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Thermal Bridging:
An Investigation of the Heat Loss Effects of Thermal Bridges common in Irish Construction Practice

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I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed Bernard Cash

Date January 1997

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List of Frequently Used Symbols and Abbreviations

A	Area
λ	Thermal Conductivity
Δx	Horizontal Spacing between Nodes
Δx	Vertical Spacing between Nodes
R	Thermal Resistance
L	Length
q	Heat Flow
T_1	Temperature at Point 1
T_2	Temperature at Point 2
t_{eo}	Outside Environmental Temperature
t_{ei}	Inside Environmental Temperature
U	U-value

BRE	Building Research Establishment
CEN	Comite Europeen de Normalisation
CIBSE	Chartered Institute of Building Services Engineers
dpc	damp proof course
dpm	damp proof membrane
ERU	Environmental Research Unit
TGD	Technical Guidance Document

Abstract

This thesis sets out to describe the effects of thermal bridges in Irish construction practice Thermal bridges are particular points where heat loss is accentuated relative to other parts of a building such as floors, walls and ceilings Thermal bridges are currently not regulated by the 1991 Building Regulations and their Technical Guidance Document, Part L, they are also an increasingly important part of energy consumption in buildings and therefore are important environmentally

There are two very common buildings found in Irish construction the bungalow and the semi-detached house Each building has approximately 10-15 thermal bridges These bridges are identified in Chapter 2

In Chapter 3, the Irish and other European Building Regulations are discussed with regard to thermal bridging

In Chapter 4, the methods of analysis of thermal bridges are discussed The European standards governing these methods are also discussed

In Chapters 5 and 6, the theory of the finite element and finite difference methods are summarised These two methods are the methods typically used in commercial thermal analysis software

In Chapter 7, the validity of the analysis of the thermal bridges and of the assumptions used in their analysis is discussed

In Chapter 8, a full analysis using several methods is performed on a thermal bridge Analyses for two thermal bridges, from a bungalow and a semi-detached house, performed using a finite element program are summarised

In Chapters 9 and 10, the results obtained by the finite element analysis of the thermal bridges identified in Chapter 2 are summarised and discussed (Appendix A contains the detailed results of all the thermal bridging simulations)

The thermal bridges listed were simulated using the ANSYS finite element program to determine their thermal effect As a percentage of total fabric heat loss, the heat loss due to thermal bridging aggregates to 25% in the bungalow and 22% in the semi-detached house The effect of thermal bridges is significant and should be taken into account in thermal calculations

Chapter 1: Introduction

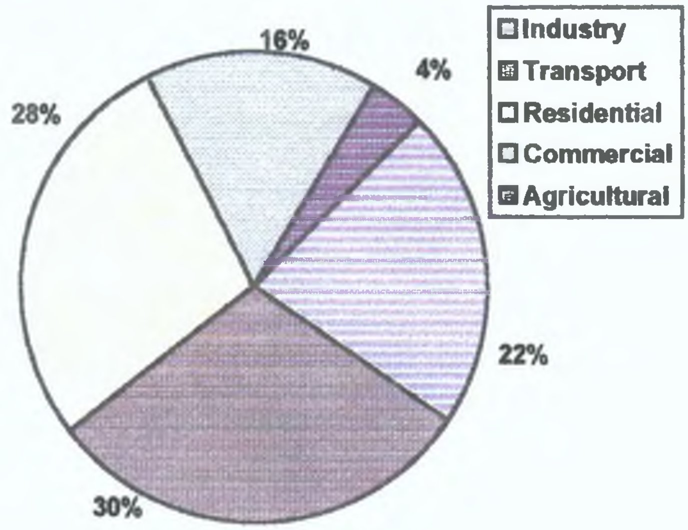
The importance of the environment and environmental issues such as global warming is ever increasing In housing and construction, this results in increasing levels of insulation to reduce the heating needed to maintain comfortable conditions and heat loss through the fabric of the building In any construction there are points of low thermal resistance These points are generally known as thermal bridges For examples, see Appendix A

The main objective of this project was to evaluate the effect of heat loss due to thermal bridging in buildings In order to evaluate this, all the bridges in several representative buildings were examined The most significant thermal bridges were selected and their effect on the representative buildings was calculated The total energy needs of the representative buildings with and without the effects of thermal bridging were also calculated The difference is the heat loss due to thermal bridging and can be referred to as the thermal bridging effect

The number of different thermal bridges and their variations which can exist in buildings is very numerous and it is therefore necessary to limit this study Buildings which are important m terms of annual energy use such as domestic housing and which can be representative of the effect of thermal bridging are selected This study is limited to housing, one of the major sectors for annual energy use in Ireland

The total final energy consumption in Ireland for 1993 was 7417[1] thousand of tonnes of oil equivalent As can be seen in the breakdown by sector in Figure 1 1 overleaf, residential and commercial sectors consume 44% of total final consumption and a very high percentage of this energy consumption is due to environmental heating of buildings[2] The residential sector consumes the highest amount of energy after transport and is the most important in terms of energy consumption within buildings In Energy In Ireland 1989-1993, A Statistical Bulletin[1], there is a direct correlation[3] between the increasing standard of living and increases in annual energy consumption. Consequently, Ireland's high economic growth rate as illustrated by an increase in Gross National Product (GDP) of 10.1% in 1995 and expected increase of 7% in 1996[4], and an overall increasing economic well being as the year 2000 approaches, will lead to higher levels of energy consumption. In this context, accurate methods of calculation for deriving the energy requirements of buildings and poor thermal performance due to any aspect of a building such as thermal bridging will become increasingly important.

Figure 1.1: Total Final Energy Consumption by Sector, 1993



Source: Department of Transport, Energy & Communications. *Energy In Ireland 1980-1993 A Statistical Bulletin*. Dublin, Department of Transport, Energy & Communications, 1993, p.15.

Effects of thermal bridges other than reducing the thermal performance of buildings such as condensation, and mould growth, will also be investigated.

References

1 Department of Transport, Energy & Communications *Energy In Ireland 1980-1993 A Statistical Bulletin* Dublin, Department of Transport, Energy & Communications, 1993, p 16

2 Dunster JE *Energy use in the housing stock* Garston, BRE, 1994

3 Department of Transport, Energy & Communications, p 9

4 Department of Finance *Economic Review and Outlook* Dublin, The Stationary Office, 1996, p 6

Chapter 2: Thermal Bridging in Irish Housing

Summary

This chapters defines thermal bridges and considers their importance Two representative buildings found within Irish construction practice are presented, the thermal bridges within these buildings are identified and the evaluation of their significance is discussed

2 1 What is Thermal Bridging?

Points of low thermal resistance can occur in buildings because of

Geometry	e g A corner
Structural requirements	e g Lintels, foundation, party wall, wall ties etc
Building practice	e g No edge insulation in ground floor

These points are generally known as thermal bridges and they are defined as follows

- Thermal bridges are paths for heat flow which are relatively uninsulated with respect to the rest of the *building structure and therefore are* **points of low thermal resistance in a building between interior and exterior**
- Thermal bridges occur in general at any junction between building components or where the building structure changes composition[1]

2 1 1 Importance of Thermal Bridges

The Technical Guidance Document (TGD) of the 1991 Building Regulations, Part L[2] does not deal to any great extent with thermal bridging

Thermal bridges result in increased heat loss in a building At present, thermal bridges are beginning to be recognised as a source of heat loss and it is considered good building practice in the TGD of the Building Regulations, Part L that thermal bridges should be prevented as shown in Thermal Insulation avoiding risks[3] In practice, they are sometimes only considered significant when they have a visible effect on a building such as condensation or mould growth This occurs with certain thermal bridges because they will have the lowest surface temperature in a room Water vapour will condense at the coldest point in a room under certain environmental conditions especially if there is limited ventilation Depending on the type of material on which condensation occurs, condensation can result in mould growth In low cost housing in particular, thermal bridging can have significant environmental health implications The importance of thermal bridges increases dramatically as the levels of insulation increase This occurs, because with increased levels of insulation, heat loss through opaque parts of buildings is reduced In such a case, thermal bridges which still remain in the building will represent a higher proportion of total heat loss than before

2.2 The Standard Reference House in Ireland: Representative Houses for Analysis

The bungalow and the semi-detached house were selected as representative houses for construction practice in Ireland These two houses were selected after analysing statistics collected in the Private Housebuilding surveys^4 carried out by the Environmental Research Unit (ERU) The above information can be the basis for several different 'reference houses' The two representative houses selected have the most common attributes found in these statistics The surveys of the Environmental Research Unit have been carried out since 1978 in fifteen counties around Ireland The surveys were split into two categories ‘Single housing’ and ‘Estate housing’ The ‘Single housing’ category is used to describe single unit one-off developments and ‘Estate housing’ is used to describe houses which have been built as part of a development of many houses Each survey is particular to each housing category and therefore the surveys do not cover exactly the same housing characteristics

For both individually built houses and for estate housing there are several houses which have different predominant aspects The two houses selected are considered to be the most representative of modern construction practice in Ireland It would be impossible to simulate each permutation of 'Single' and 'Estate' housing Therefore in selecting the reference houses, houses which fit the general characteristics of single and estate housing were selected The most important characteristic in selecting representative houses with a view to investigating the effects of thermal bridging is the type of insulation system used This determines the type of thermal bridges present in a building The two representative houses use the two most common insulation systems in use in Ireland[5], insulation within a cavity construction and internal insulation backed with plasterboard The two houses represent 60% of newly constructed housing constructed each year in terms of general characteristics and over 90% in terms of insulation system used as found in the ERU surveys[4], and their general specifications are listed overleaf

2.2.1 Selected 'Reference Houses'

<u>House 1 Single Housing 'Reference House': Bungalow</u>

Average Floor Area	142 m^2
Number of Bedrooms	4 bedroom
Number of Storeys	1 Storey
Ground Floor Construction	Concrete
Roof Construction	Framed
Roof Covering	Slates
External Wall Fabric	Cavity
Extent of Brickwork Facing	None
Window Type	PVC
Glazing Type	Double
Number of Fireplaces	1

<u>House 2 Estate Housing 'Reference House': Semi-Detached House</u>

Average Floor Area	102 m^2
Number of Bedrooms	3 Bedroom
Number of Storeys	2 Storey

Ground Floor Construction	Concrete
First Floor Construction	Timber Tongued & Grooved
Roof Construction	Trussed
Roof Covering	Tiles
External Wall Fabric	Hollow Block
Extent of Brickwork Facing	Front or Lower Upper Front
Window Type	PVC
Glazing Type	Double
Number of Fireplaces	1
Roof Insulation Material	Mineral Fibre Rolls
Floor Insulation Material	Polystyrene/ Polyurethane
Wall Insulation Method	Internal

