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The effect of edge details on heat transfer through insulated panels

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SUMMARY

This report describes the findings of a project to assess the influence of edge details on the thermal performance of insulated panels as typically used in stick system curtain walling.

Insulated panels in stick-system curtain walls differ from their large-scale cladding counterparts in one important factor - the panels are mounted into the same frame rebate as the glazing, such that the edge of the panel is considerably thinner than the centre of the panel, and so offers considerably less resistance to heat flow. Poor selection of panel materials, principally the common use of metal foil or sheet to form the skins of the panel, ensures that significant thermal bridging occurs at the panel edges. This problem is not detected however, due to an established practice of ignoring the panel edge when calculating panel U-values.

This report illustrates the problem as it currently exists, through a combination of measurement and computer simulation, and identifies good practice for the design of insulated panels in stick-system curtain walls.

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1 Introduction

The arrangement of a typical stick-system curtain wall is illustrated in Figure 1.1. In this type of construction a structural grid of (typically) aluminium framing members is used to support a combination of transparent (glazing) and opaque (insulated panel) infill elements. This type of construction has the advantages that it is lightweight, offers an endless variety of grid spacings using the same basic components and can be rapidly assembled on site. Figure 1.2 shows two typical frame types - the standard pressure-plate type fixing in Figure 1.2(a) and the more expensive structural sealant glazing system in Figure 1.2(b).

Stick system curtain walling can vary in price from less than £200 per square metre to sums in excess of £1,000 per square metre (Davis Langdon and Everest, 1997). At the upper end of the price range there is usually a significant design effort involved, and the companies responsible for design using such systems have the knowledge and resources to avoid problems such as thermal bridging. The use of insulation in such systems is generally better, and design is routinely based on assessments using detailed computer analysis techniques (which remain the best way to detect and quantify thermal bridging, as will be demonstrated later). However, at the lower end of the price range stick systems are bought as a kit of parts by a fabricator/installer, who may shop around for the best deals on the cost of components such as gaskets, glazing units and insulated panels, and who does not have the same level of technical expertise and support as a company specialising in the more expensive cladding solutions. It is at the lower-priced end of the market (which also has the most operators and most cladding contracts) which this report is aimed.

1.1 The problem

To ease the assembly of stick-system curtain walls it is conventional for all of the infills (perimeter connectors, glazing units and insulated panels) to be designed so that the edge details are of the same thickness. This allows a single type of mullion frame to be used in continuous runs without the need for spacers or adapters where the component edge detail thickness changes, and thus reduces the amount of time required for fabrication and assembly (it is through these means that costs as low as £200 per square metre are achieved).

To meet the current UK Building Regulations for insulated walls an insulation thickness of 50-90 mm is required in insulating panels (depending upon the insulation material and panel design). However, a typical insulating unit is 24 to 28 mm thick, which is also the thickness of the glazing edge, and the simplest option for the insulated panels is for them also to have a 24-28 mm thick edge detail. The need for a stiff spacer at the edge of the infill panel, to withstand wind loads, combined with the frequent use of low-cost metal sheets to face the panel, ensures that there is a thermal bridge at the edge of the panel. However, as all insulated panels are basically plane, layered, constructions they are amenable to simple one-dimensional heat transfer calculations based on the centre-panel thickness. If thermal bridging at the panel edge is allowed for the true heat transfer through an insulated infill panel can exceed the design value by 100% or more.

This problem is illustrated in Figure 1.3. Figure 1.3(a) shows a section through a typical panel. Figure 1.3(b) shows how the heat flow would appear if it could be measured across the width of the panel; near the centre of the panel the heat flow may be as designed (i.e. uniform and predicted by the centre-panel U-value) but near the edges the heat flow increases due to the thermal bridging effect of the edge detail. In Figure 1.3(c) the heat flow is separated into two components - the expected heat flow, which is related to the U-value, and an additional edge-of-panel heat flow, described by the linear edge transmittance. These terms are further explained below.

1.2 One-dimensional heat transfer assessment

One dimensional heat transfer assumes that heat flows in a straight line, from the warm side of a component to the cold side, and perpendicular to the plane of the component. This is typical of heat flow through a pane of single glazing.

One-dimensional heat transfer is always calculated by hand, using the well-known formulae identified in section A.2 of Appendix A. However, although based on the assumption that heat transfer is one-dimensional few people are actually experienced enough to look at a component and state whether it will truly experience one-dimensional heat flow. Unfortunately this approach has been inherited from the glazing and traditional wall (i.e. masonry/blockwork) industries where the majority of the heat flow is one-dimensional. Even so, even in those traditional applications the limitations of the one-dimensional method are now being realised, as the effect of the edge spacer on glazing unit performance, and of mortar joints and wall ties on masonry wall performance, are being quantified.

1.3 Two-dimensional heat transfer assessment

Two-dimensional heat transfer assumes that some lateral heat flow occurs across the plane, but that there is a set of parallel cross-sections along the component that have identical performance. This might apply to an extruded glazing frame profile, for example, away from corners and intersections.

Two-dimensional heat transfer calculation may be performed in two ways - either by using a slightly more detailed form of the hand calculation procedure identified above or by using computer simulation:

1.3.1 Calculation of two-dimensional heat transfer

The calculation of two-dimensional heat transfer is described in the CIBSE Guide Part A3 [1986] and also in BS EN ISO 6946 [1997]; the Standard has the advantage that it includes formulae for dealing with non-rectangular elements and small cavities. However, in both methods the procedure is to break a component down into a network of elements for which one-dimensional heat flow is occurring.

It is always possible, with the two-dimensional calculation, to determine two extreme thermal resistance values for a component. The lower limit for the overall resistance is found by assuming that the component comprises a series of layers, often with each layer comprising a set of parallel heat paths; this is equivalent to assuming that lateral heat flow occurs freely within each layer. The upper limit for the overall resistance is found by assuming that the component comprises a set of parallel heat paths, with each parallel path made up of a series of smaller layers; this is equivalent to assuming that no lateral heat flow occurs. The 'true' thermal resistance is generally taken as the mean of the upper and lower values.

The two-dimensional calculation method would normally be difficult to perform for components such as infill panels, which interact with the framing system. However, an analysis can be performed for a panel in a stand-alone configuration, which is relevant to the assessments in the following chapters, and section A.3 of Appendix A demonstrates such an analysis.

1.3.2 Simulation of two-dimensional heat transfer

Computer simulation techniques can also be used to assess two-dimensional heat transfer problems. Finite element analysis (FEA) or finite difference methods (FDM) solve two-dimensional heat transfer problems using two-dimensional heat transfer theory and so obtain a much more realistic solution; moreover the analyses are performed on a much finer scale than any calculation could, achieving even greater realism and accuracy by this measure.

These methods have been proven in a number of well-documented cases (NPL [1997], NFRC [1995]). Simulation techniques are now governed by a number of Standards, including BS EN ISO 10211-1 [1996], NFRC 100-91 [1991] and prEN 10077-2 [1996], and easy-to-use suitable software is now freely available (see Appendix B).

1.4 Three-dimensional heat transfer assessment

Three-dimensional heat transfer assumes that heat flow may occur in any direction. An example would be at an intersection between two or more framing components.

Three-dimensional heat transfer assessment can be performed by calculation, simulation or measurement:

1.4.1 Calculation of three-dimensional heat transfer

Calculation of three-dimensional heat transfer is based on the same procedures as for two-dimensional heat transfer, and is also covered in the CIBSE Guide Part A3 [1986] and in BS EN ISO 6946 [1997]. Again, two extreme thermal resistance networks are derived for the component, and a mean value taken. This approach has the same limitations as for two-dimensional calculation, principally that each element within the resistance network is still assumed to experience one-dimensional heat transfer. The skill of the analyst in breaking a component down into realistic heat transfer paths is an important part of the process, and limits the accuracy of the analysis.

1.4.2 Simulation of three-dimensional heat transfer

Simulation of three-dimensional heat transfer is usually limited to structures which can be defined simply in three-dimensions - the most cost-effective ways to generate a three-dimensional model are either by building the model from simple geometric shapes (preferably rectangular blocks) or if the 3-d geometry can be 'extruded' from a two-dimensional geometry (a drawing of a cross-section). Planes of symmetry are always used to simplify the analysis, and so a square panel is simpler to analyse than a rectangular panel; components which are intermittent through a structure are very difficult to assess, and three-dimensional angles and curves require careful consideration. The generation of three-dimensional heat transfer simulation models is discussed further in the following chapter.

1.4.3 Measurement of three-dimensional heat transfer

Measurement remains the best way to accurately assess three-dimensional heat transfer (or indeed one- and two-dimensional heat transfer). The only requirement for measurement is that a test specimen is available; Standards already exist by which the measurement may be performed (BS 874:Part 3:Section 3.1 [1987], BS 874:Part 3:Section 3.2 [1990], prEN 12412-1 [1996]).

The only significant issue with measurement of a component is to decide the size and arrangement of the test specimen; the test specimen should be a realistic representation of a component or system as it will be used.

1.5 The U-value and the Ψ-value

The thermal performance of an insulated panel could be described in two ways - as an average U-value (areal thermal transmittance) or as a combination of a theoretical (centre-panel) U-value and a Ψ-value (edge-of-panel linear transmittance - essentially a correction for the thermal bridging at the edge of the panel). These two forms of rating were illustrated in Figures 1.3(b) and (c) and are related as follows:

1.5.1 The average U-value

The average U-value of a component is the heat transfer through the component per unit area per unit overall temperature difference:

$$\bar{U} = \frac{Q}{A\Delta T} \quad \text{W/m}^2\text{K}$$

- Q is the total heat flow through the component, in W
- A is the projected area of the component, in m^2
- ΔT is the overall temperature difference across the component, in K

1.5.2 The Ψ-value

A Ψ-value represents the additional heat transfer through an otherwise uniform component that is caused by some linear feature of the component, such as the extra heat flow through a plane layered component caused by a non-plane edge. As shown in Figure 1.3(c) the total heat transfer through the component is then expressed in terms of the theoretical centre-panel U-value, which assumes that the whole of the component performs as the plane layered part (i.e. according to the simple one-dimensional calculation in section A.2 of Appendix A) plus a linear transmittance (Ψ-value), which relates the additional heat loss to the length of the linear feature (in this case the perimeter of the panel).

The total heat flow through the panel is then:

$$Q = (UA + \Psi L)\Delta T$$

- Q is the total heat flow through the panel, in W
- U is the theoretical centre-panel U-value of the panel, in W/m^2K
- A is the projected area of the panel, in m^2
- Ψ is the linear edge transmittance of the panel, in W/mK
- L is the perimeter of the panel, in m
- ΔT is the overall temperature difference across the panel, in K

These formulae indicate that the linear edge transmittance must be related to the average and theoretical centre-panel U-values by:

$$\Psi = \frac{A}{L}\left(\overline{U} - U\right)$$

1.5.3 Interactions with the framing system

In a real application the insulated panel would be mounted in a framing system, which would clamp or otherwise support (and thus interact with) the edge of the panel. The Ψ-value could therefore be seen as comprising two parts:

1. a component Ψ-value, which is an intrinsic property of the panel itself, plus

2. an interaction Ψ-value, which is an extrinsic property of the system.

These two Ψ-values are then added together to form the total Ψ-value. However, the interaction Ψ-value is beyond the control of the panel manufacturer, and so this report concentrates on the component Ψ-value, which clearly should be either minimised by good edge detailing or else compensated for by a reduced centre-panel U-value (i.e. by using an increased thickness of insulation).

1.6 The project

This report describes the result of a project to compare the thermal performance of insulated panels as assessed by the various different methods described above, and to present guidance for the design of panels. The report comprises four key Chapters:

- Chapter 2 compares the results of measurements made on four commercially-sourced panels to the calculated two- and three-dimensional Ψ-values and to two-dimensional computer simulations of the Ψ-value - this both validates the simulation technique and demonstrates the true heat loss through typical panels;

- Chapter 3 assesses a basic panel, in a range of materials, using one-dimensional calculation, two-dimensional calculation and two- and three-dimensional simulation - this is used to compare the accuracy and validity of the various calculation and simulation methods;

- Chapter 4 uses computer simulation to design three typical panels, thereby providing guidance for the designer;

- Chapter 5 discusses the design of insulated panels in general, and indicates those features which will give the best panel performance.

