Heat Transmission Through Walls with Slotted Steel Studs

Thomas R. Blomberg, D.Sc. **Johan Claesson, Ph.D.**

ABSTRACT

An insulated wall can be supported internally by thin steel studs. There will be extra heat loss caused by the metal U-studs, but slitting the web of the U-studs perpendicular to the heat flow direction reduces this heat loss. Calculation of the heat transmittance is a difficult numerical problem due to the high ratio of thermal conductivity between the insulation and the steel. This study presents results of calculations in three dimensions. The proper choice of the numerical mesh is discussed. Simplified equations for the U-factor are derived and implemented in a computer program. The heat transmittance is quickly calculated for different parameters—thermal conductivity of insulation and steel, steel thickness, distance between studs, and additional insulated layers (with or without cross-laid steel studs). A few results from hot box measurements are also presented.

INTRODUCTION

An insulated wall may be supported internally by steel studs, and there will be extra heat loss caused by the metal. Several authors estimate a 30% to 50% reduction of the wall thermal resistance due to the metal studs (Brown and Stephenson 1993; Kosny and Christian 1995; Trethowen 1988). Slitting the web of the studs perpendicular to the heat flow direction is an efficient way to reduce the thermal bridge effect.

Calculation of the heat transmittance is a difficult numerical problem due to the high ratio of thermal conductivity between the insulation and the steel. This study presents three-dimensional numerical calculations for a particular problem of this type. The proper choice of a numerical mesh is discussed. The dependence of the obtained U-factor on a number of different parameters is dealt with. Simplified equations for the U-factor are derived and implemented in a handy PC-program. The heat transmittance is quickly calculated for different parameters—thermal conductivity of insulation and steel, steel thickness, distance between studs, and additional insulated layers (with or without cross-laid steel studs). The PC-program HEAT3 (Blomberg, 1998) has been used for the three-dimensional calculations.

Figure 1 shows the structure of a wall in which insulation is contained between two gypsum boards of 13 mm thickness each. The distance between the metal U-studs is denoted by L_g. There is an extra heat loss caused by the metal U-studs. Slitting the web of the U-studs perpendicular to the heat flow direction, as shown in Figure 2, can reduce this heat loss. The thickness of the stud is denoted by t. The stud considered is a typical one that has been in use in Scandinavia for the last five to ten years.

DATA FOR NUMERICAL CALCULATION

The problem is not perfectly symmetrical due to different flange lengths (40 mm and 46 mm, see Figure 2). However, this is neglected in the calculations, and the left flange length

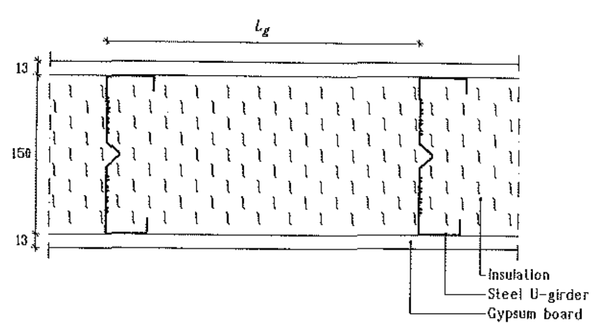

Figure 1 *Sketch of a wall with metal U-studs between two gypsum boards.*

Thomas R. Blomberg is with the Building Technology Group, Massachusetts Institute of Technology, Cambridge, and **Johan Claesson** is a professor in the Department of Building Physics, Chalmers, Gothenburg, Sweden.

