

Strength, Thermophysical And In-Service Performance of a Three-Layer 3d-Printed Wall with Expanded Polystyrene Concrete Infill

A Numerical Parametric Study and An Experimental Verification Programme

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Abstract

A non-load-bearing, three-layer external wall for a low-rise building is investigated. The wall consists of two cementitious shells manufactured by layer-by-layer extrusion-based 3D printing and a cast-in-place expanded polystyrene (EPS) concrete core. The study aims to establish relationships between wall geometry, construction-stage actions, the mechanical response of the printed shells, heat and moisture transfer, and in-service performance, and to develop a testable experimental verification programme. The baseline model has an overall thickness of 250 mm, comprising two 30 mm shells and a 190 mm core. Using illustrative thermal conductivities of 0.80 and 0.10 W/(m·K), the calculated thermal resistance of the homogeneous region is 2.145 m²·K/W and its thermal transmittance is 0.466 W/(m²·K). Increasing the design thermal conductivity of the core by 20% and 40% increases U by 17.3% and 33.9%, respectively. Continuous cementitious ribs 30 mm wide at 0.6 m spacing can increase the equivalent U-value by 33.6%; thermal optimisation must therefore consider the actual two- or three-dimensional geometry. A construction-stage analysis of fresh infill pressure gives 3.18 kPa for a density of 450 kg/m³, a dynamic factor of 1.2 and a lift height of 0.6 m. For a 30 mm thick shell strip spanning 0.6 m, the elastic stress is 0.95 MPa and the deflection is 0.40 mm at an early-age modulus of 6 GPa. Wind-response screening identifies quadratic and fourth-power relationships between support spacing and stress and deflection, respectively. A steady-state winter moisture assessment indicates a potential intersection of vapour partial pressure and saturation pressure at the cold boundary of the core. This requires transient hygrothermal modelling that accounts for drying, joints and climate data rather than specifying a vapour barrier from the simplified analysis alone. A multilevel testing programme—material, printed element, connection, wall specimen and building—and a production quality-control matrix are developed. The scientific contribution lies in the integrated parametric treatment of the filling stage, the anisotropic printed shell, thermal bridges, moisture risk and verification of in-service performance.

Keywords: Construction 3D printing; printed concrete; expanded polystyrene concrete; three-layer wall; thermal conductivity; thermal transmittance; thermal bridge; interlayer joint; moisture conditions; fresh infill pressure; building envelope.

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1. Introduction

Extrusion-based construction 3D printing enables wall shells to be formed without conventional formwork and directly links the digital model to the material deposition path. However, geometric freedom does not remove requirements for strength, thermal protection, moisture resistance, fire safety and quality control. On the contrary, layer-by-layer fabrication introduces additional interfaces, local thickness variations, process interruptions and a dependence of properties on specimen orientation. Consequently, the mechanical and thermophysical behaviour of a printed wall cannot be reliably described using tabulated properties of cast mortar alone [1–16].

In the proposed structural system, a separate frame of pultruded composite profiles resists the primary vertical and horizontal actions, while the 3D-printed wall serves as the building envelope. This separation reduces uncertainty in the global load-bearing response but does not make the wall “unloaded”. During construction, the shells resist their self-weight and the pressure of fresh EPS concrete; in service, they are subjected to wind pressure, local actions, hygrothermal deformation, frame

movements and forces in the fixings. At the same time, the ribbed printed geometry can create thermal bridges, while interlayer interfaces may provide paths for accelerated moisture transport.

The RILEM TC 304-ADC interlaboratory programme demonstrated considerable variability between materials, printing systems and specimen preparation methods, confirming the need for process-specific qualification and harmonised testing procedures [15, 16]. ISO/ASTM 52939:2023 likewise treats quality in additive construction as an interrelated set of requirements for the process, equipment, materials, operations and project [2]. A new wall system therefore requires not an isolated calculation but a traceable chain linking input data, modelling, sensitivity analysis, testing and acceptance criteria.

This study develops that chain for a 250 mm thick wall with two 30 mm printed shells and a 190 mm EPS concrete core. The work is limited to numerical and theoretical analysis and is intended to support the experimental programme. The numerical values must not be transferred directly to a design without establishing the actual properties of the mix, interlayer joints, printing regime, moisture conditions and connection details.

Analytical study workflow for the three-layer wall



Results describe illustrative relationships; design values are established after testing materials, connections and envelope specimens.

Figure 1 — Sequence of the numerical and theoretical study and subsequent verification

2. State of the Art and Research Gap

2.1. Anisotropy and defects in the printed shell

Layer-by-layer deposition changes the structure of cementitious materials relative to casting in formwork. Interlayer adhesion depends on the interval between passes, surface dehydration, rheology, nozzle height, extrusion pressure and subsequent curing [8–12]. Wolfs and co-authors showed that process parameters must be assessed in relation to the specific material and printing system, and that interlayer strength is a critical parameter in the analysis of printed elements [11]. Recent studies also report differences in modulus, strength and cracking behaviour as layer orientation changes and cold joints are introduced [16, 17].

For the non-load-bearing wall considered here, critical mechanisms include not only shell compression but also bending across the layers, local delamination, cracking near ribs and openings, and damage caused by infill pressure before the specified material age is reached. The strength of specimens cut along the printing path therefore cannot automatically be used to assess a strip bending across the layers. The analysis requires a set of directional properties and a separate representation of the interlayer interface.

2.2. The density–strength–thermal conductivity trade-off in EPS concrete

EPS concrete reduces envelope density and thermal conductivity by incorporating expanded polystyrene beads. Increasing their volume fraction, however, generally reduces the strength of the cementitious matrix and changes shrinkage, water absorption and bond to the shell [24–30]. Particularly important for this lightweight infill are uniform bead distribution, prevention of flotation and segregation, rheological compatibility with placement into a narrow printed cavity, and avoidance of excessive hydrostatic loading on the early-age shell.

The optimum core mix is not the same as that for a stand-alone load-bearing wall. In the proposed system, the core must primarily provide thermal resistance, void-free cavity filling, limited mass, deformation compatibility and durability. Its required strength class is governed by construction-stage and local actions rather than by the global vertical load of the building. This permits a lower

density to be considered but requires bond, shrinkage and fire behaviour to be checked at the level of the three-layer assembly.

2.3. Thermal and hygrothermal behaviour of 3D-printed walls

Heat transfer through a 3D-printed wall is governed by its internal topology as well as by the insulation thickness. Numerical and full-scale wall studies show that unfilled cavities often fail to provide the required thermal protection, whereas the introduction of insulating infill substantially reduces U [20–23]. Continuous ribs, webs, anchors and regions around openings form parallel heat-flow paths; a one-dimensional homogeneous-region calculation is only a first approximation for such features. ISO 6946 permits approximate methods for certain inhomogeneous layers, while detailed two- and three-dimensional thermal bridges are analysed in accordance with ISO 10211 [31, 33].

Hygrothermal behaviour is also anisotropic. Printed surfaces and interlayer joints may have different capillary water absorption and water vapour permeability coefficients, and porous infill can retain construction moisture. A simplified steady-state check under ISO 13788 is useful for identifying risk at an early stage, but it does not represent transient wetting, rain exposure, solar heating or drying [34]. The final assembly must therefore be checked using a transient model and in-situ monitoring.

2.4. Research gap

Most publications address mix printability, mechanical properties, the thermal characteristics of cavities or lightweight concrete composition separately. Their combined behaviour in a non-load-bearing three-layer envelope remains insufficiently investigated: the shell initially acts as construction formwork and subsequently as a protective and shape-defining layer, while the infill governs thermal performance. The research gap is the absence of a consistent parametric framework that simultaneously links construction-stage pressure, early-age strength, wind-induced bending, continuous thermal bridges, moisture transport, mass and an experimental acceptance plan.

Table 1 — Research gaps and the approaches adopted to address them

Issue	Common simplification	Approach adopted
Printed shell	Isotropic properties of cast mortar	Directional testing and separate control of interlayer joints
Cavity filling	Constant hydrostatic pressure	Pressure calculated from lift height and early-age stiffness
Thermal protection	One-dimensional homogeneous wall	Parallel paths and mandatory 2D/3D models of details
Moisture conditions	A single dew-point check	Steady-state screening plus transient hygrothermal verification
In-service properties	Combined material datasheets	Testing of the composite wall specimen and in-situ monitoring

3. Aim, Objectives and Scientific Contribution

The aim of the study is to establish numerical relationships governing the mechanical, thermophysical and in-service behaviour of a non-load-bearing three-layer 3D-printed wall with EPS concrete infill and to develop a multilevel experimental verification programme.

The following objectives were addressed:

- A geometric and physical model of the 30–190–30 mm wall was developed, explicitly separating the functions of the shells and core.
- The mass per unit area, fresh infill pressure, early-age stresses and shell deflection were determined.
- Shell bending under wind pressure was screened for different transverse support spacings.
- Relationships between U and core thickness, thermal conductivity, moisture effects, and the geometry and material of continuous ribs were obtained.
- The internal surface temperature and steady-state vapour balance were assessed for the assumed winter conditions.
- Heat storage, mass-law sound insulation, fire resistance and moisture resistance were analysed as areas requiring verification.
- A quality matrix and a testing hierarchy extending from the material to the building were developed.

The scientific contribution is the treatment of the three-layer 3D-printed envelope as a system whose functions change over time: during construction, the printed shells act as permanent formwork; after the core hardens, they

become part of a composite envelope assembly. In a unified framework, infill lift height, early-age shell flexural strength, rib spacing, equivalent thermal transmittance, moisture risk and production-control criteria are linked quantitatively.

4. Materials, Analytical Model and Research Methods

4.1. Geometric model of the three-layer wall

The object of the study is an external non-load-bearing wall in a low-rise building with a three-dimensional load-bearing frame of pultruded GFRP profiles. The wall does not carry vertical loads from the floors or roof. Its design functions are limited to resisting self-weight, wind pressure and suction, and local erection actions, and transferring these actions to the frame through deformation-decoupled fixings. This formulation excludes uncontrolled composite action between the brittle printed material and the more deformable composite frame, allowing structural safety and envelope service performance to be specified separately.

The baseline cross-section comprises three layers: inner and outer 3D-printed cementitious shells, each 30 mm thick, form permanent construction formwork, and the 190 mm cavity is filled with cast-in-place EPS concrete. The total wall thickness is 250 mm. The printed shells are connected by local transverse webs and erection ties. However, continuous cementitious ribs extending through the full thickness of the insulating core are treated as potential thermal bridges and are therefore assessed separately in the parametric study.

