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Citation for the published version (APA 6th)
Haavi, T., Jelle, B. P., & Gustavsen, A. (2012). Vacuum insulation panels in wood frame wall constructions with different stud profiles. *Journal of Building Physics, 36*(2), 212-226. doi:10.1177/1744259112453920

Hot Box Measurements and Numerical Simulations of Vacuum Insulation Panels in Wood Frame Wall Constructions with Different Stud Profiles

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ABSTRACT

Energy use in buildings accounts for a significant part of the energy use and greenhouse gas emissions. New building regulations and new measures have been introduced to improve the energy efficiency of buildings. In these buildings the envelope constructions will have significant amounts of traditional thermal insulation, e.g. wall thicknesses up to about 400 mm are expected in passive houses. Such large thicknesses are not desirable due to several reasons, e.g. floor area considerations, efficient material use and need for new construction techniques.

Vacuum insulation panels (VIPs) are regarded as one of the most promising existing high performance thermal insulation solutions on the market today. Thermal performances 5 to 10 times better than traditional insulation materials (e.g. mineral wool) are achieved, resulting in substantial slimmer constructions. However, the robustness of building envelope systems applying VIPs has been questioned. In addition, thermal bridging due to the vacuum insulation panel envelope and load bearing elements of the walls may have a large effect on the overall thermal performance. Degradation of thermal performance of VIPs with time is also a crucial issue due to moisture and air diffusion through the panel envelope.

In this work the thermal performance and robustness of vacuum insulation panels in wood frame wall constructions were studied by hot box measurements and numerical simulations. The thermal performance of three different wall configurations was examined. VIPs were sandwiched between traditional insulation in walls where the load bearing elements were standard 36 mm thick wooden studs, I-profiled studs and U-profiled studs. The measured mean values of the thermal transmittance (U-value) were 0.09 W/(m^{2}K) with 36 mm wooden studs, 0.10 W/(m^{2}K) with U-profiled studs and 0.11 W/(m^{2}K) with I-profiled studs.

The comparison of the three wall structures have shown that with such low U-values, the numerical simulations are more sensitive to the accuracy of the dimensions and thermal conductivities used as input. The accuracy of the numerical simulations were significantly improved by measurements of the thermal resistance of the fibreboard in the web of the I-studs and the U-studs, the thickness and thermal resistance of the VIPs, and the thermal resistance of the 36 mm wooden studs and the mineral wool. It was noted that the measured thermal conductivity of the fibreboard in the web of the I-studs and the U-studs was significantly higher in the direction of the heat flow than in the perpendicular direction.

Keywords: Vacuum insulation panel, VIP, Wood frame wall, Hot box, Numerical simulation, Thermal performance, Building insulation, Thermal bridge, Thermal conductivity, Thermal transmittance, U-value, Thermal resistance.

1. INTRODUCTION

As energy requirements for buildings are tightened, the building envelopes applying traditional building insulation materials are getting thicker in order to have a sufficient high thermal resistance, i.e. a low thermal transmittance (U-value). Traditional building insulation materials like mineral wool, expanded or extruded polystyrene have thermal conductivity values typically between 33 to 40 mW/(mK). However, there exist other materials and solutions with lower thermal conductivities than these conventional building insulation materials. One of these solutions is the vacuum insulation panel (VIP), which exhibit conductivities as low as between 3.5 to 4 mW/(mK) in the pristine non-aged condition. The VIP solution consists of an open pore structure of fumed silica core with a metallized polymer laminate envelope acting as a moisture and air barrier around the core material. Depending on the properties of the laminate envelope, the thermal conductivity of VIP will increase during the years, e.g. up to 8 mW/(mK) after 25 years ageing. A perforated VIP, e.g. by a nail, will have a thermal conductivity of about 20 mW/(mK). It will be crucial to the thermal performance, to make the construction with VIPs in the building envelope as robust as possible.

Comprehensive work has already been carried out on investigations of the thermal properties, performance and service life of VIPs (Brunner et al. 2005). It should be noted that VIPs are rather complex products, where the panel core and laminate envelope have widely different thermal properties (Tenpierik et al. 2007). The work carried out on VIPs regarding their thermal performance includes numerical calculations (Schwab et al. 2005, Willems et al. 2005), analytical evaluations (Tenpierik and Cauberg 2007), laboratory measurements on a smaller scale (Wakili et al. 2004) and field studies of building projects (Platzer 2007). A recent extensive review on VIPs for building applications has been given by Baetens et al. (2010), also including material concepts beyond VIPs.

The work presented here is part of experimental studies of VIPs applied in the building envelope. In the previous studies, the effect of changing the configuration of different VIPs was investigated with hot box measurements (Grynning et al. 2011). Other experiments have investigated the aging effects on the thermal properties and the service life of VIPs (Wegger et al. 2011), and also the applicability of VIPs when retrofitting wood frame walls (Sveipe et al. 2011). The effect of applying different structural vertical wood frame stud profiles between the VIPs in order to minimize the heat loss through the building envelopes was initially investigated with hot box measurements by Haavi et al. (2010). The objective of this work is to study further the thermal performance of standard wooden studs, I-profiled studs and U-profiled studs with VIPs as the main thermal insulation between the vertical studs, also including new numerical simulations and additional measurements.

2. EXPERIMENTAL

2.1 Test materials

Vacuum Insulation Panels

The VIPs used in the hot box measurements are of the type va-Q-vip B delivered from the company va-Q-tec (va-Q-tec 2009a). The panels used are 40 mm thick, 600 mm wide and 1000 mm high (nominal dimensions). A 0.1 mm thick multilayer MF-2 type foil is used and the panels are in addition covered with a 0.3 mm thick fire retardant glass fibre material.

Studs

Standard 36 mm wooden studs, I-profiled studs and U-profiled studs were examined with VIPs combined with mineral wool as the thermal insulation between the vertical studs. These studs and the corresponding wall structures will be referred to as *36 mm stud*, *I-stud* and *U-stud* throughout this article. The studs are shown in Figure 1. Description of the studs:

- **36 mm stud:** Standard wooden stud with 36 mm thickness and originally 198 mm depth. The depth was reduced to 170 mm, the same as the I-stud and the U-stud.
- **I-stud:** I-profiled studs where the flange material was 47 mm x 47 mm wooden studs and the web material was 8 mm thick fibreboard. The web was glued to the flanges. The total depth of the I-stud was 170 mm.
- **U-stud:** U-profiled studs where the flange material was 45 mm x 45 mm wooden studs and the web material was 8 mm thick fibreboard. The web was nailed to the flanges. The total depth of the U-stud was 170 mm.

Note: The depth of the studs is in the same direction as the thickness of the wall.

