Università degli Studi di Padova
Dipartimento di Ingegneria Industriale

Energy and buildings

Thermal calculation of thermal bridges in building constructions

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Thermal bridge

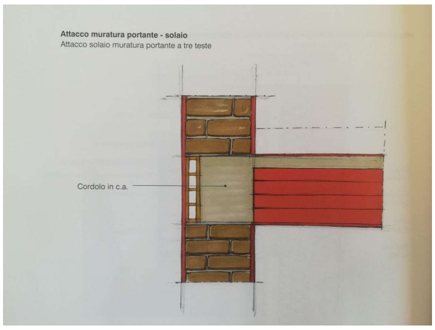
Definition according to ISO 10211

Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by

- full or partial penetration of the building envelope by **materials** with a different thermal conductivity;
- change in **thickness of the fabric** or **difference between internal and external areas** such as occur at wall/floor/ceiling junctions.

Thermal bridge

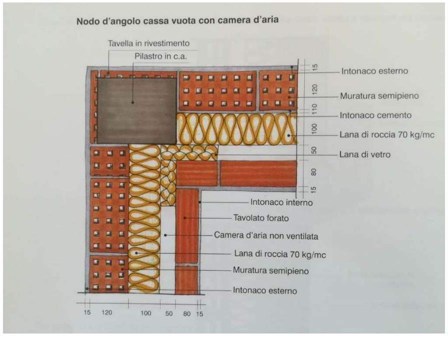
Example of penetration of the building envelope by **materials** with a different thermal conductivity: floor slab between ground and first floor of a residential building



Attacco muratura portante - solaio
(Ceccarelli, 2015)

Thermal bridge

Example of **difference between internal and external areas:** corner junction between external walls and penetration of a material with different thermal properties (reinforced concrete pillar).



Nodo d'angolo cassa vuota con camera d'aria (Ceccarelli, 2015)

Thermal bridge

Change of thermal resistance due to a discontinuity in the **materials** or **geometry** of the building envelope

- Additional heat flow has **an impact on energy needs**
- Local decrease of internal surface temperature may cause **condensation** problems in the heating season

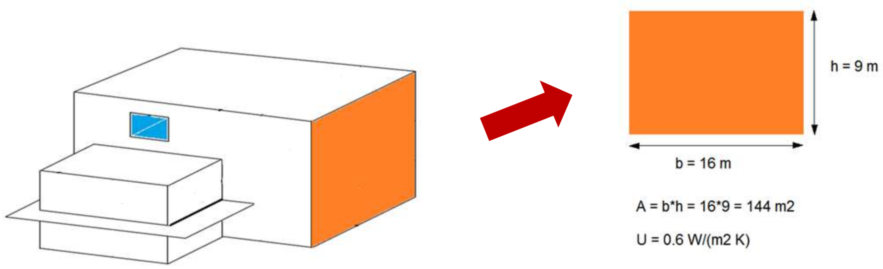
Objective of this lecture

Evaluate the additional heat flow of thermal bridges using two methods:

- Simplified method (former EN ISO 14683)
- Detailed calculation method (ISO 10211)

In the Laboratory and for the report we will apply the **detailed calculation method** using a FEM software!

Heat loss coefficient



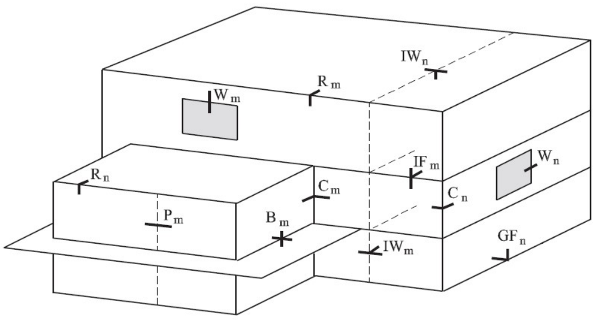
U x A = 144 x 0.6 = 86.4 W/K

$$H_T = \sum_i U_i A_i$$

The heat loss coefficient is expressed in [W/K]

The heat loss coefficient can be used with any type of Δt between inside and outside (design temperature for heating or monthly average temperature

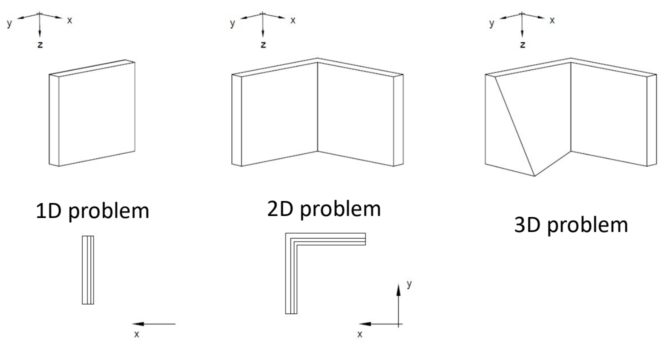
Thermal bridge



$$H_T = \sum_i U_i\, A_i + ?$$

Thermal bridge

The local thermal transmittance corresponding to the thermal bridge can be evaluated either with a 2D or with a 3D geometrical model



Linear/point thermal transmittance

How to evaluate the impact of thermal bridges on the overall heat loss of the building ?