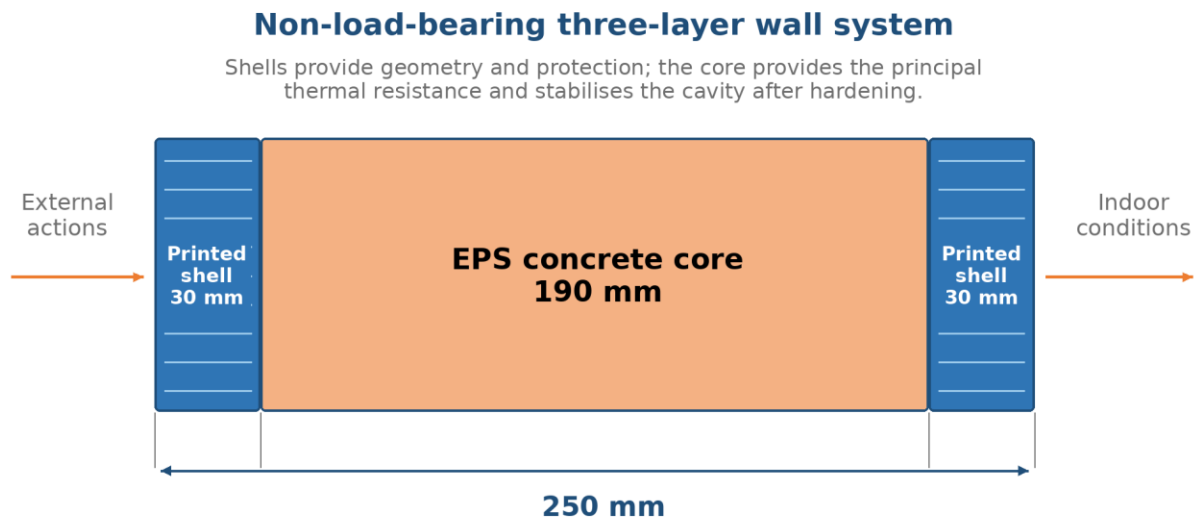


Figure 2 — Baseline 30–190–30 mm wall geometry and functional separation of the layers

Table 2 — Baseline parameters of the wall model

Parameter	Symbol	Adopted value	Status
Thickness of one printed shell	t_s	0.030 m	Illustrative geometry
EPS concrete core thickness	t_c	0.190 m	Illustrative geometry
Total wall thickness	d	0.250 m	Analytical model
Density of hardened printing mix	ρ_s	1900 kg/m ³	To be tested
Dry EPS concrete density	ρ_c	350 kg/m ³	To be tested
Shell thermal conductivity	λ_s	0.80 W/(m·K)	Screening assumption
Core thermal conductivity	λ_c	0.10 W/(m·K)	Screening assumption
Shell elastic modulus at 28 days	E_{28}	20 GPa	Screening assumption
Early-age shell elastic modulus	E_c	6 GPa	Screening assumption
Shell vapour diffusion resistance factor	μ_s	60	Screening assumption
Core vapour diffusion resistance factor	μ_c	10	Screening assumption

Note. Until the material has been characterised experimentally, all numerical parameters are used solely for comparative calculations and are not certified properties of a specific mix.

4.2. Hierarchy of input data and limits of the evidence

A key methodological principle is to distinguish input data according to their level of evidence. The geometry of the illustrative cross-section and the parameter ranges are selected by the authors to identify sensitivity. Equations and boundary conditions are adopted from established heat-transfer, mechanics-of-materials and

moisture-transfer models. Properties that affect the design must be determined by testing material batches manufactured using the specific equipment. This is particularly important for a 3D-printed cementitious composite because the interlayer interval, nozzle height, surface dehydration and specimen cutting orientation can change both strength and failure mode [8–18].

The RILEM TC 304-ADC interlaboratory programme demonstrated the need to record not only mix composition but also printing parameters, specimen orientation, curing and test method. Accordingly, the

calculated curves in this study are interpreted as a map of design options rather than as a substitute for qualification testing. Requirements for the process, controlled

characteristics and sequence of additive construction operations should follow the approach of ISO/ASTM 52939 [2].

Table 3 — Levels of input data and their permissible applications

Level	Data source	Permissible use	Invalid interpretation
A	Official codes and standards	Selection of calculation procedures, boundary conditions and criteria	Automatic confirmation of a new material's properties
B	Peer-reviewed studies	Justification of ranges, mechanisms and testing programme	Direct transfer of results to a different mix and printer
C	Illustrative calculation	Comparison of options and identification of governing parameters	Declaration of design resistance or a certified U-value
D	Material and specimen tests	Identification of design properties for a specific process	Extrapolation to connections and walls without larger-scale checks
E	Wall-specimen and building tests	Validation of interaction, quality and service performance	Disregard of variability in routine production

4.3. Thermal calculation method

The one-dimensional thermal resistance of a region that is homogeneous over its area was determined by summing layer and surface-film resistances in accordance with the principles of ISO 6946 [31]. For a vertical external wall under the illustrative winter conditions, $R_{si} = 0.13$ and $R_{se} = 0.04 \text{ m}^2 \cdot \text{K}/\text{W}$ were

$$R = R_{si} + \sum(d_i / \lambda_i) + R_{se} \quad (1)$$

where d_i is the thickness of layer i , m , and λ_i is its design thermal conductivity, $\text{W}/(\text{m} \cdot \text{K})$.

$$U = 1 / R \quad (2)$$

where U is the thermal transmittance of the envelope, $\text{W}/(\text{m}^2 \cdot \text{K})$.

The parallel heat-flow-path method was used for a preliminary assessment of regularly spaced continuous ribs. It intentionally simplifies the two-dimensional temperature distribution and is used only to rank options.

$$U_{eq} = (1 - f) \cdot U_0 + f \cdot U_{rib} \quad (3)$$

where f is the area fraction occupied by the continuous rib, and U_0 and U_{rib} are the thermal transmittances of the primary and thermal-bridge paths.

$$\theta_{si} = T_i - U \cdot R_{si} \cdot (T_i - T_e); \quad fR_{si} = (\theta_{si} - T_e) / (T_i - T_e) \quad (4)$$

where T_i and T_e are the indoor and outdoor air temperatures, and θ_{si} is the internal surface temperature.

adopted. Design thermal conductivity must account for the material temperature and in-service moisture content. The baseline λ -values were therefore varied subsequently, and the results do not replace selection of design properties under ISO 10456 and national regulations [32, 43].

Final heat flows, minimum internal surface temperatures, and linear and point thermal transmittances should be obtained from a two- or three-dimensional model under ISO 10211 [33], including corners, reveals, foundation, floor and roof junctions, and fixings.

4.4. Fresh infill pressure and shell bending

During cavity filling, the printed shells act as thin-walled permanent formwork. For conservative screening, the pressure of fresh EPS concrete is assumed to be

hydrostatic and is multiplied by a dynamic factor γ_d to account for pumping, local pulsations and process deviations. The actual pressure distribution may be

$$p(h) = \gamma_d \cdot \rho_f \cdot g \cdot h$$

where ρ_f is the density of the fresh infill and h is the height of the continuously filled lift.

A unit-width shell strip between transverse ties is idealised as a simply supported plate strip. The resulting stresses and deflections do not account for orthotropy,

$$\sigma_{\max} = 3 \cdot p \cdot L^2 / (4 \cdot t_s^2)$$

where L is the shell span between ties and t_s is the shell thickness.

$$w_{\max} = 5 \cdot p \cdot L^4 / (32 \cdot E \cdot t_s^3)$$

for a simply supported unit-width strip under uniform pressure.

$$h_{\max} = 4 \cdot f_c \cdot t_s^2 / (3 \cdot \gamma_d \cdot \rho_f \cdot g \cdot L^2)$$

where f_c is the allowable early-age flexural stress, including the required safety margin.

4.5. Moisture and in-service performance screening

The steady-state vapour balance was calculated by distributing temperatures according to thermal resistances and vapour partial pressure according to the equivalent air-layer thickness $s_d = \mu d$. This calculation follows the simplified approach of ISO 13788 [34] but does not represent capillary transport, sorption capacity, moisture-dependent properties, rain wetting or airflow through leakage paths. The result is therefore used as an indicator of the need for more detailed transient

reduced by thixotropy and structural build-up in the mix, but this effect must not be credited without rheological testing and observations on a full-scale specimen.

(5)

interlayer joints, local bearing at fixings or the three-dimensional response of the curved printed contour. They therefore serve to select a safe temporary-tie spacing and the height of an individual filling stage.

(6)

(7)

(8)

modelling and testing, not as a final conclusion that condensation is absent.

The in-service assessment covers five interconnected mechanisms: heat transfer; vapour diffusion and liquid wetting; air leakage through joints and junctions; acoustic transmission; and fire exposure. They cannot be combined into a single “universal” indicator. For example, increasing mass may improve approximate sound insulation but does not itself ensure airtightness; a low U-value does not prevent local cooling at a rib; and a non-combustible cementitious shell does not demonstrate the required fire resistance of the complete wall.

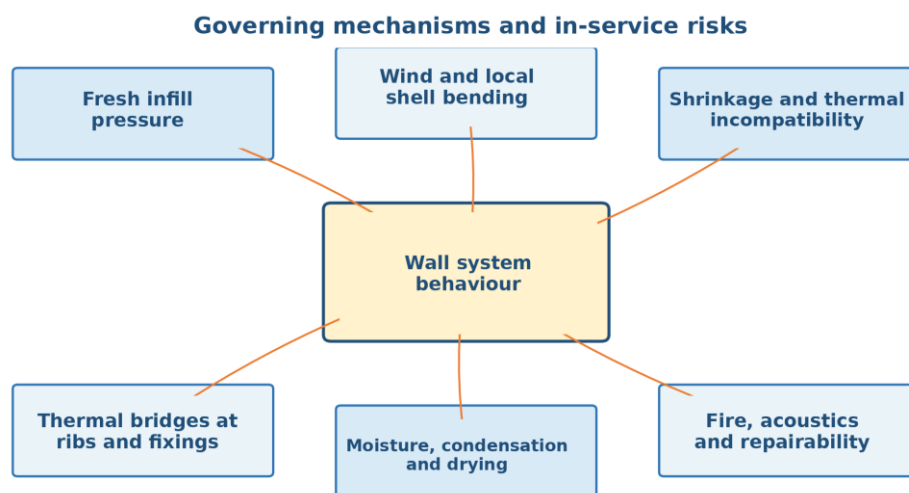


Figure 3 — Analytical mechanisms and mandatory experimental checks

5. Structural Concept and Transfer of Actions

5.1. Separation of frame and wall functions

The proposed system is based on the functional independence of the load-bearing frame and the envelope. Pultruded columns, beams and vertical bracing resist the permanent and variable building loads and provide global stability and seismic resistance. The wall panel forms the external boundary, thermal envelope and architectural surface. Its connection to the frame transfers out-of-plane wind actions while allowing the

design vertical and horizontal movements without binding.

This arrangement requires three types of detail: supports carrying wall self-weight; guide ties transferring pressure and suction perpendicular to the wall plane; and sliding or movement-accommodating fixings that limit unintended wall participation in frame action. Joints between printed wall sections, around openings and at floors must simultaneously maintain airtightness, water resistance and the ability to accommodate cyclic movement.

