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SUMMARY:
Numerical calculation programs are powerful tools for both analysing and optimising the thermal aspects of building envelope constructions. CEN suggests that these programs should be used, and within a short period of time they will be accepted as applicable projecting tools in the European countries. Only few surveys have been made to validate calculation results against measurements, and there is a need to take further this validation to ensure that calculation results are both reliable and useful. Measurements were carried out using a Guarded Hot Box with a measuring area of 1.2 m by 1.8 m. The constructions analysed were typical lightweight walls containing different types of linear thermal bridges. The Guarded Hot Box that was used was built to meet the criteria given in EN ISO 8990 "Thermal insulation – Determination of steady-state thermal transmission properties – Calibrated and guarded hot box" (European Committee for Standardisation 1996a). Numerical calculations were done using two simulation programs, HEAT2 (Blomberg 1998a) and HEAT3 (Blomberg 1998b), both of which have been validated according to EN ISO 10211-1 "Thermal bridges in building construction – Heat flows and surface temperatures – Part 1: General calculation rules" (European Committee for Standardisation 1995). The validation has proven very successful and there seems to be no apparent problems in translating the physical problems directly into model descriptions, as long as material properties are chosen as design values. All comparisons show that calculated values of thermal transmittance is within a narrow margin of measured results, and that deviations primarily depend on the magnitude and complexity of the thermal bridge in the wall. Deviations range from approximately 1 to 5 %.

1. Introduction

The European standards concerning the calculation of heat loss through the building envelope are presently being implemented. These standards suggest that calculations should be performed using numerical calculation programs in order to evaluate complex thermal bridge effects correctly.

In order to evaluate complex thermal bridge effects correctly through numerical calculation it is necessary to translate the thermal characteristics of the physical construction into a mathematical description. The translation will always, to some extent, imply an idealisation of the actual physical characteristics and therefore the mathematical description will never be able to simulate the construction exactly.

EN ISO 10211-1 specifies a validation procedure for numerical calculation programs and describes how calculations should be done in general. The validation is performed by calculating reference cases; one for each dimension the program operates with, e.g. a 3-dimensional program calls for three reference cases to be calculated. The obtained results are then compared to corresponding results obtained with a reference program. It is clear that this validation secures that the program is in agreement with the mathematical background, however it does not secure a correct translation from physical construction to model. The only way to validate programs in this context is to compare results to accurate measurements.

Previous investigations have had some success in validating numerical calculation programs. Most investigations have shown that a direct translation from physical construction to mathematical model will produce results that are too optimistic, however others have shown that a direct translation presents an adequate approximation.

Some success was achieved in validating the program HEAT2 against Guarded Hot Box measurements in (Ohlsson 1998), however the calculated values were corrected in order to obtain safe values and a satisfactory level of compliance between results. The investigation was performed for lightweight external walls containing different types of thin sheet metal studs, and it was concluded that calculated U-values for these type of walls had to be raised by 0.04 W/m^{2}K in order to make values safe for building design purposes.

The program Heating 7.2 (Childs 1995) is validated in (Kosny et al 1997). The validation was performed by comparing calculation results to measurements performed in a rotable climate chamber (Hot Box principle). The analysis was performed on lightweight external walls containing different types of thin sheet metal studs, and the conclusion was that contact resistances had to be introduced in the mathematical model, in order to obtain satisfactory results.

Quite a few other investigations have been performed using different kinds of calculation methods and different types of measuring equipment, e.g (Mao & Jóhannesson 1996), (Fryklund 1995) and (Mao 1998). Which program is used for the validation is not important as long as the program has been validated according to EN ISO 10211-1, and the measurement technique is only important in the aspect that it should be as precise as possible to present the best possible reference.

This paper presents the results of a series of Guarded Hot Box measurements. The measurements primary function is to validate existing numerical calculation programs, to ensure that the results they produce can be used for realistic analysis of building envelope constructions. Furthermore it is discussed whether or not design values of the thermal conductivity of insulation materials secure that calculated heat transfer is applicable for designing building envelope constructions.

The measurements presented here cover the aspects of linear thermal bridges in lightweight walls, e.g. thin sheet steel U-studs, wooden beam and lath skeleton. Special areas of interest were also sought analysed through the measurements, e.g. insulation faults in the form of non-ventilated air gaps.

2. Guarded Hot Box apparatus and methods

The Guarded Hot Box was built to meet the criteria given in EN 8990. The metering box had an area of 1.2 m by 1.8 m. Figure 1 shows a cross-section of the Guarded Hot Box.

