a mean U -value of 2.83 $\text{W}/(\text{m}^2 \cdot \text{K})$, which is substantially higher than that of Type 5 (1.81 $\text{W}/(\text{m}^2 \cdot \text{K})$).

This trend is further corroborated by the annual average deviation rates. The medians for Types 1, 2, and 3 are close to zero (−0.01, −0.02, and −0.01, respectively), demonstrating minimal deviation from their nominal design baselines post-moisture absorption. Conversely, Type 4 exhibits severe thermal departure, with a median deviation rate of 0.36 and a mean of 1.24, significantly underperforming all other types. Type 5 shows a moderate degradation with a median of 0.01 and a mean of 0.28. Overall, Types 1, 2, and 3 demonstrate robust thermal adaptability, whereas Types 4 and 5 are highly susceptible to chronic deviation under long-term WDR exposure.

3.2.2. Monthly Peak Degradation and Intra-Annual Volatility

The disparities among the wall configurations become even more pronounced during the worst-case months. For Types 1 and 2, the mean maximum monthly average U -values are relatively stable at 0.48 and 0.64 W/(m²·K), respectively. However, despite its stable annual average, Type 3 experiences severe episodic degradation, with its maximum monthly average U -value surging to a mean of 8.51 W/(m²·K).

In the warmer cohort, Type 5 records a mean $U_{\max,m}$ of 3.74 W/(m²·K). Type 4 suffers from extreme degradation, escalating to 16.21 W/(m²·K). Consequently, Types 3 and 4 present the highest $DR_{\max}$ of 16.13 and 11.85, respectively, indicating a high risk of extreme thermal failure in critical months. In contrast, the deviation rate for Type 1 remains negative, showing that its worst-case dynamic performance rarely exceeds the design baseline.

Metrics for intra-annual volatility (effective fluctuation amplitude and standard deviation) perfectly mirror these extremes. Types 1 and 2 exhibit minimal volatility. Conversely, the mean amplitude for Type 3 sharply increases to 7.94 W/(m²·K), indicating dramatic month-to-month hygrothermal instability. Type 4 proves to be the most volatile overall, with an extreme mean amplitude of 15.34 W/(m²·K) and a standard deviation of 4.20 W/(m²·K), highlighting both inflated thermal transmittance and the poorest performance stability.

3.2.3. Duration of Thermal Exceedance

Regarding the duration for which the dynamic U -value exceeds the design baseline, Types 1 and 2 average 5.4 and 5.7 months, respectively. Type 3 shares a similar mean (5.4 months) but exhibits a much higher dispersion (ranging from 0 to 10 months), highlighting inconsistent case-by-case responses. In contrast, Types 4 and 5 experience prolonged substandard performance, exceeding the design threshold for an average of 7.8 and 7.6 months, respectively.

As illustrated by the box plots in Figure 8, Types 1 and 2 feature narrow interquartile ranges (IQR), reflecting high numerical concentration and low dispersion among cases. Type 3, while maintaining lower means and medians, displays a significantly wider IQR and overall span, reiterating its susceptibility to episodic degradation and elevated intra-annual risk. Both Types 4 and 5 exhibit significantly higher exceedance duration than Types 1–3. Notably, Type 4 ranks highest across all statistical parameters (mean, median, and upper whisker), confirming that it suffers from the most chronic and severe thermal deviation under long-term WDR exposure.

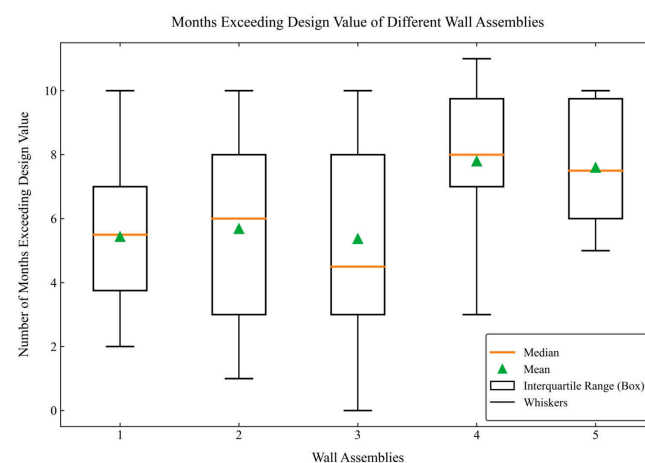


Figure 8. Box plot of months exceeding design values for different wall assemblies.

3.3. Intra-Annual Fluctuation Characteristics and Peak Months of Thermal Degradation

Building upon the comparative analysis across thermal design zones and wall assemblies, this section further evaluates the intra-annual fluctuation characteristics and worst-case monthly performance across all 68 evaluated cases.

To ensure thermodynamic consistency under rapid hygrothermal transients, the monthly dynamic U-value (U_m) is calculated strictly according to Equations (7) and (8) defined in Section 2.5. This formulation utilizes a one-month time-averaging window ($N = 720$ to 744 h), which mathematically equates to the standard Cumulative Average Method stipulated in ISO 9869-1:2014. By integrating the transient heat flux and temperature gradients over a monthly duration, the net thermal energy storage variations within the structural thermal mass approach zero and the high-frequency diurnal latent heat phase-change fluctuations are effectively smoothed out. Metrics such as the maximum monthly dynamic U-value ($U_{max,m}$), effective fluctuation amplitude (AU), and standard deviation (SD) are computed based on this standardized, energy-conservative baseline to identify seasonal thermal performance instability, as summarized in Table 5. The term “worst-case month” is defined by the occurrence of either the $U_{max,m}$ or a zero-value. Metrics such as the $U_{max,m}$, AU, and standard deviation are utilized to quantify month-to-month thermal instability, while the temporal distribution of these extremes helps identify seasonal patterns.

Table 5. Statistical results of dynamic U-value fluctuation characteristics and performance in the most unfavorable month.

Thermal Design Zones	Location	Type	Mean	$U_{max,m}$	Month of Max	Month of Min	AU	SD of Mean U-Value	Zero Months	Number of Zero-Value Months
SC	Qumalai	1	0.38	0.60	Aug.	Jan.	0.52	0.14		0
		2	0.39	0.40	Aug.	Jan.	0.04	0.01		0
		3	0.35	0.84	Oct.	Jul.	0.70	0.17		0
	Seda	1	0.38	0.58	Oct.	Jun.	0.34	0.14		0
		2	0.39	0.40	Oct.	Jun.	0.04	0.01		0
		3	0.36	1.21	Oct.	Jun.	0.85	0.22		0
	Yushu	1	0.37	0.38	Aug.	Jun.	0.07	0.02		0
		2	0.38	0.43	Aug.	Jul.	0.08	0.02		0
		3	0.35	1.66	Oct.	Jun.	1.25	0.31		0
	Erenhot	1	0.38	0.37	Jun.	May	0.03	0.01	Aug.	1
		2	0.38	0.66	Jun.	May	0.51	0.14	Aug.	1
		3	0.35	2.63	Jun.	May	2.21	0.53	Aug.	1
	Datong	1	0.36	0.38	Jun.	Aug.	0.06	0.02		0
		2	0.37	0.83	Jun.	Aug.	0.83	0.19		0
		3	0.34	4.98	Jun.	Aug.	4.29	1.14		0
	Ganzi	1	0.38	0.37	Oct.	Jun.	0.04	0.01		0
		2	0.38	0.60	Oct.	Jun.	0.50	0.14		0
		3	0.35	16.09	Oct.	Jun.	16.07	4.25		0

Table 5. Cont.

