COMPARISON OF LABORATORY INVESTIGATIONS AND NUMERICAL SIMULATIONS OF VACUUM INSULATION PANELS IN VARIOUS WALL STRUCTURE ARRANGEMENTS

Steinar Grynning [a]*, Bjørn Petter Jelle [b], Sivert Uvsløkk [c],
Ruben Baetens [d], Vivian Meløysund [e], Thomas Haavi [f] and Arild Gustavsen [g]

[a] SINTEF T, Phone +47 73 593375, Fax +47 73 593380, steinar.grynning@sintef.no
[b] SINTEF T and NTNU BAT, Phone +47 73 593377, Fax +47 73 593380, bjorn.petter.jelle@sintef.no
[c] SINTEF T, Phone +47 73 593393, Fax +47 73 593380, sivert.uvslokk@sintef.no
[d] KUL and SINTEF T, Phone +32 472 349 439, Fax +47 73 593380, ruben.baetens@bwk.kuleuven.be
[e] SINTEF O, Phone +47 22 965721, Fax +47 22 699438, vivian.meloysund@sintef.no
[f] NTNU BHT and SINTEF T, Phone + 47 98 230442, Fax +47 73 595045, thomas.haavi@sintef.no
[g] NTNU BHT, Phone +47 73 595065, Fax +47 73 595045, arild.gustavsen@ntnu.no
* Corresponding author

SINTEF T	Department of Building Materials and Structures, Trondheim, SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway.
SINTEF O	Department of Building Materials and Structures, Oslo, SINTEF Building and Infrastructure, NO-Oslo, Norway.
NTNU BAT	Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.
NTNU BHT	Department of Architectural Design, History and Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.
KUL	Department of Civil Engineering, Catholic University of Leuven, Kasteelpark Arenberg 40, B-3001 Heverlee, Belgium

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ABSTRACT

Buildings account for a significant part of the energy use and greenhouse gas emissions. Therefore one has to improve the energy efficiency of buildings. Concepts like passive houses and zero emission buildings are being introduced. Applying traditional techniques and materials in these buildings will significantly increase the amount 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. Hence, new highly thermal insulating materials and solutions are being sought. In this respect, vacuum insulation panels (VIPs) are regarded as one of the most promising existing high performance thermal insulation solutions on the market today. Thermal performance typically range 5 to 10 times better than traditional insulation materials (e.g. mineral wool), leading to substantial slimmer constructions. However, the VIPs have several disadvantages which have to be addressed. The robustness of VIPs in wall constructions is questioned, e.g. puncturing by penetration of nails. Moreover, the VIPs can not be cut or fitted at the construction site. Furthermore, thermal bridging due to the panel envelope and load-bearing elements may have a large effect on the overall thermal performance. Finally, degradation of thermal performance due to moisture and air diffusion through the panel envelope is also a crucial issue for VIPs. In this work, laboratory investigations have been carried out by hot box measurements. These experimental results have been compared with numerical simulations of several wall structure arrangements of vacuum insulation panels. Various VIP edge and overlap effects have been studied. Measured U-values from hot box VIP large scale experiments correspond quite well with numerical calculated U-values when realistic and measured values of the various parameters are used as input values in the numerical simulations.

1. INTRODUCTION

The interest for vacuum insulation and especially vacuum insulation panels (VIPs) have risen in the building and construction sector over the last years. There are many advantages as well as challenges associated with the application of VIPs in the building and construction sector. The advantages lie in the possibility of reducing the thickness of the building envelope while maintaining or even reducing the thermal transmittance (U-value) as compared to applying a substantially thicker layer of conventional insulation like mineral wool, expanded polystyrene (EPS) or similar. A certain challenge is the discussion that concerns the robustness and flexibility of these products. In order to meet these challenges work has to be carried out to ensure that robust constructions will be made with respect to both mechanical and chemical stresses. These factors, as well as the service life of the VIPs, have to be weighted against the thermal performance of the panels. Thicker, low permeable barrier envelopes will in general increase the thermal bridging effect. Exterior protection of the VIPs will increase the thickness of the building structure.

Extensive work has already been carried out in investigation of the thermal properties and performance as well as the service life of VIPs (Brunner et al., 2005). However, VIPs are complex products where the panel core and the barrier envelope have widely different thermal properties (Tenpierik et al., 2007). Most of the work performed in the field regarding thermal performance is done using numerical calculations (Schwab et al., 2005 ; Willems et al., 2005) and analytical assessments (Tenpierik and Cauberg, 2007), laboratory measurements on a smaller scale (Ghazi et al., 2004) and field studies of building projects (Platzer, 2007).

