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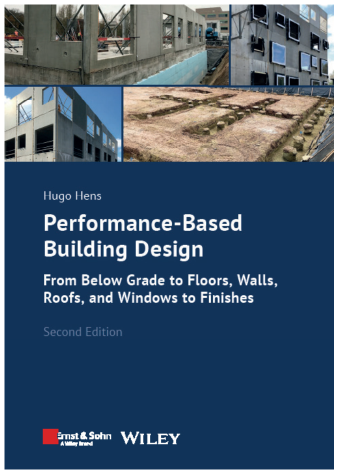

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Preface

Before the energy crises of the 1970s, designing buildings based on performance was hardly an issue. It was an art. However, together with the move towards more energy efficiency after 1973, the interest in handling a performance approach grew. The book "Applied Building Physics" forwarded an overall rationale at the whole building and building assembly level, for the last with emphasis on the heat, air, moisture requirements and metrics.

This third book in this series of three dealing with building physics and its application looks to the impact a performance requirement-linked approach has on building design and construction. It starts with a resumption of what is expected from buildings, followed by discussing a range of materials needed to guarantee a correct heat, air and moisture response. Then, the focus turns to preparing the building site, the excavations needed, the foundations, the below-grade parts and spaces, the structural systems commonly used, the floors, different types of outer walls, different types of roof assemblies, the glazing, windows, outer doors, glass façades, inside walls, balconies, all kind of shafts, chimneys, stairs, timber-frame construction, wall, floor and ceiling finishes. The whole book ends with looking to the risks deficiencies may cause.

Each time again, not only the heat, air and moisture-related metrics but also structural integrity, acoustics, durability, fire safety, maintenance, sustainability and buildability are discussed. To do so, besides years of teaching, research and curing damage cases due to failing performance, a bunch of national and international sources and literature has been consulted, which is why each chapter ends with an extended has read list.

The book uses SI units. It could be of help for undergraduate and graduate students in architectural and building engineering, although also practicing building engineers, who want to refresh their knowledge, may benefit. It is presumed that the reader has some background in structural engineering, building physics, building materials and building construction.

Acknowledgements

The book reflects the work of many, not only of the author. Therefore, we thank the thousands of students we had during 38 years of teaching. They gave us the

opportunity to test the content. The book should also not have been written the way it is if not standing on the shoulders of those who preceded. Although we started our career as a structural engineer, our predecessor Professor *Antoine de Grave* planted the seeds that fed the interest in building physics. The late *Bob Vos* of TNO, the Netherlands, and *Helmut Künzel* of the Fraunhofer Institut für Bauphysik (IBP), Germany, showed the importance of experimental work and field testing to understand building performance, while the late *Lars Erik Nevander* of Lund University, Sweden, taught that solving problems in building physics does not always ask complex modelling, mainly because reality in building construction is much more complex than any model can simulate.

During the four decades at the Unit of Building Physics and Sustainable Construction within the Department of Civil Engineering of the KU Leuven, several researchers, then PhD-students, got involved. They all contributed by the topics chosen to the advancement of the research done at the unit. Most grateful I am to *Gerrit Vermeir*, my colleague from the start in 1975 and professor emeritus now, to *Staf Roels*, *Dirk Saelens*, *Hans Janssen* and *Bert Blocken*, who succeeded me as professors at the unit.

The experiences gained as a structural engineer and building site supervisor for a medium-size architectural office the first 4 years of my career, as building assessor during some 50 years, as researcher and as operating agent of four IEA, Executive Committee on Energy in Buildings and Communities Annexes forced me to rethink the engineering-based performance approach each time again. The many ideas exchanged in Canada and the USA with Kumar Kumaran of NRC, the late *Paul Fazio* of Concordia University in Montreal, *Bill Brown*, *William B. Rose* of the University of Illinois in Urbana-Champaign, *Joseph Lstiburek* of the Building Science Corporation, *Anton Ten Wolde* and those participating in ASHRAE TC 1.12 'Moisture management in buildings' and TC 4.4 'Building materials and building envelope performance' were also of great value.

Finally, I thank my family, my wife *Lieve*, who managed living together with a busy engineering professor, our three children, our children in law and our grandchildren.

Leuven, October 2023 *Hugo S.L.C. Hens*

About the Author

Dr Ir. Hugo S.L.C. Hens is an emeritus professor at the University of Leuven (KU Leuven), Belgium. Until 1972, he worked as a structural engineer and site supervisor at a mid-sized architectural office. After the sudden death of his predecessor and promotor, Professor A. de Grave in 1975 and after defending his PhD thesis, he stepwise built up the Unit of Building Physics at the Department of Civil Engineering.

He taught building physics from 1975 to 2003, performance-based building design from 1975 to 2005 and building services from 1975 to 1977 and 1990 to 2008. He authored and co-authored 68 peer-reviewed journal papers and 174 conference papers about the research done, has helped to manage hundreds of building damage cases and acted as coordinator of the CIB W40 working group on heat and mass transfer in buildings from 1983 to 1993. Between 1986 and 2008, he was the operating agent of Annexes 14, 24, 32 and 41 of the IEA EXCO on Energy in Buildings and Communities. He was holder of the prestigious Franqui Chair at the Free University Brussels (VUB) in 2006 and is a fellow of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE).