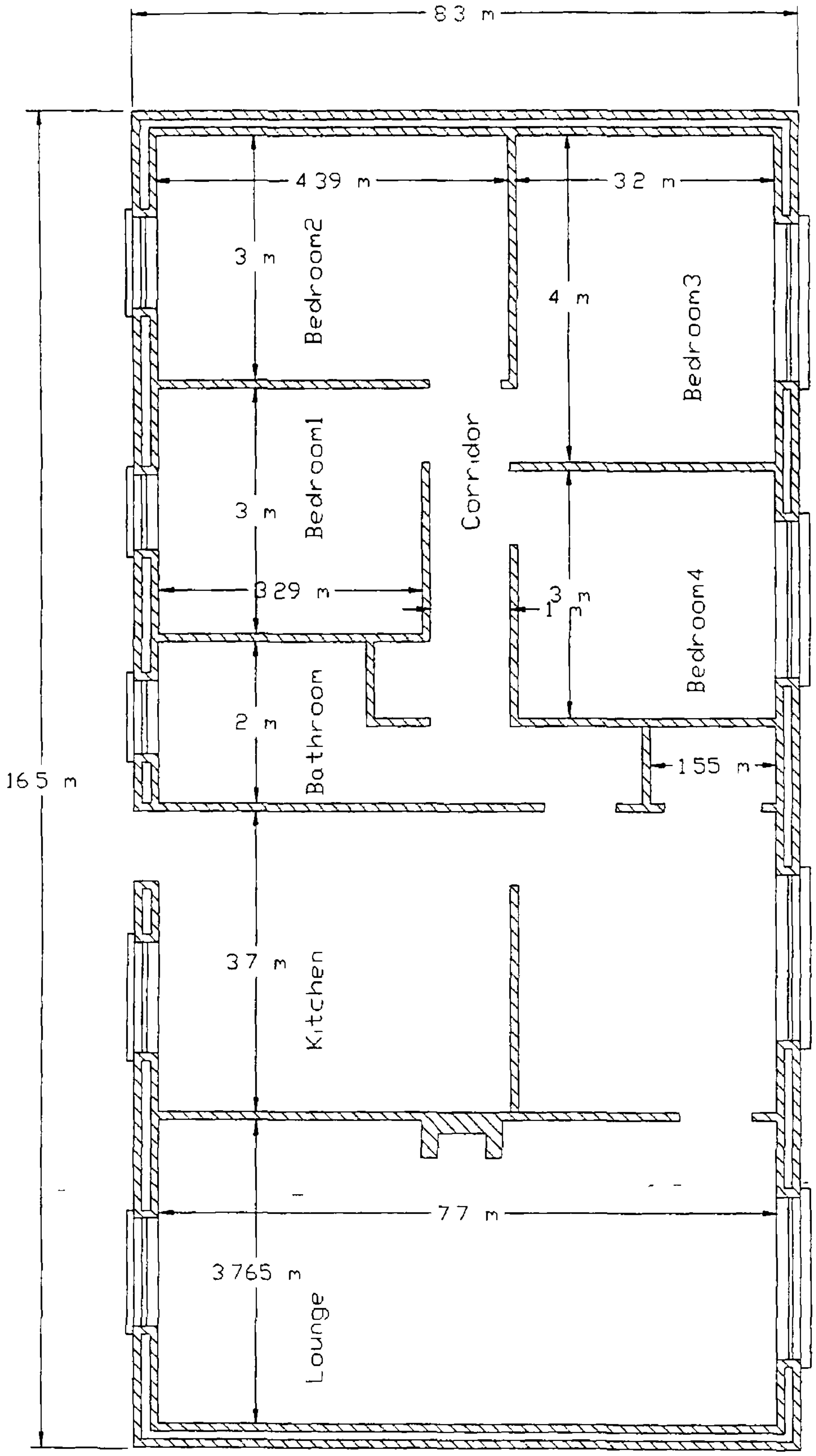


Figure 2 2 1· Bungalow Floor Plan

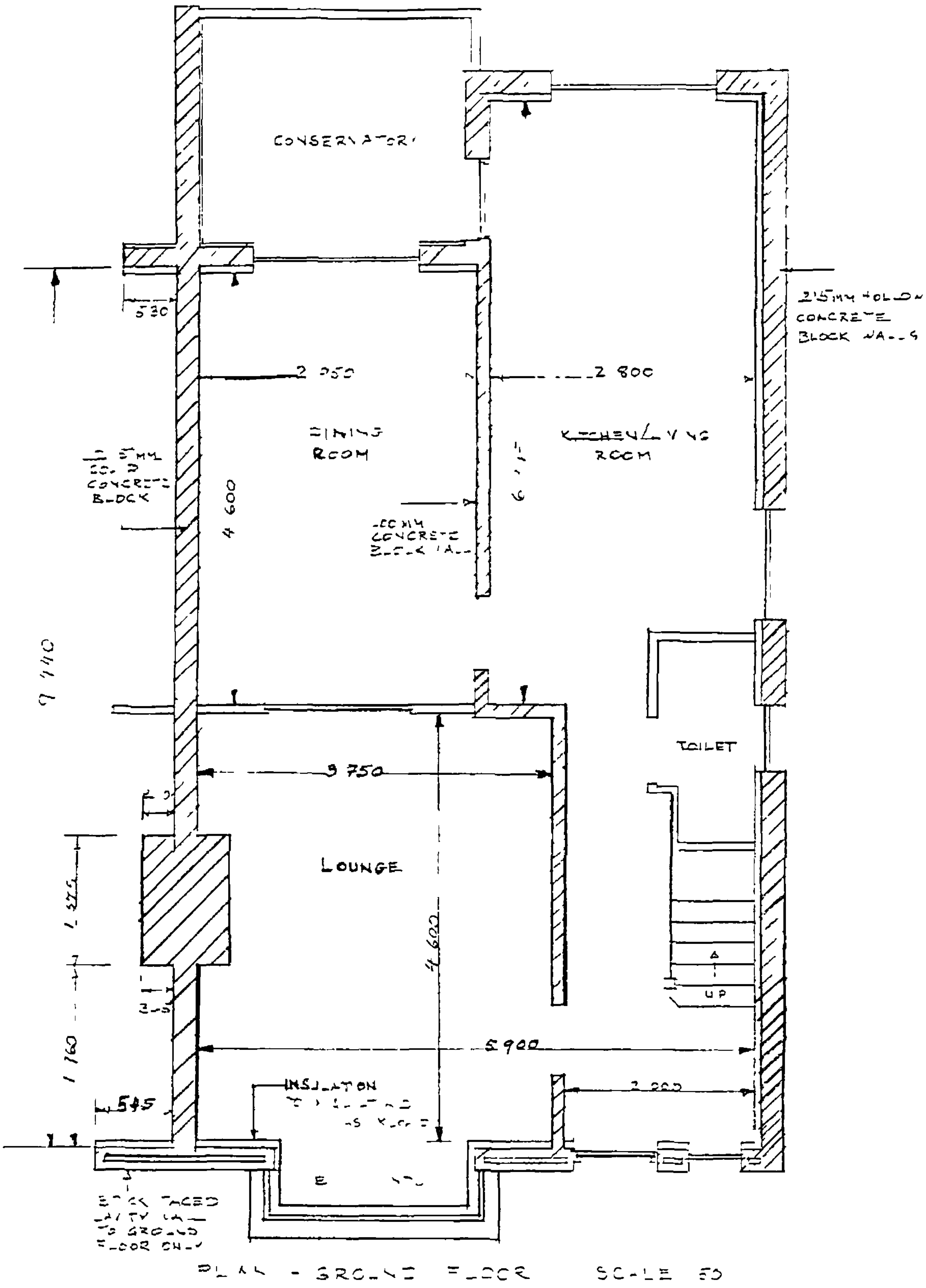


Figure 2 2 2: Semi-Detached House Ground Floor Plan

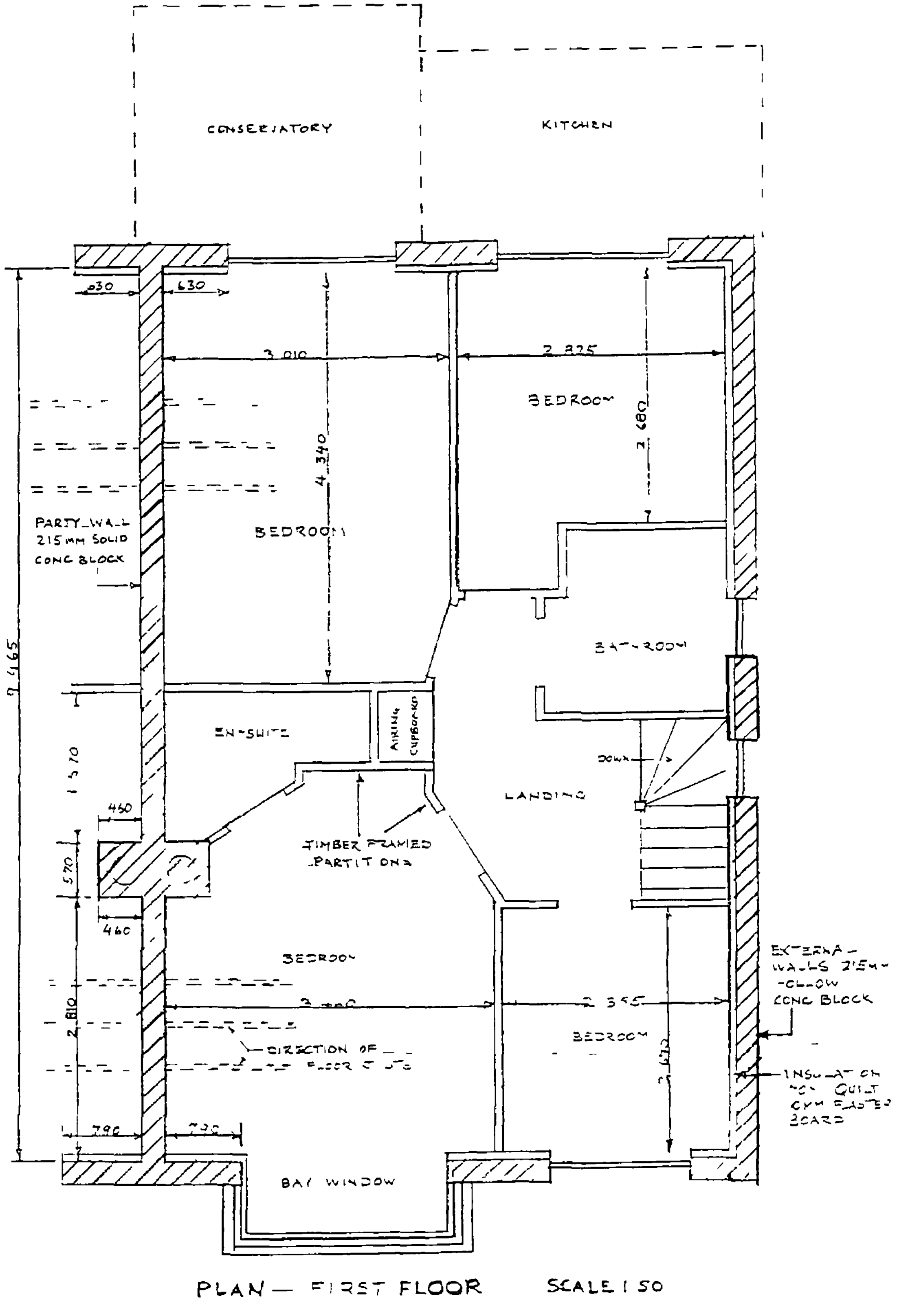


Figure 2.2.3. Semi-Detached House First Floor Plan

2 3 Thermal Bridges Commonly Present in these Houses

Each house has up to 20 thermal bridges in its construction The principal thermal bridges found in these two houses are as follows

2.3 1 Bungalow

1 Foundation, cavity wall and floor
2 Foundation, partition wall and floor
3 Window sill
4 Window jamb
5 Window lintel
6 Cavity closer at eaves level
7 Wall corner
8 Partition wall and external wall
9 Wall tie
10 Uninsulated joists above ceiling
11 Gable end wall

2.3 2 Semi-Detached House

1 Foundation, external wall and floor
2 Foundation, partition wall and floor
3 Partition wall and external wall
4 Stud partition and external wall
5 Window sill
6 Window jamb
7 Window lintel
8 Wall corner
9 Party wall to foundation
10 Party wall to attic
11 Party wall and external wall
12 Uninsulated external wall at first floor level

13 Uninsulated joists above ceiling

14 Battens

Note. Two additional bridges that could be significant in both houses are the chimney and fireplace (see Appendix E)

2 4 Evaluating the Significance of Thermal Bridges Present in the Reference Houses

To evaluate thermal bridges and their effect, a detailed analysis must be made of each In many cases the lack of insulation in a bridged area gives an obvious clue to the importance of the bridge Each thermal bridge is analysed to find out what heat loss does it incur in the building Many of these bridges may result in considerable heat loss in small sections of the building but those which are most important are the bridges which extend along the edge of the building such as the foundation, wall and floor thermal bridge Bridges such as the wall tie in the bungalow can also be very important since they are perpetuated throughout the building

The two most important factors from which to judge a thermal bridge are its bridge conductance or linear thermal transmittance and its resulting total heat loss The bridge conductance is the heat loss of the bridge per metre length

In many cases the causes of thermal bridging in housing are due to poor construction practice and poor design Poor design is an important factor particularly found in semi-detached houses Cost-cutting operations generally result in thermal bridges This is clearly the case with most thermal bridges found in the semi-detached house In cases of poor workmanship such as when mortar drops on to wall ties and when insulation is badly installed the exact effect is difficult to gauge for different houses In general, the analysis of bridges will assume correct construction practices Even when a thermal bridge is identified, in many cases it is difficult and too costly to insulate against its effect This is the case with wall corners and wall ties

Very detailed analysis encompassing the consideration of poor workmanship, turbulent air flows, moisture content in the building fabric, three dimensional effects is not practical and necessary for all thermal bridges

2 5 Conclusion

Thermal bridging is found in all buildings and its primary effect is an increased rate of heat loss for the affected building element Two representative buildings of Irish construction practice are the bungalow and the semi-detached house There are many thermal bridges present in each house which require thermal analysis The importance of a thermal bridge depends principally on its linear thermal transmittance, its recurrence through a building, and whether it causes condensation within the internal environment of a building

References

1 CEN *CEN/TC 89 N 300 E, Thermal Bridges - Simplified methods for determining Linear Thermal Transmittance and the calculation of heat loss* Brussels, CEN, 1993, p 2

2 Department of the Environment. *Building Regulations 1991 Technical Guidance Document L, Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991

3 BRE *Thermal insulation avoiding risks* London, HMSO, 1994

4 An Foras Forbartha / Environmental Research Unit *Private Housebuilding Surveys* Dublin, Department of Environment, 1974-1995

5 An Foras Forbartha *Insulation of External Walls in Housing* Dublin, An Foras Forbartha, 1987, p 7

Chapter 3. Building Regulations in Ireland and Europe

Summary

In this chapter a general summary and comparison is made with regard to thermal bridging of

- The Irish Building Regulations Part L and their Technical Guidance Document[1]
- The English/Welsh Building Regulations and their Approved Document L[2]
- Thermal bridging avoiding risks[3]
- The Danish Building Regulations[4]

3.1 The Irish Building Regulations with Regard to Thermal Bridging

The Building Regulations, 1991 Technical Guidance Document L Conservation of Fuel and Energy[1] gives the following guideline regarding thermal bridging

'When calculating U values the effects of timber joists or framing, wall ties, thin cavity closures, mortar bedding, damp-proof membranes, metal spacers and other thin components may be ignored.'

Clause 0.10

There is additionally the note

'Lintels, jambs and sills associated with window, rooflight and door openings may be counted as part of the window, rooflight and door opening area or as part of the roof, wall or floor in which the opening occurs However, in no case should the U value of,a lintel jamb or sill exceed 0.9 W/m²K'

Clause 0.13,b

The following note is given regarding design details and construction practice

'Guidance on construction practice is contained in the publications Insulation of External Walls in Housing, An Foras Forbartha, 1987 (Ref CT322) and Thermal Insulation avoiding risks, Building Research Establishment (Ref BR143)'

Clause 0.9

The following note is given regarding calculations involving thermal bridges

' in the case of a non-homogeneous or bridged material (such as a hollow concrete block for instance) by calculation in accordance with the CIBSE Guide A3 1980'

Appendix A, A2 (b)

Clauses 0 10 and 0 13,b seem to imply that no approach is taken in the TGD regarding how thermal bridges should be analysed In Clause 3, A2 (b), the TGD refers one to the methods of calculations as used in the CIBSE Guide A3 1980[5] The TGD takes into account the prevention of thermal bridging in Clause 0 9 The two publications listed in Clause 0 9 encourage awareness and better insulation of thermal bridges

In practice it appears that little account is taken of thermal bridging Perhaps, this is because there are no thermal bridging calculation examples (See Chapter 7) in the Technical Guidance Document (TGD) of the Building Regulations, or in some cases they are too difficult to analyse Calculation methods other than CIBSE Design Guide methods should also be suggested within the TGD of the Building Regulations for thermal analysis The publication 'Thermal insulation avoiding risks'[3] gives guidance on good construction practice and is referred to in the TGD The use of the insulation practices within 'Thermal insulation avoiding risks' is not compulsory, therefore, examples of good construction practice should be included in the TGD to reinforce the importance of avoiding thermal bridging

3.2 Thermal Bridging with Regard to the English/Welsh Building Regulations 1991 and their Approved Document L

In the 1995 edition of Approved Document L[2] there are several changes which are directly concerned with thermal bridging

These are the changes regarding thermal bridging

'The standards of fabric insulation have been improved by changing the method for

calculation of U-values to take account of thermal bridges such as mortar joints, timber joists and studs '

Clause 5 Guidance relevant to all buildings
Main changes in the 1995 edition

'New provisions are included for reducing thermal bridging around window and door openings '

Clause 8 Guidance relevant to all buildings
Main changes in the 1995 edition

These changes made in 1995 show that the British Department of the Environment and The Welsh Office are concerned with thermal bridging and regard it as increasingly important when considering the thermal requirements of a building

In L1 General Guidance of the Approved Document L, the following references are made with regards to thermal bridging

' *The values in the tables have been derived taking account of typical thermal bridging where appropriate '*

Clause 0 10, U-value reference tables
General Guidance

'When calculating U-values the thermal bridging effects of, for instance, timber joists, structural and other framing, normal mortar bedding and window frames should generally be taken into account using the procedure in Appendix B Thermal bridging can be disregarded, however, where the difference in thermal resistance between the bridging material and the bridged material is less than 0 1 m^2K/W *For example, normal mortar joints need not be taken into account in calculations for brickwork '*

Clause 0 11, Calculation of U-values
General Guidance

Clause 0 10 means that the Approved Document takes into account the effects of thermal bridging in its calculation tables for the insulation requirements of the building fabric Clause 0 31 specifies the use of the calculation procedure as shown in Appendix B of the Approved Document when dealing with important thermal bridges This calculation procedure is the Proportional Area method of the CIBSE Design Guide Section A3[5]

In L1 Section 1 Dwellings of Approved Document L, there exists the following references with regard to thermal bridges

'Provision should be made to limit the thermal bridging which occurs around windows, doors and other wall openings This is necessary in order to avoid excessive additional heat losses and the possibility of local condensation problems '

Clause 1 22, Thermal bridging around openings

'Lintel, jamb and sill designs similar to those shown in Diagram 3 would be satisfactory and heat losses due to thermal bridging can be ignored if they are adopted '

Clause 1 23, Thermal bridging around openings

Diagram 3 (not shown) referred to above shows ways of insulating against thermal bridges around openings

'An alternative way of demonstrating compliance would be to show by calculation that the edge details around openings will give a satisfactory performance Appendix D gives a procedure for this '

Clause 1 24, Alternative method

In L1 Section 2 - Buildings other than dwellings (Section 2 also deals with residential buildings other than dwellings i e buildings in which people temporarily or permanently reside e g institutions, hotels and boarding houses) of the Approved Document L there are the following references to thermal bridging

'Provision should be made to limit the thermal bridging which occurs around windows, doors and other openings This is necessary in order to avoid excessive additional heat losses and the possibility of local condensation problems '

Clause 2 21, Thermal bridging around openings

'Lintel, jamb and sill designs similar to those shown in Diagram 7 would be satisfactory and the heat losses due to thermal bridging can be ignored if they are adopted '

Clause 2 22, Thermal bridging around openings

Diagram 7 (not shown) is the same as Diagram 3 which was mentioned earlier

'An alternative way of demonstrating compliance would be to show by calculation that the edge details around openings will give a satisfactory performance Appendix D gives a procedure for this '

Clause 2 23, Alternative method

Section 2 of the Approved Document L is very similar to Section 1 in terms of dealing with thermal bridges

In the appendices of the Approved Document L, the following is included regarding thermal bridges Two full examples using the proportional area calculation method for determining U-values of structures containing repeating thermal bridges are given in Appendix B This method is taken from the CIBSE Design Guide Section A3[5]

Appendix C of the Approved Document L, Calculation of U-Values of Ground Floors[6] makes the following points

'Care should be taken to control the risk of condensation by thermal bridging at the floor edge See BRE Report BR 262 Thermal insulation avoiding risks '

Clause C3

For further information on floor U-values see BRE IP 3/90 BRE IP 7/93 shows how the U-value of a floor is modified by edge insulation (including low-density foundations), and BRE IP 14/94 gives procedures for basements '