In this work, the first series from hot box measurements of various full scale VIP wall structure arrangements are presented. The results from these measurements are compared with numerical simulations. The hot box measurements and numerical simulations explore the effect and importance of several ways of arranging different VIPs in various VIP large scale structures, e.g. single and double layer configurations versus panel thicknesses, edge effects including air gaps between the VIPs, staggering of VIPs and taped VIP joints. Thus these initial laboratory investigations are not meant to illustrate real VIP building envelopes. They are the first in a series of large scale tests of VIPs to be investigated in the research program *Robust Envelope Construction Details for Buildings of the 21st Century* (ROBUST). On-going and future work include tests on VIPs in more practical and useable configurations.

2. NUMERICAL SIMULATIONS

U-values and thermal bridge values have been calculated using the two dimensional, finite element program THERM (Mitchell et al., 2006). Values for the linear thermal bridges are calculated according to the rules and definitions given in NS-EN ISO 10211:2007. The total U-values of the test samples, U_{wall}, were calculated using equation 1.

$$U_{wall} = \frac{U_{cop}A_{wall} + \psi_p l_p}{A_{wall}} \qquad (1)$$

U_{wall}	= Total U-value of test field	(W/(m²K))
U_{cop}	= U-value of the centre area of the VIPs	(W/(m²K))
A_{wall}	= Total area of test field	(m²)
Ψ_p	= Panel joint thermal bridge value	(W/(mK))
l_p	= Length of panel joint	(m)

3. EXPERIMENTAL

3.1. 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 20 mm or 40 mm thick and have dimensions as described in Figure 1 and 3. A 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.

3.2. Heat flow meter apparatus measurements

Measurements of λ_{cop}, which is the centre of panel conductivity of the VIPs, for a 20 and 40 mm thick VIP were conducted in a heat flow meter apparatus. These values were used to calculate a centre of panel U-value, U_{cop}, for the test field. Measurements in the heat flow meter apparatus have been performed according to the governing standard, NS-EN 12667:2001.

3.3. Hot box measurements

Measurements in the hot box have been carried out according to the governing standard, NS-EN ISO 8990:1997. The hot box at SINTEFs laboratory in Trondheim, Norway is a guarded hot box with a measuring area of 2.5 m by 2.5 m. The uncertainties of the measured values presented in the results tables are estimated standard deviations of the mean values (99.73 % confidence interval), while no systematic errors are included. Measurements in the hot box were done for the following VIP configurations:

1. Single layer of 40 mm VIPs,
2. Single layer of 40 mm VIPs with taped panel joints
3. Single layer of 20 mm VIPs
4. Double layer of 20 mm VIPs
5. Double layer of 20 mm VIPs with staggered joints

The principal layout of the panels in the hot box surround panel is shown in Figure 1.

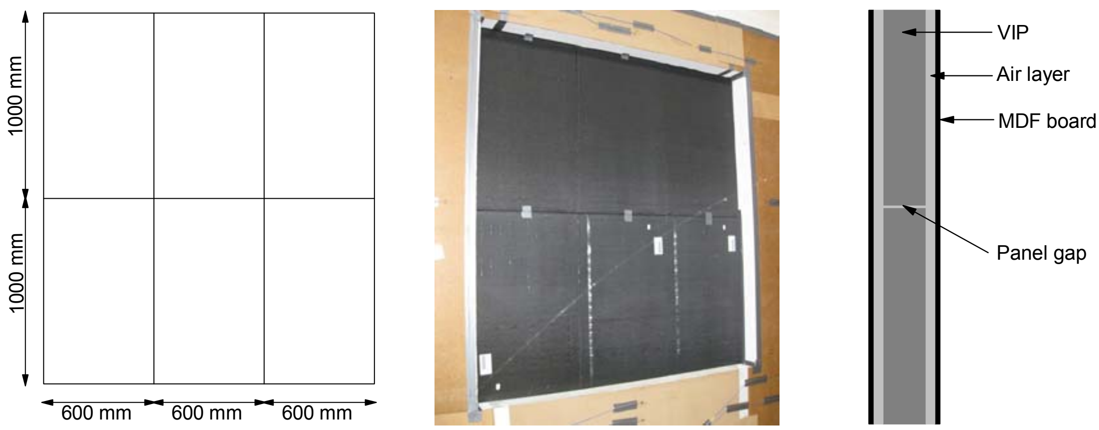

Figure 1. VIP configuration for hot box measurements, series 1 to 4. Test field cross section on the right. Note that the photo in the middle is shown without the MDF boards in front.