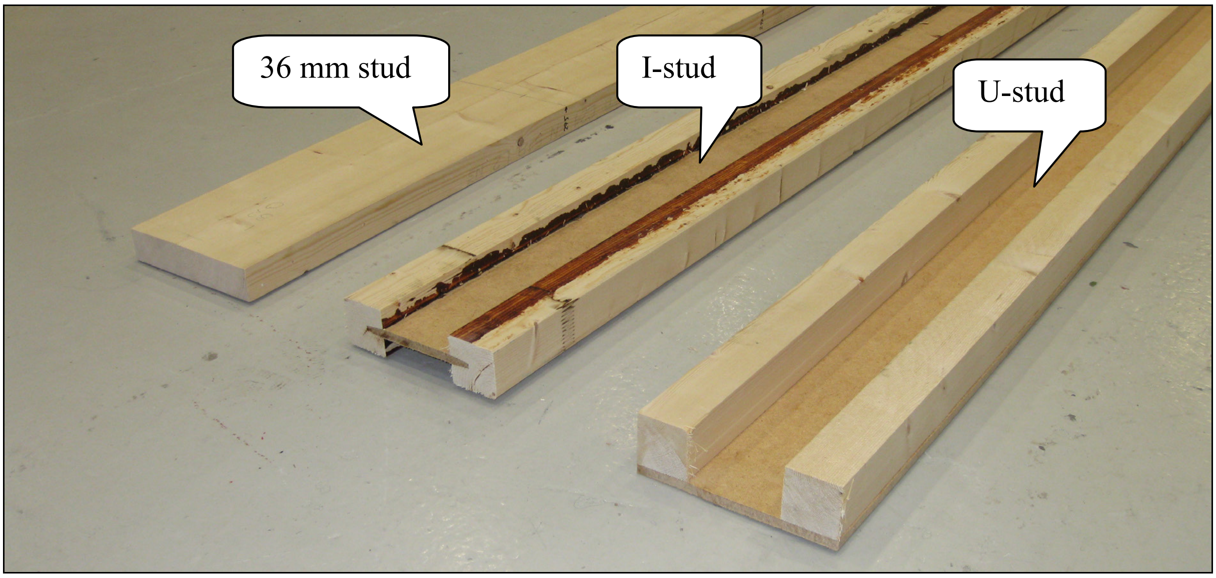

Figure 1 The different studs used in the wood frame wall constructions.

Mineral wool

Mineral wool with 25 mm and 70 mm thickness was used in the tested wall constructions, on both sides of the VIPs and in the I-stud and the U-stud (see Figure 3 to Figure 5).

Medium density fibreboard

Medium density fibreboard (MDF) with 6 mm thickness was used on both sides of the tested wall constructions, outside the insulation and the studs (see Figure 3 to Figure 5).

2.2 Test equipment

Measurements in the hot box have been carried out according to the governing standard, NS-EN ISO 8990 (1997). The hot box at NTNU/SINTEFs laboratory in Trondheim, Norway is a guarded hot box with a metering area of 2.45 m by 2.45 m, depicted in Figure 2. The U-values reported for the wall sections are however for the sizes reported in the figure texts for each wall section (Figure 3 to Figure 5). Measurements in the hot box were done for the following wood frame wall constructions with vacuum insulation panels:

1. Wall with 36 mm studs
2. Wall with I-studs
3. Wall with U-studs

The temperature was 20˚C on the hot side, and 0˚C on the cold side of the walls.

Figure 2 Photograph of the guarded hot box. The hot box is to the left and the cold box is to the right, with the sample in between.

2.3 Wall with 36 mm studs

The wall consists of two 36 mm studs with insulation as shown in Figure 3. The sections with insulation have a nominal total thickness of 182 mm, and consist of the following layers: 6 mm MDF – 65 mm mineral wool – 40 mm VIP – 65 mm mineral wool – 6 mm MDF.

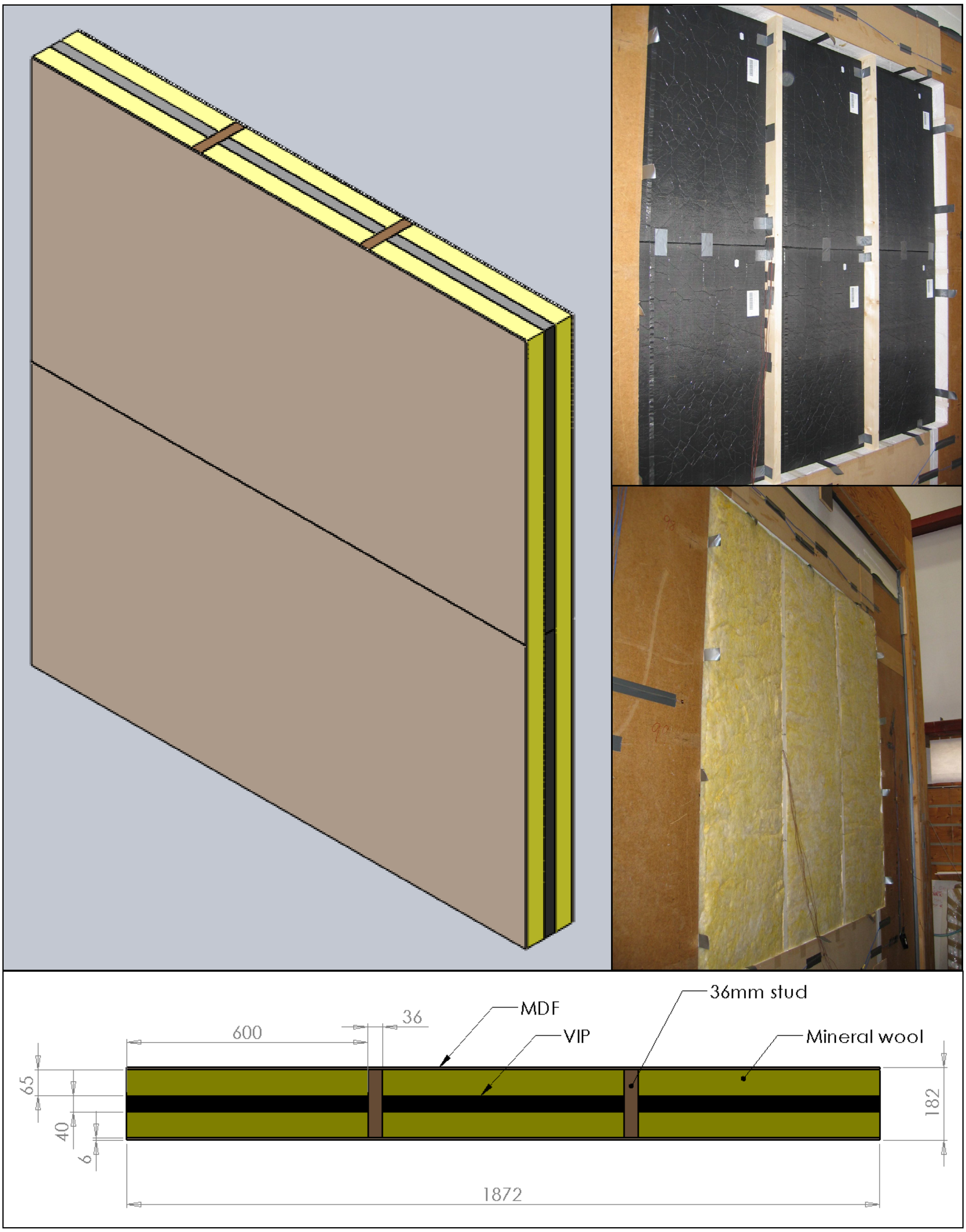

Figure 3 Wall with 36 mm studs. Nominal dim.: h = 2000 mm, w = 1872 mm, t = 182 mm.