Table 4 — Functions of wall components and design limitations

Component	Primary function	Design action	Function not to be assumed without verification
Outer printed shell	Weather protection, architectural surface and formwork	Wind, self-weight and fresh-core pressure	Building load-bearing action or unconditional watertightness
Inner printed shell	Internal surface, fire-protective layer and formwork	Local loads and filling pressure	Suspension of heavy equipment without embedded items
EPS concrete core	Principal thermal resistance and shell stabilisation	Self-weight, shrinkage and thermal strains	Design load-bearing function without testing
Transverse ties/ribs	Maintaining shell geometry and erection restraint	Tension/compression during filling and wind exposure	Continuous cementitious section without a thermal assessment
Frame fixings	Wind transfer and out-of-plane restraint	Cyclic transverse force, bearing and pull-out	Rigid restraint preventing frame deformation
Movement joints	Movement accommodation and sealing	Temperature, shrinkage and interstorey drift	Maintenance-free operation without assessing sealant service life

5.2. Design stages over the life cycle

Wall behaviour changes fundamentally with time and cannot be analysed solely in its fully hardened state. Five stages are distinguished: shell printing; early-age curing; cavity filling; installation and development of core properties; and service. Fresh-layer stability and

geometric accuracy govern the first stage. Uneven drying and interlayer bond are critical in the second. Infill pressure and shell opening govern the third. Shrinkage, thermal incompatibility and development of the layer interfaces are critical in the fourth. In service, wind,

hygrothermal cycling, joint tightness and durability of the external surface dominate.

Control criteria must be specified separately for each stage. The strength of a 28-day specimen does not characterise the shell's ability to withstand filling after 24–72 hours. The laboratory λ of a dry core is not its design λ under moist conditions. The sound insulation of a homogeneous region does not describe leakage through electrical sockets and junctions. A staged approach provides traceability between the process parameter, the measured property and the design limit state.

6. Mechanical and Construction-Stage Behaviour of the Wall

6.1. Mass per unit area and permanent action

At the assumed densities, the two printed shells have a combined mass of 114.0 kg/m² and the EPS concrete core has a mass of 66.5 kg/m². The total mass per unit area is 180.5 kg/m², corresponding to a self-weight of approximately 1.77 kN/m². This is appreciably below that of a solid cementitious wall of the same thickness but still requires designed supports at the foundation or load-relieving supports at each floor. Transfer of self-weight solely by adhesion to the composite frame is not permitted.

Table 5 — Calculation of mass per unit area for the baseline wall

Layer	Thickness, m	Density, kg/m ³	Mass, kg/m ²	Share, %
Outer printed shell	0.030	1900	57.0	31.6
EPS concrete core	0.190	350	66.5	36.8
Inner printed shell	0.030	1900	57.0	31.6
Total	0.250	—	180.5	100.0

Note. The masses of finishes, fixings, embedded items and possible absorbed water are not included.

6.2. Pressure of fresh EPS concrete infill

The illustrative calculation adopts a fresh infill density of 450 kg/m³ and a dynamic factor of 1.20. For a continuous filling lift of 0.60 m, the maximum pressure at its lower

boundary is 3.18 kPa. Despite this relatively low absolute value, the thin shell is sensitive to tie spacing because bending stress is proportional to L^2 and deflection to L^4 .

Table 6 — Input parameters and results for the filling-stage calculation

Parameter	Symbol	Value	Comment
Fresh infill density	ρ_f	450 kg/m ³	Confirm for the actual mix
Dynamic factor	γ_d	1.20	Screening allowance
Height of one lift	h	0.60 m	Process parameter
Temporary-tie spacing	L	0.60 m	Analytical strip span
Shell thickness	t_s	0.030 m	Baseline geometry
Early-age elastic modulus	E_e	6 GPa	To be tested
Maximum pressure	p_{max}	3.18 kPa	Equation (5)
Strip stress	σ_{max}	0.954 MPa	Equation (6)
Strip deflection	w_{max}	0.397 mm	Equation (7)

The calculation shows that early-age shell flexural strength directly limits the height of a single filling lift. For $f_c = 0.8, 1.0, 1.2, 1.5$ and 2.0 MPa, the permissible lift heights are 0.503, 0.629, 0.755, 0.944 and 1.258 m, respectively. A fixed lift height specified without real-

time control of shell age and strength therefore creates a hidden risk: identical geometry may be safe under cool, humid conditions but unacceptable under accelerated surface drying or prolonged interlayer intervals.

Permissible fresh infill lift based on early-age shell strength

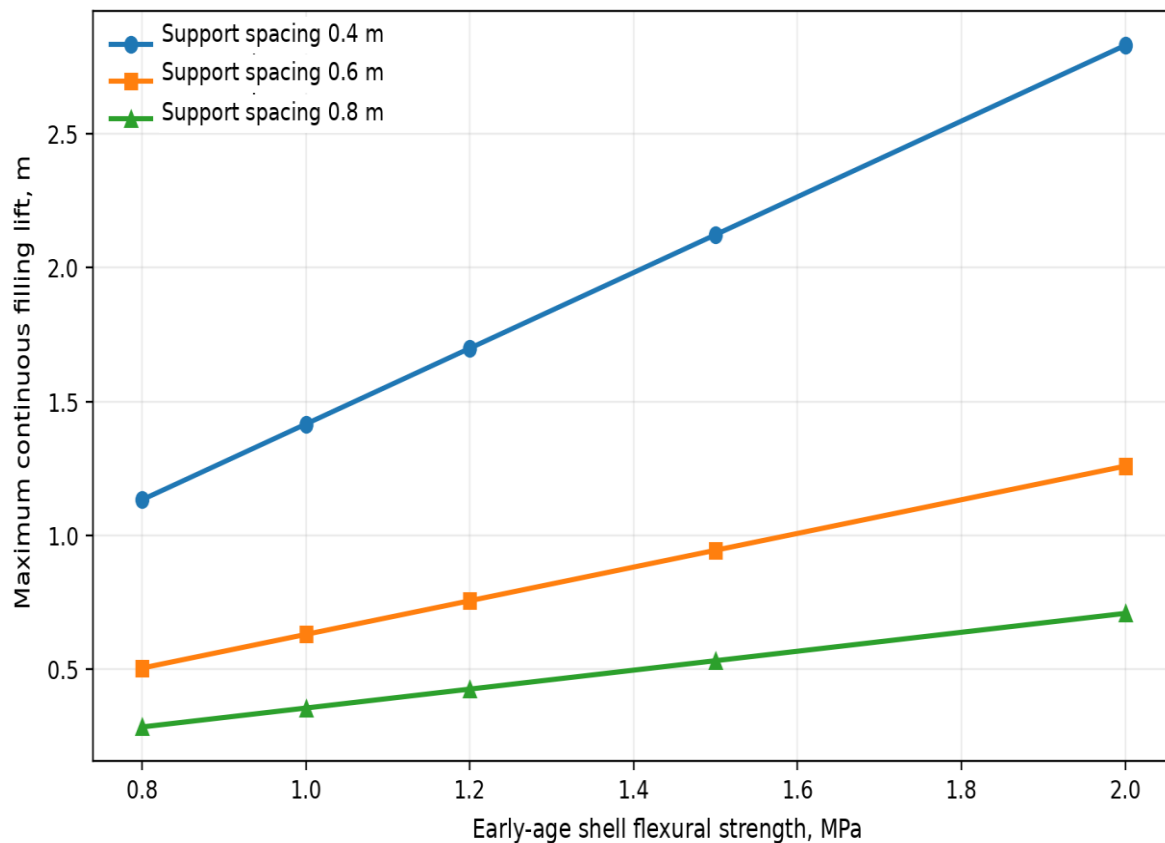


Figure 4 — Permissible continuous filling height as a function of early-age shell flexural strength

Table 7 — Calculated lift height for different early-age strengths

f_c , MPa	0.80	1.00	1.20	1.50	2.00
hmax, m	0.503	0.629	0.755	0.944	1.258

Note. The calculation uses $t_s = 30$ mm, $L = 0.60$ m, $\rho_f = 450$ kg/m³ and $\gamma_d = 1.20$. The process limit must additionally be restricted by deflection, layer stability and the results of full-scale filling tests.

6.3. Shell bending under wind pressure

In the service stage, a region of one shell between transverse supports is considered under a design pressure $q = 0.80$ kPa. This scenario does not replace a three-

dimensional analysis of both shells, the core and the fixings; it identifies the scale effect of tie spacing. At $E = 20$ GPa, increasing the span from 1.0 to 3.0 m increases the elastic stress from 0.67 to 6.00 MPa and the deflection from 0.23 to 18.75 mm. Strength and crack-control criteria may therefore produce different limiting spacings.

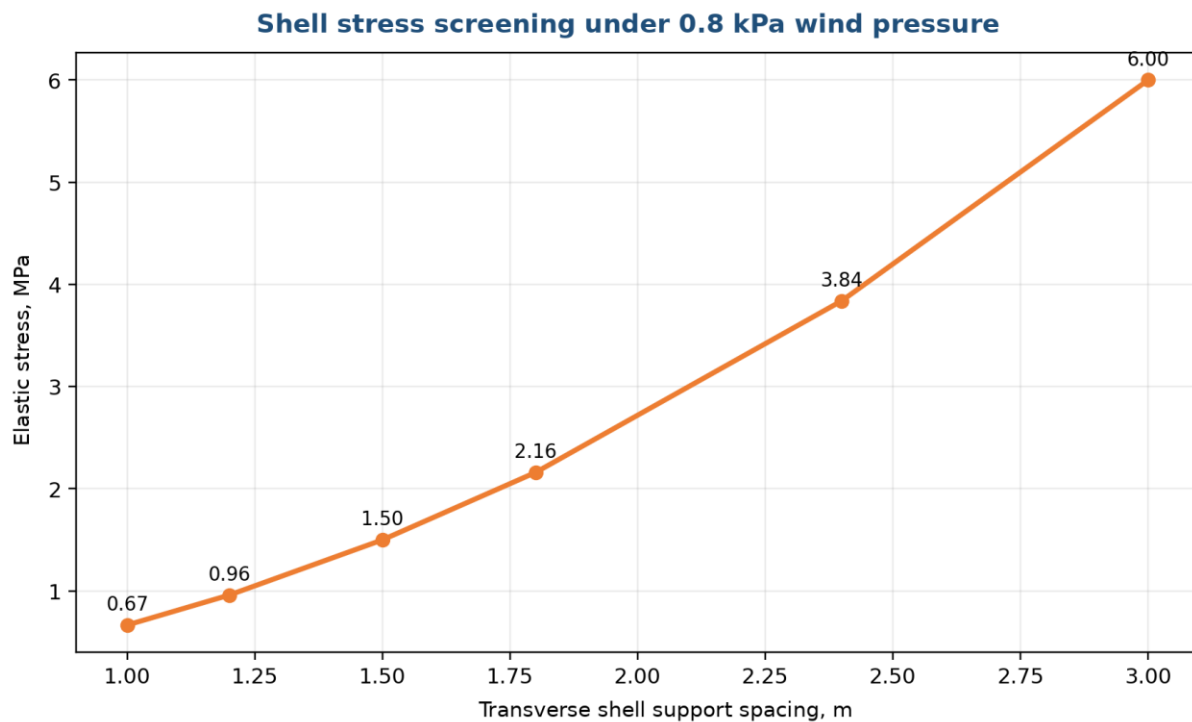


Figure 5 — Screening relationship between shell bending stress and transverse support spacing

