Development of Limits for the Linear Thermal Transmittance of Thermal Bridges in Buildings

A. Janssens, PhD *Member ASHRAE* **E. Van Londersele** **B. Vandermarcke** **S. Roels, PhD**

P. Standaert, PhD **P. Wouters, PhD**

ABSTRACT

Numerical tools for two-dimensional or three-dimensional heat transfer are readily available to the building professional to calculate the thermal transmittance of thermal bridges. However, designers need appropriate limits to compare the predicted performance and decide whether it is necessary to improve the detailing. This paper presents a methodology to develop such limiting values. First, the influence of thermal bridge geometry and insulation thickness on the linear transmittance is analyzed. Then the two-dimensional transmission heat loss resulting from all joints encountered in five typical masonry dwelling designs is quantified. The distribution of the heat loss over different components (junctions with roof, window, foundation, etc.) is presented. Finally, limits for the linear thermal transmittance are developed in order to minimize two-dimensional transmission heat loss. The limiting values differ as a function of thermal bridge geometry and take into account the technical feasibility of the requirements.

INTRODUCTION

A thermal bridge is defined as part of the building envelope where the otherwise uniform thermal resistance is significantly changed by (1) a full or partial penetration of the building envelope by materials with a different thermal conductivity, (2) a change in thickness of the fabric, or (3) a difference between internal and external areas, such as occurs at wall, floor, and ceiling junctions (EN 1995). Such thermal bridges typically occur at the junction of different building components where it is difficult to achieve continuity in the thermal insulation layer. Thermal bridges give rise to two- or three-dimensional heat flows and have a major effect on the thermal performance of the building envelope. Numerical calculation methods for two- or three-dimensional heat transfer are readily available to the building professional for use in determining the thermal performance of building details in a precise way. For this, different software tools are available. In this paper the software tools Eurokobra (Physibel 2002) and TRISCO (Physibel 2003) are used.

The results of a two- or three-dimensional heat transfer calculation may be used to evaluate either the internal surface temperatures or the additional heat flow caused by the presence of the thermal bridge. The internal surface temperature is one of the parameters that defines the risk of mold growth on the internal surface. Consequently, in the past, a lot of research was devoted to this aspect of thermal bridge performance (Adan 1994; Hens 1999; Sedlbauer 2001). Scientific results have found their way into technical publications and standards with recommendations to control and prevent the occurrence of mold growth on interior surfaces. Typically, the minimum dimensionless surface temperature or temperature factor f is used as an indicator to characterize thermal bridge performance (EN 1995). Since the interior surface film resistance has an important effect on the result of the heat transfer calculation, its value is often indicated as a suffix, e.g., $f_{0.2}$. Design criteria may vary from country to country but, in general, a lower limiting value of 0.7 is accepted for the temperature factor to reduce the risk of mold growth in dwellings (IEA Annex 14 1990; Wouters et al. 2003).

__A. Janssens__ is an associate professor and __E. Van Londersele__ is a researcher at the Department of Architecture and Urban Planning, Gent University, Gent, Belgium. __B. Vandermarcke__ is a professor at St. Lucas School of Architecture, Gent and Brussels, Belgium. __S. Roels__ is an associate professor at the Department of Building Physics of Catholic University of Leuven, Belgium. __P. Standaert__ is head of Physibel, a software company, and associate professor at Catholic University of Leuven. __P. Wouters__ is director of development and valorisation, Belgian Building Research Institute and manager of EUROKOBRA EEIG, Brussels.

However, a constructional detail that meets the mold control criteria is not necessarily a detail with minimized heat flow. While design guidelines have focused on mold control in the past, in building practice, thermal bridges have often emerged with acceptable performance for mold control but with an important influence on transmission heat loss. This is certainly the case in masonry cavity wall construction, where it is difficult to create a thermal break between the interior and exterior masonry leaf at all junctions for structural reasons. Figure 1 gives an example of a typical thermal bridge for a window lintel. As the temperature factor of the detail is larger than 0.7, the mold growth risk is small.

The better the insulation of the building envelope, the larger the relative contribution of thermal bridges on the overall transmission heat loss of the building and the more important it is to develop improved constructional details. However, designers need appropriate limits to compare the predicted performance and decide whether it is necessary to improve the detailing. Moreover, the existence of sufficiently severe limits may stimulate the development and application of innovative solutions for thermal bridges in the building market. Based on these arguments, the Flemish government in Belgium aims to introduce guidelines on thermal bridges as part of new legislation on the energy performance of buildings.

