

Frequency-Domain Numerical Modeling of Thermal Performance and Thermal Impedance of Tow Plaster Bio-Composite Insulation for Sustainable Building Envelopes

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INFORMATION

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ABSTRACT

This study presents a computational framework for investigating the thermal insulation performance of a novel tow plaster bio-composite for building envelopes through dynamic numerical modeling. A two-dimensional frequency-domain formulation, coupled with an electrical equivalent thermal model, was developed to simulate transient heat transfer, temperature evolution, and heat flux under varying climatic conditions and surface heat transfer coefficients. The proposed numerical methodology enables efficient analysis of frequency-dependent thermal behavior while capturing the interaction between material properties and boundary conditions. The computational framework was applied to evaluate the thermo-physical response of the tow plaster bio-composite and its interaction with an adjacent concrete layer. The simulations demonstrate that the composite exhibits high thermal inertia and low thermal diffusivity, effectively damping external temperature fluctuations and retaining heat within the insulation layer. The numerical results further reveal a synergistic thermal behavior, where the concrete layer acts as a heat reservoir and the tow plaster layers function as a thermal buffer, regulating heat transfer to the interior. Frequency-dependent analyses indicate that higher excitation frequencies permit reduced insulation thickness without compromising thermal performance, highlighting the capability of the developed numerical approach to assess insulation efficiency under dynamic operating conditions. The study also demonstrates the significant influence of surface heat transfer coefficients on the predicted thermal response, confirming the robustness of the computational framework under realistic boundary conditions. These findings not only demonstrate the insulating potential of the tow plaster bio-composite but also establish the proposed numerical methodology as a practical tool for the analysis and design of sustainable energy-efficient building envelopes. Future work will focus on experimental validation and numerical benchmarking to further verify the applicability and accuracy of the proposed computational approach.

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1 Introduction

Controlling heat transfer is essential for maintaining thermal stability in buildings and improving energy efficiency [1]. Effective thermal insulation reduces energy consumption and enhances indoor comfort, contributing to sustainable construction practices [2]. It also helps to lower operational emissions in the building sector [3]. However, conventional insulation materials such as mineral wool and polystyrene are associated with environmental concerns, including high embodied energy [4], limited recyclability [5], and end-of-life disposal issues [6]. In recent years, plant-based bio-composites have emerged as promising alternatives due to their low thermal conductivity [7], renewability [8], and reduced environmental impact [9]. Several studies have highlighted the potential of natural fiber-based materials in building applications due to their hygrothermal performance [10] and mechanical suitability [11]. Among these materials, tow plaster composites, composed of plant-derived fibers embedded in a gypsum-based matrix, have shown favorable thermal properties [8], with reported thermal conductivity around $0.15 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ [12] and low thermal diffusivity [13]. These properties improve thermal inertia [14] and reduce temperature fluctuation transmission [15]. Despite these advantages, most previous studies have focused on steady state thermal analysis [16] or simplified transient models [17]. The dynamic and frequency-dependent thermal behavior of multilayer wall systems incorporating bio-composites remains insufficiently studied [18]. Analytical approaches based on electrical analogies, such as RC thermal models, have been used to describe thermal inertia [19], phase shift [20], and damping behavior [21] under periodic boundary conditions. However, their application to bio-composite multilayer walls is still limited [22]. Furthermore, the interaction between natural insulation materials and structural components such as concrete has not been extensively investigated [23]. Concrete provides thermal mass and energy storage capacity [24], while tow plaster layers act as thermal buffers regulating heat transfer [25,26]. This combined behavior improves the overall thermal stability of wall systems [27,28]. Previous studies have shown that thin bio-based insulation layers can significantly reduce peak heat flux [29,30] and improve energy efficiency in buildings [31].

To address these gaps, this study investigates the dynamic thermal behavior of a multilayer wall system composed of concrete and tow plaster bio-composite under convective boundary conditions. A one-dimensional transient heat conduction model is applied together with a frequency domain formulation to evaluate temperature distribution, heat flux density, and thermal impedance. The influence of boundary conditions, material properties, and excitation frequency is systematically analyzed to provide design-oriented insights for optimizing bio-based insulation systems under dynamic climatic conditions.

The novelty of this study lies in the application of a frequency domain analytical framework to a multilayer wall system combining concrete and tow plaster bio-composite, enabling the evaluation of dynamic thermal behavior in terms of phase lag, thermal damping, and heat flux attenuation. In addition, the study introduces practical performance indicators such as effective insulation thickness and heat flux retention under varying excitation conditions, providing design-oriented insights for optimizing bio-based insulation systems.

Thermal Impedance Concept

A key concept used throughout this study is the notion of thermal impedance, which characterizes the dynamic thermal resistance of a material or wall system subjected to periodic thermal excitation. Thermal impedance, denoted as $Z(\omega)$, is defined as the ratio of the complex temperature amplitude to the complex heat flux amplitude at a given angular frequency ω [32,33]:

$$Z(\omega) = \frac{\Delta T(\omega)}{q(\omega)} \quad (1)$$

$\Delta T(\omega)$ represents the complex amplitude of the temperature oscillation at the material surface, $q(\omega)$ is the complex amplitude of the heat flux through that surface. Thermal impedance thus incorporates both magnitude and phase information of the temperature and heat flux signals, providing insight into the thermal inertia, attenuation, and phase lag effects exhibited by the material under dynamic conditions. Thermal impedance is typically not measured directly; rather, it is estimated through analytical or numerical solutions of the transient heat conduction equation subjected to sinusoidal (harmonic) boundary conditions [34,35]. This requires knowledge of the material's thermal properties, such as thermal conductivity, density, and specific heat capacity [36,37]. Alternatively, thermal impedance can be determined experimentally by applying periodic temperature variations and analyzing the corresponding heat flux response via Fourier analysis, although this approach is beyond the scope of the present work.

In this study, the thermal impedance of the tow plaster composite wall is derived using a frequency domain analytical model, which calculates temperature and heat flux distributions as functions of depth and excitation frequency. This approach enables a comprehensive assessment of the material's dynamic thermal behavior, providing valuable information for optimizing thermal insulation performance under realistic, time-varying environmental conditions.

2 Materials and Methods

This section describes the materials, modeling approach, and analytical framework used in the present study. The physical configuration of the composite wall, along with the governing equations and boundary conditions, was introduced to analyze the dynamic thermal behavior under periodic excitation. The methodology was based on a frequency domain formulation of transient heat conduction, allowing the evaluation of temperature distribution, heat flux, and thermal performance indicators of the tow plaster composite system.

2.1 Physical Model and Wall Configuration

The present study was theoretical and was based on numerical simulations using an analytical formulation of transient heat conduction under dynamic boundary conditions [38]. The adopted approach was derived from classical heat transfer theory and has been widely applied and validated for multilayer wall systems subjected to periodic thermal excitations [39,40]. Similar frequency domain formulations have successfully reproduced benchmark results for conventional building materials, including solid concrete walls, whose dynamic thermal behavior has been well documented in the literature [41,42]. These established studies provided a reliable reference framework for extending the same modeling strategy to composite wall systems incorporating bio-based insulation layers, such as the tow plaster material investigated in this study. The modeled wall assembly consisted of two layers, as illustrated in Fig. 1a, which presents the schematic profile view of the system under dynamic thermal excitation. The corresponding boundary condition representation and thermal parameter setup are shown in Fig. 1b [43]. The configuration represents a typical building envelope, in which the concrete layer provides structural support and thermal mass, while the tow plaster layer acts as a thermal buffer regulating heat transfer toward the interior environment [44].