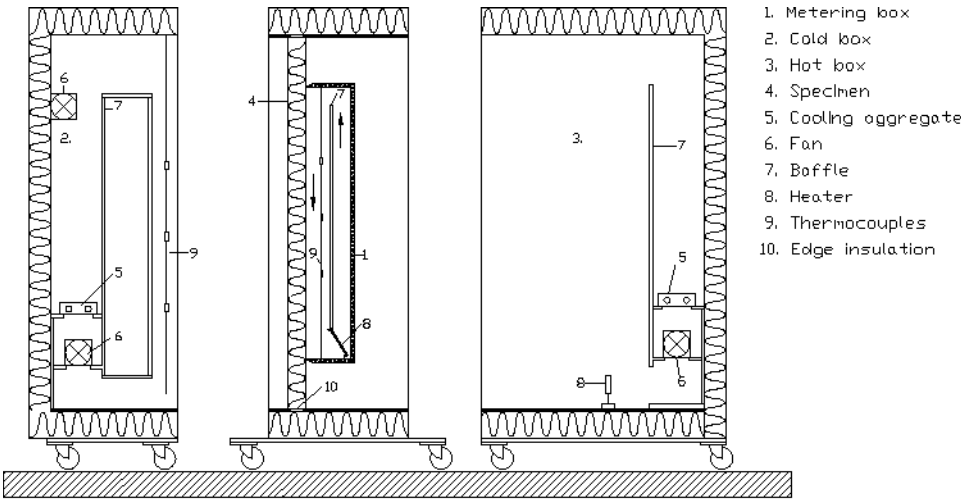

Figure 1: Guarded Hot Box, vertical cross-section.

In the Guarded Hot Box, the metering box is surrounded by a guard box in which the environment is controlled to minimise lateral heat flow in the specimen and heat flow through the metering box walls. A simplified PID-controller based upon the measured temperature difference over the metering box walls, controls the environment in the guard box.

The cold box is kept at a temperature of 0 °C and this temperature is stable within approximately 0.5 % of the overall temperature difference, when the entire measurement has attained stability. The relatively high instability of this temperature is due to the fact that no PID-controller is used for controlling this temperature.

The metering box is kept at an environmental temperature, i.e. the temperature 'seen' by the specimen, of 20.55 °C using the same PID-controller as used for the guard box. In this case though, the controller is based upon the actual measured temperature in the metering box. This temperature is stable within approximately 0.05 % of the overall temperature difference. The high stability on this temperature is achieved by an ordinary PID-controller.

The surface resistance on the cold side is established by controlling the wind speed along the specimen using a ventilator. On the warm side of the specimen the surface resistance is induced automatically by the rotation of air in the metering box. The surface resistances are kept at values of approximately 0.04 m^2K/W on the cold side and 0.13 m^2K/W on the warm side.

Measurements were performed with an accuracy that meets the demands in the supplementary criteria to EN ISO 8990. Analysis has shown that the Guarded Hot Box has an expected error of less than 3 %, according to prEN 1946 (European Committee for Standardisation 1998) and has been shown to reproduce measurements on a simple construction with a deviation of less than 1 %.

3. Specimen descriptions

The total specimen size was height x width = 2.85 m x 1.80 m and the metering area 1.80 m by 1.20 m = 2.16 m^2. Nine specimens were measured/calculated. The reference specimen was (from cold to warm side):

2 layers of 9 mm gypsum board

2 layers of 100 mm mineral wool

2 layers of 13 mm gypsum board.

First a measurement was performed on the reference specimen in order to test and calibrate the equipment. Eight other measurements were performed on different kinds of linear and combined linear/point thermal bridges. The specimens are described below, and details are shown in Figures 2 to 9 (measurements in mm):

1 Reference specimen, no thermal bridges.
2 Reference specimen + 1 mm massive steel U-stud. Figure 2.
3 Reference specimen + 1 mm slotted steel U-stud type 1. Figure 3.
4 Same as 3 with insulation fault 1. Figure 4.
5 Same as 3 with insulation fault 2. Figure 5.
6 Reference specimen + 1 mm slotted steel U-stud type 2. Figure 6.
7 Same as 6 with insulation fault 3. Figure 7.
8 Reference specimen + 50 mm · 200 mm wooden beam. Figure 8.
9 Reference specimen + 2 · 50 mm · 100 mm crossed lath skeleton. Figure 9.