Clause C10

In Appendix D of the Approved Document L, Thermal Bridging at the Edges of Openings[7] the following procedure is given regarding thermal bridges

'As an alternative to the examples given in Diagrams 4 and 9, this Appendix gives a procedure for establishing whether

a there is an unacceptable risk of condensation at the edges of openings, and/or

b the heat losses at the edges of openings are significant'

Clause D1

'The procedure involves the assessment of the minimum thermal resistance between inside and outside surfaces at the edges of openings This requires identification of minimum thermal resistance paths, and calculation of their thermal resistance, taking into account the effect of thin layers such as metal lintels '

Clause D2

'These minimum thermal resistances are then compared with satisfactory performance criteria to see whether corrective action is indicated '

Clause D3

'A heat loss factor for a particular detail could be obtained by numerical method and used to modify the calculation of the average U-value or the total rate of heat loss A calculation procedure for deriving such loss factors is given in BRE IP 12/94, Assessing condensation risk and heat loss at thermal bridges around openings '

Clause D10

The Approved Document L of the English/Welsh Building Regulations gives significant attention to thermal bridges They include several examples of calculation of U-values which include the effects of thermal bridging These examples use the proportional area method[8] and an alternative manual calculation method from the publication BRE IP 12/94 Assessing condensation risk and heat loss at thermal bridges around openings[9] The use of computer numerical methods for analysing thermal bridges and buildings is completely ignored in the Approved Document In terms of thermal bridging this is important because for many thermal bridges it is impossible to do accurate manual calculations on their effects Therefore it could be argued that thermal bridges other than openings or repeating thermal bridges are not dealt with fully in the Approved Document

Yet, it is noted at the beginning of the Approved Document that

'***There is no obligation to adopt any particular solution contained in an Approved Document if you prefer to meet the relevant requirement in some other way*** *However, should a contravention of a requirement be alleged then, if you have followed the guidance in the relevant Approved Documents, that will be evidence tending to show that you have complied with the Regulations If you have not followed the guidance, then that will be evidence tending to show that you have not complied. It will then be for you to demonstrate by other means that you have satisfied the requirement '*

Evidence supporting compliance,
Use of Guidance

Therefore, the use of computer methods in the analysis of thermal bridges is not ruled out by the Approved Document

The thermal bridging examples within the Approved Document show clearly that thermal bridging is an important consideration when calculating U-values, which is not clear in the Irish Building Regulations and their TGD The English/Welsh Building Regulations insulation requirement tables for specific U-values contained within the Approved Document L, include the effects of thermal bridging and are based on the proportional area method This is a significant difference from the equivalent tables in the Irish Building Regulations which do not include any thermal bridging effects

3.3 The BRE Publication 'Thermal insulation avoiding risks' (BR 143)

The 1995 Building Regulations Approved Document L from the British Department of the Environment and The Welsh Office makes specific reference to the document Thermal insulation avoiding risks[3]

'Risks Inherent in High Standard of Insulation

Paragraphs 0 5 to 0 8 of the Approved Document draw attention to certain risks which high standards of thermal insulation may introduce When outside temperatures are low, those parts of an element which lie on the cold side of the insulating layer will remain colder and inner surfaces will be warmer This steeper temperature gradient may result in condensation within the construction the colder water layers allow deeper rain penetration and mean slower drying times, frost attack is more likely and differential thermal movement may cause cracking The effect of 'cold bridges' may be exaggerated and result in local internal condensation

A designer must therefore anticipate the physical consequences of high insulation standards and modify his designs to counteract these technical risks The BRE *publication 'Thermal insulation avoiding risks' contains comprehensive advice about avoiding trouble,'*

This paragraph is a good example of the importance with which the British Department of Environment regards the document Thermal insulation avoiding risks

In the TGD Part L of the 1991 Irish Building Regulations the following paragraph is written

'Guidance on avoiding risks which might arise from the application of energy conservation measures will be found in the relevant standards Guidance on construction practice is contained in the publications Insulation of External Walls in Housing, An Foras Forbartha, 1987 (Ref CT322) and Thermal Insulation avoiding risks, Building Research Establishment (Ref BR143) The guidance given in these documents is not exhaustive and designers and builders may have well established details using other materials which are equally suitable Technical Guidance Document F Ventilation, includes guidance on the provision of ventilation to reduce the risk of condensation'

Clause 0 9, Design Details and Construction Practice
TGD, Part L, 1991 Building Regulations

In the introduction to the BRE guide it is pointed out that it *'represents the recommendations of BRE on good design and construction practice associated with thermal standards'* The guide deals with the risk associated with meeting the requirements of building regulations for thermal insulation The guide is split into sections which deal with the different sections of a building

3 3.1 Roofs

The guide gives the following comment concerning thermal bridging in roof spaces

'Where gaps occur in the insulation a thermal bridge is created and there is a risk of condensation A thermal bridge can occur at the junction of a roof or a ceiling with a masonry wall '

The guide suggests in order to avoid thermal bridging that where it is necessary to close the wall cavity the insulation in roof spaces should be carried out completely over the joists and top of the external wall Insulating block, mineral wool in a polythene cover or a thin board such as calcium silicate should be used as a cavity closer

In the cases of gable walls, the gap between the last ceiling joist and the gable wall should be insulated and both the loft and the wall insulation should be taken to at least 225 mm above ceiling level and an insulating block should be used for the inner leaf

The following comment is made regarding condensation at thermal bridges in roofs

'Gaps or lack of continuity in the insulation create thermal bridges allowing condensation to form on cold surfaces '

A quality control question list is included at the end of each section of the guide If the guidelines found in the guide are followed regarding roofs it is considered impossible for thermal bridges to cause any major heat loss or condensation problems

3 3.2 Walls

For masonry cavity walls the following comment is made regarding condensation risks at thermal bridges

'If the continuity of wall insulation is broken by a dense element or an uninsulated component, the internal surface temperature may fall below dew point, causing mould growth and damage to wall decorations '

Regarding thermal bridges the guidelines suggest that one should avoid recessed meter boxes and if not avoided they should adequately insulated against Chimneys at external walls should be also adequately insulated

Another possible thermal bridge is air movement behind cavity wall insulation The guide notes *'Heat loss is increased if cold air from the cavity is able to move behind partial fill insulation or through an air permeable inner leaf to the interior via holes for services or gaps around dry lining '*

For masonry walls with internal insulation the principle risk of thermal bridges and condensation is well noted in the guide· *'At junctions with separating walls and internal partitions, the continuity of internal insulation is broken, creating a potential thermal bridge '* These walls should be built *'using masonry with the lowest possible density compatible with requirements for structural stability'* Since low density masonry has generally a lower thermal conductivity, the bridge effect is thus reduced

Avoidance of thermal bridging at separating or party wall junctions should be guaranteed by the following

- insulating the corresponding uninsulated part of the junction
- using low density block at the junction

Thermal bridging at partition junctions should be avoided by the following measures

- using insulating blockwork for partitions and for the external wall
- taking the internal insulation across the external wall and constructing a timber stud partition up to it
- the use of insulating blockwork for any new masonry partitions, the partition should be tied to the external wall and finished with dry lining

Guidance is also given for walls with external insulation and timber framed construction

3 3 3 Windows

The following comment is given in relation to thermal bridges, condensation and mould *'If a dense part of the construction interrupts the continuity of the insulating layer, the internal surface temperature may fall locally below dewpoint, causing mould growth and damage to wall decorations '*

Window and door frames should have a closer or a strip of insulation with a thermal resistance of 0 25 m^{2}K/W between the inner and outer leaf walls The window frame should overlap the insulation by at least 25 mm In the case where there is blockwork cavity closer, the frame should overlap by at least 45 mm if the conductivity of the blockwork is 0 2 W/mK or less, or by the full frame width if the thermal conductivity of the block is 0 3 W/mK or less

For window jambs and beneath the window board at the sill, insulation should be applied to the cavity closer and have a resistance of at least 0 25 m^{2}K/W where

- the window frame is set forward within the outer masonry leaf
- the wall is insulated with internal insulation
-

An insulated lining should be added to the under-surface of lintels when

- the window frame is set forward within the outer masonry leaf
- the wall is insulated with internal insulation
- they are made of steel and have a continuous lower web

As much space as possible between the frame and the wall should be filled with insulation The insulated cavity closers of the sill, lintel and jambs should be in the same plane or overlap against each other

The guide discusses increased heat loss due to air movement and mould growth on window reveals due to contact with metal window frames Double glazed windows are discussed in detail in terms of condensation but not in terms of thermal bridging

3.3 4 Floors

The following comment is made on condensation at thermal bridges *'Where the continuity of the insulation is broken at junctions between the floor and external walls or load bearing internal walls, a thermal bridge occurs and there is the risk of surface condensation '*

Cavity insulation should be started below damp proof course (dpc) level and at least to the level of the ground floor slab or use insulating blockwork below dpc level

For ground supported slabs a vertical slip of insulation should be used at the perimeter of the slab in order to provide an overlap with cavity insulation where the inner leaf cavity wall insulation is not insulating the blockwork, or to link in with insulating blockwork A strip of insulation should also be included at the perimeter of the slab when using internal insulation for walls

When internal loadbearing walls make a junction with an external wall, edge or perimeter vertical insulation should be included for a distance of one metre from the external wall (insulating blockwork can also be used)

For ground floors with suspended slabs similar insulation techniques should be used

The guide discusses damage from moisture in the floor and risks associated with services in ground floors Concrete ground floors with insulation above the structure are discussed in detail Also discussed are concrete ground floors with only edge insulation and suspended timber ground floors

3.3 5 Upper Floors

The following comment is made on thermal bridging and condensation on upper floors in the guide *'When a concrete intermediate floor has an edge beam built into* *a cavity external wall, the edge beam often projects into the cavity and the continuity of cavity insulation is broken, causing a thermal bridge If the floor projects to a balcony, the insulation layer is also interrupted Similarly, edge beams supporting the external wall at exposed floors create a potential thermal bridge and the risk of condensation '*

A continuity of insulation should be ensured at first floor level

'Thermal insulation avoiding risks' is suggested as guidance on good construction practice in the English/Welsh Building Regulations and its Approved Document L and also in the Irish Building Regulations and its TGD The use of the guidance in the publication does not exclude the possibility of significant thermal bridges existing within constructions which follow this guidance The reason for this is that to avoid thermal bridges occurring, an exact knowledge of a construction's thermal behaviour must be obtained prior to building In most cases, the only practical way of having such information is by carrying out detailed thermal analysis of each construction 'Thermal insulation avoiding risks' cannot give such data but only help in avoiding thermal bridges that may occur due to poor workmanship or poor design

3 4 The Danish Building Regulations and Thermal Bridging

Part 8 of the Danish Building Regulations[10] concerns thermal insulation and has relevance to thermal bridging The following requirement is given regarding thermal bridges

'Because of the risk of condensation thermal bridging must as far as possible be avoided in external construction elements, including windows and doors The energy effect of thermal bridges must be taken into account in calculating the thermal transmittance, the U-value, for the various construction elements'

Clause 8 1(2)

The Danish Building Regulations thus make compulsory the analysis of heat loss due to thermal bridges in buildings The Danish Building Regulations set the following U values[11]

External walls with a mass of less than 100 kg/m^2	0 2 W/m^{2}K
External walls with a mass of more than 100 kg/m^2	0 3 W/m^{2}K
Ground floors	0 2 W/m^{2}K
Ceiling and roof structures	0 15 W/m^{2}K
Windows and doors	1 8 W/m^{2}K

3 5 Conclusion

The Irish Building Regulations and their TGD largely ignore thermal bridging and provide no regulation requiring their inclusion in the calculation of construction element U-values The English/Welsh Building Regulations and their TGD contain manual examples on how to account for thermal bridging and include thermal bridging effects in their U-values tables of windows, doors and rooflights and other constructional elements The Danish Building Regulations require the analysis of thermal bridges for their calculation of U-values for building elements The Irish Building Regulations and its TGD does not therefore compare well in terms of consideration of thermal bridges with other European Building Regulations discussed within this chapter

References

1 Department of Environment *Building Regulations 1991 Technical Guidance Document L Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991

2 Department of Environment and The Welsh Office *The Building Regulations 1991 Conservation of fuel and power Approved Document L* London, HMSO, 1994

3 BRE *Thermal insulation avoiding risks (BR 143)* London, HMSO, 1994

4 Danish Ministry of Housing *Building Regulations* Copenhagen, Danish Building and Housing Agency, 1995

5 CIBSE *CIBSE Guide Volume A Design Data Section A3* London, CIBSE, 1986

6 Department of Environment and The Welsh Office p 39

7 Ibid, p 41
8 CIBSE p A3-9

9 Ward TI *BRE IP 12 / 94 Assessing condensation risk and heat loss at thermal bridges around openings* Garston, BRE, 1994

10 Danish Ministry of Housing *Building Regulations* Copenhagen, Danish Building and Housing Agency, 1995, p 109

11 Ibid, p 110

Chapter 4: Methods of Thermal Analysis

Summary

In this chapter, the CIBSE Guide Volume A, Design Data Section A3[1] analysis methods for thermal bridges are summarised The CEN standards relating to thermal bridges and also computer based analysis are both discussed and summarised

4.1 CIBSE Design Guide Methods

The CIBSE (Chartered Institute of Building Services Engineers) Guide Volume A, Section A3 recognises three main types of thermal bridges and suggests methods for their analysis These are discrete bridges, multi-webbed bridges and finned element bridges It contains methods of analysis for discrete bridges and multi-webbed bridges and indicates that computer programs should be used for analysis of finned element bridges

Simple methods of dealing with thermal bridging are included in the CIBSE Guide Volume A Section A3 The methods of analysis used in CIBSE are the methods which should be used in reference to the TGD of the Building Regulations, Part L[2]

There are two methods described the Proportional Area Method and the Combined Method

4 1 1 Proportional Area Method

'Discrete bridges are contained wholly within the main structure where the size of the bridged area in relation to the rest of the structure is small, e g solid lintels and concrete beams The proportional area method of calculation can be used in these cases '

'The proportional area method assumes that heat flow is in one direction, perpendicular to the surfaces of the construction Consequently the thermal transmittance of each heat flow path can be calculated separately and then added together in direct proportion to their areas '

CIBSE Guide Section A3, Page A3-9

4.1.2 Combined Method

The Combined Method is used in the analysis of multi-webbed bridges such as slotted or hollow blocks and perforated bricks and is similar in many ways to the proportional area method

These methods of calculation are only approximate and are not designed to estimate heat loss when there exists complex heat flow patterns

CIBSE Guide Calculation using the Combined Method Cavity Block

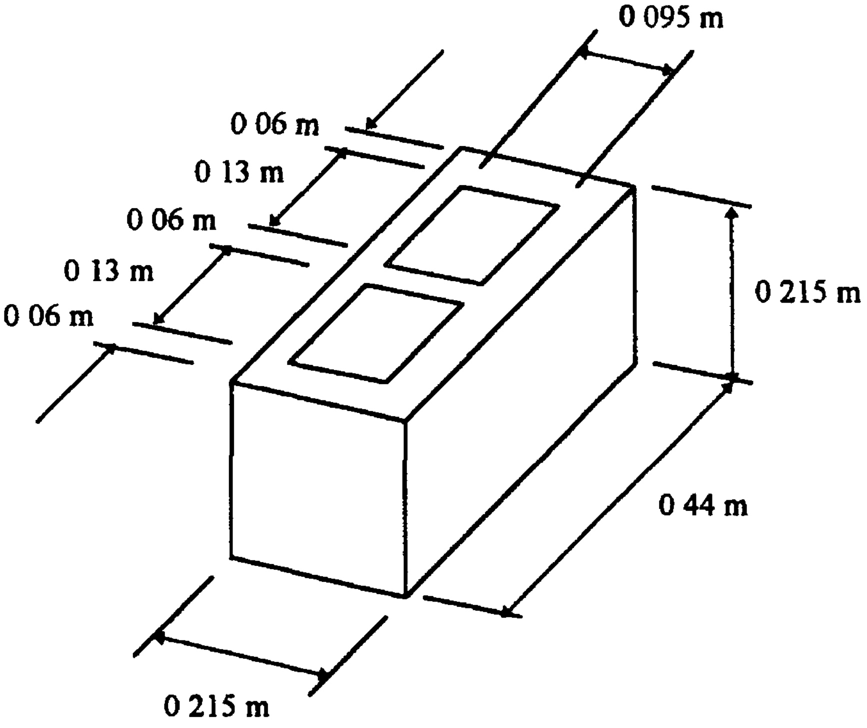


Figure 4.1.1: Hollow Block

Thermal conductivity of concrete λ

Resistance of air cavities = 0 2 m^{2}K/W (Table A3 7 CIBSE Guide Section A3)