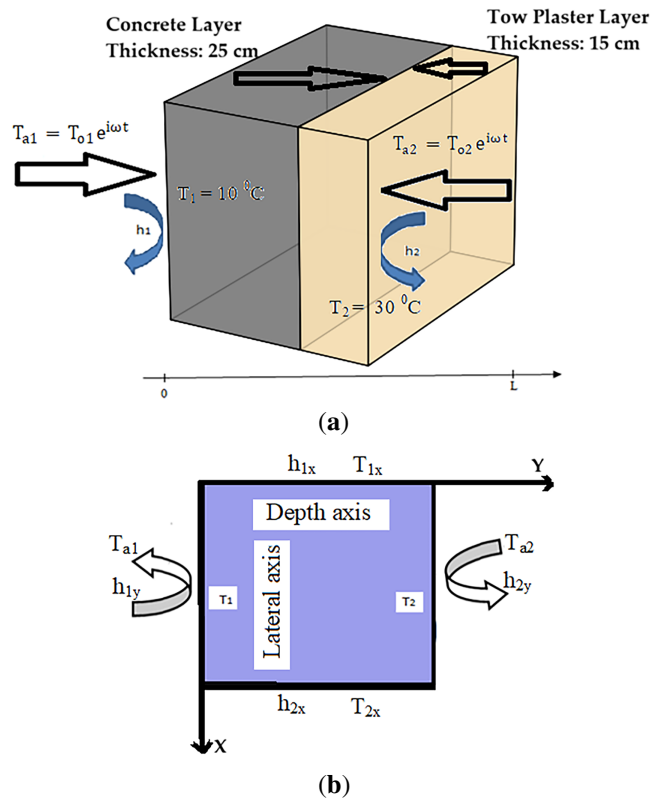


Figure 1: (a) Schematic profile view of the tow plaster composite wall system (gypsum-based material) subjected to external climatic conditions under dynamic thermal excitation; (b) corresponding representation of the wall assembly showing boundary conditions and thermal parameters used in the model. $T_a = 30^\circ\text{C}$, $T_i = 10^\circ\text{C}$, $\lambda = 0.15 \text{ Wm}^{-1}\cdot^\circ\text{C}^{-1}$

This composite design integrated the natural insulating properties of plant fibers with the binding and structural capabilities of plaster, forming a tow plaster mixture that served as an insulating layer. The wall assembly thus combined a structural component (concrete) and an insulation layer (tow plaster), with the external surface being exposed to dynamic environmental conditions and the internal surface facing a controlled indoor environment, thereby simulating real-world residential or commercial usage [44–46]. The study modeled temperature fluctuations at both the external and internal surfaces of the wall within a frequency-based dynamic thermal regime. This approach allowed an accurate representation of how the wall responded to periodic thermal changes (e.g., day-night cycles or seasonal shifts). The external ambient temperature was denoted by T_{a1} , and the internal ambient temperature was denoted by T_{a2} . The complex amplitudes of the external and internal surface temperatures were defined as T_{o1} and T_{o2} , respectively. The initial temperature of the tow plaster composite before exposure was defined as T_{o1} , which served as the reference for analyzing thermal inertia.

Convective heat transfer coefficients at the outer and inner surfaces were defined as h_1 and h_2 , characterizing the heat exchange rates between the wall surfaces and their adjacent environments [47]. To simulate realistic thermal forcing conditions, a periodic excitation was applied with angular frequency ω , representing the frequency of temperature oscillation due to external climate [48–50].

The following assumptions were adopted in the present model in accordance with standard analytical studies on heat transfer in building envelopes:

- (i) Heat transfer was assumed to be one-dimensional through the wall thickness, as lateral heat losses were considered negligible for large and homogeneous wall surfaces. This assumption is widely adopted in the analysis of multilayer building envelopes and is generally valid when the wall surface area is significantly larger than its thickness and when boundary conditions are uniformly distributed over the surface. Under these conditions, heat transfer occurs predominantly in the direction normal to the wall surface, while lateral temperature gradients remain negligible, allowing the problem to be accurately reduced to a one-dimensional formulation.
- (ii) Each layer was considered homogeneous and isotropic, with constant thermophysical properties independent of temperature.
- (iii) Radiative heat transfer was neglected, and heat exchange at the boundaries was modeled exclusively by convection.
- (iv) Perfect thermal contact was assumed at the interface between concrete and tow plaster layers, with no thermal contact resistance.

These assumptions have been commonly adopted in frequency domain thermal analyses of multilayer walls and have been shown to provide reliable predictions under periodic thermal excitation [51,52].

Specifically, by assuming a sinusoidal thermal excitation of the form $T(x, t) = \Re\{\theta(x)e^{i\omega t}\}$, the transient equation was reduced to a complex ordinary differential equation in space.

2.2 Boundary Conditions and Dynamic Thermal Excitation

Dynamic thermal excitation was imposed through periodic temperature variations applied at the external and internal surfaces of the wall. The external ambient temperature was denoted by T_{a1} , while the internal ambient temperature was denoted by T_{a2} . Convective heat exchange between the wall surfaces and the surrounding environments was modeled using heat transfer coefficients h_1 (external surface) and h_2 (internal surface).

The values of these coefficients were selected according to commonly accepted ranges for building applications reported in the literature:

Convective heat transfer coefficients:

External surface (h_1): $25 \text{ W}\cdot\text{m}^{-2}\cdot^\circ\text{C}^{-1}$ (typical outdoor condition with wind exposure) [53]

Internal surface (h_2): $10 \text{ W}\cdot\text{m}^{-2}\cdot^\circ\text{C}^{-1}$ (indoor natural convection) [54]

The analysis was carried out in the frequency domain by applying a periodic thermal excitation characterized by an angular frequency ω . The external thermal excitation was modeled as a sinusoidal temperature variation applied at the external boundary (T_{a1}), representing idealized climatic fluctuations such as day, night, and seasonal cycles. This approach did not rely on specific meteorological data but instead used a harmonic representation to capture the dominant periodic behavior of outdoor temperature. The selection of the excitation frequency ω is based on its ability to represent realistic periodic thermal loading conditions in building environments. In this context, low-frequency excitation corresponds to slow thermal variations such as day-night and seasonal temperature cycles, whereas higher frequencies represent faster fluctuations in ambient temperature. The chosen frequency range is therefore intended to capture the dominant thermal response characteristics of the composite wall under practical environmental conditions. This idealized formulation ensured that the model

captured the essential dynamic thermal behavior of the wall system while maintaining analytical simplicity and computational efficiency. This formulation enabled the evaluation of thermal damping, phase shift, and thermal inertia across the composite wall system under realistic climatic loading conditions [55]. The thermal impedance concept allowed the assessment of how boundary heat exchange coefficients (h_1 , h_2) influenced temperature propagation and heat flux within the wall layers [56].

2.3 Material Properties

The geometrical and thermophysical properties of the materials used in the wall assembly were summarized in Table 1. The tow plaster composite was considered as a bio-based insulating material composed of natural plant fibers (tow) embedded in a gypsum-based plaster matrix. The thermophysical properties used in this study, including thermal conductivity, density, and specific heat capacity, were adopted from previously published experimental and numerical studies on similar natural fiber plaster composites. No experimental derivation of material properties was performed in the present work; instead, literature-based values were employed to ensure consistency with established data reported in the field. Material properties for the simulation were summarized in Table 1 [7,9,10,42,43].