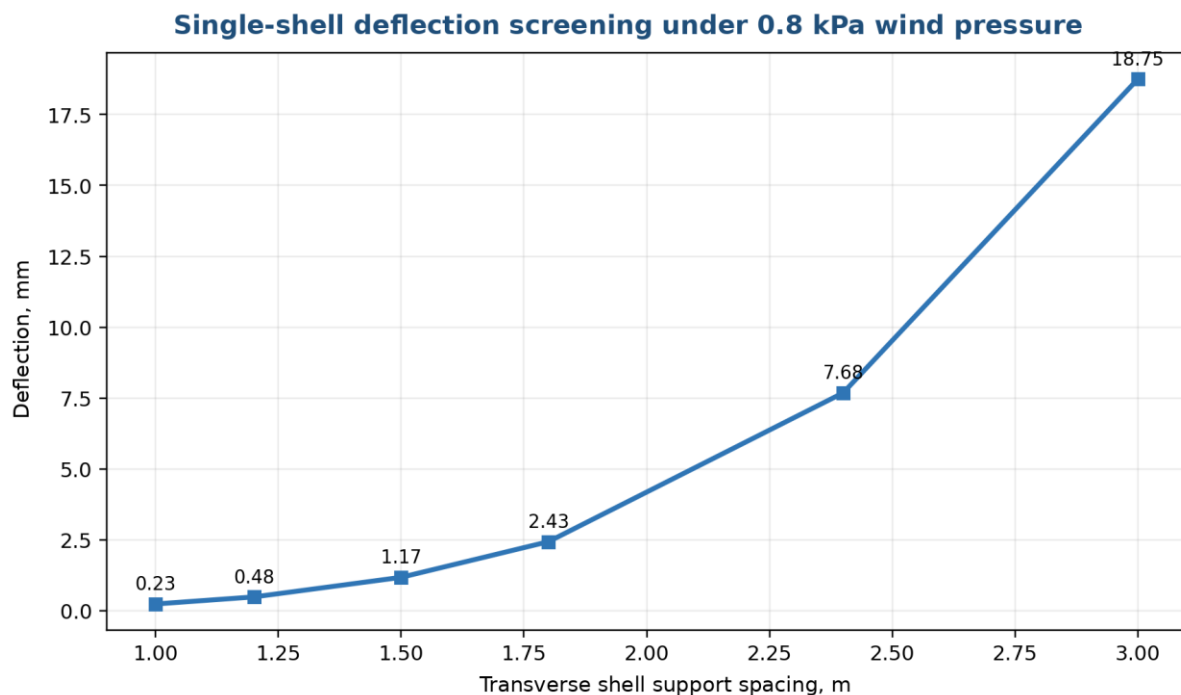


Figure 6 — Screening relationship between shell deflection and transverse support spacing

Table 8 — Reference results from wind-response screening

Parameter	L = 1.0 m	L = 1.5 m	L = 2.4 m	L = 3.0 m	Relationship
Maximum stress, MPa	0.67	1.50	3.84	6.00	Proportional to L^2
Maximum deflection, mm	0.23	1.17	7.68	18.75	Proportional to L^4

Note. The results apply to an idealised strip of a single 30 mm thick shell and do not account for interaction with the core and second shell, printing-path curvature or cracking.

6.4. Interlayer bond, shrinkage and contact with the core

The interlayer planes are the most vulnerable regions of the printed shell. The experiments reviewed in [9–18] show that longer interlayer intervals and surface dehydration can reduce bond, while the loading direction relative to the printing path affects the measured strength. Design flexural and tensile strengths must therefore be based on specimens cut from printed elements in several orientations, rather than on cast control cubes.

The shell–core interface can follow three scenarios: full bond; partial bond with slip; or separation due to shrinkage. An unsupported assumption of full composite action is particularly unsafe because it artificially increases model stiffness. Until interface shear and full-scale bending tests have been performed, a conservative assumption is that each shell resists local bending independently, while the core provides thermal insulation and limited transverse stabilisation.

Shrinkage and thermal strains differ between the layers. The dense cementitious shell, lightweight EPS concrete and composite frame have different moduli, thermal expansion coefficients and shrinkage kinetics. Crack limitation requires controlled printed-section lengths, movement joints, controlled moist curing, geometrically flexible inter-shell ties and details allowing movement relative to the frame. Quantitative parameters for these details should be addressed in the article on connections and in a separate cyclic testing programme.

7. Thermophysical Characteristics of the Wall

7.1. Baseline one-dimensional calculation

For the 30–190–30 mm section, with $\lambda_s = 0.80 \text{ W/(m}\cdot\text{K)}$ and $\lambda_c = 0.10 \text{ W/(m}\cdot\text{K)}$, the combined resistance of the two printed shells is $0.075 \text{ m}^2\cdot\text{K/W}$, the resistance of the EPS concrete core is $1.900 \text{ m}^2\cdot\text{K/W}$, and the total resistance including surface films is $2.145 \text{ m}^2\cdot\text{K/W}$. The calculated thermal transmittance of the homogeneous region, U_0 , is $0.466 \text{ W/(m}^2\cdot\text{K)}$. The lightweight core provides more than 88% of the total resistance; an error in its design thermal conductivity therefore affects U much more strongly than a comparable relative error in shell λ .

Table 9 — Components of thermal resistance for the baseline homogeneous region

Component	Thickness, m	λ , W/(m·K)	R, m ² ·K/W	Share of total R, %
Internal surface film	—	—	0.130	6.1
Inner printed shell	0.030	0.80	0.0375	1.7
EPS concrete core	0.190	0.10	1.900	88.6
Outer printed shell	0.030	0.80	0.0375	1.7
External surface film	—	—	0.040	1.9
Total	0.250	—	2.145	100.0

Note. $U_0 = 1/R = 0.466 \text{ W/(m}^2\cdot\text{K)}$. This value applies to the homogeneous wall field, excluding ribs, fixings, corners, reveals, joints and moisture effects.

The calculated value must be compared with the required resistance for the specific city, building use and energy strategy. Climate parameters must be selected from the applicable SHNK 2.01.01-22 data [44], and thermal protection requirements from the applicable edition of the national regulations [43]. No single regulatory upper limit for U is introduced in this article because it depends on project location and the regulatory assessment method.

7.2. Sensitivity to core thickness and thermal conductivity

The parametric range $\lambda_c = 0.08\text{--}0.20 \text{ W/(m}\cdot\text{K)}$ covers both an efficient dry lightweight material and a denser or moisture-affected core. Core thickness was varied from 100 to 500 mm. The U -value map shows a hyperbolic reduction in heat transfer as thickness increases and a rapid deterioration as λ increases. The effect of additional thickness is greatest for thin walls; at larger d_c , the absolute reduction in U for each additional 50 mm decreases.

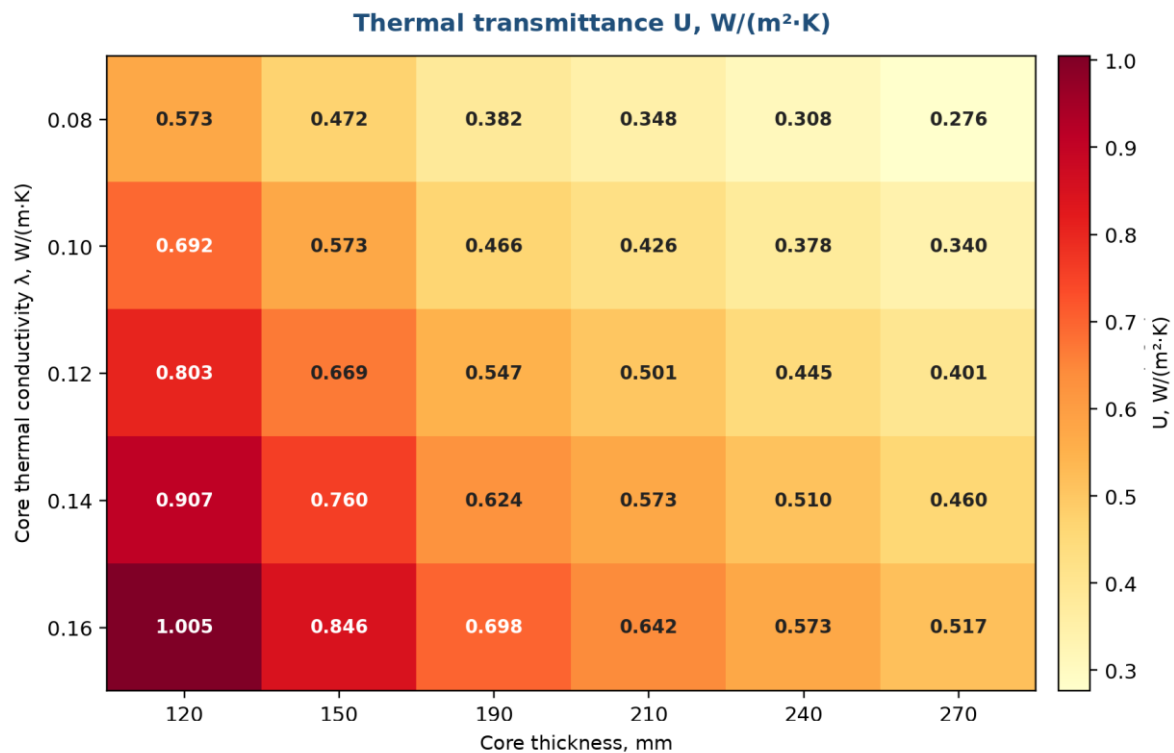


Figure 7 — Thermal transmittance of the homogeneous region as a function of core thickness and thermal conductivity

The inverse problem—selecting core thickness for a specified U -value—is useful during early design. For example, to achieve $U = 0.40 \text{ W}/(m^2 \cdot K)$, the required core thickness is approximately 180 mm at $\lambda_c = 0.08$ and

361 mm at $\lambda_c = 0.16 \text{ W}/(m \cdot K)$. Specifying the geometry before measuring thermal conductivity may therefore introduce an approximately twofold error in the required thickness.