2.2.3 Other Properties

2.2.3.1 Mechanical

Due to their very high porosity, insulation materials only have limited strength and stiffness. When loaded, many behave like mattresses. The low stiffness also incurs creep, relaxation and sometimes instability. Through that, insulation materials are hardly suited for load-bearing functions. Of course, some applications require mechanical performance. Insulation in floors and foundations needs enough compressive strength, and insulation in sandwich panels needs enough shear strength.

2.2.3.2 Moisture

Most insulation materials are non-hygroscopic. The quite large cells in fact are limiting the specific surface that could adsorb vapour, while capillary condensation requires nearly 100% RH. Closed-cell insulations are even impervious to water. Limited vapour diffusion across an insulation material and hardly any condensation risk in the cells themselves require a high vapour resistance factor, which again favours the closed-cell types. Fibrous insulation materials instead are really vapour-permeable, pervious to water and only non-capillary if the binder used is hydrophobic. Whether moist insulation materials lose strength and stiffness, degrade biologically or rot depends on the matrix material.

2.2.3.3 Air

Good air tightness requires closed cells. No problem with foams. Fibrous insulation materials instead are extremely air-permeable.

2.2.3.4 Temperature, IR and UV

The resistance against IR and UV depends on the type of matrix material. Organic and synthetic insulations may not behave that well, while inorganic ones hardly suffer.

2.2.3.5 Fire

The type of matrix material is again responsible. The organic and synthetic insulating foams could be flammable.

2.2.4 Insulating Building Materials

2.2.4.1 How Characterized?

Insulating building materials combine quite a low thermal conductivity when dry with an acceptable load-bearing capacity. To characterize them, the following schedule is used:

Short description

Properties	Density, thermal, hygric, air, strength and stiffness
Behaviour	Under mechanical load, sensitivity to temperature, IR and UV, under moisture load, when exposed to fire, other if relevant
Application	Where and how

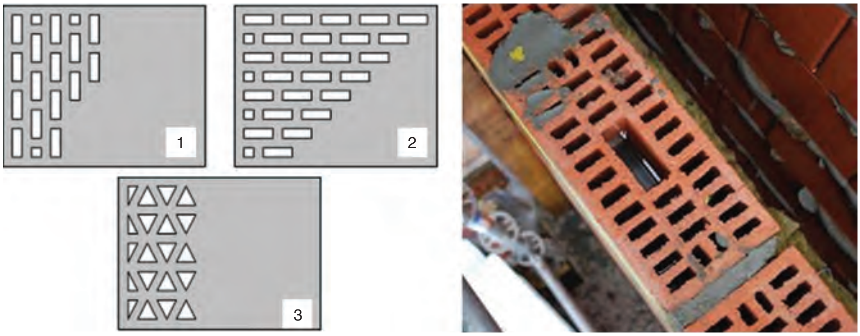

Figure 2.1 Perforation patterns in quick building bricks: (2) and (3) are better than (1).

2.2.4.2 Lightweight Brick Masonry

Getting brick masonry with high thermal resistance requires large, low-density bricks that combine a light potsherd with optimal perforation patterns (Figure 2.1).

Being large gives the coupled benefit of fewer joints per m^2 to be filled with insulating mortar. Of course, extra thickness is also helpful. As for the size, after World War II, quick building bricks, $L \times W \times H = 29 \times 14 \times 14$ or $= 29 \times 19 \times 14$ cm stepwise replaced the traditional $19 \times 9 \times 6.5$ cm massive brick. A lighter potsherd is obtained by adding sawdust or polystyrene pearls to the clay during mixing. When fired, the sawdust carbonizes and the polystyrene sublimates. The result is a cloud of macropores lowering the density considerably. The staggered top–down perforations are at the same time elongating the transmission path, while in the insulating mortar, perlite or vermiculite granules replace a part of the sand normally used.

2.2.4.2.1 Properties

Density	Between 750 and 880 kg/m^3. Dense brickwork weighs up to 2000 kg/m^3
Thermal	
Specific heat capacity	Dry 840 J/(kg K), independent of density
Thermal resistance	0.5 m^2 K/W for a 14 cm thick lightweight quick building brick wall with a density of 900 kg/m^3, whereas a 14 cm normal quick building brick wall only gives 0.28 m^2 K/W. Some 29 cm-thick extra-lightweight quick-building brick walls may even give 1.7 m^2 K/W.
Hygric	
Moisture content	Bricks are hardly hygroscopic.
Diffusion thickness	Due to badly filled joints and microcracks around the bricks, any masonry mostly shows a lower diffusion thickness than the brick has. An estimate is $\mu \approx 5d$, with d the wall thickness in m.
Capillary water absorption coefficient	From very moderate (0.05 $kg/(m^2\ s^{0.5})$) to high (0.8 $kg/(m^2\ s^{0.5})$), depending on the brick's porous structure.

Figure 2.2 Aerated concrete: blocks and an industrial premise, built with elements.

2.2.4.2.2 Application Lightweight quick-building bricks are well suited as inner leaf of cavity walls. When used for massive walls, a rain-tight outside render is necessary. Anyhow, looking at the actual requirements, their thermal conductivity is too high to replace thermal insulation. Also not negligible are the embodied energy and CO_2. Happily, service life can easily pass a century.