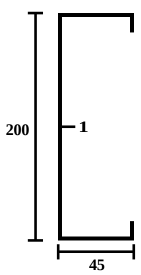

Figure 2: Massive.

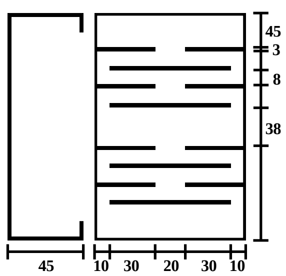

Figure 3: Slotted 1.

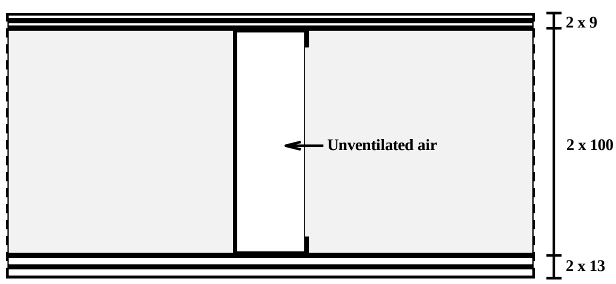

Figure 4: Insulation fault 1.

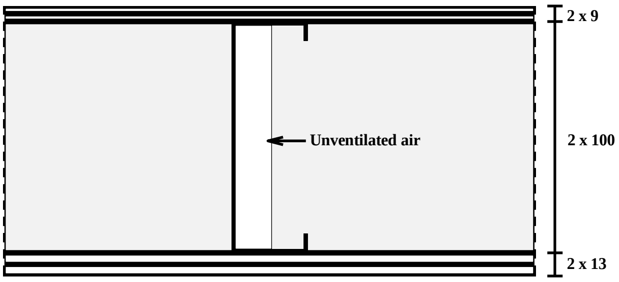

Figure 5: Insulation fault 2.

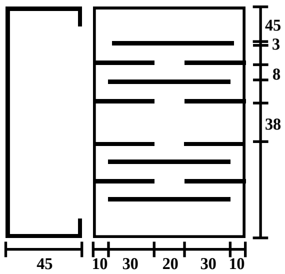

Figure 6: Slotted 2.

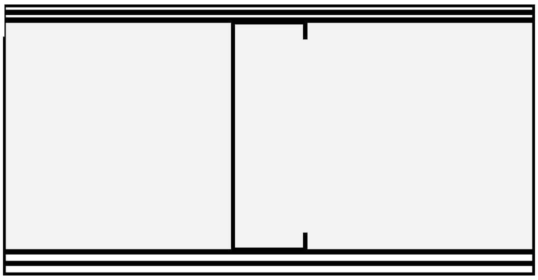

Figure 7: Insulation fault 3.

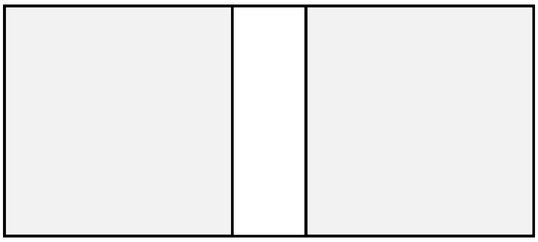

Figure 8: Wooden beam.

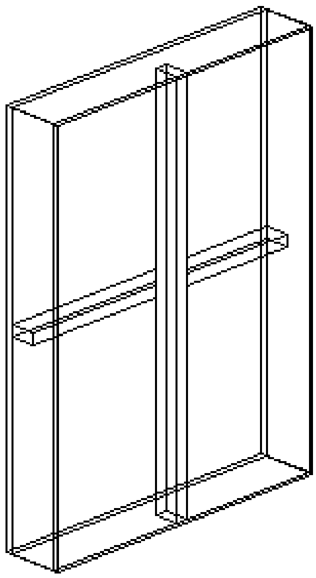

Figure 9: Wooden lath skeleton.

These specimens were chosen because they represent some typical thermal bridges in building construction and therefore they are very relevant with respect to the aforementioned validating process.

For all constructions, the connections between gypsum boards were sealed with tape to ensure that no air could be drawn from neither cold nor warm environment into the construction. This way any intentional or unintentional air gaps in the construction would be unventilated and without any direct influence coming from any of the two climates on either side of the measured constructions.