Figure 1.1 The stick-system curtain wall

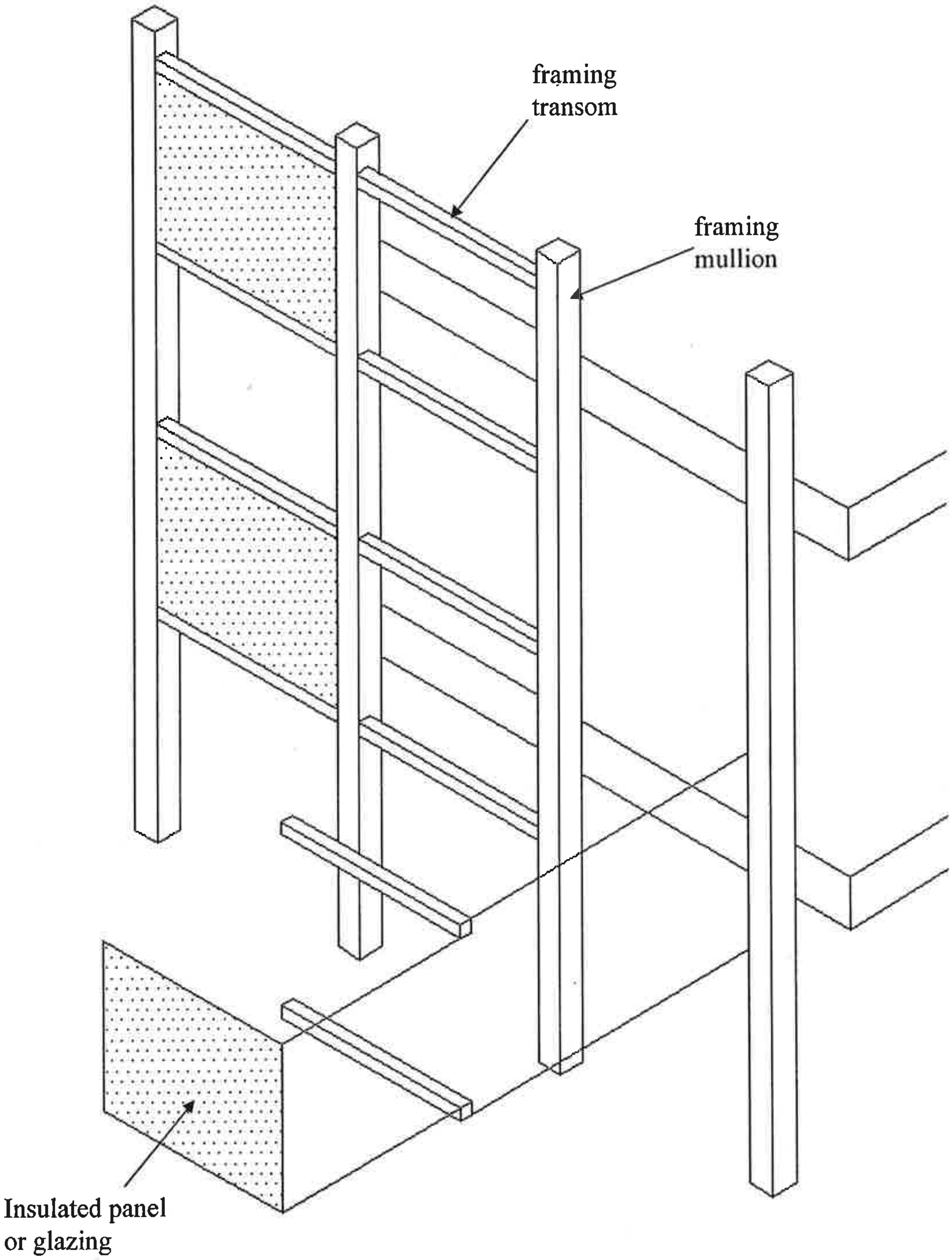
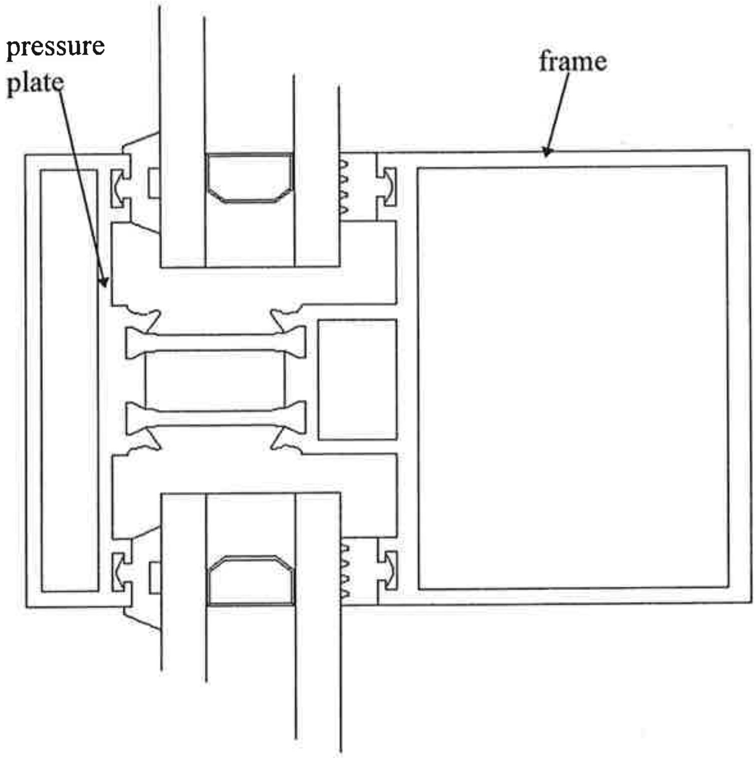
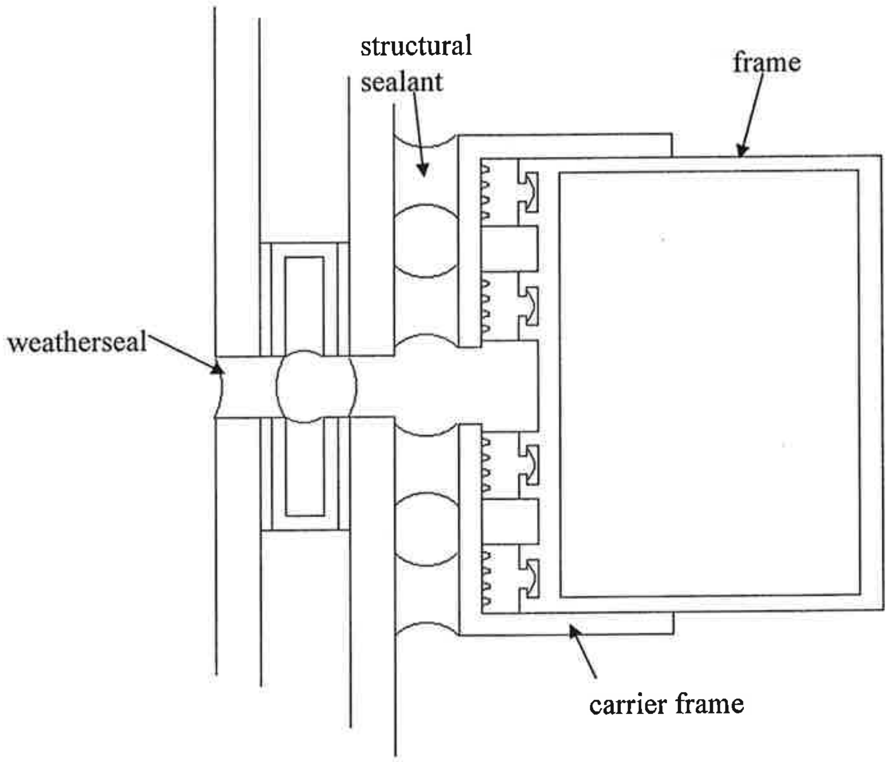


Figure 1.2 Frame types in stick-system curtain walls

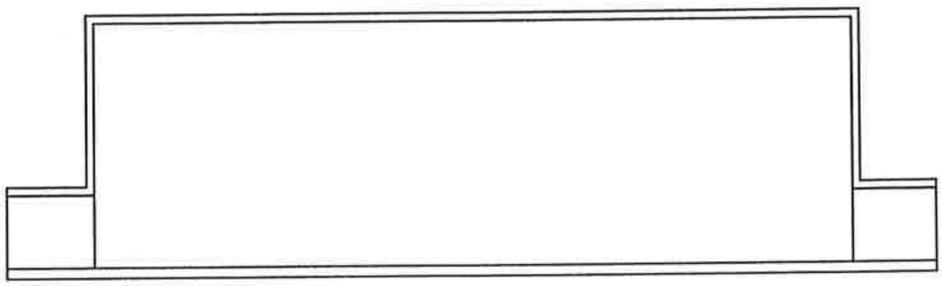


(a) the pressure-plate glazing system

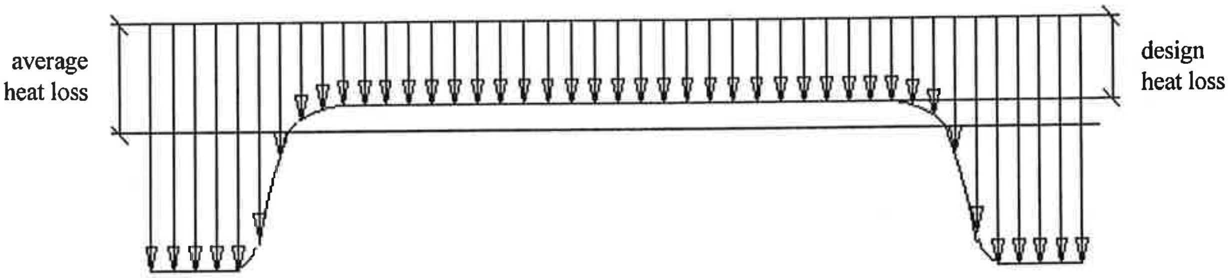


(b) the structural sealant glazing system

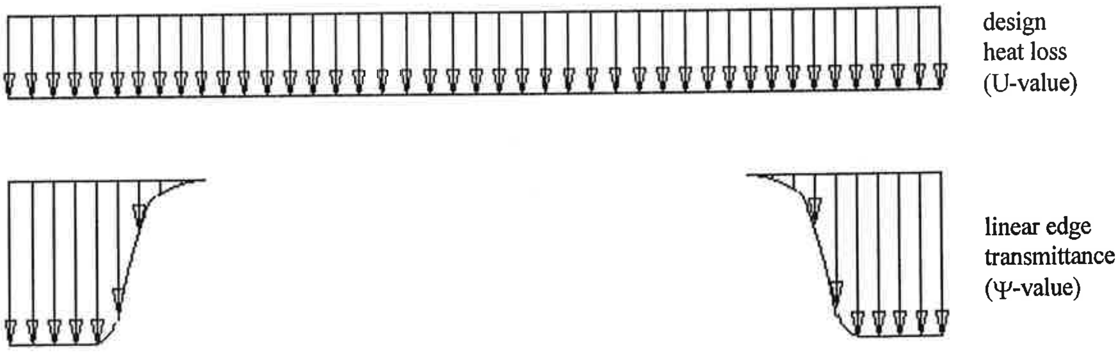
Figure 1.3 Heat flow through a typical panel



a) typical panel



b) heat flow through panel showing increase at edges



c) heat flow broken down into U-value and Ψ-value components

2 Comparing measured, calculated and simulated insulated panel performance for four typical panel designs

2.1 Introduction

This chapter compares the measured, calculated and simulated ψ-values of four commercially-sourced insulated panels.

2.2 The panels

The panels comprise:

1. A single glass pane with a closed-cell foam plastic insulation bonded to the back;
2. A double glazed unit with a closed-cell foam plastic insulation bonded to the back;
3. A single glass pane with a closed-cell foam plastic insulation-filled aluminium tray bonded to the back;
4. A single glass pane with a mineral fibre insulation-filled aluminium tray bonded to the back.

The panels are each nominally 1200 mm square, in accordance with the requirements of the measurement Standard prEN 12412-1 [1996].

The panels are not mounted in a framing system, since this would affect the results differently according to the type of framing system. However, when mounted in a frame the clearance between the side of the panel and the side of the frame is usually small, 5-10 mm being typical, as indicated in Figure 2.1(a). In such a small gap air is not able to circulate and so heat transfer to the side of the panel is reduced. To mimic this effect in a test the gap at the edge of the panel is filled with an insulating material, as illustrated in Figure 2.1(b). The thermal conductivity of the material used in the tests reported here was 0.035 W/mK.

2.3 The results

The heat flow through each panel has been measured by the National Physical Laboratory, using the method described in the draft European Standard prEN 12412-1. The Ψ-value for each panel has been extracted using the formula

$$\Psi = \frac{A}{L}\left(\overline{U} - U\right)$$

where the centre-panel U-value U is calculated from the one-dimensional formula given in section A.2 of Appendix A. For the measurement panels the perimeter L is 4.8 m and the projected area A is 1.44 m^2.

The performance of each panel has also been predicted using commercially available finite element analysis software, following the method described in prEN 10077-2

[1996]. A two-dimensional section from the centre of a panel to the midpoint of an edge is assessed; however when a two-dimensional section is simulated the software generally assumes a unit depth in the third dimension, as indicated in Figure 2.2. The formula above can be used to extract a Ψ-value from the simulation results but it must be understood that the simulated detail is a panel 0.6 m wide by 1.0 m long with an edge detail along one edge only, i.e. L = 1.0 m and A = 0.6 m.

Finally two- and three-dimensional calculation models similar to those described in Appendix A have been used to predict a Ψ-value for each panel.

The results for each panel are:

	Ψ-value [W/mK]			
Panel	Measured (3-d)	2-d Calculation	3-d Calculation	2-d Simulation
1	0.002	0.045	0.020	0.007
2	0.007	0.008	0.006	0.009
3	0.213	0.203	0.118	0.206
4	0.198	0.172	0.100	0.201

It is clear from these results that the measured (3-d) and simulated 2-d Ψ-values are almost identical in every case - this suggests that the three-dimensional effects associated with the corners of panels are sufficiently small not to affect the Ψ-values too much. Interestingly panels 1 and 2, which do not use metal trays to enclose the insulation, perform very well, whilst panels 3 and 4 require considerably thicker insulation than the one-dimensional calculation method would predict.

The calculated Ψ-values are very different however – reflecting the need for the assessor to properly determine how to divide the panel up into realistic elements. It is also interesting to note that the 3-d calculated Ψ-value is approximately one-half of the 2-d calculated Ψ-value.

2.4 Conclusions

The use of conducting trays which bridge the edge of the insulation in an insulated panel increases the heat flow through the panel by a significant amount.

The use of simulation techniques which allow for two-dimensional heat flow predicts the additional heat flow which will occur without the over-prediction that occurs with the two- and three-dimensional simple calculation methods.