For all VIP configurations in the hot box, the VIPs were encased with 6 mm medium density fibre (MDF) boards on the facings. For the test field, consisting of six VIPs, as shown in Figure 1, the total length of the butt joints between the VIPs was l_p = 5.8 m. The total area of the test field was A_{wall} = 3.6 m^2. The thicknesses of the VIPs, t_p, were measured to 19 mm for the *20 mm* VIPs and 38 mm for the *40 mm* VIPs i.e. 5 % thinner than the nominal values. To prevent any air leakages between hot and cold side, the perimeter of the test field MDF boards were taped against the EPS of the surround panel using an airtight tape.

3.4. Panel gaps

Dimensional irregularities of the VIPs lead to gaps in the panel joints in the test field, as illustrated in Figure 2. In order to study the effect of air gaps between VIPs on the total edge loss, the average width of the panel gaps were measured on each test series. The gaps were measured to an average width of 2 mm. It must be noted that the values varied between 0 mm and 7 mm.

Figure 2. Irregularities in the VIP dimensions result in gaps of varying size between the VIPs.

3.5. Air layers between VIP and MDF

The use of MDF as cover for the VIPs led to the occurrence of air layers between the VIPs and the MDF boards due to the curving of the MDF boards. In order to reduce the thickness of the air layer, plastic fasteners with a cross section of 1 mm by 2 mm were used in two positions to hold the MDF boards tight to the VIPs. It was ensured that no air leakage occurred through the holes for the fasteners in the MDF boards. The effect of the additional heat flow through the fasteners on the total U-value of the test field was assumed to be negligible. If no convection occurs between hot and cold side, these air layers will in theory give a reduction of the U-value for the test field compared to an *ideal* situation without any such air layers. The effect of these air layers have been corrected for in the measurements according to equation 2.

$$U'_{wall} = \left(\frac{1}{U_{wall}} - R_{air\ layer} \right)^{-1} \tag{2}$$

U'_{wall} = U-value of test field corrected for air layers (W/(m²K))
$R_{air\ layer}$ = Thermal resistance of air layers between VIP and MDF (m²K/W)

Values for R_{cavity} are taken from NS-EN ISO 6946 based on the average measured air layer thickness for each series, and takes into account all forms of heat transfer internal in the cavity. The corrected value, U'_{wall}, is given in tables below, adjacent to the directly measured values of U_{wall}. This correction was applied to resemble the numerical simulations in which no air layer was modelled.

3.6. Thermal bridge values of panel joints

The values of the measured panel joint thermal bridges were calculated according to equation 3 below:

$$\psi_p = \frac{U'_{wall} - U_{cop}}{l_p} \tag{3}$$

It must be noted that this way of calculating the thermal bridges, all kinds of additional heat loss contribute to the U_{cop}. In practice, contributions might come from other sources, e.g. convection. This will be discussed further in the results and discussion chapter.

4. RESULTS AND DISCUSSION

4.1. Heat flow meter apparatus measurements

Heat flow meter apparatus measurements were carried out on a single sample for both the 20 and 40 mm VIPs. The measured conductivity values are given in Table 1.

Table 1. Measured centre of panel thermal conductivity values, λ_{cop}, for 20 and 40 mm VIPs.

VIP thickness Nominal values	Measured thermal conductivity value λ_{cop} (W/(mK))	VIP measured thickness t_p (mm)	U-value, centre of panel U_{cop} (W/(m²K))
20 mm	0.0042 ± 0.0001	18.9 ± 0.2	0.207 ± 0.005
20 mm, double layer	0.0042 ± 0.0001	37.8 ± 0.4	0.107 ± 0.003
40 mm	0.0044 ± 0.0001	38.0 ± 0.1	0.112 ± 0.002

4.2. Comparison of Numerical Simulations and Hot box measurements

The numerical simulations were performed applying both nominal and measured input values for the physical properties of the VIPs. The nominal values for foil conductivity λ_{foil} = 0.54 W/(mK) (Tenpierik and Cauberg, 2007), and the fire protective glass fibre λ_{gf} = 0.31 W/(mK) (va-Q-tec, 2009b) were used for all numerical simulations. That is, values for λ_{foil} and λ_{gf} were not measured. Thermal bridge values, ψ_p, and U-values, U_{cop} and U_{wall}, from numerical simulations are given in the following tables next to the belonging measured values in their respective chapters. Both nominal values for core conductivity λ_{cop} = 0.004 W/(mK) and VIP thickness t_p as given in Table 1 and corresponding measured values are used in the comparison of the various VIP configurations.

