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Performance Based Building Design 2

From Timber-framed Construction to Partition Walls

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Professor Hugo S. L. C. Hens
University of Leuven (KULeuven)
Department of Civil Engineering
Building Physics
Kasteelpark Arenberg 40
3001 Leuven
Belgium

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To my wife, children and grandchildren

In remembrance of Professor A. de Grave
who introduced building physics as a new discipline
at the University of Leuven, KULeuven, Belgium, in 1952

Preface

Overview

Just like building physics, performance based building design was hardly an issue before the energy crises of the 1970s. With the need to upgrade energy efficiency, the interest in overall building performance grew. The volume on applied building physics discussed a performance rationale and performance requirements at the building and building enclosure level, with emphasis on heat, air, moisture checks. As in the third volume, volume four continues this rationale for structural aspects, acoustics, fire safety, maintenance and buildability. And as with volume three, it is the result of thirty-eight years of teaching architectural, building and civil engineers, coupled to more than forty years of experience in research and consultancy. Where and when needed, input and literature from around the world has been used, with a list of references and literature at the end of each chapter.

The book can be used by undergraduates and graduates in architectural and building engineering and also building engineers who want to refresh their knowledge may also benefit. The level of discussion assumes a sound knowledge of building physics, along with a background in structural engineering, building materials and building construction.

Acknowledgements

A book of this magnitude reflects the work of many, not only the author. Therefore, first of all, we want to thank our thousands of students. They gave us the opportunity to test the content and helped in upgrading by the corrections they proposed and the experience they offered in learning what parts should be better explained.

This is a text that has been written standing on the shoulders of those who came before us. Although we started our career as a structural engineer, our predecessor, Professor Antoine de Grave planted the seeds from which our interest in building physics, building services and performance based building design slowly grew. The late Bob Vos of TNO, the Netherlands, and Helmut Künzel of the Fraunhofer Institut für Bauphysik, Germany, showed the importance of experimental work and field testing for understanding building performance, while Lars Erik Nevander of Lund University, Sweden, taught that application does not always ask extended modeling, mainly because reality in building construction is much more complex than any simulation is.

During the four decades at the Laboratory of Building Physics, several researchers and Ph. D.-students got involved. I am very grateful to Gerrit Vermeir, Staf Roels, Dirk Saelens and Hans Janssen who became colleagues at the university; to Jan Carmeliet, now professor at the ETH-Zürich; Piet Standaert, a principal at Physibel Engineering; Jan Lecompte, at Bekaert NV; Filip Descamps, a principal at Daidalos Engineering and part-time professor at the Free University Brussels (VUB); Arnold Janssens, professor at the University of Ghent (UG); Rongjin Zheng, associate professor at Zhejiang University, China, and Bert Blocken, professor at the Technical University Eindhoven (TU/e), who all contributed by their work. The experiences gained by working as a structural engineer and building site supervisor at the start of my career, as building assessor over the years, as researcher and operating agent of four Annexes of the IEA, Executive Committee on Energy Conservation in Buildings and Community Systems, forced me to rethink the engineering based performance approach each time again. The many ideas I exchanged with Kumar Kumaran, Paul Fazio, Bill Brown,

William B. Rose, Joe Lstiburek and Anton Ten Wolde in Canada and the USA were also of great help. A number of reviewers took time to examine the book. Although we do not know their names, we also thank them here.

Finally, I thank my family, my wife Lieve, who managed living together with a busy engineering professor, my three children who had to live with that busy father and my many grandchildren who do not know their grandfather is still busy.

Leuven, June 2012 *Hugo S. L. C. Hens*

Contents

0 Introduction

0.1 Subject of the book

This is the second part of the third volume in a series of books on building physics, applied building physics and performance based building design:

- Building Physics: Heat, Air and Moisture
- Applied Building Physics: Boundary Conditions, Building Performance and Material Properties
- Performance Based Building Design 1
- **Performance Based Building Design 2**

Performance Based Building Design 2 continues the application of the performance based engineering rationale, discussed in 'Applied Building Physics: Boundary Conditions, Building Performance and Material Properties' to the design and construction of building assemblies. In order to do that, the text considers the performance requirements presumed or imposed, their prediction during the design stage and the technology needed for realization.