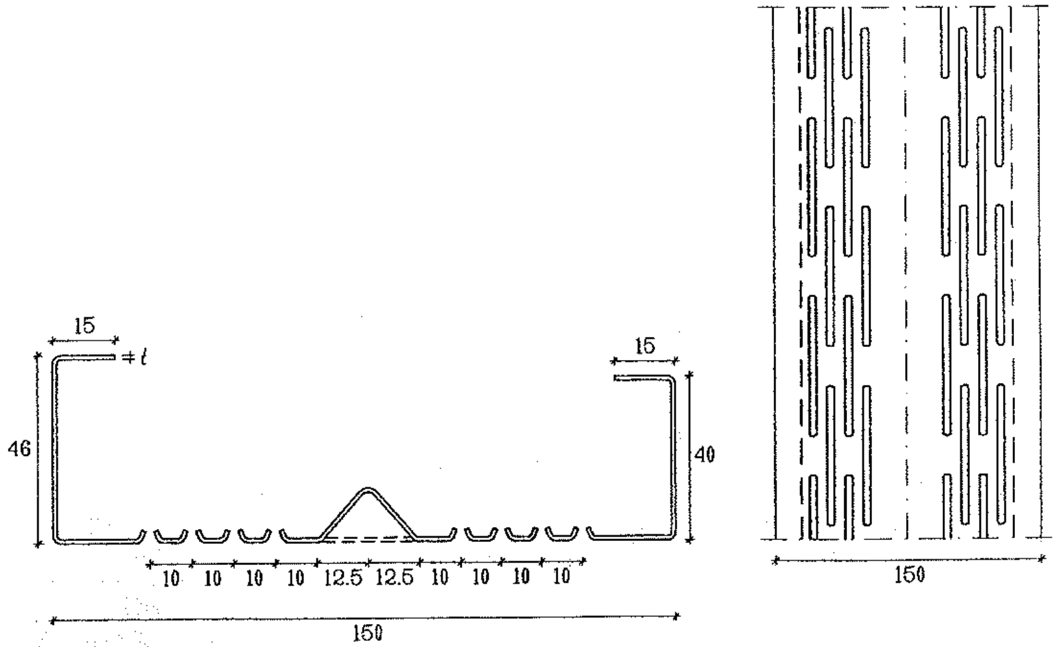

Figure 2 *Slotted steel studs (cross section to the left) decrease the heat conduction.*

(46 mm) is used for both sides. The Swedish standards normally prescribe that the sum of the inner and outer surface (air film) resistances be 0.17 m²·K/W for U-factor calculations. The inner and the outer surface resistances are put to half this value (0.085 m²·K/W) in the calculations that follow. The elevated part in the middle of the web is neglected, and the web is modeled as being straight, as shown in Figure 2 (left) by the dashed lines. Numerical tests show that this will give a slightly overestimated value for the heat flow through the wall of 0.2%. The slitting process causes small elevated rims, as shown in Figure 2. These rims are neglected in the calculations. This gives an underestimated heat flow by about 2-3%.

Calculations have been made for the shaded volume shown in Figure 3. The height (perpendicular to the plane in Figure 1) is denoted by s. The temperature in the air is 0°C on one side of the wall and 0.5°C at the line of symmetry in the middle of the wall. The thermal conductivity is 0.036 W/(m²·K) and 0.22 W/(m²·K) for the insulation and the gypsum, respectively.

NUMERICAL MESH

The number of cells required to obtain satisfactory numerical accuracy depends on various parameters, such as geometry, materials, and boundary conditions.

The calculated heat flow for a reference case (see next section) is shown in Table 1 for five different meshes. For an increasing number of cells, the solution converges to the stable flow 0.00797 W. The relative errors compared to the last case with one million cells are given in the fifth column. The error for the case with 29,000 cells is 1.3%. The required run-time on a 450 MHz processor, labeled as "CPU time," is also shown. The over-relaxation coefficient (see Hirsch [1992] or

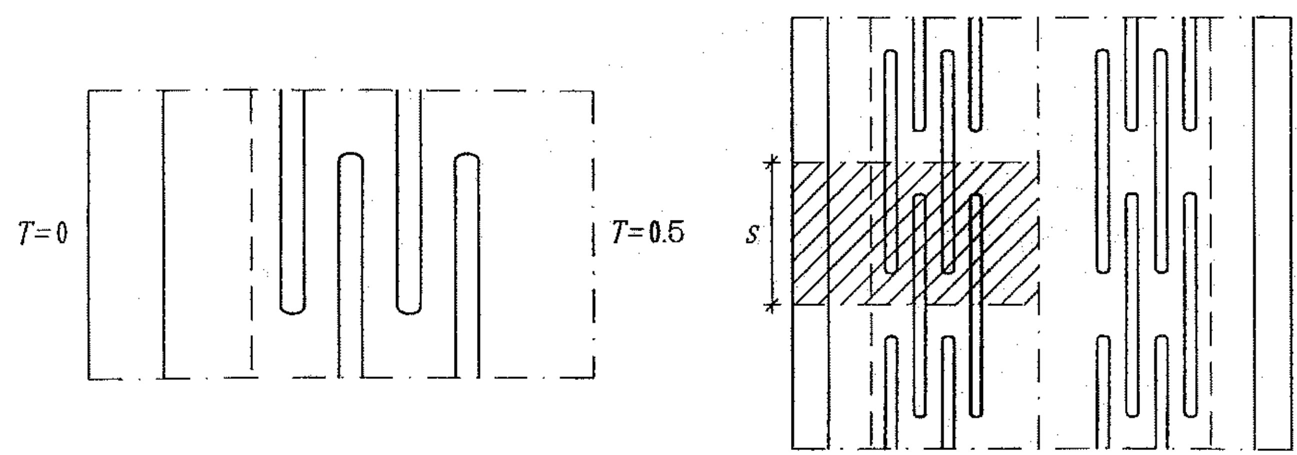

Figure 3 *The part of the stud used in the simulations.*

TABLE 1
Calculated Heat Flow for Five Different Meshes

Cells	Iterations	CPU Time	Q (W)	Error (%)
180	203	0 s	0.00756	5.4
5400	342	1 s	0.00783	1.8
29000	813	22 s	0.00787	1.3
120000	1213	1 m 42 s	0.00793	0.5
1000000	5026	1 h	0.00797	-