Width of block cavity 0 13 m

Length of block cavity 0 095 m

Lower Limit The lower limit is set by assuming that the temperature is uniform and that there is no resistance to lateral heat flow

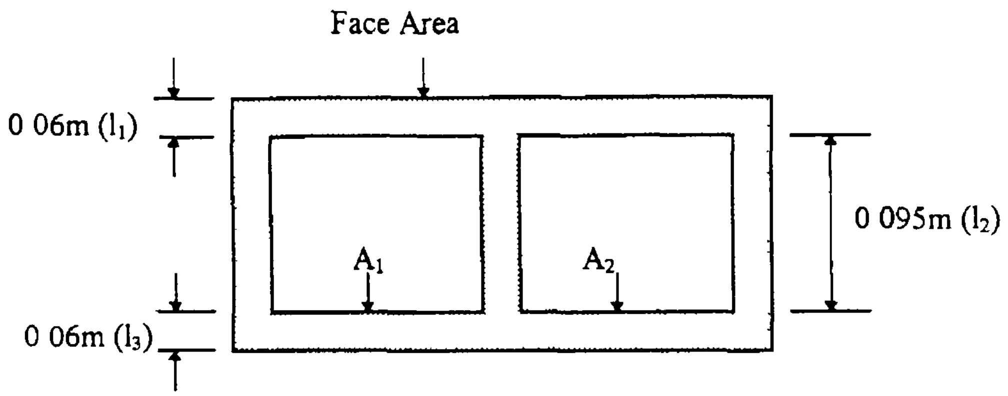


Figure 4.1.2. Cross Section of Hollow Block

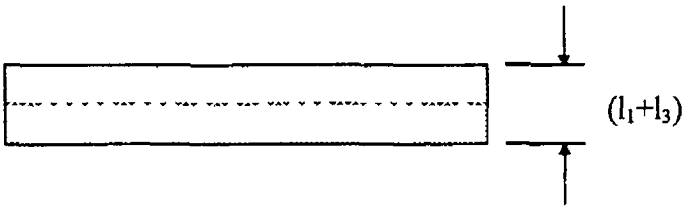


Figure 4.1.3: Slice (a) of Hollow Block

$R_{m(a)}$ is the thermal resistance of the solid material in Slice (a)

$R_{(a)}$ is the thermal resistance of Slice (a)

$$R_{m(a)} = \frac{l_1 + l_3}{\lambda} = \frac{0.06 + 0.06}{\lambda} = \frac{0.12}{\lambda}$$

In this case, $R_{m(a)}=R_{(a)}$

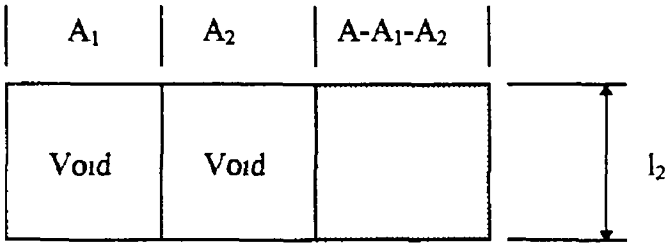


Figure 4.1.4 Slice (b) of Hollow Block

Thermal Resistance of material in Slice (b) $R_{m(b)} = \frac{l_2}{\lambda} = \frac{0\ 095}{\lambda}$

Thermal Resistance of voids in Slice (b) $R_{vo}= 0\ 2\ m^2K/W$

Resistance of Slice(b), $R_{(b)}$ is given by

$$\frac{A}{R_{(b)}} = \frac{A_1 + A_2}{R_{vo}} + \frac{(A-(A_1+A_2))}{R_{m(b)}}$$

$$\frac{0\ 215 \times 0\ 44}{R_{(b)}} = \frac{2 \times 0\ 13 \times 0\ 215}{0\ 2} + \frac{(0\ 44-(2\times 0\ 13))0\ 215}{\frac{0\ 095}{\lambda}}$$

$$\frac{0\ 44}{R_{(b)}} = 1\ 3 + 1\ 8947\lambda$$

$$0\ 44 = (1\ 3 + 1\ 8947\lambda)R_{(b)}$$

$$\Rightarrow R_{(b)} = \frac{0\ 44}{1\ 3+1\ 8947\lambda}$$

Total equivalent thermal resistance (Lower Limit) R_L

$$R_L = R_{(a)} + R_{(b)} = \frac{0\ 12}{\lambda} + \frac{0\ 44}{1\ 3+1\ 8947\lambda}$$

Upper Limit The upper limit is set by assuming that the outer and inner faces of the block are at uniform temperatures and that there is no lateral heat flow

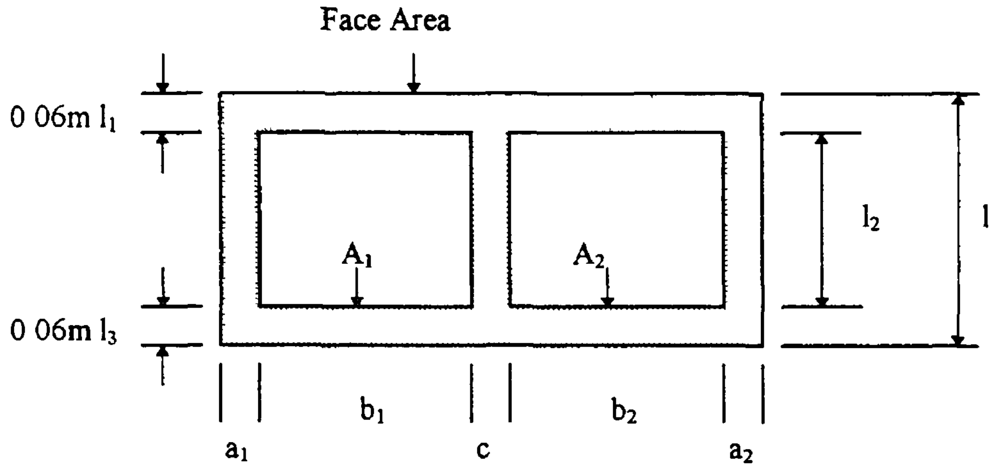


Figure 4 1 5: Cross-Section of Hollow Block with Lateral Dimensions

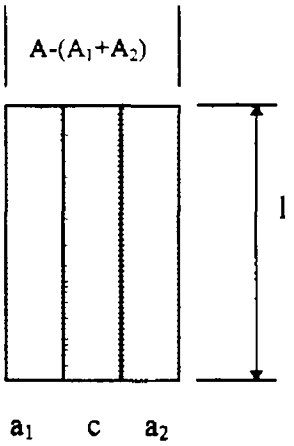


Figure 4 1 6 Section (a) of Hollow Block

Material $\Rightarrow R_{m(a)} = \frac{l}{\lambda} = \frac{0\ 215}{\lambda}$

$$R_{(a)} = \frac{0\ 215}{\lambda}$$

$A_{(m)}$=0 18×0 215= 0 0387 m^2

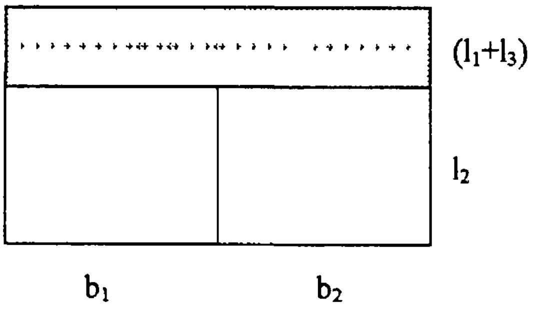


Figure 4 1 7· Section (b) of Hollow Block

$$R_{m(b)} = \frac{l_1 + l_3}{\lambda}$$

Voids $R_{(b)} = \frac{l_1 + l_3}{\lambda} + R_{vo} = \frac{012}{\lambda} + 0\,2 = \frac{012 + 0\,2\lambda}{\lambda}$

Total thermal resistance of block (upper limit) is given by

$$\frac{A}{R_U}=\frac{A_{(a)}}{R_{(a)}}+\frac{A_{(b)}}{R_{(b)}}$$

$$\frac{044\times0215}{R_U}=\frac{018\times0215}{\frac{0215}{\lambda}}+\frac{026\times0215}{\left(\frac{012}{\lambda}+02\right)}$$

$$\frac{044}{R_U}=08372\lambda+\frac{026\lambda}{012+02\lambda}$$

$$\begin{aligned}R_U&=\frac{044}{08372\lambda+\frac{026\lambda}{012+02\lambda}}\\&=\frac{0\ 44}{\frac{0\ 8372\lambda(0\ 12+0\ 2\lambda)+0\ 26\lambda}{(0\ 12+0\ 2\lambda)}}\\&=\frac{0\ 44(0\ 12+0\ 2\lambda)}{016744\lambda^2+01005\lambda+026\lambda}\\&=\frac{0\ 0528+0\ 088\lambda}{0\ 16744\lambda^2+03605\lambda}\end{aligned}$$

The mean equivalent resistance is derived from the upper and lower limits and is the resistance used to obtain the overall U-value

$$\begin{aligned}R_M&=\frac{R_U+R_L}{2}\\&=\frac{1}{2}\left(\frac{00528+0088\lambda}{016744\lambda^2+03605\lambda}+\frac{012}{\lambda}+\frac{044}{13+18947\lambda}\right)\\&=\frac{1}{2}\left(\frac{044}{08372\lambda+\frac{026\lambda}{012+02\lambda}}+\frac{012}{\lambda}+\frac{044}{13+18947\lambda}\right)\\&=\left(\frac{022}{08372\lambda+\frac{026\lambda}{012+0.2\lambda}}+\frac{006}{\lambda}+\frac{022}{13+18947\lambda}\right)\end{aligned}$$

λ=1 63 W/mK Heavy-weight Concrete Block (Table A3 15 CIBSE Section A3)

$$R_M = \left(\frac{0.22}{1.3646 + \frac{0.4238}{0.446}} + 0.0368 + \frac{0.22}{1.3 + 3.08836} \right)$$

$$= \frac{0.22}{2.314} + 0.0368 + 0.05013 = 0.18216 \text{ m}^2\text{K/W}$$

λ=0.51 Medium-weight Concrete Block (Table A3.15 CIBSE Section A3)

$$R_M = \left(\frac{0.22}{0.427 + \frac{0.1326}{0.222}} + 0.1176 + 0.097 \right)$$

$$= 0.215 + 0.2147 = 0.429 \text{ m}^2\text{K/W}$$

4.2 CEN Standards for the Simulation of Thermal Bridges

CEN (Comite Europeen de Normalisation) is the European Committee for Standardization. CEN standards are European standards, of those, some standards deal specifically with thermal bridges. CEN members are members of the European Union and Iceland, Norway and Switzerland. The two standards which deal with thermal bridging are CEN/TC 89 N 300 E[3] (still at draft stage) and CEN/TC 89 N 293 E[4]

4.2.1 CEN/TC 89 N 300 E: Simplified Methods for Determining Linear Thermal Transmittance and the Calculation of Heat Loss

This European standard describes thermal bridges as

'Thermal bridges, which in general occur at any junction between building components or where the building structure changes composition, have two consequences

a) a change in heat flow rate and

b) a change in internal surface temperature *compared with those of the unbridged structure* '

It is noted that thermal bridges usually give rise to complex heat flows, which can be precisely determined by numerical calculation as specified in the standard CEN/TC 89 293 E

The standard gives the following examples of potential thermal bridges wall/wall, wall/floor, and wall/roof junctions, balconies, basements, foundations, lintels, sills, reveals, columns integral to the building element, external columns bearing suspended floors, beams exposed both to the internal and external air

It is noted that three dimensional thermal bridges such as wall ties should be included in the overall U-value of a building element

The standard gives simplified methods for dealing with heat flows through thermal bridges These calculation methods are essentially design tools which deal with U values for linear thermal bridges, thermal bridge catalogues and hand calculations The standard assumes calculations for steady-state conditions, physical properties independent of temperature and an absence of heat sources

The standard gives the following definitions

Thermal bridge: Part of the building envelope where the otherwise uniform thermal resistance is significantly changed by

a) full or partial penetration of the building envelope by materials with a different thermal conductivity

and/or

b) a change in thickness of the fabric

and/or

c) a difference between internal and external areas, such as occur at wall/floor/ceiling junctions

Linear thermal bridge Thermal bridge with a uniform cross section in one direction

Point thermal bridge Thermal bridge with no uniform cross section in any direction

Thermal coupling coefficient $L_{i,j}$ (W/K). Heat flow per unit temperature difference between two environments i,j which are thermally connected by the construction under consideration

Linear thermal transmittance (W/mK): Correction term for the influence of a linear thermal bridge when calculating the thermal coupling coefficient L from 1-D calculations

Overall internal dimensions of the building: Dimensions of the building ignoring all internal partitions

The section entitled 'The influence of thermal bridges on overall heat flow' defines the relationships between buildings, thermal bridges and heat loss The first relationship CEN defines is the thermal coupling coefficient which relates heat loss to the difference between external and internal temperatures The equation given below is then defined and relates thermal bridges (linear thermal transmittance) to overall heat loss and is the basis of calculations involving thermal bridging in buildings

$$L_{i,e}=\Sigma U_j.A_j+\Sigma\Psi_k\ l_k$$

Where.