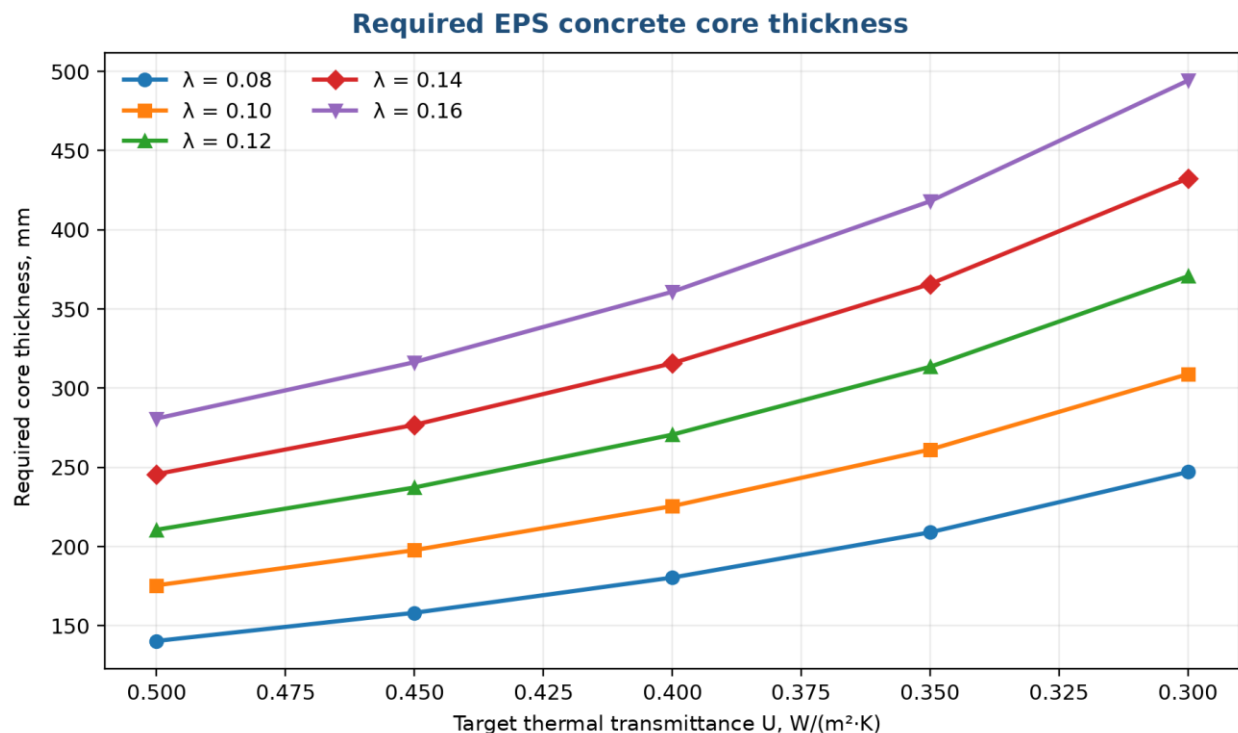


Figure 8 — Required EPS concrete core thickness for a specified thermal transmittance

Table 10 — Required core thickness, mm, for specified U and λ_c

Target U, W/(m ² ·K)	$\lambda_c = 0.08$	$\lambda_c = 0.10$	$\lambda_c = 0.12$	$\lambda_c = 0.14$	$\lambda_c = 0.16$
0.30	247	309	371	432	494
0.35	209	261	313	366	418
0.40	180	226	271	316	361
0.45	158	198	237	277	316
0.50	140	176	211	246	281

Note. The calculation retains two 30 mm shells, $\lambda_s = 0.80$ W/(m·K), $R_{si} = 0.13$ and $R_{se} = 0.04$ m²·K/W.

7.3. Effect of in-service moisture

EPS concrete is a porous cementitious composite whose in-service thermal conductivity depends on density, pore structure, moisture content and temperature. To avoid assigning an unverified moisture-dependence relationship to a specific mix, a dimensionless scenario

analysis was performed: core λ was increased by 10–40% relative to the dry baseline. With unchanged geometry, U increases from 0.466 to 0.624 W/(m²·K), or by 33.9%. Protection against precipitation, capillary rise and construction moisture is therefore part of energy performance, not merely a matter of finish durability.

Heat-transfer sensitivity to infill moisture effects

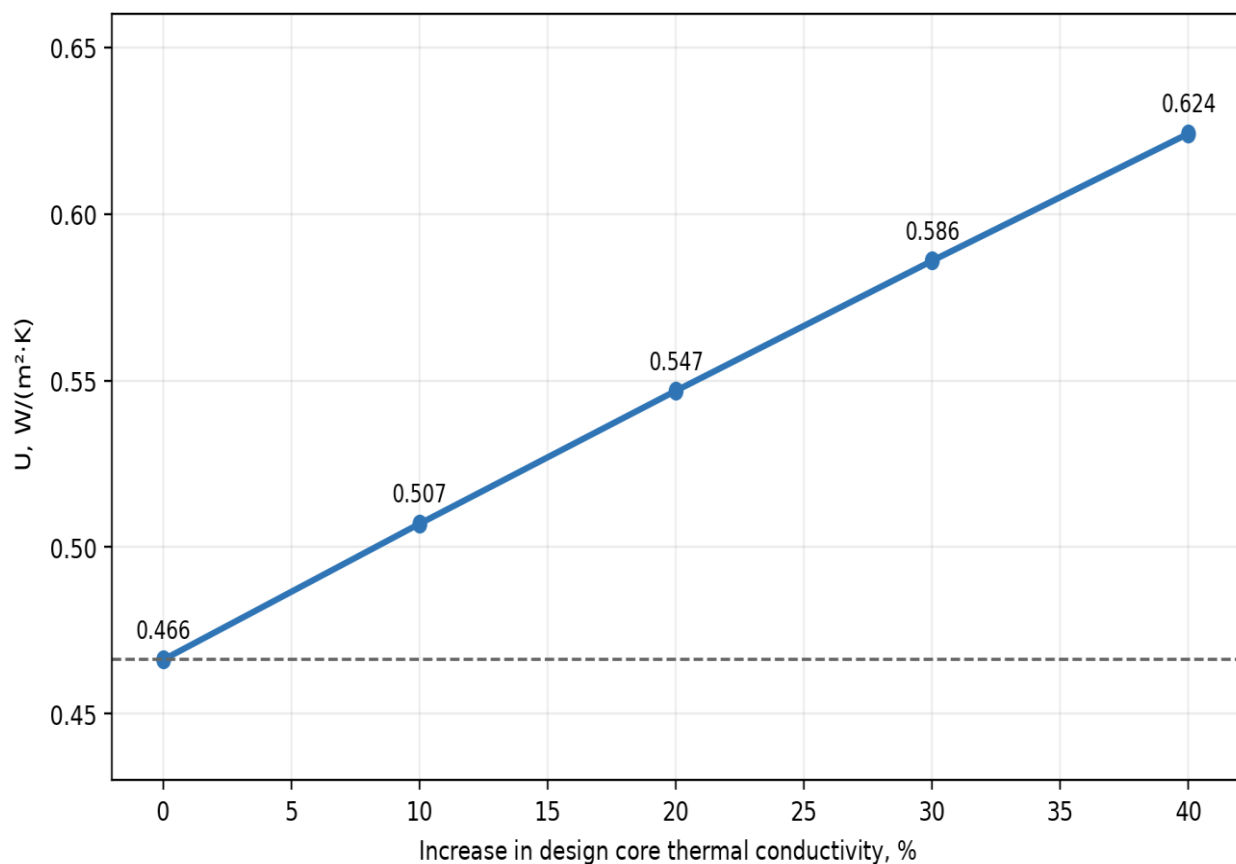


Figure 9 — Sensitivity of thermal transmittance to a moisture-related increase in core thermal conductivity

Table 11 — Scenario-based effect of increasing λ_c on heat transfer

Increase in λ_c from baseline	λ_c , W/(m·K)	U, W/(m ² ·K)	Increase in U, %	Interpretation
0%	0.100	0.466	0.0	Dry calculation baseline
+10%	0.110	0.507	8.8	Moderate deterioration
+20%	0.120	0.547	17.3	Substantial deterioration
+30%	0.130	0.586	25.7	High sensitivity
+40%	0.140	0.624	33.9	Moisture must not be ignored

The practical implication is the need to distinguish laboratory thermal conductivity of a dried specimen from the design thermal conductivity of a layer in the envelope. The verification programme should include λ measurements in at least dry and conditioned states and, where wetting is possible, after capillary saturation and freeze-thaw cycling. Residual construction moisture must also be controlled before the internal finish layers are closed.

7.4. Continuous ribs and thermal bridges

The least favourable geometry is a solid cementitious rib, 30 mm wide, connecting the outer and inner shells. For regular spacing s , the thermal-bridge-path fraction is taken as $f = 30/s$. Even the simplified parallel-path calculation shows that 300 mm spacing increases the equivalent U-value from 0.466 to 0.771 W/(m²·K), or by 65.5%. At 1200 mm spacing, the increase remains significant at 17.0%.

Effect of continuous ribs on equivalent heat transfer

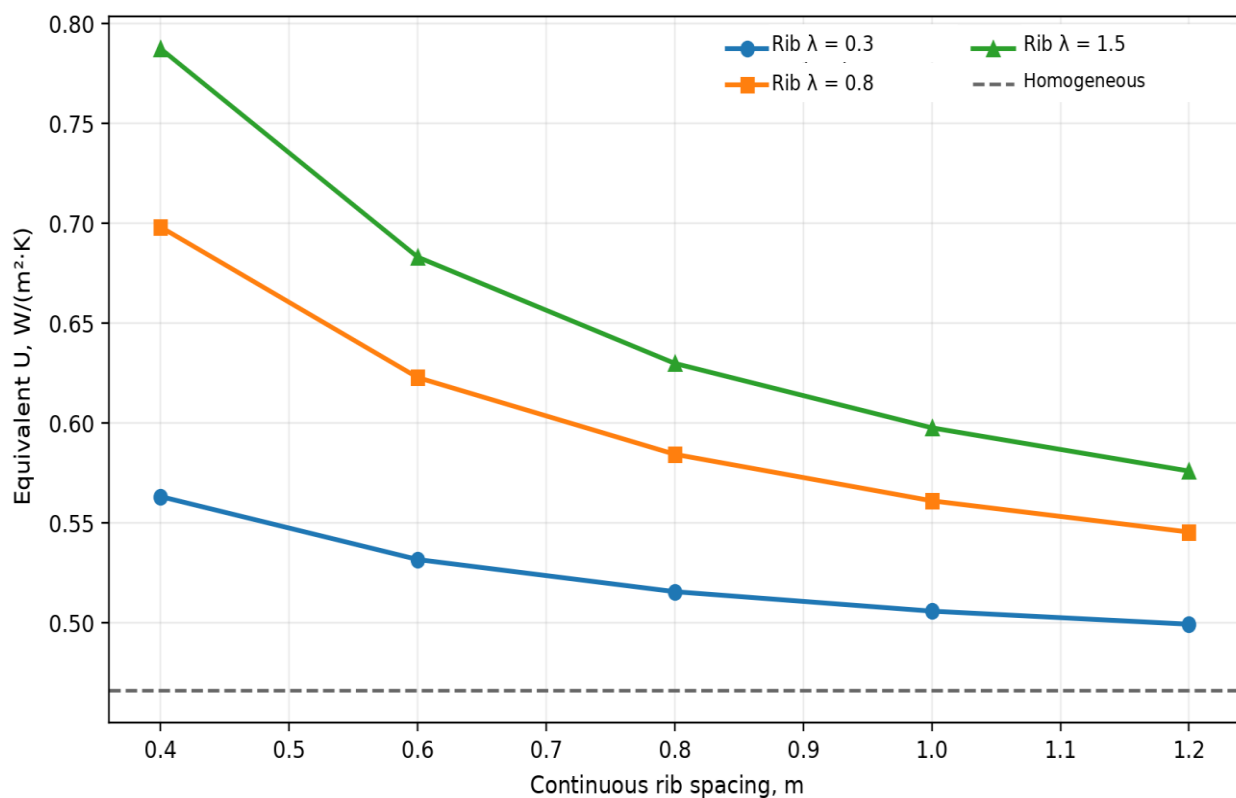


Figure 10 — Effect of continuous cementitious rib spacing on equivalent thermal transmittance

Table 12 — Screening assessment of regularly spaced continuous ribs 30 mm wide

Rib spacing, mm	Rib fraction f, %	Ueq, W/(m ² ·K)	Increase over U ₀ , %	Design assessment
300	19.00	0.771	65.5	Highly unfavourable
400	14.44	0.698	49.8	Unfavourable
600	9.75	0.623	33.6	Significant thermal bridge
800	7.36	0.584	25.4	Requires optimisation
1000	5.91	0.561	20.4	Still significant
1200	4.94	0.546	17.0	2D/3D analysis required

Note. The parallel-path method does not account for lateral spreading of heat flow. The final assessment must follow ISO 10211 using the actual connection geometry.