2.4 Wall with I-studs

The wall consists of two I-studs with insulation as shown in Figure 4. The sections with insulation have a nominal total thickness of 182 mm, and consist of the following layers: 6 mm MDF – 65 mm mineral wool – 40 mm VIP – 65 mm mineral wool – 6 mm MDF. The volume between the web and the flanges of the I-stud is filled with mineral wool.

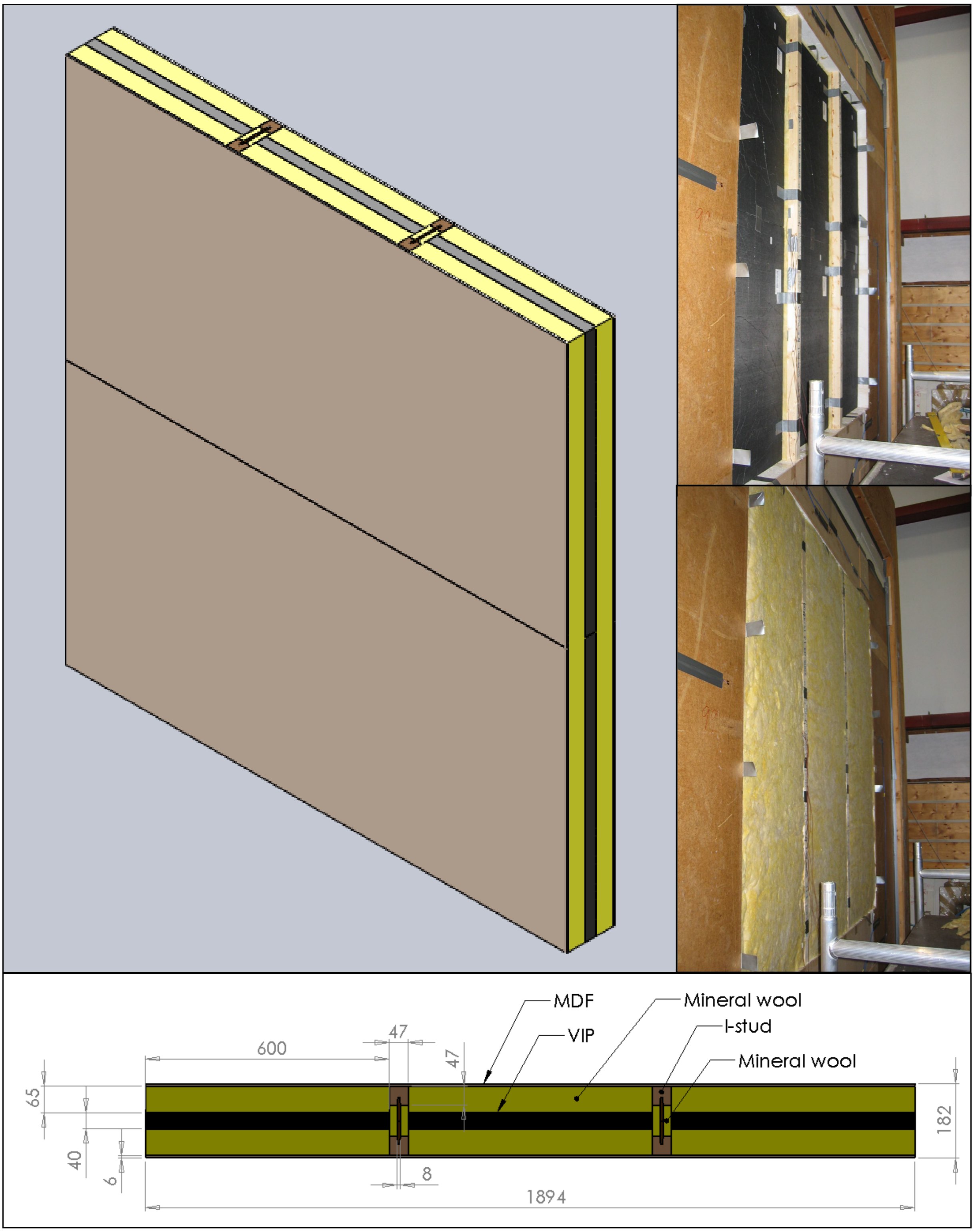

Figure 4 Wall with I-studs. Nominal dim.: h = 2000 mm, w = 1894 mm, t = 182 mm.

2.5 Wall with U-studs

The wall consists of two U-studs with insulation as shown in Figure 5. The sections with insulation have a nominal total thickness of 182 mm, and consist of the following layers: 6 mm MDF – 65 mm mineral wool – 40 mm VIP – 65 mm mineral wool – 6 mm MDF
The volume between the flanges of the U-stud and the VIP is filled with mineral wool.