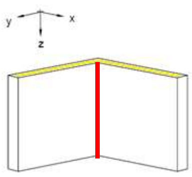
HEAT LOSS DUE TO TRANSMISSION THROUGH THE ENVELOPE	$q_T = H_T\,(\theta_i - \theta_e)$
TRANSMISSION HEAT TRANSFER COEFFICIENT – **without thermal bridges**	$H_T = \sum_i U_i\,A_i$
TRANSMISSION HEAT TRANSFER COEFFICIENT – **with thermal bridges**	$H_T = \sum_i U_i\,A_i + \sum_j \Psi_j\,l_j + \sum_k \chi_k$

LINEAR THERMAL BRIDGES

POINT THERMAL BRIDGES

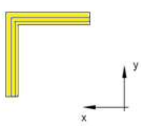
Linear/point thermal transmittance

Example: corner junction between external walls



$$H_T = \sum_i U_i\,A_i + \sum_j \Psi_j\,l_j$$

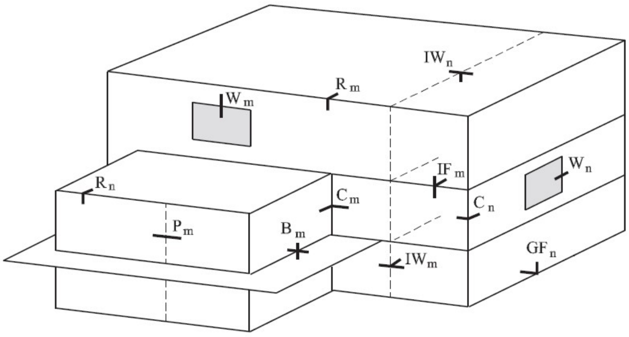
Length of the linear thermal bridge, l (m) depends on the building dimensions (specific to the building considered!)



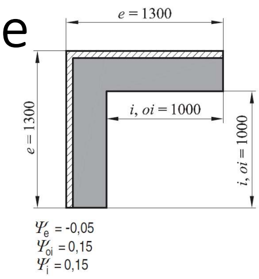
Linear thermal transmittance, $\boldsymbol{\Psi}$ depends on the type of the thermal bridge → 2D heat conduction problem on the cross-section!

Potential thermal bridges

Pre-calculated values of **linear thermal transmittance Ψ** for default thermal bridges

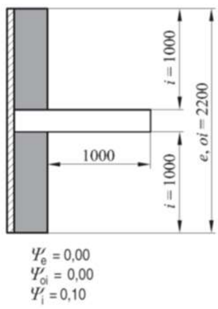


Reference length for the thermal bridge



Internal and external dimensions

- **internal dimensions**: measured between the finished internal faces of each room in a building (thus excluding the thickness of internal partitions);
- **overall internal dimensions**: measured between the finished internal faces of the external elements of the building (thus including the thickness of internal partitions);
- **external dimensions**: measured between the finished external faces of the external elements of the building.



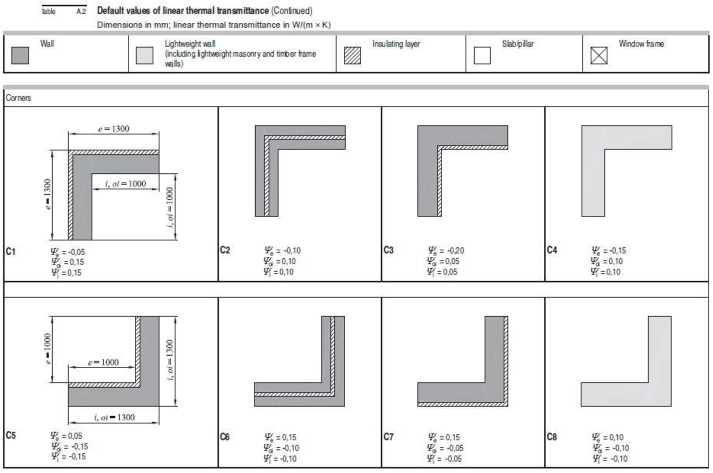
Simplified method (former EN ISO 14683)

Linear thermal transmittance Ψ

Default values of EN ISO 14683

Corners

(C1..C8)



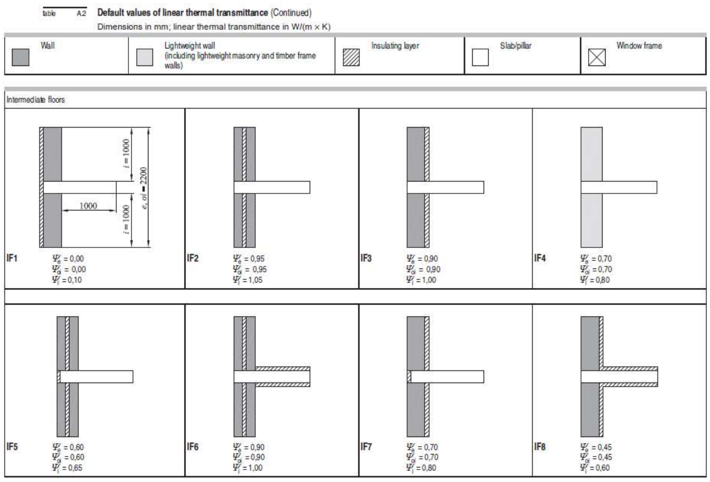
Simplified method (former EN ISO 14683)

Linear thermal transmittance Ψ

Default values of EN ISO 14683

Intermediate floors

(IF1..IF8)



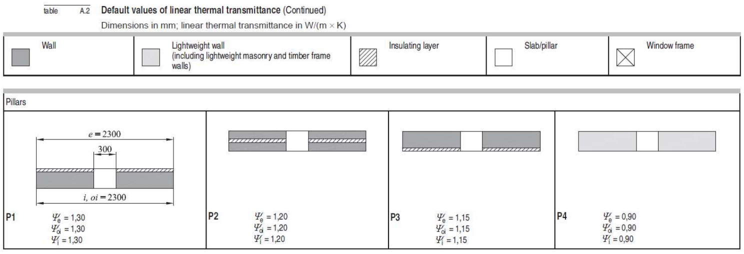
Simplified method (former EN ISO 14683)

Linear thermal transmittance Ψ

Default values of EN ISO 14683

Pillars

(P1..P4)