The result supports replacing closely spaced continuous cementitious webs with discrete ties of small cross-sectional area, discontinuous geometries, local composite connectors or a printing path that lengthens the heat-flow route. Thermal optimisation must not, however, reduce shell stability during printing and filling. Tie geometry is therefore a multicriteria problem requiring simultaneous control of pull-out, shear, shell opening, thermal bridging, printability and void-free cavity filling.

7.5. Internal surface temperature

For $T_i = +20\text{ °C}$ and $T_e = -10\text{ °C}$, the internal surface temperature of the homogeneous region is 18.18 °C and the temperature factor f_{Rsi} is 0.939. For an idealised solid cementitious path, the temperature falls to 11.92 °C and f_{Rsi} to 0.731. With an assumed critical surface temperature of 12.63 °C , the thermal-bridge region falls within a potential risk zone. The specific criterion must be determined from indoor humidity, room classification and the national method; the minimum θ_{si} must be obtained from a two-dimensional model.

The lower surface temperature at a rib has two consequences. First, local relative humidity and the risk of biological growth on the finish increase. Second, the temperature field becomes visibly non-uniform and may produce soiling streaks. Checking the area-averaged U-value alone is therefore insufficient. Acceptance of a prototype wall specimen should include thermography under a stable temperature difference and comparison with the calculated temperature map.

7.6. Heat storage capacity

For an indicative assessment of dynamic behaviour, specific heat capacities of 0.84 kJ/(kg·K) for the printing mix and 1.20 kJ/(kg·K) for EPS concrete were adopted. The calculated areal heat capacity of the wall is approximately $175.8\text{ kJ/(m}^2\cdot\text{K)}$: the shells contribute $95.8\text{ kJ/(m}^2\cdot\text{K)}$ and the core $79.8\text{ kJ/(m}^2\cdot\text{K)}$. This value characterises heat storage but is not equal to the effective internal heat capacity under daily fluctuations, because only part of the thickness participates in the dynamic response.

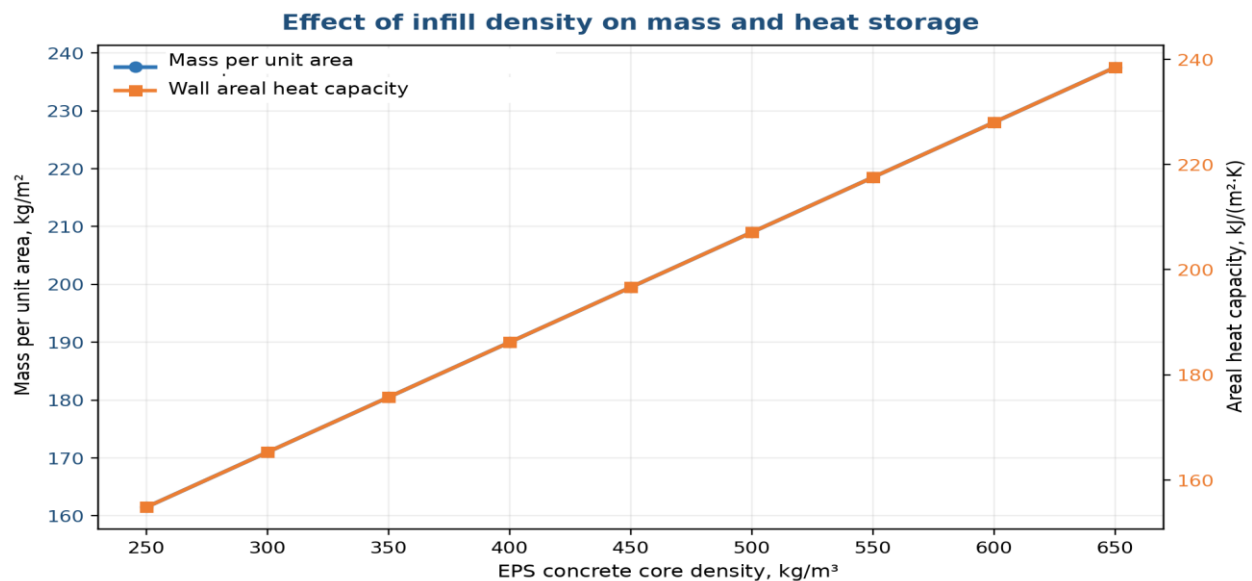


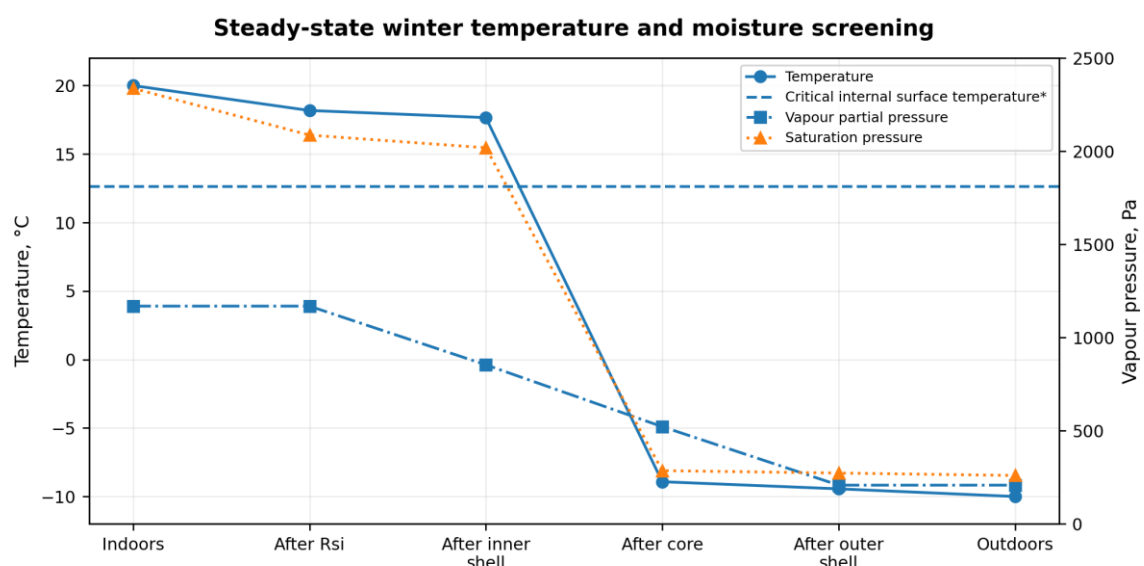
Figure 11 — Contribution of the layers to wall mass per unit area and calculated heat capacity

For $\lambda_s = 0.80 \text{ W/(m}\cdot\text{K)}$, $\rho_s = 1900 \text{ kg/m}^3$ and $c_s = 840 \text{ J/(kg}\cdot\text{K)}$, the shell thermal diffusivity is approximately $2.60 \cdot 10^{-7} \text{ m}^2/\text{s}$ and the penetration depth of a daily thermal wave is approximately 84 mm. Since each shell is 30 mm thick, the inner shell participates substantially in daily heat exchange, while the insulating core delays the transmission of external fluctuations. The exact time lag and decrement factor must be calculated dynamically under ISO 13786 [35] using measured thermophysical properties.

8. Moisture Resistance and Other In-Service Characteristics

8.1. Steady-state diffusion screening

Under the illustrative winter conditions $T_i = +20 \text{ }^\circ\text{C}$, $\phi_i = 50\%$, $T_e = -10 \text{ }^\circ\text{C}$ and $\phi_e = 80\%$, water vapour partial pressure decreases from 1169 Pa indoors to 208 Pa outdoors. At $\mu_s = 60$ and $\mu_c = 10$, the combined equivalent air-layer thickness of the three layers is 5.50 m. At the cold boundary of the core, the calculated temperature is $-8.92 \text{ }^\circ\text{C}$, the vapour partial pressure is approximately 522 Pa and the saturation pressure is approximately 286 Pa. The simplified model therefore indicates the possibility of interstitial condensation.



* The 12.6 °C threshold corresponds to the assumed limiting surface relative humidity of 80%.

Figure 12 — Distributions of temperature, vapour partial pressure and saturation pressure through the wall

Table 13 — Reference points in the steady-state moisture calculation

Position	Temperature, °C	p_v , Pa	p_{sat} , Pa	Calculated ϕ , %
Indoor air	20.00	1169	2338	50.0
Internal surface	18.18	1169	2087	56.0
After inner shell	17.66	854	2019	42.3
After EPS concrete core	−8.92	522	286	182.9
After outer shell	−9.44	208	273	76.1
Outdoor air	−10.00	208	260	80.0

Note. A value of ϕ above 100% indicates that the assumption of steady-state transport without phase change is violated. This calculation does not determine the amount of condensate or seasonal drying.

Formally adding a warm-side vapour-control layer with μ of approximately 16.7 m would reduce vapour partial pressure at the cold boundary to the saturation level under the assumed conditions. This value is not, however, a ready-to-use specification: the actual solution depends on external moisture protection, the wall's capacity to dry in both directions, climate, air-conditioning operation, construction moisture and air permeability. An incorrectly positioned vapour-impermeable layer can trap moisture.

Before selecting a design solution, transient modelling over at least an annual cycle is required, including rain, solar radiation and moisture-dependent properties, followed by verification of a prototype specimen using temperature and relative humidity sensors. The simplified ISO 13788 method explicitly excludes capillary transport and air leakage. A favourable or unfavourable steady-state result should therefore prompt further analysis rather than be treated as definitive evidence [34].

8.2. Capillary wetting and freeze–thaw resistance

The outer shell is exposed to wind-driven rain, splash water at the plinth and possible ingress through cracks. The EPS concrete core must be separated from the base by a capillary break and protected against direct water entry. The plinth detail must provide drainage, raise the moisture-sensitive core above the splash zone, and include continuous waterproofing and a repairable external system. The water absorption coefficient by partial immersion may be assessed under ISO 15148 [37], but the actual wall also requires spray testing of joints and connections.