Kreith and Bohn [1986]) is 1.98 here. This is an optimal value, or close to the optimal value, for the five cases in Table 1.

Since the solution technique is iterative, a criterion for when to stop the iterations must be employed. The following stop criterion, which is recommended as a European standard (CEN 1995), is used: the sum of all heat flows (positive and negative) entering the boundaries, divided by the sum of the absolute values of all these heat flows, must be equal to or less than 0.001. In the present case, this means the flow into the wall on the warm side minus the flow out through the cold side, divided by the sum of these two absolute values, is less than 0.001. However, a stricter value (0.0001) was used in the above calculations to ensure proper comparison of the numerical error.

About 30,000 cells are used in the following calculations to ensure numerical errors less than 1% to 2%. Figure 4 shows the projection of the numerical mesh on the (x,y) plane and the (x,z) plane in the case involving 30,000 cells. The thicker lines show the position of the steel stud. Figure 5 shows a part of the mesh and the temperatures in gray scale. The insulation has been removed in the figure.

FORMULA FOR THE HEAT FLOW

The total heat flow Q depends on many variables. Two important ones are the distance between the studs L_g and the thermal conductivity of the steel λ_s. The flow may be considered to consist of the one-dimensional flow and an extra contribution from the steel stud:

$$Q(L_g,\lambda_s) = U_{1d} \cdot L_g \cdot s + Q_{extra}(L_g, \lambda_s) \text{ (W/K)} \qquad (1)$$

where U_{1d} denotes the U-factor of the wall without a stud. The cross-sectional area $L_g \cdot s$ refers to the volume used in the calculations.

We will see below that Q_{extra} is virtually independent of L_g provided that L_g is not too small:

$$Q_{extra} = Q_{extra}(\lambda_s) \text{ (W/K)} \qquad (2)$$

It is reasonable to assume that Q_{extra} is more or less directly proportional to λ_s. Then we have the first approximation:

$$Q_{extra}(\lambda_s) = Q_{extra}(\lambda_{s,ref}) \cdot (\lambda_s/\lambda_{s,ref}) \text{ (W/K)} \qquad (3)$$

Here, $Q_{extra}(\lambda_{s,ref})$ is the numerically calculated value for a reference thermal conductivity.

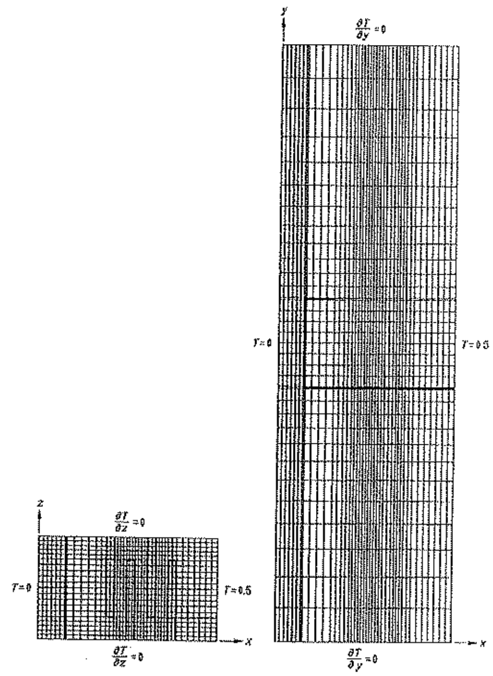

Figure 4 *Projection of the numerical mesh on the (x,z) plane and the (x,y) plane in the case involving about 30,000 computational cells.*

The thermal conductivity of the steel is much greater than the thermal conductivity of the insulation. Therefore, the heat flow between the steel and the insulation should be relatively small compared with the flow along the steel through the wall. This means that another possible approximation for Q_{extra} can be made by calculating the heat flow in steel and gypsum only. The boundary condition between the steel and the insulation, and between the gypsum and the insulation, is adiabatic. Again, Q_{extra} is more or less directly proportional to λ_s. We have the second approximation:

$$Q_{extra}(\lambda_s) = Q_{steel,ref} \cdot (\lambda_s/\lambda_{s,ref}) \text{ (W/K)} \qquad (4)$$