Performance Based Building Design 1 ended with massive outer walls. Performance Based Building Design 2 begins with lightweight building and outer wall systems: timber-framed and metal-based. Then low-sloped, pitched, and metal roofs follow to finish the enclosure-related subjects with glazed surfaces and windows. Attention then turns to balconies, chimneys, shafts, staircases, inside partitions, and finishes. The volume closes with a chapter on risk analysis. Of course, for principals acceptable risk is an important issue. As in Performance Based Building Design 1, the impact of performance requirements on design and execution is highlighted. For decades, the Laboratory of Building Physics at the KULeuven not only tested highly insulated massive façade assemblies, but also lightweight façade assemblies and roofs. The results are used in the discussions.

0.2 Units and symbols

The book uses the SI-system (internationally mandatory since 1977). Base units are the meter (m), the kilogram (kg), the second (s), the Kelvin (K), the ampere (A) and the candela. Derived units of importance are:

Unit of force:	Newton	(N);	$1\ \mathrm{N} = 1\ \mathrm{kg \cdot m \cdot s^{-2}}$
Unit of pressure:	Pascal	(Pa);	$1\ \mathrm{Pa} = 1\ \mathrm{N/m^2} = 1\ \mathrm{kg \cdot m^{-1} \cdot s^{-2}}$
Unit of energy:	Joule	(J);	$1\ \mathrm{J} = 1\ \mathrm{N \cdot m} = 1\ \mathrm{kg \cdot m^2 \cdot s^{-2}}$
Unit of power:	Watt	(W);	$1\ \mathrm{W} = 1\ \mathrm{J \cdot s^{-1}} = 1\ \mathrm{kg \cdot m^2 \cdot s^{-3}}$

For the symbols, the ISO-standards (International Standardization Organization) are followed. If a quantity is not included in these standards, the CIB-W40 recommendations (International Council for Building Research, Studies, and Documentation, Working Group 'Heat and Moisture Transfer in Buildings') and the list edited by Annex 24 of the IEA, ECBCS (International Energy Agency, Executive Committee on Energy Conservation in Buildings and Community Systems) are applied.

Table 0.1. List with symbols and quantities.

Symbol	Meaning	Units
a	Acceleration	m/s^2
a	Thermal diffusivity	m^2/s
b	Thermal effusivity	$W/(m^2 \cdot K \cdot s^{0.5})$
c	Specific heat capacity	$J/(kg \cdot K)$
c	Concentration	kg/m^3, g/m^3
e	Emissivity	–
f	Specific free energy	J/kg
	Temperature ratio	–
g	Specific free enthalpy	J/kg
g	Acceleration by gravity	m/s^2
g	Mass flow rate, mass flux	$kg/(m^2 \cdot s)$
h	Height	m
h	Specific enthalpy	J/kg
h	Surface film coefficient for heat transfer	$W/(m^2 \cdot K)$
k	Mass related permeability (mass may be moisture, air, salt …)	s
l	Length	m
l	Specific enthalpy of evaporation or melting	J/kg
m	Mass	kg
n	Ventilation rate	s^{-1}, h^{-1}
p	Partial pressure	Pa
q	Heat flow rate, heat flux	W/m^2
r	Radius	m
s	Specific entropy	$J/(kg \cdot K)$
t	Time	s
u	Specific latent energy	J/kg
v	Velocity	m/s
w	Moisture content	kg/m^3
x, y, z	Cartesian co-ordinates	m
A	Water sorption coefficient	$kg/(m^2 \cdot s^{0.5})$
A	Area	m^2
B	Water penetration coefficient	$m/s^{0.5}$
D	Diffusion coefficient	m^2/s
D	Moisture diffusivity	m^2/s
E	Irradiation	W/m^2

Table 0.1. (continued)