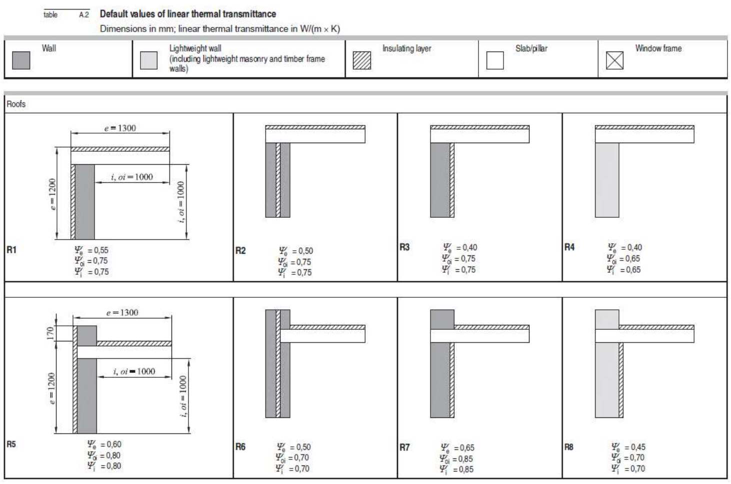
Simplified method (former EN ISO 14683)

Linear thermal transmittance Ψ

Default values of EN ISO 14683

Roofs

(R1..R8)

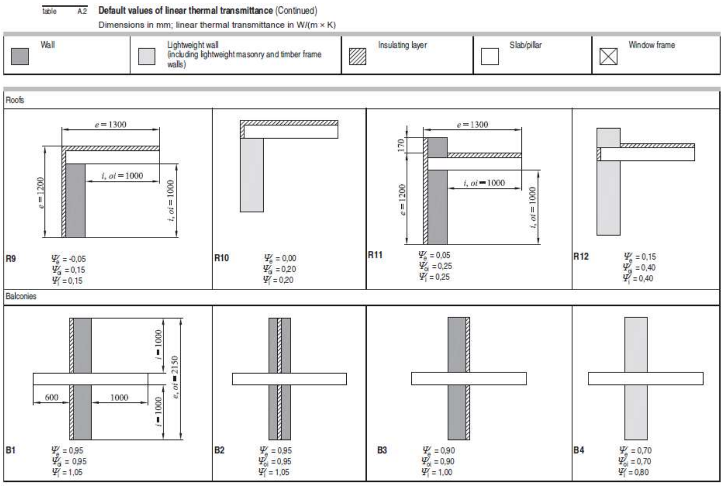


Simplified method (former EN ISO 14683)

Linear thermal transmittance *Ψ*

Default values of EN ISO 14683

Roofs (R9..R12) and balconies (B1..B4)



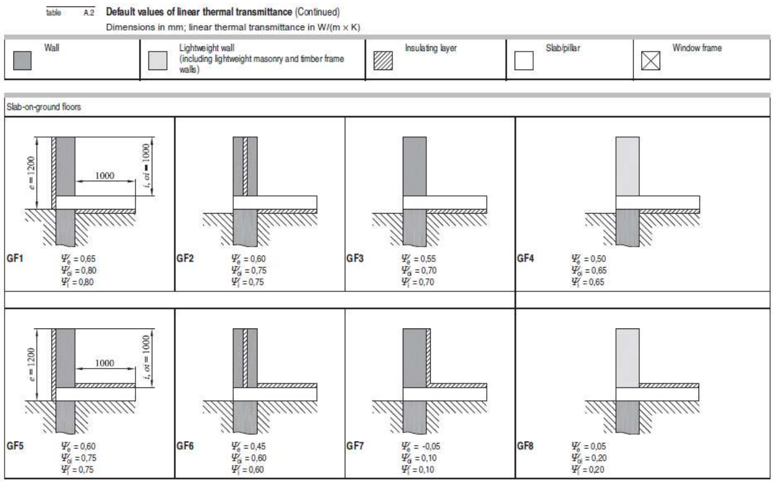
Simplified method (former EN ISO 14683)

Linear thermal transmittance *Ψ*

Default values of EN ISO 14683

Slab-on-ground floors

(GF1..GF8)



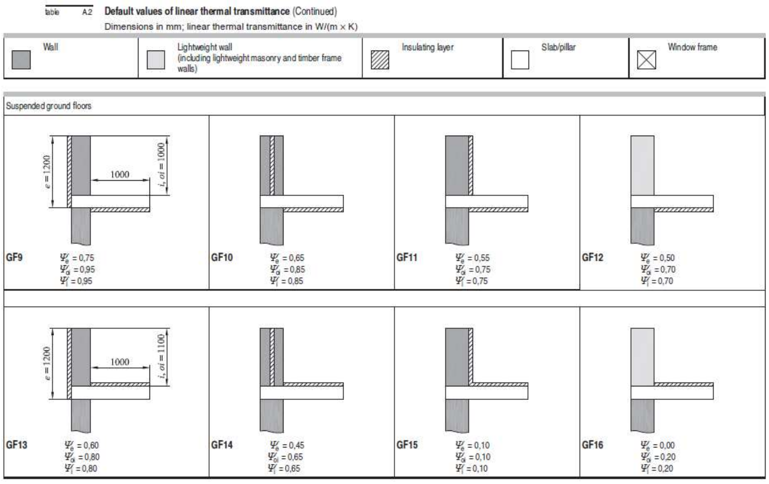
Simplified method (former EN ISO 14683)

Linear thermal transmittance Ψ

Default values of EN ISO 14683

Suspended ground floor

(GF9..GF16)

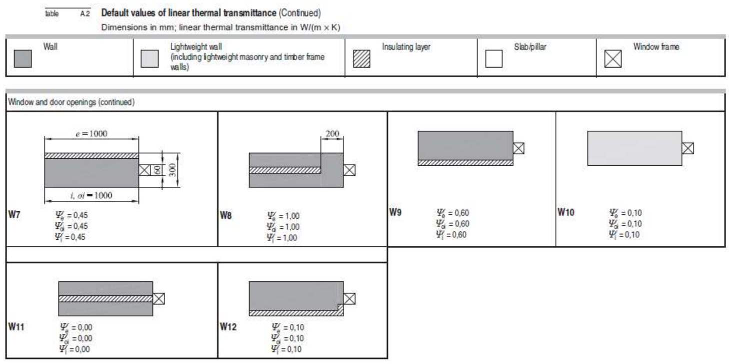


Simplified method (former EN ISO 14683)

Linear thermal transmittance Ψ

Default values of EN ISO 14683

Windows and door openings (W1..)