4.2.1. 20 mm VIPs in a single layer configuration

Hot box measurements were performed on a configuration using a single layer of 20 mm VIPs. Measured and numerically calculated values are shown in Table 2.

Table 2. Calculated and measured U-values and edge losses with 20 mm VIPs in a single layer configuration.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value test field U_{wall} (W/(m²K))	U-value test field, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated				
Nominal λ_{cop} and t_p, no panel gap	0.189	0.198		0.0055
Nominal λ_{cop} and t_p, 2 mm panel gap	0.189	0.201		0.0073
Measured λ_{cop} and t_p, 2 mm panel gap	0.207	0.219		0.0078
Measured in hot box				
Series #68301	0.207 ± 0.005	0.227 ± 0.001	0.243 ± 0.001	0.0223 ± 0.0009

The measured thermal bridge value due to the panel edge loss, ψ_p, is substantially larger than the calculated values. Since the panel gaps not were made airtight in any way during this measurement series, this is most likely a consequence of convection through the panel gaps between the MDF boards on the hot and cold side of the VIPs. This creates an air loop between the hot and the cold side which short-circuits some of the insulation capacity of the VIPs. This additional heat loss becomes part of the thermal bridge value when calculated according to equation 3.

The measured corrected U-value of the test field, U'_{wall} (0.243 W/(m²K)), is approximately 21 % higher than the numerically calculated value (0.201 W/(m²K)) using nominal values and 2 mm panel gaps. There might be several reasons for this. First, the measured thicknesses of the panels are approximately 5 % lower than the stated nominal thickness. Secondly, the measured λ_{cop} is between 5 and 10 % higher than the nominal value. The variation in these two parameters gives an increase of U'_{wall} by approximately 10 % if one uses the measured values as input variables in the numerical simulation. The remaining difference is most likely caused by the earlier mentioned convection.

4.2.2. 20 mm VIPs in a 40 mm double layer configuration

Hot box measurements were performed on a configuration using a double layer of 20 mm VIPs. Measured and numerically calculated values are shown in Table 3.

Table 3. Calculated and measured U-values and edge losses with 20mm VIPs in a double layer configuration.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value test field U_{wall} (W/(m²K))	U-value test field, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated				
Nominal λ_{cop} and t_p, no panel gap	0.097	0.102		0.0031
Nominal λ_{cop} and t_p, 2 mm panel gap	0.097	0.106		0.0053
Measured λ_{cop} and t_p, 2 mm panel gap	0.107	0.116		0.0054
Measured in hot box				
Series #68704	0.107 ± 0.003	0.114 ± 0.001	0.118 ± 0.001	0.0068 ± 0.0005

The measured values of ψ_p are slightly higher than the calculated values and much more coherent to the numerical simulations than the single layer 20 mm VIP measurements. This is probably due to variations in panel dimensions which lead to a certain degree of displacement of the panel joints in the second layer compared to the first layer. This will likely reduce the convection between hot and cold side compared to a single layer configuration where air can circulate more freely through the gaps between panels.

The measured, corrected U-value of the test field U'_{wall} (0.118 W/(m²K)), is about 11 % higher than the numerical value (0.106 W/(m²K)) calculated with nominal VIP properties and panel gaps of 2 mm. If correcting the VIP properties to the measured values for t_p and λ_{cop}, the measured and numerical value corresponds with only a minor deviation. This deviation can possibly be attributed to uncertainties in panel joint widths, and measured VIP properties.

4.2.3. 40 mm VIPs in a single layer configuration with and without tape

In order to study the effect of convection between hot and cold side, measurements were performed on one configuration without taping the panel joints and one where all panel joints had been taped. Due to large variations in the panel dimensions the measured gaps range from 0 mm to 7 mm for the 40 mm VIPs. Measured values and values from numerical simulations of these test configurations are shown in Table 4.