Thermal Design Zones	Location	Type	Mean	$U_{\max,m}$	Month of Max	Month of Min	AU	SD of Mean U-Value	Zero Months	Number of Zero-Value Months
C	Taiyuan	1	0.42	0.63	Apr.	Aug.	0.51	0.13		0
		2	0.43	0.79	Apr.	Aug.	0.69	0.17		0
		3	0.39	1.36	Apr.	Aug.	0.87	0.22		0
	Daofu	1	0.43	0.62	Oct.	Jun.	0.35	0.15		0
		2	0.44	0.45	Aug.	Jun.	0.08	0.02		0
		3	0.40	5.66	Oct.	Jun.	4.71	1.33		0
	Shijiazhuang	1	0.44	0.40	Apr.	Sep.	0.06	0.01		0
		2	0.46	0.86	Apr.	Sep.	0.81	0.18		0
		3	0.42	16.85	Apr.	Sep.	15.91	4.35		0
	Xuzhou	1	0.47	0.40	Apr.	Sep.	0.03	0.01		0
		2	0.49	0.62	Apr.	Sep.	0.49	0.14		0
		3	0.44	34.94	Apr.	Sep.	34.17	9.41		0
	Qingdao	1	0.47	0.40	Jul.	Sep.	0.06	0.01		0
		2	0.48	0.69	Jul.	Sep.	0.52	0.14		0
		3	0.44	2.79	Jul.	Sep.	2.42	0.58		0
HSCW	Hefei	1	1.44	0.39	Jul.	Sep.	0.04	0.01	Jun.	1
		2	0.99	0.82	Jul.	Jun.	0.69	0.17		0
		3	1.39	1.50	Jul.	Nov.	1.15	0.28	Jun.	1
		4	3.78	3.37	Jul.	Aug.	3.30	0.82	Jun.	1
		5	1.76	3.61	Jul.	Aug.	2.75	1.17	Jun.	1
	Nanjing	1	2.52	0.65	Jun.	Sep.	0.54	0.14		0
		2	1.29	0.46	Jun.	Oct.	0.06	0.01		0
		3	2.68	2.36	Jun.	Oct.	1.83	0.43		0
		4	7.12	3.50	Jun.	Aug.	3.08	1.00		0
		5	3.16	8.83	Jun.	Aug.	7.99	2.07		0
	Yibin	1	2.91	0.66	Jun.	Oct.	0.38	0.16	Jul./Aug.	2
		2	2.06	0.70	Jun.	Aug.	0.52	0.14	Jul.	1
		3	3.80	5.58	Jun.	Oct.	4.68	1.30	Jul./Aug.	2
		4	5.39	20.50	Jun.	Feb.	19.94	5.19	Jul./Aug.	2
		5	2.78	5.28	Sep.	Mar.	5.28	1.51	Oct./Nov.	2
	Guangchang	1	1.15	0.40	May	Jun.	0.04	0.01		0
		2	0.86	0.85	May	Jun.	0.81	0.18		0
		3	1.09	14.39	May	Jun.	13.47	3.67		0
		4	1.71	46.40	Sep.	Aug.	46.01	12.46	Jun.	1
		5	1.32	5.56	May	Jun.	4.66	1.41		0
	Fuding	1	1.10	0.40	May	Jun.	0.03	0.01		0
		2	0.83	0.63	Apr.	Jun.	0.46	0.14		0
		3	1.02	23.32	Apr.	Jun.	22.41	6.18		0
		4	1.52	40.27	Sep.	Jun.	38.28	10.59		0
		5	1.33	1.82	May	Jun.	0.53	0.16		0

Table 5. Cont.

Thermal Design Zones	Location	Type	Mean	$U_{\max,m}$	Month of Max	Month of Min	AU	SD of Mean U-Value	Zero Months	Number of Zero-Value Months
HSWW	Fuzhou	4	2.09	1.67	Sep.	Jun.	1.05	0.28		0
		5	1.86	1.89	Sep.	Jun.	1.58	0.55		0
	Fogang	4	1.43	2.18	Oct.	Jul.	1.54	0.35	May/Jun./Aug./Sep.	4
		5	1.29	4.37	Oct.	May	3.09	0.79		0
	Yuanmou	4	1.49	6.53	Aug.	May	5.40	1.51		0
		5	1.57	2.10	Jul.	May	1.26	0.38		0
	Guangzhou	4	1.87	18.60	Oct.	Jun.	17.46	4.76	Aug./Sep.	2
		5	1.49	2.09	Oct.	Sep.	1.20	0.33		0
	Shantou	4	1.85	19.1	Oct.	Aug.	17.81	4.97	Sep.	1
		5	1.50	1.83	Oct.	May	0.45	0.12		0

3.3.1. Magnitude of Intra-Annual Volatility and High-Volatility Cases

Overall statistics reveal pronounced disparities in intra-annual volatility among the cases. Across all 68 cases, the mean of $U_{\max,m}$ is $5.19 \text{ W}/(\text{m}^2\cdot\text{K})$. The A_U averages $4.70 \text{ W}/(\text{m}^2\cdot\text{K})$, and the standard deviation averages $1.29 \text{ W}/(\text{m}^2\cdot\text{K})$.

A closer examination of cases with the highest effective fluctuation amplitudes reveals distinct regional and structural concentrations. Among the top 10 most volatile cases, 5 are located in the HSCW zone, 2 in the C zone, and 2 in the HSWW and 1 in the SC zones. Structurally, Type 3 and 4 account for five cases each. Specifically, the Type 4 assembly in Guangchang recorded the highest AU of $46.01 \text{ W}/(\text{m}^2\cdot\text{K})$, corresponding to a maximum monthly U-value of $46.39 \text{ W}/(\text{m}^2\cdot\text{K})$ and a standard deviation of $12.46 \text{ W}/(\text{m}^2\cdot\text{K})$. Similarly, the Type 4 assembly in Fuding and the Type 3 assembly in Xuzhou exhibited massive fluctuation amplitudes of $38.28 \text{ W}/(\text{m}^2\cdot\text{K})$ and $34.17 \text{ W}/(\text{m}^2\cdot\text{K})$, respectively.