$L_{i,e}$ **is the thermal coupling coefficient of the building between the internal and external environment, in W/K,**

U_j **is the thermal transmittance of part j of the building envelope in W/(m^2.K),**

A_j **is the area over which the U_j-value applies, in m^2,**

Ψ_k **is the linear thermal transmittance of the k linear thermal bridge, in W/(K m),**

l_k **is the length over which the Ψ_k-value applies, in m,**

This equation can be expressed as

$U_{\text{value of building}}$ * Area of building = Σ ($U_{\text{value of unbridged section of building}}$ * Area of unbridged section of building) + Σ ($U_{\text{value of bridge}}$ * Bridge length)

Importantly, the presence of thermal bridges is noted as increasing the total heat flow of a building and the above equation is said to give the correct heat flow from a building The problem with the above equation is that it does not deal with 'point' or three dimensional thermal bridges and only deals with linear thermal bridges

In calculating linear thermal transmittances any consistent method of building measurement may be used

The CEN standard gives importance to design values, thermal bridge catalogues and numerical calculations in defining the importance of a thermal bridge Design linear thermal transmittance values are given for standard thermal bridges in a catalogue format as an example These design values were obtained using numerical calculations and were based on specific thermal conductivities and dimensions

Thermal transmittance values from catalogues are considered inflexible in the CEN standard because they introduce uncertainty in the calculations since in general given examples in the catalogue do not match up with the actual details been considered They should be used when the catalogue thermal bridge matches closely the one under consideration or when the catalogue provides a more severe thermal bridge
The CEN standard also defines how such a catalogue should be presented

In the case of hand calculations, the standard states that in order to be useful as a source of linear thermal transmittance values the hand calculations should provide detailed information such as dimensional limits for which the model is valid and an estimate of accuracy for the calculation

This standard although recognising the importance of thermal bridging in buildings is too general for detailed analysis of thermal bridges

4 2 2 CEN/TC 89 N 293 E

This CEN standard refers principally to the simulation of two and three dimensional heat flows using numerical methods Part I is exclusively devoted to high precision numerical analysis of two and three dimensional heat flow and Part II to less precise analysis of two dimensional heat flow The standard defines the analysis of thermal bridges for two purposes the calculation of the total heat loss from a building and the calculation of minimum surface temperatures to assess condensation risk It is important to note that the standard has slightly different calculation methods for each purpose

It is assumed in the standard, that in the analysis of thermal bridges steady state conditions apply, that all physical properties are independent of temperature, that there is an absence of heat sources, and that boundary conditions are defined and may only vary when specified by the standard

The standard defines thermal bridges and related terms exactly as in CEN standard TC 89 N 300 E The standard defines additionally

3-D geometrical model· Geometrical model, deduced from building plans, such that for each of the orthogonal axes, the cross-section perpendicular to that axis changes within the boundary of the model

3-D flanking element Part of the 3-D geometrical model which, when considered in isolation can be represented by a 2-D geometrical model

2-D geometrical model Geometrical model deduced from building plans, such that for one of the orthogonal axes, the cross-section perpendicular to that axis does not change within the boundaries of the model

Construction planes: Planes in the 3-D or 2-D model which separate different materials, the geometrical model from the remainder of the construction, the flanking elements from the central element

Other technical terms not defined in CEN standard TC 89 N 300 E which are defined in this standard are 3-D central element, cut-off planes, auxiliary planes, quasi-homogeneous layer, temperature difference ratio, temperature factor at internal surface, temperature weighting factor, internal reference temperature, dry resultant temperature and point thermal transmittance

The CEN standard bases itself on the principle that unknowns such as temperature and heat flow can be calculated if the boundary conditions are known The CEN standard defines an analysis procedure which is made up of three principle steps which entail discretising the model, determining and defining the boundary conditions and then solving for unknown temperatures by using a numerical calculation method

(i) Discretising the Model

The standard has a detailed approach for dealing with the geometrical model of a building or a construction to be analysed Generally, for large constructions or buildings, the model is split into separate parts or geometrical models using cut-off planes

Table 4 2 1 Location of Cut-off Planes in the Subsoil

Direction of Heat Flow	**Purpose of Calculation**	
	Surface Temperatures	Heat Flow
Horizontal inside the building	at least 1 metre	0 5b
Horizontal outside the building	same distance as inside the building	2 5b
Vertical below ground level	3 metres	2 5b
Vertical below floor level (for floors more than 2 m below ground level)	1 metre	-

Source CEN CEN/TC 89 N 293 E Thermal bridges in building construction - Heat flows and surface temperatures - Part I General calculation methods Brussels, CEN, 1993, p 15

Note b is the width (the smaller dimension) of the ground floor in metres

Cut-off planes are defined by the standard as the boundaries of such geometrical models and are typically one metre away from the bridge, at a symmetry plane or for constructions at ground level as specified in Table 4 2 1 They should include a central element and a flanking element The standard states that the splitting up of the geometrical model should be carried out in such a way that no difference occurs between a calculation involving an individual part of the building and a calculation which simulates the complete building

The geometrical models are then further discretised by the use of auxiliary planes, which divide the models into cells of homogeneous material conductivities

Simplification of the Geometrical Model

The CEN standard within the discretisation procedure presents the following methods of simplifying a geometrical model

- Change, according to tolerances provided by CEN, in the location of the surface of a block of material adjacent to the internal or external surface of the geometrical model This applies with rounded or profiled surfaces
- A boundary between two materials, can be changed as long as the material with the lower thermal conductivity is replaced by the material of higher thermal conductivity,

and the relocation is perpendicular to the surface This can be applied to recesses for sealing strips and connecting details

- Layers of not more than 1 mm thickness such as the damp-proof membrane (dpm) or damp-proof course (dpc) can be ignored
- Appendages attached to the outside surface such as gutters or discharge pipes can be neglected
- Quasi-homogeneous layers can be used to model non-homogeneous constructions which include linear and point thermal bridges The main conditions for applying quasi-homogeneous layers are that no important thermal bridges should be present within the construction and that the thermal conductivity of the quasi-homogeneous layer should not be more than 1 5 times lower than the thermal conductivity of the material with the lowest thermal conductivity For this purpose two equations to calculate the thermal conductivity of a quasi-homogeneous layer are given in the standard They apply in the overall analysis procedure in the calculation of the internal surface temperature and the linear thermal transmittance or the point thermal transmittance

The CEN standard states that results obtained with unsimplified geometrical models take precedence over results obtained with simplified geometrical models and that in the simplification of geometrical models, materials with conductivities greater than or equal to 3 W/mK cannot be changed

(ii) Calculation Values and Boundary Conditions

Regarding the thermal conductivities of building materials a reference is given to the appropriate European standard[5] For example, the value given for the thermal conductivity of soil λ=2 0 W/mK (if local soil conditions are available then they should be used)

A different set of surface resistances is used compared to the CIBSE Guide[1] surface resistance values Different values are also given for the upper and lower parts of rooms and some effort is made to take into account air stratification and non uniform radiant temperature

The boundary temperatures for simulation are governed in the CEN standard by the purpose of calculation and by several assumptions Below is a table which lists the boundary temperatures when using CEN analysis

Table 4 2.2· Boundary Temperatures for Simulation

Position	**Purpose of Calculation**	
	Surface Temperature	**Heat Flow**
Internal	air temperature	dry resultant temperature
External	air temperature, assuming that the sky is completely overcast	air temperature, assuming that the sky is completely overcast
Soil (horizontal cut-off plane)	at the distance below ground level given in table 1 yearly average external air temperature	at the distance below ground level given in table 1 adiabatic boundary condition

Source CEN CEN/TC 89 N 293 E Thermal bridges in building construction - Heat flows and surface temperatures - Part I General calculation methods Brussels, CEN, 1993, p 26

Regarding the modelling of an air cavity the standard considers it as a homogeneous conductive material with a thermal conductivity λ_c The conductivity of an air cavity is calculated directly from its resistance and dimensions, the resistance of the cavity is taken from the main direction of heat flow

Air cavities with dimensions of more than 0 5 m along each one of the orthogonal axis shall be treated as rooms

(iii) Calculation Method

The geometrical model representing a building under consideration is divided into a number of cells as describe in the discretisation of the model, each with a characteristic point or node The law of conservation of energy, Fourier's Law, and the boundary conditions are used to determine a system of equations which are functions of temperature of the nodes The equations are solved using a direct technique or an iterative method, and a temperature field is obtained Heat flows are calculated from temperature data obtained and using Fourier's Law

In perpendicular directions, heat flow values must satisfy Fourier's Law in the CEN standard form of analysis In general, cut-off planes are assumed to be adiabatic

In the evaluation of models with several boundary temperatures and several environments the same equation holds heat flow is equal to the total coupling coefficient multiplied by the temperature difference

For a full three dimensional analysis of a building, the following equation applies

$$L_{i,j} = \sum_{n=1}^{N} L^{3D}_{n(i,j)} + \sum_{m=1}^{M} L^{2D}_{m(i,j)} \, l_m + \sum_{p=1}^{P} U_{p(i,j)} \, A_p$$

where

$L_{n(i,j)\,3D}$ is the thermal coupling coefficient obtained from a 3-D calculation for part n of the room or building in W/K,

$L_{n(i,j)\,2D}$ is the linear thermal coupling coefficient obtained from a 2-D calculation for part n of the room or building in W/mK,

l_m is the length over which the $L_{m(i,j)\,2D}$ value applies in m,

U_p is the thermal transmittance obtained from a 1-D calculation for part p of the room or building in W/m^{2}K,

A_p is the area over which the U_p value applies in square metres

N is the total number of 3-D parts,

M is the total number of 2-D parts,

P is the total number of 1-D parts,

For several boundary temperatures, temperature weighting factors are used to locate temperatures at any part of the inner surface If two boundary temperatures exist they are described in a dimensionless formula in CEN

The CEN standard also gives a detailed description of what should constitute input and output data The following results are given with CEN style analysis in simulation

- thermal coupling coefficients L between adjacent rooms involved in heat transfer through the building components
- temperature factors or temperature difference ratios for the points of lowest surface temperature in each room involved (including the location of these points if more than two boundary temperatures are used)
- Heat transmission from environment i to environment j
- Heat flows in watts per metre for 2-D cases or watts for 3-D cases
- Estimate of error

4.3 Computer Methods

In the analysis of thermal bridges computer programs must be used because of the complexity of the heat flows occurring within them

Although there are many programs available three programs which can be used to analyse thermal bridging are ANSYS (a finite element package), ESP (a building energy simulation package using the finite volume method) and Kobra (a specialised package designed to analyse thermal bridges which uses the finite difference method and complies with CEN standards)

4 3 1 ANSYS

One of the most widely used finite element computer programs is ANSYS Finite element computer packages can be used to model nearly any physical effect encountered in engineering but are mainly used for stress and thermal analysis ANSYS is representative of many finite element packages which are available in the market and which can be used for thermal analyses This program is designed primarily as an engineering tool and is not made specifically for building or thermal bridge analysis The advantage of finite element packages such as ANSYS is their flexibility They can be used to model many different conditions, awkward shapes and can be used for two and three dimensional analysis and steady state and transient analysis

The main disadvantages of the ANSYS program have to do with cost and the complexity of simulations Depending on ANSYS software version used, there are generally set limits on the size and complexity of a simulation one can carry out, beyond which the ANSYS program will crash This does not occur with the more expensive versions of the ANSYS program, but the prices of such versions are prohibitive for non-commercial operations This means that during the simulation process one must try to avoid using too many elements and simplify complex geometries This is particularly the case for three dimensional analysis The simulation process itself is complex, and it can take a considerable amount of time for a user to use the ANSYS program correctly

4 3.2 ESP

The ESP program has been developed by the University of Strathclyde in Scotland over the last twenty years It is an important tool in terms of dynamic thermal simulation of buildings and is used in many universities throughout the world The main difference between this package and ANSYS is that this program is used specifically to simulate buildings and not individual components such as in ANSYS

ESP is a package which simulates a building for real time conditions and can create a sophisticated model of a building's thermal behaviour Analysis of thermal bridges is possible The advantages of this package are the ability to create very realistic models which take into account many factors of a building's thermal behaviour such as thermal bridging Its main disadvantage is that in the analysis of thermal bridges it requires a lot of computer time to complete a simulation

4.3 3 Kobra

Kobra is a software package which is specifically designed to analyse thermal bridges developed by Physibel, Belgium Eurokobra is a database of thermal bridges accessed It uses the finite difference method of analysis and complies with CEN standards Its main disadvantage is that it is not capable of dealing with non-rectangular shapes The advantages of its use are that simulation of thermal bridges can be done in a short period of time and that it does not require significant operating time to learn how to use it

4 4 Application and Approach to Thermal Bridging

Computer methods are the only methods which can be used in the analysis of many thermal bridges

4 4 1 Application of ANSYS

The ANSYS program is split up into three groups of procedures pre-processing, solution and post-processing In pre-processing the element type, mesh density, material properties and geometric properties of the model are specified The model can be represented by two dimensional areas or three dimensional volumes Once the geometry is specified, the model is then meshed with a suitable mesh density This is an automated process in ANSYS In the solution phase, the convection loads are specified by applying them to the corresponding lines on the model, the solution can then be executed The analysis of results is carried out in the post-processing section

4.4.2 Application of the Finite Difference Programs

This method can be applied using spreadsheets for simple models The Kobra program models thermal bridges in two dimensions The ESP program is used for modelling buildings and is one dimensional in normal use but has three dimensional capability for more detailed studies

Kobra In Kobra, the first step is to write a file which will describe the geometric properties of a bridge under scrutiny The model's material properties and dimensions can be changed at any time and therefore once the first step is completed, the simulation of variations in a thermal bridge is almost automatic A database of thermal bridge types can be built up and therefore in some cases the only steps necessary to carry out a simulation are the selection of the bridge to be analysed and the input of its dimensions and material properties

ESP Simulation in ESP involves data input, simulation and results analysis The geometry of the building, composition of the building fabric, openings for ventilation, occupancy patterns, central heating schedules, latent gains within the building are all specified Any factor which may be considered to have an effect on the thermal behaviour of the building is specified In the case of thermal bridging a three dimensional mesh is generated for the bridge under consideration The configuration of the model is checked and if this is correct the simulation is carried out The simulation can be carried with a view to collecting specific data such as temperature at a specific point, the relative humidity in a room or ventilation rates between rooms for example

4.4 3 Use of ANSYS in Analysis of Thermal Bridges

With respect to this study the ANSYS finite element program has been used for the simulation and analysis of thermal bridges The main reasons for the use of ANSYS were that the finite element method is recommended in the CIBSE Guide Section A3 for analysing complex heat flows in thermal bridges, that ANSYS is a sophisticated and recognised thermal analysis program, that ANSYS is capable of carrying out analysis on irregular shapes and that ANSYS has three dimensional analysis capability ANSYS can also be used in dynamic analysis, however, in this study only steady-state analysis has only used as the behaviour on average of thermal bridges has been assumed to be adequately represented by steady-state conditions (see Chapter 7)

4 5 Conclusion

The CIBSE Design Guide has manual methods which are limited in the analysis of thermal bridges CEN standards define the approach and theoretical basis for the analysis of thermal bridges In the case of complex thermal bridges the standard defines the appropriate symmetry and cut-off lines, boundary conditions and rules for their simplification Computer analysis methods can be validated with validation tests from the CEN standards There are several computer methods available for the analysis of thermal bridges and the use of a specific program depends on the type of analysis needed

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3 CEN *CEN/TC 89 N 300 E THERMAL BRIDGES - Simplified methods for determining Linear Thermal Transmittance and the calculation of heat loss* Brussels, CEN, 1993

4 CEN *CEN/TC 89 N 293 E Thermal bridges in building construction - Heat flows and surface temperatures - Part I General calculation methods* Brussels, CEN, 1993

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Chapter 5. Finite Element Theory

Summary

The finite element method is a mathematical method of analysis where a model is split up into small parts called elements, then conservation equations for each individual element are generated and solved for the whole model The main advantages are that it can deal with complicated geometries and that loads can be applied in a variety of ways

5 1 The Finite Element Method

The finite element method was first used in stress analysis problems, but can be used in heat transfer analysis The finite element method is a numerical procedure where many simultaneous equations are produced and solved This is done by computers One of the principal concepts of the method is the discretisation of the problem under consideration The main steps in the method can be seen in Figure 5 1 1

5 1 1 Procedure

1 In order to ascertain the distribution of an unknown variable such as temperature in a region, the region is divided into subdivisions called elements with interconnected joints called nodes This process is called discretisation The amount and type of elements used depend on what is being modelled and the variable is assumed to act in each element in a defined manner

2 Element equations are then generated These have a constant format for each element type and for each analysis type such as thermal or stress