Furthermore, for each measurement the measuring box was tested to air pressure. Hereby it could be ensured that there was no unintentional air leakage from the measuring box to the surroundings.

The measured and calculated U-values are valid for a thermal bridge centre-to-centre distance of 1200 mm. The U-value for any centre-to-centre distance can be calculated by determining the linear thermal transmittance of the thermal bridge. For apparent reasons this is not applicable for the lath-skeleton.

4. Calculation programs and methods

The calculations were performed using HEAT2 (specimen 1, 2 and 8) and HEAT3 (specimen 3, 4, 5, 6, 7 and 9). Both of these programs use the Finite Difference Method (FDM), which means that the geometry is restricted to rectangular shapes. This does not present a problem, as all the specimens that were measured could be modelled from rectangular shapes or by using simplifications that does not alter the overall heat flow significantly.

In the calculations the following thermal conductivities were used:

Mineral wool:	0.0352	W/mK
Gypsum boards:	0.2000	W/mK
Steel:	50.000	W/mK
Pine wood (450 kg/m^3)	0.1200	W/mK

The thermal conductivity of the steel is the design value according to EN ISO 12524 (European Committee for Standardisation 1996b). The thermal conductivity of the mineral wool was measured by λ-apparatus at the Department of Buildings and Energy, TUD (Dyrbøl 1998). The thermal conductivity of gypsum and pine were taken from (Dansk Ingeniørforening 1986).

Calculations were performed on ideal models of the specimens. This means for instance, that no contact resistances were used between the two layers of gypsum boards on either side of the specimens, in order to evaluate any existing air layers between these or in other parts of the constructions.

Special modelling was utilised when constructions containing insulation faults were analysed. In these cases an equivalent thermal conductivity was used for the air layers. The equivalent thermal conductivities were calculated using the simplified formulae in EN ISO 10077-2 (European Committee for Standardisation 1997).

All calculations were performed under steady-state conditions. This means that it was not necessary to minimize the number of computational cells in the models, as calculation times would be short. Therefore, in order to achieve the maximum accuracy in the calculations, the calculating programs were used more or less to their full extent, meaning that typically 250 x 250 cells were used in 2D calculations and 100 x 100 x 100 cells were used in 3D calculations, depending on the complexity of the specimens. Both HEAT2 and HEAT3 offers the possibility of using expansive mesh, i.e. to focus the computational mesh in the areas where the heat flows are most complex, and this feature was also utilised.

For the specimens where 3-dimensional heat flows occur and hence 3D calculations were necessary, calculations were split into parts, i.e. isolating 3-dimensional, 2-dimensional and 1-dimensional effects, in order to achieve the best possible accuracy on results. Furthermore, as a general rule, symmetry was used for reducing the geometrical extent of the models in order to better utilise the accessible number of computational cells, i.e. for the slotted steel U-girders the symmetry lines reduce the model from 1.2 x 1.8 x 0.2 m to 1.2 x 0.05 x 0.1 m, and this is without splitting the model into 1-, 2- and 3-dimensional effects.

All in all, the methods mentioned above produced a very high degree of accuracy in the calculation results.

5. Results

The results of both measurements and calculations are presented in Table 1. The relative deviation between measurements and calculations are also given in Table 1.

Table 1: Measured and calculated results and relative deviation.

Specimen description	Measured U-value [W/m^2K]	Calculated U-value [W/m^2K]	Relative deviation [%]
1) No thermal bridge	0.167	0.165	-1.2
2) Massive 1 mm steel U-stud	0.241	0.249	3.2
3) Slotted 1 mm steel U-stud type 1	0.194	0.185	-4.2
4) Specimen 3 w/ insulation fault 1	0.232	0.228	-1.5
5) Specimen 3 w/ insulation fault 2	0.223	0.219	-1.9
6) Slotted 1 mm steel U-stud type 2	0.194	0.187	-4.0
7) Specimen 6 w/ insulation fault 3	0.197	0.186	-5.4
8) Wooden beam (50 mm x 200 mm)	0.180	0.180	-0.3
9) Wooden lath skeleton (2 x 50 mm x 100 mm)	0.181	0.174	-4.2

6. Discussion

The object of interest in the analysis is the deviation between measured and calculated U-values, that occurs as a result of the translation from physical construction to mathematical description, e.g. the idealisation. These deviations cannot readily be extracted from the results given in Table 1 as the total deviation is dependent on both the idealisation and the accuracy of the Guarded Hot Box.