Notably, extreme intra-annual volatility does not strictly correlate with high annual average U-values. For instance, the Type 3 assembly in Xuzhou maintains a low annual average dynamic U-value of $0.44 \text{ W}/(\text{m}^2\cdot\text{K})$ but suffers a massive fluctuation amplitude of $34.17 \text{ W}/(\text{m}^2\cdot\text{K})$. A similar discrepancy is observed in the Type 3 assembly in Ganzi with an annual mean U-value of $0.35 \text{ W}/(\text{m}^2\cdot\text{K})$ and an amplitude of $16.07 \text{ W}/(\text{m}^2\cdot\text{K})$. This indicates that thermal degradation often manifests as intense, episodic spikes in specific months rather than uniform, year-round deterioration.

3.3.2. Seasonal Distribution of Peak Thermal Degradation

The occurrence of $U_{\max,m}$ exhibits strong seasonal clustering (Figure 9). Among the 68 cases, the $U_{\max,m}$ occurred in October (16 cases), June (15 cases), and April (11 cases). Less frequent occurrences were recorded in July (9 cases), May (6 cases), August (6 cases), and September (5 cases). Thus, the critical months for peak thermal degradation are predominantly April, June, and October.

Further stratification by thermal design zone reveals clear regional dependencies driven by local transient climatic conditions and hygrothermal boundary shifts. In the SC zone, peak degradation primarily occurs in October (8 cases) and June (6 cases). The C zone is heavily concentrated in April (9 cases). The HSCW zone peaks during June (9 cases) and May (6 cases), whereas the HSWW zone is dominated by October (6 cases). From a structural perspective, the distribution is more scattered but still indicative: Type 3 peaks predominantly in October (5 cases), Type 4 in September and October (3 cases each), while Types 1 and 2 are distributed across April, June, August, and October. There-

fore, the timing of the worst-case month is influenced by both regional climates and structural configurations.

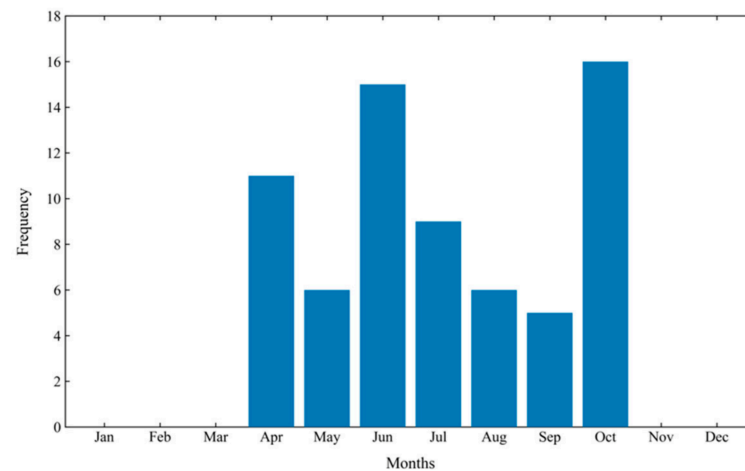


Figure 9. Distribution of months with maximum monthly mean U-Values.

3.3.3. Heat Flow Reversals and Zero-Value Analysis

Beyond peak values, the occurrence of zero-value months is a critical characteristic of intra-annual fluctuation (Figure 10). In this context, a zero-value does not imply that the absolute thermal resistance of the wall is zero. Instead, it denotes a reversal in the heat transfer direction, from the exterior to the interior, relative to the defined forward direction (interior to exterior). Because the dynamic U-value evaluation focuses on the wall's ability to resist outward heat loss, negative values resulting from reversed heat flow are systematically recorded as zero for statistical purposes.

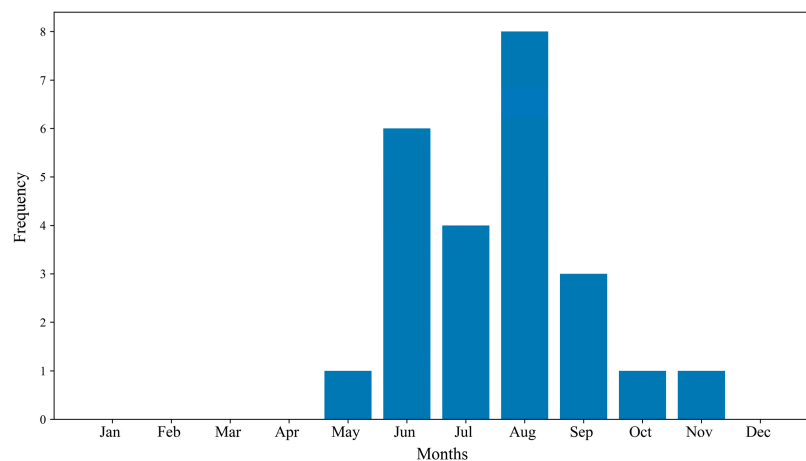


Figure 10. Distribution of months with U_m at Zero.

The statistical analysis shows that 16 out of the 68 cases experienced zero U -value months during the final simulation year, indicating that this phenomenon is case-specific rather than universal. Temporally, these heat flow reversals peak in August (8 occurrences) and June (6 occurrences), followed by July (4) and September (3), with rare, isolated instances in May, October, and November.

Comparing the temporal distribution of $U_{max,m}$ and zero-value months reveals both significant overlap and clear misalignment. Peak forward heat transfer is concentrated in October, June, and April, while heat flow reversals (zero U -values) dominate in August, June, July, and September. The shared critical month is June, indicating that June is not merely a smooth climatic transition; rather, it is a period of intense hygrothermal instability.

During this month, some cases exhibit severe forward heat loss with high maximum U -values, while others experience complete heat flow reversals with zero U -values, signifying a high frequency of bidirectional heat transfer switching. In contrast, the July–September period is primarily characterized by heat flow reversals, while October is overwhelmingly dominated by extreme forward heat loss.

These pronounced seasonal fluctuations demonstrate that the thermal risk profile of a wall assembly cannot be adequately captured by annual averages or nominal design values alone. To translate these intra-annual volatility characteristics into a meaningful assessment of practical adaptability, the following section establishes a dynamic re-ranking framework that accounts for both the magnitude and the persistence of thermal deviation under WDR stress.

3.4. Dynamic Re-Ranking of Thermal Adaptability Across Wall Assemblies

3.4.1. Evaluation Framework and the Limitations of Normative Compliance

The preceding analyses demonstrate that different thermal design zones and wall assemblies exhibit distinctly different dynamic thermal performance characteristics under WDR exposure. To thoroughly evaluate the adaptability of wall assemblies, these variances must be translated into the actual thermal performance of different assemblies within their respective thermal design zones.

