Project two:

Thermal bridging in energy efficient wall details.

BBSc 432:
Buildings & Energy
//
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Contents

B→B+

A useful literature review _ for identifying the resources. Only partially understood I think & definitely not well summarised. You do not provide a coherent argument for 1,2 or 3D calculations.

The research comprises 4 very simple calculations. You compare the results of these 10 minute calculations and conclude the walls with thicker insulation are better. This has nothing to do with the detailing

Excellent details in terms of illustration not well described in terms of rationale

Definitions

For the purpose of this report the following definitions shall apply:

Material thermal resistance (R_m). The thermal resistance between faces of a slab of given thickness of a uniform homogeneous material.

R-Value (total thermal resistance). The value of thermal resistance of a building element (e.g. wall, floor or roof) which is the sum of the surface resistances on each side of a building element and the thermal resistances of each component of the building element including any cavities in the element. [m^{2}°C/W]

Standard total thermal resistance. For compliance purposes within New Zealand, the total thermal resistance when the outside surface thermal resistance is standardised at 0.03 m^{2}°C/W and the inside surface thermal resistance is standardised at 0.09 m^{2}°C/W.

Surface thermal resistance (R_s). The thermal resistance which arises between the external surface (R_{se}) or the internal surface (R_{si}) of a building component and the air adjacent to it.

System thermal resistance (R_{sy}). The thermal resistance associated with a system or construction of materials where there may not be a single uniform homogeneous material between faces.

Thermal bridge resistance (R_b). The thermal resistance of the bridging portion of a building envelope component that is not continuous but is bridged by one or more sets of material passing through its thickness.

Thermal conductivity (k). The heat flow (thermal transmission) in unit time through unit area of a slab of a uniform homogeneous material of unit thickness when unit difference of temperature is maintained between its two surfaces (W/mK). It is related to material thermal resistance, for a material of thickness l, by the expression:

$$k = \frac{l}{R_m}$$

Thermal resistance (R). A measure of resistance to the flow of heat. It can be determined by measuring the temperature difference which is maintained between surfaces or planes when there is constant heat flow between them in unit time through unit area. [m^{2}°C/W]

Total thermal resistance (R_T). The total thermal resistance, including surface thermal resistances, between the air on either side of a building element.

Symbols and units

The following general symbols and units are used in this report.

Symbol	*Quantity*	*Unit*
A	area	[m^2]
l	thickness	[m]
k	thermal conductivity	[W/mK]
R_m	material thermal resistance	[m^2°C/W]
R_{sy}	system thermal resistance	[m^2°C/W]
R_b	thermal bridge resistance	[m^2°C/W]
R_{se}	external surface resistance	[m^2°C/W]
R_{si}	internal surface resistance	[m^2°C/W]
R_T	total thermal resistance	[m^2°C/W]

Introduction

The 2010 Draft New Zealand Energy Strategy states that;

> Around two thirds of New Zealand homes are poorly insulated or not insulated at all. These homes can be costly to heat and can lead to health problems for the occupants.(Ministry of Economic Development)

In New Zealand there are approximately 1.5 million homes, therefore this figure represents 1 million poorly insulated homes. Insulating walls represents one of the simplest and cost effective solutions for decreasing heat losses in the building envelope. Traditionally in New Zealand most homes were insulated to the minimum standard specified by the New Zealand Building Code. With government and the construction industry promoting energy efficiency in homes there is a trend emerging of buildings specifying higher levels of insulation to create warm, dry, energy efficient homes. Adding a layer of insulation is not, however, necessarily a sufficient solution to reduce heat loses. Thermally low points, commonly known as thermal bridges in wall constructions decrease the effectiveness of insulation.(Déqué, Ollivier and Roux) As the level of thermal insulation increases, the role thermal bridges play in the overall heat loss of the building envelope also increases. Traditional timber wall constructions are limited in the amount of thermal performance they can provide therefore it is necessary to look at alternative constructions.

Big Leap in logic vs earlier text

There is debate on the methods for determining the effect that thermal bridges have on the overall heat loss of the building envelope. Some researchers claim that simple one-dimensional calculations traditionally used by building practitioners are inaccurate for innovative building and insulation techniques. There is research into using complex two- and three-dimensional simulation models to accurately determine the amount of thermal bridging in wall details to calculate the heating and cooling loads of any equipment used to modify the environment of the building.

ref?