A Guarded Hot Box that can determine the heat flow through the specimen with certain accuracy measures the physical construction. The accuracy in each separate measurement depends primarily upon the construction being measured, but also other factors, e.g. heat exchange with surroundings influence the measurement accuracy.

The measurements are erroneous, e.g. due to data logger inaccuracies etc., and analysis has shown that the expected error for the Guarded Hot Box equipment is less than 3 %. The expected error is dependent on the severity of the thermal bridge, i.e. the higher the total heat flow the higher the expected error due to data logger inaccuracies, temperature measurements etc.

It is expected that calculations in general should underestimate the U-value due to the idealisation when translating from physical construction to mathematical description. However, as shown in (Kosny et al) contact resistances can result in the opposite being true. From Table 1 it is evident that all calculations underestimate heat flow except for specimen 2. The probable causes for this discrepancy are discussed later on.

The largest deviation on the U-value occurs for the specimen containing insulation fault 3, i.e. specimen 7. This specimen was extremely hard to build in the measuring apparatus, as the insulation material could not be properly fitted to the intended geometry. This fact suggests that this type of insulation fault is not typical for lightweight external walls. The relatively large deviation between measurement and calculation for this specimen is probably due to the fact that a larger (more influential) thermal bridge has been induced in the effort to fit the insulation material as planned around the flanges of the stud.

Specimen 1 is expected to produce the most accurate measurement, as there are no thermal bridges or similar areas that influence the results. Therefore specimen 1 will give the best possible insight concerning the influence of the idealisation that is introduced when translating from physical construction to mathematical description. However, the idealisation error will not be constant from specimen to specimen, as it is dependent upon the complexity of the construction. Therefore the only thing that can be concluded from the analysis of specimen 1 is, that the idealisation error is probably around 1 % for the simple case and higher for more complex cases.

6.1 Tendencies

By looking at each of the measurements individually, it is possible to extract certain tendencies from the results. From such investigations it is possible to gain a better overview of the different factors that influence the total deviation. Hereby it should be possible to get a little closer to dividing the total deviation into an idealisation error and a measurement error.

6.1.1 Slotted steel U-studs

For specimen 3 and 6 it is interesting to notice that the calculated U-value is underestimated quite substantially but with the approximate same relative amount. These two specimens contain slotted steel U-studs without any insulation errors.

If calculated and measured results are compared for specimen 7 the exact same tendency as seen for specimen 3 and specimen 6 is encountered, and therefore it is possible that calculations of slotted studs to some extent are performed in a wrongful manner.

The reason why this effect is not as evident for the specimens including the larger insulation faults is that the effects are ‘washed out’ as the thermal bridge increases dramatically. In other words when a large thermal bridge is introduced, e.g. as a non-ventilated air gap between the flanges of the stud, the thermal bridge will be the most influential part whereas minor errors concerning the modelling of the slots in the stud are less influential.

In (Blomberg 1996) the different aspects concerning slots in steel studs is dealt with, especially any radiation effects in the slots. These investigations have shown that there are little or no radiation effects in the slots. If the insulation material is fitted tightly around the stud from both sides, the slots will be filled with insulation material, leaving no room for radiative effects.

The reduction of thermal bridge effects due to the slotting of the studs is still however to some extent overestimated. The massive stud introduced in specimen 2 is the exact same type of stud as the slotted one used in specimen 3, except the slots naturally. For this specimen the U-value is overestimated in the calculation, and therefore the problems that occur in the cases where slotted studs are used, could be explained by the fact that the slots are modelled incorrectly. Another source of error for this specimen is the fact that the massive stud was a little bent and therefore it is possible that the thermal contact between the flanges of the stud and the gypsum boards could be less than ideal resulting in a lower U-value for the measurement.

6.1.2 Specimen 2

Specimen 2 is the only wall where the U-value is overestimated in the calculations. The overestimation is relatively high compared to the other deviations. This could indicate that there are areas concerning the actual modelling that are not in compliance with the physical construction that was measured.

As mentioned above, the massive stud was bent a little and this could reduce the thermal contact in the construction with a reduced heat loss as effect.

If the calculations are performed using contact resistances between the flanges of the stud and the gypsum boards equal to ½ mm of air, the U-value can be calculated as U = 0.2424 W/m^2K. This could to some extent be the explanation for the fact that the initial calculation overestimates the U-value, as the calculations in general are performed under the assumption of total thermal contact between all materials.