3 The individual element equations are then assembled into system equations The behaviour of the whole model is described by these For thermal analysis the system equations generally take the form

$$\{q\}=[\lambda]\{T\}$$

where $[\lambda]$ is the global conductance matrix

$\{q\}$ is the vector of nodal heat flows

{T} is the vector of unknown nodal temperatures

4 Incorporation of boundary conditions or constraint conditions on the system equations

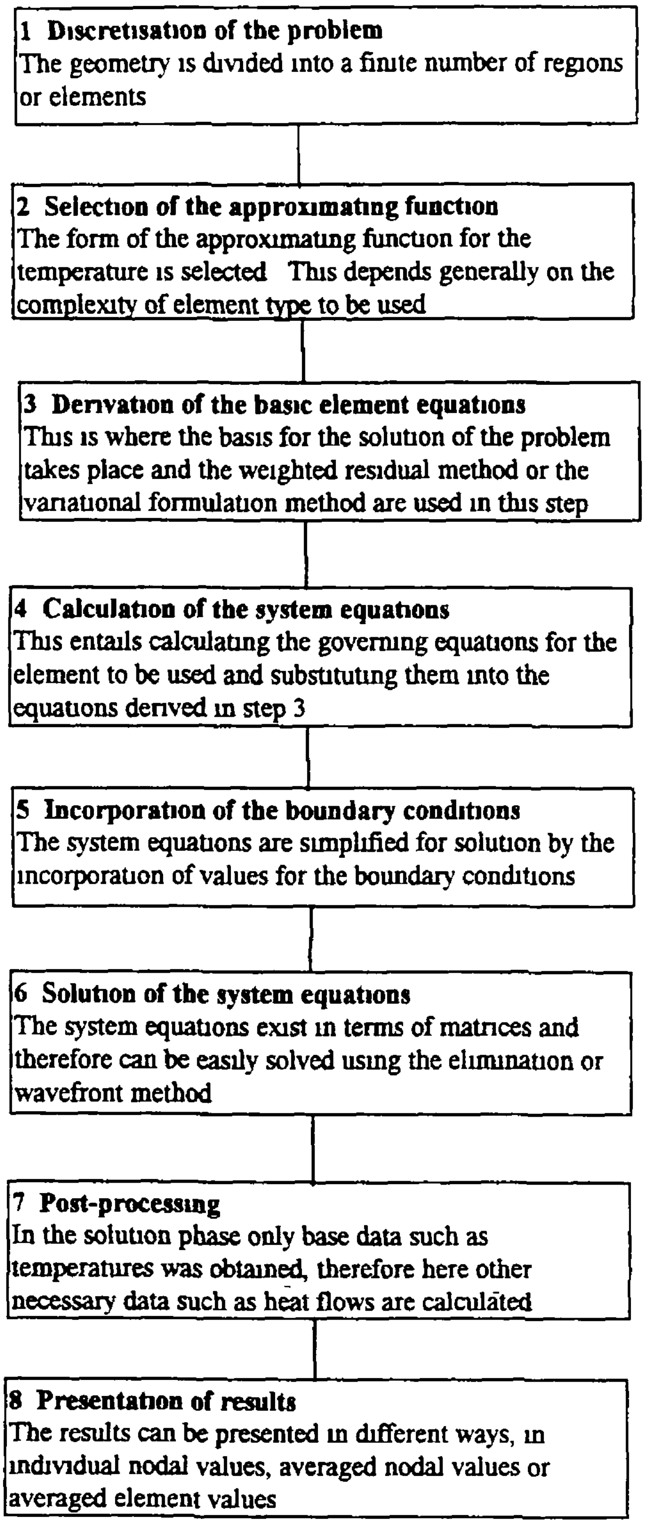
5 Solution of the system equations

6 Post processing of solutions

After solutions have been obtained for the unknown temperatures, heat flows may be calculated and graphs produced

It is important to note that finite element solutions are approximate

Figure 5 1 1 The Finite Element Analysis Process



1 Discretisation of the problem
The geometry is divided into a finite number of regions or elements

2 Selection of the approximating function
The form of the approximating function for the temperature is selected This depends generally on the complexity of element type to be used

3 Derivation of the basic element equations
This is where the basis for the solution of the problem takes place and the weighted residual method or the variational formulation method are used in this step

4 Calculation of the system equations
This entails calculating the governing equations for the element to be used and substituting them into the equations derived in step 3

5 Incorporation of the boundary conditions
The system equations are simplified for solution by the incorporation of values for the boundary conditions

6 Solution of the system equations
The system equations exist in terms of matrices and therefore can be easily solved using the elimination or wavefront method

7 Post-processing
In the solution phase only base data such as temperatures was obtained, therefore here other necessary data such as heat flows are calculated

8 Presentation of results
The results can be presented in different ways, in individual nodal values, averaged nodal values or averaged element values

Source Fagan MJ *Finite Element Analysis Theory and Practice* Harlow, Longman Scientific and Technical, 1992

5 1 2 A Simple One-Dimensional Element The Thermal Bar

The simplest element to introduce the finite element method in thermal analysis is the one-dimensional bar This element is based on Fourier's law which relates the heat flow rate q to the product of the materials' thermal conductivity, λ, the cross-sectional area, A, and the temperature gradient, dT/dx, in the direction of the conduction and which is expressed mathematically as follows

$$q = -\lambda A \frac{dT}{dx}$$

Considering a thermal element of length, L, with a constant temperature difference between its extremities as shown in Figure 5 1 2, the following equation is derived

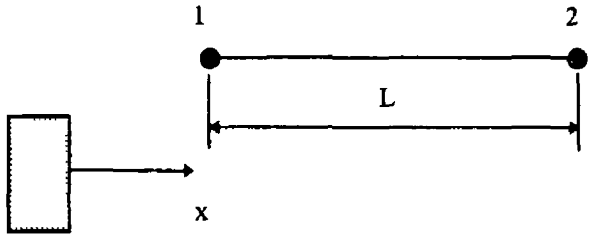


Figure 5 1 2 A Thermal Bar Element of Length, L

$$\frac{dT}{dx} = \frac{T_2 - T_1}{x_2 - x_1} = \frac{T_2 - T_1}{L}$$

Therefore, the heat flow from node 1 to 2 is

$$q_1 = -\frac{\lambda A}{L}(T_2 - T_1)$$

The heat flow from node 2 to 1 is

$$q_2 = -\frac{\lambda A}{L}(T_1 - T_2)$$

In matrix format the two equations can be assembled as follows

$$\begin{Bmatrix} q_1 \\ q_2 \end{Bmatrix} = \frac{\lambda A}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix}$$

When considering more than one element the matrices are assembled and give a system equation {q} = [λ] {T}

5 1 3 Heat Conduction Through a Wall

Considering the cavity wall below

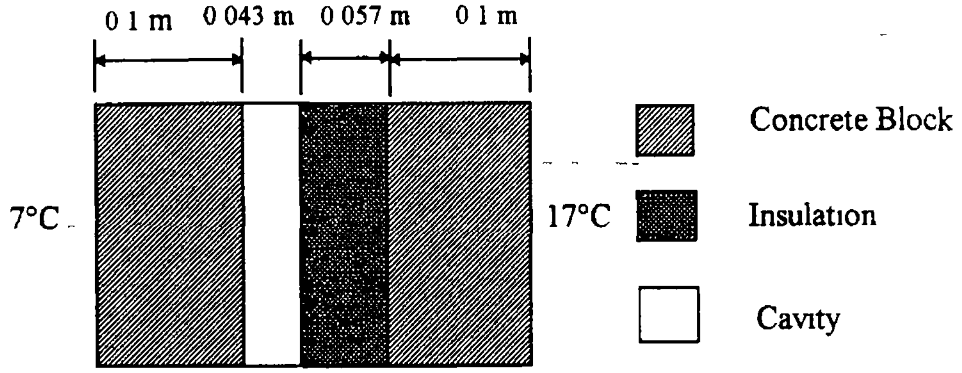


Figure 5 1 3· Cavity Wall

The cavity wall can be discretised and modelled with four one dimensional thermal bar elements as shown below

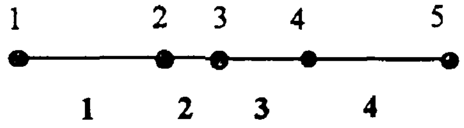


Figure 5 1 4. Discretised Finite Element Model of Cavity Wall

The thermal conductivities of the cavities wall materials are listed below

$\lambda_{\text{concrete block}} = 1\ 63$ W/mK
$\lambda_{\text{cavity}} = 0\ 239$ W/mK
$\lambda_{\text{insulation}} = 0\ 035$ W/mK

The element equations are generated
(Matrix equations below refer to each individual element Assuming unit area)

Element 1 $$\begin{Bmatrix} q_1 \\ q_2 \end{Bmatrix} = \frac{\lambda A}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix} = \begin{bmatrix} 163 & -163 \\ -163 & 163 \end{bmatrix}\begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix}$$

Element 2 $$\begin{Bmatrix} q_2 \\ q_3 \end{Bmatrix} = \begin{bmatrix} 556 & -556 \\ -556 & 556 \end{bmatrix}\begin{Bmatrix} T_2 \\ T_3 \end{Bmatrix}$$

Element 3 $$\begin{Bmatrix} q_3 \\ q_4 \end{Bmatrix} = \begin{bmatrix} 061 & -061 \\ -061 & 061 \end{bmatrix}\begin{Bmatrix} T_3 \\ T_4 \end{Bmatrix}$$

Element 4 $$\begin{Bmatrix} q_4 \\ q_5 \end{Bmatrix} = \begin{bmatrix} 16\ 3 & -16\ 3 \\ -16\ 3 & 16\ 3 \end{bmatrix} \begin{Bmatrix} T_4 \\ T_5 \end{Bmatrix}$$

The element equations are now assembled into a system equation

$$\begin{bmatrix} 16\ 3 & -16\ 3 & 0 & 0 & 0 \\ -16\ 3 & 21\ 9 & -5\ 6 & 0 & 0 \\ 0 & -5\ 6 & 6\ 21 & -0\ 61 & 0 \\ 0 & 0 & -0\ 61 & 16\ 91 & -16\ 3 \\ 0 & 0 & 0 & -16\ 3 & 16\ 3 \end{bmatrix} \begin{bmatrix} 7 \\ T_2 \\ T_3 \\ T_4 \\ 17 \end{bmatrix} = \begin{bmatrix} q_1 \\ 0 \\ 0 \\ 0 \\ q_5 \end{bmatrix} \qquad (5\ 1\ 1)$$

The boundary conditions of 7°C and 17°C have been incorporated in the system equation (5 1 1) Since there is steady-state heat flow and no heat generation at internal nodes q_2, q_3, $q_4 = 0$ q_1 and q_5 are the heat flows that are effectively applied at nodes 1 and 5

The solution of the system equation is now undertaken by multiplying out the matrix

$114\ 1-16\ 3\ T_2 = q_1$ (5 1 2)

$-114\ 1+21\ 86\ T_2-5\ 56\ T_3 = 0$ (5 1 3)

$-5\ 56T_2+6\ 21\ T_3 -0\ 61\ T_4 = 0$ (5 1 4)

$-0\ 61T_3+16\ 91\ T_4 -277\ 1 = 0$ (5 1 5)

$-16\ 3\ T_4+277\ 1 = q_5$ (5 1 6)

From equation (5 1 3) $T_2 = 5\ 22 + 0\ 254\ T_3$ (5 1 7)

Substituting (5 1 7) into (5 1 4) $T_3 = 6\ 101 + 0\ 128\ T_4$ (5 1 8)

Substituting (5 1 8) into (5 1 5) $T_4 = 16\ 684$ °C (5 1 9)

Solving for temperatures using equation (5 1 9) gives

$T_2 = 7\ 3$ °C, $T_3 = 8\ 24$ °C

Postprocessing gives $q_1 = -q_5 \cong 5\ 1\ \mathrm{W/m^2}$

5 2 Analysis and Evaluation of Model

5 2 1 Geometrical Approximations

In finite element analysis and in many other forms of analysis, approximations can be made to model three dimensional problems in two dimensions that are useful and accurate A composite wall can be modelled using one-dimensional elements This simplification can be made because it is known that heat flow through a wall is one-dimensional For different models different assumptions and approximations can be made that simplify substantially the analysis involved In cases where geometrical approximation is not possible and a full three dimensional model of the structure has to be analysed, it can still be possible to take advantage of any symmetry that the problem might exhibit

Axial, planar, cyclic, and repetitive symmetry occur in many models and this allows substantial simplification to take place The only difficulty that may be encountered with this process is that thermal and constraint conditions have to be applied in such a way that they reflect accurately the symmetry of the problem The most common types of symmetry found in analysing building components are planar and repetitive symmetries

5 2 2 Selection of Element Type

Elements range in shape from points with no dimensions to three-dimensional shapes and can be quite irregular or rectangular or triangular in shape The sides of elements can be straight or curved When irregular elements or elements with curved sides are used the solution will be complex and time consuming This occurs because with irregular elements it is necessary to describe the geometry of an element using a polynomial If this polynomial is not similar or of the same order as the interpolation function of the element (the interpolation function approximates the variation of temperature within a thermal element) this results in a more complex analysis If the two functions are of the same order of each other and are similar to each other then the element is known as isoparametric Isoparametric elements are used in finite element programs Therefore, when a finite element program encounters an irregular element it changes the order of its interpolation function until it matches the elements geometry polynomial

For the majority of thermal problems elements where a two or three dimensional thermal field is allowed are used These types of elements are described as solid elements Elements developed for thermal problems are relatively simpler than other elements because they describe temperature, which is a scalar quantity Normally, a structured input of the model's geometry would be made so that all elements that are formed during the meshing procedure would be as geometrically simple as possible

In commercial finite element packages, a large number of element types are available for use in analysis Their selection is straight forward although it depends entirely on the problem being analysed In thermal problems, obviously, only thermal elements are used, for one-dimensional models one dimensional elements are used, for two dimensional models only two dimensional elements are used and so on In certain cases where only one part of the model is important and where a simpler element will be accurate, elements of one, two and three dimensions may be used in the same model Use of three and two dimensional elements where a one dimensional element can be used is to be avoided This increases modelling time yet produces no advantage in the analysis of the problem

5 3 Discretisation and Element Generation

5 3 1 Discretization

This is the initial step in the finite element procedure, mentioned previously, where the model under examination is divided into elements In this step, care and time is taken because the finer the mesh of a discretised body, the more computing power is needed to obtain a solution Most finite element packages have limits on the number of elements that can be used, and the cost of the package increases as its capability for analysis increases

5 3 2 Accuracy and Mesh Size and Density

The greater the number of elements in analysis the better the accuracy When modelling any problem, the greater the number of elements the closer the solution approximates to the real solution This can shown using a simple graph Yet small increases in accuracy sometimes need a very large increase in mesh density and analysis time, and therefore it is always useful to remember that the finite element method is approximate

5 3 3 Mesh Shape and Distortion

As described earlier, the more irregular the shape of an element the more complex is its analysis For extremely distorted elements, errors in the element formulations become more common Therefore, as element distortion increases, errors in the element formulation become increasingly important The more regular the shape of the element, the quicker and more accurate the analysis In two-dimensional analysis, the element shapes that produce the least distortion are the equilateral triangle and the square The importance of element distortion differs from model to model in thermal problems Where temperature remains nearly constant element distortion produces small errors, conversely, where important temperature changes occur, element distortion is more important One measure of distortion is aspect ratio This is the ratio of the longest side of an element to the shortest side In commercial packages, warnings of excessive aspect ratio and of excessive element distortion are given if they occur

5 3 4 Factors in Mesh Generation

The location of elements and therefore the location of nodes must reflect any changes in material properties, geometry, constraint conditions and applied loads The conductance matrix of each element depends on the material properties of that region in the model and consequently an element cannot comprise two different materials Therefore, a line or area of nodes will always be required at the interface of different materials Therefore, a finite element mesh must take account of any discontinuities such as abrupt changes in cross-section, material properties or, special load convection or, heat flux conditions These changes act as planes of discontinuity, and in the analysis of results it is necessary to view the results of parts of the model divided by such planes separately

Linear Interpolation Polynomials for Simplex Elements[1]

The One-Dimensional Simplex Element[1]

This is the one dimensional conducting bar, its interpolation was shown earlier After solution its interpolation function takes the form

$$T = N_i x_i + N_j x_j = [N]\{\Phi\}$$

where N_i and N_j are shape functions and represent the geometric properties of the element The shape functions are always polynomials of the same order as the interpolation function Shape functions are also described as trial or hat functions, if a graph of N against x is plotted their values always vary between one and zero

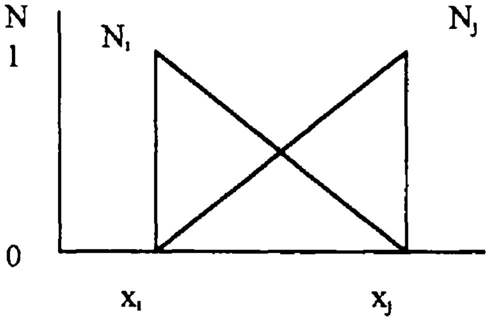


Figure 5.3.1· Graph of Shape Functions Against Displacement

The Two Dimensional Simplex Element[1]