?, I do not understand the link you imply?..

Therefore the aim of this research is to investigate the relationship between thermal bridging and the overall thermal resistance of external wall construction.

To achieve this aim, Chapter 2 *Background* provides a review of the current practices and theories in thermal bridging. From the conclusions in the previous section, Chapter 3 *Method* presents the hypothesis and outlines the process to achieve the research aim including a rationale for the method selection. Chapter 4 *Walls* details the four wall constructions for comparison, breaking down each component of the wall and providing a brief rationale for their design with regards to reducing the amount of thermal bridging. Chapter 5 *Results* presents the findings from the calculations for a comparative analysis of the role thermal bridging plays in the overall thermal resistance. A discussion on whether the results back up the hypothesis will be presented. Chapter 6 *Conclusions* relates the findings from the previous chapter to the initial research aim. Finally Chapter 7 *Further research* discusses how the conclusions found in this research can lead on to other studies into thermal bridging in walls.

Background

Insulation & thermal bridging

The most common method of construction in New Zealand is using floor-to-ceiling height timber frames typically constructed on-site. Under the Building Code, new homes and additions to existing homes must be insulated to a minimum standard, as shown by table 1 below.

		Building Code minimum	**Better Practice**	**Best Practice**
		[W/m^{2}C°]	[W/m^{2}C°]	[W/m^{2}C°]
Zone 1 & 2	Walls	*R* 1.5	*R* 2.1	*R* 2.6
Source: New Zealand Standards 4218:2004 and 4244:2003				

Table 1: New Zealand insulation standards

Two studies by Çomakli and Yüksel, and Hasan looked at optimising insulation thickness using life cycle cost as a measure. From the studies it was found that as insulation thickness increases, the heating load decreases, as does the cost of fuel and total cost of heating. However, as the insulation thickness increases so does the price for the insulation. The total cost of fuel and insulation was plotted against insulation thickness and where the two costs met represented the optimum insulation thickness.(Çomakli and Yüksel) (Hasan) As the optimum insulation thickness is based on cost and not thermal performance, it is possible to achieve higher thermal performance with increased insulation.

? Heating load decreases & therefore fuel cost ?

I've read this sentence 5 times & I still don't understand it.

With new buildings being encouraged to increase the level of insulation of the building envelope, the role thermal bridges play in the overall effectiveness of the wall to insulate the building is also increased.

said earlier

During the winter months the temperature of the inside surface over a thermal bridge is lower than that of the adjacent construction. This temperature difference can cause condensation and mould growth, reducing the indoor air quality and creating a potential health risk to the occupants.(Larbi)

The current method to determine the amount of thermal bridging in walls is the New Zealand Standard, NZS 4214, which provides one-dimensional methods of determining the total thermal resistance of parts of buildings in steady-state environmental conditions. The Standard is intended to be used as a means of compliance with the relevant requirements of the New Zealand Building Code, though it is not intended to calculate the *R*-values for use in computer thermal performance simulation programs. (Standards New Zealand)

Déqué, Ollivier and Roux argue that evaluating the heat losses through thermal bridging and their effect on ~~of~~ the overall building performance is difficult with the standard configurations and calculations that go back to 1977, stating that "they are not sufficient to classify, calculate or take into account innovative building and insulation techniques."(Déqué, Ollivier and Roux) Using such methods can potentially lead to an under-estimation of the heat losses caused by thermal bridges. They suggest that numerical simulation addresses this issue with the two categories of tools available in construction. The first, simulation tools for evaluating the overall building energy performance. Programs such as SUNREL, ENERGY PLUS and DOE-2, are based on a description of the whole building envelope – opaque and glass walls – the heating systems and their regulation. The calculation of thermal bridges in this category of software is often very approximate. The second simulation tool such as THERM 5.0 is a calculation program specific to heat transfers in walls. Geometry is entered in two-dimensions (2D) or three dimensions (3D) of the thermal bridges through a graphic interface. They calculate the distribution of flows and temperatures under steady-state conditions, however, they do not evaluate the effect of thermal bridges on the overall performance of the building.(Déqué, Ollivier and Roux)