2.2.4.3 Lightweight Concrete, Aerated Concrete

A step towards insulating concrete consisted of replacing the gravel normally used by furnace slag, expanded clay, perlite or polystyrene pearls. Density, apparent thermal conductivity, strength and stiffness dropped, while shrinkage and creep increased. Anyhow, much more effective is to skip any addition and use gas formation to foam the sand/mortar mixture in an autoclave. The result is aerated concrete, thermally by far the best and available in $59.5 \times 29.5 \times 29.5\ \text{cm}^3$ large blocks or in ready-to-use façade and roof elements (Figure 2.2). Even more, its porous structure allows sawing and milling.

2.2.4.3.1 Properties

Density	While 'normal' concrete weighs $\approx 2200\ \text{kg/m}^3$, for expanded clay concrete it is $1600\ \text{kg/m}^3$ if structurally applied and $650\ \text{kg/m}^3$ if used otherwise. For polystyrene concrete, it is $260\ \text{kg/m}^3$ when used as post-fill to $800\ \text{kg/m}^3$ for other uses, while for aerated concrete, it is $350–800\ \text{kg/m}^3$.
Thermal	
Specific heat capacity	Dry 840 J/(kg K), whatever the density may be.
Thermal conductivity	For normal concrete, standards give 1.6–2 W/(m K) as 'dry value', measurements gave 2.6 W/(m K). For $600 < \rho < 1200\ \text{kg/m}^3$ heavy expanded clay concrete, it drops to: $\lambda = 0.024 \exp(0.0027\rho)$. $250 < \rho < 800\ \text{kg/m}^3$ heavy olystyrene concrete gives: $\lambda = 0.041 \exp(0.00232\rho)$ $450 < \rho < 620\ \text{kg/m}^3$ heavy aerated concrete guarantees: $\lambda = 0.12 + 0.000375\rho$

Hygric	
Moisture content	The cement gel turns concrete into a hygroscopic material
Diffusion thickness	Drops with decreasing density and increasing moisture content.
Capillary water absorption coefficient	The second digit behind the decimal point differs from zero.
Strength and stiffness	Despite its low density, constructing 4–5 storey-high buildings with aerated concrete blocks is doable.

2.2.4.3.2 Behaviour

Under moisture load	The lower the density, the higher the hygric shrinkage. The reason is less particle resistance when passing from gravel over expanded clay and polystyrene pearls to no particles at all in aerated concrete! When building with aerated concrete blocks, due to the 200–250 kg/m^3 production moisture they contain, proper detailing is a challenge.
Exposure to fire	The combination of non-combustible, insulating and low thermal expansion gives aerated concrete walls excellent fire resistance.

2.2.4.3.3 Application Air-dry, 30 cm-thick aerated concrete walls have a U-value < 0.5 W/(m^2 K). Before the values mandated by law turned tougher, 30 cm-thick outside wall and roof elements required no extra thermal insulation, which was preferred when building industrial premises.

2.2.5 Insulation Materials

2.2.5.1 How Characterized?

The indication 'insulating' presumes a material having a dry thermal conductivity (λ_{dry}) below 0.07 W/(m K). In addition to the schedule given for insulating building materials, figuring as an extra characteristic is the type of material forming the pore-enclosing matrix:

Matrix	Matrix material	Acronym
Organic	Cork	C
	Cellulose fibre	Cel
	Sea grass, sheep wool, straw, flax	
Inorganic	Glass fibre	MW
	Mineral wool	MW
	Cellular glass	CG
	Perlite, vermiculite	
Synthetic	Expanded polystyrene	EPS
	Extruded polystyrene	XPS
	Polyurethane foam	PUR
	Polyisocyanurate foam	PIR
	Phenol, ureumformaldehyde, polyethylene foam	
Mixed	Pressed perlite boards	PPB

Figure 2.3 Cork insulation.

Quite different from these insulation materials are radiant barriers, transparent (TIM) and vacuum insulation (VIP). Only those printed in standard letters are discussed with reference to the schedule given for insulating building materials.

2.2.5.2 Cork

The source of cork is the bark of the cork oak. After stripping and grinding it, the grains so formed are autoclaved using steam at 350 °C. While expanding, moulds and bacteria get killed, VOCs evaporate and the resin binds the grains into blocs that, once cooled, are cut to size. An alternative consists of drying the grains by heating them, then drenching them in bitumen and pressing the resulting mixture into boards (Figure 2.3).

2.2.5.2.1 Properties

Density	80–250 kg/m^3. Quite high for an insulating material.
Thermal	
Specific heat capacity	Dry ≈ 1880 J/(kg K) independent of density
Thermal conductivity	For a density of 111 kg/m^3 and $\theta = 0$–$40\,°C$: $\lambda = 0.042\,(1 + 1.8 \times 10^{-3}\theta)$ For a volumetric moisture ratio of 0–6% m^3/m^3: $\lambda = 0.042\,(1 + 4.3 \times 10^{-2}\Psi)$
Hygric	
Moisture content	Due to its organic origin, cork is hygroscopic and somewhat capillary.
Vapour resistance factor	Between 5 and 20. Drops with higher moisture content

Air	Its open structure makes cork air permeable
Strength and stiffness	Cork has a low compressive strength and is quite deformable. 0.05 MPa pressure gives an instantaneous strain of 1.5%

2.2.5.2.2 Behaviour

Under mechanical load	Cork creeps. 1 day subjected to 0.05 MPa sees the strain increasing from 1.5% to 5%. For 145 kg/m^3 dense boards, 1 day subjected to 0.11 MPa ends with 10% strain. Stress allowed is 1/3 of the 10% strain value (σ_{10})
Sensitivity to temperatures, IR and UV	Here, cork scores quite good. The thermal expansion coefficient is rather high ($\pm 40 \times 10^{-6}$ K^{-1}) but the resistance against low and high temperatures is excellent. UV only causes some discolouration.
Moisture load	Like all organic materials, cork swells when wet and shrinks when drying. If humid for a long time, it turns mouldy and may rot.
Exposure to fire	Cork burns

2.2.5.2.3 Application Although cork was well suited as an insulating material for low-slope roofs and cold stores, synthetic foams have taken over. Never apply cork where a high RH is likely! Using it to upgrade airborne and contact sound insulation makes no sense, as the material is too stiff for that. Anyhow, heavy boards perform well as vibration dampers.