Overall heat loss

How can we calculated the overall heat loss?

1. Evaluate types of thermal bridge and lengths
2. The heat transmission coefficient H_T to account for additional heat flow due to thermal bridge

$$H_T = \sum_i U_i A_i + \sum_j \Psi_j l_j$$

Possible calculation methods:

Expected accuracy

When selecting a particular method, its accuracy should reflect the accuracy required in calculating the overall heat transfer, taking into account the lengths of the linear thermal bridges. Possible methods for determining ψ include:

- **numerical calculations** (typical accuracy **±5%**);
- thermal bridge catalogues (typical accuracy ±20%);
- **default values** (typical accuracy **0% to 50%**)

Table A.2 of UNI EN ISO 14683 provides default values, calculated for parameters representing worst-case situations → OVERRATE!

Heat conduction in solids

Fourier law + conservation of energy

$$\begin{cases} \vec{q} = -k\,\nabla T \\ q + \dot{q}_v = \rho c_p \dfrac{\partial T}{\partial t} \end{cases}$$

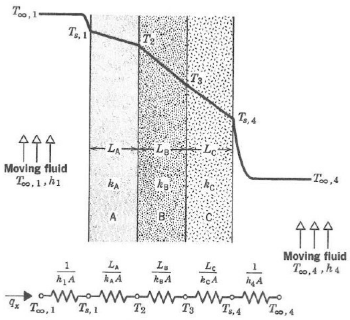
$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + \dot{q}_v = \rho c_p \frac{\partial T}{\partial t}$$

Heat conduction in solids

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + \dot{q}_v = \rho c_p \frac{\partial T}{\partial t}$$

Assumption		Equation
2D problem	$\frac{\partial T}{\partial z} = 0$	$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}$
no internal heat generation	$\dot{q}_v = 0$	$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) = \rho c_p \frac{\partial T}{\partial t}$
steady-state	$\frac{\partial T}{\partial t} = 0$	$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) = 0$

Heat conduction in solids

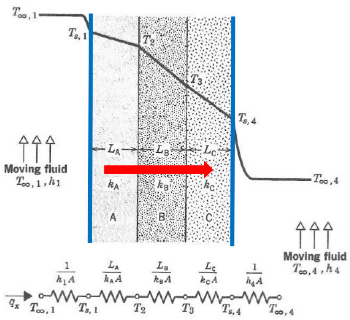


Equivalent thermal circuit for a composite wall
(Incropera & DeWitt, 1981)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) = 0$$

Heat conduction in solids

Analytical solution for 1D steady-state problem on a composite wall



Equivalent thermal circuit for a composite wall
(Incropera & DeWitt, 1981)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) = 0$$

ELECTRICAL ANALOGY (1)

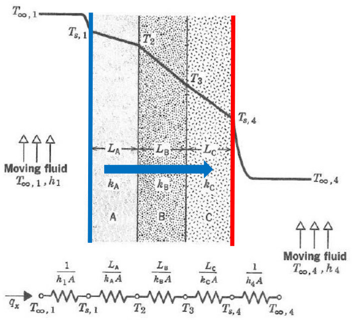
Fix temperature difference (T_1 - T_2)

→ find heat flow q_x

$$q_x = \frac{(T_1 - T_2)}{\sum_i R_i}$$

Heat conduction in solids

Analytical solution for 1D steady-state problem on a composite wall



Equivalent thermal circuit for a composite wall
(Incropera & DeWitt, 1981)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) = 0$$

ELECTRICAL ANALOGY (2)

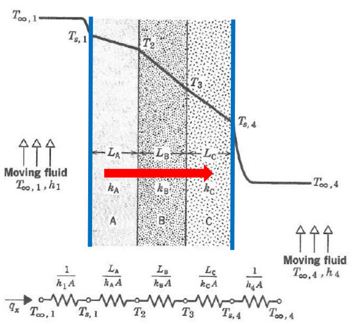
Fix one temperature and heat flow q_x

→ find other temperature

$$T_2 = T_1 - \frac{q_x}{\sum_i R_i}$$

Heat conduction in solids

Analytical solution for 1D steady-state problem on a composite wall



Equivalent thermal circuit for a composite wall
(Incropera & DeWitt, 1981)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) = 0$$

Input variables (boundary conditions)	Temperature of internal and external air $T_{\infty,1}, T_{\infty,4}$
Parameters	Physical and geometrical properties $h_1, h_4, L_A, k_A, L_B, k_B, L_C, k_C$
Output variable	Heat flow rate $q_x = A \dfrac{T_{\infty,1} - T_{\infty,4}}{\frac{1}{h_1} + \frac{L_A}{k_A} + \frac{L_B}{k_B} + \frac{L_C}{k_C} + \frac{1}{h_4}}$

Heat conduction in solids

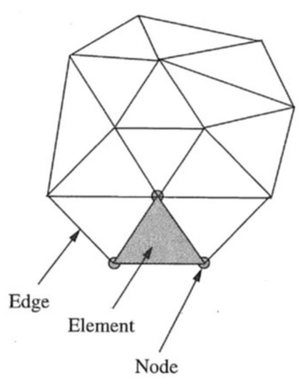
The same logic applies for the 2D problem:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) = 0$$

1. Set physical and geometrical parameters;
2. Set boundary conditions (fixed temperature or heat flow rate);
3. Calculate the temperature distribution on the x-y plane with a numerical method T = T(x,y);
4. Calculate heat flow through the thermal bridge based on the temperature distribution.