Table 4. Calculated and measured U-values and edge losses with 40 mm VIPs in a single layer configuration.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value test field U_{wall} (W/(m²K))	U-value test field, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated				
Nominal λ_{cop} and t_p, no panel gap	0.097	0.102		0.0031
Nominal λ_{cop} and t_p, 2 mm panel gap	0.097	0.106		0.0053
Measured λ_{cop} and t_p, 2 mm panel gap	0.112	0.121		0.0054
Measured in hot box				
40 mm (Series #68201)	0.112 ± 0.002	0.121 ± 0.001	0.125 ± 0.001	0.0080 ± 0.0004
40 mm, w/ taped joints (Series #68211)	0.112 ± 0.002	0.115 ± 0.001	0.119 ± 0.001	0.0043 ± 0.0004

The measured thermal bridge value, ψ_p, is slightly larger than the numerically calculated value using measured panel properties. By taping the seams the measured thermal bridge value is halved compared to the non-taped configuration. If a similar VIP wall structure arrangement is being used in a building the effect of taping should be taken into consideration. The numerical simulations were performed for the case equivalent to applying taped joints.

The use of tape to reduce convection in panel joints reduces U_{wall} with approximately 5 %. If there are larger air cavities on both the hot and cold side of the VIPs, the convection may increase further, thereby reducing of thermal performance of the VIPs. This will increase the effect of taping even more.

4.2.4. 20 mm VIPs in a 40 mm double layer configuration with staggered layers

These measurement series were performed on a test field configuration using two layers of 20 mm VIPs with a staggered second layer. Using different panels sizes, the second layer were mounted in such a manner that the panel joints had a maximum dislocation towards the first layer. The configuration of the second layer is shown in Figure 3. Measured values are shown in Table 5.

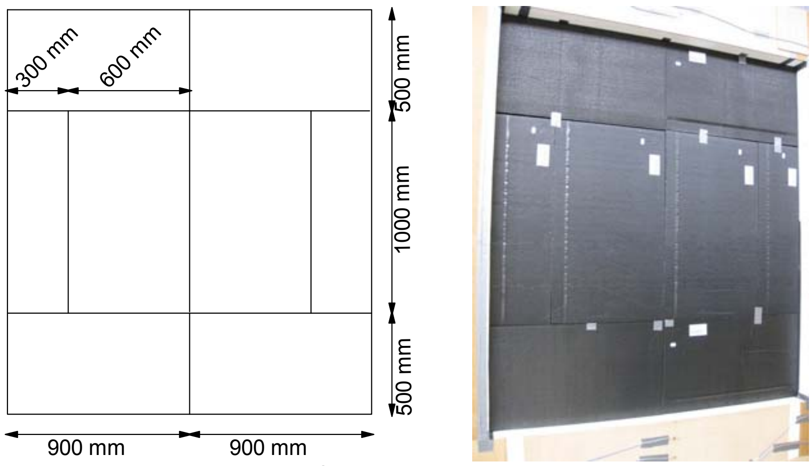

Figure 3. VIP configuration with staggered joints for hot box measurements, series 5.

Table 5. Calculated and measured U-values and edge losses with 20mm VIPs in a 40 mm double layer configuration with staggered joints.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value test field U_{wall} (W/(m²K))	U-value test field, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated				
Nominal λ_{cop} and t_p, no panel gap	0.097	0.101		0.0023
Nominal λ_{cop} and t_p, 2 mm panel gap	0.097	0.102		0.0029
Measured λ_{cop} and t_p, 2 mm panel gap	0.107	0.112		0.0030
Measured in hot box				
Staggered layer (#68702)	0.107 ± 0.002	0.106 ± 0.001	0.109 ± 0.001	0.0012 ± 0.0005

The numerically calculated thermal bridge values will be reduced by 26 to 45 % compared to a non-staggered configuration (comparing values in Table 3 and 5). However, the effect on U_{wall} is smaller, by approximately 1 to 4 % depending on panel gap width.

The measurements on a staggered layer configuration shows a slight reduction of U'_{wall} compared to the measurements on a double layer of 20 mm VIPs without staggered joints.

The measured value of ψ_p seems to reach a value lower than the one from the numerical simulations.

The reduction of the U-value must however be weighted against the practical aspects relevant for this configuration. Challenges at both the installation stage as well as at the planning stage must be considered.