Figure 2.1 The panel-to-frame edge clearance

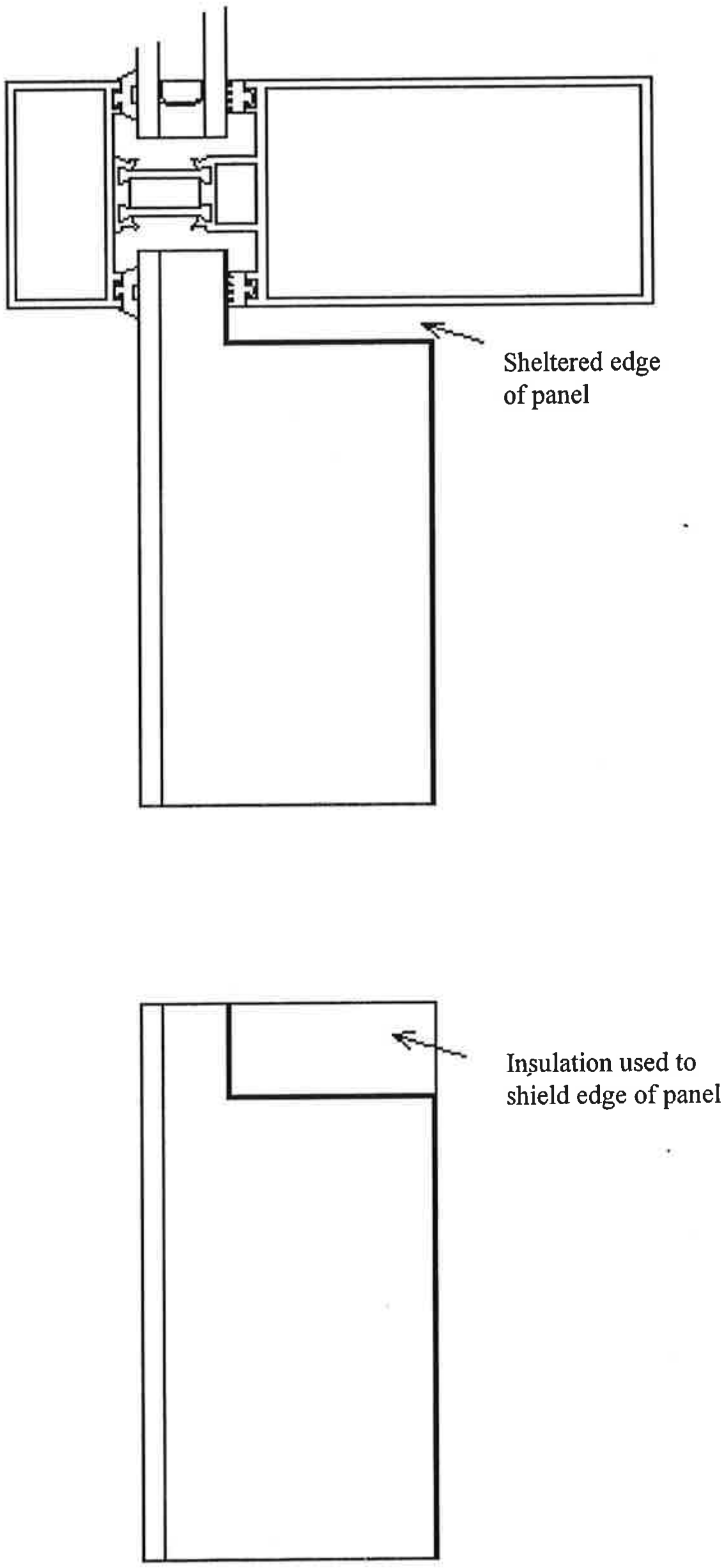
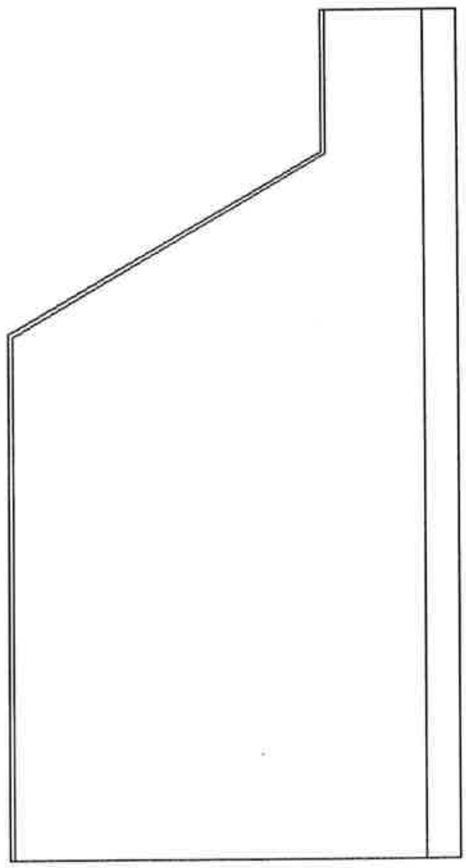
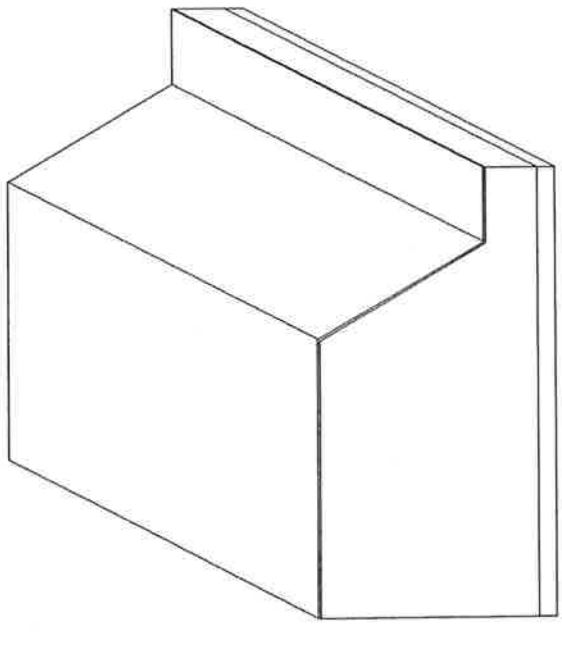


Figure 2.2 The simulated detail



a) the cross-section as simulated



b) the cross-section as interpreted by the software

3 Comparing calculated and simulated insulated panel performance for basic panel designs

3.1 Introduction

This chapter describes the comparison of calculation and simulation methods for determining the U-value of some basic insulated panels.

3.2 The standard panel

The assessments are based on a basic panel design, as shown in Figure 3.1. This panel comprises two thin sheets (skins) of material, encapsulating a layer of insulation material, with the sheets separated at the edges by a rectangular spacer. This simple configuration is highly versatile, as the sheets and the spacer can be formed from a wide range of materials - similar basic cartridges are available from a number of manufacturers in a range of sizes and form the basis of many insulated panels.

3.2.1 The assessed panels

Four different panel make-ups have been assessed, comprising:

A. aluminium inner and outer skins

B. glass outer skin with an aluminium foil inner skin

C. steel inner and outer skins

D. plastic inner and outer skins

The required insulation thickness for each panel, based on a theoretical U-value of 0.45 W/m^{2}K, can be determined from the one-dimensional model described in section A.2 of Appendix A. The material thicknesses, t, and thermal conductivities, λ, are summarised below:

Panel	External skin (Skin E)		Internal skin (Skin I)		Insulation		U-value
	t_E mm	λ_E W/mK	t_I mm	λ_I W/mK	λ_{INS} W/mK	t_{INS} mm	U_{CP} W/m^{2}K
A	2	200 (aluminium)	2	200 (aluminium)	0.04	82	0.45
B	6	1.0 (glass)	0.2	200 (alu. foil)	0.04	82	0.45
C	0.7	55 (steel)	0.7	55 (steel)	0.04	82	0.45
D	3	0.20 (plastics[1])	3	0.20 (plastics[1])	0.04	81	0.45

Note that the thermal conductivity value taken for the plastic skins (0.20) sensibly includes PVC (actual λ=0.17 W/mK), PVC-U (0.16), polycarbonate (0.23) and acrylic (0.20). The same value of thermal conductivity is also used for the plastic edge spacer.

3.2.2 The panel edge details

For the purpose of this simple assessment three types of edge detail have been considered, as shown in Figure 3.2:

I. skins brought together at edge of panel;

II. skins separated at edge by 6 mm thick, 20 mm wide plastic spacer;

III.skins brought sufficiently together to fit into 24 mm glazing rebate, and gap filled with 20 mm wide plastic spacer.

These edge details represent the three most commonly found - bringing the inner and outer skins directly together at the edge of the panel is the simplest option (they are sometimes separated by a thin adhesive foam strip, but this is often less than 1 mm thick and is of limited benefit in terms of avoiding thermal bridging). A 6 mm thick spacer gives a more visible separation, and also helps to stiffen the edge of the panel - this approach also allows the panel to be used in any thicker glazing rebate (the minimum thickness is the cumulative thickness of the skins plus 6 mm, and packers are then used in larger rebates). The third option uses the size of spacer between the skins needed to exactly fit the edge of the panel into the same rebate as a typical 24 mm glazing unit.

Note that in every case where a spacer is used it is assumed that the spacer will be a rigid plastic simply because the current onus in the Building Regulations on avoiding cold-bridging is unlikely to see metal spacers being used (many designers are capable of identifying that a metal spacer would certainly be a cold bridge, but do not see the cold-bridging possibilities of a 6 mm thick plastic spacer compared to an 82 mm thickness of insulation - cold bridges are relative, not absolute).

Materials such as timber are not generally considered for edge spacers because they are not sufficiently durable to allow their use in locations where they cannot be inspected for mould growth or rot.

3.2.3 The analysed panels

The complete set of panels that has been analysed is summarised below. It should be noted that where aluminium foil is used as the inner skin it is conventional not to use an edge spacer and so panel type B has only been assessed in one form. It should also be noted that the thickness of the spacer varies where the edge is designed to have an overall thickness of 24 mm; this is not unusual however. The figure given in parentheses for the 'edges brought together' panels is the actual thickness of the panel edge:

Panel	External skin	Internal skin	Edge
AI	2 mm aluminium	2 mm aluminium	skins together (4 mm)
AII	"	"	6 mm plastic spacer
AIII	"	"	20 mm plastic spacer
BI	6 mm glass	0.2 mm aluminium	skins together (6.2 mm)
CI	0.7 mm steel	0.7 mm steel	skins together (1.4 mm)
CII	"	"	6 mm plastic spacer
CIII	"	"	22.6 mm plastic spacer
DI	3 mm plastic	3 mm plastic	skins together (6 mm)
DII	"	"	6 mm plastic spacer
DIII	"	"	18 mm plastic spacer

3.3 The calculation study

The ten panel designs identified above have each been subjected to a set of two- and three-dimensional calculations, to estimate the heat transfer through each panel.

The predicted three-dimensional performance is based on an overall panel size of 1200 mm by 1200 mm (the same panel size as used for the measurement study in Chapter 2). The predicted two-dimensional performance is based on a slice through the panel edge, from the midpoint of an edge to the centre of a 1200 mm square panel. In both cases the result is given only as a Ψ-value.

For the purpose of the calculation any interaction with a framing system is ignored, but again it is assumed that a packer is used at the exposed edge of the panel, consistent with the measurement technique described in Chapter 2; the packer material has a thermal conductivity of 0.04 W/mK.

3.3.1 The calculation formulae

The calculation formulae are fully defined in Appendix A. Note that there are two models for each of the two-dimensional and three-dimensional cases, one for the series resistance and one for the parallel resistance, but that the average resistance is determined before a Ψ-value can be calculated - it is not appropriate to extract a Ψ-value from each of the series and parallel resistances.

An important feature of the resistance models is that each individual resistance assumes one-dimensional heat flow - when it is said that a resistance model is multi-dimensional it is really meant that the model is a multi-dimensional network of one-dimensional resistances.

3.3.2 The calculation spreadsheet

The calculation models have been written into a spreadsheet which automatically calculates the panel U- and Ψ-values for each of the four models. The spreadsheet calculates the value of each elemental resistance and then combines these to form the series and parallel resistances. The series and parallel resistances are then averaged and converted to a U-value, which is then used to extract a Ψ-value. Note that in the two-dimensional case the calculation model comprises a 'slice' through the panel which is of unit length in the third dimension; a 0.6 metre wide slice is thus equal to a panel 0.6 metres wide by 1 metre long but with an edge detail running along one long edge only (as shown in Figure 2.2). This means that the two-dimensional model has a false ratio of edge length to area, and so the average U-value arising from this model is not realistic (the Ψ-value is derived based on a proper ratio of edge length to area and so is realistic).

3.4 Simulating panel performance

The Ψ-value for each of the panel designs given above can also be predicted using the same computer simulation methods as in Chapter 2, using either two- or three-dimensional models. It should be noted that the computer simulation will always predict true multi-dimensional heat transfer. The comparison of simulation and calculation results is therefore expected to further highlight the limitations of the simple calculation methods.

3.5 Comparing the calculation and simulation results

The table below summarises the results for the basic panel:

Panel	Calculated 2-d Ψ_{2d}	Simulated 2-d[1] Ψ_{2d}	Calculated 3-d Ψ_{3d}	Simulated 3-d[2] Ψ_{3d}
AI	0.226	0.852	0.127	0.702
AII	0.200	0.351	0.113	0.319
AIII	0.151	0.150	0.087	0.143
BI	0.110	0.161	0.074	0.146
CI	0.112	0.196	0.077	0.191
CII	0.103	0.146	0.071	0.140
CIII	0.081	0.089	0.057	0.086
DI	0.005	0.004	0.005	-0.014
DII	0.006	0.005	0.006	-0.014
DIII	0.008	0.007	0.008	-0.013

[1] simulated 2-d results obtained using Therm 2.0 (see Appendix B)

[2] simulated 3-d results obtained using ANSYS (see Appendix B)

A number of issues are raised:

1. The calculated Ψ-values are lower than the corresponding simulated Ψ-values; the simple calculation methods would under-predict the effect of thermal bridging.

2. For a given panel the 2-d and 3-d calculated Ψ-values do not compare well, and the 3-d values are lower.

3. The 2-d and 3-d simulated Ψ-values for each panel are in much better agreement, with the level of agreement improving as the Ψ-value reduces. It must be noted however that the 3-d finite element 'mesh' (the grid into which the component is sub-divided for simulation) is necessarily very coarse (it is limited by the computer hardware) and inaccuracies are expected as a result. The 2-d simulation results are therefore preferred.

4. The Ψ-values are significant - for panel BI, with a glass outer skin and a 200 micron aluminium foil inner skin, the simulated 2-d Ψ-value of 0.161 represents an actual U-value of 0.99 W/m^{2}K, 120% above the target U-value. Even the thinnest metal skins can therefore cause significant thermal bridging.

Figure 3.3 further illustrates this last point - this figure gives the true average U-value as a percentage increase over the design (1-d centre-panel) U-value for a range of Ψ- and U-values. It is apparent that even a Ψ-value as low as 0.05 W/mK represents a significant additional heat loss through a panel which is designed to have a U-value of 0.45 W/m^2K.