This a two dimensional element with a linear interpolation function and therefore a triangle The linear interpolation function takes the form

$$T = a + bx + cy$$

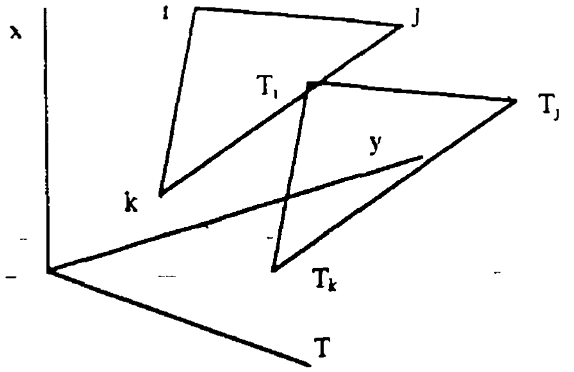


Figure 5.3 2. Graphical View of Linear Interpolation Function

where

$$a = (d_i T_i + d_j T_j + d_k T_k)/2A$$

$$b = (e_i T_i + e_j T_j + e_k T_k)/2A$$

$$c = (f_i T_i + f_j T_j + f_k T_k)/2A$$

where A is the area of the triangle

$$A = \frac{1}{2}\begin{vmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_z & y_z \end{vmatrix} = \frac{1}{2}(x_i y_j + x_j y_k + x_k y_i - x_i y_k - x_j y_i - x_k y_j)$$

where

$$d_i = x_j y_k - x_k y_j \quad e_i = y_j - y_k \quad f_i = x_k - x_j$$

$$d_j = x_k y_i - x_i y_k \quad e_j = y_k - y_i \quad f_j = x_i - x_k$$

$$d_k = x_i y_j - x_j y_i \quad e_k = y_i - y_j \quad f_k = x_j - x_i$$

The interpolation can be written as

$$T = N_i x_i + N_j x_j + N_k x_k = [N]\ \{\Phi\}$$

where

$$N_i = (d_i + e_i x + f_i y)/2A$$

$$N_j = (d_j + e_j x + f_j y)/2A$$

$$N_k = (d_k + e_k x + f_k y)/2A$$

Each shape function will equal unity at one node and zero at the other two In practice numerical nodal values are available for x and y This simplifies the interpolation function substantially

The Three-Dimensional Simplex Element[1]

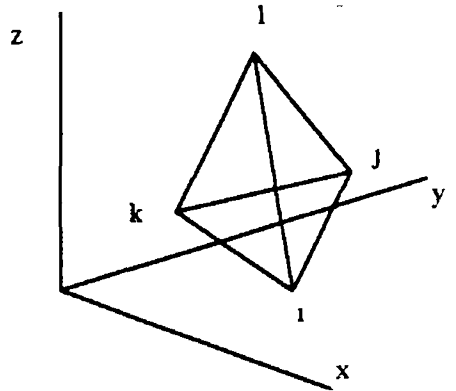


Figure 5.3.3: The Three Dimensional Simplex Element

The interpolation function is

$$T = a + bx + cy + dz$$

This can be expressed using shape functions

$$T = N_i x_i + N_j x_j + N_z x_z + N_l x_l = [N]\ \{\Phi\}$$

The shape functions are given by

$$N_\lambda = (e_\lambda + f_\lambda x + g_\lambda y + h_\lambda z) \qquad \lambda = i, j, k, l$$

E, f, g and h are constants and functions of the nodal co-ordinates They take the form

$$e_i = \begin{vmatrix} x_j & y_j & z_j \\ x_k & y_k & z_k \\ x_l & y_l & z_l \end{vmatrix} \qquad f_i = \begin{vmatrix} 1 & y_j & z_j \\ 1 & y_k & z_k \\ 1 & y_l & z_l \end{vmatrix}$$

$$g_i = \begin{vmatrix} x_j & 1 & z_j \\ x_k & 1 & z_k \\ x_l & 1 & y_l \end{vmatrix} \qquad h_i = \begin{vmatrix} x_j & y_j & 1 \\ x_k & y_k & 1 \\ x_l & y_l & 1 \end{vmatrix}$$

The coefficients of other are similar and depend on the interchange of i, j, k, l

Equations for elements with higher order interpolation functions are significantly more difficult to derive but follow a similar process to the simplex interpolation functions

Natural Co-ordinates

The description of element shape functions can be made easier by the use of natural co-ordinates Natural co-ordinates are effectively the local co-ordinates of each element They are effectively ratios involving local dimensions and this means that they are dimensionless and have a maximum magnitude of unity This concept is of no real significance for one dimensional elements but for higher order two and three dimensional elements it is an important tool

5 4 Derivation of the Basic Element Equations

The two most common ways of deriving the system equations in finite element analysis are variational formulation and the method of weighted residuals in particular Galerkin's method

5 4.1 Field Equation for Thermal Problems

The field equation governing thermal problems is

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) + Q = 0$$

where T=T$_1$ on surface S$_1$, and

$$\lambda_x \frac{\partial T}{\partial x} l_x + \lambda_y \frac{\partial T}{\partial y} l_y + \lambda_z \frac{\partial T}{\partial z} l_z + q = 0$$

$$\lambda_x \frac{\partial T}{\partial x} l_x + \lambda_y \frac{\partial T}{\partial y} l_y + \lambda_z \frac{\partial T}{\partial z} l_z + h(T - T_\infty) = 0$$

on surfaces S$_2$ and S$_3$ respectively, where S$_1$, S$_2$, S$_3$ form the complete boundary of the region under consideration and l_x, l_y, l_z are the direction cosines of the outward normal to the boundary λ_x, λ_y, λ_z are the thermal conductivities in three directions and Q is an internal heat source, h is a convection coefficient and q is the surface heat loss, T_∞ is the ambient temperature

5 4 2 Variational Formulation

Variational formulation involves minimising a functional which is a function of several other functions such as the heat transfer field equation

The use of calculation of variations mathematics for the heat transfer field equation produces the following functional

$$I = \int_v \frac{1}{2}\left[\lambda_x\left(\frac{\partial T}{\partial x}\right)^2 + \lambda_y\left(\frac{\partial T}{\partial y}\right)^2 + \lambda_z\left(\frac{\partial T}{\partial z}\right)^2 - 2QT\right]dV$$

$$+\int_{s_2} qTdS + \int_{s_3} h(T - T_\infty)^2 dS$$

The variational formulation method requires that the functional is minimised with respect to the system variable, T, so that I is at minimum The minimisation of the functional also requires that the governing equations and the boundary conditions are satisfied The minimisation involves the partial differentiation of the functional

5 4.3 The Weighted Residual Method

$$D(T) - q = 0$$

Where D is a differential operator acting on an unknown function T e g

$$\frac{d^2T}{dx^2} - q = 0$$

The weighted residual method involves substituting an approximate solution into the governing differential equation and then working with the resulting error or residual e.g. if an approximation T(x) is used with

$$T(x) = \sum N_i T_i \qquad i = 1,2, \ldots ,n$$

$$\Rightarrow \qquad \frac{d^2T(x)}{dx^2} - q = R \neq 0 \qquad \text{where R= Residual}$$

The residual is multiplied by a function w, which is function of x, and the integral of the product is then required to be zero

$$\Rightarrow \qquad \int_r w_i R = 0$$

Number of w_i = Number of N_i and T_i

Different weighting functions may be chosen, but the most used approach is known as Galerkin's method. This uses the same weighting functions that are used in the approximating equation

Hence,

$$\int_r N_i R dx = 0$$

N_i are the shape functions

The concept behind the finite element method is of course to discretize the region under consideration so that

$\int_V N_i R dx = 0$ must be converted into elemental form The number of weighting coefficients is equal to the number of nodes in the model and therefore B is composed of n equations for n nodes Therefore for a general body V

$$\int_V [N]^T R dV = 0 \qquad [N]^T = (N_1, N_2, N_3 \quad N_n)$$

Region is subdivided into E elements

$$\sum_{e=1}^{E} \int_{V^{(e)}} \left[N^{(e)}\right]^T R^{(e)} dV = \sum_{e=1}^{E} \{G^{(e)}\} = 0$$

5 4 4 Result of the Variational Formulation and Weighted Residual Methods

In matrix format, for a whole system of elements the use of the variational formulation method and the weighted residual method gives an equation in the following format

$$\sum_{e=1}^{E} \left([\lambda^{(e)}]\{T^{(e)}\} - \{q^{(e)}\}\right) = 0$$

The above equation is the same format for all analysis Solutions for any problem using any element type are derived using the same general approach The approximating functions of specific elements must be taken into account each time the variational or weighted residual methods are used and this is the only difference in the application of the methods

5.5 Assembly and Solution of the Finite Element Equations

The assembly and solution of finite elements equations are not as difficult conceptually as the derivation of finite element equations In terms of computer processing, they are the most demanding and time consuming The solution, in particular, is the most demanding part of analysis

5 5.1 Assembly of the Element Equations

Before some element thermal matrices can be assembled into the global thermal matrix, it is necessary to perform a co-ordinate transformation on the matrix This generally occurs when it is easier to generate a local co-ordinate system rather than the global system To convert from one system to another involves a transformation matrix which is used to pre and post multiply the thermal matrix derived in the local co-ordinate system

Assembly of the element equations into the system equations is simply a question of adding the coefficients of each element thermal matrix into the corresponding places of the global thermal matrix, and summing the force vector coefficients into the global force vector This procedure is similar for all problems The easiest way to assemble the elements is to label each row and column of the element matrix with its corresponding degree of freedom, and then to work through the coefficients of the matrix, adding each into the global matrix which has been similarly labelled

5 5.2 Incorporation of the Boundary Equations[1]

Once the system equations have been assembled to give the system equation, the boundary conditions of the problem must be incorporated The equations cannot be solved without applying any boundary conditions because the conductance matrix will be singular, and therefore its inverse will not exist

There are several ways to incorporate the boundary conditions into the system equations One method is to rearrange the equations and to partition the matrix so that all the specified degrees of freedom are together i e

$$\begin{bmatrix} [\lambda_{11}] & [\lambda_{12}] \\ [\lambda_{21}] & [\lambda_{22}] \end{bmatrix} \begin{Bmatrix} \{U_1\} \\ \{U_2\} \end{Bmatrix} = \begin{Bmatrix} \{F_1\} \\ \{F_2\} \end{Bmatrix}$$

where $\{U_1\}$ is the vector of unknown degrees of freedom, while those in $\{U_2\}$ are all specified Consequently, $\{F_1\}$ will contain only the known nodal forces, and $\{F_2\}$ will contain the unknown reactions By multiplying out the matrices and rearranging them it is then possible to solve the resulting equations in a standard way for the unknown variables $\{U_1\}$ The reactions are then calculated, that is $\{F_2\}$ This method of dealing with the defined boundary conditions is straightforward, but it does require the equations to be renumbered, since it is most unlikely that the specified degrees of freedom will occur at the end of the vector $\{U\}$

The second method is similar, but it does not require the equations to be reordered The matrices are rewritten so that one section of the equation is taken across the equals sign This means that the thermal matrix will have one term set zero and make the procedure easily solvable Generally, the process of incorporating the boundary equations means that the equations for which the boundary exist are easily solvable and from there it is simple mathematics to solve all other equations

When the boundary conditions have been incorporated into the system equations, the final step is the solution for the unknown variables There, are many techniques available The most common methods are Gaussian elimination and Cholesky decomposition In commercial finite element packages, the method most commonly used is the wavefront method

Solution by the Wavefront Method[1]

The system equations have not been completely assembled when this technique is used The model is scanned to determine which element is first and which is last to use each of the nodes This information is stored for later use The element equations are then calculated in turn and assembled into a temporary matrix and vector After the element equations are added in, the nodes are checked for last appearances using the previously derived list When the last entry of a degree of freedom is noticed, the associated equation and corresponding column are removed by Gaussian elimination and written to a decomposed matrix file for later use When the last occurrence of a specified variable (i e boundary condition) is detected, the associated equation is eliminated, and is rewritten to allow the calculation of the reaction

When the last element has been considered, the last degree of freedom can be evaluated Back substitution into the previously stored equations reveals all the unknown degrees of freedom If the reactions are required, then the reaction equations are evaluated At any time there will only be a limited number of degrees of freedom in the temporary matrix Consideration of the model shows that these degrees of freedom form a line across the model which gradually moves like a wave over the model, hence the name of the wavefront method To make the best use of the available computing power, the wavefront, and consequently the size of the temporary matrix, must be kept to a minimum The order m which the elements are considered is important, the element must be must be theoretically be labelled across the shortest dimension of a model to keep the wavefront at a minimum Commercial finite elements packages can carry out these procedures automatically

5 6 Conclusion

Finite element analysis is a complex and a reasonably difficult form of mathematical analysis With the use of computers finite element analysis becomes a very useful and practical tool It is important to note that finite element analysis is based on approximation and therefore even when obtaining very precise results, the results themselves are still an approximation

References

1 Fagan MJ *Finite Element Analysis Theory and Practice* Harlow, Longman Scientific and Technical, 1992

Chapter 6 Finite Difference Theory

Summary

In this chapter two mathematical procedures to generate finite difference equations for thermal problems are presented and defined, the methods of solution of finite difference equations are summarised

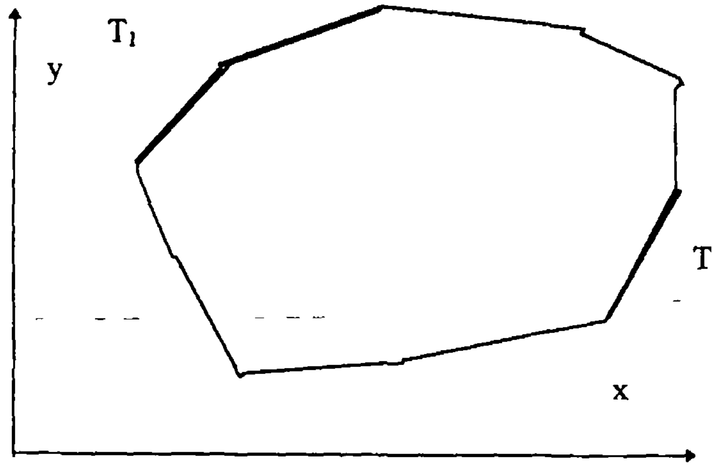
6.1 The Finite Difference Method

The finite difference method consists in generating a mathematical model of a problem by representing it as a group of nodes and generating equations for these nodes

6 1.1 Procedure

The equations used in this modelling process can be generated using a mathematical or an energy balance approach Even in simple models large numbers of equations are generated and therefore this method is generally impracticable manually The solution of these equations can be carried out using matrix inversion and other iterative procedures

Figure 6.1 1. Two Dimensional Region with a Temperature Difference



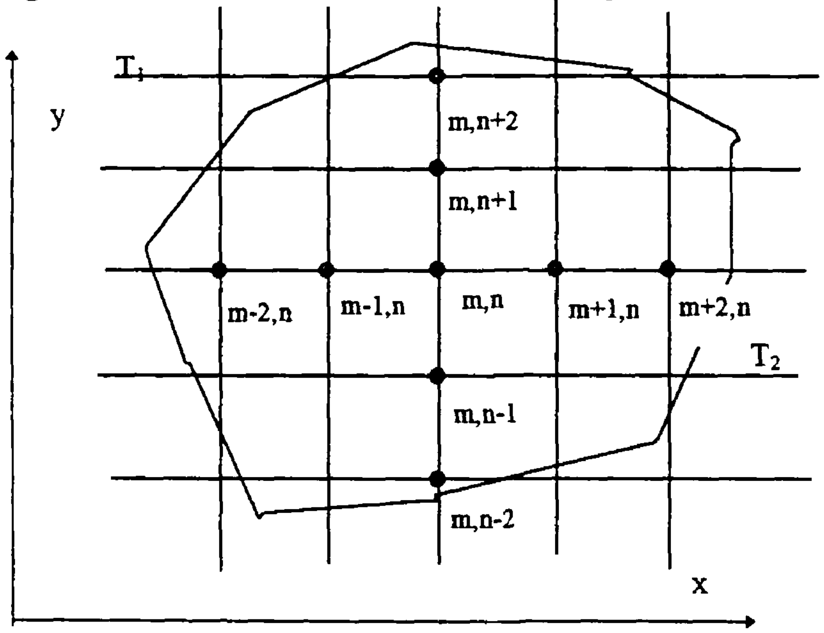
Source. Janna WS *Engineering Heat Transfer* Hong Kong, Van Nostrand Reinhold, 1988, p 214

If a temperature difference is imposed on the region shown in Figure 6 1 1, then heat will flow from the high-temperature surface to the low-temperature surface For two dimensional conduction with constant thermal conductivity, the following equation applies