In a study by Kośny and Kossecka, three walls with a 20% framing factor made of timber, concrete and steel were simulated using a simplified one-dimensional model of heat transfer (normally used in DOE-2, BLAST or ENERGY PLUS simulations) and more complicated (closer to reality) models. For the timber framed wall, the differences between simplified one-dimensional model of heat transfer and finite difference simulations were below 2%. However, for walls with concrete and steel framing, errors of the one-dimensional approximations were about 27 and 44%, respectively. In the same study it was concluded that the effects of thermal bridges are intensified by a high ratio between the thermal conductivities of the framing and insulation materials. A typical timber framed wall has a ratio of 3:1 while steel framed walls have a ratio of about 1000:1.(Kośny and Kossecka)

For most wall constructions, the part of the wall that is traditionally analysed is the flat part of the wall, uninterrupted by details comprises only 50-80% of the total area of the wall. The remaining 20-50% is not analysed nor are the effects incorporated in the overall thermal performance of the building envelope. These details can affect the overall wall *R*-values by 20-30% depending on the materials.(Kośny and Desjarlais) When determining these values for compliance to the current Building Code, they could overestimate the thermal resistance and could also have consequences when determining the heating and cooling systems for a building.

Increasing insulation levels in wall construction leads to the thermal bridges becoming an important factor in terms of heat losses. This can lead to potential health risks due to reduced indoor air quality. With regards to evaluating heat losses through thermal bridging NZS 4214 provides a simple method of calculating the thermal resistance of building elements. The study by Déqué, Ollivier and Roux suggested that standard calculations are insufficient to analyse innovative construction and insulation techniques, instead recommending more complicated simulation tools. The other side of this issue is provided by Kośny and Kossecka's research in which they conclude that for timber framed walls the difference between the two methods was below 2%.

Method

It was found in the previous chapter, that increases in insulation also increase the role of thermal bridges in terms of overall heat loss through the building envelope. The difference between simplified one-dimensional models of heat transfer and more complicated two- and three-dimensional models for timber construction was less than 2%. This chapter outlines the method used in order to achieve the aim of investigating the relationship between thermal bridging and the overall thermal resistance of external wall construction.

The hypothesis of this research is that using energy efficient details in external wall construction will reduce the amount of thermal bridging and increase the overall *R*-value.

The first step in proving this hypothesis was to design a standard wall construction designed to NZS 3604 as the baseline measure. To reduce the amount of thermal bridging, three alternative wall constructions utilising energy efficient details were designed.

NZS 4214 provides a method for determining total thermal resistance of building components including the thermal bridge resistance.

Thermal bridge resistance

a) Select two planes parallel to the plane of the wall, which enclose the portion of structure within which thermal bridging occurs;
b) Subdivide this portion into regions so that each has only one set of stacked "layers" within the region. Number these regions;
c) Where metal framing is used, thermal bridging shall be of an "enclosing equivalent solid rectangle";
d) For each of these regions, calculate the area fraction (f_x) and the thermal resistance which would apply if that region existed alone;
e) Calculate the thermal resistance of the selected portion, using the two equations below;

f) Add the resistances of any layers outside the selected portion, to give the total thermal resistance.

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} + \frac{f_3}{R_3} + \dots$$

and then:

$$R_b = \frac{1}{\left[\frac{1}{R_b}\right]}$$

Where

f_x	is the fraction of the cross-section at right angles to the direction of heat flow occupied by each region, and where x = 1, 2, 3 etc.
R_x	is the thermal resistance through the region corresponding to f_x
R_b	is the thermal resistance through the bridged portion of the structure.

From this the *total thermal resistance* is calculated using the formula:

$$R_T = R_{si} + R_1 + R_2 + \dots + R_n + R_{se}$$

Where

R_T	is the total resistance
R_{si}	is the internal surface resistance
R_1, R_2, ...R_n	are the thermal resistances of each layer, including bridged layers
R_{se}	is the external surface resistance

With only a 2% difference between using a simplified one-dimensional model of heat transfer and more complicated (closer to reality) models when looking at timber framed walls, using the NZS 4214 method saves time while remaining accurate to generate reliable results.