4.3. Comparison of thermal bridge values for various VIP configurations

The thermal bridge values from the tables above are plotted in Figure 4. The measured values for the thermal bridges of the panel edge losses correspond quite well with the numerical simulations, as shown in Figure 4. The only series where a large deviation occurred is the single 20 mm VIP configuration. This large deviation is probably caused by a larger degree of convection compared to the other VIP configurations.

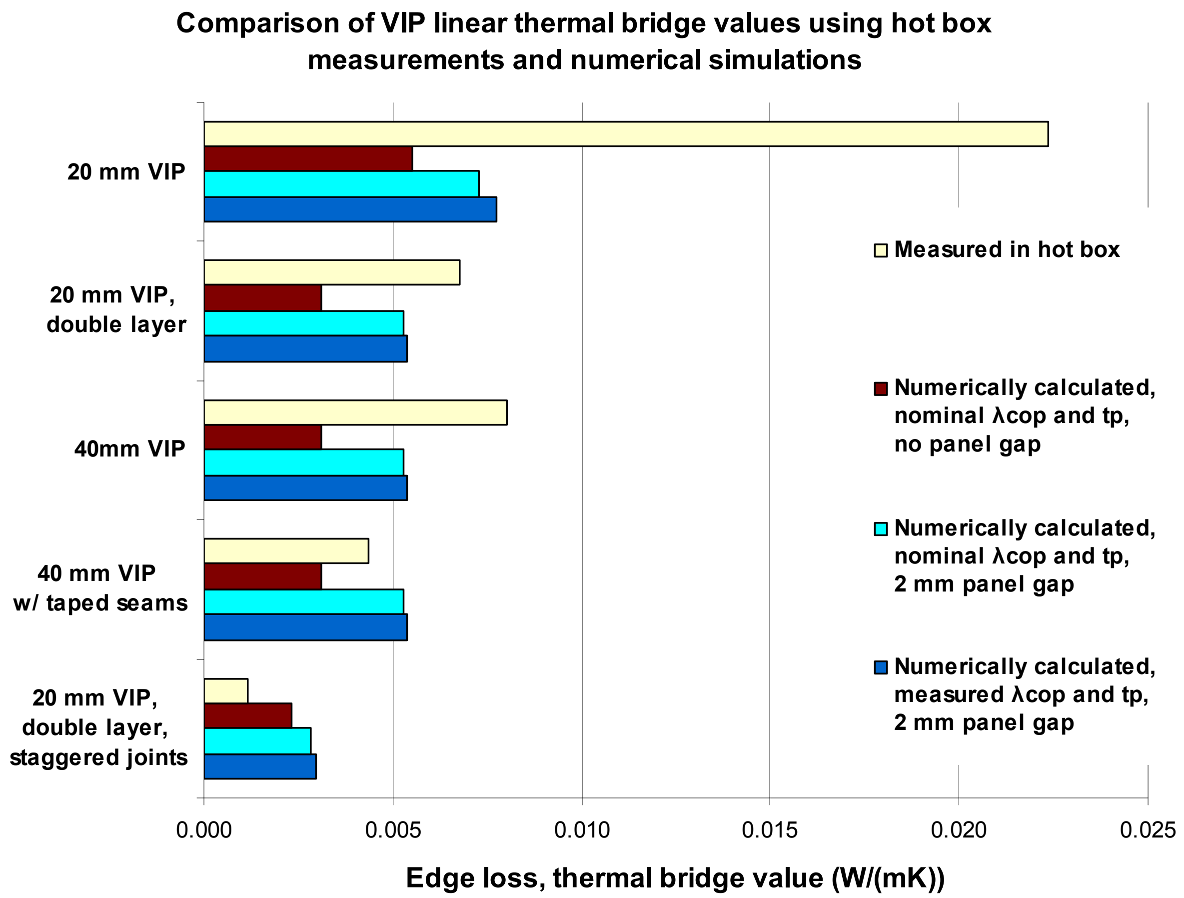

Figure 4. Comparison of thermal bridge values, ψ_p, for various VIP arrangements.

4.4. Comparison of U-values for various VIP configurations

Figure 5 shows the hot box measurements which indicate that the effective U-value of VIPs in a wall structure arrangement like the ones discussed in this article is somewhat higher than expected through numerical simulations. The main reasons for this seems to result from the fact that measured thicknesses of the VIPs t_p is lower than the nominal thicknesses and that the measured core conductivity is slightly higher than the nominal value of λ_{cop}. Measurements carried out on a limited number of panels indicate that the thicknesses of the panels are approximately 5 % less than the nominal values.