REFERENCE CASE

An initial numerical simulation is presented for a reference case with slotted steel as shown in Figures 1 through 3 with the following data. The thermal conductivity of the steel is put to $\lambda = 60$ W/(m²·K). The distance between the studs is $L_g = 0.6$ m and the thickness of the steel is $t = 0.7$ mm (see Figures 1 and 2). The two gypsum boards are of 13 mm thickness each. The total thermal resistance for the wall is $0.17+2 \cdot 0.013/0.22+0.150/0.036 = 4.44$ m²K/W, and U_{1d} becomes $1/4.44 = 0.225$ W/(m²·K).

The calculated heat flow through the wall with cross-sectional area $L_g \cdot s = 0.6 \cdot 0.05$ becomes $Q = 0.00787$ W/K. The extra heat loss is, according to Equation 1, $Q_{extra}(\lambda_{s,ref} = 60) = 0.00787 - 0.225 \cdot 0.6 \cdot 0.05 = 0.00112$ W/K.

The heat flow as a function of λ_s (for $L_g = 0.6$ m) becomes, according to Equations 1 and 3,

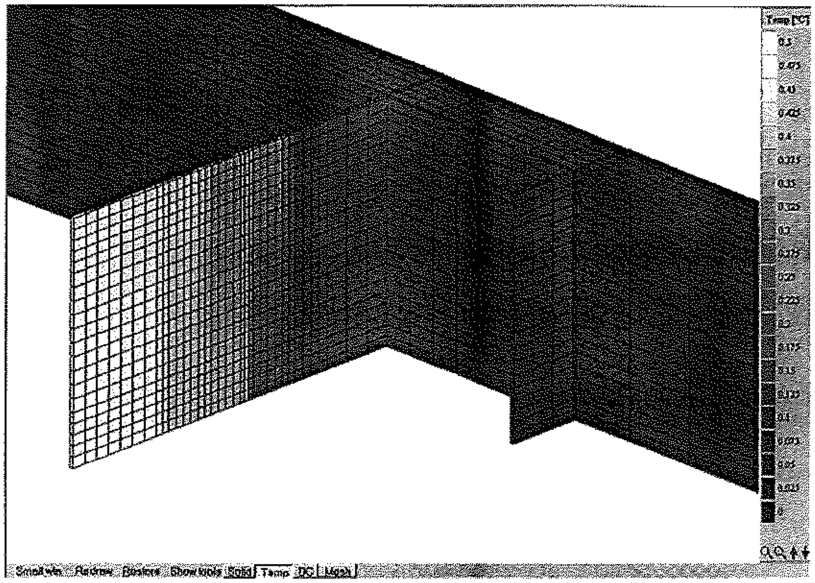

Figure 5 *Part of the mesh and the temperatures in gray scale. The insulation has been removed in the figure (only the steel and the gypsum board are shown here).*

$$Q(\lambda_s) = 0.225 \cdot 0.6 \cdot 0.05 + 0.00112 \cdot \lambda_s/60$$
$$= 0.00675 + 18.7 \cdot 10^{-6} \cdot \lambda_s \text{ (W/K)} \qquad (5)$$

This equation is shown in Figure 6 as Approximation 1. The black triangles in Figure 6 show direct numerical calculations for different λ_s.

According to the second approximation, the problem may be separated into two cases. Adding the two flows turns out to provide a rather good approximation. In the first case, the steel is not taken into account. The one-dimensional flow with a temperature difference of 1 is for the reference case $U_{1d} \cdot L_g \cdot s = 0.225 \cdot 0.6 \cdot 0.05 = 0.00675$ W/K.

The second case considers heat flow in steel and gypsum only. The boundary condition between the steel and the insulation and between the gypsum and the insulation is adiabatic. Numerical simulation gives for $\lambda_s = 60$ a heat flow of $Q_{steel,60} = 0.00105$ W/K. Equations 1 and 4 give the second approximation:

$$Q = 0.00675 + 17.5 \cdot 10^{-6} \cdot \lambda_s \text{ (W/K)}. \qquad (6)$$

This equation is shown in Figure 6 as Approximation 2.

We see that the first and second approximations give quite good agreement with the direct numerical calculations. A better approximation can be achieved when a limited range for the thermal conductivity is considered. A straight line between values for $\lambda_s = 10$ and $\lambda_s = 60$ gives

$$Q = 0.00696 + 15 \cdot 10^{-6} \cdot \lambda_s. \quad \text{(W/K)} \qquad (7)$$

This equation is shown in Figure 6 as "fitted curve."