Symbol	Meaning	Units
F	Free energy	J
G	Free enthalpy	J
G	Mass flow (mass = vapour, water, air, salt)	kg/s
H	Enthalpy	J
I	Radiation intensity	J/rad
K	Thermal moisture diffusion coefficient	$kg/(m \cdot s \cdot K)$
K	Mass permeance	s/m
K	Force	N
L	Luminosity	W/m^2
M	Emittance	W/m^2
P	Power	W
P	Thermal permeance	$W/(m^2 \cdot K)$
P	Total pressure	Pa
Q	Heat	J
R	Thermal resistance	$m^2 \cdot K/W$
R	Gas constant	$J/(kg \cdot K)$
S	Entropy, saturation degree	J/K, –
T	Absolute temperature	K
T	Period (of a vibration or a wave)	s, days, etc.
U	Latent energy	J
U	Thermal transmittance	$W/(m^2 \cdot K)$
V	Volume	m^3
W	Air resistance	m/s
X	Moisture ratio	kg/kg
Z	Diffusion resistance	m/s
α	Thermal expansion coefficient	K^{-1}
α	Absorptivity	–
β	Surface film coefficient for diffusion	s/m
β	Volumetric thermal expansion coefficient	K^{-1}
η	Dynamic viscosity	$N \cdot s/m^2$
θ	Temperature	°C
λ	Thermal conductivity	$W/(m \cdot K)$
μ	Vapour resistance factor	–
ν	Kinematic viscosity	m^2/s

Symbol	Meaning	Units
ρ	Density	kg/m^3
ρ	Reflectivity	–
σ	Surface tension	N/m
τ	Transmissivity	–
ϕ	Relative humidity	–
α, ϕ, Θ	Angle	rad
ξ	Specific moisture capacity	kg/kg per unit of moisture potential
Ψ	Porosity	–
Ψ	Volumetric moisture ratio	m^3/m^3
Φ	Heat flow	W

Table 0.2. List with suffixes and notations.

Symbol	Meaning
Indices	
A	Air
c	Capillary, convection
e	Outside, outdoors
h	Hygroscopic
i	Inside, indoors
cr	Critical
CO_2, SO_2	Chemical symbol for gases
m	Moisture, maximal
r	Radiant, radiation
sat	Saturation
s	Surface, area, suction
rs	Resulting
v	Water vapour
w	Water
ϕ	Relative humidity
Notation	
[ ], bold	Matrix, array, value of a complex number
Dash	Vector (ex.: $\overline{a}$)

0.3 References and literature

[0.1] CIB-W40 (1975). Quantities, Symbols and Units for the description of heat and moisture transfer in Buildings: Conversion factors, IBBC-TNP, report No. BI-75-59/03.8.12, Rijswijk.

[0.2] ISO-BIN (1985). Standards series X02-101 – X023-113.

[0.3] Kumaran, K. (1996). *Task 3: Material Properties*. Final Report IEA EXCO ECBCS Annex 24. ACCO, Louvain, p. 135.

1 Timber-framed construction

1.1 In general

In the Low Countries on the North Sea, timber was the common construction material for rural and municipal dwellings until the 13th – 14th century. Brick construction was an aristocrat's privilege. Many devastating town fires, the sociological fact that bricks stood for wealth and growing wood shortages slowly turned brick building into the new standard.

Timber construction still is the reference in many countries worldwide, like the US, Canada, Norway, Sweden, Finland, Russia, Japan and other countries rich in forests and often with a cold climate. There, the framed type has an important advantage compared to massive construction: it is easy to insulate, which is why even in northwest Europe timber-frame construction has regained popularity, now for passive houses. However, the disadvantages also deserve mentioning: hardly any thermal inertia, air tightness critical and less moisture tolerant than brick construction.

In timber framing, load- and non-bearing outer and partitions walls consist of a framework of timber studs and crossbeams, called plates. The outer wall frames are externally finished with structural sheathing. Where the studs bear all vertical loads and the outer wall ones have also to withstand the wind component, normal to the façade, the sheathing provides overall stiffness against horizontal loading. It also prevents buckling of the studs parallel to their lowest inertia radius. From the three common framing approaches – platform, balloon, post and beam – the platform type, composed of storey-high stud walls and timber floors is the most popular (Figure 1.1).