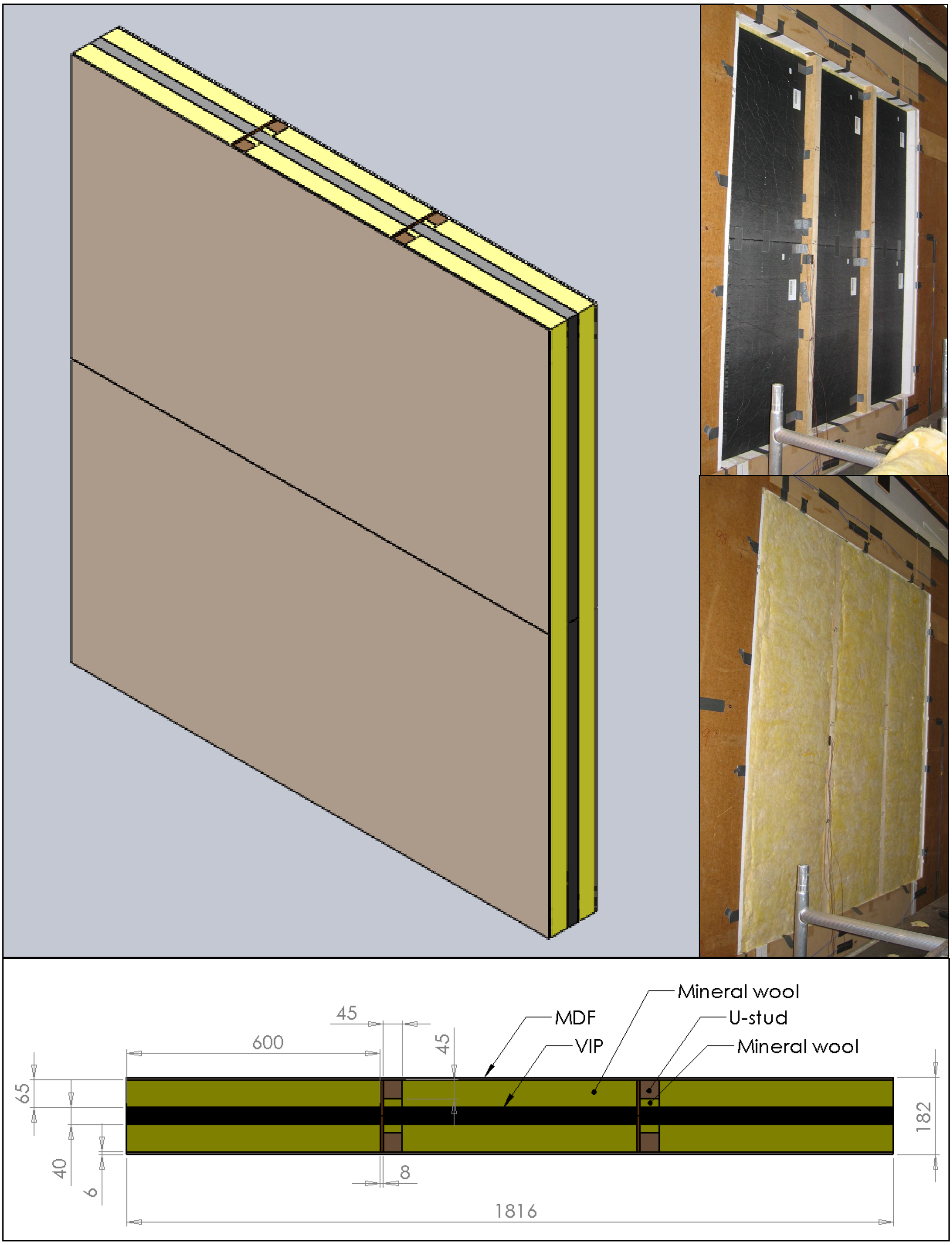

Figure 5 Wall with U-studs. Nominal dim.: h = 2000 mm, w = 1816 mm, t = 182 mm.

2.6 Instrumentation

In addition to the general instrumentation in the hot box, the wall constructions were instrumented with 40 thermocouples and 2 heat flow meters as shown in Figure 6. There were 14 thermocouples on each side of the wall, and 6 thermocouples on the web of each stud. The heat flow meters were located on the hot side of the wall, close to the centre of the VIPs between the studs (approximately 100 mm to the left of the centre to avoid interference with the thermocouples). The two heat flow meters, referred to as TNO PU 43T.0024 and TNO PU 43T.0025, have been calibrated in a heat flow meter apparatus.

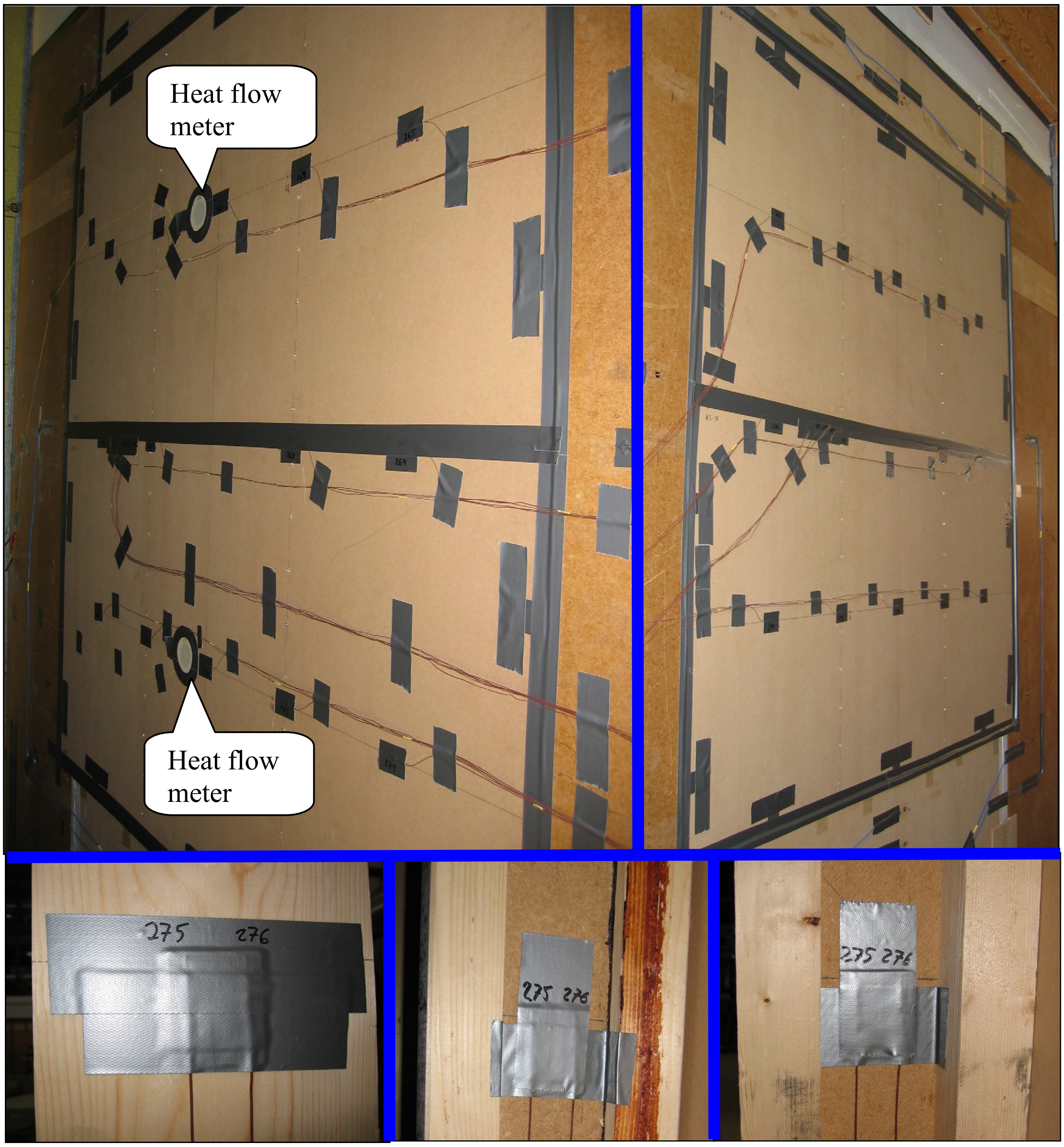

**Figure 6 Placement of thermocouples and heat flow meters on wall and studs.
Upper left: Hot side, Upper right: Cold side.
Lower left: 36 mm stud, Lower middle: I-stud, Lower right: U-stud.**

3. NUMERICAL SIMULATIONS

U-values have been calculated using the two dimensional, finite element program THERM Version 6.3.19 (Mitchell et al. 2011). The wall constructions which were tested in the hot box were modelled as shown in Figure 7, using the dimensions and thermal conductivities summarised in Table 1. Two cases were simulated. The first case, which is referred to as *nominal*, had typical thermal conductivities and nominal dimensions as input. This input is summarised in the two first columns in Table 1.

The second case, which is referred to as *modified*, had measured thermal conductivities for the VIP, the 36 mm wooden studs, the mineral wool and the fibreboard in the web of the I-stud and the U-stud. In addition, the measured thickness of the VIP was used. This input is summarised in the two last columns in Table 1.

The simulations were carried out with both *nominal* and *modified* input parameters, to examine the importance of applying correct material data, as these are often not available.