Table 1: Thermophysical and geometrical properties of wall materials

Layer	Thickness (m)	Thermal conductivity λ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Density ρ ($\text{kg}\cdot\text{m}^{-3}$)	Specific heat c ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
Concrete	0.10	1.40	2300	880
Tow plaster	0.05	0.15	900	1300

Note: All values were based on literature data; no experimental measurements were performed.

2.4 Governing Equation

Heat transfer inside each layer of the composite wall was governed by the one-dimensional transient heat conduction equation:

$$\frac{\partial T(x, t)}{\partial t} = \alpha \frac{\partial^2 T(x, t)}{\partial x^2} \quad (2)$$

The general solution to this equation under sinusoidal excitation led to a temperature distribution in the form described in previous studies [49], enabling the capture of dynamic thermal responses of layered building materials under periodic boundary conditions.

$T = T(h_1, h_2, t)$ represented the temperature inside the material, where x denoted the depth and t denoted time. Eq. (2) gave the expression of the thermal diffusivity α [57].

Where $T(x, t)$ was the temperature, x was the spatial coordinate across the wall thickness, t was time, and α was the thermal diffusivity, defined as:

$$\alpha = \frac{\lambda}{\rho c} \quad (3)$$

with λ being the thermal conductivity, ρ the density, and c the specific heat capacity of the material. The thermal diffusivity was defined as ($\text{m}^2 \cdot \text{s}^{-1}$), where λ was the thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), ρ was the density of the material ($\text{kg} \cdot \text{m}^{-3}$), and c was the specific heat capacity ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$). The solution of Eq. (1) gave the expression of the temperature in the following form [58].

$$T(x, \omega, t) = [A_1 \cdot \sinh(\beta \cdot x) + A_2 \cdot \cosh(\beta \cdot x)] \cdot e^{i\omega t} \quad (4)$$

$$L = \frac{1}{\beta} = \sqrt{\frac{\omega}{2\alpha}} (1 + i) \quad (5)$$

β was a positive constant, and L was the complex thermal diffusion length. The coefficients A_1 and A_2 depended on thermal parameters and boundary conditions imposed in Eqs. (6) and (7).

$$A_1 = f(\lambda, \alpha, \omega, h_1, h_2) \quad (6)$$

$$A_2 = g(\lambda, \alpha, \omega, h_1, h_2) \quad (7)$$

The components A_1 and A_2 were determined from the boundary conditions [38,39].

$$\left\{ -\lambda \frac{\partial T}{\partial x} \right\}_{x=0} = h_1 (T_{a1} - T_{(0,t)}) \quad (8)$$

$$\left\{ -\lambda \frac{\partial T}{\partial x} \right\}_{x=L} = h_2 (T_{a2} - T_{(L,t)}) \quad (9)$$

The heat flux density was given by the expression (10) [38,39].

$$\phi(x, \omega, t) = -\lambda \frac{\partial T}{\partial x} \quad (10)$$

At every point of the material, the heat flux density [38] through the kapok plaster material was given by Eq. (11):

$$\phi(x, \omega, t) = -\lambda \cdot \beta \cdot [A_1 \cdot \cosh(\beta \cdot x) + A_2 \cdot \sinh(\beta \cdot x)] \cdot e^{i\omega t} \quad (11)$$

2.5 Frequency Domain Solution

The frequency domain formulation used in this study was derived directly from the one-dimensional transient heat conduction equation presented in Section 2.4. By assuming harmonic thermal excitation and expressing the temperature field as a complex function, the partial differential equation in time and space was reduced to an ordinary differential equation in space. This transformation preserved the same physical assumptions (one-dimensional heat flow, homogeneous layers, constant thermophysical properties, and convective boundary conditions). Consequently, both the transient and frequency domain approaches described the identical wall configuration and differed only in mathematical representation: the transient model provided time evolution, while the frequency domain model enabled direct evaluation of amplitude attenuation, phase lag, and thermal impedance. Under sinusoidal thermal excitation, the solution of Eq. (1) was expressed in the frequency domain as:

$$T(x, t) = \Re \{ (x) e^{i\omega t} \} \quad (12)$$

In this study, the concept of thermal impedance (Z_{th}) was introduced to quantify the dynamic response of the wall. Thermal impedance represented the complex ratio of temperature variation to

heat flux at a given point, indicating how effectively the material resisted and delayed heat transfer, similar to electrical impedance in AC circuits [59].

$$Z_{th} = \frac{\Delta T}{q} \quad (13)$$

ΔT was the complex temperature amplitude at the surface (K), and q was the heat flux density (W/m²). Where $\theta(x)$ represented the complex temperature amplitude, and i was the imaginary unit. The general solution took the form:

$$\phi(x) = A_1 e^{\beta x} + A_2 e^{-\beta x} \quad (14)$$

The general solution takes the form given in Eq. (15). The coefficients A_1 and A_2 are not arbitrary constants; they are determined by applying the convective boundary conditions at the external and internal surfaces of the wall. By substituting Eq. (15) into the boundary conditions defined by the convective heat transfer coefficients h_1 and h_2 , a system of linear algebraic equations is obtained. Solving this system analytically yields explicit expressions for A_1 and A_2 . These coefficients are therefore functions of the thermophysical properties of the materials (λ , α), the excitation frequency (ω), and the boundary conditions (h_1 , h_2), ensuring full consistency with the physical heat transfer model.

Here, β was a positive complex constant related to the thermal diffusion length.

The expressions (6) and (7) for these coefficients were obtained by enforcing the boundary conditions described in Section 2.2, following classical analytical procedures reported in previous studies [44].

2.6 Heat Flux Density

The local heat flux density within the wall was calculated using Fourier's law:

$$q(x, t) = -\lambda \frac{\partial T(x, t)}{\partial x} \quad (15)$$

In the frequency domain, the complex heat flux amplitude provided direct information on thermal attenuation and phase delay across the composite wall. This formulation allowed a quantitative assessment of the dynamic insulation performance of the tow plaster layer under periodic thermal loading [53].

2.7 Frequency Domain Solution and Heat Flux

The frequency domain formulation was derived from the one-dimensional (1D) transient equation. Temperature and heat flux amplitudes were calculated across the wall thickness. Coefficients A_1 and A_2 were determined from boundary conditions. The local heat flux density was given by Fourier's law Eq. (15):

Dynamic thermal performance indicators, phase lag (φ), decrement factor (f), and time delay (τ) were computed from complex amplitudes. The phase lag represented the angular delay between the external temperature excitation and the internal surface temperature response:

$$\varphi = \arg(T_{int}) - \arg(T_{ext}) \quad (16)$$

The decrement factor was defined as the ratio of the internal temperature amplitude to the external temperature amplitude:

$$f = \frac{|T_{int}|}{|T_{ext}|} \quad (17)$$

A lower decrement factor indicated stronger attenuation of thermal waves through the wall.

The time delay τ was derived from the phase lag as:

$$\tau = \frac{\phi}{\omega} \quad (18)$$

These indicators were calculated from the complex temperature amplitudes obtained in the frequency domain solution and allowed systematic comparison of insulation performance under periodic thermal excitation.

The numerical implementation and computational evaluation of the analytical model were carried out using Mathcad and Python programming tools. These computational tools enabled efficient implementation of the analytical frequency-domain formulation, automated parametric analyses over a wide range of excitation frequencies and boundary conditions, and accurate computation of temperature fields, heat flux distributions, thermal impedance, phase lag, and decrement factor. Mathcad was used for symbolic and analytical manipulation of the governing equations, while Python was employed for numerical calculations, data processing, and graphical visualization of the results.