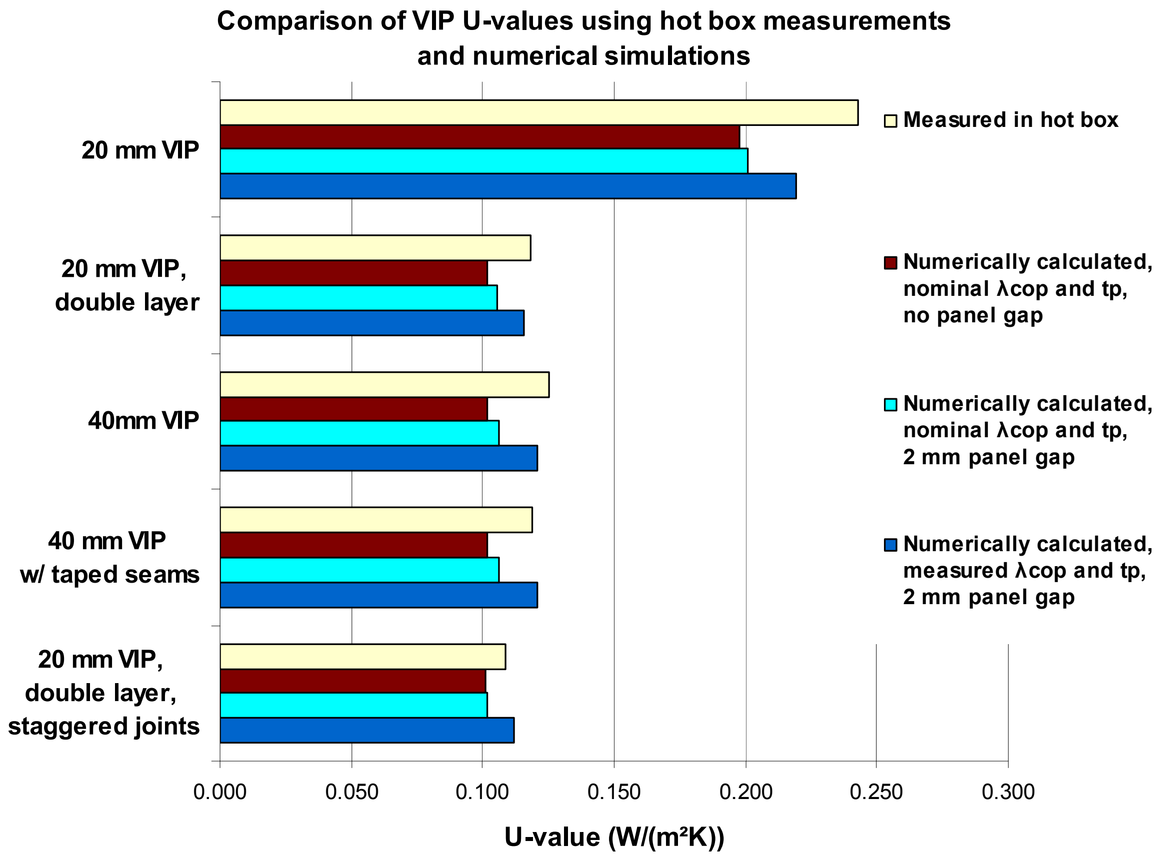

Figure 5. Comparison of VIP test field U-values using hot box measurements and numerical and analytical assessments for various VIP arrangements.

It is shown in Figure 5 that the U-values from numerical simulations with nominal values and no panel gap and 2 mm panel gap correspond quite well, i.e. a difference of 2 mm panel gap does only result in a minor U-value difference in the numerical model. Furthermore, Figure 5 demonstrates that the measured U-values from the hot box correspond quite well with the numerical calculated U-values when measured values of the various parameters are used as input values in the numerical simulations.

5. CONCLUSIONS

Based on numerical simulations and full scale tests on various VIP wall structure arrangements it seems that the numerical simulation tools and methods for calculating thermal bridge values and U-values for VIPs in large scale structures are applicable. However, the input parameters must be treated with a certain degree of carefulness. It is found that the measured U-values from hot box investigations correspond quite well with the numerical calculated U-values as long as realistic and measured values of the various parameters are chosen as input values in the numerical simulations.

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