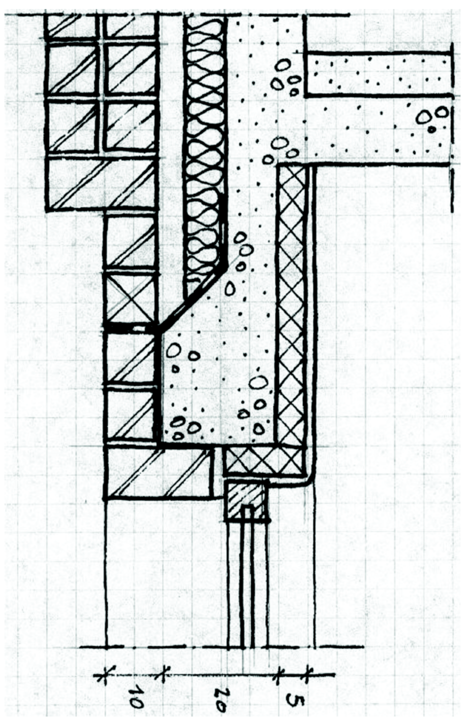

Figure 1 *Example of a typical detail cavity wall—window lintel optimized for mold control but not for heat loss:* $f_{0.2}$ *= 0.74,* ψ_e *= 0.53 W/m·K.*

This paper presents a methodology to develop such limiting values. First, the influence of thermal bridge geometry and insulation thickness on the linear transmittance is analyzed. Then the two-dimensional transmission heat loss resulting from all joints encountered in five typical masonry cavity wall dwelling designs is quantified. The distribution of the heat loss over different components (junctions with roof, window, foundation, etc.) is presented. Finally, limits for the linear thermal transmittance are developed in order to minimize two-dimensional transmission heat loss. The limiting values differ as a function of thermal bridge geometry and take into account the technical feasibility of the requirements.

LINEAR THERMAL TRANSMITTANCE

Definition

Linear thermal transmittance may be calculated from the steady-state two-dimensional heat flow, predicted with a numerical finite element or finite difference method. The two-dimensional nature of the heat flow results in additional heat losses that cannot be evaluated simply by one-dimensional U-factor calculations. The way in which the supplementary heat flow through building element junctions is calculated depends in the first place on the way the one-dimensional heat transfer is defined. This can be done on the basis of conventions and simplifications concerning the dimensions of the surfaces that correspond to different U-factors. These conventions are generally defined in national standards on heat transmission, and they differ, in general, from country to country. In this paper, we assume by convention that the one-dimensional heat flow is determined on the basis of external dimensions for all building components, measured between the finished external faces of a building (Figure 2).

The linear thermal transmittance (Ψ) now defines the additional two-dimensional heat loss in comparison to the one-dimensional reference heat loss in the adjacent building elements, each with a certain U-factor and area (Equation 1). The system of dimensions on which the linear thermal transmittance is based is represented by a suffix (Ψ_e).

$$\Psi = \frac{\Phi_{2D}}{L(\theta_i - \theta_e)} - \sum_n (A_i U_i) \qquad (1)$$

In Equation 1, Ψ is the linear thermal transmittance (W/m·K); Φ_{2D} is the global heat flow through the junction as predicted with the numerical method (W); L is the length of the junction, often 1 m in the geometrical model; $\theta_i - \theta_e$ is the temperature difference between the inside and outside environments (K); U_i (W/m^2·K) is the thermal transmittance of the adjacent building element, i; and A_i is the surface within the two-dimensional geometrical method for which the value U_i applies (m^2).

Influencing Factors

The evaluation of the Ψ-value of a building detail is less straightforward than the evaluation of a U-factor of a building component. According to the definition, the Ψ-value should be seen as a correction factor for the one-dimensional transmission heat loss reference, whereby geometrical aspects (given assumed dimensions) as well as the increasing heat flow have to be taken into account. Consequently, its value depends on several factors:

- Continuity of the thermal insulation layer
- U-factor of adjacent building elements
- Geometrical aspects: position of the thermal insulation, difference between internal and exterior areas (exterior or interior corners), etc.

Before we proceed with the analysis of the influence of building details on transmission heat loss in the next section, we first investigate the influence of thermal bridge geometry and insulation thickness on the linear thermal transmittance.

Continuity and Thickness of Thermal Insulation. A discontinuity in the thermal insulation causes additional one- and two-dimensional heat loss, which is defined by the Ψ-value of the discontinuity. For example, a junction between a concrete column and an external wall with interior insulation is considered (Figure 3). Near the column, the insulation is interrupted over a height, H. It is common to calculate the one-dimensional heat loss through the exterior wall based on the assumption that the thermal insulation is continuous. In this case, the lower boundary of the Ψ-value for the junction may be estimated by Equation 2, based on a one-dimensional calculation of the actual heat loss:

$$\Psi_e \geq H(U_2 - U_1) \tag{2}$$

Figure 3 shows the relation between the Ψ-value of the thermal bridge and the U-factor of the exterior wall. Because of the two-dimensional nature of the heat flow, the Ψ-value, based on numerical calculations, is approximately 25% larger than the one predicted by Equation 2. As the U-factor decreases (thicker insulation), the additional heat loss becomes more important and the Ψ-value increases. At lower U-factors, the Ψ-value first reaches a nearly constant value and then slightly decreases again as the thermal resistance of the concrete column becomes higher with increasing wall thickness. However, at wall U-factors smaller than 0.6 W/m^2·K, the variation of Ψ is limited (less than 5%) and the linear thermal transmittance may be regarded as a measure for the thermal quality of the building detailing, independent of the U-factor of the adjacent building elements.