Construction looks as follows: once the foundations and foundation walls are ready, the ground floor is laid, in humid climates preferably a concrete deck, though in dry climates also timber joists with plywood or OSB (oriented strand board) deck apply, the crosscut end sides being closed with header plates. In such case, ripped half-width standard timber beams form the floor joists with struts at half-span excluding lateral buckling. Then one fixes the bottom plates, after which the studs are nailed and coupled with top plates. To stabilize the frame corners, doubling these is an option. After, a plywood, OSB or stiff insulation board (XPS) sheathing is nailed to the outer wall frames. The joists of the second floor, which are fixed at the top plates then follow. Header plates again close the crosscut end sides and plywood or OSB forms the running surface. The same cycle restarts for the second storey: bottom plate, studs, top plates, sheathing, floor joists, running surface, etc.

A timber framework or rafters, axis to axis at the same distance as the studs, shape the load-bearing roof structure with an external sheathing once more providing stiffness. Timber framing ends with wrapping up the outer walls with waterproof, wind tight building paper, stapled from bottom to top on the sheathing with the higher strips overlapping the lower ones. Platform framing lends itself to modular construction and prefabrication.

From inside to outside the outer wall assembly looks like (Figure 1.2): inside lining (gypsum board); (service cavity); air (always) and vapour (when necessary) retarder; bays between studs filled with insulation (mineral wool or cellulose); plywood, OSB or stiff insulation board sheathing; building paper; outside finish (timber siding, brick veneer, EIFS, etc).

Aside from timber framing, also metal framed construction exists, with metal studs and plates replacing the timber ones.

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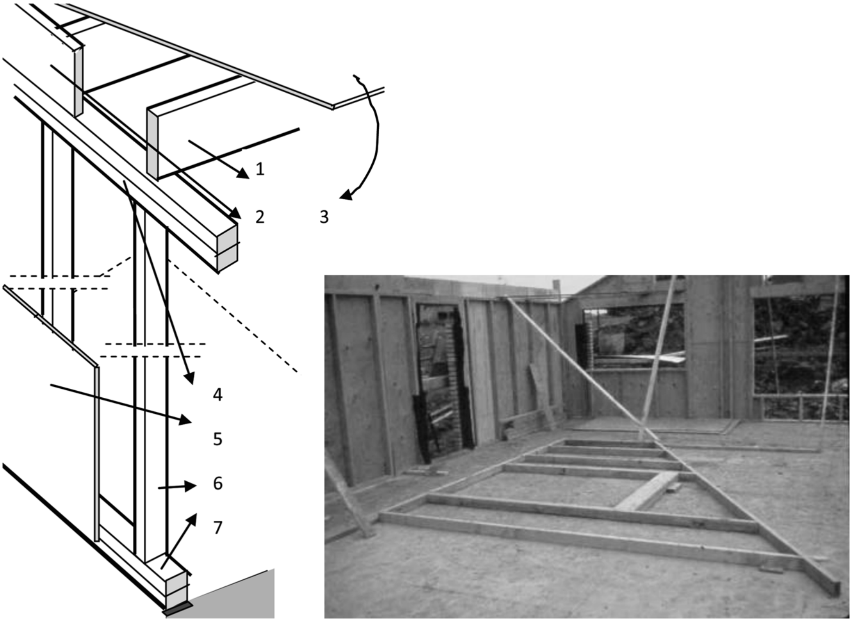

Figure 1.1. Platform type (1: joists, 2: header plate, 3: running surface, 4: top plates, 5: sheathing, 6: studs, 7: bottom plates).