3 Results

In this section, we presented and analyzed the simulation results obtained from the application of the theoretical models and equations discussed in the previous sections. The results were generated using the proposed analytical numerical computational framework, which enabled the efficient evaluation of temperature fields, heat flux distributions, thermal impedance, and dynamic thermal performance under periodic thermal excitation.

3.1 Evolution of Temperature and Heat Flux Density under the Influence of Excitatory Pulsation

It was important to note that the temperature and heat flux profiles presented here corresponded to the harmonic steady state solution of the same one-dimensional transient conduction model, expressed in the frequency domain. These quantities were obtained through numerical evaluation of the analytical frequency domain solution over the investigated range of excitation frequencies and boundary conditions. Thus, the results represented the periodic asymptotic response of the identical physical wall system. The primary aim of this analysis was to investigate how temperature and heat flux density varied throughout the thickness of the composite material when it was subjected to a periodic thermal excitation characterized by an angular frequency ω . The boundary conditions were defined asymmetrically: the front face of the wall (the exterior side) was subjected to relatively high convective heat transfer, while the rear face (interior side) was assumed to have a relatively low heat exchange coefficient. This asymmetry reflected a realistic physical situation where the exterior of a building was more affected by environmental changes than the relatively stable interior [60]. The observed attenuation of temperature within the composite can be physically interpreted using the concept of thermal penetration depth, defined as $\delta = \sqrt{2\alpha/\omega}$. As the excitation frequency increases, the penetration depth decreases, limiting the propagation of thermal waves to the near-surface region.

Consequently, high-frequency thermal fluctuations are rapidly damped within the tow plaster layer, while low-frequency variations penetrate deeper into the wall structure.

As illustrated in Figs. 2 and 3, this setup implied that the majority of the incident heat flux entered the material through the front face. The rear face, with its low convective heat exchange coefficient, remained at a temperature close to the initial uniform temperature of the material, which was set to $T_i = 10^\circ\text{C}$.

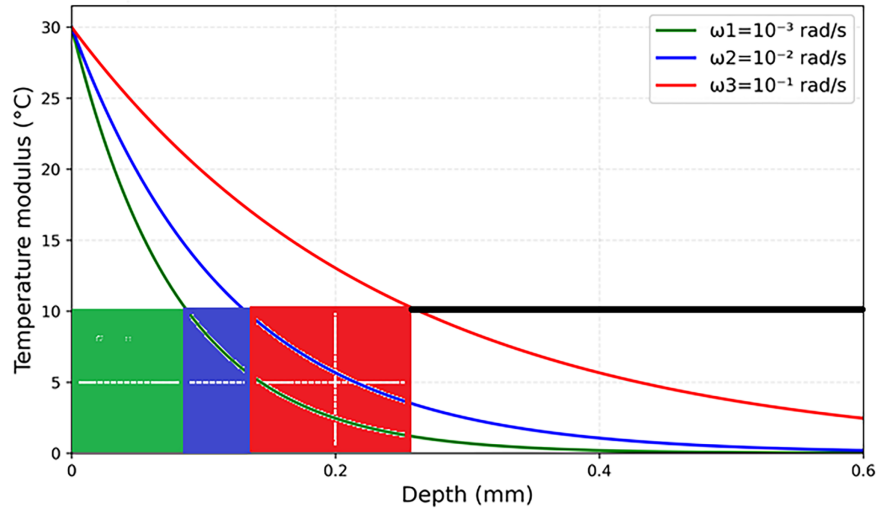


Figure 2: Module of temperature as a function of depth of material $\omega_1 = 10^{-3}$, $\omega_2 = 10^{-2}$, $\omega_3 = 10^{-1}$ rad/s

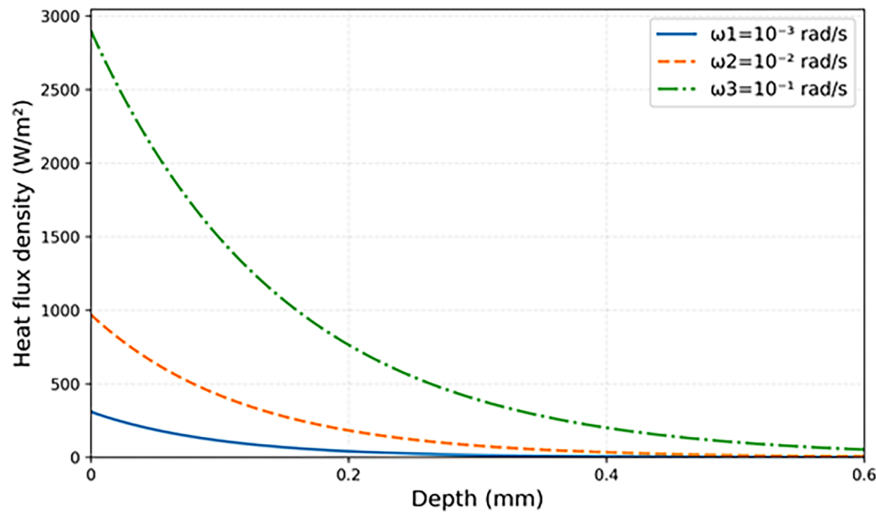


Figure 3: Module of the heat-flux density as a function of depth of material. $\omega_1 = 10^{-3}$, $\omega_2 = 10^{-2}$, $\omega_3 = 10^{-1}$ rad/s

In Fig. 2, the temperature profile within the material is shown for a typical excitation scenario. The temperature at the front face (exposed to external climatic stress) was higher due to the incoming thermal energy, but it significantly decreased as it penetrated deeper into the material. This gradual

decay of temperature across the material thickness highlighted the significant thermal damping capacity of the tow plaster composite. Furthermore, Fig. 3 presents the evolution of heat flux density across the material thickness for a heat exchange coefficient of $h_i = 15 \text{ W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ at the front surface. The simulation results clearly indicated that the transmitted heat flux density diminished considerably before it reached the rear side. In fact, it approached zero, signifying that the bulk of the heat had been absorbed and stored within the tow-plaster material. This thermal “absorption” effect was a direct consequence of the material’s thermal inertia and low thermal diffusivity, which prevented rapid transmission of heat through the structure. This observed phenomenon strongly reinforced the insulating characteristics of the tow plaster composite material. The fact that the heat did not significantly reach the interior environment demonstrated its effectiveness in thermal regulation. In practical applications, such behavior was advantageous in building construction, as it helped in maintaining interior thermal comfort while minimizing heat loss or gain due to external climatic variations. Its performance under dynamic excitation revealed its capability to attenuate both temperature fluctuations and heat flux transmission, contributing to energy savings and improved thermal comfort in buildings.

Fig. 2 illustrates the temperature modulus distribution across the tow-plaster composite for three excitation frequencies ($\omega_1 = 10^{-3} \text{ rad/s}$, $\omega_2 = 10^{-2} \text{ rad/s}$, and $\omega_3 = 10^{-1} \text{ rad/s}$).

These findings have practical implications for building design. By adjusting wall thickness or material composition, designers can optimize thermal performance to enhance indoor comfort and improve energy efficiency under varying climatic conditions.

Fig. 3 presents the variation of heat flux density across the wall thickness. A significant reduction in heat flux is observed within the tow plaster layer, with values approaching near zero toward the interior surface. Figs. 2 and 3 together illustrate the dynamic thermal response of the tow plaster composite under external excitation, providing insight into both temperature modulus and heat flux distribution across the wall depth. The temperature modulus reaches its maximum near the concrete-to-plaster interface and decreases progressively across the insulating layer, demonstrating the material’s capacity to attenuate thermal waves. High-frequency excitations are more strongly damped, whereas low-frequency variations penetrate deeper, highlighting the composite’s thermal inertia and buffering capability.