Geometry of Corners. The value of the linear thermal transmittance is also affected by the difference between the interior and exterior dimensions of the components connected at the building junction, as is the case at building corners. When external building dimensions are used to define the heat loss surface, the heat loss surface is overestimated at building junctions near exterior corners. The opposite is true near interior corners. As a consequence, the linear thermal transmittance of corner details differs from zero, even when a continuous thermal insulation is present at the corner.

As demonstrated in Figure 4, there exists an analytical solution to calculate the linear thermal transmittance of a corner detail in case the wall consists of a single material layer with given thermal conductivity, λ, and an isothermal interior and exterior surface (Bejan 1993). The analytical solution shows that the linear thermal transmittance assumes a negative value at exterior corners and a positive value at interior corners. The higher the thermal conductivity of the wall layer,

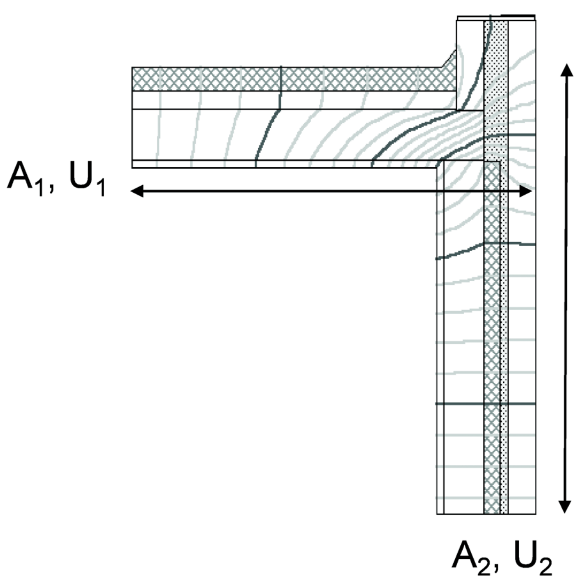

Figure 2 *Building junction with conventions for the one-dimensional geometrical reference.*

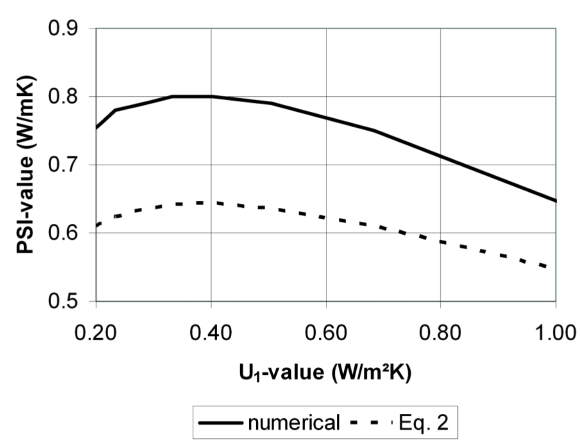

Figure 3 *External wall with interior insulation: relation between the Ψ-value of a concrete column intersection and the U-factor of the exterior wall.*

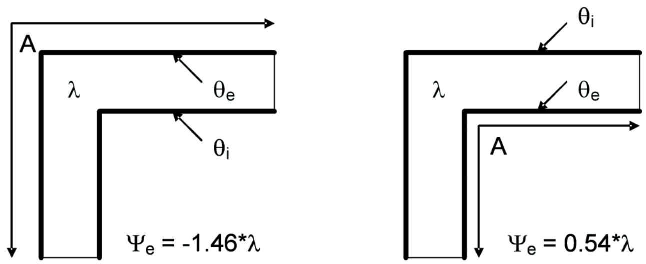

Figure 4 *Analytical solution for the linear thermal transmittance, Ψ_e, for exterior (left) and interior (right) corner junctions (Bejan 1993).*

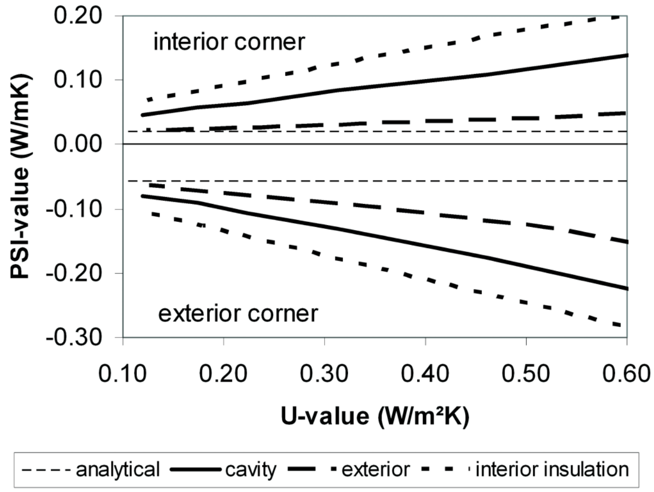

Figure 5 *Ψ-value of corner junctions of insulated masonry walls with exterior, interior, or cavity insulation.*

the stronger Ψ_e deviates from zero. This is only due to the overestimation or underestimation of the heat loss surface.