Heat conduction in solids

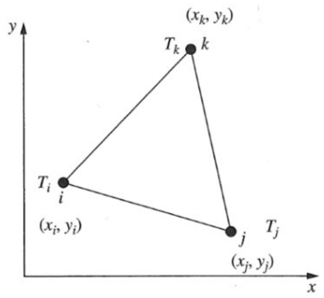
Finite Element Methods (FEM)



- The domain is subdivided into a set (**mesh**) of triangular elements

Heat conduction in solids

Finite Element Methods (FEM)



- The domain is subdivided into a set (**mesh**) of triangular elements
- The temperature between adjacent nodes is set to be linearly dependent on the space variables *x* and *y*

$$T(x, y) = \alpha_1 + \alpha_2 x + \alpha_3 y$$

- The temperature distribution is expressed through so-called **shape functions**

$$T = N_i T_i + N_j T_j + N_k T_k = \begin{bmatrix} N_i & N_j & N_k \end{bmatrix} \begin{Bmatrix} T_i \\ T_j \\ T_k \end{Bmatrix}$$

Detailed method (EN ISO 10211)

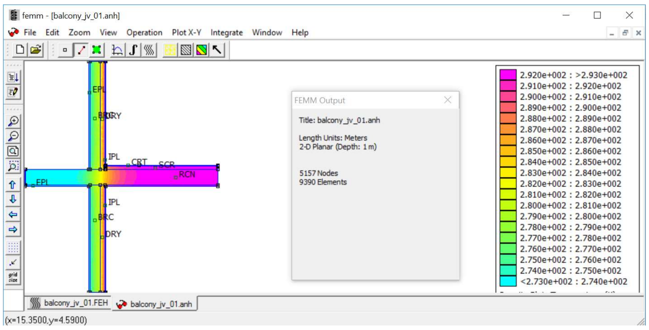
Some free softwares for 2D/3D heat conduction problems

- FEMM 4.2 http://www.femm.info/wiki/Download
- THERM https://windows.lbl.gov/tools/therm/software-download
- QuickField https://quickfield.com/free_soft.htm (limited mesh size)
- ..and many other commercial softwares!

Please download and install FEMM 4.2 on your computer for next week!

Detailed method (EN ISO 10211)

The FEMM 4.2 software is a **finite element** package for solving **2D planar** and axisymmetric magnetic, electrostatic, **steady-state heat conduction**, and current flow **problems**.



Detailed method (EN ISO 10211)

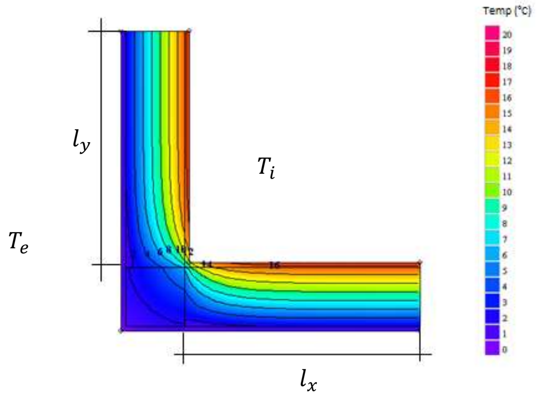
Thermal coupling coefficient

The thermal coupling coefficient ($\boldsymbol{L_{2D}}$ **or** $\boldsymbol{L_{3D}}$) is heat flow rate per temperature difference between two environments which are thermally connected by the construction under consideration.

$$L_{2D} = \frac{Q_{ie}}{l(T_i - T_e)}$$

Detailed method (EN ISO 10211)

Calculation of the linear thermal transmittance

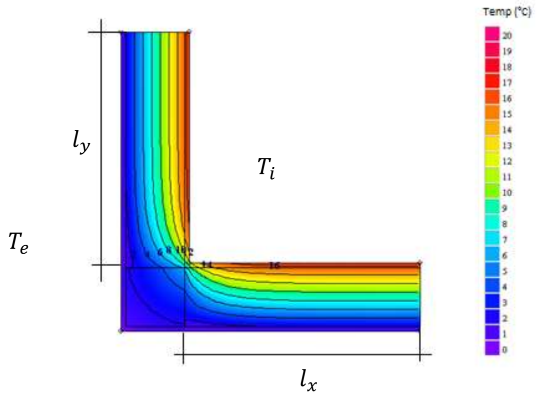


1. Evaluate **temperature distribution** with 2D/3D heat conduction calculation software on a section of the thermal bridge

2. Integrate temperature difference over normal surface to get the **heat flow rate per unit length** of the thermal bridge q_{ie} [W/m]

Detailed method (EN ISO 10211)

Calculation of the linear thermal transmittance



3. Calculate the **thermal coupling coefficient** of the thermal bridge

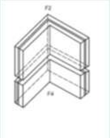
$$L_{2D} = \frac{q_{ie}}{(T_i - T_e)}$$

4. Calculate the **linear thermal transmittance** (additional heat flow rate due to thermal bridge)

$$\Psi = L_{2D} - (U_x l_x + U_y l_y)$$

Detailed method (EN ISO 10211)