3.6 Conclusions

From this simple study it can be concluded that two- and three-dimensional simple calculation models which take some account of the edge detail of insulated panels give more realistic results, but that they also tend to under-predict the heat loss through the panels. Simulation methods therefore offer a more efficient method of analysis, and should therefore be used for design purposes.

It is evident that the thickness of insulation must be increased to allow for the thermal bridging effect of the panel edge detail. The following Chapter examines the true thickness of insulation that is required in typical panel designs.

Figure 3.1 The basic panel

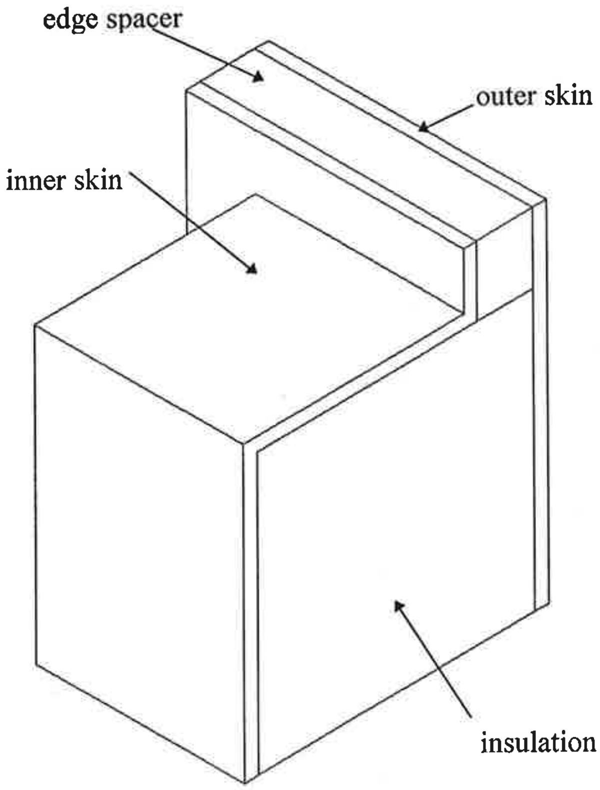
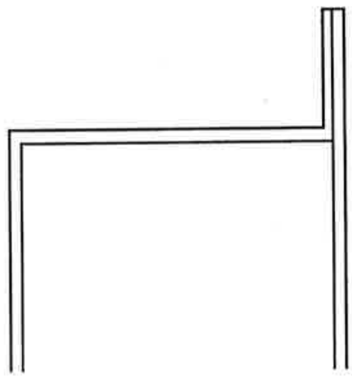
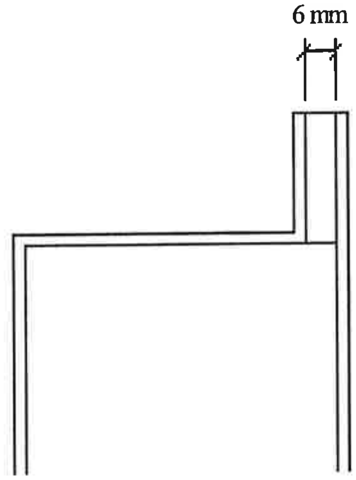


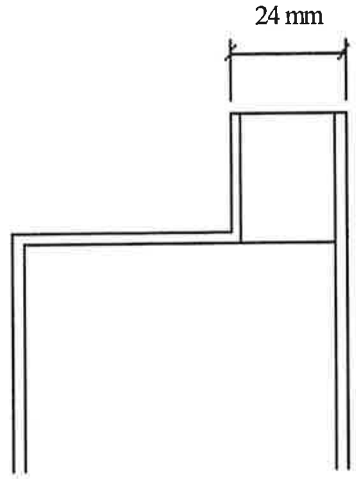
Figure 3.2 The basic edge details



a) panel with skins brought together at edge

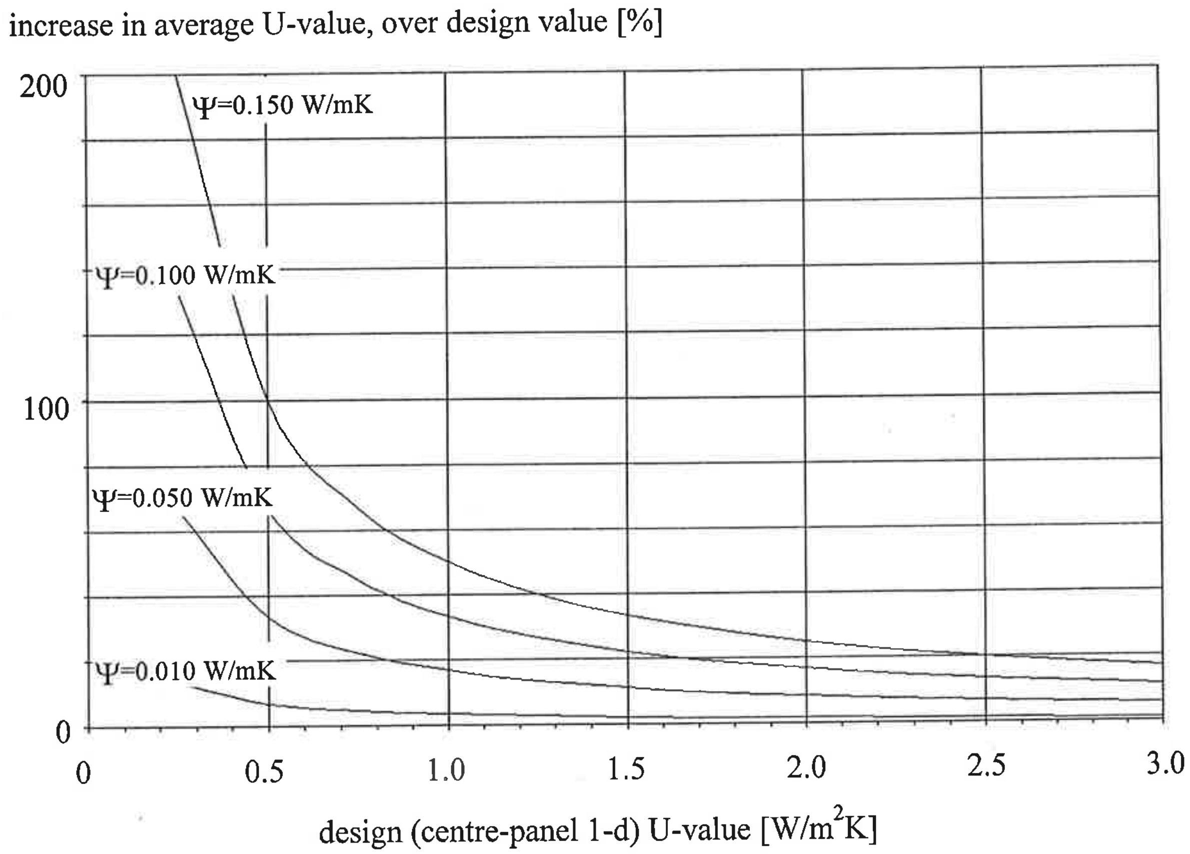


b) panel with 6 mm thick edge spacer



c) panel with skins brought to 24 mm thickness at edge

Figure 3.3 The effect of the Ψ-value on the average U-value, for a 1200 mm square panel



4 Designing the Insulated Panel

4.1 Introduction

The previous chapters have shown that the linear edge transmittance for a given panel design can be determined to a good level of accuracy using two-dimensional finite element analysis. Given that suitable software is now freely available, such as the Therm 2.0 software used for the analyses in this report (see Appendix B), it is possible for the manufacturers of such panels to achieve the design U-values with little effort.

This chapter demonstrates how panels would be designed using two-dimensional computer simulation techniques.

4.2 Panel Design

4.2.1 The centre-panel construction

The first stage in panel design is to identify the centre-panel construction; what are the skins to be made from, and what type of insulation material is to be used? With these items identified the initial insulation thickness can be determined from the one-dimensional calculation method.

If the centre-panel construction comprises an outer skin, a layer of insulation and an inner skin then the initial insulation thickness is:

$$t_{INS} = \lambda_{INS}\left(\frac{1}{U_{CP}} - R_{SI} - R_{SE} - \frac{t_E}{\lambda_E} - \frac{t_I}{\lambda_I}\right)$$

- t_{INS} is the thickness of the insulation, in m
- λ_{INS} is the thermal conductivity of the insulation material, in W/mK
- U_{CP} is the target centre-panel U-value, in W/m^{2}K
- R_{SI} is the internal surface resistance, taken here as 0.13 m^{2}K/W
- R_{SE} is the external surface resistance, taken here as 0.04 m^{2}K/W
- t_E is the thickness of the external skin, in m
- λ_E is the thermal conductivity of the external skin material, in W/mK
- t_I is the thickness of the internal skin, in m
- λ_I is the thermal conductivity of the internal skin material, in W/mK

4.2.2 The edge detail

The next step is to identify the required edge detail, and to decide upon the spacer size and material. It should be noted that the use of tapes to seal the edges of panels against moisture penetration might be important, and that these tapes should be included in the finite element analysis.

4.2.3 Preliminary analysis

The third step is to analyse the panel design and determine a value for the linear edge transmittance Ψ. The analysis should be based on a two-dimensional section through the edge of the panel, and include a width of panel equal to one-half of the shortest panel side (the effect of thermal bridging may reach to the centre of the panel, and the shortest distance to the centre from the edge is one-half of the shortest side). For the two-dimensional analysis an 'average' U-value will be obtained, which is converted to a Ψ-value using the formula

$$\Psi = \frac{x}{2}\left(\overline{U} - U_{CP}\right) \text{ W/mK}$$

- x is the shortest panel side, in m

The true average U-value of the panel is then given by

$$U = U_{CP} + \frac{2\Psi(x+y)}{xy}$$

- y is the longest panel side, in m

4.2.4 Final analysis

It is now necessary to determine the true insulation thickness that is required to give the correct average panel U-value. The first step is to assume that the Ψ-value will not be affected by the insulation thickness; the formula above can be rearranged to give a new target centre-panel U-value

$$U_{CP2} = U_{CP} - \frac{2\Psi(x+y)}{xy}$$

This new target U-value is then used to determine a new insulation thickness

$$t_{INS2} = \lambda_{INS}\left(\frac{1}{U_{CP2}} - R_{SI} - R_{SE} - \frac{t_E}{\lambda_E} - \frac{t_I}{\lambda_I}\right)$$

and the finite element analysis can be repeated. The new analysis will result in a new Ψ-value, which will then lead to a new actual U-value, and the last stage above can be repeated until the true average U-value is acceptable.

4.3 Example 1

The panel used in this example comprises a 6 mm toughened glass outer skin, a foamed plastic insulation with a thermal conductivity of 0.024 W/mK, and a 0.7 mm thick aluminium inner skin. The edge spacer is of the same material as the insulation core, and is nominally 18 mm thick and 25 mm wide. The edge of the inner tray is angled inwards by 30°. The target average U-value is 0.4 W/m^{2}K, and the finished panels are to be 1500 mm wide by 950 mm high, including the edge detail.

4.3.1 Stage 1 - Centre-panel construction

The centre-panel construction is clearly defined. Taking a thermal conductivity of 1.0 W/mK for the glass, and 200 W/mK for the aluminium skin gives an initial centre-panel insulation thickness of

$$t_{INS} = 0.024\left(\frac{1}{0.4} - 0.13 - 0.04 - \frac{0.006}{1.0} - \frac{0.0007}{200}\right) = 0.0558 \quad \text{m}$$

The initial insulation thickness is therefore taken as 56 mm.

4.3.2 Stage 2 - Edge detail

The proposed edge detail uses a 18 mm thick by 25 mm wide block of the core insulating material, and the side of the aluminium inner skin is angled inwards by 30° as shown in Figure 4.1.

4.3.3 Stage 3 - Preliminary analysis

The initial analysis, using Therm 2.0, gave a U-value of 0.44 W/m^{2}K. The Ψ-value is therefore

$$\Psi = \frac{0.95}{2}(0.44 - 0.4) = 0.019 \quad \text{W/mK}$$

The true average U-value of the panel is then

$$U = 0.4 + \frac{2(0.019)(0.95 + 1.50)}{0.95(1.50)} = 0.465 \ \text{W/m}^2\text{K}$$

4.3.4 Stage 4 - Final analysis

The new target centre-panel U-value is

$$U_{CP2} = 0.4 - \frac{2(0.019)(0.95 + 1.50)}{0.95(1.50)} = 0.335 \quad \text{W/m}^2\text{K}$$

This new target U-value gives a new insulation thickness

$$t_{INS} = 0.024\left(\frac{1}{0.335} - 0.13 - 0.04 - \frac{0.006}{1.0} - \frac{0.0007}{200}\right) = 0.0674 \quad \text{m}$$

A repeat finite element analysis with the insulation thickness increased to 68 mm gives the following results:

$$\overline{U} = 0.403 \quad \text{W/m}^2\text{K}$$

$$\Psi = \frac{0.95}{2}(0.403 - 0.335) = 0.032 \quad \text{W/mK}$$

$$U = 0.335 + \frac{2(0.032)(0.95 + 1.50)}{0.95(1.50)} = 0.445 \quad \text{W/m}^2\text{K}$$

$$U_{CP3} = 0.4 - \frac{2(0.032)(0.95 + 1.50)}{0.95(1.50)} = 0.290 \quad \text{W/m}^2\text{K}$$

$$t_{INS} = 0.024\left(\frac{1}{0.290} - 0.13 - 0.04 - \frac{0.006}{1.0} - \frac{0.0007}{200}\right) = 0.0785 \quad \text{m}$$

It is noted however that the use of an angled panel edge would expose more of the panel surface to heat transfer. For the third simulation therefore the panel edge is returned to a perpendicular arrangement. The third simulation gives

$$\overline{U} = 0.362 \quad \text{W/m}^2\text{K}$$

$$\Psi = \frac{0.95}{2}(0.362 - 0.290) = 0.034 \quad \text{W/mK}$$

$$U = 0.290 + \frac{2(0.034)(0.95 + 1.50)}{0.95(1.50)} = 0.407 \quad \text{W/m}^2\text{K}$$

This is within 2% of the target of 0.40 and is considered acceptable. The required insulation thickness is 78.5 mm, with a square panel edge.