In reality, the wall surfaces are nonisothermal. Still, the analytical findings are confirmed by the results of numerical calculations of corners in insulated masonry walls. Figure 5 shows results for masonry wall corners continuously insulated with exterior, interior, or cavity insulation. The figure relates the U-factor to the Ψ_e-value of corner junctions. Also, here the Ψ_e-value deviates more from zero when the wall is poorly insulated. In the limit of an ideal thermal insulation ($U \rightarrow 0$), the result of the numerical calculation corresponds to the analytical solution given in Figure 4 (based on a thermal conductivity of 0.039 W/m·K of the thermal insulation used in the numerical calculations). Also, the position of the thermal insulation has an influence on the linear thermal transmittance. When the thermal insulation is positioned closer to the interior, the assumption that the heat loss surface is defined by the exterior dimensions deviates more from the physical reality. As a consequence, the Ψ_e-value diverges more strongly from zero.

Similar geometrical effects play a role for all details where the internal area differs from the external, e.g., in wall-window junctions. These results indicate that linear thermal transmittances are only comparable when the junctions have an equivalent geometry. When junctions with a dissimilar geometry are compared, differences in the Ψ_e-value are not necessarily a sign of better or poorer thermal quality of the detailing.

INFLUENCE OF BUILDING DETAILS ON TRANSMISSION HEAT LOSS

Definitions

The transmission heat flow rate between the interior and exterior environments is expressed in Equation 3. The effect of thermal bridges is often ignored in heat loss calculations because the correct calculation of linear thermal transmittance is quite laborious. However, buildings can contain significant thermal bridges, either because of a large length of junctions per unit of the heat loss surface or because of junctions with a large linear thermal transmittance. If the influence of point thermal bridges is neglected, the contribution of thermal bridges, ΔU_{TB}, to the average thermal transmittance of the building envelope may be expressed by Equation 4.

$$\Phi_T = (\sum U_i A_i + \sum \Psi_j L_j + \sum \chi_k)(\theta_i - \theta_e) = U_m A_T(\theta_i - \theta_e) \quad (3)$$

$$\Delta U_{TB} = \sum \Psi_j L_j / \sum A_i \quad (4)$$

In the above equations, Φ_T is the transmission heat loss (W); U_i is the thermal transmittance of component i of the building envelope (W/m^2·K); A_i is the area over which U_i applies (m^2); Ψ_j is the linear thermal transmittance of building junction j (W/m·K); L_j is the length over which Ψ_j applies (m); χ_k is the point thermal transmittance of the point thermal bridge, k (W/K); U_m is the average thermal transmittance of the building envelope (W/m^2·K); and A_T is the overall transmission heat loss surface (m^2).

In many countries the legislation defines maximum values for the average thermal transmittance of the building envelope. In Flanders (Belgium), building regulations have become more severe since January 2006, with limiting values depending on building compactness (heated volume over heat loss surface). For buildings with a compactness smaller than one (typically detached single-family houses), a maximum value of 0.45 W/m^2·K must be respected for the average U_m- value. For buildings with a compactness larger than four, the requirement is 0.90 W/m^2·K. For buildings with a compactness between one and four, the maximum U_m-value is interpolated between 0.45 and 0.90 W/m^2·K. At the moment, no specific requirements for thermal bridges are given in the legislation.

In the following sections, the contribution of the two-dimensional transmission heat loss to the average thermal transmittance is analyzed in more detail on the basis of Equation 4.

Reference Dwellings

To create a better understanding of the relative importance of thermal bridges, the two-dimensional transmission heat loss resulting from all junctions encountered in five typical masonry cavity wall dwelling designs is quantified. The reference dwelling designs have been developed in the framework of a research project on the optimization of building envelopes and services for low-energy residential buildings. The five dwellings are all single-family houses with the same program (four-person families) and the same useful floor area, corresponding to national statistical figures. The dwellings only differ in typology and building compactness, ranging from a detached bungalow to a flat in a six-floor apartment building. Table 1 gives a survey of all geometrical characteristics of the five dwellings. Table 2 gives an overview of the length and typology of all junctions encountered in the dwellings.