FORMULA FOR THE U-FACTOR

A total U-factor for the wall with slotted steel studs may be obtained by adding the extra heat flow caused by a slotted stud to the one-dimensional heat flow:

$$U(L_g,\lambda_s) = U_{1d} + Q_{extra}(\lambda_s)/(L_g \cdot s) \text{ (W/[m}^2\text{·K])} \qquad (8)$$

Equation 1 gives the fitted curve (Equation 7) for the reference case:

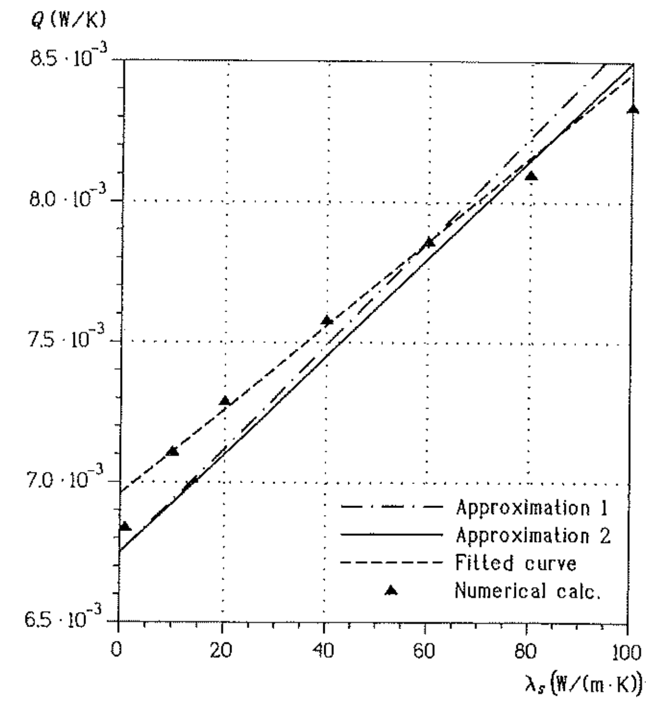

Figure 6 *Heat flow as a function of* λ_s.

$$Q_{extra} = 0.00696 + 15 \cdot 10^{-6} \cdot \lambda_s - 0.225 \cdot 0.6 \cdot 0.05 = 2.1 \cdot 10^{-4} + 15 \cdot 10^{-6} \cdot \lambda_s \text{ (W/K)} \quad (9)$$

The U-factor becomes

$$U(L_g,\lambda_s) = U_{1d} + (2.1 \cdot 10^{-4} + 15 \cdot 10^{-6} \cdot \lambda_s)/(L_g \cdot 0.05) = U_{1d} + (0.0042 + 0.0003 \cdot \lambda_s)/L_g \text{ (W/[m}^2\text{·K])} \quad (10)$$

Table 2 shows U-factors based on Equation 10. The U-factors obtained from direct numerical calculations are given in brackets. The error is less than 2%.

TABLE 2
U-Factors for the Wall with Slotted Steel Studs*

λ_s	L_g=0.1 m	L_g=0.3 m	L_g=0.6 m	L_g=1.0 m
60	0.447 (0.456)	0.299 (0.300)	0.262 (0.262)	0.247 (0.246)
40	–	0.279 (0.282)	0.252 (0.253)	0.241 (0.241)
20	–	0.259 (0.263)	0.242 (0.243)	0.235 (0.235)
10	–	0.249 (0.252)	0.237 (0.237)	0.232 (0.232)

* Slotted steel studs have different steel thermal conductivities λ_s and distances between the studs L_g based on Equation 10 and on direct calculations in three dimensions (in brackets).

Since the heat flow in the steel is approximately proportional to λ_s, one can assume that it is also proportional to the thickness of the steel t. With t = 7 mm in the reference case, Equation 10 is modified to

$$U = U_{1d} + (0.0042 + 0.0003 \cdot \lambda_s \cdot t/0.0007)/L_g \text{ (W/[m}^2\text{·K])} \quad (11)$$

or, as in the final formula for different L_g, λ_s, and t:

$$U = U_{1d} + (0.0042 + 0.43 \cdot \lambda_s \cdot t)/L_g \text{ (W/[m}^2\text{·K])} \quad (12)$$

Based on direct calculations, this equation has a maximum error of 2% if

$$L_g > 0.1 \text{ m}, \lambda_s > 10 \text{ W/(m·K)}, t > 0.1 \text{ mm}. \quad (13)$$

Table 3 shows U-factors for a few values of t, L_g, and λ_s based on Equation 12. The results obtained from the numerical calculations are in brackets. The maximum error is 2%.