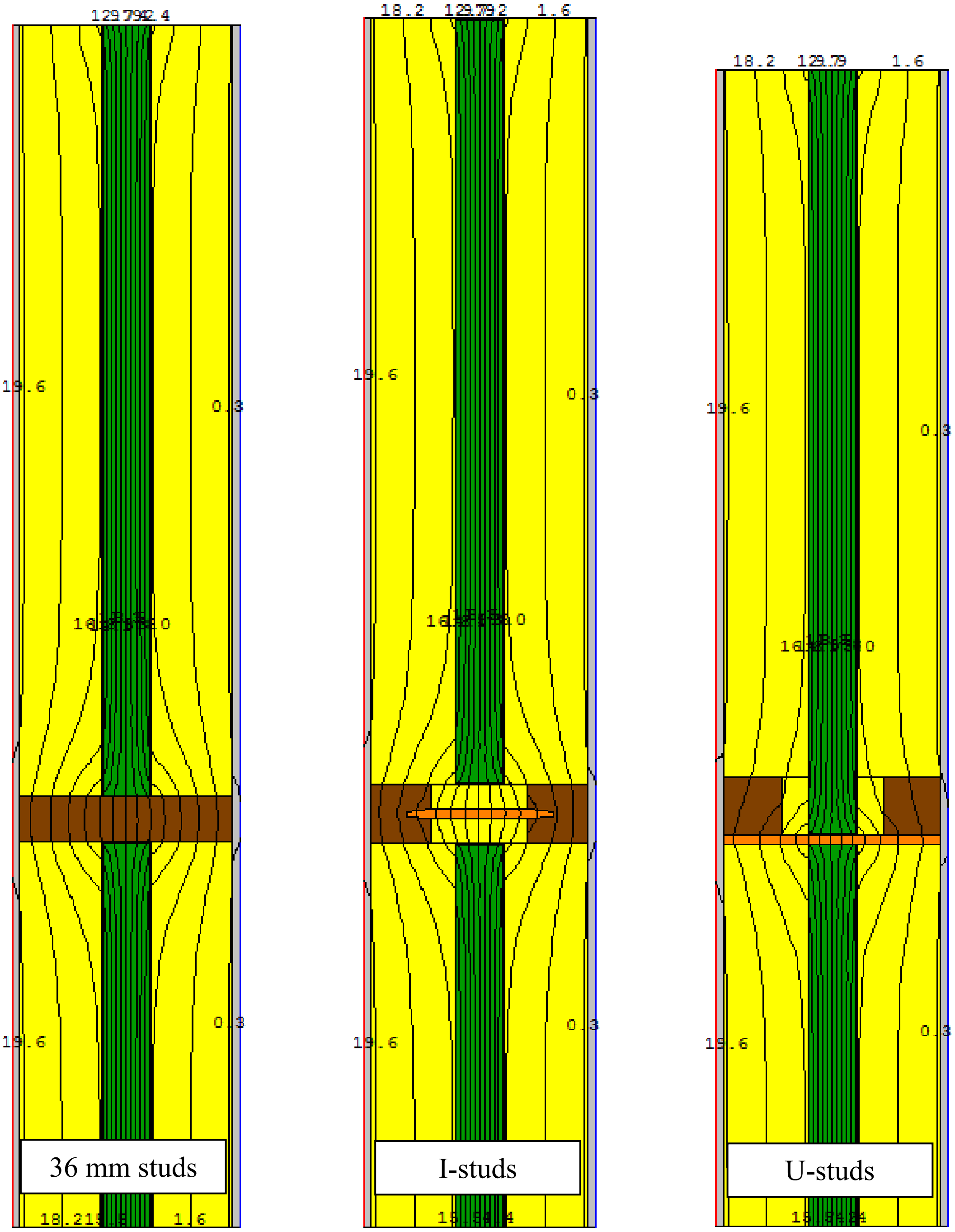

Figure 7 Numerical simulation models with temperature isotherms (modified case).

Table 1 Thermal conductivities and dimensions used in the numerical simulations.

Item	Nominal		Modified	
	Thermal conductivity [W/mK]	Thickness [mm]	Thermal conductivity [W/mK]	Thickness [mm]
VIP core	0.0039	39.2	0.0043 *)	37.4 *)
VIP multilayer MF-2 type foil	0.54	0.1	0.54	0.1
VIP fire retardant glass fibre material	0.31	0.3	0.31	0.3
36 mm wood stud	0.13	36	0.10 *)	36
Wooden flange in I-stud and U-stud	0.13	See Figure 4 and Figure 5	0.10	See Figure 4 and Figure 5
Fibreboard in web of I-stud and U-stud	0.18	8	0.38 *)	8
Mineral wool	0.037	65	0.034 *)	65.8
MDF	0.18	6	0.18	6

***) Based on measurements of the material which were used in the hot box tests.**

3.1 Geometry

Nominal dimensions as shown in Figure 3 to Figure 5 have in general been used, except for the VIP panels. The measured average thickness of the VIP panels was 38.2 mm. This is only 1.8 mm less than the nominal dimension of 40 mm, but still a reduction of 5 %. The measured thickness was therefore included in the *modified* numerical simulations. The thickness of the mineral wool was increased accordingly to 65.8 mm.

3.2 Material properties

Vacuum Insulation Panels

The thermal conductivity for a VIP panel is typically about 0.004 W/(mK) after production (Erb et al. 2005), i.e. at the centre of the panel (λ_{cop}) without taking into account the thermal bridges around the edges. This thermal conductivity was used in the simulations with *nominal* input parameters.

The thermal resistance of two VIP panels were measured in a heat flow meter apparatus according to the governing standard NS-EN 12667 (2001). The average of the results from these measurements was $\lambda_{cop} = 0.00435$ W/(mK), which is 9 % higher than the nominal thermal conductivity. This measured value was used together with the values for VIP foil conductivity $\lambda_{foil} = 0.54$ W/(mK) (Tenpierik and Cauberg 2007) and VIP fire protective glass fibre $\lambda_{gf} = 0.31$ W/(mK) (va-Q-tec 2009b) to calculate an average VIP core conductivity $\lambda_{core} = 0.00426$ W/(mK). These values were used in the simulations with *modified* input.

Wood

Typical thermal conductivity for wood is 0.13 W/(mK) (NS-EN ISO 10456 2007). This thermal conductivity was used in the simulations with *nominal* input parameters, i.e. for the 36 mm studs, as well as for the wooden flanges in the I-studs and U-studs.

The thermal resistance of one of the 36 mm studs were measured in a heat flow meter apparatus according to the governing standard NS-EN 12667 (2001). The result from this measurement was $\lambda_{w\ 36mm} = 0.10$ W/(mK), which is 23 % less than the nominal thermal conductivity. This thermal conductivity was used in the simulations with *modified* input for the 36 mm studs, but also for the wooden flanges in the I-studs and U-studs although their thermal conductivity was not measured.

Fibreboard in web of I-stud and U-stud

The thermal conductivity of the fibreboard webs in the I-studs and U-studs, was specified to be $\lambda_{fb} = 0.18$ W/(mK) in the European technical approval (SITAC 2009). This thermal conductivity was used in the simulations with *nominal* input parameters.