Thermal Quality of Building Details

The transmission heat loss related to linear thermal bridges was analyzed for each of the dwellings. The building envelope consisted of traditional constructions that are most commonly found in the Belgian housing stock: insulated cavity walls, warm flat roofs with concrete floors, insulated cathedral ceilings with woodframe structures, concrete ground floors and floors above grade, etc. To determine a representative linear transmittance for each junction, the two-dimensional heat loss was calculated assuming a thermal insulation thickness of 20 cm ($U \approx 0.2$ W/m^2·K). As Figures 3 and 5 show, the Ψ_e-value of a building junction assumes a nearly constant value at lower U-factors. This way, the result of the transmission heat loss analysis gives a safe assessment of the influence of thermal bridges.

The analysis is based on three different scenarios with respect to the thermal quality of building details. The difference between the three scenarios is illustrated in Figure 6.

1. *Business as usual*. Various random checks at construction sites have established that, in building practice, still little attention is paid to a minimization of heat loss at building junctions (BBRI 1998). In this scenario, typical structural intrusions in the thermal insulation are present at window reveals, roof eaves and elevations, foundation junctions, balconies, bearing walls, etc. However, at junctions between the façade and the inner walls and floors, the insulation is assumed to be continuous.
2. *Standard*. In this scenario, the insulation layer is no longer interrupted around window junctions, but structural breaks at other locations (eaves, bearing walls, etc.) remain unsolved.
3. *Thermal bridge avoidance.* In this case, different techniques were applied to achieve continuous insulation over the building envelope. At all structural connections, specific thermal-break materials or components are present to minimize supplementary heat loss, e.g., aerated concrete blocks or cellular glass insulation blocks in bearing masonry walls, prefabricated reinforcements with thermal breaks at concrete balcony or canopy floors, etc.

The linear thermal transmittances of all building details have been defined by means of numerical methods for two-dimensional heat transfer. Table 3 lists the results of these calculations. The highest transmittance values are found at junctions where the insulation layer is intruded by a structural concrete floor, such as at balconies. The lowest (negative) values are found at exterior corners where the insulation layer is uninterrupted, such as at building corners and at roof eaves.

Table 4 shows the distribution of all junctions over the five types: window, roof (flat and cathedral), floor, and wall junctions. The distribution is based both on total length of building junctions and on total specific heat loss at the junctions for the three detailing scenarios and for all reference dwellings. The total specific heat loss is obtained by adding the products of the linear thermal transmittance and length for each junction. Clearly, the window and floor junctions are more dominant in length. However, for all detailing scenarios, the two-dimensional heat loss at window junctions is the largest compared to other junctions. Even when the window details are optimized (standard scenario), their influence is still about 40% of the total specific heat loss for all junctions. Floor junctions may be further optimized by thermal break solutions so that their influence is reduced by a factor of four (thermal bridge avoidance scenario).

Contribution of Thermal Bridges to Overall Thermal Transmittance

On the basis of all these data, the contribution of thermal bridges to the average thermal transmittance of the building envelope may now be defined according to Equation 4. The increase of the average thermal transmittance as a result of two-dimensional heat transfer at building junctions is given in Figure 7 for the five different reference dwellings. The figure shows the following:

- The relative importance of building junctions on transmission heat loss increases when the building geometry becomes more compact. This is because, in the more compact buildings (terraced houses, apartment buildings), the specific junction length per unit heat loss surface is in general higher (Table 1). Also, in the more compact buildings, the relative length of junctions at exterior corners is smaller. It is only at this type of junctions that the Ψ_e-value becomes negative with good quality of detailing (overestimation of heat loss area [Table 3]) and that the two-dimensional heat loss at other junctions is partly compensated.
- When insufficient attention is paid to the avoidance of thermal bridges, the contribution of building junctions to the overall thermal transmittance amounts to 0.06 to 0.15 W/m^2·K. Compared to the current requirements in Flemish building regulation, the construction details

Table 1. Geometrical Characteristics of Reference Dwellings

	Detached Bungalow	Detached House	Semi-Detached	Terraced House	Apartment Flat
Compactness, m	0.9	1.3	1.6	2.1	3.8
Heated volume, m^3	557.3	528.7	521.0	493.6	450.0
Heat loss area, m^2	611.3	395.4	330.1	231.9	118.4
Number of floors	1	2	2	3	1 (in six-story building)
Total length of building junctions, m	298.6	257.8	218.8	206.2	89.0
Length/area, m/m^2	0.49	0.65	0.66	0.89	0.75