2.2.5.3 Cellulose

Are the source of cellulose: unsold newspapers. To limit the combustibility and mould sensitivity, the fibres are mixed with borax salts. Cellulose is applied as loose fill (Figure 2.4 left) or in the form of dense boards.

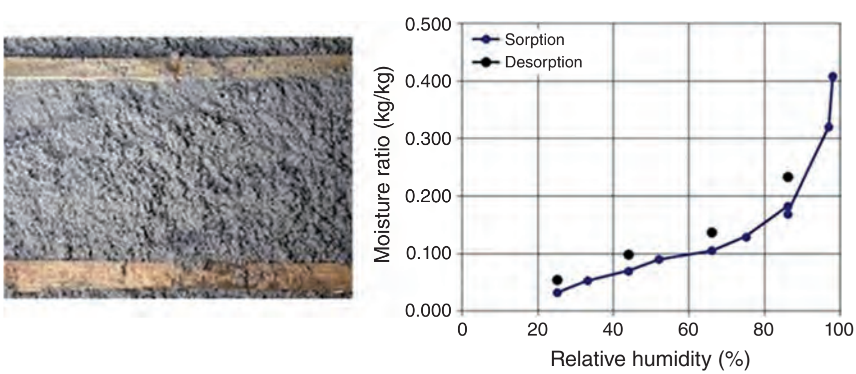

Figure 2.4 Left: cellulose fibre; right: its sorption/desorption graph.

2.2.5.3.1 Properties

Density	24–60 kg/m^3, for loose fill depending on the spraying pressure
Thermal	
Specific heat capacity	Dry ≈1880 J/(kg K), independent of density
Thermal conductivity	Air dry: $$\lambda = \frac{d/1000\,(1 + 0.00289(\theta - 24)}{(0.205 + 0.0247d) - (0.00201 + 0.0000143d)\rho}$$ with d thickness in mm, θ temperature in °C, and ρ density in kg/m^3
Hygric	
Moisture content	Cellulose fibres are hygroscopic and somewhat capillary. The borax salts added increase sorption; see Figure 2.4 right.
Vapour resistance factor	<1.9 for a density of 50 kg/m^3. Drops with increasing moisture content. The low value reflects the fibrous structure.
Air	The fibrous structure makes cellulose air permeable, $k_a \approx 1.6{\times}10^{-3}$ s.
Strength and stiffness	Loading loose fill beyond its weight is excluded.

2.2.5.3.2 Behaviour

Under mechanical load	At low density, static and dynamic forces induce irreversible settling. Measured is (a time in years): $s = 100\rho\{1/a + t/b + [1 - \exp(-dt)]/c\}$ with:

ρ	a	b	c	d
kg/m^3	kg/m^3	$kg\,a/m^3$	kg/m^3	a^{-1}
30	1.50	6827.9	247.2	1.87
35	1.75	8018.3	288.4	1.87
40	2.00	9165.9	329.6	1.87

Under moisture load	Cellulose swells and shrinks hygrically. Wet spray induces drying shrinkage. At moisture contents above 20% kg/kg, the fibres clog together and may rot
Exposure to fire	Despite the borax salts added, cellulose remains combustible. The very thick layers, often applied in passive houses, form a real hazard for firefighters
Other	Cellulose dust may induce respiratory problems. During spraying, a mask must be worn. Borax salt has its own drawbacks. A simple exposure can cause respiratory problems and skin irritation. Ingestion can cause gastrointestinal distress: nausea, vomiting, abdominal pain and diarrhoea. Effects on the vascular system and the brain with headaches and lethargy as symptoms are less frequent. Signs of poisoning are a beefy red skin rash affecting the palms, soles, buttocks and scrotum. When severely poisoned, erythematous and exfoliative rash, unconsciousness, respiratory depression, and renal failure may happen.

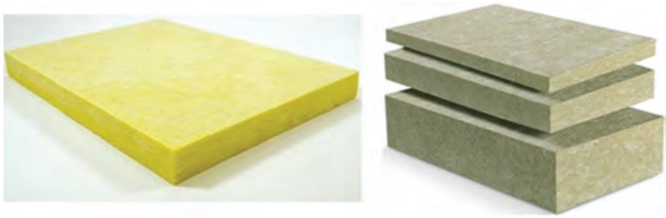

Figure 2.5 Glass fibre and mineral wool boards.

2.2.5.3.3 Application Dry or wet-sprayed cellulose is presented as an alternative for glass and mineral fibre. The application includes insulating timber-frame walls, insulating low-slope roofs by filling the bays between the purlins and insulating attic floors. Dense boards may be used in pitched roofs. Cellulose should not be applied in cavities exposed to high RH such as in cavity walls.