4.4 Example 2

The second example considers a panel with an external 3 mm thick aluminium skin and an internal 0.7 mm galvanized steel skin. The insulation material is to be a mineral fibre with a thermal conductivity of 0.034 W/mK. The inner skin has edges that are perpendicular to the panel, and uses a 10 mm thick by 20 mm wide foam plastic spacer with a material thermal conductivity of 0.05 W/mK. The required average U-value is 0.45 W/m^{2}K, and the finished panels are to be 1050 mm wide by 1050 mm high, including the edge detail.

4.4.1 Stage 1 - Centre-panel construction

The centre-panel construction is clearly defined. Taking a thermal conductivity of 200 W/mK for the aluminium, and 55 W/mK for the galvanized steel skin gives an initial centre-panel insulation thickness of

$$t_{INS} = 0.034\left(\frac{1}{0.45} - 0.13 - 0.04 - \frac{0.003}{200} - \frac{0.0007}{55}\right) = 0.0698 \quad \text{m}$$

The initial insulation thickness is therefore taken as 70 mm.

4.4.2 Stage 2 - Edge detail

The proposed edge detail uses a 10 mm thick by 20 mm wide foam plastic spacer. The edge detail is as shown in Figure 4.2.

4.4.3 Stage 3 - Preliminary analysis

The initial analysis, using Therm 2.0, gave a U-value of 0.583 W/m^{2}K. The Ψ-value is therefore

$$\Psi = \frac{1.05}{2}(0.583 - 0.45) = 0.070 \quad \text{W/mK}$$

The true average U-value of the panel is then given by

$$U = 0.45 + \frac{2(0.070)(1.05 + 1.05)}{1.05(1.05)} = 0.717 \quad \text{W/m}^2\text{K}$$

4.4.4 Stage 4 - Final analysis

The new target centre-panel U-value is

$$U_{CP2} = 0.45 - \frac{2(0.07)(1.05 + 1.05)}{1.05(1.05)} = 0.183 \quad \text{W/m}^2\text{K}$$

This new target U-value gives a new insulation thickness

$$t_{INS} = 0.034\left(\frac{1}{0.183} - 0.13 - 0.04 - \frac{0.003}{200} - \frac{0.0007}{55}\right) = 0.180 \quad \text{m}$$

A repeat finite element analysis with the insulation thickness increased to 180 mm gives the following results:

$$\overline{U} = 0.317 \quad \text{W/m}^2\text{K}$$

$$\Psi = \frac{0.95}{2}(0.317 - 0.183) = 0.071 \quad \text{W/mK}$$

$$U = 0.183 + \frac{2(0.071)(0.95 + 1.50)}{0.95(1.50)} = 0.453 \quad \text{W/m}^2\text{K}$$

This is within 0.7% of the target of 0.45 and is considered acceptable. The required insulation thickness is 180 mm. This is more than 2.5 times the initial insulation thickness and so an alternative solution might be sought - the next example demonstrates one such alternative.

4.5 Example 3

The final example considers a panel which is part of a more complex insulated wall detail. The proposed detail is shown in Figure 4.3.

This detail uses a panel to provide a waterproof insulated layer in a curtain walling system, but the exterior of the panel is masked with a decorative stone spandrel and the interior of the panel is hidden behind a dry lining. The U-value of the insulated panel detail is not to exceed 0.45 W/m^2K.

The panel comprises a 2 mm aluminium skin to the exterior and a 0.7 mm galvanised steel skin to the interior. The insulation is a mineral fibre lamella with a thermal conductivity of 0.04 W/mK. The edge spacer is a 6 mm thick hard foam rubber block, 25 mm wide. The insulated panel will have overall dimensions, including the edge detail, of 850 mm high by 1150 mm wide.

The stone is a 40 mm thick granite slab (thermal conductivity 2.5 W/mK), separated from the insulated panel by a 10 mm vented air gap. The dry lining is a 15 mm plywood sheet (thermal conductivity 0.16 W/mK) with an applied aluminium foil backing facing the insulated panel, to act as a vapour barrier. The plywood and insulated panel are separated by a 60 mm air gap.

4.5.1 Preliminary stage - determine U-value required of panel

The contribution of the additional layers (stone, plywood and two air gaps) can be simply subtracted from the analysis. The required overall resistance of the detail is

$$R = \frac{1}{U} = 2.222 \quad m^2K/W$$

The resistance of the four additional layers can be determined as follows:

The stone is a simple conduction layer

$$R_{STONE} = \frac{t}{\lambda} = \frac{0.04}{2.5} = 0.016 \qquad m^2K/W$$

The plywood is a similar conduction layer

$$R_{PLYWOOD} = \frac{t}{\lambda} = \frac{0.015}{0.16} = 0.094 \ m^2K/W$$

In a 10 mm air gap convection is unlikely to occur and the overall resistance combines terms due to conduction and radiation heat transfer. Assuming that the aluminium surface has a high emissivity of 0.9 (due to the possible accumulation of dirt, which can enter a vented space), as does the stone surface, and using the formulae in section A.1 of Appendix A gives a resistance for an unvented 10 mm air gap of

$$R_{10}^{UNVENTED} = \frac{1}{\frac{\lambda}{t} + h_R} = \frac{1}{\frac{0.025}{0.01} + 4.206} = 0.149 \qquad m^2K/W$$

where

$$h_R = \frac{4\sigma T_m^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = \frac{4(5.67 \times 10^{-8})283^3}{\frac{1}{0.9} + \frac{1}{0.9} - 1} = 4.206 \qquad W/m^2K$$

However, prEN 10077-2 [1996] indicates that for a vented airspace the equivalent thermal conductivity of the air space must be doubled, which is equivalent to halving the resistance, giving a resistance for the vented 10 mm air gap of

$$R_{10} = \frac{0.149}{2} = 0.075 \quad m^2K/W$$

This could also be expressed as an equivalent thermal conductivity of

$$\lambda_{10} = \frac{t}{R_{10}} = \frac{0.01}{0.075} = 0.133 \qquad W/mK$$

The 60 mm cavity between the plywood and the back of the panel can be treated differently - beyond a cavity thickness of 25 mm the resistance of a cavity is reasonably constant, due to the presence of fully-developed convection currents. In this case the deep cavity also has a low-emissivity surface (the aluminium foil, which is facing into a sealed cavity). The CIBSE Guide Part A3 [1996] defines a thermal resistance for a cavity greater than 25 mm deep, with a single low emissivity surface, of

$$R_{>25}^{low-\varepsilon} = 0.35 \qquad m^2K/W$$

Each of the four additional resistances can be subtracted from the overall resistance to give the required resistance for the insulated panel (including surface effects)

$$R = \frac{1}{U} - R_{STONE} - R_{PLYWOOD} - R_{10} - R_{>25}^{low-\varepsilon} = 1.687 \qquad m^2K/W$$

The target centre-panel U-value for the insulated panel is

$$U_{CP} = \frac{1}{R} = 0.59 \quad \text{W/m}^2\text{K}$$

4.5.2 Stage 1 - Centre-panel construction

The centre-panel construction is already defined. Taking a thermal conductivity of 200 W/mK for the aluminium, and 55 W/mK for the galvanized steel skin gives an initial centre-panel insulation thickness of

$$t_{INS} = 0.04\left(\frac{1}{0.59} - 0.13 - 0.04 - \frac{0.002}{200} - \frac{0.0007}{55}\right) = 0.061 \text{ m}$$

The initial insulation thickness is therefore taken as 61 mm.

4.5.3 Stage 2 - Edge detail

The proposed edge detail uses a 6 mm thick by 25 mm wide closed-cell foam rubber spacer. The edge detail is as shown in Figure 4.4.

4.5.4 Stage 3 - Preliminary analysis

The initial analysis, using Therm 2.0, gave a U-value of 0.828 W/m^{2}K. The Ψ-value is therefore

$$\Psi = \frac{0.85}{2}(0.828 - 0.59) = 0.101 \quad \text{W/mK}$$

The true average U-value of the panel is then given by

$$U = 0.59 + \frac{2(0.101)(0.85+1.15)}{0.85(1.15)} = 1.003 \quad \text{W/m}^2\text{K}$$

4.5.5 Stage 4 - Final analysis

The new target centre-panel U-value is

$$U_{CP2} = 0.59 - \frac{2(0.101)(0.85+1.15)}{0.85(1.15)} = 0.177 \quad \text{W/m}^2\text{K}$$

This new target U-value gives a new insulation thickness

$$t_{INS} = 0.04\left(\frac{1}{0.177} - 0.13 - 0.04 - \frac{0.002}{200} - \frac{0.0007}{55}\right) = 0.219 \quad \text{m}$$

This is a considerable increase from 61 mm to 219 mm of insulation, and clearly this would fill the 60 mm gap between the dry lining and the panel. In this instance however there is a more obvious solution - place the additional insulation outside the panel. This alternative solution avoids thermal bridging. If it is assumed that the panel has an average U-value of 1.00 W/m^{2}K (as calculated above) then this gives a panel resistance of

$$R = \frac{1}{U} = 1.00 \quad \text{m}^2\text{K/W}$$

The target panel U-value is 0.59 W/m^{2}K, which requires a resistance of

$$R = \frac{1}{U} = 1.695 \quad \text{m}^2\text{K/W}$$

Sufficient insulation is required to increase the overall resistance of the panel by 0.695 m^{2}K/W. For an insulation thermal conductivity of 0.04 W/mK this requires an insulation thickness of

$$t = R\lambda = 0.0278 \quad \text{m}$$

The fixing of 28 mm of insulation to the back of the insulated panel will therefore have the desired effect and will only reduce the gap between panel and dry lining to 32 mm, leaving the gap thermal resistance unchanged.

4.6 Conclusions

This chapter has used three examples to demonstrate the procedure for determining the insulation thickness to be used in typical insulated panels with reduced edge thickness'. The tools required for this analysis are now freely available (Appendix B), and the procedure is reasonably straightforward; in each of the three examples given above the time required to design each panel did not exceed one hour. It is strongly recommended that this method is used for insulated panel design, to eliminate the additional heat losses that presently occur and yet are entirely unrecognised.