TABLE 3
U-Factors Based on Equation 12 and on Numerical Calculations (in Brackets)

t (mm)	λ_s (W/[m·K])	L_g (m)	U (W/[m·K])
1	60	0.6	0.275 (0.272)
1.5	60	0.6	0.296 (0.289)
1	10	1.0	0.233 (0.233)
1.5	10	0.3	0.260 (0.265)

STUDS WITHOUT SLOTS

A wall with slotted studs, according to Table 2, has only 16% greater heat flow than a wall without any stud (0.262/0.225 = 1.16), see Table 4. If λ_s = 20 W/(m^2·K), the U-factor becomes 6% larger (0.242/0.225 = 1.06).

TABLE 4
U-Factors for Walls with and without Slots Compared to a Wall without Steel

	U-Factor for Wall, (W/[m^2·K])
Without Steel	0.225
Slotted Studs	0.262 (16%)
Nonslotted Studs	0.413 (83%)

Numerical calculations have also been made for a wall with nonslotted studs (λ_s = 60, t = 0.7 mm, and L_g = 0.6 m). The U-factor becomes U = 0.413 W/(m²·K), which is 58% larger than the U-factor for the wall with slotted studs (0.413/0.262 = 1.58).

Another way to express this is to compare the wall above (U = 0.413 W/[m²·K]) with a wall containing slotted studs of steel possessing higher thermal conductivity. According to Equation 12, a wall with a slotted stud in which λ_s = 360 W/(m²·K), or t = 4.2 mm, has the same U-factor, 0.413 W/(m²·K). This shows that either the thermal conductivity or the thickness has to be decreased by a factor of six to make up for the slots. The heat flow through a stud will decrease even more with an increase in the number of narrow slots.

This underlines again the importance of an efficient slitting of the steel. Figure 7 illustrates this further. The temperature field in the steel plane through the wall is shown for the

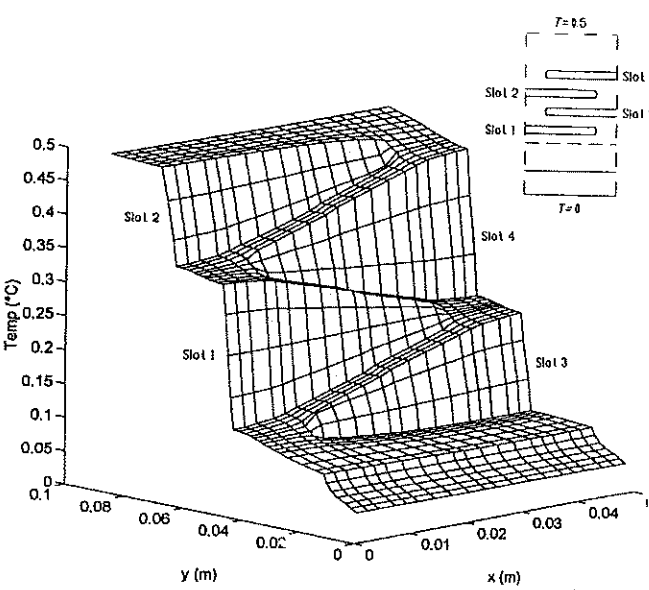

Figure 7 *Temperature field in the steel plane through the wall.*

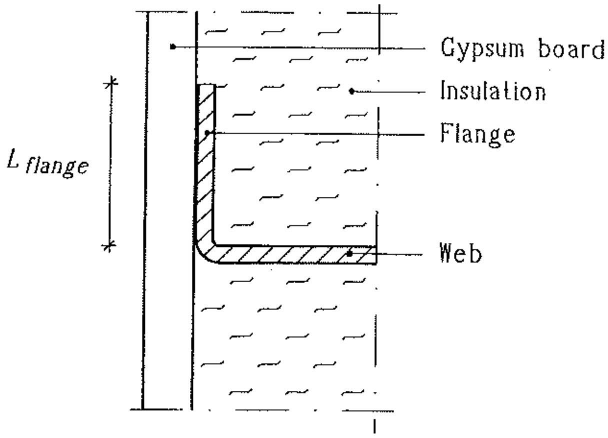

Figure 8 *The heat flow along the web decreases as* L_{flange} *decreases.*

reference case with slots. The path for the heat flow is increased due to the slots.