It is common to measure the thermal conductivity through the thickness of fibreboard plates (ref. perpendicular direction in Figure 8), but the thermal conductivity in the longitudinal direction is not well known. The thermal resistance in the longitudinal direction (see Figure 8 and Figure 9), i.e. the direction of the heat flow through the I-studs and the U-studs, was therefore measured in a heat flow meter apparatus according to the governing standard NS-EN 12667 (2001). The result from the measurement was $\lambda_{fb\parallel} = 0.38$ W/(mK), which is 111 % higher than the value from the technical approval. This measured value was used in the simulations with *modified* input.

The thermal conductivity from an equivalent measurement in the perpendicular direction was $\lambda_{fb\perp} = 0.14$ W/(mK).

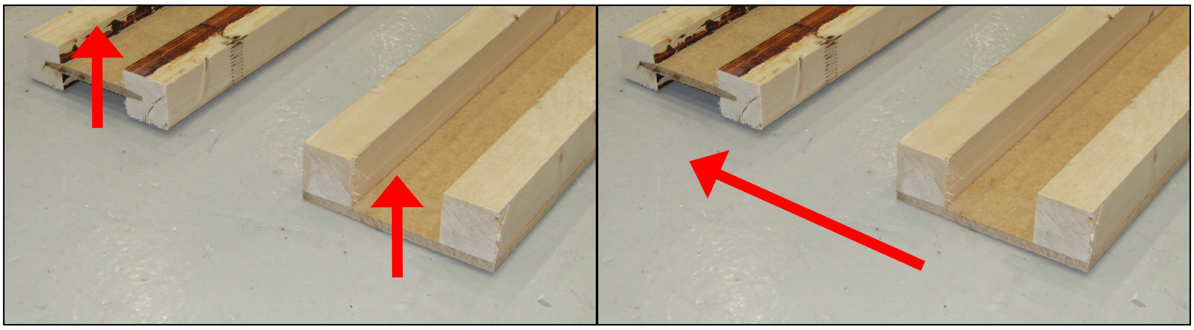

Figure 8 Perpendicular direction to the left, and longitudinal direction to the right.

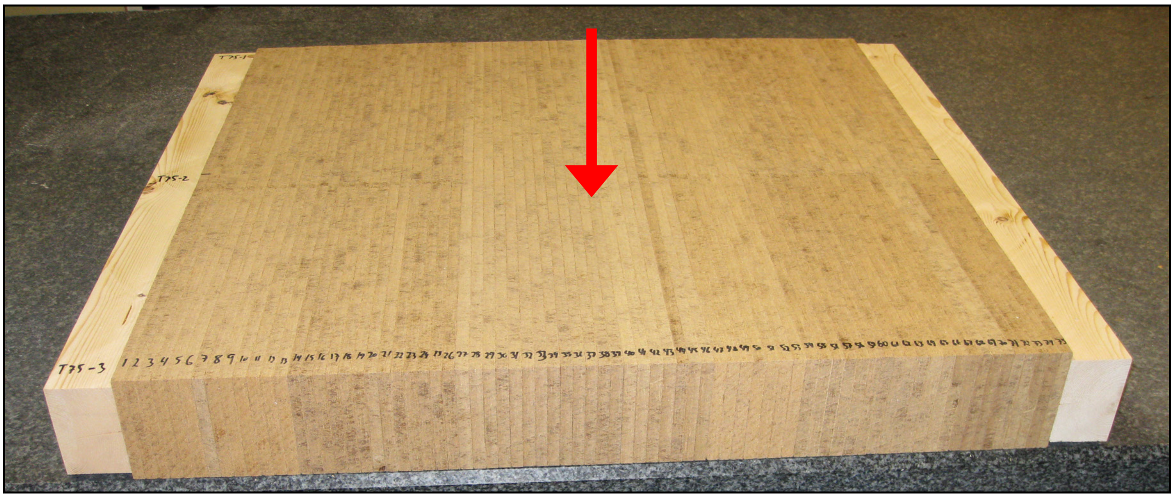

Figure 9 Test specimen with arrow showing heat transfer in longitudinal direction.

Mineral wool

The manufacturer specified a thermal conductivity of 0.037 W/(mK) for the mineral wool (Glava 2008). This thermal conductivity was used in the simulations with *nominal* input parameters.

The thermal resistance of the mineral wool was also measured in a heat flow meter apparatus according to the governing standard NS-EN 12667 (2001). A 70 mm thick test specimen of mineral wool was compressed to 66 mm and then measured. The thermal conductivity from the measurement was 0.034 W/(mK), which is 8 % less than the nominal value. This measured value was used in the simulations with *modified* input.

Medium density fibreboard

A typical thermal conductivity for medium density fibreboard (MDF) was taken from the standard NS-EN ISO 10456 (2007). The thermal conductivity for MDF was 0.18 W/(mK), and were used in the simulations with both the *nominal* and the *modified* input parameters.

4. RESULTS

The results from the testing in the hot box are summarised in Table 2 and Table 3. The presented results are the mean, maximum and minimum value of the thermal transmittance (U-value) during the time interval where the results were extracted. The results in Table 2, shows the average U-value for the different wall constructions with studs. The results in Table 3, shows the U-value which is measured with the heat flow meters (HFM), i.e. close to the centre of the VIPs, excluding the effect of the studs.

A comparison of the hot box measurements and the numerical analyses are shown in Table 4, Table 5, Figure 10 and Figure 11.

Table 2 U-value measured in hot box. Average for wall with studs.

	Mean U-value	**Difference**	**Maximum U-value *)**	**Minimum U-value *)**
	[W/(m^{2}K)]	[%]	[W/(m^{2}K)]	[W/(m^{2}K)]
36 mm studs	0.094	Reference	0.096	0.092
I-studs	0.108	14.8	0.109	0.107
U-studs	0.103	9.1	0.105	0.101

***) Maximum/minimum U-value for the time interval where the results were extracted.**

Table 3 U-value measured by HFM in the hot box at the centre of the VIPs.

	Mean U-value	**Difference**	**Maximum U-value *)**	**Minimum U-value *)**
	[W/(m^{2}K)]	[%]	[W/(m^{2}K)]	[W/(m^{2}K)]
36 mm studs	0.082	Reference	0.083	0.082
I-studs	0.084	1.8	0.084	0.084
U-studs	0.083	0.8	0.084	0.082

***) Maximum/minimum U-value for the time interval where the results were extracted.**

Table 4 Thermal transmittance (U-value) for the wall with studs. Comparison of measurements and numerical analyses with nominal and modified input parameters as described in Chapter 3.

	Hot Box	Nominal		Modified	
		Numerical	Difference	Numerical	Difference
	[W/(m²K)]	[W/(m²K)]	[%]	[W/(m²K)]	[%]
36 mm studs	0.094	0.104	10.8	0.102	8.6
I-studs	0.108	0.098	-9.5	0.107	-1.5
U-studs	0.103	0.091	-11.6	0.105	2.1

Table 5 Thermal transmittance (U-value) through the wall at the centre of the VIPs. Comparison of measurements and numerical analyses with nominal and modified input parameters as described in Chapter 3.