Figure 4.1 The first example panel edge detail

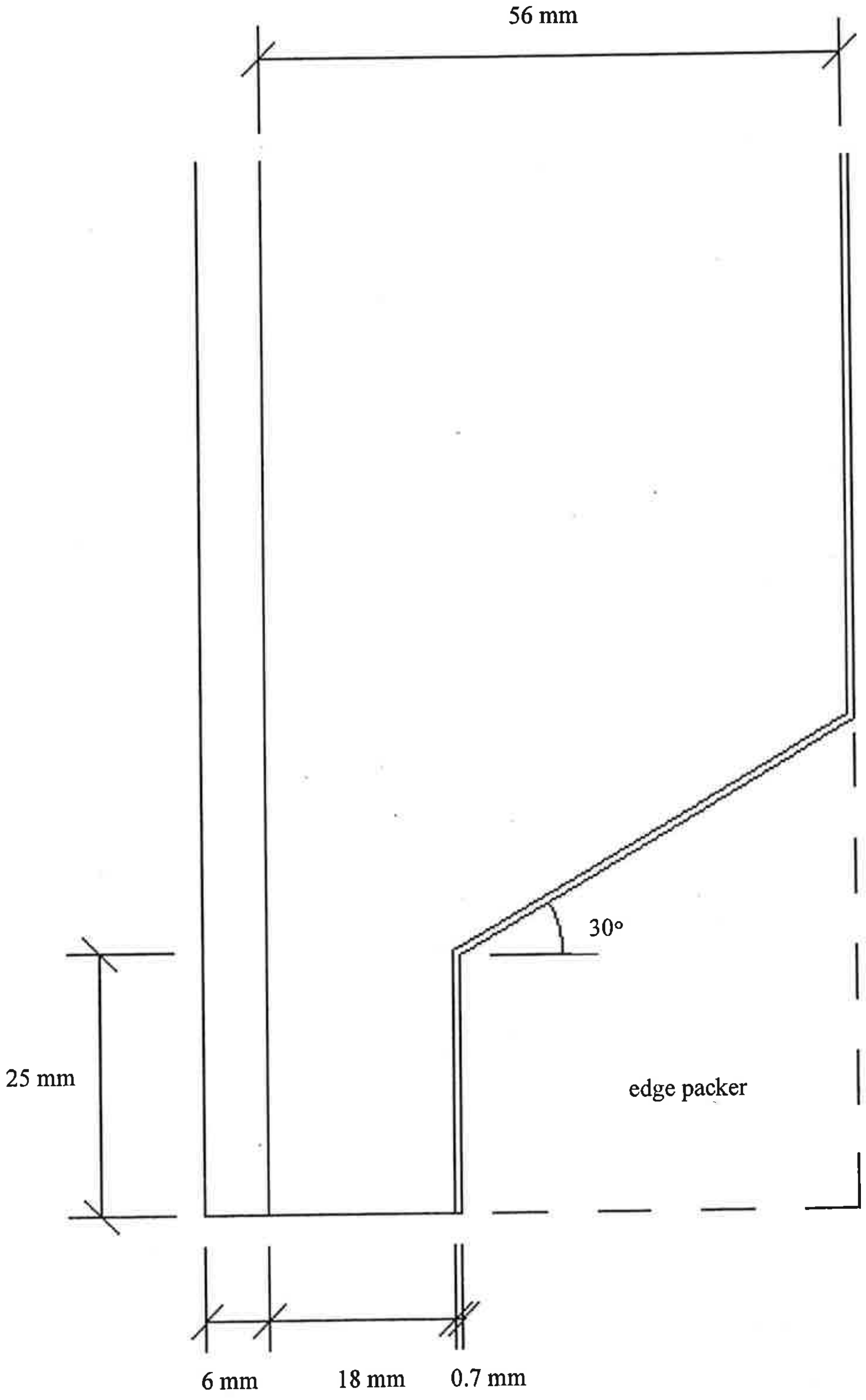


Figure 4.2 **The second example panel edge detail**

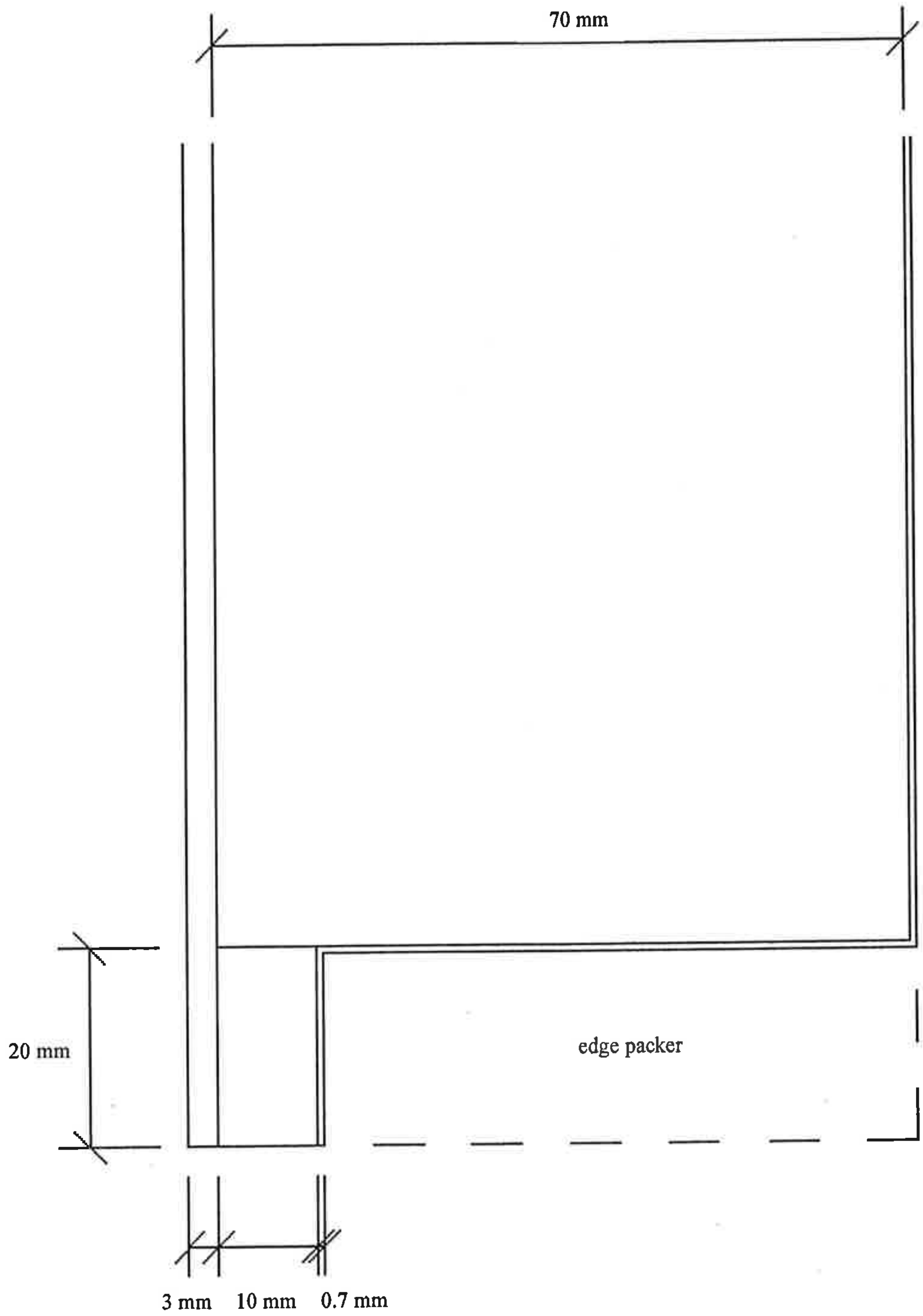


Figure 4.3 The third example panel construction

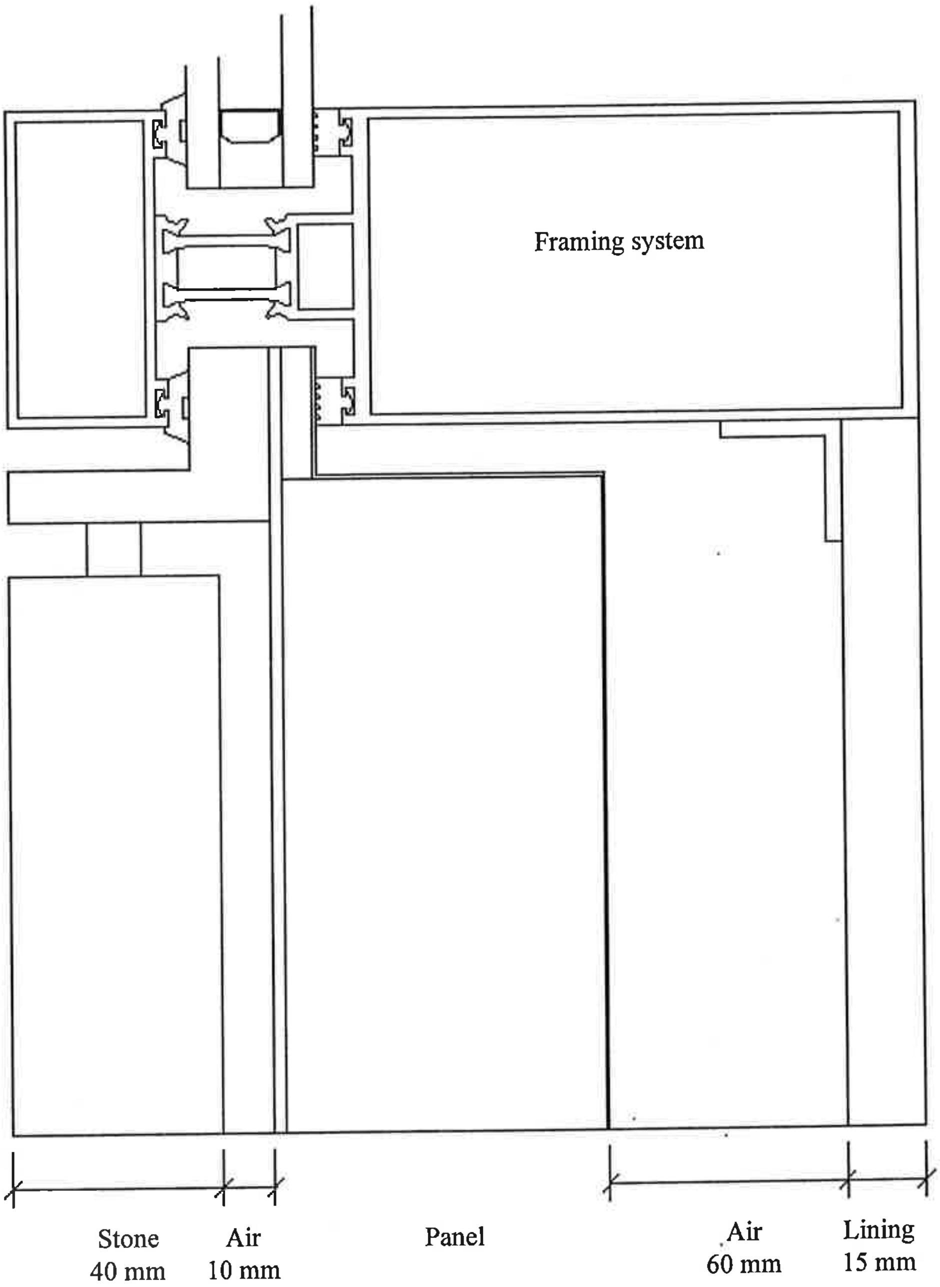
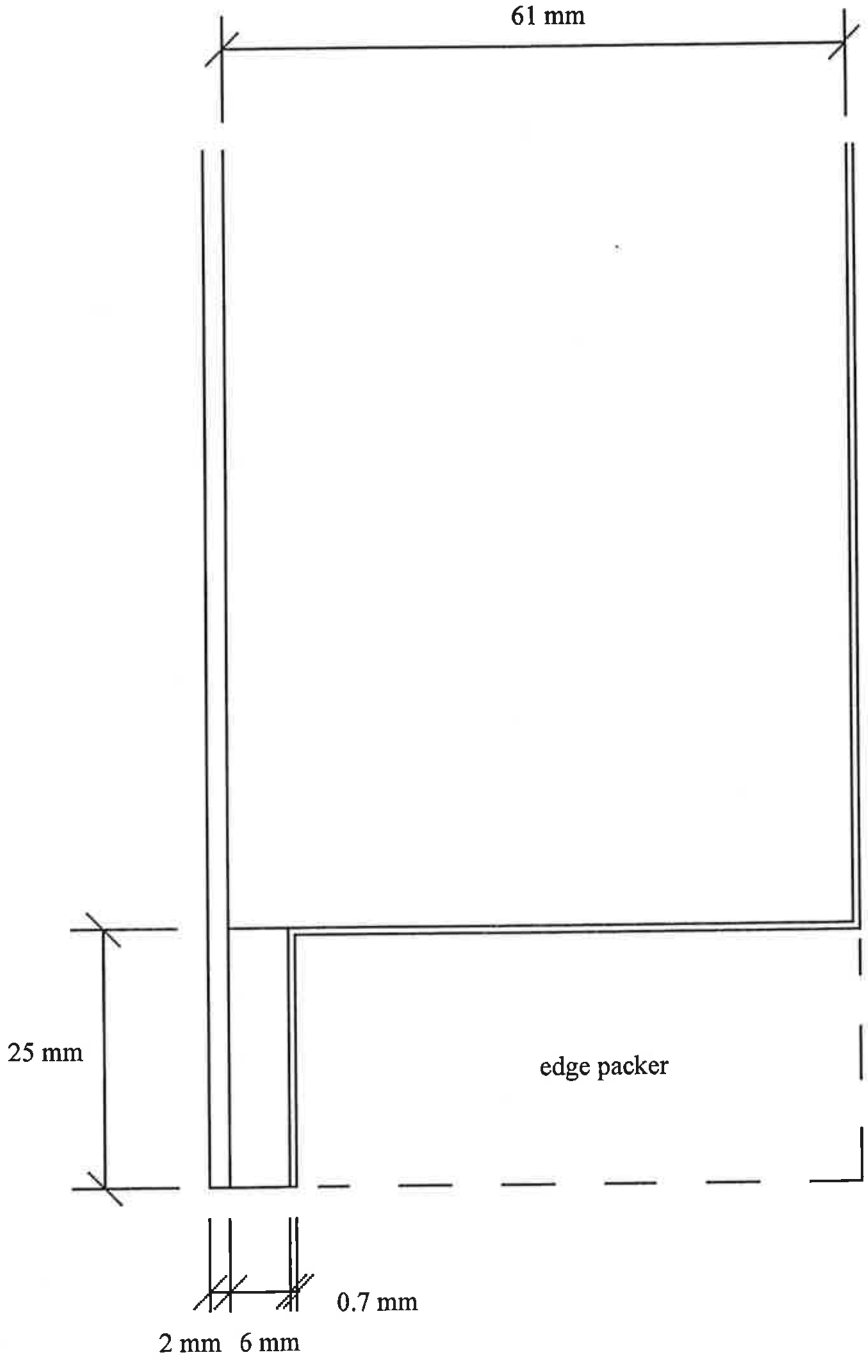


Figure 4.4 The third example panel edge detail



5 Some Features of Insulated Panel Design

5.1 Introduction

Prefabricated insulated panels generally comprise a thickness of insulation sandwiched between two skins, one or both of which may be a metal foil or sheet. At the edges of the panel the skins are brought together and separated by a small rigid spacer. If it is important to exclude water vapour from the insulation material then a vapour seal is effected at the edge of the panel either by using vapour-tight spacers joined to the skins with a vapour-tight adhesive or sealant, or by wrapping a vapour-tight tape around the edge of the panel. However, there are a number of features of the panel design that may influence thermal bridging and require the use of a greater thickness of insulation.

5.2 Aluminium Foils

Aluminium is an excellent conductor of heat, with a thermal conductivity of 200 W/mK. If the insulation is wrapped around with an aluminium foil, typically 200 micron (0.2 mm) thick, this can lead to significant thermal bridging.

If the insulation is 1200 mm square and has a thermal conductivity of 0.04 W/mK then its three-dimensional thermal resistance for a given thickness t is

$$\Re_{INS} = \frac{t}{\lambda A} = \frac{t}{0.04(1.2)^2} = 17.4t$$

If the perimeter of the insulation is bridged by a 0.2 mm wide aluminium strip then the resistance of the aluminium strip is

$$\Re_{ALU} = \frac{t}{\lambda A} = \frac{t}{200(0.0002)(4.8)} = 5.2t$$

where 4.8 is the perimeter of the insulation (i.e. 4 times 1.2 m).

This shows that the aluminium foil strip has one-third of the thermal resistance of the insulation layer; this is highly significant and demonstrates that even the thinnest metal bridge can increase the heat loss significantly. The use of non-conducting tapes to provide a vapour seal should be preferred.

5.3 Panel Sides

The side of the panel, where the inner skin turns past the insulation, may be raked back from the edge of the panel. Where this is done the internal skin has more exposed surface and so thermal bridging will be increased. The inner skin should have sides which are perpendicular to the face of the panel, maximising the use of insulation.

5.4 Double-sided Adhesive Tapes

Double-sided adhesive tapes are sometimes used to bond the skins of the panel to the edge spacer. These tapes are often very thin and do not provide a significant degree of thermal isolation; tapes which are made from softer materials often crush under the pressure of assembly and provide even less thermal benefit. The edge spacer thickness should always be maximised if the best-performing edge details are required.

5.5 Built-up Panels

Insulated walling which is built up in situ, such as that shown in example 3 of Chapter 4, will not suffer from thermal bridging problems if the designer uses non-conductive sheet materials as the facings. Alternatively a conductive facing material may work if it is only uses across the face of the panel and does not return past the side of the insulation – the edge of the insulation could be spanned by the use of an extruded plastic profile. If the need to provide fire resistance prohibits the use of plastic materials then using a steel skin with insulation bonded to the warm surface, as proposed as a solution to example 3 of Chapter 4, may be an acceptable solution.