Conventional compliance conclusions are based primarily on normative thermal transmittance, evaluating applicability solely on whether the nominal design U -value meets regional thermal requirements. Under this normative framework, Types 1, 2, and 3 are universally deemed applicable for the SC and C zones; Types 1 through 5 are considered applicable for the HSCW zone; and Types 4 and 5 are deemed applicable for the HSWW zone. However, this conclusion reflects applicability solely under standard dry design conditions and does not guarantee static thermal performance or adaptability under actual operating conditions.

To further compare the deviation between the actual moisture-affected thermal performance and the nominal design state, a scatter plot correlating the actual dynamic U -values with the nominal design U -values was generated, as illustrated in Figure 11. A substantial number of cases are distinctly distributed above the reference line, indicating that their actual thermal transmittance has exceeded the design baseline to varying degrees. This evidence suggests that relying exclusively on normative applicability judgments is insufficient to fully capture a wall's thermal performance in realistic hygrothermal environments.

Consequently, this study adopts a hierarchical evaluation framework to analyze the relative dynamic thermal adaptability of different assemblies within each thermal design zone. DR_{mean} is utilized as the primary indicator, directly quantifying the magnitude of thermal deviation post-moisture absorption. The duration exceeding the design baseline (N_{ex}) serves as the secondary indicator, representing the chronicity of this deviation throughout the year. When primary indicators show clear discrepancies, they serve as the definitive ranking criterion; when primary indicators are comparable, the secondary indicator is incorporated for further stratification. The statistical results of these key dynamic indicators across different zones and assemblies are detailed in Table 6.

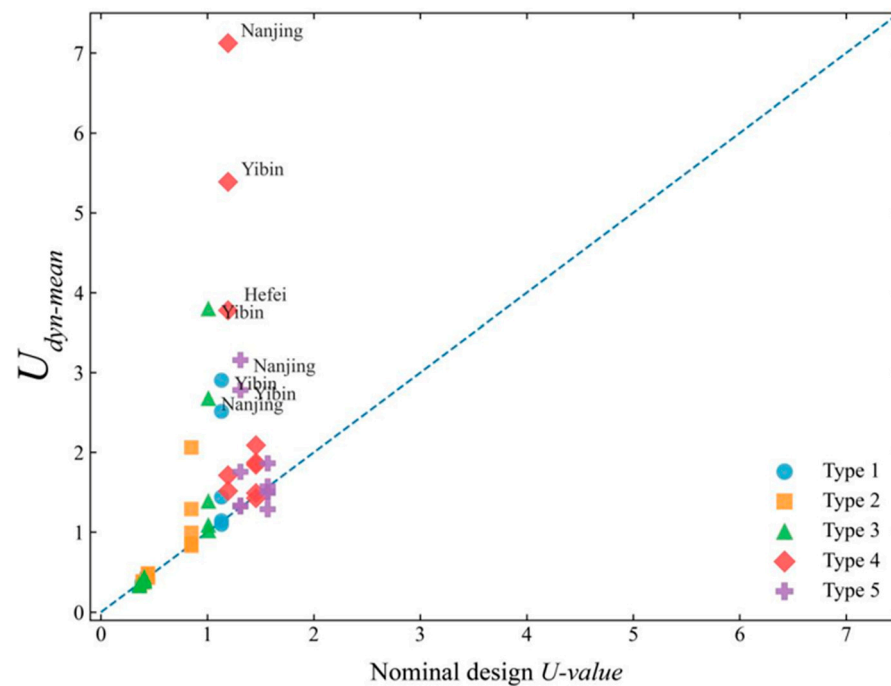


Figure 11. Scatter plot of design U -value vs. annual mean dynamic U -value.

Table 6. Statistical summary of key dynamic thermal performance indicators for different wall assemblies across thermal design zones.

Thermal Design Zones	Type	$U_{\text{dyn-mean}}$ $\text{W}/(\text{m}^2 \cdot \text{K})$		DR_{mean}		N_{ex}	
		Mean	Median	Mean	Median	Mean	Median
SC	1	0.38	0.38	−0.029	−0.025	3.5	3.5
	2	0.38	0.38	−0.029	−0.023	3.2	3
	3	0.35	0.35	−0.032	−0.026	3.5	3.5
C	1	0.45	0.44	0.030	0.025	7.6	8
	2	0.46	0.46	0.035	0.034	8	9
	3	0.42	0.42	0.028	0.021	6	8
HSCW	1	1.82	1.44	0.611	0.274	5.6	6
	2	1.21	0.99	0.420	0.167	6.4	7
	3	2.00	1.39	0.981	0.380	7	7
	4	3.91	3.78	2.271	2.164	9.8	10
	5	2.07	1.76	0.580	0.341	8.8	10
HSWW	4	1.75	1.85	0.199	0.268	5.8	7
	5	1.54	1.51	−0.015	−0.040	6.4	6

3.4.2. Zone-Specific Dynamic Rankings

To systematically elucidate the impact of regional climates on the hygrothermal resilience of different wall assemblies, a zone-by-zone evaluation was conducted. The results indicate a clear geographical gradient. As the climatic context shifts from cold-dry regions to warm-humid environments, the deviation between normative design assumptions and actual dynamic performance becomes increasingly severe, thereby reshaping the adaptability hierarchy.

SC Zone: The overall dynamic performance differences among Types 1, 2, and 3 are minimal. Their primary indicators are −0.029, −0.029, and −0.032, respectively. The negative values indicate that, on average, these configurations do not exceed their nominal design baselines and maintain robust thermal performance after moisture exposure. Type 3 exhibits the lowest deviation. Because the primary indicators for Types 1 and 2 are nearly

identical, their secondary indicators were compared (3.5 and 3.2 months, respectively), showing Type 2 has a slightly shorter deviation duration. Consequently, the original static equivalence (Types 1–3 all compliant) is refined into a dynamic ranking of Type 3 > Type 2 > Type 1. Given the marginal absolute differences, this represents a nuanced stratification rather than a fundamental shift in applicability.

C Zone: Structural disparities are more pronounced than in the SC zone. The primary indicators for Types 1, 2, and 3 are 0.030, 0.036, and 0.028, respectively. Concurrently, their secondary indicators are 7.6, 8.0, and 6.0 months, perfectly aligning with the primary indicator trends. Accordingly, the dynamic thermal adaptability ranking in this zone is established as Type 3 > Type 1 > Type 2. Under the dynamic framework, Type 3 demonstrates the highest thermal stability, while Type 2 exhibits slightly elevated degradation magnitude and duration.

HSCW Zone: This zone exhibits the most dramatic structural disparities and the most significant departure from normative applicability judgments. While normative codes treat Types 1–5 as equally compliant, dynamic metrics reveal they can no longer be viewed as parallel. The primary indicators span a massive range of 0.61 (Type 1), 0.42 (Type 2), 0.98 (Type 3), 2.27 (Type 4), and 0.58 (Type 5). Type 2 performs best, while Type 4 performs worst. Comparing the closely clustered Types 1 and 5, Type 1 is superior due to a significantly shorter secondary indicator (5.6 months vs. 8.8 months). Thus, the dynamic ranking completely breaks the normative parity, establishing a definitive hierarchy of Type 2 > Type 1 > Type 5 > Type 3 > Type 4. Under the combined effects of a warm-humid climate and intense WDR, moisture-induced thermal feedback differences are vastly amplified.