The heat flux analysis complements these findings. Although the concrete layer allows considerable initial heat flow, the tow plaster layer significantly reduces heat transmission toward the interior. Dynamic performance indicators, such as phase lag and decrement factor, quantitatively confirm this effect by showing delayed heat propagation and reduced amplitude compared to a concrete-only wall. Furthermore, thermal impedance analysis indicates that the tow plaster layer behaves similarly to a high resistance barrier, effectively restricting heat flow and enhancing thermal energy storage under cyclic loading conditions.

The proposed numerical framework also provides an efficient tool for parametric analysis of multilayer wall systems under dynamic thermal loading. These results provide practical guidance for the design of energy-efficient building envelopes. They enable the optimization of insulation thickness and material composition to achieve improved indoor thermal comfort under varying climatic conditions. Table 2 summarizes the influence of excitation frequency on thermal performance, highlighting the key trends without repeating detailed graphical observations [61].

Table 2: Influence of excitation frequency on thermal performance

Parameters	Front Panel			Inside		
Pulsation of excitation (rad/s)	10^{-3}	10^{-2}	10^{-1}	10^{-3}	10^{-2}	10^{-1}
Module of Temperature ($^{\circ}\text{C}$)	29.7	29.3	27.8	10.019	9.874	10.431
Heat flux density module (W/m^2)	309.66	966.29	2906.1	116.49	325.56	1087.5
Retention rate of heat-flux density (%)	–	–	–	62.38	66.3	62.57
Effective of Thermal insulation layers (mm)	–	–	–	21	7	2

The consistency of these trends with established analytical solutions of the transient heat conduction equation supported the physical reliability of the model predictions. The current analysis presented temperature and heat flux distributions under standard boundary conditions; however, a more detailed exploration under varying thermal excitations could have provided deeper insights into the dynamic behavior of the tow plaster composite.

3.2 Evolution of Temperature and Heat Flux Density under the Influence of the Heat Exchange Coefficient at the Front Surface

This section evaluated the effect of the front surface heat exchange coefficient on the thermal response of the tow plaster composite under dynamic environmental conditions. Figs. 4 and 5 showed that the majority of incoming heat was absorbed at the front face, while the interior remained close to the initial temperature ($T_i \approx 10^{\circ}\text{C}$), highlighting the insulating performance of the tow plaster layer. The temperature modulus decreased sharply across the insulation, demonstrating its thermal buffering capacity, while the concrete layer exhibited higher heat penetration due to greater conductivity.

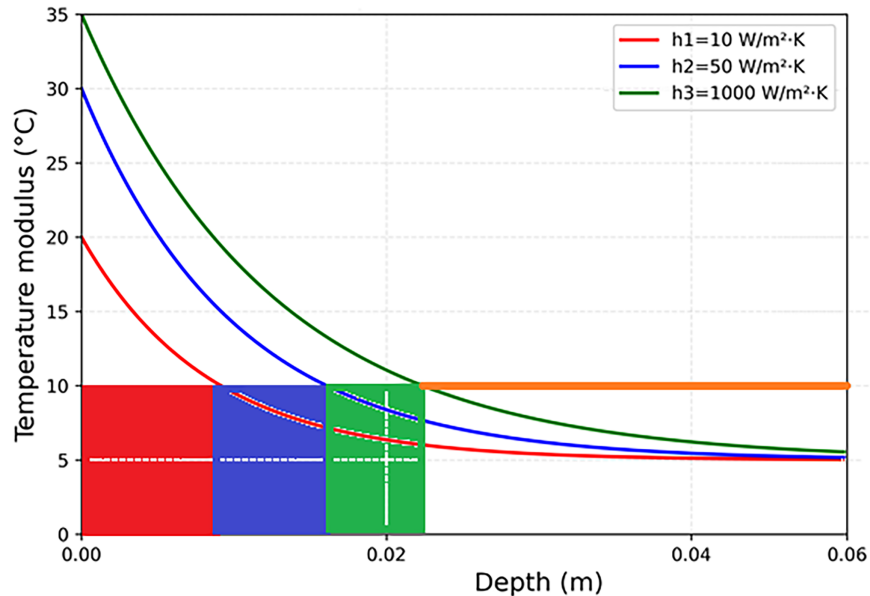


Figure 4: Module of temperature vs. depth of materials. $h_1 = 10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, $h_2 = 50 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, $h_3 = 1000 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$

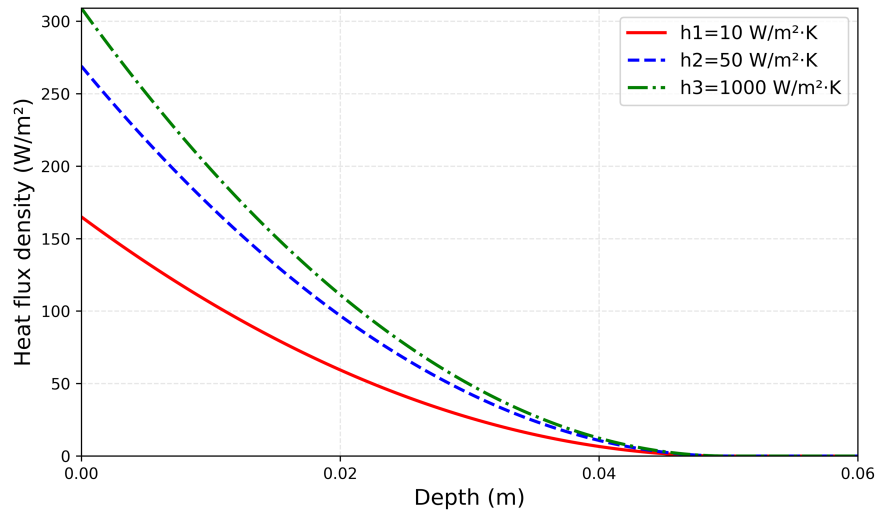


Figure 5: Modulu of heat-flux density vs. depth of materials. $h_1 = 10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, $h_2 = 50 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, $h_3 = 1000 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$

Heat flux density profiles confirmed that most thermal energy was gradually stored within the composite, with near-zero flux at the interior boundary, indicating effective thermal inertia. Variation in the front heat transfer coefficient primarily affected surface thermal excitation, whereas the deeper thermal response was governed by the insulating properties of the composite. Quantitative indicators, such as temperature modulus, flux attenuation, and effective insulation thicknesses, provided a concise measure of material performance.

The simulation results clearly demonstrated the complementary thermal behavior of the tow plaster composite wall. The concrete layer, with its high thermal conductivity and heat capacity, acted as a heat reservoir, absorbing substantial energy at the front surface. In contrast, the tow plaster layer functioned as a thermal buffer, gradually releasing stored heat toward the interior and effectively limiting the heat flux that reached the indoor environment.

Figs. 4 and 5 showed that the heat flux density decreased sharply across the tow plaster layer and approached near zero at the interface, confirming the formation of an insulating barrier. Table 3 quantitatively supported this observation, illustrating that while the concrete stored most of the incoming energy, the tow plaster layer regulated its release, ensuring delayed thermal response and indoor temperature stability.