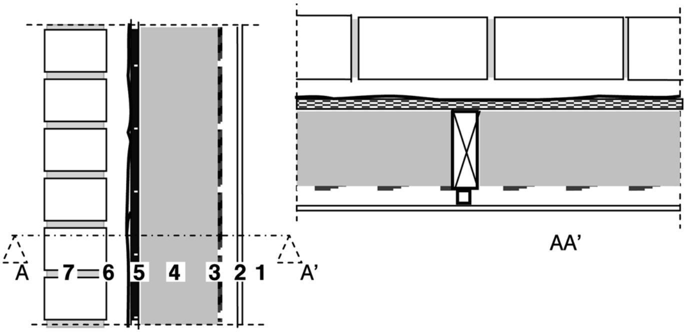

Figure 1.2. Timber-framed outer wall, reference assembly (1: inside lining, 2: service cavity, 3: air and vapour retarder, 4: thermal insulation; 5: sheathing, 6: building paper, 7: outside finish).

1.2 Performance evaluation

1.2.1 Structural integrity

Timber-framed buildings are so lightweight that anchoring in the foundation walls is necessary to prevent displacement under extreme wind load (Figure 1.3).

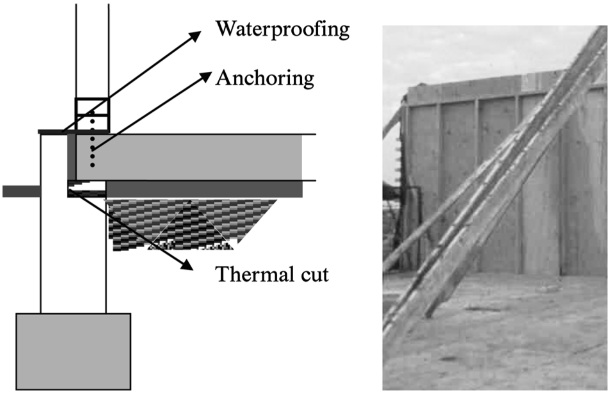

Figure 1.3. Timber-framed construction, anchoring in the foundation walls.

Wind loading and buckling of the outer and partition wall studs demands proper attention. The sheathing or inside finishes block it in the lowest moment of inertia direction. The direction normal to the walls needs a control. Table 1.1 gives the buckling factors vertical loads have to be multiplied by, as a function of the stud's slenderness (*i*):

$$i = \frac{L}{\sqrt{\frac{I}{A}}} \tag{1.1}$$

with *L* the effective stud span (in timber framed construction equal to the distance between bottom and top plates), *I* the moment of inertia around the neutral axis of the combination stud/sheathing (if shear-stiff coupled) and *A* total active cross section.

If this product gives stresses in the timber beyond acceptable, or, if for a given span the stud's radius of inertia is too low, then two options are left: diminishing the centre-to-centre distance between studs or using deeper ones. The first is disadvantageous in terms of whole wall thermal transmittance whereas the second allows larger insulation thicknesses, thus, a lower whole wall thermal transmittance.

Table 1.2 summarizes the mechanical properties of softwood and plywood. For the stiffness against horizontal loads, the same rules as for massive construction hold: the floors as rigid horizontal decks, at least 3 sheathed or wind-braced walls whose centre planes do not cross in one point, the stiff walls preferentially distributed in a way the resulting wind load vector crosses their stiffness centre.

Table 1.1. Buckling factors (slenderness vertically in steps of 10, horizontally in steps of 1).