HSWW Zone: Comparing the two applicable assemblies (Types 4 and 5), the primary indicators are 0.20 and -0.02 , respectively. Type 5 demonstrates significantly less deviation, remaining much closer to its nominal design state post-moisture absorption. Although Type 4 exhibits a marginally shorter exceedance duration (5.8 vs. 6.4 months), the stark contrast in the primary degradation magnitude dictates a final ranking of Type 5 > Type 4.

3.4.3. Summary of Adaptability Shifts

The comparison between the original nominal applicability assessments and the dynamic U-value based re-rankings is summarized in Table 7. Overall, the dynamic adaptability rankings do not perfectly align with normative compliance. By introducing deviation rates and exceedance durations, the previously indistinguishable Types 1, 2, and 3 in the SC and C zones can now be stratified. More critically, the broad normative parity in the HSCW zone is shattered, revealing severe vulnerabilities in certain configurations. Ultimately, dynamic thermal performance analysis does not invalidate the basic applicability boundaries defined by normative codes; rather, it transforms coarse, generalized applicability thresholds into a precise, comparative hierarchy.

Table 7. Comparison between the original static applicability assessment and the relative ranking based on dynamic U-values.

Thermal Design Zones	Original Ranking	Dynamic U-Value Ranking
SC	1 = 2 = 3	3 > 2 > 1 (The overall difference is small.)
C	1 = 2 = 3	3 > 1 > 2
HSCW	1 = 2 = 3 = 4 = 5	2 > 1 > 5 > 3 > 4
HSWW	4 = 5	5 > 4

Note: The ranking is based primarily on the annual average deviation rate and secondarily on the number of months exceeding the design value.

4. Discussion

4.1. Limitations of Nominal Design U-Value and Implications for Climate

The results strongly indicate that the nominal design U-value, which relies on a standard dry-state assumption, presents significant limitations when evaluating building thermal performance in warm and humid climates. As demonstrated by the data, the actual dynamic thermal capacities in the HSCW and HSWW zones under WDR exposure not only vastly exceed the design baselines but also persist in this degraded state for over half the year. This implies that relying solely on U_{design} limits for energy simulation in these regions may lead to a severe underestimation of actual heating and cooling loads. While normative thermal codes attempt macroscopic control by adjusting U-value thresholds across zones, they inherently neglect the debilitating effect of external dynamic moisture loads on the thermal conductivity of porous materials.

Fundamentally, the disparities in dynamic thermal performance across climatic zones reveal the underlying mechanistic interplay between WDR loads and the regional drying potential. In the SC zone, limited precipitation coupled with low outdoor absolute humidity provides the exterior surface with a strong outward drying potential, yielding high thermal robustness. In the C zone, increased moisture loads outpace the drying potential, causing thermal degradation to manifest primarily as a prolonged duration of deviation. Conversely, in the HSCW zone, the superimposition of high-frequency WDR and a persistently humid environment triggers a detrimental positive feedback loop. In this loop, moisture accumulation reduces the thermal resistance of the wall, which in turn lowers the temperature of the internal layers. This exacerbates interstitial condensation and culminates in devastating systemic thermal deterioration. This finding is supported by the study by Gao et al. [18], which underscores that moisture-driven thermal degradation is often underestimated in standard design, confirming that external moisture loads should be a prerequisite factor in envelope durability assessments. Based on these findings, future building thermal design must pivot from a purely thermal-driven approach to a coupled hygrothermal-driven paradigm. This paradigm shift is strongly advocated by Xue et al. [21], who demonstrated that traditional design approaches often fail to account for dynamic climate conditions, leading to inadequate moisture control and increased risks of condensation and biodeterioration.

For high-risk moisture zones such as HSCW and HSWW, merely satisfying nominal design U-value standards should be considered a minimum baseline. In engineering practice, the capacity to resist WDR must be prioritized as a prerequisite for selecting wall configurations, e.g., favoring hydrophobic insulation materials with low water absorption, designing rainscreens, and applying surface water-repellent coatings. Only by integrating dynamic moisture loads into the analytical framework of regional climate adaptability can the long-term energy efficiency goals for near-zero energy buildings (nZEBs) in humid regions be genuinely realized.

4.2. Influence of Assemblies and Material Configuration on Hygrothermal Resilience

The statistical divergence in dynamic thermal performance across the five wall types reveals that the hygrothermal resilience of a building envelope under WDR is not dictated solely by the external climatic load but is fundamentally governed by the intrinsic material composition and layer configuration.

As demonstrated by the results, assemblies that theoretically satisfy thermal requirements can exhibit radically different dynamic responses when exposed to transient moisture. For instance, while Types 1 and 2 maintain robust thermal stability throughout the year, Type 3 proves highly vulnerable to episodic, extreme monthly degradation despite a seemingly acceptable annual average. This highlights the risk of relying exclusively on annual

averages, which can mask severe, short-term hygrothermal failures caused by the high capillary water absorption of specific inorganic fibrous materials.

Furthermore, self-insulation systems relying on porous structural blocks demonstrated the most catastrophic and prolonged thermal deviation, proving highly incompatible with WDR-heavy climates unless substantially modified. Therefore, in the assessment of climate adaptability, relying on dry-state design values is inadequate. Engineering practices must pivot to prioritize the dynamic hygrothermal feedback characteristics of the specific assembly. For configurations prone to severe moisture-induced degradation, such as Types 3 and 4, it is imperative to couple them with targeted protective measures, such as ventilated rainscreens or highly effective hydrophobic coatings, to sustainably maintain their intended thermal resistance under realistic environmental stress. This necessity is corroborated by Soulios et al. [6], who demonstrated that the hygrothermal performance of insulated masonry walls is significantly improved by hydrophobization, proving that intrinsic material modification is essential for resilience against WDR-induced moisture degradation.

To further clarify the component-level drivers behind these U-value increases, the macroscopic thermal degradation originates from the moisture-dependent thermal conductivity (λ) of specific layers within each assembly configuration. The dominant element driving the thermal collapse varies distinctly across the wall types. In the self-insulating system (Type 4), the autoclaved aerated concrete (AAC) block core is the absolute dominating element responsible for the systemic U-value escalation. The high open porosity of the AAC matrix promotes rapid capillary absorption of WDR, causing a non-linear spike in its operational thermal conductivity that single-handedly compromises the envelope's insulation baseline. For the multi-layer configurations, the dynamic vulnerability is highly insulation-dependent: in Type 3, the mineral wool (MW) insulation layer dominates the episodic U-value spikes because its inorganic fibrous structure possesses high moisture sensitivity and low vapor resistance, allowing liquid water to easily displace trapped air within the fiber matrix. Conversely, in Types 1 and 2, the insulation boards (EPS/XPS) maintain low water absorption and stable thermal conductivity; consequently, their minor dynamic fluctuations are primarily dictated by moisture tracking within the outer rendering mortar and concrete substrate. This component-level distinction explains why multi-layer polymer insulation configurations retain superior thermal stability compared to porous single-layer or fibrous systems under identical wind-rain scenarios.