Calculation of the linear/point thermal transmittance

Geometrical model	Example	Method
2D		Linear thermal transmittance, Ψ (W/(m K)) Thermal coupling coefficient from 2D calculation, L_{2D} (W/(m K)) $\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \, l_j$
3D		Point thermal transmittance, χ (W/K) Thermal coupling coefficient from 3D calculation, L_{3D} (W/K) $\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \, A_i - \sum_{j=1}^{N_j} \Psi_j \, l_j$

Detailed method (EN ISO 10211)

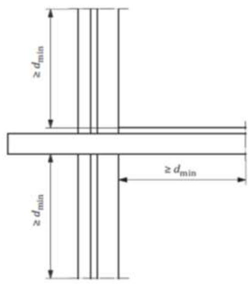
Steps for the calculation of the thermal bridge with FEMM 4.2:

1. Import geometry from a .dxf file
2. Set material properties for each building component
3. Set boundary conditions (internal and external temperature and surface heat transfer coefficients)
4. Create a mesh to discretize the domain
5. Run the FEM solver to calculate the temperature distribution
6. Assess thermal coupling coefficient (L_{2D}) and minimum surface temperature

Detailed method (EN ISO 10211)

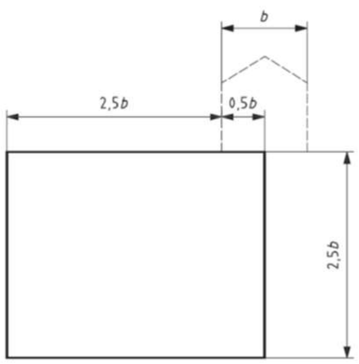
Calculation of the 2D thermal coupling coefficient

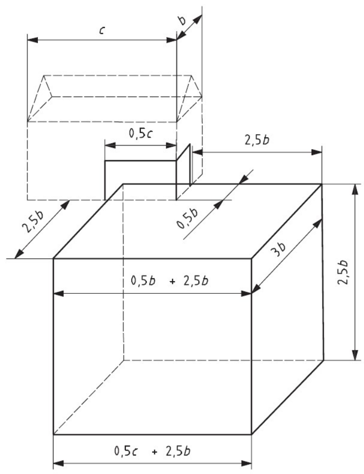
Minimum distances of cut-off planes for 2D geometrical models is a function of envelope thickness



Detailed method (EN ISO 10211)

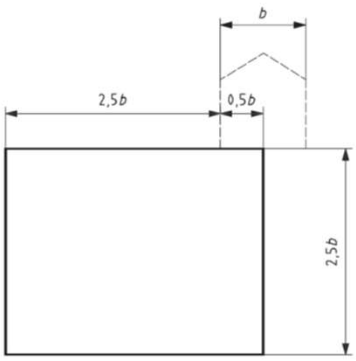
Cut-off planes in the ground

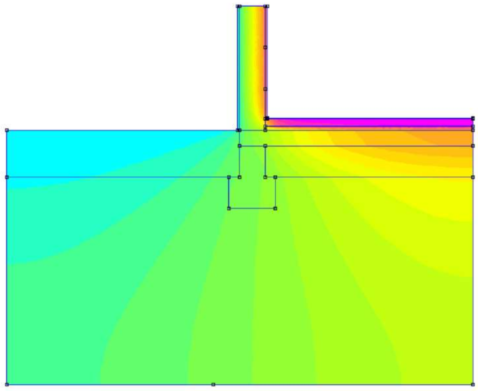




Detailed method (EN ISO 10211)

Cut-off planes in the ground





Detailed method (EN ISO 10211)

More than two boundary temperatures

The procedure is longer: one thermal coupling coefficient must be calculated for each of the mutual thermal connections between the environments.

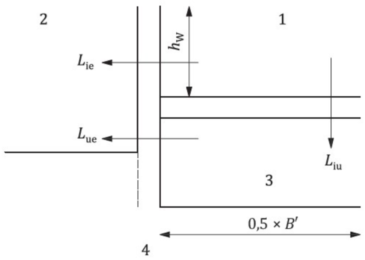
$$q_{i,j} = L_{2D_{i,j}}(T_i - T_j)$$

$$q = \sum_{i<j} |q_{i,j}|$$

Detailed method (EN ISO 10211)

More than two boundary temperatures

Annex E provides a useful calculation example for a suspended floor with indoors (1), outdoor (2) and unheated space (3) with two options: with and without ventilation in the unheated space.



Key

1 internal environment, θ_i

2 external environment, θ_e

3 underfloor space, θ_u

4 ground

B' characteristic dimension of floor

h_W minimum distance from junction to cut-off plane

L_{ie} thermal coupling coefficient between internal and external environments

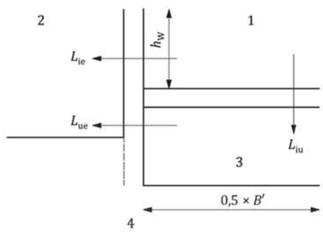
L_{iu} thermal coupling coefficient between internal environment and underfloor space

L_{ue} thermal coupling coefficient between underfloor space and external environment

Detailed method (EN ISO 10211)