2.2.5.4 Glass and Mineral Fibre

The basic material for glass fibre is recycled glass, and for mineral fibre diabase stone. Both are melted, after which a spinning head produces the fibres having a diameter <10 μm. While falling down on a conveyor belt transporting the facings for the blankets, the bats and, if needed, the boards, they pass a phenol or silicon binder spray. The filled belt then enters a heated press where the binder hardens and the blankets, bats and boards get their shape, after which they are cut to size. Final products range from loose fill, over blankets and bats to soft, semi-dense and dense boards. At first sight, glass and mineral fibre look alike, but glass is amorphous and the fibres long and ordered, while diabase stone is crystalline and the fibres short and unordered (Figure 2.5).

2.2.5.4.1 Properties

Density	For glass fibre 10–150 kg/m^3, for mineral fibre 30–190 kg/m^3
Thermal	
Specific heat capacity	Same value as for stony materials, dry ± 840 J/(kg K)
Thermal conductivity	For glass fibre at 20 °C: $\lambda = 0.0262 + 5.6 \times 10^{-5}\rho + 0.184/\rho$, for mineral fibre at 20 °C: $\lambda = 0.0331 + 3.2 \times 10^{-5}\rho + 0.221/\rho$. The temperature impact is largest for low densities. For the same density, glass fibre has the lowest λ-value. Upgraded manufacturing even gave 0.032 W/(m K).
Hygric	
Moisture content	Both materials are hardly hygroscopic. Without a hydrophobic binder, the boards show some capillarity. With a hydrofobic binder, they withstand small water heads.
Vapour resistance factor	Due to their fibrous nature, very low: 1.2–1.5.

11

Concrete Panel and Sheet-Metal Outer Walls

11.1 In General

Masonry outer walls, as discussed in the previous three chapters, were and are still a reference in residential construction. For office buildings and other non-residential complexes, concrete panels and, mainly for industrial premises, sheet metal choices often figure as consciously chosen outer wall assemblies. This chapter first looks at concrete panel outer walls, to move then to sheet-metal outer walls.

11.2 Concrete Panels

11.2.1 Common Assemblies

Considered are outer walls composed of factory-made storey-high concrete panels. The number of different types, the number per type and their complexity fixes the investment. Truck transport in turn limits their dimensions and the crane's lifting capacity their weight. Types applied are either sandwich panels with an outer leaf in facing concrete, an inner leaf in normal concrete and an insulation layer in between, or monolithic panels, after mounting either insulated inside or outside (Figure 11.1).

11.2.2 Performance Checks

11.2.2.1 Remark

Monolithic panels, insulated inside- or outside, perform as massive walls insulated this way. Therefore, in what follows, the discussion is paid to sandwich panels only.

11.2.2.2 Structural Integrity

Assembling heavy panel façades is done floor by floor (Figure 11.2). Load-bearing façades composed of heavyweight panels have to withstand related forces and must, once all mounted, bear the façade's own weight and part of the own weight, dead weight and useful load of the floors supported. In low-rises, they must also guarantee wind stiffness, which requires a rigid coupling to the floors. In medium and high rises, stiff cores take over wind stability, so the panels there only have to bear vertical loads. During transport and mounting, the two leaves composing the panels may

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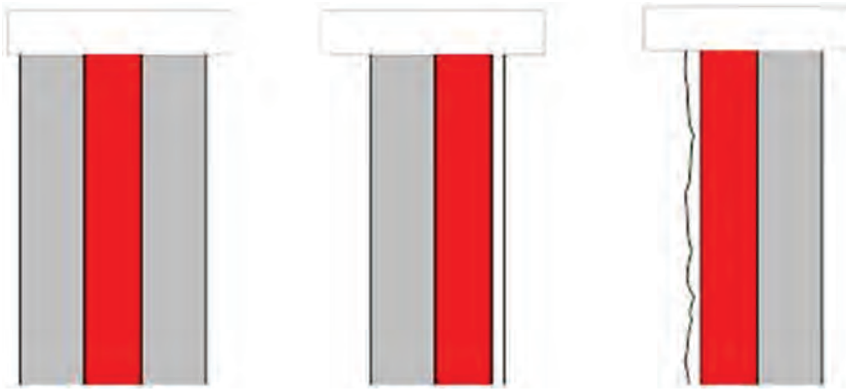


Figure 11.1 (a) Sandwich panel, (b) monolithic panel insulated inside, (c) monolithic panel insulated outside.

not shift or rotate compared to each other. To exclude this, the first choice was coupling them along the perimeter with a concrete edge. However, the thermal bridge so created had such an impact on the thermal transmittance that, with the increase in requirements, another coupling solution was introduced: a hollow stainless-steel cylinder in the centre of gravity of the panels together with ties at the perimeter (Figure 11.2). If, for any reason, the cylinder had to be included below that centre, then above, close to the perimeter, a coupler had to be added.

In non-load-bearing façades, the panels only have to bear their own weight and must be able to withstand the assembling forces and the local push and pull of the wind. Mounting here starts once the load-bearing structure is ready. The panels with supporting strips down and strap anchors up are fixed storey-wise using the structural edge beams as strip support and the loadbearing edge columns or the structural edge beams above as strap anchor fixings. While the strips have to endure bending and shear, the strap anchors must resist tension. Assembling requires mounting each panel perfectly vertically and in a way that zigzagging horizontally is excluded, that, by using adjusting screws in the supporting strips and strap anchors (Figure 11.3).