Table 2. Length and Typology of Building Junctions

	Length, m	Detached Bungalow	Detached House	Semi-Detached	Terraced House	Apartment Flat
Window	Windowsill	22.7	15.9	15.4	10.8	9.6
	Window lintel	18.4	20.9	18.9	15.0	7.8
	Window reveal	25.9	33.2	27.2	27.6	20.0
	Dormer window	0.0	4.0	12.0	24.0	0.0
Flat Roof	Eaves	66.0	0.0	0.0	4.8	2.0
	Roof—upper wall	0.0	0.0	0.0	2.2	0.0
	Common wall	0.0	0.0	0.0	2.6	2.4
	Canopy	13.8	0.0	0.0	0.0	1.8
Cathedral Roof	Eaves	0.0	15.2	16.3	12.6	0.0
	Gable wall	0.0	6.1	5.7	0.0	0.0
	Ridge	0.0	11.9	8.1	6.3	0.0
	Upper wall	0.0	2.0	0.0	0.0	0.0
	Bearing wall	0.0	2.0	6.9	9.2	0.0
Floor	Attic floor	0.0	15.2	16.3	12.6	0.0
	Ground floor—exterior wall	75.9	34.1	23.6	11.0	3.0
	Ground floor—interior wall	43.4	20.9	21.6	8.3	0.0
	Ground floor—windowsill	3.9	5.0	3.6	4.2	0.9
	Balcony floor—wall	0.0	0.0	0.0	0.0	3.4
	Balcony floor—window	0.0	0.0	0.0	0.0	5.8
	Floor above grade—wall	0.0	34.9	27.2	21.1	10.0
Wall	Exterior corner	20.0	23.7	8.1	2.9	5.6
	Interior corner	8.6	4.3	0.0	2.9	5.6
	Common wall	0.0	0.0	8.1	28.3	11.2

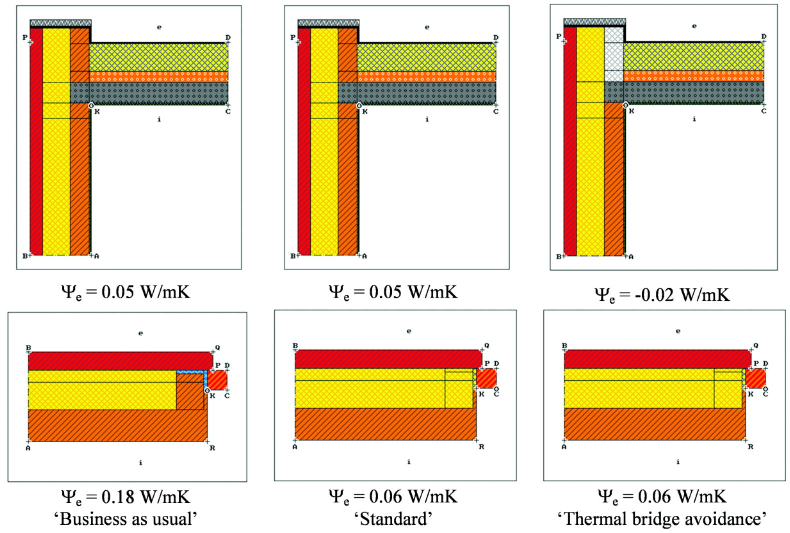

Figure 6 *Typological examples (above: roof eaves; below: window reveal) of building junctions for three scenarios with respect to the thermal quality of building details.*

thus represent 13% to 17% of acceptable transmission heat loss. These results are obtained with the external building dimensions as a reference for the heat loss surface. Of course, when internal dimensions are the reference, the heat transfer at building junctions becomes even more important.

- When attention is paid to thermal bridge avoidance in construction detailing, the contribution of building junctions to the thermal transmittance may be minimized to 0.01 to 0.04 W/m^2·K. This represents only 1% to 4% of current transmission heat loss requirements. In low-energy building design, this quality of detailing is certainly necessary to obtain a sufficiently low average thermal transmittance of the building envelope.

LIMITS FOR THE LINEAR THERMAL TRANSMITTANCE OF THERMAL BRIDGES

There is little information in standards on criteria to evaluate the Ψ-values of building details. The European standards only indicate that a thermal bridge with a Ψ_e-value larger than 0.10 W/m·K may be avoided by improved detailing (EN 1999). In the frame of the Eurokobra project (Wouters et al. 2003), a classification of thermal bridge effects was developed in which a Ψ_e-value larger than 0.50 W/m·K corresponds to a very important effect on heat losses, between 0.25 and 0.50 W/m·K to an important effect, and between 0.10 and 0.25 W/m·K to a reduced effect.

However, these criteria do not take into account the geometrical factors in the value of the linear thermal transmittance. Junctions at exterior corners quite easily obtain a Ψ_e-value smaller than 0.10 W/m·K, even when the thermal insulation is interrupted (see the eaves detail in Figure 6). On the other hand, junctions at interior corners may have a Ψ_e-value larger than 0.10 W/m·K, even with perfectly continuous insulation (Figure 5).

Based on the findings in the previous paragraphs, a new set of Ψ_e-limits is proposed in Table 5, with limiting values adjusted to the geometrical typology of different junctions. When a building design meets this set of requirements, the effect of building junctions on transmission heat loss is limited to 0.02 W/m^2·K for less compact buildings and to 0.05 W/m^2·K for more compact buildings. As a result, the effect of thermal bridges on the thermal transmittance of the building envelope is less than 5%, except for the more compact building types. These figures are found when the limiting values for linear thermal transmittance proposed in Table 5 are introduced in the analysis of the five reference dwellings.