To analyse the effect that thermal bridging has on the total thermal resistance in energy efficient wall details the details were compared to the standard wall. The *thermal bridge resistance* and *total thermal resistance* of the alternative construction details were compared to see how different wall construction details affect the amount of thermal bridging.

Walls

NZS 3604 8.1.1 states that the wall system consist of a system to resist vertical and horizontal loads and loads from any other walls. Bracing design involves the determination of wind and earthquake forces, called the bracing demand, the wall bracing system must be designed to provide bracing capacity that exceeds the bracing demand.

NZS 3604 8.5.4 states that all studs must be supported by either: exterior wall claddings fixed to the studs by directing nailing provided that building paper separates the cladding material from the stud; or dwangs, wailings, or metal angle wailings. Using a compliant exterior wall cladding or interior lining can eliminate dwangs, wailings or metal angles for lateral support.

Table 8.2 provides the stud sizes for loadbearing walls. Stud sizes and spacing depends on a number of factors including but not limited to the stud height and wind zone. In an amendment to NZS 3604, all timber sizes were changed from call (nominal) sizes to actual minimum dried sizes. when? relevance in this?

The following details will show the structural composition of each of the wall constructions breaking down the layers of the wall that will be used in the thermal resistance calculations. The construction drawings are drawn to scale 1:10 a (except sheets). A short paragraph explaining the rationale for each construction detail will be given, along with comments on the calculations.

The table, below, presents the thermal conductivity, *k*, of each of the materials in the different wall details as provided by table E1 in NZS 4214. These values were used in the calculations of the *material thermal resistance*, R_m, of each material in the wall constructions.

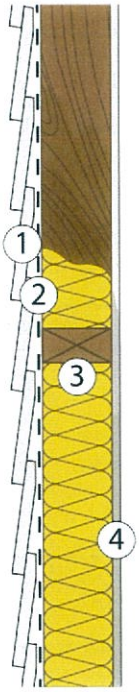
Material	Conductivity [W/mK]
Fibre-cement weatherboards	0.25
Building paper	0.14
Insulation	0.04
Rigid Insulation	0.03
Timber - softwood	0.12
GIB lining	0.22

To calculate the *material thermal resistance*, the following formula is used:

$$R_m = \frac{l}{k}$$ ← thickness!!

Standard construction detail

The wall was designed to achieve the *better practice* standard of insulation, *R* 2.1. The wall has been broken up into vertical layers as per the instructions given by NZS 4214. Two dwangs at 800 mm centres was used as the standard construction, four dwangs at 600 mm centres is also another option. Fibre-cement weatherboards were used as the cladding material however can easily be substituted for another material.



	[mm]	Standard construction from outside to inside
1	7.5	Fibre-cement weatherboards
2	< 3	Building paper
3	90	Glass wool insulation bet. vertical studs*
4	10	GIB lining

*90 x 45 mm timber studs with two 90 x 45 mm dwangs at 800 mm centres and 45 x 90 mm top and bottom plates

For more information on the calculation of the thermal resistance for the standard construction, refer to appendix 1.1.

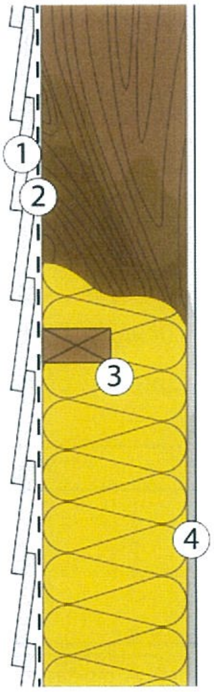
Alternative construction details

Deeper studs

The stud depth for this construction was two call ? sizes above the standard construction. The construction uses only one dwang at 1,200 mm centre and is not the same depth as the stud. This creates an almost continuous layer of insulation separating the interior.

what holds the linings in place?

Due to the dwang not being continuous through the stud depth, to calculate the *thermal bridging resistance*, layer 3 was split into two vertical layers. For more information on the calculation process, refer to appendix 1.2.