Freeze–thaw resistance depends not only on the material grade but also on its degree of saturation at the time of freezing. Interlayer cracks and voids near webs can retain water locally, so testing a small homogeneous cube does

not cover the geometric defects of a printed element. The programme should include cycling of printed specimens in the most adverse orientation, mass monitoring, ultrasonic or other non-destructive testing, joint inspection and determination of residual flexural strength.

8.3. Air permeability and airtightness

The thermal resistance of the layers does not guarantee low infiltration. The most likely leakage paths are horizontal cold joints between printed sections, shell-to-frame junctions, electrical sockets, service penetrations, window reveals and movement joints. Airborne moisture transport through a gap may substantially exceed diffusion through the material. A continuous airtight layer must therefore be designed as an independent system, with a clearly identifiable line in every section. For the prototype building, envelope air-permeability testing with smoke or thermographic leakage localisation is advisable. The acceptance criterion should reflect the building use and climate, and the results should be compared with the log of printing defects and installation joints. This links the whole-building indicator to specific operations requiring correction rather than to “3D printing” in the abstract.

8.4. Fire resistance

Cementitious shells are potentially effective protective layers, but the fire resistance of a three-layer wall cannot be inferred solely from the non-combustibility of its surface. Possible cracking and spalling, thermal decomposition of the polymer infill, gas generation, cavity conditions, and the behaviour of fixings and movement joints must be considered. Integrity and insulation are the key criteria for a non-load-bearing envelope; any claimed load-bearing function additionally requires assessment of load-bearing capacity under fire.

Testing must be carried out on a full-scale specimen incorporating the actual joints, fixings and external finish, using the applicable fire-exposure procedure. The general principles of the standard temperature regime are specified in ISO 834-1 [40]. Before such testing, only a hypothesis regarding the shell's protective role is justified; a specific EI or REI fire-resistance rating must not be declared.

8.5. Sound insulation

Sound insulation was assessed preliminarily using the mass law for a homogeneous infinite plate with a mass per unit area of 180.5 kg/m^2 . The calculated transmission loss increases from approximately 40.1 dB at 125 Hz to 64.1 dB at 2000 Hz. These values are not an R_w index: the model excludes double-shell resonance, core elasticity, coincidence effects, flanking transmission, joints and openings.

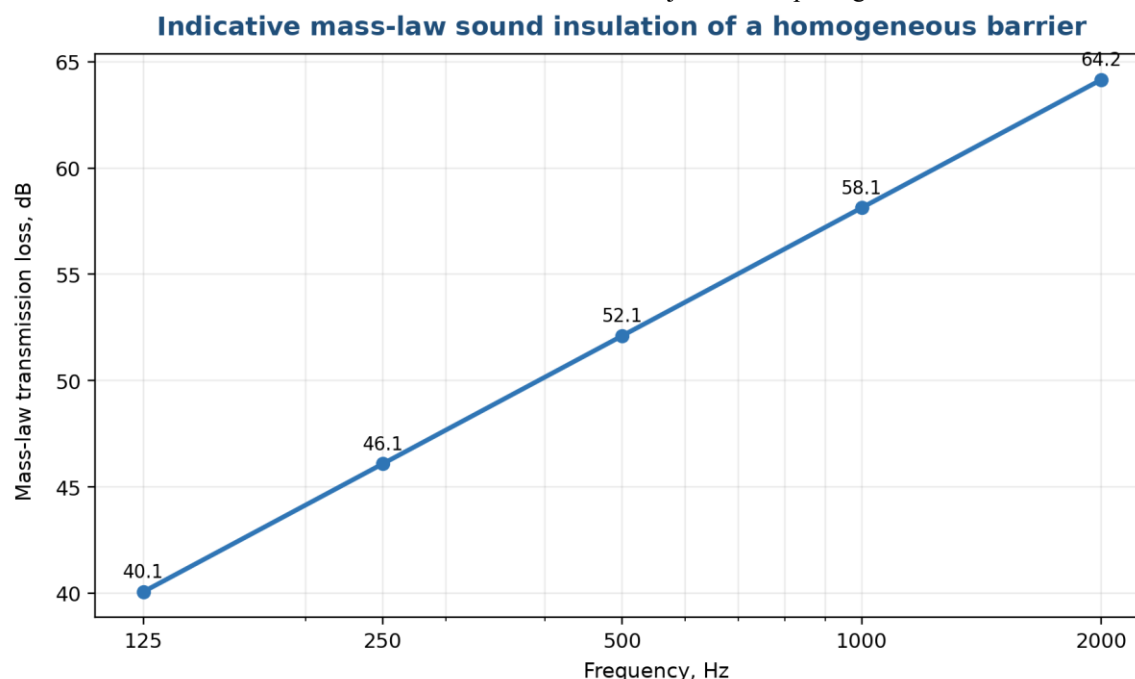


Figure 13 — Indicative mass-law sound transmission loss for the baseline mass per unit area

Table 14 — Screening indicators of in-service performance and required verification

Characteristic	Calculated indicator	Required verification	Methodological reference
Heat transfer	$U_0 = 0.466 \text{ W/(m}^2\cdot\text{K)}$	U of specimen including bridges and connections	ISO 9869-1; ISO 8990
Surface temperature	18.18 °C; 11.92 °C at rib	Minimum θ_{si} at 2D/3D details	ISO 10211
Moisture conditions	Risk at cold core boundary	Annual balance and drying	ISO 13788 plus transient model
Heat capacity	$175.8 \text{ kJ/(m}^2\cdot\text{K)}$	Dynamic wall response	ISO 13786
Sound insulation	40.1–64.1 dB by mass law	Frequency response and R_w	ISO 10140-2; ISO 717-1
Air permeability	Not calculated	Airtightness of details and building	In-situ testing
Fire resistance	Not declared	Integrity and insulation	ISO 834-1 and applicable procedure

Laboratory sound-insulation testing should use a full-size panel incorporating a window or service detail

where it is representative. The frequency response measured under ISO 10140-2 [41] should be converted

to a single-number rating under ISO 717-1 [42]. Flanking transmission through the composite frame and rigid transverse ties must be investigated separately, because the lightweight frame and inhomogeneous envelope may create transmission paths that are absent from the mass-law model.

9. Multicriteria Assessment of Design Options

9.1. Options compared

To move from individual calculated indicators to a design choice, five concepts were compared: a solid printed wall; an unfilled hollow double-shell wall; the baseline wall with EPS concrete; the same wall with closely spaced continuous cementitious ribs; and an optimised

wall with discrete ties and an interrupted direct heat-flow path. A scale of 1 to 5 was used, with 5 representing the preferred outcome. The scores constitute engineering screening rather than a statistically validated ranking.

The criteria include thermal protection, mass per unit area, construction stability during filling, controllability of quality, repairability and thermal-bridge risk. No weights were deliberately assigned because their selection depends on climate and building use. Thermal protection and moisture safety may dominate in a cold climate, whereas ease of quality control and a minimum number of wet processes may receive greater weight on a remote site.

Table 15 — Qualitative multicriteria matrix of wall options

Option	Thermal protection	Low mass	Stability during fabrication	Quality control	Low bridge risk	Total / 25
A. Solid printed wall	1	1	4	4	5	15
B. Two shells with an air cavity	2	5	3	3	4	17
C. Shells plus EPS concrete	4	4	4	4	4	20
D. Option C with closely spaced solid ribs	3	4	5	4	1	17
E. Option C with discrete thermally decoupled ties	5	4	4	3	5	21

Note. The scores are intended solely to select the direction of further development. They should be refined using test results, costs and project-specific requirements.

9.2. Preferred structural configuration

The combined screening criteria favour the option with an EPS concrete core and discrete thermally decoupled ties. Its advantage results not from a single material but from coordinated functional separation: the shells provide form and protection, the lightweight core provides the principal thermal resistance, and local ties maintain geometric stability while minimising the thermal-bridge area. Nevertheless, option E requires particularly careful verification of the fixings, since reducing tie area increases local stresses and sensitivity to installation defects.

The following geometric principles are recommended for further development: eliminate direct solid cementitious webs; lengthen the heat-flow path using a zigzag geometry; use discrete GFRP or other low-conductivity connectors; provide local reinforcement only at supports

and openings; design channels for filling and void inspection; provide a continuous internal airtight layer; and use external moisture protection that allows the assembly to dry.

10. Experimental and Numerical Verification Programme

10.1. Verification framework

The programme follows the sequence material–interface–element–connection–wall specimen–building. Progression to the next level is permitted only after the properties at the preceding level have been confirmed and their variability recorded. This prevents satisfactory cube strength from being misinterpreted as sufficient wall reliability when the actual limit state is governed by an interlayer joint, an infill void or a fixing.

Hierarchy of experimental and in-situ verification

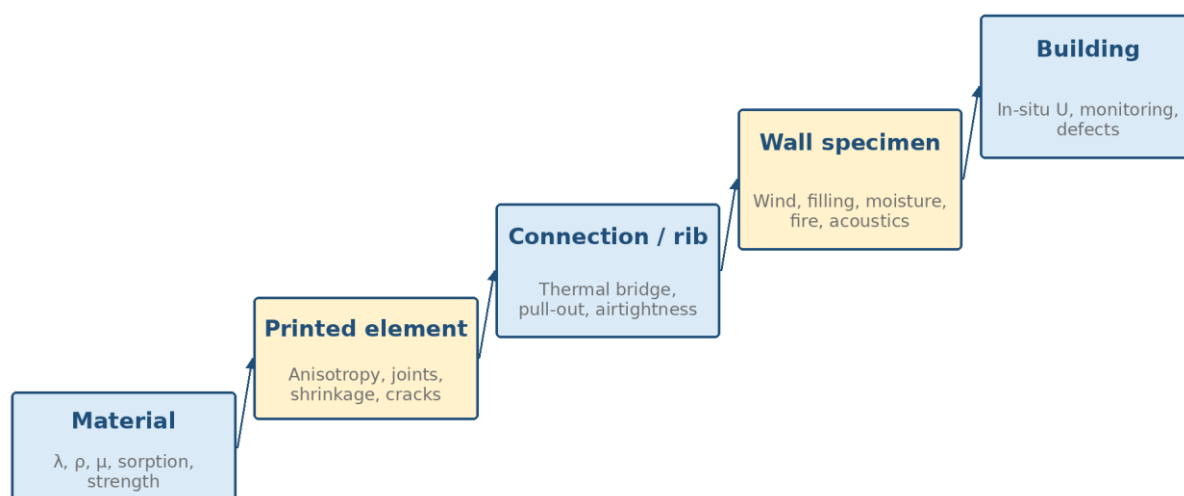


Figure 14 — Hierarchy of experimental and numerical verification of the wall system

10.2. Testing of materials and interfaces

The printing mix requires assessment of rheological suitability, layer shape stability, early-age strength and modulus at the actual filling age, compressive, flexural and direct or indirect tensile strength in three orientations, elastic modulus, shrinkage, density, water absorption, water vapour permeability and thermal conductivity. Specimens must be cut from printed blocks. Cast control specimens should serve as a reference, not as the sole source of design properties.