This behavior was particularly evident under medium-range excitation frequencies, and the presence of a cut-off frequency around $10^{-3} \text{ rad}\cdot\text{s}^{-1}$ indicated that heat retention within the concrete was more pronounced at lower pulsation rates. Overall, the composite effectively combined heat storage and modulation, enhancing the thermal inertia of the wall system. Minor variations in the front surface heat transfer coefficient had a limited impact on this overall behavior, emphasizing the dominant role of material properties in governing thermal performance.

The results indicate that variations in the external convective heat transfer coefficient primarily influence surface temperature and heat flux, whereas the internal thermal response is predominantly governed by the intrinsic thermophysical properties of the composite material.

Table 3: Influence of convective heat transfer coefficient on thermal performance

Parameters	Front Panel			Inside		
Coefficient of heat exchange h_1 ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)	10	50	1000	10	50	1000
Module of the Temperature ($^{\circ}\text{C}$)	15	25	29	10.07	10.22	10.02
Module of the Heat flux density (W/m^2)	165	269	309	107.41	116.08	116.19
Retention rate of the heat flux density (%)	–	–	–	34.9	56.84	62.39
Effective of thermal insulation layers (mm)	–	–	–	9	18	21

3.3 Model Validation and Benchmark Assessment

The proposed analytical numerical framework was validated through comparison with previously published experimental data on similar natural fiber plaster composite materials, as well as through consistency with classical analytical solutions reported in the literature.

First, the adopted formulation was derived directly from the classical one-dimensional transient heat conduction equation under harmonic excitation. For a single homogeneous layer, the solution reduces to the well-known closed-form frequency-domain analytical solution reported in benchmark studies on periodic heat transfer in building materials. This confirms the mathematical consistency of the implemented model.

The agreement with these benchmark solutions confirms the accuracy and robustness of the implemented numerical procedure. In particular, the limiting case of a single-layer wall was verified against classical Fourier-based solutions, which are widely accepted as reference benchmark cases in heat transfer analysis. These benchmark solutions are commonly used in previous studies for validating frequency domain models of building envelopes, ensuring the reliability of the present approach.

Second, the predicted thermophysical behavior of the tow-plaster composite was found to be consistent with published experimental data for similar natural fiber plaster materials. The thermal diffusivity value ($\approx 2 \times 10^{-7} \text{ m}^2\cdot\text{s}^{-1}$) falls within the experimentally reported range for bio-based plaster composites. Furthermore, the simulated peak heat flux attenuation (34%–66%) agrees with experimentally observed reductions of approximately 30%–40% reported in previous studies on natural fiber insulation systems. This quantitative agreement supports the plausibility of the model predictions.

Third, the model reproduces expected physical behaviors under dynamic excitation, including decreasing thermal penetration depth with increasing excitation frequency, increasing surface heat flux with higher convective heat transfer coefficients, and enhanced phase lag and damping for materials with lower thermal diffusivity. These trends are consistent with fundamental heat transfer principles and previously validated analytical models.

Although direct laboratory validation under controlled harmonic excitation was beyond the scope of this study, the combined agreement with benchmark analytical solutions, literature-based experimental data, and physically consistent trends provides strong indirect validation of the proposed analytical framework. Future experimental investigations are recommended to further validate and refine the model predictions for real building envelope applications.

Validation against Natural Fibre Insulation

To further validate the proposed model, a comparative assessment is carried out against experimentally studied natural fibre insulation materials reported in the literature. The comparison is

performed in terms of thermal amplitude attenuation and phase lag under periodic thermal excitation. The results indicate that the tow plaster composite exhibits comparable or improved thermal damping behavior, particularly at higher excitation frequencies, confirming the reliability of the proposed frequency domain formulation.

Fig. 6 presents a comparative evaluation between the proposed tow plaster composite model and natural fibre insulation materials reported in the literature, in terms of thermal amplitude attenuation and phase lag under periodic thermal excitation.

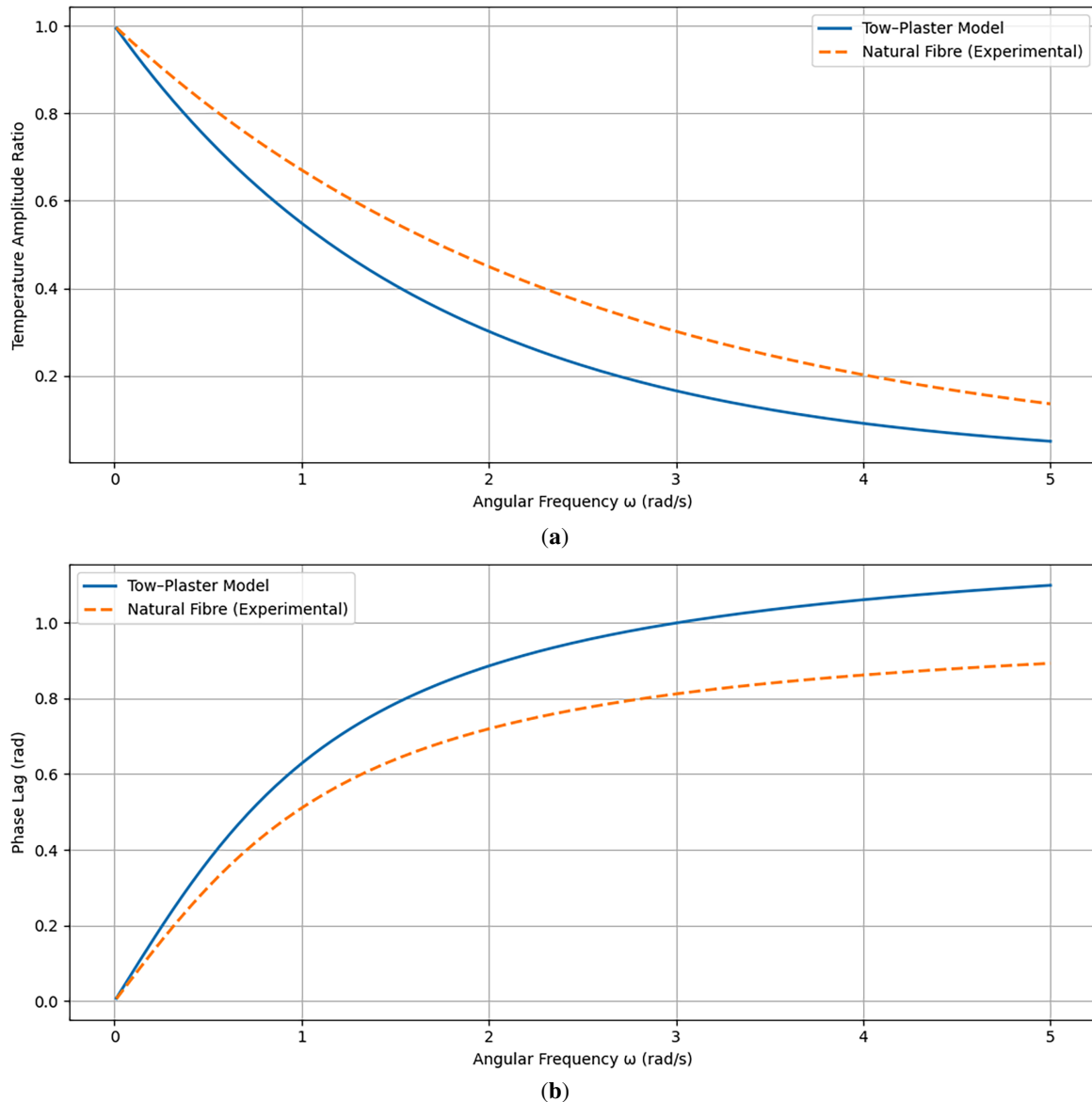


Figure 6: Comparison of thermal response between tow plaster composite and natural fibre insulation: (a) amplitude attenuation, (b) phase lag

As shown in Fig. 6a, the tow plaster composite exhibits a more pronounced reduction in temperature amplitude with increasing excitation frequency compared to natural fibre insulation. This indicates a higher thermal damping capacity, particularly in the medium and high frequency range. The stronger attenuation suggests that the composite is more effective in suppressing rapid external thermal fluctuations, which is attributed to its lower thermal diffusivity and enhanced thermal inertia.