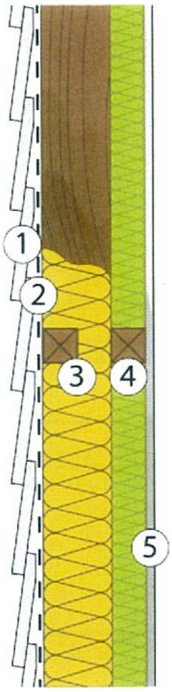


	[mm]	Alternative construction from outside to inside
1	7.5	Fibre-cement weatherboards
2	< 3	Building paper
3	190	Glass wool insulation bet. vertical studs*
4	10	GIB lining

*190 x 45 mm timber studs with a single 90 x 45 mm dwang at 1,200 mm centre and 45 x190 mm top and bottom plates

Timber battens

This detail almost completely removes thermal bridging through the timber stud framing by creating a wall of insulation between the interior and the frame. The only thermal bridges will be through the top and bottom plates and the small junctions where the battens and studs meet. The horizontal timber battens in layer 4 are to provide a fixing for the GIB lining.



	[mm]	Alternative construction from outside to inside
1	7.5	Fibre-cement weatherboards
2	< 3	Building paper
3	90	Glass wool insulation bet. vertical studs*
4	45	Rigid insulation bet. horizontal battens**
5	10	GIB lining

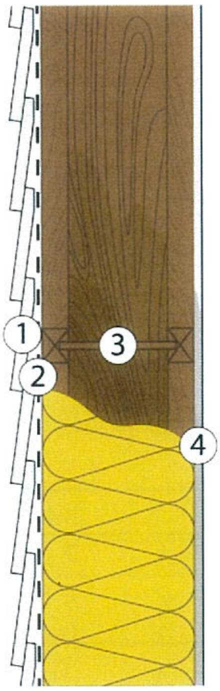
*90 x 45 mm timber studs with a single 45 x 45 mm dwang at 1,200 mm centre and 45 x 140 mm top and bottom plates
**45 x 45 mm battens at 1,200 mm centres

The calculation of the thermal bridging and total thermal resistance for the timber battens can be found in appendix 1.3.

Timber i-beams

This wall construction utilises the thin plywood web of a timber i-beam in order to reduce the thermal bridging and allow for a greater area of insulation. i-beams also have a large depth to increase the space for insulation. The top and bottom plates are still rectangular due to structural requirements.

Layer 3 was split into three vertical layers in order to calculate the *thermal bridging resistance*. For more information on the calculation process of the timber i-beam, refer to appendix 1.4.



	[mm]	Alternative construction from outside to inside
1	7.5	Fibre-cement weatherboards
2	< 3	Building paper
3	200	Glass wool insulation bet. vertical i-beams*
4	10	GIB lining

* A single 200 x 35 mm i-beam dwang at 1,200 mm centre and 45 x 200 mm top and bottom plates

Results

The research set out to investigate the relationship between thermal bridging and the overall thermal resistance of external wall construction with the hypothesis that using energy efficient details in external wall construction will reduce the amount of thermal bridging and increase the overall *R*-value.

The calculated results of the *thermal bridge* and *total thermal resistances* for each of the wall constructions are presented in table 2 below.

	Unit	Standard	Deeper studs	Timber battens	Timber i-beams
Total thickness	[mm]	108	208	153	218
Thermal bridge resistance	[W/m²C°]	1.92	4.26	3.28	4.58
Total thermal resistance	[W/m²C°]	2.18	4.52	3.54	4.84

Table 2: Calculated thermal resistances of the wall constructions

From the results above it is clear that the energy efficient wall details perform significantly better than a standard wall construction. With each of the three alternative thermal resistances over 1.5 times the standard, the hypothesis has been accepted.

Not true: you know that making a wall thicker will improve R values so your baseline has to be the deeper studs option not the 108mm wall

When calculating the *thermal bridging resistances* of the four wall constructions it was clear that increasing the depth of the wall made a significant difference in the thermal performance of each of the resized elements. Therefore the *material thermal resistance* of these elements was increased at the same time as reducing the amount of thermal bridging.

There is conclusive evidence that reducing the area of framing vs. insulation, improves the *thermal bridging resistance*. Below is an example of the calculation of the *thermal bridging resistance* from the timber batten wall. With no stud present in this layer, f_2, or the area of framing is reduced which in turn increases the *R*-value of the thermal bridge.