4.3. Limitation of Annual Averages and the Complexity of Seasonal Hygrothermal Instability

While the analysis of annual mean values provides a broad overview, the intra-annual fluctuation data reveal an important nuance that warrants further discussion. The analysis of intra-annual fluctuation amplitudes exposes a critical flaw in relying solely on annual average metrics to evaluate the climate adaptability of wall assemblies. This supports the methodology proposed by Zhou et al. [46], who emphasized that standard reference years often fail to capture the transient hygrothermal extremes critical for building envelope safety. Their work highlights that annual averaging masked the localized, moisture-induced risks that are most detrimental to building energy performance.

As demonstrated by specific cases (e.g., Shantou Type 4 and Datong Type 2), a wall assembly can maintain a seemingly excellent annual average dynamic U-value while simultaneously suffering from severe short-term thermal degradation. This phenomenon indicates that WDR-induced thermal failure often manifests as highly concentrated, episodic spikes rather than a uniform, year-round deterioration. Consequently, traditional assessments that average out these extreme months will underestimate the peak heating or cooling loads required to maintain indoor thermal comfort during those critical periods.

The temporal mapping of maximum U-values and heat flow reversals (zero-values) highlights the profound influence of seasonal transitional periods on hygrothermal stability. June emerges as the most volatile month, uniquely characterized by a high frequency of both peak outward heat loss and complete heat flow reversal. This dual nature suggests that June is not merely a smooth climatic transition; rather, the superimposition of intense WDR events (e.g., the Plum Rain season in the HSCW zone) and rapidly fluctuating indoor–outdoor temperature gradients forces the wall into a state of bidirectional heat transfer. In contrast, the mid-summer months from July to September primarily exhibit heat flow reversals driven by sustained high outdoor temperatures, while the transitional autumn month of October triggers maximum forward heat loss as WDR accumulation coincides with dropping external temperatures.

Regarding assessment standards, the intra-annual volatility of a wall's thermal performance is not determined merely by its baseline insulation capacity, but is synergistically driven by peak elevation, zero-value truncation, and their seasonal distribution. For wall assemblies with high moisture sensitivity operating in WDR-heavy climates, evaluating hygrothermal adaptability strictly based on nominal U-values or annual dynamic averages is fundamentally inadequate. Future building codes and engineering evaluations must incorporate fluctuation amplitudes and worst-case month performance as mandatory design criteria to ensure genuine thermal resilience across all seasons.

4.4. Physical Interpretation of Extreme Dynamic U-Values in Transitional Seasons

To avoid misinterpretation of the extreme U-values reported above, it should be noted that the extreme maximum monthly dynamic U-values observed in certain transitional months (e.g., 46.40 W/(m²·K) in the Guangchang Type 4 case) do not represent the intrinsic material thermal transmittance under dry conditions, which is fundamentally capped by surface thermal resistances. Instead, these massive values are mathematical artifacts characteristic of dynamic hygrothermal assessments during transitional seasons. When the indoor–outdoor temperature difference (ΔT) approaches zero, the dynamic calculation ratio ($q/\Delta T$) inevitably spikes, as the heat flow (q) becomes decoupled from the minute temperature gradient. In our simulations, intense outward heat fluxes (q) driven by the latent heat of moisture evaporation and thermal mass delayed heat release coincide with these low-gradient periods, forcing the U-value calculation to exhibit extreme sensitivity. Such results are consistent with the methodological constraints highlighted by Bienvenido et al. [47], who demonstrated that a temperature gradient of at least 5 °C is often required to ensure the physical relevance of calculated thermal transmittance. This observation is further supported by ISO 9869-1:2014 (Clause 7.3), which explicitly cautions against relying on the average method when the envelope temperature difference is small.

Notably, these extreme transitional values do not undermine the validity of the core findings of this study. The annual mean dynamic U-value ($U_{\text{dyn-mean}}$) is dominated by heating-season performance, where the calculation remains physically meaningful. The zone-level and assembly-level rankings established in Section 3.4 are derived from DR_{mean} and N_{ex} both of which reflect long-term deviation trends rather than short-term transitional extremes. Therefore, while the absolute magnitude of these extreme spikes warrants careful interpretation, their presence does not alter the cross-climatic comparative hierarchy or the practical engineering implications derived from this study. These extreme values should be interpreted as indicators of intense hygrothermal instability.

Regarding the treatment of reverse thermal fluxes, the zero-truncation convention applied to negative dynamic U-values is strictly dictated by the inherent algorithmic protocols of the WUFI post-processor framework. As explicitly defined in the official WUFI methodology, the post-processor engine is intended to assess heat losses; under warm

outdoor conditions, heat may flow into the building, mathematically resulting in negative R - and U -values, which are systematically set to zero by the software to maintain the physical legibility of envelope transmission losses. Retaining these negative hourly U -values in annual mathematical integrations would artificially offset and underestimate the actual moisture-induced thermal resistance degradation during critical heat-loss periods. To quantify the mathematical effect of this software convention on the reported fluctuation indicators (SD and AU), our analysis indicates that this zero-truncation strictly impacts only 16 out of the 68 evaluated cases, clustered exclusively within the low-gradient summer months of June and August. Consequently, while this built-in clipping bounds the peak negative variance during brief summer thermal inversions, its absolute distorting effect on the overall annual SD and AU is highly localized and minor. Importantly, it leaves the core heating-season vulnerability metrics, which dictate the geographic degradation gradients and the dynamic assembly re-ranking unaffected.

4.5. Transitioning from Normative Compliance to Dynamic Hygrothermal Adaptability

The recalibration of wall adaptability rankings based on dynamic U -values reveals that thermal adaptability is not an immutable, static attribute defined at the design stage. Rather, it is a dynamic transient state heavily modulated by the severity of WDR exposure, the accumulation of interstitial moisture, and the subsequent duration of thermal deviation.

The results from the HSCW zone prominently illustrate the limits of normative compliance. Under normative U -value assessment, all five configurations theoretically satisfy regional insulation codes and are treated as equally viable engineering solutions. However, real-world hygrothermal feedback completely shatters this parity, exposing configurations like Type 4 to massive, chronic thermal failure, while configurations like Type 2 maintain robust performance.