Building designers or manufacturers may use these guiding values to compare the predicted performance of building junctions and decide whether it is necessary to improve the detailing. As Table 3 shows, for most types of building junctions, a further optimization of the Ψ_e-value below the limiting values is useful and technically feasible, often at low cost.

At the moment, the Flemish government in Belgium aims to introduce guidelines on thermal bridges by 2008 as part of the new legislation on the energy performance of buildings, which was introduced in January 2006 in response to the European Energy Performance in Buildings Directive. The preservation of the energy performance legislation is based on a system of as-built evidence coupled with fines in cases of non-compliance. With the guidelines on thermal bridges, the construction market should be motivated to adopt building detailing with reduced thermal bridge effects. Basically, builders and designers will have three possible options to comply with the guidelines:

Table 3. Linear Thermal Transmittance for Different Junctions and Scenarios

	Ψ_e, W/m²·K	Business as Usual	Standard	Thermal Bridge Avoidance
Window	Window sill	0.11	0.02	0.02
	Window lintel	0.66	0.07	0.07
	Window reveal	0.18	0.06	0.06
	Dormer window	0.13	0.13	0.10
Flat Roof	Eaves	0.05	0.05	–0.04
	Roof—upper wall	0.19	0.19	0.05
	Common wall	0.13	0.13	0.10
	Canopy	0.46	0.46	0.10
Cathedral Roof	Eaves	–0.07	–0.07	–0.07
	Gable wall	0.07	0.07	–0.01
	Ridge	0.00	0.00	0.00
	Upper wall	0.06	0.06	0.06
	Bearing wall	0.21	0.21	0.02
	Attic floor	–0.04	–0.04	–0.04
Floor	Ground floor—exterior wall	0.06	0.06	0.02
	Ground floor—interior wall	0.17	0.17	0.01
	Ground floor—window sill	0.19	0.19	0.10
	Balcony floor—wall	0.54	0.54	0.17
	Balcony floor—window	0.76	0.76	0.22
	Floor above grade—wall	0.00	0.00	0.00
Wall	Exterior corner	–0.10	–0.10	–0.10
	Interior corner	0.12	0.12	0.12
	Common wall	0.00	0.00	0.00

1. The thermal influence of building details is calculated in detail by means of numerical methods for two-dimensional and/or three-dimensional heat transfer and taken into account in the calculation of the overall thermal transmittance of the building envelope, which should meet the legal requirements. This way of working is quite laborious and will probably be applied for larger building projects or by specialized designers for specific building details.
2. In case the builder or designer does not pay attention to the avoidance of thermal bridges, the design should meet more severe requirements for the overall thermal transmittance. The contribution of thermal bridges to the overall thermal transmittance is set to a default value of 0.1 W/m^2·K for less compact buildings (C < 1 m) and 0.2 W/m^2·K for more compact buildings (C > 4 m). As Figure 7 shows, this supplement is not unrealistic. The government aims for a dissuading effect with the introduction of this supplement, since the cost to compensate for the supplement by means of thicker insulation layers, improved insulating glazing, etc., is quite high.
3. The thermal influence of thermal bridges is taken into account as a minor supplement of 0.02 (C < 1 m) to 0.04

Table 4. Thermal Bridge Influence over Different Types of Junctions Added over Five Reference Dwellings

	Window	Flat Roof	Cathedral Roof	Floor	Wall
Length, m	329.2	95.6	146.4	361.6	129.1
Specific heat loss, W/K					
Business as usual	73.2	3.4	0.3	25.4	–2.3
Standard	18.1	3.4	0.3	25.4	–2.3
Thermal bridge avoidance	16.6	0.8	–4.6	6.4	–2.3

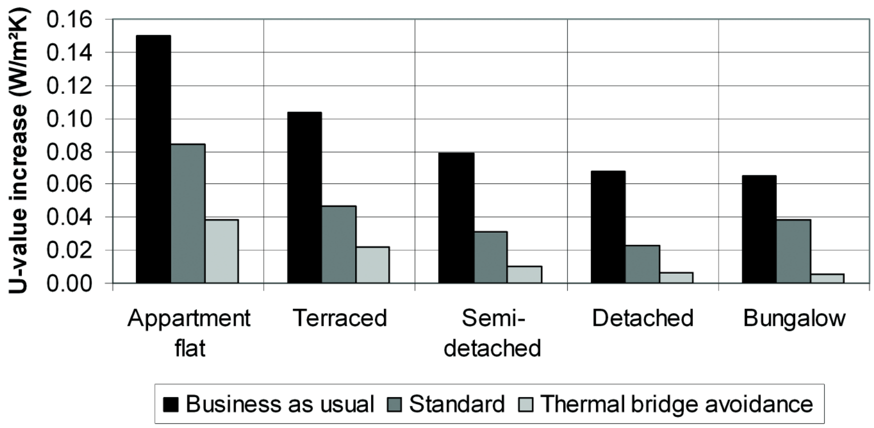

Figure 7 *Contribution of building junctions to the average thermal transmittance of the building envelope as a function of the quality of constructional detailing.*