3 R_1 – 45 mm rigid insulation $= 1.5$

R_2 – 45 mm timber framing $= 0.375$

$$f_1 = \frac{(600) \times (2400 - (3 \times 45))}{600 \times 2400} = 0.94$$

$$f_2 = 1 - 0.94 = 0.06$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.94}{1.5} + \frac{0.06}{0.375} = 0.79$$

$$\therefore R_b = \frac{1}{0.79} \qquad = 1.27$$

This could potentially be compared to one of the other layers in the timber batten wall, however, because the layer has a different type of insulation, this would also affect the *R*-value.

A question is, is using the calculation method from NZS 4214 accurate to reality. Due to time restrictions this was unable to be tested, however could potentially be done in the future.

Conclusions & further research

The experiment was successful in investigating the relationship between thermal bridging and the overall thermal resistance of external wall construction. The results showed that when using a simple one-dimensional heat transfer model the thickness and area of the insulation and framing play an important role. The energy efficient wall details performed significantly better than the standard wall construction.

A limitation with the results was found in that changing the thicknesses of each of the walls affected the overall thermal resistance in conjunction with the reduction in thermal bridging. The calculation method used provided a simple framework for the changes to be made, and more energy efficient details could be tested using the methods used in this research. Comparing fixed width wall details would solve this issue and would give a clear picture of the relationship between thermal bridges and the overall *R*-value of the wall. The method used in this research paper could be modified to use only the relevant parts of the equations, looking at just the *thermal bridging resistance* calculation.

The accuracy of the values calculated from this method is also something that could be looked in to. Comparing the values from the simple calculations to the more complex two- and three-dimensional heat transfer models would confirm whether the standard calculation used is reliable in determining accurate *R*-values.

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Appendices

Appendix 1: Thermal bridging and total thermal resistance calculations

1.1 Standard Construction

R

$[\mathrm{m^2 °C/W}]$

R_{se} (exterior surface) = 0.03

Layer 1 (cladding) = 0.10

Layer 2 (building paper) = 0.001

Layer 3, R_b (insulated frame space)

R_1 – 90 mm R 2.6 insulation = 2.6

R_2 – 90 mm deep timber framing, $k = 0.12$ W/mK $= \frac{l}{k} = \frac{0.09}{0.12}$ = 0.75

Assuming that the wall is 2.4 m high:

$$f_1 = \frac{(600 - 45) \times (2400 - (4 \times 45))}{600 \times 2400} = 0.856$$

$$f_2 = 1 - 0.856 = 0.144$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.856}{2.6} + \frac{0.144}{0.75} = 0.521$$

$$\therefore R_b = \frac{1}{0.521} = 1.92$$

Layer 4 (lining) = 0.04

R_{si} (interior surface) = 0.09

Total thermal resistance, R_T = 2.18 m²°C/W

1.2 Alternative construction: Deeper studs

R

$[\mathrm{m}^{2\circ}\mathrm{C/W}]$

R_{se} (exterior surface) $= 0.03$

Layer 1 (cladding) $= 0.10$

Layer 2 (building paper) $= 0.001$

Layer 3, R_b (insulated frame space)

1 R_1 – 90 mm R 2.6 insulation $= 2.6$

R_2 – 90 mm timber framing $= 0.75$

$$f_1 = \frac{(600 - 45) \times (2400 - (3 \times 45))}{600 \times 2400} = 0.873$$

$$f_2 = 1 - 0.873 = 0.127$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.873}{2.6} + \frac{0.127}{0.75} = 0.51$$

$$\therefore R_b = \frac{1}{0.51} = 1.98$$

2 R_1 – 100 mm R 2.6 insulation $= 2.9$

R_2 – 100 mm timber framing $= 0.83$

$$f_1 = \frac{(600 - 45) \times (2400 - (2 \times 45))}{600 \times 2400} = 0.89$$

$$f_2 = 1 - 0.89 = 0.11$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.89}{2.9} + \frac{0.11}{0.83} = 0.44$$

$$\therefore R_b = \frac{1}{0.44} \qquad = 2.28$$

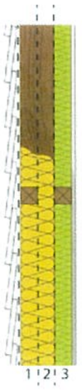
R_b total = 4.26

Layer 4 (lining) = 0.04

R_{si} (interior surface) = 0.09

Total thermal resistance, R_T = 4.52 $\mathrm{m^2{}^\circ C/W}$

1.3 Alternative construction: Timber Battens



R

$[m^{2\circ}C/W]$

R_{se} (exterior surface) $= 0.03$

Layer 1 (cladding) $= 0.10$

Layer 2 (building paper) $= 0.001$

Layer 3, R_b (insulated frame space)