Slenderness	0	1	2	3	4	5	6	7	8	9
0	1	1	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.04
10	1.04	1.04	1.05	1.05	1.06	1.06	1.06	1.07	1.07	1.08
20	1.08	1.09	1.09	1.10	1.11	1.11	1.12	1.13	1.13	1.14
30	1.15	1.16	1.17	1.18	1.19	1.20	1.21	1.22	1.24	1.25
40	1.26	1.27	1.29	1.30	1.32	1.33	1.35	1.36	1.38	1.40
50	1.42	1.44	1.46	1.48	1.50	1.52	1.54	1.56	1.58	1.60
60	1.62	1.64	1.67	1.69	1.72	1.74	1.77	1.80	1.82	1.85
70	1.88	1.91	1.94	1.97	2.00	2.03	2.06	2.10	2.13	2.16
80	2.20	2.23	2.27	2.31	2.35	2.38	2.42	2.46	2.50	2.54
90	2.58	2.62	2.66	2.70	2.74	2.78	2.82	2.87	2.91	2.95
100	3.00	3.06	3.12	3.18	3.24	3.31	3.37	3.44	3.50	3.57
110	3.63	3.70	3.76	3.83	3.90	3.97	4.04	4.11	4.18	4.25
120	4.32	4.39	4.46	4.54	4.61	4.68	4.76	4.84	4.92	4.99
130	5.07	5.15	5.23	5.31	5.39	5.47	5.55	5.63	5.71	5.80
140	5.88	5.96	6.05	6.13	6.22	6.31	6.39	6.48	6.57	6.66
150	6.75	6.84	6.93	7.02	7.11	7.21	7.30	7.39	7.49	7.58
160	7.68	7.78	7.87	7.97	8.07	8.17	8.27	8.37	8.47	8.57
170	8.67	8.77	8.88	8.98	9.08	9.19	9.29	9.40	9.61	9.61
180	9.72	9.83	9.94	10.05	10.16	10.27	10.38	10.49	10.60	10.72
190	10.83	10.94	11.06	11.17	11.29	11.41	11.52	11.64	11.76	11.88
200	12.00	12.12	12.24	12.36	12.48	12.61	12.73	12.85	12.98	13.10
210	13.23	13.36	13.48	13.61	13.74	13.87	14.00	14.13	14.26	14.39
220	14.52	14.65	14.79	14.92	15.05	15.19	15.32	15.46	15.60	15.73
230	15.87	16.01	16.15	16.29	16.43	16.57	16.71	16.85	16.99	17.14
240	17.28	17.42	17.57	17.71	17.86	18.01	18.15	18.30	18.45	18.60

Table 1.2. Mechanical properties of softwood and plywood.

Property			**Softwood**			**Plywood**	
			Class 1	**Class 2**	**Class 3**	**// fibres outer laminates**	**+ fibres outer laminates**
Modulus of elasticity		MPa					
// fibres				11 000		7 000	
⊥ fibres				300		3 000	
Shear modulus		MPa		500			
Allowed stress							
Bending	// fibres	MPa	7	10	13		
	⊥ plywood	MPa				13	5
	// plywood	MPa				9	6
Tension	// fibres	MPa	0	8.5	10.5		
	// plywood	MPa				8	4
Compression	// fibres	MPa	6	8.5	11		
	⊥ fibres	MPa	2	2	2		
	⊥ plywood	MPa				3	3
	// plywood	MPa				8	4
Shear	// fibres	MPa	0.9	0.9	0.9		
	⊥ plywood	MPa				1.8	1.8
	// plywood	MPa				0.9	0.9

1.2.2 Building physics: heat, air, moisture

1.2.2.1 Air tightness

Air tightness of timber-framed envelopes is not taken for granted. The outside finish, the building paper, the sheathing, as well as the insulation, all are air-permeable. Contributing factors are, for the building paper, the overlaps between the strips, for the sheathing the joints between boards and for the thermal insulation the material itself and the gaps between insulation, studs and plates. It is the inside finish to guarantee air-tightness. Non-perforated gypsum board linings without cracks between boards have an air permeance of $(K_a) \approx 3.1 \cdot 10^{-5}\ \Delta P_a^{-0.19}$. For an air pressure difference of 10 Pa, that value limits air leakage to 0.43 $m^3/(m^2 \cdot h)$. However, when sockets and others perforate the lining and cracks form between boards, this value may increase by a factor of 10, which is why inclusion of an additional air barrier deserves recommendation. In moderate and cold climates, one used a PE-foil, stapled against the timber frame, preferentially with a service cavity left between foil and inside lining. Recently, OSB with taped joints emerged as an alternative (Figure 1.4). But also with additional air barrier, perfect air-tightness is hard to realize. Even excellent workmanship did not result in tested air leakages below 3 $dm^3/(m^2 \cdot h)$ at 1 Pa air pressure difference. In hot and humid climates, it is up to the outside finish to guarantee air-tightness.