More than two boundary temperatures

Calculation number	θ_{int} (°C)	θ_u (°C)	θ_e (°C)
1	1	0	0
2	0	1	0
3	0	0	1



$$L_{iu} = 0.5\,(L_1 - L_2 + L_3)$$

$$L_{ie} = 0.5\,(L_1 + L_2 - L_3)$$

$$L_{ue,c} = 0.5\,(L_2 + L_3 - L_1)$$

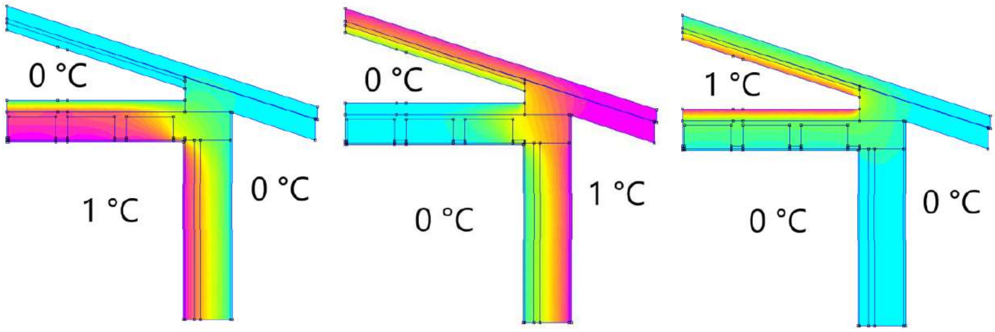
$$L_{ue} = L_{ue,c} + L_{ue,ve} = L_{ue,c} + \rho\, c_p \dot{V}$$

$$\begin{cases} q = L_{iu}(\theta_{int} - \theta_u) + L_{ie}(\theta_{int} - \theta_e) \\ q = L_{2D}\,(\theta_{int} - \theta_e) \end{cases}$$

$$L_{2D} = \frac{L_{iu} L_{ue}}{L_{iu} + L_{ue}} + L_{ie}$$

Detailed method (EN ISO 10211)

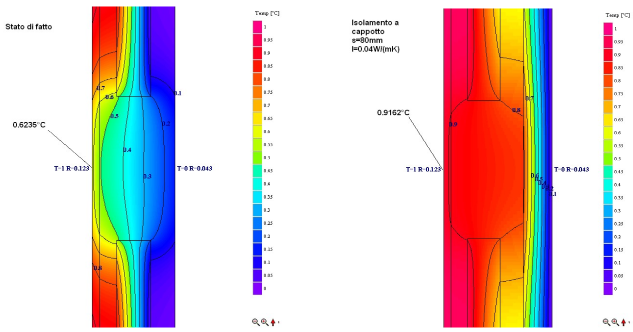
More than two boundary temperatures



Detailed method (EN ISO 10211)

Example of temperature distribution

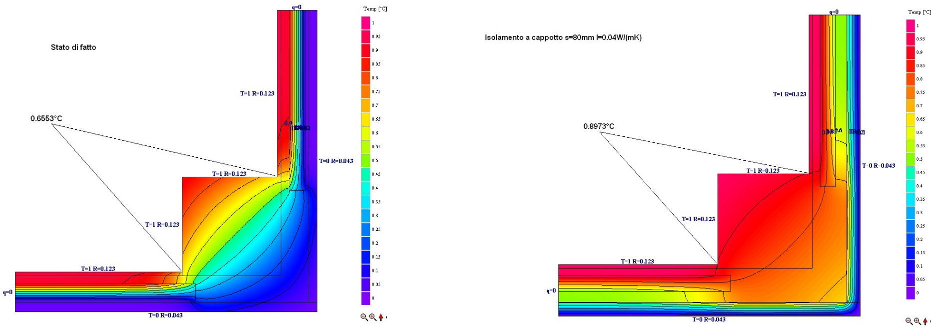
Full or partial penetration of the building envelope by **materials** with a different thermal conductivity: pre-fabricated sandwich panels for industrial buildings



Detailed method (EN ISO 10211)

Example of temperature distribution

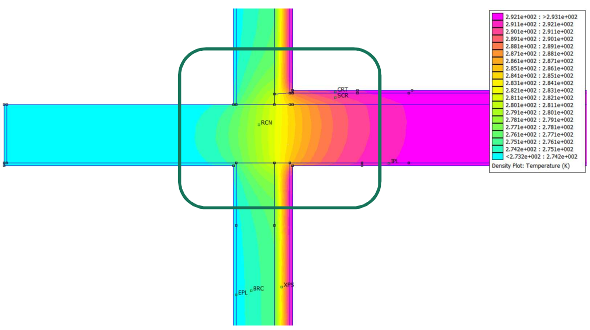
Change in **thickness of the fabric** or **difference between internal and external areas:** wall junctions by concrete pillars.

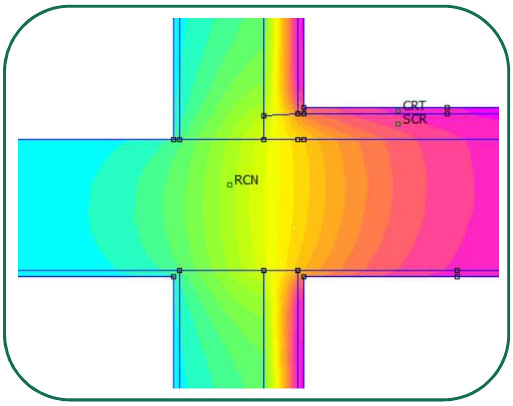


Detailed method (EN ISO 10211)

Example of temperature distribution

Balcony without thermal insulation





Detailed method (EN ISO 10211)

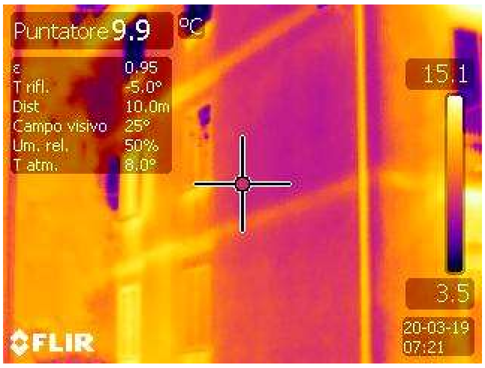
Example of temperature distribution

Balcony without thermal insulation

Detailed method (EN ISO 10211)