1 R_1 – 45 mm R 2.6 insulation $= 1.3$

R_2 – 45 mm timber framing $= 0.375$

$$f_1 = \frac{(600 - 45) \times (2400 - (3 \times 45))}{600 \times 2400} = 0.873$$

$$f_2 = 1 - 0.873 = 0.127$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.873}{1.3} + \frac{0.127}{0.375} = 1.01$$

$$\therefore R_b = \frac{1}{1.01} = 0.99$$

2 R_1 – 45 mm R 2.6 insulation $= 1.3$

R_2 – 45 mm timber framing $= 0.375$

$$f_1 = \frac{(600 - 45) \times (2400 - (2 \times 45))}{600 \times 2400} = 0.89$$

$$f_2 = 1 - 0.89 = 0.11$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.89}{1.3} + \frac{0.11}{0.375} = 0.978$$

$\therefore R_b = \dfrac{1}{0.978}$ = 1.02

3 R_1 – 45 mm rigid insulation = 1.5

R_2 – 45 mm timber framing = 0.375

$f_1 = \dfrac{(600) \times (2400 - (3 \times 45))}{600 \times 2400}$ = 0.94

$f_2 = 1 - 0.94$ = 0.06

$\dfrac{1}{R_b} = \dfrac{f_1}{R_1} + \dfrac{f_2}{R_2} = \dfrac{0.94}{1.5} + \dfrac{0.06}{0.375}$ = 0.79

$\therefore R_b = \dfrac{1}{0.79}$ = 1.27

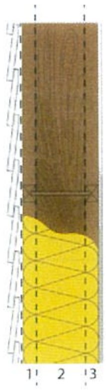
R_b total = 3.28

Layer 4 (lining) = 0.04

R_{si} (interior surface) = 0.09

Total thermal resistance, R_T = 3.54 m^{2}°C/W

1.4 Alternative construction: Timber i-beams



		R $[m^{2\circ}C/W]$
R_{se}	(exterior surface)	= 0.03
Layer 1	(cladding)	= 0.10
Layer 2	(building paper)	= 0.001
Layer 3, R_b	(insulated frame space)	

1 R_1 – 35 mm R 2.6 insulation = 1.0

R_2 – 35 mm timber framing = 0.292

$$f_1 = \frac{(600 - 35) \times (2400 - (3 \times 35))}{600 \times 2400} = 0.9$$

$$f_2 = 1 - 0.9 = 0.1$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.9}{1.0} + \frac{0.1}{0.292} = 1.24$$

$$\therefore R_b = \frac{1}{1.01} = 0.8$$

2 R_1 – 130 mm R 2.6 insulation = 3.71

R_2 – 130 mm timber framing = 1.08

$$f_1 = \frac{(600 - 35) \times (2400 - ((2 \times 45) + 10)}{600 \times 2400} = 0.9$$

$$f_2 = 1 - 0.9 = 0.1$$

$$\frac{1}{R_b} = \frac{f_1}{R_1} + \frac{f_2}{R_2} = \frac{0.9}{3.7} + \frac{0.1}{1.08} = 0.34$$

$\therefore R_b = \dfrac{1}{0.34}$ = 2.98

3 R_1 – 35 mm R 2.6 insulation = 1.0

R_2 – 35 mm timber framing = 0.292

$f_1 = \dfrac{(600 - 35) \times (2400 - (3 \times 35))}{600 \times 2400}$ = 0.9

$f_2 = 1 - 0.9$ = 0.1

$\dfrac{1}{R_b} = \dfrac{f_1}{R_1} + \dfrac{f_2}{R_2} = \dfrac{0.9}{1.0} + \dfrac{0.1}{0.292}$ = 1.24

$\therefore R_b = \dfrac{1}{1.01}$ = 0.8

R_b total = 4.58

Layer 4 (lining) = 0.04

R_{si} (interior surface) = 0.09

Total thermal resistance, R_T = 4.84 m²°C/W