	Hot Box (HFM)	Nominal		Modified	
		Numerical	Difference	Numerical	Difference
	[W/(m²K)]	[W/(m²K)]	[%]	[W/(m²K)]	[%]
36 mm studs	0.082	0.073	-11.8	0.078	-5.6
I-studs	0.084	0.073	-13.4	0.078	-7.3
U-studs	0.083	0.073	-12.6	0.078	-6.4

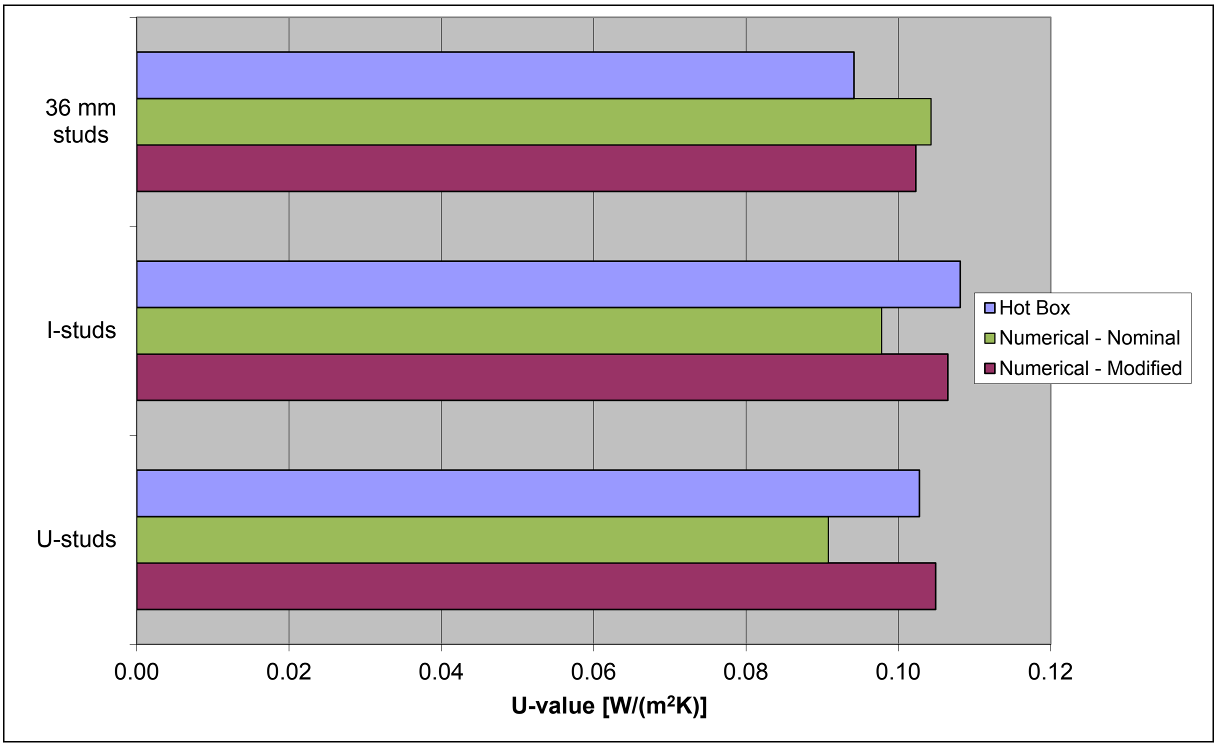

Figure 10 Thermal transmittance (U-value) for the wall with studs. Comparison of measurements and numerical analyses with nominal and modified input parameters (ref. Table 4).

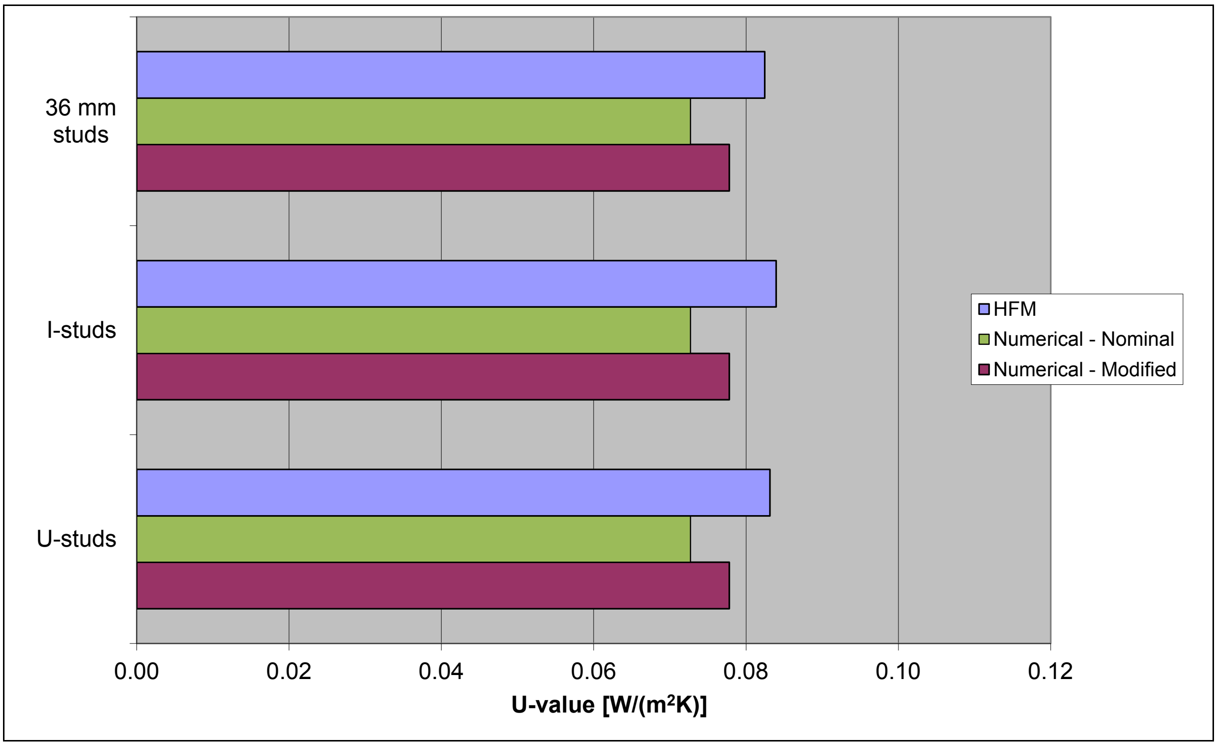

Figure 11 Thermal transmittance (U-value) through the wall at the centre of the VIPs. Comparison of measurements and numerical analyses with nominal and modified input parameters (ref. Table 5).

5. DISCUSSION

5.1 Thermal properties

The hot box results (see Table 2, Table 4 and Figure 10) show that the wall with 36 mm studs has the lowest U-value, that the U-value of the wall with U-studs is 9.1 % higher, and that the wall with I-studs has the highest U-value, i.e. 14.8 % higher than the wall with 36 mm studs.