Slitting the Flanges

The flanges act as collectors of heat. If the flange length L_{flange} in Figure 8 is decreased, the U-factor will also decrease. Table 5 shows U-factors for $\lambda_s = 60$ W/(m²·K), $t = 0.7$ mm, and $L_g = 0.6$ m obtained from two-dimensional calculations for a wall with studs without slots.

It is clearly better to use shorter flanges. This may be difficult due to structural constraints. However, the flanges could instead be slotted. This would decrease the U-factor for the same reason as in the case of the shorter flanges.

TABLE 5
U-Factors for a Wall with Nonslotted Studs for Different Flange Lengths

L_{flange} (m)	U (W/[m²·K])	Lowered U-Factor
0.046	0.413	—
0.020	0.389	6%
0.005	0.347	16%

Heat Transfer within the Slots

The cavities formed by the slots will probably be filled with air instead of insulation. In the numerical computations, this space is assumed to be filled with insulation material. The heat transferred by radiation and convection inside the gaps will be of the same magnitude as that transferred by pure conduction in the insulation (Blomberg 1996). Thus, the heat flow between the gaps is negligible compared with the flow along the steel.

Slotted Steel Studs Compared with Wooden Studs

It may be interesting to compare the U-factor for a wall having steel U-studs with that of a wall having wooden studs placed in the same position. Calculations show that, for $\lambda_s = 60$, $t = 0.7$ mm, and $L_g = 0.6$ m, the reference wall containing slotted steel studs has the same U-factor as a wall with 0.04 m thick wooden studs with a thermal conductivity of 0.14 W/(m²·K). A wall with 0.22 m thick wooden studs would have the same heat loss as a wall with nonslotted studs.

COMPUTER PROGRAM WITH SIMPLIFIED EQUATIONS

Equation 12 accounts for the center-to-center distance between the studs L_g, the steel thickness t, and the thermal conductivity of the steel λ_s. Equations taking into account other parameters, such as the wall thickness H and the thermal conductivity of the insulation λ_{insul}, have also been derived. The layer with the slotted steel may also have additional covering layers on each side. The covering layer on the inside may be insulation, either with crossing steel U-studs (un-slotted) or thermally unbroken. Additional covering layers may also be used on the outside.

The derived equations are based on some hundred three-dimensional calculations, where each parameter has been varied. The equations have been fitted to give a maximum error of 3% compared with full numerical calculations in three dimensions.

These simplified equations have been implemented in a computer program. The input window is shown in Figure 9. Information of this program is provided by Lindab Profil AB (see www.lindab.se).

HOT BOX MEASUREMENTS

Measurements of the heat flow through walls with and without slotted steel studs were carried out during 1997-1998 using a guarded hot box (Ohlsson 1998).

Measurements for a wall without studs were compared to measurements for the wall with steel studs. The difference in the heat flux between these two results is due to the seven steel studs (see Figure 10), and an extra heat flow per meter stud was calculated.

A relatively small center-to-center distance between the studs was used ($L_g = 0.3$ m) in order to increase the heat flow and decrease the measuring error. The distance is large enough that the heat flows due to any two studs that are adjacent to each other have negligible influence on each other.

Figure 10 shows how the studs were placed. The size of the test walls was 3 m² × 3 m². The size of the measuring area was 2.4 m² × 2.4 m².

U-factors based on measurements and calculations for $L_g = 0.6$ m are shown in Table 6. The wall thicknesses are 150 mm

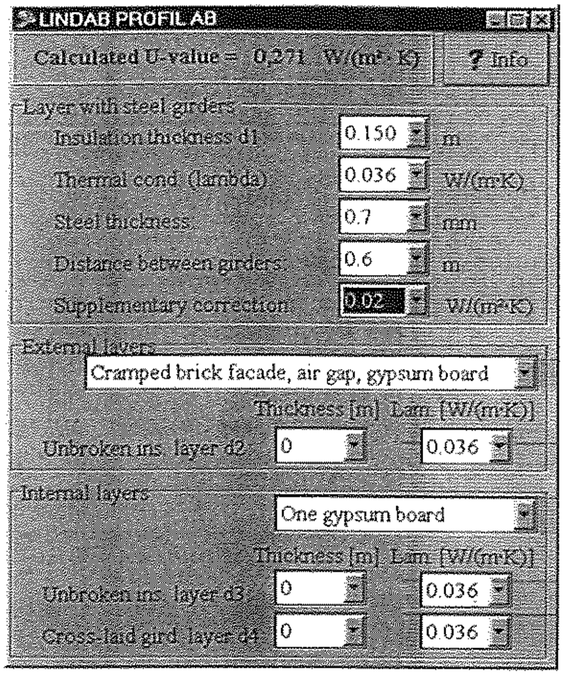

Figure 9 *The heat transmittance through a wall with slotted steel U-studs is instantly calculated for different parameters, such as the thermal conductivity of insulation and steel, the steel thickness and center-to-center distance, and additional insulated layers (with or without cross-laid steel studs).*

and 200 mm, respectively. The calculated heat flows are between 7% and 17% lower than the measured ones for the slotted steel studs but 24% higher in the case with nonslotted steel. Two explanations for this discrepancy may be that the measurement errors increase due to the high heat flow caused by the nonslotted steel or due to a contact resistance between the steel and the gypsum boards.