This contrast carries significant implications for building code development and envelope engineering. Relying exclusively on standard dry-state thermal transmittance for envelope selection systematically underestimates the risk of in-service thermal deterioration, particularly in regions characterized by severe WDR and high drying constraints. To ensure genuine climate adaptability and bridge the energy performance gap, it is imperative to transition toward a dynamic evaluation paradigm.

This transition is essential, as highlighted by Aste et al. [48] who argued that standardized parameters like U -values and insulation thickness often fail to account for dynamic thermal properties, which are critical for long-term performance, and that current reliance on normative design parameters is insufficient for accurately predicting the long-term energy efficiency of envelopes in complex climatic contexts. The dynamic U -value, coupled with its deviation duration, needs to be integrated into future wall assembly selection guidelines to accurately predict and benchmark the true operational lifespan and energy efficiency of building envelopes.

4.6. Comparative Synthesis and Practical Implications

The dynamic hygrothermal variations, geographical gradients, and structural adaptability patterns identified in this study converge on two findings that merit comparison with existing literature: (i) the systematic underestimation of moisture-induced thermal degradation by normative dry-state assessments, and (ii) the critical role of localized moisture dynamics in shaping the severity and distribution of thermal failure.

Regarding the first point, the present study demonstrates that nominal U -values systematically underestimate actual thermal degradation, yielding an operational mean $U_{\text{dyn-mean}}$ of $1.25 \text{ W}/(\text{m}^2 \cdot \text{K})$ and a peak of $7.13 \text{ W}/(\text{m}^2 \cdot \text{K})$ across all 68 cases. This finding is consistent with the parametric sensitivity analysis of Zhou et al. [49], who showed that

exterior liquid water absorption and WDR loads exert a far more dominant influence on long-term hygrothermal risks than the nominal thermal conductance of insulation materials. The present study extends this insight by translating structural moisture risk into quantifiable performance degradation metrics such as DR_{mean} , N_{ex} , $U_{\text{max,m}}$, thereby providing direct numerical evidence that normative compliance does not guarantee actual thermal resilience.

Regarding the second point, the geographical escalation of dynamic thermal damage, from the SC zone to the HSCW zone, where $U_{\text{dyn-mean}}$ jumps to $2.20 \text{ W}/(\text{m}^2 \cdot \text{K})$ and $U_{\text{max,m}}$ reaches $7.69 \text{ W}/(\text{m}^2 \cdot \text{K})$ must be interpreted with attention to spatial non-uniformity of environmental forcing. Vanderschelden et al. [50] demonstrated via coupled CFD-HAM modeling that spatial wetting and drying patterns across a building facade are highly localized: traditional simplified uniform boundary conditions significantly underestimate critical peak rain loads at specific envelope regions such as top edges and corners, while overestimating surface convective drying potential. Consequently, in regions like the HSWW and HSCW zones, the localized actual thermal degradation at critical geometric junctions is expected to be substantially more severe than the spatially averaged 1D predictions reported herein, highlighting a critical localized vulnerability in existing building stocks. Similarly, Yu et al. [51] demonstrated that structural fractures and defects act as preferential fluidic pathways that radically accelerate moisture penetration depth. If realistic joint defects or micro-cracks are present in vulnerable configurations such as the porous self-insulating block system (Type 4), the resulting moisture bypass would further exacerbate thermal collapse, rendering its performance even more precarious relative to resilient multi-layer configurations (Type 2).

These synthesized findings carry direct implications for engineering practice. First, to counteract the systematic underestimation of peak moisture loads, building designers should adopt microclimate-aware boundary parameters during early-stage HVAC and insulation layout selection, replacing idealized constant coefficients with variable, location-specific WDR exposure data. Second, for configurations identified as high-risk (notably Types 3 and 4), protective measures, including hydrophobic surface coatings, ventilated rainscreens, or architectural overhangs, must be geometrically optimized based on localized wind-rain exposure thresholds rather than generic code requirements. Third, to ensure long-term service reliability under changing future climates, envelope specifications should incorporate risk-adjusted safety premiums, e.g., allocating additional thermal performance allowance over nominal design U-values in severely exposed regions.

In summary, the dynamic classification framework proposed herein bridges the gap between theoretical hygrothermal modeling and resilient architectural design by providing practicing engineers with targeted, evidence-based defense workflows that account for transient moisture risks rather than static thermal criteria alone.

4.7. Sensitivity of Dynamic Performance to Indoor Moisture Boundary Conditions

The transient hygrothermal simulations in this study deliberately utilized a standardized indoor climate without occupant-induced internal moisture sources, e.g., respiration, cooking, and bathing. This simplification is highly climate- and typology-dependent. In the HSWW zone, inward vapor drive dominates during cooling seasons; omitting internal moisture maintains a lower indoor relative humidity, which artificially maximizes the indoor–outdoor vapor gradient, representing a conservative baseline for assessing moisture intrusion. In the HSCW zone during winter, outward vapor drive prevails. For internally insulated walls (IITS), omitting internal moisture may slightly underestimate interstitial condensation risks under poor ventilation. For externally insulated walls (EIFS), the warm concrete core safely throttles this outward flux, rendering them highly insensitive.

Overall, while the absolute quantities of moisture accumulation may shift marginally for IITS under specific winter scenarios, the relative performance hierarchies, adaptability rankings, and degradation paths of the 68 evaluated wall assemblies remain highly robust and physically consistent.

5. Conclusions

This study established a comprehensive dynamic evaluation framework to investigate the transient hygrothermal performance of five representative exterior wall assemblies under WDR exposure across four major thermal design zones, analyzing a total of 68 cases. The main conclusions are drawn as follows:

1. Limitations of Normative Compliance Assessments

The evaluation responds to the question regarding the insufficiency of normative standards. Relying exclusively on nominal design U -values derived from standard dry-state conditions systematically underestimates the operational thermal degradation of building envelopes. Across all 68 evaluated cases, the actual $U_{\text{dyn-mean}}$ reached a mean of $1.25 \text{ W}/(\text{m}^2 \cdot \text{K})$ against a right-skewed distribution peaking at $7.13 \text{ W}/(\text{m}^2 \cdot \text{K})$. The overall DR_{mean} averaged 0.37, while the mean N_{ex} spanned 6.15 months. These metrics quantitatively demonstrate that binary normative compliance has limits to guarantee genuine thermal resilience under actual dynamic moisture loads.

2. Geographical Gradients of Dynamic Thermal Degradation

The dynamic thermal degradation of wall envelopes exhibits a profound geographical dependency, escalating systematically from the northern cold zone to the southern warm-humid zone as follows:

SC Zone: Envelope performance remains highly robust; the regional $U_{\text{dyn-mean}}$ stays strictly below the $0.40 \text{ W}/(\text{m}^2 \cdot \text{K})$ control threshold, yielding a minor mean DR_{mean} of -0.03 and a limited N_{ex} of 3.4 months.