For EPS concrete, mandatory properties include fresh and dry density, delivery rheology, actual filling ability in narrow cavities, thermal conductivity at different moisture contents, shrinkage, strength, modulus, and sorption and capillary characteristics. The shell–core interface is investigated by shear and pull-off testing and cyclic hygrothermal exposure. Inter-shell connectors and embedded items are tested separately for pull-out, shear and creep.

10.3. Testing of elements and full-scale specimens

Three series are proposed at element level. The first comprises shell strips and panels under transverse bending, including cold joints and different interlayer intervals. The second comprises specimens at least one storey high subjected to staged filling, with measurements of pressure, shell opening and deformation. The third comprises filled panels subjected to cyclic wind-simulating pressure and suction, with monitoring of cracking, residual deflection, fixing pull-out and airtightness.

The thermal specimen must include a typical rib, vertical and horizontal joints, a corner, a window reveal and a connection to the composite frame. Laboratory or in-situ heat-transfer measurements under ISO 8990 or ISO 9869-1 [38, 39] are compared with the 2D/3D model. Once calibrated, the model may be used for options that cannot all be tested, but only within the validated range of geometry and properties.

Table 16 — Minimum experimental verification matrix

Level	Object	Varied factors	Measured indicators	Purpose
1. Material	Printing mix	Orientation, interlayer interval, age	fc, ft, ff, E, shrinkage, ρ, λ, μ	Shell design properties
1. Material	EPS concrete	Density, moisture content, age	ρ, λ, E, shrinkage, water absorption	Core properties
2. Interface	Interlayer joint	Interval, drying, treatment	Strength and fracture energy	Shell anisotropy
2. Interface	Shell–core	Roughness, filling age	Pull-off, shear, slip	Contact model
3. Element	Shell during filling	Tie spacing, lift height	Pressure, stresses, deflection, cracks	Process specification

Level	Object	Varied factors	Measured indicators	Purpose
3. Element	Filled panel	Wind $\pm$, number of cycles	Stiffness, strength, residual deflection	Service behaviour
4. Connection	Frame fixing	Eccentricity, gap, cycling	Pull-out, shear, bearing, displacement	Connection analysis and detailing
5. Wall specimen	Corner/window/joint	Temperature, humidity, rain	U, θ_{si} , leakage, wetting	Envelope validation
6. Building	Prototype house	Seasonal operation	Heating demand, indoor conditions, defects	System verification

10.4. Numerical model and calibration criteria

The mechanical finite element model must include orthotropic or layered shell properties, contact with the core, discrete ties and cracking nonlinearity. Calibration proceeds from strip bending to the filled panel and then to the fixing detail. Permissible discrepancies should be specified before the results are examined; for example, no more than 10–15% for stiffness and 15–20% for ultimate load, provided the failure mechanism is reproduced correctly. Matching a single maximum force while predicting an incorrect deformation pattern does not constitute validation.

The thermal model is constructed in 2D/3D with a mesh-convergence study, measured λ -values and boundary heat-transfer coefficients. Calibration uses heat flux and temperatures at no fewer than three representative points,

including a thermal-bridge region. The moisture model is checked against the time-dependent relative humidity and temperature within the core over a seasonal cycle. Parameters should not be fitted simultaneously without ensuring identifiability; each property should preferably be measured in an independent test.

10.5. Quality control in production and on site

Quality control must be linked to a digital process record. For each wall section, the record should retain the mix-batch identifier, ambient temperature and humidity, printing time of each layer, pauses, delivery rate, toolpath, nozzle height, actual geometry, filling time and control-specimen results. This provides traceability from a building defect to a process event and follows the process-based approach to additive construction qualification [2].

Table 17 — Proposed in-process quality-control plan

Operation	Controlled parameter	Control method	Action on deviation
Mix preparation	Flow spread, temperature, density, time	Rapid test and batch log	Prohibit printing or adjust under an approved procedure
Layer printing	Width, height, toolpath position	Camera/scanner, reference marks	Stop and classify the defect
Interlayer interval	Time and surface condition	Automatic log, visual inspection	Treat the joint or reject the printed section
Curing	Temperature, RH, wind/sun protection	Microclimate sensors	Adjust the curing regime
Tie installation	Spacing, embedment, position	Template, photographs	Add a tie or repair
Core filling	Density, lift height, pressure	Level marks, pressure sensors	Stop delivery and allow curing
Void inspection	Filling continuity	Endoscopy/ultrasound/thermography	Local supplementary filling under the procedure
Sealing	Joint continuity and adhesion	Inspection, pull-off test, smoke	Repeat preparation and sealing
Acceptance	U/ θ_{si} , air permeability, cracks	Sensors, thermography, in-situ test	Repair and retest

11. Discussion

11.1. Comparison with contemporary research

The relationships obtained are consistent with the general direction of research on 3D-printed envelopes: complex cavity geometry alone does not ensure low heat transfer. Infill thermal conductivity, the proportion of cementitious webs and insulation continuity are decisive. In a numerical study of 32 printed-wall configurations, cavity insulation substantially improved energy performance, whereas uninsulated options failed to meet the adopted requirements [20]. The present work extends this approach to a three-layer assembly with a cast-in-place EPS concrete core and separately demonstrates sensitivity to moisture and regularly spaced ribs.

The experimental characterisation of printed cementitious mortar in [18] confirms the need to measure not only mechanical but also hygrothermal properties of the specific material. This is fundamental to the proposed wall: a 20% increase in core λ increased U by 17.3%, while continuous ribs at 600 mm spacing produced a further 33.6% increase in the simplified assessment. Optimising the mix without optimising the geometry, or the geometry without controlling moisture, therefore does not ensure consistent performance.

The mechanical assessment supports findings from interlayer-bond research: process parameters cannot be separated from design properties [10, 11, 17]. The RILEM interlaboratory programme, involving dozens of laboratories and thousands of results, identified substantial scatter and the need for repeated tests, consistent orientation rules and process documentation [15, 16]. Accordingly, the proposed method measures early-age shell strength at the actual filling interval and links the permissible lift height to the batch test result.

11.2. Governing parameters

The parametric analysis identified four governing groups. The first comprises early-age shell properties and transverse-tie spacing, which control filling safety. The second comprises core λ and moisture content, which control the area-averaged U -value. The third is the geometry of through-thickness ties, which controls thermal bridging and local surface temperature. The fourth is continuity of the airtight and water-protective layers, which cannot be reliably predicted by material calculations alone.

The strongest nonlinearity is associated with shell span: deflection increases as L^4 . A small increase in tie spacing intended to reduce thermal bridges can therefore markedly worsen construction-stage and wind performance. The rational solution is not simply to move

cementitious ribs farther apart, but to change their material and shape, introduce temporary removable ties during filling, and retain relatively sparse discrete connectors in service.

11.3. Practical significance for low-rise construction

The proposed wall combines automated forming, relatively low mass and an insulating core produced directly on site. For a low-rise building, this reduces the need for heavy lifting equipment and permits architectural variation without bespoke formwork. Economic benefits, however, are realised only with standardised connection details, a consistent mix and digital control; otherwise, costs shift from formwork to repair, inspection and reworking.

The numerical example also shows that a 250 mm thickness is not a universal solution. At $\lambda_c = 0.10$ W/(m·K), it provides $U_0 = 0.466$ W/(m²·K), but the required thickness may differ with climate and target energy use. The structural system should permit the core thickness to be scaled without changing the basic shell-fixing concept or introducing new continuous thermal bridges.

12. Limitations of the Study

All numerical results relate to the illustrative geometry and assumed parameter set. No physical tests of the specific printing mix, EPS concrete, interfaces or fixings were performed. The stated strengths, moduli, thermal conductivities and vapour permeabilities therefore cannot be used as design properties. The shell is analysed using a linear-elastic strip model that excludes orthotropy, cracking, creep, geometric imperfections and three-dimensional behaviour.

The one-dimensional thermal calculation describes only the homogeneous wall field. The parallel-path rib assessment is a screening method; corners, reveals, fixings and junctions require 2D/3D analysis. The steady-state diffusion model excludes rain, capillarity, sorption and air leakage. The acoustic mass-law calculation does not provide R_w , and fire resistance was not calculated. Technical, economic and environmental indicators are addressed in a separate article in the series. Despite these limitations, the model is suitable for identifying sensitivity and planning experiments. Its value lies not in declaring a finished product but in establishing testable relationships between geometry, construction processes, properties and in-service criteria.

13. Conclusions

The numerical parametric study supports the following conclusions:

- The three-layer wall must be treated as a system whose functions change over time. The printed shells act as permanent formwork during filling and as protective envelope layers in service, while an independent composite frame carries the vertical building loads.
- For the baseline 30–190–30 mm section, the calculated mass per unit area is 180.5 kg/m², of which the two printed shells account for 63.2%. Self-weight must be transferred to designed supports rather than solely through adhesion and guide fixings.
- At a fresh infill density of 450 kg/m³, a dynamic factor of 1.20 and a lift height of 0.60 m, the maximum pressure is 3.18 kPa. For a shell span of 0.60 m, $\sigma_{\max} = 0.954$ MPa and $w_{\max} = 0.397$ mm.
- The permissible continuous filling height varies linearly with early-age flexural strength and inversely with the square of tie spacing. For $f_c = 0.8$ –2.0 MPa, the calculated $h_{\max}$ range is 0.503–1.258 m, supporting operation-specific control of early-age strength.
- Wind screening identifies high deflection sensitivity to support spacing: increasing L from 1.0 to 3.0 m increases the deflection of one shell from 0.23 to 18.75 mm. Thermal-bridge optimisation must not be achieved simply by increasing the span without changing the tie system.
- For the homogeneous region of the baseline wall, $R = 2.145$ m²·K/W and $U_0 = 0.466$ W/(m²·K). The EPS concrete core provides the principal resistance, making its in-service thermal conductivity the governing parameter.
- A scenario-based increase in core λ of 10–40% increases U by 8.8–33.9%. Protection against construction moisture, precipitation and capillary rise is necessary to maintain the calculated energy performance.
- Continuous cementitious ribs are critical thermal bridges. For 30 mm wide ribs at 300–1200 mm spacing, the simplified U_{eq} exceeds U_0 by 17.0–65.5%. Discrete low-conductivity ties and a longer heat-flow path are preferable.
- The steady-state winter calculation identifies potential condensation at the cold boundary of the core. A transient moisture model, measured μ -values and sorption properties, and prototype monitoring are required. The calculated $s_d \approx 16.7$ m is not a ready-to-use vapour-barrier specification.

- Fire resistance, sound insulation, airtightness and durability cannot be inferred solely from the layer composition. A hierarchical testing programme from the material and interface to full-scale details and a prototype building is proposed for verification.
- The preferred development direction is a wall with an EPS concrete core, discrete thermally decoupled ties, separate self-weight supports and deformation-decoupled attachment to the composite frame.

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