5.6 Summary

There are a number of simple rules which will aid the designer in achieving target insulated panel U-values:

i. the insulation should be continued as close to the edge of the panel as possible;

ii. the insulation should be full thickness across it full width;

iii. the edge spacer should be as thick as possible;

iv. the edge spacer should have a low thermal conductivity;

v. metal skins will increase the risk of thermal bridging if used – they should be as thin as possible;

vi. conductive aluminium foils will still lead to thermal bridging and must be included in the analysis even if only used as a vapour seal around the edges of panels.

If these simple guidelines are followed the designer will find it easier to achieve target U-values. However the use of two-dimensional finite element analysis eliminates guesswork and will lead to better design.

6 Conclusions

This report has considered the effect of edge details on the heat transfer through pre-fabricated insulated panels as typically used in stick system curtain walls. It is shown that the practice of basing insulation thickness on a simple calculation of centre-panel performance is seriously inaccurate, and dramatically under-predicts the true heat loss through these panels. Any metal layer in these panels can lead to significant thermal bridging.

It is proposed to design insulated panels using two-dimensional finite element analysis software. Easy-to-use software for this purpose is already freely available and is easy to learn and use. This report demonstrates the method for designing insulated panels to take full account of thermal bridging at the panel edges.

REFERENCES AND BIBLIOGRAPHY

The following publications are referenced in this report:

BS 874:Part 3:Section 3.1, 1987, *Methods for determining thermal insulating properties with definitions of thermal insulating terms Part 3. Tests for thermal transmittance and conductance Section 3.1. Guarded hot-box method*, British Standards Institution, London

BS 874:Part 3:Section 3.2, 1990, *Methods for determining thermal insulating properties with definitions of thermal insulating terms Part 3. Tests for thermal transmittance and conductance Section 3.2. Calibrated hot-box method*, British Standards Institution, London

BS EN ISO 6946, 1997, *Building components and building elements - thermal resistance and thermal transmittance - calculation method*, British Standards Institution, London

BS EN ISO 10211-1, 1996, *Thermal bridges in building construction - Heat flows and surface temperatures Part 1. General calculation methods*, British Standards Institution, London

Building Regulations Approved Document L, 1995 edition, *Conservation of fuel and power*, Building Regulations 1991, Department of the Environment and the Welsh Office, HMSO, London

CIBSE A3, 1986, *Thermal properties of building structures*, CIBSE Guide Part A3, Chartered Institution of Building Services Engineers, London

Davis Langdon and Everest, 1997, *Cladding and curtain walling costs*, aj focus, February 1997, pp22

NFRC, 1995, *Certified products directory*, 4th edition January 1995, National Fenestration Rating Council, Maryland, USA

NFRC 100-91, 1991, *Procedure for determining fenestration product thermal properties (currently limited to U-values)*, National Fenestration Rating Council, Maryland, USA

NPL, 1997, *Comparison between the measured, simulated and calculated U-values of eight window systems*, DoE Research Contract 39/3/279, NPL Report QM 131, National Physical Laboratory, London

prEN 10077-2, 1996, *Window and door components - Thermal transmittance - Part 2: Numerical calculation method*, CEN/TC 89/WG 7 N 114, Comité Européen de Normalisation

prEN 12412-1, 1996, *Windows, doors and shutters - Determination of thermal transmittance by hot-box method - Part 1: Windows and doors*, Comité Européen de Normalisation

Appendix A The Calculation Models

This appendix describes the mathematical models used to calculate the one-, two- and three-dimensional performance of insulated panels.

A.1 Basic thermal resistances

A.1.1 One-dimensional heat transfer assessment

For uniform plane layered components, where the heat transfer is one-dimensional and perpendicular to the layers, the overall thermal resistance of the panel is calculated by adding together the resistance of each layer in the component, together with 'surface' resistances representing heat transfer between the exposed surfaces and the environment:

$$R = R_{SI} + \sum_{j=1}^{n} R_j + R_{SE}$$

- R is the overall component thermal resistance, in m^2K/W
- R_{SI} is the internal surface resistance, in m^2K/W
- R_j is the layer thermal resistance, in m^2K/W
- R_{SE} is the external surface resistance, in m^2K/W

The U-value of the layered component is then:

$$U = \frac{1}{R}$$

- U is the thermal transmittance (U-value), in W/m^2K

The layer resistance, R_J, depends upon the heat transfer process in the particular layer.

A.1.1.1 Conduction layer thermal resistance

For a conduction process through a layer of uniform thickness and thermal conductivity the resistance is

$$R_j = \frac{t}{\lambda}$$

- t is the layer thickness, in m
- λ is the layer thermal conductivity, in W/mK

This formula also assumes that the layer is of unit area - if all of the layers are of the same area (they must be for a one-dimensional component) then the area cancels out of the final equation.

A.1.1.2 Convection layer thermal resistance

For a convection process in a gas-space it is necessary to calculate a convective heat transfer coefficient h, in which case

$$R_j = \frac{1}{h}$$

- h is the convective heat transfer coefficient, in W/m^2K

The convective heat transfer coefficient h is usually determined from an empirical correlation. For simple gas-spaces the formulae in BS 6993:Part 1 [1989] and EN 673 [1997] are suitable.

A.1.1.3 Radiation layer thermal resistance

For a radiation heat transfer process, through a gas-space between two parallel surfaces, it is possible to calculate an equivalent radiation heat transfer coefficient, which is given by

$$h_R = \frac{\sigma\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \approx \frac{4\sigma T_m^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

- σ is the Stefan-Boltzmann constant, $\sigma = 5.67\times10^{-8}$ W/m^2K^4
- T_1 is the temperature of the first surface, in K
- T_2 is the temperature of the second surface, in K
- T_m is the mean surface temperature, in K ($T_m = \frac{1}{2}T_1 + \frac{1}{2}T_2$)
- ε_1 is the effective emissivity of the first surface (dimensionless)
- ε_2 is the effective emissivity of the second surface (dimensionless)

This formula assumes that the dimensions of the surfaces are large compared to the gap between the surfaces, and for infill panels this is generally the case. The use of the mean surface temperature T_m is an approximation which can readily be shown to be sufficiently accurate for the surface temperature range usually found in infill panels.

Once the equivalent radiation heat transfer coefficient has been determined then the thermal resistance of the layer is

$$R_j = \frac{1}{h_R}$$

- h_R is the radiative heat transfer coefficient, in W/m^2K

A.1.1.3.1 Combining radiation with conduction or convection heat transfer

If radiation heat transfer is occurring through a gas-space, then either conduction or convection heat transfer must also be occurring, unless the space has been evacuated. In this case the heat transfer processes are occurring in parallel and the overall thermal resistance of the layer is

$$R_j = \frac{1}{\frac{\lambda}{t} + h_R}$$ in the case of conduction with radiation, or

$$R_j = \frac{1}{h + h_R}$$ in the case of convection with radiation.

Note that the surface resistances combine a radiation process with a convection process using this last formula.

A.1.1.4 Limitations of the one-dimensional method

It is fundamental to the one-dimensional heat transfer assessment that heat transfer is truly one-dimensional. This means that the layers must be of a uniform thickness, with equal areas, a uniform thermal conductivity or heat transfer coefficient, and extending to the edges of the component without deviation. Penetrations through a layer, a variation of layer thickness or a non-uniformity of the material properties will usually invalidate the basic assumption of one-dimensional heat transfer and another method must be sought.

A.2 The one-dimensional model

In current practice a simple one-dimensional calculation is used to determine the thickness of insulation required to achieve a given centre-panel U-value. For the majority of the examples considered in this report the centre-panel U-value is taken as 0.45 W/m^{2}K - the target value assumed in the Building Regulations Approved Document L [1995] for opaque insulated walls.

For a simple three-layered structure there are five resistances: the inner surface resistance, the inner skin of the panel, the insulation, the outer skin of the panel and the external surface resistance. The internal and external surface resistances are taken as those currently defined in the various draft European standards. This gives:

$R_{SE} = 0.04$ m^{2}K/W

$$R_E = \frac{t_E}{\lambda_E}$$

$$R_{INS} = \frac{t_{INS}}{\lambda_{INS}}$$

$$R_I = \frac{t_I}{\lambda_I}$$

$$R_{SI} = 0.13 \quad m^2K/W$$

The overall thermal resistance of the panel is thus

$$R = R_{SE} + R_E + R_{INS} + R_I + R_{SI} = 0.17 + \frac{t_E}{\lambda_E} + \frac{t_{INS}}{\lambda_{INS}} + \frac{t_I}{\lambda_I}$$

and the centre-panel U-value is

$$U_{CP} = \frac{1}{R}$$

- R_{SE} is the external surface resistance, in m^2K/w
- R_E is the layer resistance of the external skin, in m^2K/w
- t_E is the thickness of the external skin, in m
- λ_E is the thermal conductivity of the external skin, in W/mK
- R_{INS} is the layer resistance of the insulation, in m^2K/w
- t_{INS} is the thickness of the insulation, in m
- λ_{INS} is the thermal conductivity of the insulation, in W/mK
- R_I is the layer resistance of the internal skin, in m^2K/w
- t_I is the thickness of the internal skin, in m
- λ_I is the thermal conductivity of the internal skin, in W/mK
- R_{SI} is the internal surface resistance, in m^2K/w
- R is the overall resistance, in m^2K/w

This formula is frequently used to determine the required thickness of insulation to achieve a given centre-panel U-value. Substituting the known values and rearranging gives

$$t_{INS} = \lambda_{INS}\left(\frac{1}{U_{CP}} - 0.17 - \frac{t_E}{\lambda_E} - \frac{t_I}{\lambda_I}\right)$$

A.3 The two-dimensional model

In two-dimensions the panel can be considered as either a set of thermal resistances placed in series, or a set of resistances in parallel. Figure A1 illustrates shows both of these alternatives; note that the insulating packer has been assumed at the edge of the panel.

Figure A2 shows the notation used for the dimensions of various elements of the panel. It should be noted here that the dimension w_{INS} is the distance from the centre of the panel to the edge of the insulation, and that the full projected width of the 2-d panel is thus $w_{INS}+w_S$.

A.3.1 2-d Series configuration

The 2-d series configuration comprises 7 layers. Using the symbols from Figure A2 the equations for the resistance of each layer can be determined as follows:

Layer $S1^{2d}$: $$\Re_{S1}^{2d} = \frac{1}{h_{SI}\left(w_{INS} + w_S\right)}$$

Layer $S2^{2d}$: $$\Re_A^{S2-2d} = \frac{t_I}{\lambda_I\left(w_{INS} + t_I\right)}$$

$$\Re_B^{S2-2d} = \frac{t_I}{\lambda_P\left(w_S - t_I\right)}$$

$$\frac{1}{\Re_{S2}^{2d}} = \frac{1}{\Re_A^{S2-2d}} + \frac{1}{\Re_B^{S2-2d}}$$

Layer $S3^{2d}$: $$\Re_A^{S3-2d} = \frac{t_{INS} - t_S - t_I}{\lambda_{INS} w_{INS}}$$

$$\Re_B^{S3-2d} = \frac{t_{INS} - t_S - t_I}{\lambda_I t_I}$$

$$\Re_C^{S3-2d} = \frac{t_{INS} - t_S - t_I}{\lambda_P\left(w_S - t_I\right)}$$

$$\frac{1}{\Re_{S3}^{2d}} = \frac{1}{\Re_A^{S3-2d}} + \frac{1}{\Re_B^{S3-2d}} + \frac{1}{\Re_C^{S3-2d}}$$

Layer $S4^{2d}$: $$\Re_A^{S4-2d} = \frac{t_I}{\lambda_{INS} w_{INS}}$$

$$\Re_B^{S4-2d} = \frac{t_I}{\lambda_I w_S}$$

$$\frac{1}{\Re_{S4}^{2d}} = \frac{1}{\Re_A^{S4-2d}} + \frac{1}{\Re_B^{S4-2d}}$$

Layer S5^{2d}: $\Re_A^{S5-2d} = \dfrac{t_S}{\lambda_{INS} w_{INS}}$

$$\Re_B^{S5-2d} = \frac{t_S}{\lambda_I w_S}$$

$\dfrac{1}{\Re_{S5}^{2d}} = \dfrac{1}{\Re_A^{S5-2d}} + \dfrac{1}{\Re_B^{S5-2d}}$ when a spacer is present, or

$\Re_{S5}^{2d} = 0$ when the skins meet at the edge

Layer S6^{2d}: $\Re_{S6}^{2d} = \dfrac{t_E}{\lambda_E (w_{INS} + w_S)}$

Layer S7^{2d}: $\Re_{S7}^{2d} = \dfrac{1}{h_{SE} (w_{INS} + w_S)}$

The overall resistance is $\Re_S^{2d} = \Re_{S1}^{2d} + \Re_{S2}^{2d} + \Re_{S3}^{2d} + \Re_{S4}^{2d} + \Re_{S5}^{2d} + \Re_{S6}^{2d} + \Re_{S7}^{2d}$

A.3.2 2-d Parallel configuration

There are three parallel heat transfer paths, each formed from a series of resistances. Using the symbols from Figure A2 the equations for the resistance of each path can be determined as follows:

Path P1^{2d}: $\Re_A^{P1-2d} = \dfrac{1}{h_{SI} (w_S - t_I)}$

$$\Re_B^{P1-2d} = \frac{t_{INS} - t_S}{\lambda_P (w_S - t_I)}$$

$$\Re_C^{P1-2d} = \frac{t_I}{\lambda_I (w_S - t_I)}$$

$$\Re_D^{P1-2d} = \frac{t_S}{\lambda_S (w_S - t_I)}$$

$$\Re_E^{P1-2d} = \frac{t_E}{\lambda_E (w_S - t_I)}$$

$$\Re_F^{P1-2d} = \frac{1}{h_{SE} (w_S - t_I)}$$

$$\Re_{P1}^{2d} = \Re_A^{P1-2d} + \Re_B^{P1-2d} + \Re_C^{P1-2d} + \Re_D^{P1-2d} + \Re_E^{P1-2d} + \Re_F^{P1-2d}$$