The gypsum boards are screwed to the stud flanges per 300 mm vertically, and therefore it would be expected that there should be a good thermal contact between the gypsum boards and stud flanges. The effect of an eventual air gap between flanges and boards should therefore not be expected to be of any influence and a ½ mm air gap is probably a little to optimistic an explanation.

Apart from this, it is not possible to conclude further on why this specimen produces results that deviate from the general tendency of underestimating the calculated U-values.

6.1.3 Specimen 6 and 7

Specimen 6 and 7 produce approximately the same results and the two values deviate less than 1 %, i.e. equal to the reproducibility of the measurements. Insulation fault 3, i.e. specimen 7 therefore does not give any clue as to what influence the theoretical insulation fault might have for the U-value of the construction. It is possible that specimen 6 and 7 are more or less identical.

6.1.4 Specimen 9

The deviation between calculation and measurement for specimen 9 is relatively large compared to the simple geometry of this construction. Furthermore, it should be expected that the accuracy would be more or less the same as for specimen 8, i.e. the wooden beam and it is hard to explain why this deviation occurs.

There seems no apparent reason for the magnitude of this deviation, and it is concluded that there has probably been some deviations between geometry, materials or both, e.g. air gaps, material inhomogenities, moisture content etc., from physical construction to mathematical description.

Building the construction presented a few problems, as the laths were not entirely straight. This could mean that the insulation material was not fitted perfectly around the laths and that in turn could result in unintended air gaps that could explain the relatively high deviation.

6.2 Design values for insulation materials

As mentioned earlier the thermal transmission coefficient for the insulation material was measured using λ-apparatus. To analyse the importance of this value for the comparisons, the calculations were repeated using a thermal transmission coefficient of 0,036 W/mK. The results are shown in Table 2.

Table 2: Measured and calculated results and relative deviation.

Specimen description	Calculated U-value λ_{wool} = 0,0352 [W/m^{2}K]	Calculated U-value λ_{wool} = 0,0360 [W/m^{2}K]	Relative deviation [%]
1) No thermal bridge	0.165	0.169	2.1
2) Massive 1 mm steel U-stud	0.249	0.252	1.4
3) Slotted 1 mm steel U-stud type 1	0.185	0.189	1.9
4) Specimen 3 w/ insulation fault 1	0.228	0.232	1.5
5) Specimen 3 w/ insulation fault 2	0.219	0.222	1.4
6) Slotted 1 mm steel U-stud type 2	0.187	0.190	1.8
7) Specimen 6 w/ insulation fault 3	0.186	0.189	1.8
8) Wooden beam (50 mm x 200 mm)	0.180	0.183	1.8
9) Wooden lath skeleton (2 x 50 mm x 100 mm)	0.174	0.177	2.0

If we compare the two sets of calculated results in Table 2 it is obvious that the thermal transmission coefficient of the insulation material plays a role for the U-values. The thermal transmission coefficient is increased by approximately 2.3 % resulting in an increase in U-values between 1.4 % and 2.1 % depending on the severity of the thermal bridge, e.g. the more severe the thermal bridge the less the increase in U-value.

The insulation material used in all of the measurements classifies, according to Danish regulations, as having a design thermal transmission coefficient of 0,039 W/mK. Had this value been used in the calculations, all calculated results would have been higher than corresponding measured results, thus making the calculations applicable for building envelope design.

7. Conclusion

From the comparisons between measurements and calculations it is apparent that the numerical calculation programs are very efficient and accurate when determining transmission heat loss coefficients.

Building materials are not ideal and building constructions cannot be built to ideal geometrical specifications. When numerical calculation programs are utilised, ideal geometrical models with ideal materials and boundary conditions are used. The translation from physical construction to mathematical description is extremely complex, as the physical construction is anything but ideal. However, the investigations described in this paper have shown that a straight translation, e.g. modelling the theoretically correct geometry with accurately determined material properties, will produce very precise results.

It is, of course, a problem if U-values are underestimated, and therefore it should be stressed that material properties in general should be taken as values that take into account any inhomogenities or other aspects that could conclude in a higher thermal transmittance.

These investigations have shown that numerical calculation of thermal bridges in building construction seems relatively straightforward. There seems to be no apparent problems in translating directly from the physical construction to the mathematical description. However, further investigations should be carried out, as there are other areas that need to be analysed, i.e. point thermal bridges, geometrical thermal bridges and thermal bridges due to moisture and condensation.

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