11.2.2.3 Building Physics: Heat, Air and Moisture

11.2.2.3.1 Airtightness At panel level, airtightness is normally guaranteed. If nevertheless leakage is noted, badly sealed joints between panels are the most likely cause. Caring for correct jointing in between and at floor and ceiling level is therefore a challenge when mounting panel outer walls.

11.2.2.3.2 Thermal Transmittance Should the insulation form an uninterrupted layer, then a clear wall thermal transmittance of 0.4–0.1 $W/(m^2 \cdot K)$ will require the insulation thicknesses of Table 11.1. Anyhow, the thicker the boards used, the higher the load the leaf couplers must withstand, the more voluminous the panels become and the less net area is left if the outer dimensions must remain the same.

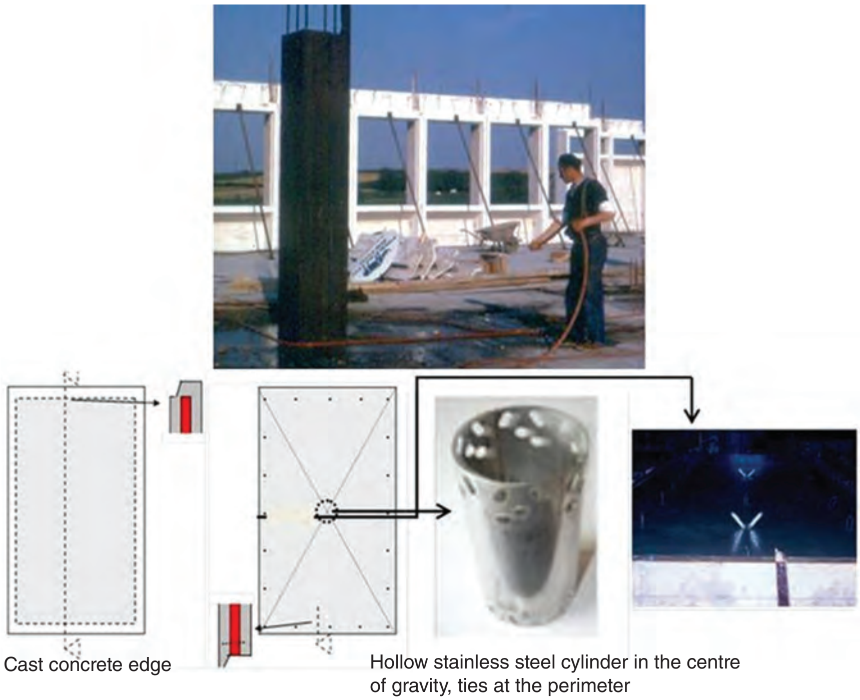


Figure 11.2 Top: building floor by floor; below: sandwich panels: both leafs coupled.

Figure 11.3 Non-load-bearing panels, mounting.

Table 11.1 Insulation thickness (sandwich panel, outer leaf 8 cm, inner leaf 14 cm thick).

U_o-value	Insulation thickness (m)			
W/(m^2 · K)	MW	EPS	XPS	PUR
0.4	0,08	0,08	0,07	0,05
0.2	0,17	0,18	0,15	0,11
0.1	0,35	0,37	0,31	0,22

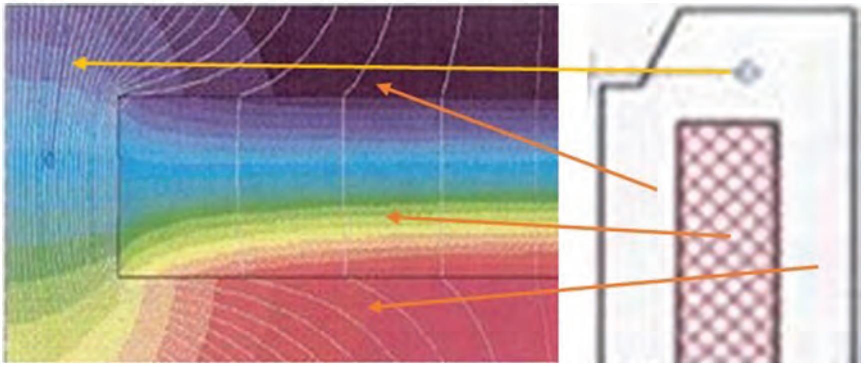


Figure 11.4 Cast concrete perimeter edge, isotherms (purple = coldest, red = warmest).

Table 11.2 Whole wall thermal transmittance of a 3.6 m tall and 2.4 m wide panel.

Wall, 6 cm concrete/MW 6 cm concrete	U_o W/(m^2 · K)	ψ W/(m · K)	U W/(m^2 · K)	$\Delta U/U_o$ (%)
Cast concrete edge all around				
MW, $d = 8$ cm	0.45	0.55	1.21	169
MW, $d = 12$ cm	0.31	0.51	1.02	229
MW, $d = 16$ cm	0.24	0.48	0.90	275
		χ, W/K		
Central stainless-steel hollow cylinder filled with insulation (1st number), edge ties (2nd number)				
MW, $d = 8$ cm	0.45	0.15/0.044	0.55	22
MW, $d = 12$ cm	0.31	0.13/0.031	0.38	23
MW, $d = 16$ cm	0.24	0.11/0.024	0.29	21

However, for panels with the perimeter coupled by edges in cast concrete, related linear thermal bridging turns the clear wall values listed in the table into meaningless numbers. Figure 11.4 shows the isotherms at such an edge, while Table 11.2 lists the linked whole wall thermal transmittances for storey-high panels. Also, joints between carelessly embedded insulation boards figure as linear thermal bridges. Even a central stainless-steel hollow cylinder, surely when unwantedly filled with concrete instead of insulation, and the ties as couplers along the perimeter induce some local thermal bridging. The impact is also given in Table 11.2.