Path P2[2d]: $$\Re_A^{P2-2d} = \frac{1}{h_{SI} t_I}$$

$$\Re_B^{P2-2d} = \frac{t_I + t_{INS} - t_S}{\lambda_I t_I}$$

$$\Re_C^{P2-2d} = \frac{t_S}{\lambda_S t_I}$$

$$\Re_D^{P2-2d} = \frac{t_E}{\lambda_E t_I}$$

$$\Re_E^{P2-2d} = \frac{1}{h_{SE} t_I}$$

$$\Re_{P2}^{2d} = \Re_A^{P2-2d} + \Re_B^{P2-2d} + \Re_C^{P2-2d} + \Re_D^{P2-2d} + \Re_E^{P2-2d}$$

Path P3[2d]: $$\Re_A^{P3-2d} = \frac{1}{h_{SI} w_{INS}}$$

$$\Re_B^{P3-2d} = \frac{t_I}{\lambda_I w_{INS}}$$

$$\Re_C^{P3-2d} = \frac{t_{INS}}{\lambda_{INS} w_{INS}}$$

$$\Re_D^{P3-2d} = \frac{t_E}{\lambda_E w_{INS}}$$

$$\Re_E^{P3-2d} = \frac{1}{h_{SE} w_{INS}}$$

$$\Re_{P3}^{2d} = \Re_A^{P3-2d} + \Re_B^{P3-2d} + \Re_C^{P3-2d} + \Re_D^{P3-2d} + \Re_E^{P3-2d}$$

The overall resistance is $$\frac{1}{\Re_P^{2d}} = \frac{1}{\Re_{P1}^{2d}} + \frac{1}{\Re_{P2}^{2d}} + \frac{1}{\Re_{P3}^{2d}}$$

A.3.3 2-d Overall resistance and Ψ-value

The mean resistance is $$\Re^{2d} = \frac{\Re_S^{2d} + \Re_P^{2d}}{2}$$

the average U-value is $$U^{2d} = \frac{1}{\Re^{2d}(w_{INS} + w_S)}$$

and the Ψ-value is then $\Psi^{2d} = \left(U^{2d} - U_{CP}^{1d}\right)\left(w_{INS} + w_S\right)$

where the centre-panel U-value is determined from the one-dimensional calculation

$$U_{CP}^{1d} = \frac{1}{\frac{1}{h_{SI}} + \frac{t_I}{\lambda_I} + \frac{t_{INS}}{\lambda_{INS}} + \frac{t_E}{\lambda_E} + \frac{1}{h_{SE}}}$$

The model described above is only applicable to the panel design of Figure A2. It should be noted that the average U-value applies only to a 'panel' of projected width $w_{INS}+w_S$ and length 1 m with an edge along one side only.

A.4 The three-dimensional model

Three-dimensional calculations can be performed using the same method as described above, but with an adjustment for the area of each element - in the 2-d model the area is based on a 1 metre third dimension, but in the 3-d model the area is based on a true square panel. However, for consistency with the 2-d model the dimension w_{INS} is still taken as the dimension from the centre to the edge of the insulation, so that the overall width of the panel is $2w_{INS}+2w_S$.

Again the insulating packer has been assumed at the edge of the panel.

A.4.1 3-d Series configuration

Using the symbols from Figure A2 the equations for the resistance of each layer can be determined as follows:

Layer $S1^{3d}$: $$\Re_{S1}^{3d} = \frac{1}{4h_{SI}\left(w_{INS} + w_S\right)^2}$$

Layer $S2^{3d}$: $$\Re_A^{S2-3d} = \frac{t_I}{4\lambda_I\left(w_{INS} + t_I\right)^2}$$

$$\Re_B^{S2-3d} = \frac{t_I}{4\lambda_P\left[\left(w_{INS} + w_S\right)^2 - \left(w_{INS} + t_I\right)^2\right]}$$

$$\frac{1}{\Re_{S2}^{3d}} = \frac{1}{\Re_A^{S2-3d}} + \frac{1}{\Re_B^{S2-3d}}$$

Layer $S3^{3d}$: $$\Re_A^{S3-3d} = \frac{t_{INS} - t_S - t_I}{4\lambda_{INS} w_{INS}^2}$$

$$\Re_B^{S3-3d} = \frac{t_{INS} - t_S - t_I}{4\lambda_I\left[(w_{INS} + t_I)^2 - w_{INS}^2\right]}$$

$$\Re_C^{S3-3d} = \frac{t_{INS} - t_S - t_I}{4\lambda_P\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$$

$$\frac{1}{\Re_{S3}^{3d}} = \frac{1}{\Re_A^{S3-3d}} + \frac{1}{\Re_B^{S3-3d}} + \frac{1}{\Re_C^{S3-3d}}$$

Layer $S4^{3d}$: $\Re_A^{S4-3d} = \frac{t_I}{\lambda_{INS} w_{INS}^2}$

$$\Re_B^{S4-3d} = \frac{t_I}{4\lambda_I\left[(w_{INS} + w_S)^2 - w_{INS}^2\right]}$$

$$\frac{1}{\Re_{S4}^{3d}} = \frac{1}{\Re_A^{S4-3d}} + \frac{1}{\Re_B^{S4-3d}}$$

Layer $S5^{3d}$: $\Re_A^{S5-3d} = \frac{t_S}{4\lambda_{INS} w_{INS}^2}$

$$\Re_B^{S5-3d} = \frac{t_S}{4\lambda_I\left[(w_{INS} + w_S)^2 - w_{INS}^2\right]}$$

$\frac{1}{\Re_{S5}^{3d}} = \frac{1}{\Re_A^{S5-3d}} + \frac{1}{\Re_B^{S5-3d}}$ when a spacer is present, or

$\Re_{S5}^{3d} = 0$ when the skins meet at the edge

Layer $S6^{3d}$: $\Re_{S6}^{3d} = \frac{t_E}{4\lambda_E (w_{INS} + w_S)^2}$

Layer $S7^{3d}$: $\Re_{S7}^{3d} = \frac{1}{4h_{SE} (w_{INS} + w_S)^2}$

The overall resistance is $\Re_S^{3d} = \Re_{S1}^{3d} + \Re_{S2}^{3d} + \Re_{S3}^{3d} + \Re_{S4}^{3d} + \Re_{S5}^{3d} + \Re_{S6}^{3d} + \Re_{S7}^{3d}$

A.4.2 3-d Parallel configuration

Using the symbols from Figure A2 the equations for the resistance of each path can be determined as follows:

Path $P1^{3d}$: $\Re_A^{P1-3d} = \frac{1}{4h_{SI}\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$

$$\Re_B^{P1-3d} = \frac{t_{INS} - t_S}{4\lambda_P\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$$

$$\Re_C^{P1-3d} = \frac{t_I}{4\lambda_I\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$$

$$\Re_D^{P1-3d} = \frac{t_S}{4\lambda_S\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$$

$$\Re_E^{P1-3d} = \frac{t_E}{4\lambda_E\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$$

$$\Re_F^{P1-3d} = \frac{1}{4h_{SE}\left[(w_{INS} + w_S)^2 - (w_{INS} + t_I)^2\right]}$$

$$\Re_{P1}^{3d} = \Re_A^{P1-3d} + \Re_B^{P1-3d} + \Re_C^{P1-3d} + \Re_D^{P1-3d} + \Re_E^{P1-3d} + \Re_F^{P1-3d}$$

Path P2^{3d}:

$$\Re_A^{P2-3d} = \frac{1}{4h_{SI}\left[(w_{INS} + t_I)^2 - w_{INS}^2\right]}$$

$$\Re_B^{P2-3d} = \frac{t_I + t_{INS} - t_S}{4\lambda_I\left[(w_{INS} + t_I)^2 - w_{INS}^2\right]}$$

$$\Re_C^{P2-3d} = \frac{t_S}{4\lambda_S\left[(w_{INS} + t_I)^2 - w_{INS}^2\right]}$$

$$\Re_D^{P2-3d} = \frac{t_E}{4\lambda_E\left[(w_{INS} + t_I)^2 - w_{INS}^2\right]}$$

$$\Re_E^{P2-3d} = \frac{1}{4h_{SE}\left[(w_{INS} + t_I)^2 - w_{INS}^2\right]}$$

$$\Re_{P2}^{3d} = \Re_A^{P2-3d} + \Re_B^{P2-3d} + \Re_C^{P2-3d} + \Re_D^{P2-3d} + \Re_E^{P2-3d}$$

Path P3^{3d}:

$$\Re_A^{P3-3d} = \frac{1}{4h_{SI}w_{INS}^2}$$

$$\Re_B^{P3-3d} = \frac{t_I}{4\lambda_I w_{INS}^2}$$

$$\Re_C^{P3-3d} = \frac{t_{INS}}{4\lambda_{INS} w_{INS}^2}$$

$$\Re_D^{P3-3d} = \frac{t_E}{4\lambda_E w_{INS}^2}$$

$$\Re_E^{P3-3d} = \frac{1}{4h_{SE} w_{INS}^2}$$

$$\Re_{P3}^{3d} = \Re_A^{P3-3d} + \Re_B^{P3-3d} + \Re_C^{P3-3d} + \Re_D^{P3-3d} + \Re_E^{P3-3d}$$

The overall resistance is $\frac{1}{\Re_P^{3d}} = \frac{1}{\Re_{P1}^{3d}} + \frac{1}{\Re_{P2}^{3d}} + \frac{1}{\Re_{P3}^{3d}}$

A.4.3 3-d Overall resistance and Ψ-value

The mean resistance is $\Re^{3d} = \frac{\Re_S^{3d} + \Re_P^{3d}}{2}$

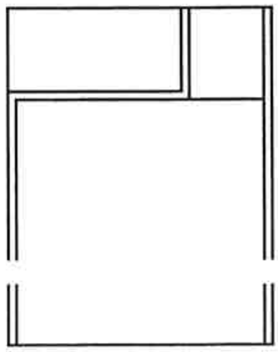
the average U-value is $U^{3d} = \frac{1}{\Re^{3d}(2w_{INS} + 2w_S)^2}$

and the Ψ-value is then $\Psi^{3d} = \left(U^{3d} - U_{CP}^{1d}\right)\frac{(w_{INS} + w_S)}{2}$

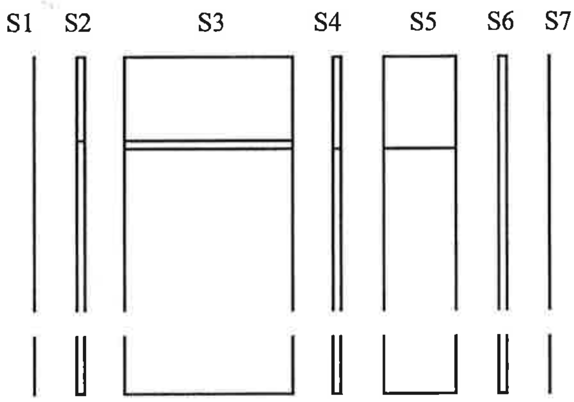
where the centre-panel U-value is given by the same formula as in the previous section.

In this case the average U-value is exact, as it properly relates the perimeter length of the panel to the area, but only for a square panel.

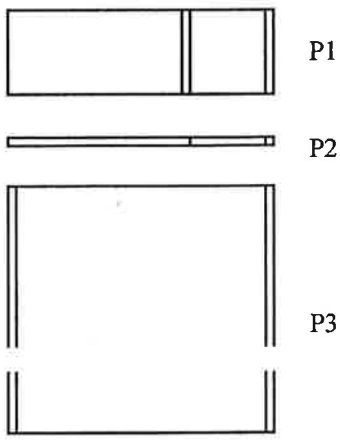
Figure A1 Series and parallel resistance diagrams for standard panel



a) Panel edge, including packer

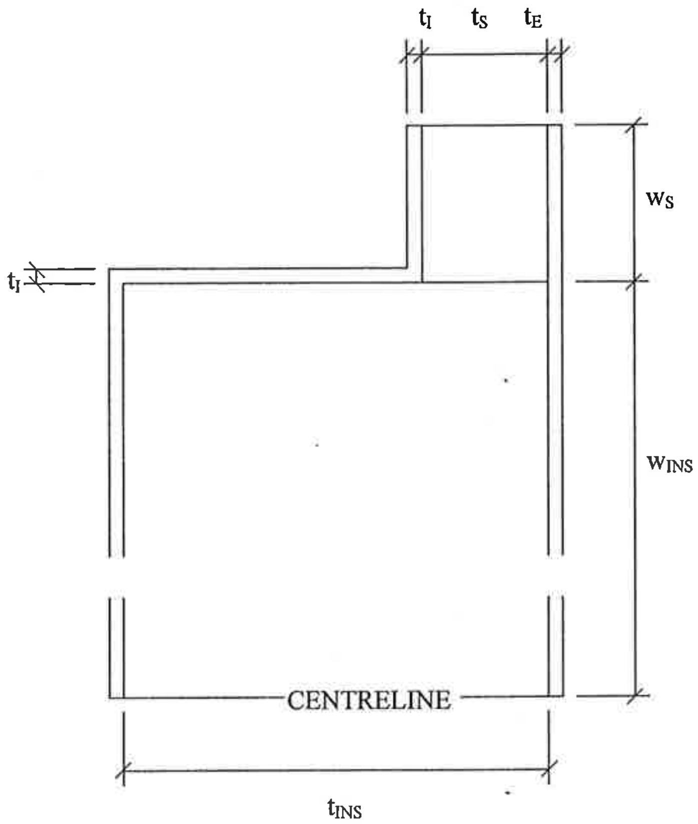


b) Series model



c) Parallel model

Figure A2 **Panel dimensions, two-dimensional section from centre to mid-side of edge of square panel**



Appendix B

Finite Element Analysis Software

This report has used software from two sources:

The program ANSYS is a commercial package capable of analysing a huge range of two- and three-dimensional dynamic and steady-state problems in all areas of engineering (i.e. not just heat transfer) and is published by:

ANSYS, Inc.
201 Johnson Road
Houston, PA 15342-1300
USA

The program Therm 2.0 has been developed with the aid of US Government Funding specifically to analyse steady-state heat transfer problems in cladding systems, and is currently available at no cost from:

Windows and Daylighting Group
Building Technologies Group
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
Berkeley, CA 94720
USA

Therm 2.0 can also be downloaded from the World Wide Web through the site http://windows.lbl.gov/software/therm/default.htm.

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