C Zone: Systemic volatility emerges; though the mean $U_{\text{dyn-mean}}$ of $0.44 \text{ W}/(\text{m}^2 \cdot \text{K})$ is marginally below the $0.45 \text{ W}/(\text{m}^2 \cdot \text{K})$ limit, the mean DR_{mean} rises to 0.03, and the deviation duration N_{ex} sharply jumps to 7.2 months, shifting the primary risk from magnitude elevation to protracted deviation duration.

HSWW Zone: Degradation becomes systemic, with the mean $U_{\text{dyn-mean}}$ breaching the $1.50 \text{ W}/(\text{m}^2 \cdot \text{K})$ baseline to reach $1.65 \text{ W}/(\text{m}^2 \cdot \text{K})$ accompanied by a mean DR_{mean} of 0.09.

HSCW Zone: This region presents the most severe risk, where the mean $U_{\text{dyn-mean}}$ surges to $2.20 \text{ W}/(\text{m}^2 \cdot \text{K})$ with an extensive mean DR_{mean} of 0.97, and the mean $U_{\text{max,m}}$ reaches $7.69 \text{ W}/(\text{m}^2 \cdot \text{K})$.

3. Seasonal Characteristics of Thermal Volatility and Heat Flow Reversals

Moisture-induced thermal damage is highly episodic and concentrated in transitional seasons rather than distributed uniformly year-round. Peak thermal degradation exhibits intense seasonal clustering, primarily occurring in October (16 cases), June (15 cases), and April (11 cases). Furthermore, 16 out of 68 cases experience complete heat flow reversals (recorded as zero-value due to outward heat flux definition), which peak in August (8 occurrences) and June (6 occurrences). June acts as the most volatile transitional phase, simultaneously exhibiting intense forward heat loss in some cases and complete thermal inversion in others, driven by the superimposition of severe WDR events and diminishing indoor–outdoor temperature gradients.

4. Dynamic Re-Ranking of Wall Assembly Adaptability

The dynamic evaluation framework effectively overrides the parity assumed under normative frameworks, stratifying previously indistinguishable configurations into a defini-

tive adaptability hierarchy. Within the HSCW zone, the broad compliance equivalence is refined into a strict structural hierarchy: Type 2 > Type 1 > Type 5 > Type 3 > Type 4. Porous self-insulation block systems (Type 4) exhibit the highest vulnerability, suffering from catastrophic and prolonged thermal deviation, with a mean $U_{\max,m}$ of 16.21 W/(m²·K) and an extreme mean A_U of 15.34 W/(m²·K). Conversely, specific multi-layer assemblies (Type 2) maintain exceptional hygrothermal resilience.

5. Limitations and Future Work

To address the persistent building energy performance gap and promote the development of climate-adaptive envelope design, future research needs to extend the scope of the present study.

First, the methodology adopted in this work is based on a one-dimensional (1D) hygrothermal transfer model, which treats wall assemblies as homogeneous continuous media. Although this 1D approach effectively isolates the macroscopic thermal degradation induced by wind-driven rain (WDR), it inherently overlooks the complex hygrothermal dynamic processes occurring at geometric intersections. Subsequent research should extend the proposed dynamic framework to two-dimensional (2D) numerical simulations to explicitly characterize localized vulnerabilities, including structural corners, window-wall joints and actual construction defects, where the coupling effects of WDR concentration accumulation and two-dimensional thermal bridging are the most significant.

Second, although this study captures intra-annual hygrothermal variability based on a representative single-year (2020) meteorological dataset, it fails to account for the altered hygrothermal loads driven by future extreme weather events. Future research should incorporate multi-decade long-term climate projection models to assess the evolving chronicity and severity of thermal degradation under the background of global climate change.

Thirdly, this framework constrains its scope to component-level hygrothermal degradation metrics rather than translating the observed U-value surges into whole-building heating and cooling energy demands. Because conductive transmission heat loss through the opaque envelope is directly and linearly proportional to its U-value under a given temperature gradient, the dynamic U-value inflation reported herein serves as a direct proxy for the proportional inflation of structural thermal load penalties, providing a clearer baseline for material optimization. Subsequent studies will focus on expanding the proposed framework to fully quantify the dynamic thermal performance of the whole building and the corresponding variation in energy consumption under continuous WDR exposure. This expansion can connect hygrothermal degradation with building energy penalties, thus providing a comprehensive theoretical basis for improving the long-term climate resilience of urban buildings.

Fourthly, this study excluded internal moisture sources such as occupancy, cooking, and bathing to isolate outdoor meteorological stressors. A sensitivity analysis shows this simplification is highly climate- and typology-dependent. In the HSWW zone, inward vapor drive dominates during cooling seasons; omitting internal moisture maintains a lower indoor relative humidity, which artificially maximizes the indoor–outdoor vapor gradient, representing a conservative baseline for assessing moisture intrusion. In the HSCW zone during winter, outward vapor drive prevails. For internally insulated walls (IITS), omitting internal moisture may slightly underestimate interstitial condensation risks under poor ventilation. For externally insulated walls (EIFS), the warm concrete core safely throttles this outward flux, rendering them highly insensitive. Overall, while absolute moisture levels vary slightly for IITS, this exclusion does not alter the relative performance and adaptability rankings of the 68 typologies.

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Nomenclature

Symbol	Parameter	Unit	Description
U	Thermal transmittance	$W/(m^2 \cdot K)$	The amount of heat transferred per unit time through a unit area of a component under a unit temperature difference.
U_t	Dynamic thermal transmittance at time t	$W/(m^2 \cdot K)$	Used to calculate the annual average dynamic U-value.
$U_{\text{dyn-mean}}$	Annual average dynamic U-value	$W/(m^2 \cdot K)$	The average of the dynamic U-values calculated over the statistical year.
U_{design}	Nominal design U-value	$W/(m^2 \cdot K)$	The design limit corresponding to the respective thermal design zone.
DR_{mean}	Annual average deviation rate	-	The degree of deviation of the annual average dynamic U-value relative to the nominal design baseline.
U_m	Monthly average dynamic U-value for month m	$W/(m^2 \cdot K)$	Used for month-scale statistical analysis.
$U_{\text{max},m}$	Maximum monthly average U-value	$W/(m^2 \cdot K)$	The highest monthly average U-value among the 12 months.
$U_{\text{min},m}$	Minimum monthly average U-value	$W/(m^2 \cdot K)$	The lowest monthly average U-value among the 12 months.
DR_{max}	Maximum average U-value deviation rate	-	The degree of deviation of the maximum monthly average U-value relative to the nominal design baseline.
AU	Effective fluctuation amplitude	$W/(m^2 \cdot K)$	The difference between the maximum and minimum monthly average U-values within the year.
SD	Standard deviation of dynamic U-values	$W/(m^2 \cdot K)$	The degree of dispersion of the dynamic U-values within the year.
$AWDR$	the annual cumulative WDR load on the dominant facade	(mm/a)	-
N_{ex}	Months exceeding the design value	-	-

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