Table 5. Limits for the Linear Thermal Transmittance of Building Details with Reduced Effect on Heat Loss

Junctions at Exterior Corners • Roof eaves (façade, gable, etc.) • Façade above overhanging floor	Ψ_e < 0.00 W/m·K
Junctions at Interior Corners • Roof junction with upper wall • Façade below overhanging floor	Ψ_e < 0.15 W/m·K
Balconies	Ψ_e < 0.10 W/m·K
Window Junctions • Sill • Lintel • Reveal • Dormer	Ψ_e < 0.10 W/m·K
Structural Connections • Roof or wall junction with inner bearing wall • Wall junction with ground floor • Wall junction with ground floor or floor above grade	Ψ_e < 0.05 W/m·K

Note: At junctions that are not listed (e.g., wall corners), the thermal insulation should be continuous.

W/m^2·K (C > 4 m) to the overall thermal transmittance if the building details are in accordance to given rules of good practice. For this purpose, a set of design principles and a catalog of exemplary details are in development to show how to meet the limiting values given in Table 5. This way of working is comparable to the German approach (DIN 2004) and should be quite easy to adopt in traditional building construction. Vandermarcke et al. (2006) give more information on the development of these rules of good practice.

CONCLUSIONS

This paper presents a methodology to develop limiting values for the linear thermal transmittance of building junctions in order to minimize the influence of thermal bridges on transmission heat loss. First, the influence of thermal bridge geometry and insulation thickness on the linear transmittance was analyzed. Then the two-dimensional transmission heat loss resulting from all joints encountered in five reference dwellings with traditional masonry construction was quantified. The distribution of the heat loss over different components (junctions with roof, window, foundation, etc.) was presented and the important contribution of window junctions was revealed. The results showed the important contribution of building junctions to the overall thermal transmittance of the building envelope, depending on the quality of the constructional detailing. Typically, the influence of thermal bridges was found to increase for more compact buildings up to 0.15 W/m^2·K. Finally, limits for the linear thermal transmittance were developed and their application in building regulations was described. The limiting values differ as a function of thermal bridge geometry and take into account the technical feasibility of the requirements.

ACKNOWLEDGMENTS

This study on the effect of thermal bridges was conducted with financial support of the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) as part of the research projects "ELEP Residential Buildings," guided by Catholic University of Leuven and "IDEE," guided by St. Lucas School of Architecture. Their support and guidance is gratefully appreciated.

REFERENCES

Adan, O. 1994. On the fungal defacement of interior finishes. Doctoral thesis, Technische Universiteit Eindhoven.

Bejan, A. 1993. *Heat Transfer*. New York: John Wiley & Sons, Inc.

BBRI. 1998. Isolatie, ventilatie en verwarming in nieuwbouwwoningen. Resultaten van het SENVIVV onderzoek (Studie van de Energieaspecten van Nieuwbouwwoningen in Vlaanderen: Isolatie, Ventilatie, Verwarming). Scientific Report. Belgian Building Research Institute, Brussels.

DIN. 2004. *DIN 4108, Supplement 2, Thermal Insulation and Energy Economy in Building Thermal Bridges: Examples of Planning and Performance.* Berlin: Deutsches Institut für Normung.

CEN. 1995. *EN ISO 10211, Thermal bridges in building construction—Calculation of heat flows and surface temperatures.* Brussels: European Committee for Standardization.

CEN. 1999. *ISO 14683, Thermal bridges in building construction: Linear thermal transmittance—Simplified methods and default values.* Brussels: European Committee for Standardization.

Hens. H. 1999. Fungal defacement in buildings: A performance related approach. *HVAC&R Research* 5(3):265–89.

IEA Annex 14. 1990. *Condensation and Energy*, *Volume 2: Guidelines and Practice*. Leuven, Belgium: K.U. Leuven, Laboratory for Building Physics.

Physibel. 2002. *Eurokobra.* Physibel Software, Maldegem, Belgium.

Physibel. 2003. *TRISCO,* Version 10.0w. Physibel Software, Maldegem, Belgium.

Sedlbauer, K. 2001. Vorhersage von schimmelpilzbildung auf und un bauteilen. Doctoral thesis, Universität Stuttgart.

Vandermarcke, B., J. Schietecat, G. Houvenaghel, D. Van Orshoven, S. Roels, and A. Janssens. 2006. Handling thermal bridges in the context of EPBD: Description of the approach developed in Belgium. *Proceedings of the EPIC-AIVC Conference, Lyon*, *France.*

Wouters, P., J. Schietecat, and P. Standaert. 2003. Practical guide for the hygrothermal evaluation of thermal bridges. A SAVE-COPRACTICE Project document. www.eurokobra.org.