In the first case of the numerical simulations, i.e. with *nominal* input parameters, the ranking of the walls were quite different. The wall with the 36 mm studs had the highest U-value in these simulations. This could be explained by the fact that the actual thermal conductivity of the fibreboard in the web of the I-studs and the U-studs were significantly higher than specified in the European technical approval (SITAC 2009). The measured thermal conductivity, in the direction of the heat flow was $\lambda_{fb\parallel} = 0.38$ W/(mK), which is 111 % higher than $\lambda_{fb} = 0.18$ W/(mK) which was specified in the technical approval. This is most likely because it is common to measure the thermal conductivity through the thickness of plates, and thereby failing to reveal the anisotropic thermal conductivity of the fibreboard. The thermal conductivity from an equivalent measurement through the thickness of the fibreboard plates was $\lambda_{fb}\perp = 0.14$ W/(mK).This means that the thermal bridge effect of the I-studs and U-studs is significantly higher than expected, and therefore increases the average U-value of these walls. In addition, the actual thermal bridge effect of the 36 mm studs is lower than expected. The thermal conductivity of the 36 mm studs from measurement was $\lambda_{w\ 36mm} = 0.10$ W/(mK), which is 23 % less than the nominal thermal conductivity, and therefore decreases the average U-value of this wall. This can be explained by the relatively low density of the 36 mm studs. The thermal conductivity can be related to the dry density of wood (Grynning et. al. 2008), which means that the thermal conductivity decreases when the dry density is decreasing.

In addition to the above mentioned factors which affect the thermal bridge effect, it was also shown that measurements of the VIP and the mineral wool improved the results from the numerical simulations. The measured thickness of the VIPs was only 1.8 mm less than the nominal dimension of 40 mm, but this is still a reduction of 5 %, which also means an equivalent reduction of the thermal resistance of the VIPs. The average thermal conductivity from the measurements at the centre of the VIP panels was $\lambda_{cop} = 0.00435$ W/(mK), which is 9 % higher than the nominal thermal conductivity. In addition to the VIP measurements, the thermal conductivity from the measurement of mineral wool was 0.034 W/(mK), which is 8 % less than the nominal value.

Both the lower thickness and the higher thermal conductivity of the VIPs reduce the thermal resistance of the walls, while the lower thermal conductivity of the mineral wool increases the thermal resistance. The variations in the properties of the VIPs have nevertheless a more significant influence on the total thermal resistance of the wall, since the VIPs accounts for a larger share of the total thermal resistance.

All in all, the numerical simulations with *modified* input parameters has significantly better correlation with the hot box measurements than the simulations with *nominal* input parameters. With *nominal* input parameters, the ranking of the walls regarding lowest and highest U-value is not the same as for the hot box measurements, and the deviation between hot box measurements and simulations varies between -11.6 % and 10.8 %. With *modified* input parameters, the ranking of the walls regarding lowest and highest U-value is the same as for the hot box measurements, and the deviation between hot box measurements and simulations varies between -1.5 % and 8.6 %, which is very good correlation.

The hot box results in Table 3, Table 5 and Figure 11 shows the U-value which is measured with the heat flow meters (HFM), i.e. close to the centre of the VIPs, excluding the effect of the studs. The measured U-value at the centre of the VIPs is almost the same for all three wall constructions, which is expected, since this area should not be influenced by the studs. The comparison of the HFM measurements and the numerical simulations also shows that the simulations with *modified* input parameters have better correlation with the HFM results than the simulations with *nominal* input parameters. With *nominal* input parameters, the deviation between HFM measurements and simulations varies between -13.4 % and -11.8 %. With *modified* input parameters, the deviation between hot box measurements and simulations varies between -7.3 % and -5.6 %, which is quite good correlation.

It should be noted that all the U-values are very low. This means that the measured U-values are more sensitive to variations in the assembly of the full-scale wall constructions and possible air leakages. The low U-values also imply that the numerical simulations are more sensitive to the accuracy of the dimensions and thermal conductivities used as input. Relatively small variations in the thermal conductivity and the thickness of the VIP panels, as well as variations in the thermal conductivities of the studs, have significant impact on the average U-value of the wall. This is illustrated by the deviation between the simulations with *nominal* input parameters compared with the simulations with *modified* input parameters. The accuracy of the numerical simulations was significantly improved by measurements of the input parameters which have most influence on the U-values.

5.2 Robustness and buildability

The thermal performance of the VIPs is very dependent on the metallized polymer laminate envelope acting as a moisture and air barrier around the core material (Baetens et al. 2010, Wegger et al. 2011). If the envelope is perforated, the thermal conductivity will be about five times higher than in the pristine non-aged condition. All three wall constructions in these experiments are considered to be relatively robust, due to the mineral wool layer on each side, which reduces the risk of perforating the VIP envelope, e.g. with a nail.

It was initially assumed that the low thickness (8 mm) of the web in the I-studs and the U-studs was going to reduce the thermal bridge effect, compared with the traditional 36 mm thick studs. The improved thermal properties of the wall were supposed to compensate for the additional work of insulating the small gaps between the VIPs and the I-studs and the U-studs. However, the measured thermal conductivity of the fibreboard in the web of the I-studs and the U-studs was significantly higher than specified in the direction of the heat flow. Hence, the construction of the three different walls and the following tests in the hot box, have shown that the traditional wood frame wall construction with 36 mm wood studs has the lowest U-value and is easiest to build. The buildability of all three walls is strongly influenced by the fixed dimensions of the VIPs, which require better planning and higher precision, since the size of the VIPs can not be adapted on the building site.

6. CONCLUSIONS

The hot box testing of different wood frame wall constructions with vacuum insulation panels gave the following thermal transmittance (U-value):

Wall with 36 mm studs:	0.09 W/(m^{2}K)
Wall with I-studs:	0.11 W/(m^{2}K)
Wall with U-studs:	0.10 W/(m^{2}K)

The wall sections had a somewhat low fraction of wood frame members and the results are not necessarily representative for normal walls. However, the comparison of the three wall structures have shown that with such low U-values, the numerical simulations are more sensitive to the accuracy of the dimensions and thermal conductivities used as input.

The accuracy of the numerical simulations were significantly improved by applying measured values of (a) thermal resistance of the fibreboard in the web of the I-studs and U-studs, (b) the thickness and thermal resistance of the VIPs, and (c) the thermal resistance of the 36 mm wooden studs and the mineral wool.

It was discovered that the thermal conductivity of the fibreboard in the web of the I-studs and the U-studs was significantly higher than the nominal value $\lambda_{fb} = 0.18$ W/(mK), which was specified in the European technical approval. The measured thermal conductivity was $\lambda_{fb\parallel} = 0.38$ W/(mK) in the direction of the heat flow, and $\lambda_{fb\perp} = 0.14$ W/(mK) in the perpendicular direction.

The experiments show that application of VIPs makes it possible to obtain wall construction U-values of about 0.1 W/(m^{2}K) with a wall thickness of less than ~20 cm.

The proposed wall assemblies improve the robustness of the VIPs, since they are protected by a layer of mineral wool on both sides.

The use of VIPs in wood frame constructions, require better planning and higher precision during construction, since the size of the VIPs can not be adapted on the building site.

ACKNOWLEDGEMENTS

This work has been supported by the Research Council of Norway, AF Gruppen, Glava, Hunton Fiber as, Icopal, Isola, Jackon, Maxit, Moelven ByggModul, Rambøll, Skanska, Statsbygg and Takprodusentenes forskningsgruppe through the SINTEF and NTNU research project ”*Robust Envelope Construction Details for Buildings of the 21st Century*” (ROBUST). The company va-Q-tec, by Roland Caps, is acknowledged for supplying the vacuum insulation panel test samples.

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