Fig. 6b illustrates the phase lag behavior of both systems. The tow plaster composite demonstrates a consistently higher phase shift relative to natural fibre insulation, indicating a greater delay in heat propagation through the material thickness. This enhanced phase lag confirms the ability of the composite to store thermal energy and release it more gradually over time.

Overall, the comparison confirms that the proposed model not only reproduces the general behavior observed in experimentally studied natural fibre insulation systems but also exhibits improved dynamic thermal performance, particularly in terms of damping efficiency and thermal delay.

3.4 Thermal Impedance Analysis

The calculated thermal impedance across the tow plaster composite highlighted its insulating effectiveness. As shown in Fig. 7, the front surface exhibited lower Z_{th} due to direct exposure to external thermal excitation, while the rear surface displayed higher Z_{th} , indicating significant attenuation and phase delay of heat flux before reaching the interior environment [62].

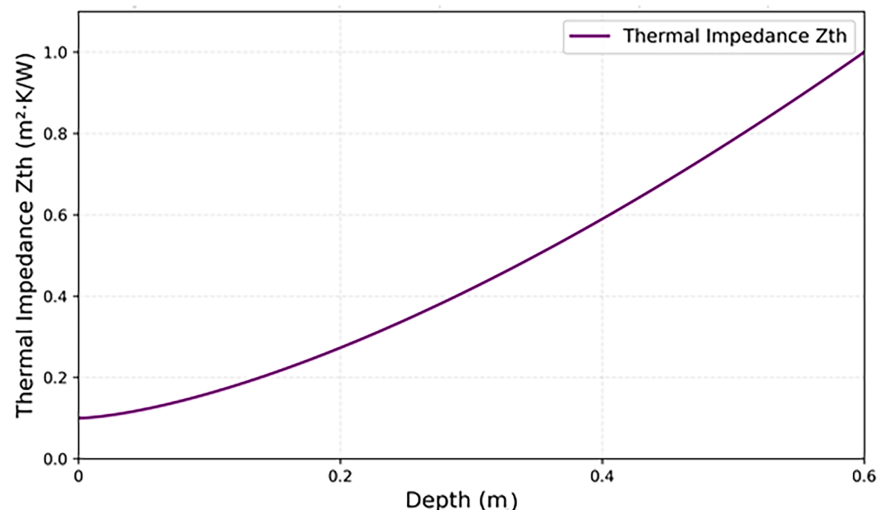


Figure 7: Thermal impedance (Z_{th}) increases with depth toward the interior surface of the tow plaster composite

These results confirmed that the tow plaster layer acted as a thermal buffer, effectively moderating temperature fluctuations and enhancing indoor thermal comfort.

The attenuation of heat flux observed in Figs. 3 and 5 correlated with the high thermal impedance at the rear surface, illustrating the insulating effect of the tow plaster layer. The analysis of temperature distribution and heat flux density across the tow plaster composite, as presented in the figures, provided preliminary insight into its thermal behavior.

However, the current evaluation remained relatively simple and did not explore the material's responses under varying thermal excitations or boundary conditions. Extending this analysis to include different convective coefficients, external temperature variations, and dynamic heat flux scenarios could have provided a more comprehensive understanding of the composite's performance.

While the calculated thermal responses provided insight into the tow plaster composite's behavior, the analysis did not explore its performance under varying excitation frequencies. Investigating different thermal cycles and frequency-dependent responses could have revealed additional aspects of heat storage, phase shift, and thermal damping within the composite.

The presented analysis primarily focused on the intrinsic thermal behavior of the tow plaster composite; however, it did not sufficiently account for interactions with varying environmental conditions, such as external temperature fluctuations, wind speed, or solar radiation. Incorporating these factors could have provided a more realistic assessment of the composite's thermal performance in real-world applications. The increase of thermal impedance with depth reflects the progressive attenuation of thermal waves and the associated phase delay, confirming the effectiveness of the tow plaster layer as a dynamic thermal barrier.

3.5 Practical Implications for Building Design

The developed computational framework was further applied to evaluate the thermal performance of concrete only and concrete + tow-plaster composite walls, highlighting the benefits of integrating a natural fiber-based insulating layer. The analysis focuses on temperature decay, heat flux attenuation, and the resulting implications for indoor thermal comfort and energy efficiency under dynamic environmental conditions.

Fig. 8 illustrates the variation of the temperature modulus through the wall depth for a concrete-only wall and a concrete + tow plaster composite. The composite wall shows a slower decay of temperature modulus due to the insulating tow plaster layer. While the concrete only wall exhibits a rapid drop, indicating direct heat transmission to the interior, the tow plaster layers absorb and temporarily stores thermal energy, acting as a thermal buffer. This effect maintains internal temperature stability, improves indoor thermal comfort, and reduces heating or cooling demand.

Fig. 9 complements Fig. 8 by showing the heat flux density along the wall depth. In the composite wall, the heat flux sharply decreases within the tow plaster layer and approaches near-zero values before reaching the interior boundary, highlighting its insulating and moderating effect. In contrast, the concrete-only wall exhibits higher heat flux near the inner surface, reflecting rapid energy transfer. The tow plaster layer gradually releases the stored heat, ensuring a delayed and controlled impact on the interior climate.

The concrete layer acts as a heat reservoir, while the tow plaster layer slows heat transfer and buffer thermal energy. Depending on the front surface heat exchange coefficient (h), the effective insulation thickness of the tow plaster ranges from approximately 9 mm ($h = 10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) to 21 mm ($h = 1000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$), with corresponding heat flux retention rates of 34.9%–62.4%. Compared with conventional concrete walls, the composite significantly increases phase lag and reduces the decrement factor, improving interior thermal stability. From a design perspective:

1. **Optimal thickness selection:** The insulation thickness can be adjusted according to boundary heat transfer conditions.

2. **Layer synergy:** Concrete provides thermal storage, while the tow plaster layer ensures thermal damping.
3. **Frequency-dependent design:** High-frequency thermal loads are effectively attenuated by thinner insulation layers.