The lower the clear wall value, the more cast concrete perimeter edges affect the insulation efficiency. Hollow cylinders at the point of gravity and ties along the perimeter do noticeably better, given the much smaller difference in % between related clear and whole wall U-values.

Table 11.3 Sandwich panels: temperature damping, dynamic thermal resistance, admittance.

Panel, out 8 cm, in 14 cm concrete	Temperature damping		Dynamic thermal resistance		Admittance	
Insulation	–	Time shift, h	$m^2 \cdot K/W$	Time shift, h	$W/(m^2 \cdot K)$	Time shift, h
6 cm EPS	40.9	9.2	6.2	7.9	6.6	1.3
19 cm EPS	120.8	10.1	18.3	6.6	6.6	1.3

11.2.2.3.3 Transient Response Table 11.3 lists the temperature damping, the dynamic thermal resistance and the admittance on a one-day basis for a sandwich heavyweight panel insulated with an uninterrupted 6 cm ($U = 0.57\,W/(m^2 \cdot K)$) or 19 cm ($U = 0.2\,W/(m^2 \cdot K)$) thick EPS layer. As temperature damping largely exceeds the value 15, the dynamic thermal resistance outperforms the steady-state thermal resistance and the admittance scores much higher than half the surface film coefficient inside ($7.8\,W/(m^2 \cdot K)$), the transient response looks excellent. However, as such panels were often used for office buildings, looking at the large glazed surfaces in the façade and indoors the hung ceilings, raised floors and lightweight partitions present, their use per floor as panel strips finishing the façade under the row of windows hardly helped in tempering overheating.

11.2.2.3.4 Moisture Tolerance

Wind-driven rain: As concrete has a really low capillary water absorption coefficient ($0.018\,kg/(m^2 \cdot s^{0.5})$), the time needed for rain hitting the panels (t_r) to start running-off fingering is really short:

$$t_r = 0.000162/g_{ws}^2 \text{ (s)} \tag{11.1}$$

where g_{ws} is the wind-driven rain intensity ($kg/(m^2 \cdot s)$). That fingering is a main reason why, after some years, panels may start turning dirty. In fact, on spots where run-off stays for a while, dust is taken with it to be deposited elsewhere along the façade. Run-off also loads the joints around panels and windows, which is another reason for excellent sealing to be crucial.

Mould and surface condensation: For panels with clear wall thermal transmittances $\leq 0.4\,W/(m^2 \cdot K)$ and no cast concrete perimeter edges as coupler, the temperature ratio on the inner face will largely pass 0.7, even behind cupboards. The mould and surface condensation risk therefore remains well below 0.05. Instead, with these as couplers, things may go wrong; see ‘thermal bridging ’.

Interstitial condensation: No issue, mainly because the often-humid concrete outer leaf is more vapour permeable than the air-dry concrete inner leaf. The panels so reflect the correct design. If a diffusion-based calculation should nonetheless give some winter deposit on the backside of the outer leaf, in reality this will be nothing more than some increase in the concrete’s hygroscopic moisture content.

11.2.2.3.5 Thermal Bridging If the lowest temperature ratio on the inside face of a panel with both leaves coupled at the perimeter with cast concrete edges drops below the value of the glazing used, then mould will become a pending risk. Instead, for well insulated sandwich panels having both leafs coupled with a hollow cylinder and ties, the lowest temperature ratio hardly deviates from the value the clear wall thermal transmittance gives, meaning mould is not an issue.

11.2.2.4 Building Physics: Acoustics

The airborne sound transmission loss of concrete sandwich panels is really high. But again, the windows are what fix the façade's sound insulation.

11.2.2.5 Durability

As Table 11.4 underlines, even small insulation thicknesses suffice to thermally load the inside- and outside leaf quite differently. A cast concrete coupled perimeter edge may consequently induce important stresses. To give an indication, assume shrinkage after manufacturing is relaxed by storing the panels in a 10 °C warm, humid environment. Once mounted on site, in a temperate climate the outer leaf can warm up to 48 °C during a hot day, while the inner leaf will remain at 23.4 °C. Their coupling will cause tension in the inner leaf with stresses touching 3.4 MPa, a value concrete fortunately can cope with.

During a really cold winter day, both leafs will cool down, the inner to 14.6 °C and the outer to −14.4°C. It's the outer that will experience up to 6.7 MPa tensile stress now, a value beyond the concrete's tensile strength yet, which makes spread cracking likely. That may expose the reinforcement bars in the outer leaf to the outdoors, as a result of which increased wetness and easier carbonisation will accelerate their corrosion, whereby related swelling may spall the concrete cover above.

Once the initial shrinkage, kept moderate by keeping the concrete wet, has worn off, contrary to the thermal load, the hygric load still to be expected becomes minimal. As said, concrete is hygroscopic but hardly capillary. In case thermal cracking could be avoided by embedding a welded steel mesh in both leafs during production, then rain sucking by the outer leaf will be too slow and the rainy periods too short to ever get it capillary wet over its whole thickness. And even if, the difference in hygroscopic moisture content remains too small to cause any problematic swelling.