A supplementary correction (see Figure 9) for the U-factor of 0.02-0.04 (W/m²·K) should be used according to the Swedish standards for a wall containing these kinds of steel

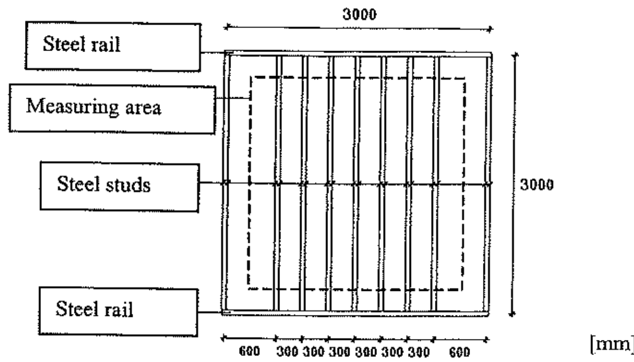

Figure 10 *Test wall with outlined measuring area. A relatively small center-to-center distance between the girders was used (L_g = 0.3 m) in order to increase the heat flow and decrease the measuring error.*

studs. Adding 0.04 to the U-factors based on the calculations should give results on the safe side.

It should be noted that earlier hot box calibrations indicate that the measured heat flow is 9% to 10% too high (made for a 200 mm test wall of cellular plastic with λ = 0.03293 W/m·K). Taking this into account would decrease the error for the cases with slotted steel but, on the other hand, increase it for the case with nonslotted steel.

The thermal conductivity of the steel (λ = 60 W/m·K) and the insulation (λ = 0.036 W/m·K) has not been validated.

IMPROVING THERMAL PERFORMANCE

The following list shows a few ways to decrease the heat loss through a wall with metal studs:

- Use thinner steel with a thermal conductivity as low as possible.
- Increase the spacing between the studs.
- Increase the number of slots and the slitting length; optimize configuration of slots.
- Add a thermal break. An extra layer of insulation will efficiently reduce the thermal bridge effect.

TABLE 6
U-Factors Based on Measurements and Calculations for L_g = 0.6 m

Wall Thickness	Steel Thickness	U-Factor from Measurements	U-Factor from Calculations	Relative Error
150 mm	0.7 mm	0.298 (W/[m²·K])	0.262 (W/[m²·K])	14%
150	1.5	0.328	0.295	11
200	0.7	0.248	0.212	17
200	1.5	0.263	0.245	7
200	0.7 Nonslotted	0.319	0.396	–24

A study by (Kosny and Christian 1995) with 12 different configurations of metal frame walls showed that the thermal resistance was increased 40%-60% when an additional layer of 2.5 cm expanded polystyrene (EPS) was added to a layer with 9 cm EPS with steel studs.

CONCLUSIONS

An efficient way to decrease the heat flow is to use slotted steel studs. One example showed that either the thermal conductivity or the thickness of the steel had to be decreased by a factor of six to make up for the slitting. The heat flow through a stud decreases as the number of narrow slots increases.

Equation 12 gives a U-factor that depends on the thermal conductivity of the steel λ_s, the center-to-center distance between the studs L_g, and the steel thickness t. The error is less than 2% compared with direct three-dimensional numerical calculations.

Simplified equations for the U-factor are derived and implemented in a computer program. The heat transmittance is quickly calculated for different parameters—thermal conductivity of insulation and steel, steel thickness, distance between studs, and additional insulated layers (with or without cross-laid steel studs).

It has been shown that a rather complex, genuinely three-dimensional problem can be solved on a desktop computer. Some 30,000 nodal points are sufficient to give a numerical error of 1% to 2%. The CPU time is less than a minute. The simulation time for the case with one million cells (5000 iterations) was about one hour. This means that an energy balance is made for about 1.4 million cells each second.

A supplementary correction (see Figure 9) for the U-factor of 0.02-0.04 (W/m²·K) should be used according to the Swedish standards for a wall containing these kinds of steel studs. Adding 0.04 to the U-factors based on the calculations should give results on the safe side.

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