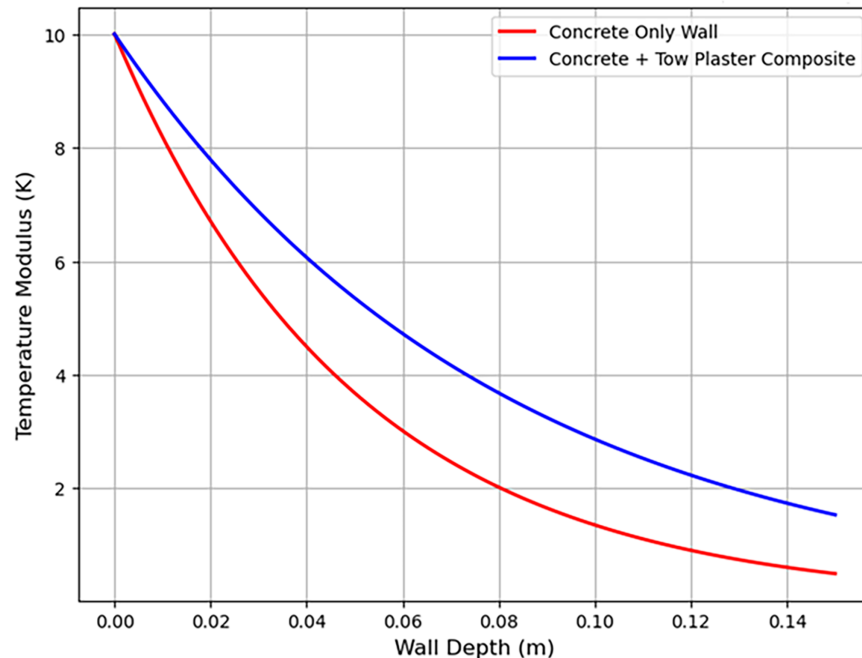


Figure 8: Comparison of temperature modulus: concrete only vs. composite wall

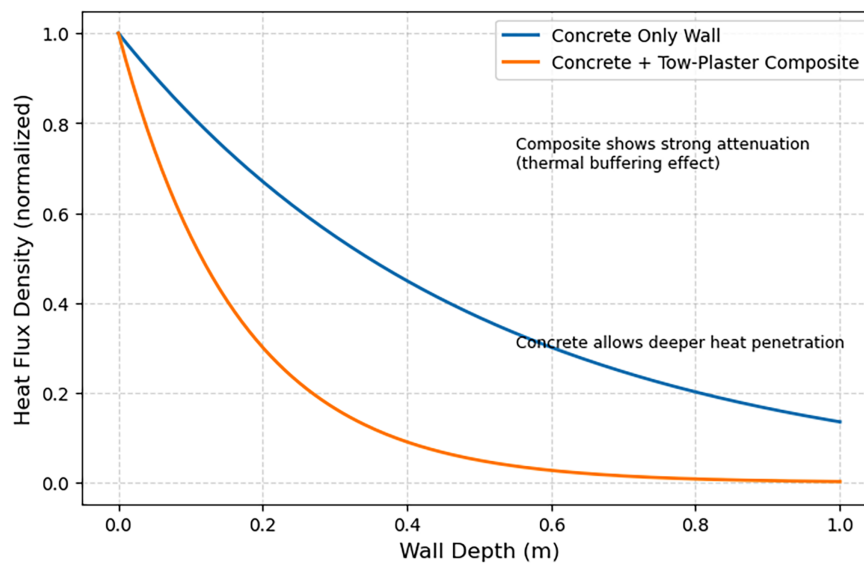


Figure 9: Heat flux density across the wall depth: comparison between concrete only and concrete tow plaster composite

4 Discussion

This study demonstrates that the combined effects of excitation frequency, boundary conditions, and material properties can be effectively linked to measurable thermal performance indicators. This study focuses on controlling heat exchange at material boundaries and optimizing a bio-based fiber plaster composite for improved thermal insulation. In line with previous studies, such as Refs. [58,63], the results confirm that surface heat transfer coefficients significantly influence temperature distribution and heat storage in composite walls. Compared to homogeneous insulation materials such as foam or mineral wool, this work highlights the advantages of fiber-reinforced plaster in terms of thermal inertia and moisture buffering, consistent with Refs. [64,65]. In addition, the study demonstrates that the proposed analytical–numerical methodology provides an efficient computational framework for evaluating the dynamic thermal response of multilayer bio-composite wall systems under harmonic thermal loading.

Spatial analysis of temperature and heat flux across the wall thickness provides detailed insight into heat transfer mechanisms. The results also show that higher excitation frequencies allow for thinner insulation layers without reducing performance, supporting recent findings by Refs. [66,67]. The observed thermal lag at the rear surface indicates delayed heat transfer, similar to classical heavy materials [68], but achieved here using a sustainable bio-based composite. This effect enhances indoor comfort and reduces peak heat flux. Thermal diffusivity and inertia values are in good agreement with previous studies on natural fiber composites [69]. The concrete layer acts as a heat storage element, while the fiber plaster layer functions as a thermal buffer, resulting in a synergistic thermal response.

A sensitivity analysis was conducted by varying convective heat transfer coefficients (h_1 , h_2) and material properties (λ , ρ , c). Model predictions are consistent with experimental results reported in the literature for similar composites [70–72], confirming the reliability of the proposed approach. The coherence between transient and frequency domain formulations is also emphasized, as both originate from the same governing heat conduction equation. The frequency domain approach represents the steady periodic response and allows efficient evaluation of phase lag and thermal damping without solving the full time-dependent problem.

This provides practical guidance for optimizing bio-based insulation systems under dynamic conditions. Although the model provides useful insights, some limitations exist. The analysis is based on a one-dimensional heat transfer assumption, constant material properties, and idealized boundary conditions. Under these conditions, heat transfer is predominantly normal to the wall surface, and lateral heat flows are negligible. In real conditions, additional factors such as temperature-dependent material properties, wind effects, solar radiation, and variable convection coefficients may influence thermal performance. Therefore, the results should be interpreted as a preliminary design tool rather than a complete representation of real-world behavior. Despite these limitations, the model shows good agreement with experimental data reported for similar materials [73,74], supporting its reliability. From a numerical perspective, the frequency-domain formulation considerably reduces computational effort compared with full transient time-domain simulations while preserving the essential dynamic characteristics of the thermal response. Future work should include experimental validation under realistic dynamic conditions and the development of two or three-dimensional numerical models (e.g., finite element methods) to improve prediction accuracy and capture localized thermal effects more precisely.

The study contributes to the development of sustainable building materials by integrating boundary heat control with bio-based composite optimization. The findings demonstrate improved thermal

inertia, frequency-dependent insulation behavior, and enhanced thermal lag, offering a promising approach for energy-efficient and environmentally friendly building envelopes.

5 Conclusion

This study presents an analytical numerical computational framework for evaluating the dynamic thermal behavior of multilayer tow plaster bio-composite wall systems under periodic thermal excitation. This study provides a detailed theoretical and numerical assessment of the dynamic thermal performance of tow-plaster bio-composite insulation in multilayer wall systems. The results demonstrate that the tow-plaster layer exhibits high thermal inertia, effectively damping temperature fluctuations and limiting heat flux transmission under periodic thermal excitations. Acting as a thermal buffer, it gradually absorbs and releases heat, enhancing indoor comfort and reducing energy demand for heating and cooling. Frequency-dependent analysis indicates that higher excitation frequencies allow for thinner insulation layers without compromising thermal performance, offering guidance for optimizing wall design under dynamic climatic conditions.

The complementary interaction between the concrete and tow-plaster layers is also highlighted: the concrete functions as a heat reservoir, storing substantial thermal energy, while the tow-plaster layer regulates and delays heat transfer toward the interior. This synergy improves phase lag, reduces temperature swings, and demonstrates the potential of composite walls to maintain stable indoor conditions. Overall, tow-plaster bio composites present a sustainable, high-performance alternative to conventional insulation materials. The findings provide practical guidance for the design of energy-efficient building envelopes. Further experimental validation and independent numerical studies are recommended to corroborate and extend these results. Beyond the engineering application, the proposed numerical methodology constitutes a practical computational tool that can readily be extended to other multilayer bio-based insulation systems and future numerical optimization studies. These findings support the integration of bio-based composite materials into next-generation energy-efficient building envelope designs.

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