Table 11.4 Manufactured sandwich panel: in- and outside leaf, temperature load.

		Temperature difference across the leaf (°C)		
Panel, from out- to inside: 8 cm concrete EPS14 cm concrete	**Leaf**	**Mean, between a cold winter and hot summer day**	**During a cold winter day**	**During a hot summer day**
EPS15, $d = 6$ cm	Inner	9.5	0.6	0.8
	Outer	61.5	19.7	27.7
EPS15, $d = 19$ cm	Inner	7.2	0.2	0.2
	Outer	62.5	20.0	29.1

11.2.2.6 Fire Safety

Even with EPS, the fire resistance of sandwich panels scores high. Flame spread along panelized façades anyhow could become an issue in case of glass rupture. Therefore, having per floor in the façade panels strips with a height ≥1 m above the glazing below is mandatory.

11.2.2.7 Maintenance

To minimize soiling, hindering rain run-off should guide panel design: not flat, though with some relief. Although this could accelerate dirt deposits, related soiling will look more equal then. Regular cleaning, however, will remain necessary. The hygroscopicity of concrete also facilitates algae growth, so it demands regular treatment with extirpating products. Repairing a spalled concrete cover in outer leafs requires removing the cover and treating the freed bars with a corrosion inhibitor, after which the cover must be repaired with a suitable mortar.

11.2.3 Design and Execution

To make a façade built with heavyweight sandwich panels affordable requires a modular design that limits the panel shapes needed and makes the number per shape as large as possible. Suitable as insulation materials are dense mineral wool (MW), expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane and polyisocyanurate (PUR/PIR) boards. Coupling both leafs so that any rotation compared to the other is excluded requires corrosion resistant attachments that ensure strength, stiffness, shape retention and minimal thermal bridging. As shown, the best is a hollow stainless-steel cylinder at the point of gravity and ties all around at the perimeter. A well scaled concrete with a low water/cement factor cured in a humid environment and welded steel meshes in both leafs with enough concrete cover will curb aging. And, of course, if the design goes for a panelized façade, then it has to fulfil all requirements mandated or requested by the client.

11.3 Sheet-metal Options

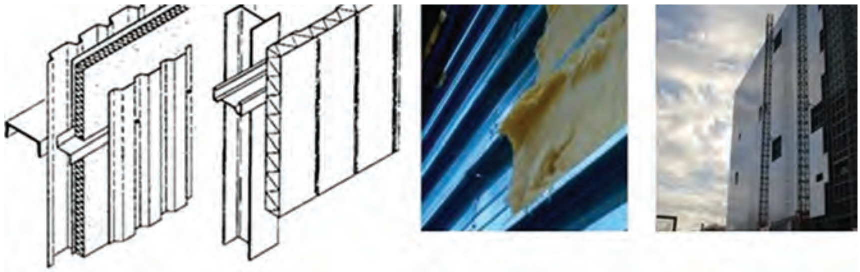
11.3.1 Common Assemblies

Most sheet-metal outer wall panels or elements are either plate, sandwich, cellular or clad based. Plates are composed of a corrugated inner and outer sheet with insulation in between. Sandwiches have the insulation glued between two metal sheet covers. Cellular refers to elements composed of vertical or horizontal metal boxes filled with insulation. Clad types finally collect all metal sheets used as outside linings (Figure 11.5).

11.3.2 Performance Checks

11.3.2.1 Structural Integrity

Sheet-metal panels or elements are, by definition, non-load-bearing. A structural evaluation only requires a strength and stiffness control looking at their own weight,



(a) (b) (c) (d)

Figure 11.5 Sheet-metal elements: (a) plate with vertical profiling, (b) sandwich, (c) cellular, (d) clad based.

the push and pull of the wind and the possible structural impacts of the thermal stress experienced. The fastening systems used must, of course, ensure a safe transfer of these loads to the building's structural system, but they should anyhow simultaneously allow some limited movement.

11.3.2.2 Building Physics: Heat, Air and Moisture

11.3.2.2.1 In General Outer walls made of sheet-metal elements struggle with airtightness and thermal bridging, the last due to the high λ-value of the metal used. The transient thermal response leaves nothing to desire as all are too lightweight for that, while the risk of getting interstitial condensation may score high, surely if too air-permeable. The way metal-sheet clads behave from a heat, air, moisture perspective largely depends on the material used as thermal insulation and which inside leaf, if any, is applied.

11.3.2.2.2 Air Tightness A separate sheet-metal element is perfectly airtight. The problem is the joints. They can be unexpectedly air permeable as Table 11.5 shows for cellular elements.

Carelessly mounted insulation may enable and ease air looping, which will strongly degrade the thermal quality left. Inside air outflow could also blow-up the deposit interstitial condensation cares for.

Table 11.5 Air permeance of cellular sheet-metal outer wall systems ($K_a = a\Delta P_a^{b-1}$).

Cellular element, boxes filled with 80 mm mineral wool	Air permeance, kg/(m^2 · s · Pa)	
	a	$b-1$
1. No special measures	$7.9 \cdot 10^{-5}$	−0.003
2. Screw eyes caulked	$6.7 \cdot 10^{-5}$	−0.101
3. As 2, joints between boxed taped	$1.6 \cdot 10^{-5}$	−0.084