Example of temperature distribution

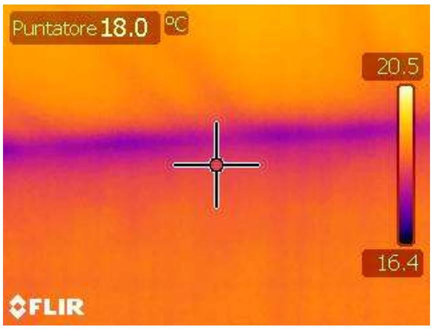
Intermediate floor junctions

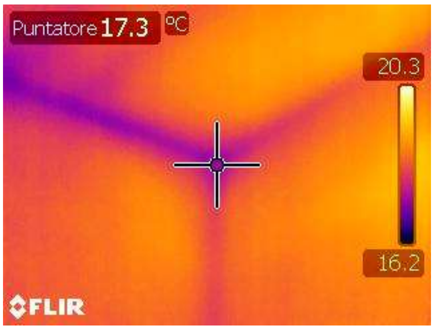


Detailed method (EN ISO 10211)

Example of temperature distribution

Intermediate floor junctions

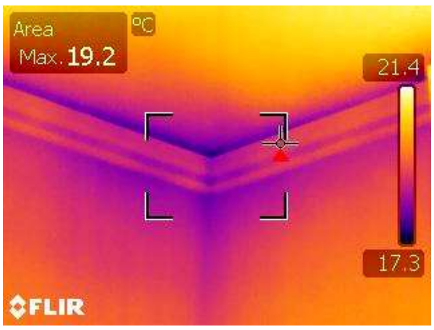


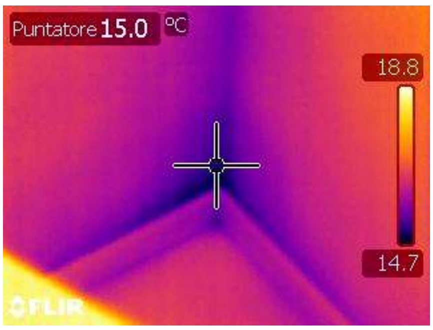


Detailed method (EN ISO 10211)

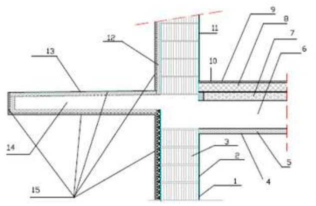
Example of temperature distribution

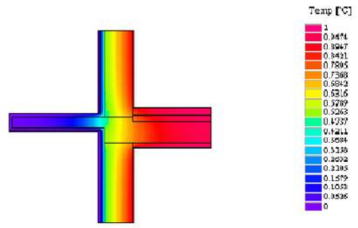
Intermediate floor junctions





Detailed method (EN ISO 10211)





TRASMITTANZA parete verticale [W/m²K]	0,35
TRASMITTANZA solaio [W/m²K]	0,33
TRASMITTANZA terrazza [W/m²K]	0,45

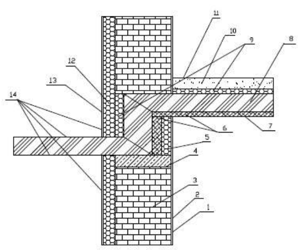
L2D = 0.973 W/(m K)

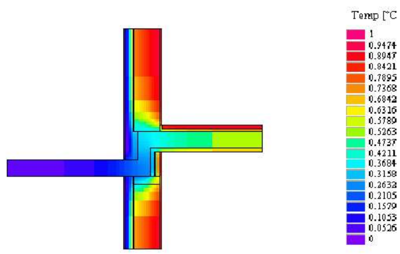
Ψi = 0.273 W/(m K)
Ψe = 0.0735 W/(m K)

FRsi = 0.934

N	DESCRIZIONE STRATO dall'interno all'esterno	s [mm]	λ [W/mK]	R [m²K/W]
1	adduttanza interna metà superiore della stanza	0	0	0,25
2	intonaco ecologico	15	0,8	0,01875
3	mattoni ad alta resistenza meccanica M.V.800	380	0,297	1,279461
4	isolante a soffitto	50	0,024	2,083333
5	adduttanza interna soffitto	0	0	0,108
6	soletta in c.a. non esposto	290	1,16	0,25
7	sotto fondo di ricoprimento	80	0,49	0,163265
8	massetto per pannello radiante	90	0,52	0,173077
9	pavimentazione	15	0,45	0,033333
10	adduttanza interna del pavimento	0	0	0,172
11	adduttanza interna metà inferiore della stanza	0	0	0,35
12	cappotto isolante	50	0,04	1,25
13	cappotto isolante	40	0,04	1
14	soletta in c.a. non esposto	140	1,16	0,12069
15	adduttanza esterna comune a tutte le pareti esterne	0	0	0,04

Detailed method (EN ISO 10211)





TRASMITTANZA TERMICA parete verticale[W/m²K]	0,377

L2D = 4.574 W/(m K)

Ψi = 3.823 W/(m K)
Ψe = 3.74 W/(m K)

FRsi = 0.584

N	DESCRIZIONE STRATO dall'interno all'esterno	s [mm]	λ [W/mK]	R [m²K/W]
1	adduttanza interna	0	0	0,13
2	intonaco interno	15	0,35	0,0428571
3	muratura	240	0,56	0,4285714
4	elemento di sostenimento	240	0,79	0,3037975
5	pannello isolante	40	0,04	1
6	pannelli di rivestimento della trave	20	0,79	0,0253165
7	adduttanza interna lato soffitto	0	0	0,108
8	trave portante in acciaio IPB 140	140	60	0,0023333
9	pannelli isolanti	20	0,04	0,5
10	massetto	40	1,4	0,0285714
11	adduttanza interna lato pavimento	0	0	0,172
12	cappotto esterno	80	0,04	2
13	intonaco esterno	8	0,87	0,0091954
14	adduttanza esterna comune a tutte le pareti	0	0	0,04

References

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