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

Rewriting this equation using a finite-difference scheme the first step is to divide the region under consideration into a number of nodal points whose temperature will be determined numerically This is shown in the diagram below

Figure 6 1 2 Discretised Two Dimensional Region



Source Janna WS *Engineering Heat Transfer* Hong Kong, Van Nostrand Reinhold, 1988, p 214

Δx and Δy are the dimensions of the grid spacing in the x and y directions respectively and their size depends on the desired accuracy of the analysis and the geometry of the model The temperatures on the grid are denoted by the subscripts m and n to correspond to its nodal position The temperature at node m,n would be thus denoted as $T_{m,n}$

The derivatives of the temperature were evaluated as

$$\left.\frac{\partial T}{\partial x}\right|_{m+\frac{1}{2}\,n} = \frac{T_{m+1\,n} - T_{m\,n}}{\Delta x}$$

$$\left.\frac{\partial T}{\partial x}\right|_{m-\frac{1}{2}\,n} = \frac{T_{m\,n} - T_{m-1\,n}}{\Delta x}$$

$$\left.\frac{\partial T}{\partial y}\right|_{m\,n+\frac{1}{2}} = \frac{T_{m\,n+1} - T_{m\,n}}{\Delta y}$$

$$\left.\frac{\partial T}{\partial y}\right|_{m\,n-\frac{1}{2}} = \frac{T_{m\,n} - T_{m\,n-1}}{\Delta y}$$

Differentiating for a second time

$$\left.\frac{\partial^2 T}{\partial x^2}\right|_{m\,n} = \frac{\left.\left(\frac{\partial T}{\partial x}\right)\right|_{m+\frac{1}{2}\,n} - \left.\left(\frac{\partial T}{\partial x}\right)\right|_{m-\frac{1}{2}\,n}}{\Delta x}$$

$$= \frac{\frac{T_{m+1\,n} - T_{m\,n}}{\Delta x} - \frac{T_{m\,n} - T_{m-1\,n}}{\Delta x}}{\Delta x}$$

$$\left.\frac{\partial^2 T}{\partial x^2}\right|_{m\,n} = \frac{T_{m+1\,n} - 2T_{m\,n} + T_{m-1\,n}}{(\Delta x)^2}$$

$$\left.\frac{\partial^2 T}{\partial y^2}\right|_{m\,n} = \frac{T_{m\,n+1} - 2T_{m\,n} + T_{m\,n-1}}{(\Delta y)^2}$$

Substituting the above equations into the following equation

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

gives

$$\frac{T_{m+1\,n} - 2T_{m\,n} + T_{m-1\,n}}{(\Delta x)^2} + \frac{T_{m\,n+1} - 2T_{m\,n} + T_{m\,n-1}}{(\Delta y)^2} = 0$$

Choosing equal grid spacing in x and directions i e $\Delta x = \Delta y$

$$T_{m+1\,n} + T_{m-1\,n} + T_{m\,n+1} + T_{m\,n-1} - 4T_{m\,n} = 0 \qquad (6\ 1\ 1)$$

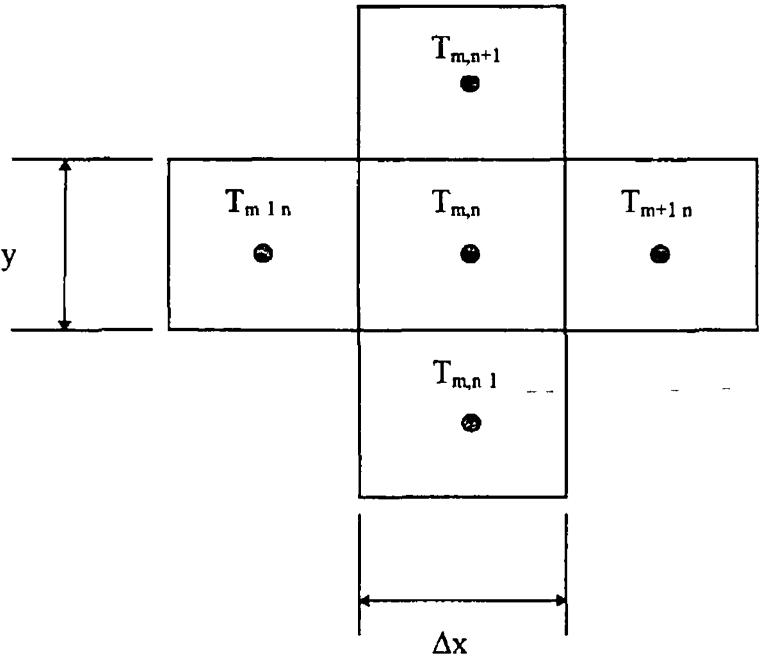
Solving for $T_{m,n}$,

$$T_{m\,n} = \frac{T_{m+1\,n} + T_{m-1\,n} + T_{m\,n+1} + T_{m\,n-1}}{4} \qquad (6\ 1\ 2)$$

Therefore, for any interior node (that is a node which is surrounded by material) where the grid spacing is the same in the x and y directions, the temperature at that node is equal to the average of the temperatures of the four surrounding nodes

The above equation was derived using a mathematical finite difference approach This can also be carried out using a simpler method An equation defining the temperature at the node can be derived by using an energy balance approach Consider the node m,n and surrounding nodes as shown in Figure 6 1 3 below

Figure 6 1.3 Node with Four Surrounding Nodes



Source Janna WS *Engineering Heat Transfer* Hong Kong, Van Nostrand Reinhold, 1988, p 216

The assumption is made that node m,n exchanges energy with the four adjacent nodes according to

Energy flow in = Energy flow out

$\Rightarrow$ The heat transferred by conduction from node m-1,n to m,n is

$$q_{(m-1\,n)-(m\,n)} = \lambda A\frac{\Delta T}{\Delta x} = \lambda\Delta y(1)\frac{T_{m-1\,n} - T_{m\,n}}{\Delta x}$$

Unit depth has been assumed, and Δx is the distance between the nodes In a similar way, an energy balance analysis can be carried out from the point of view of the three remaining surrounding nodes to node m,n giving the following equations

$$q_{(m+1\,n)-(m\,n)} = \lambda\frac{\Delta y}{\Delta x}\left(T_{m+1\,n} - T_{m\,n}\right)$$

$$q_{(m\,n+1)-(m\,n)} = \lambda\frac{\Delta x}{\Delta y}\left(T_{m\,n+1} - T_{m\,n}\right)$$

$$q_{(m\,n-1)-(m\,n)} = \lambda\frac{\Delta x}{\Delta y}\left(T_{m\,n-1} - T_{m\,n}\right)$$

Adding the four heat balances and the node spacing of Δx = Δy gives the following equations

$$0 = \left(T_{m-1\,n} - T_{m,n}\right) + \left(T_{m+1\,n} - T_{m\,n}\right) + \left(T_{m\,n+1} - T_{m\,n}\right) + \left(T_{m\,n-1} - T_{m\,n}\right)$$

$$\Rightarrow 0 = T_{m-1\,n} + T_{m+1\,n} + T_{m\,n+1} + T_{m\,n-1} - 4T_{m\,n} \qquad (6\ 1\ 3)$$

Equation 6 1 3 obtained using the energy balance method can be seen to be the same as equation 6 1 1 which obtained using a mathematical finite difference approach When considering a model nodal equations must be written for each node in the model For each boundary condition, there exists a different form of nodal equations This means, for example that all interior nodes have equations of the same form Equations for nodes with a particular type of boundary condition can be derived using the energy balance method in the same way as for interior nodes Equations of different form have to be derived for the following nodes nodes at lines of symmetry, nodes exposed to convection, radiation, nodes at boundaries between two materials and for combinations of all these conditions

An equation for a node at the edge of a plane wall with convection acting on it is be derived below

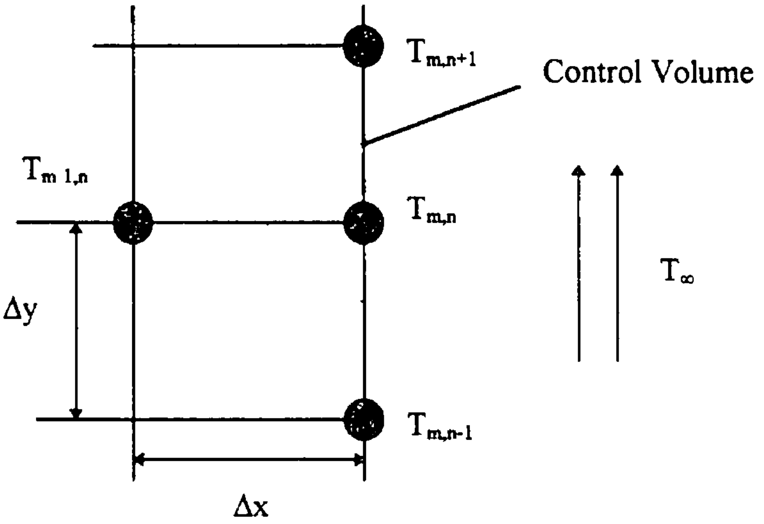


Figure 6.1 4. Node Exposed to Convection with Surrounding Nodes

Performing an energy balance on the wall

Energy conducted to the wall = Energy convected away

$$q_{(m\ n-1)-(m\ n)} = \lambda A\frac{\Delta T}{\Delta y} = \lambda\frac{\Delta x}{2\Delta x}(1)\left(T_{m\ n-1} - T_{m\ n}\right)$$

$$q_{(m-1\ n)-(m\ n)} = \lambda\frac{\Delta x}{\Delta y}(1)\left(T_{m-1\ n} - T_{m\ n}\right)$$

$$q_{(m\ n+1)-(m\ n)} = \lambda\frac{\Delta x}{2\Delta y}(1)\left(T_{m\ n+1} - T_{m\ n}\right)$$

The heat transferred by convection from node m, n to the ambient fluid is

$$q_c = h_c A\Delta T = h_c\Delta y(1)\left(T_{m\ n} - T_\infty\right)$$

Making the energy balance

$$\frac{\lambda}{2}\left(T_{m\ n-1} - T_{m\ n}\right) + \frac{\lambda}{2}\left(T_{m-1\ n} - T_{m\ n}\right) + \frac{\lambda}{2}\left(T_{m\ n+1} - T_{m\ n}\right) = h_c\Delta y\left(T_{m\ n} - T_\infty\right)$$

$\Delta x=\Delta y$ Therefore, the following equation can be obtained

$$0=\left(T_{m,n-1}+2T_{m-1,n}+T_{m,n+1}\right)+\frac{2h_c\Delta y}{\lambda}T_\infty-2T_{m,n}(2+\frac{h_c\Delta y}{\lambda})$$

Following this type of analysis equations can be derived for nodes with other geometrical and boundary conditions

When dealing with real models, the model must first be meshed with nodes and equations for all the nodes derived Certain data such as the node spacing can be decided previously, and is important because when node spacing is unequal in the x and y directions this makes the equations defining the model significantly more complicated Complex geometries such as curves make modelling several times more difficult and generally when using manual methods of calculation models with curved geometries should be avoided[1] Once the equations for a model have been obtained they must be solved using numerical methods

6 2 Methods of Solving Simultaneous Finite Difference Equations[1]

Solution by Gaussian elimination is appropriate for systems in which the equations can be set up in matrix form[2] Another possible method of solution involving matrices is the matrix inversion method[2] The simultaneous equations can be written in matrix form as the following notation

$C_{11}T_1+C_{12}T_2+\ \ C_{1n}T_n=A_1$

$C_{21}T_1+C_{22}T_2+\ \ C_{2n}T_n=A_2$

$C_{n1}T_1+C_{n2}T_2+\ \ C_{nn}T_n = A_n$

The coefficients C_{11}, C_{12}, etc ,and the constants A_1, A_2, etc , are known numerically They involve the physical parameters of the problem such as the thermal conductivity k, the convection coefficient h_c, and increment Δx

In matrix form the simultaneous equations become

$$[C][T]=[A]$$

The solution for temperature is obtained when the inverse of the coefficient matrix $[C]^{-1}$ is found

$$[C][C]^{-1}[T]= [C]^{-1} [A]$$

The product $[C][C]^{-1}$ gives a diagonal matrix with elements which are equal to unity (i e the unity matrix), this implies

$$[T]=[C]^{-1}[A]$$

Therefore, the problem lies in solving for the inverse of a matrix A computer can solve complicated problems quickly

Another possible method of solution is the relaxation method in which the equations for the nodal temperature are written in terms of residuals The objective in this method is to reduce the residuals to zero A temperature value is put into the temperature equations so that a value is obtained for the residual and this is repeated until the residual is approximately zero Once the temperatures are obtained heat transfers are easy to calculate

6 3 Conclusion

The finite difference method was presented for simple two dimensional geometrical shapes The method is difficult to apply to non-rectangular shapes Differential equations can be represented in matrix format and solved using several methods

References

1 Incropera FP, De Witt DP *Fundamentals of heat and mass transfer* New York, John Wiley & Sons, 1990

2 Janna WS *Engineering Heat Transfer* Hong Kong, Van Nostrand Reinhold, 1988

Chapter 7: Simulation of Thermal Bridges

Summary

The assumptions used in the analysis of thermal bridging such as those referring to heat transfer coefficients, cavities, temperatures etc are listed and their validity and accuracy discussed

7 1 Steady-State Conditions

Steady-state conditions have been assumed to represent average conditions The behaviour of thermal bridges has been correspondingly assumed to be adequately represented by steady-state conditions This type of analysis also relates directly to the methods of calculation used in standard construction design practice

7.2 One, Two and Three Dimensional Analysis

One dimensional thermal analysis was applied only for the manual analysis of thermal bridges Most of the thermal bridges under consideration in this project were linear thermal bridges That is, thermal bridges with a uniform cross section in one direction which have been assumed to be two dimensional for the purposes of ANSYS analysis The effects of three dimensional corners were ignored

An axi-symmetric model was used to analyse the most common form of bungalow wall tie This has been assumed to be adequate for the analysis because of the narrow cross-section of the wall tie under consideration

7.3 Temperatures

Values of 7°C and 17°C were used in the simulation of thermal bridges for internal and external temperatures respectively In 1995, the external air temperature in Ireland varied from -12°C to 30°C and the internal temperature can also substantially vary, therefore how important was the use of these values with regard to the results of the thermal simulations?

The analysis of thermal bridges has been carried out with the winter heating season in mind That is, from October to May where an average external air temperature of 7°C is typical[1] The value of the internal temperature has been selected arbitrarily although it would appear to be indicative of mean temperature in Irish houses in the same period

In regard to the ANSYS simulation of thermal bridges, the values of temperatures are completely arbitrary From the temperature distribution obtained, heat flows are evaluated, the bridge conductances (W/K) are then determined by dividing by the total temperature difference The ANSYS analysis depends principally on the values of the heat transfer coefficients used and these have been assumed to remain constant with values as specified in the CIBSE Guide Section A3[2]

Individually, thermal bridges can experience different temperatures Internally, temperatures can substantially vary within small distances For example, since warm air rises it would be expected that in a warm internal environment that the air temperature at ceiling level would be substantially warmer than the air temperature at ground floor level Other factors which can affect the local temperature in a building are infiltration, drafts, solar radiation, shading etc

External temperatures can also vary substantially within small distances depending on orientation, shading, solar radiation, wind direction and surrounding sheltering etc Such considerations have been ignored with regard to this project and the standard temperature values (mentioned above) have been used for internal and external temperatures in the simulation of all thermal bridges

Soil temperatures have been assumed to be the same as the external air temperature There is some evidence that this is the case as stated in The climate of Ireland[1] The logic for this assumption is that during the winter heating season with its generally heavy rainfall, the ground in Ireland is likely to be saturated with water

Consequently, as far as the foundation, external and internal walls and ground floor slab are concerned the surrounding earth has been assumed to be the average external air temperature of 7°C

7.4 Heat Transfer Coefficients

In the simulation of thermal bridges the following assumptions have been made regarding heat transfer coefficients

- The heat transfer coefficients have been assumed to remain constant on internal and external surfaces
- The heat transfer coefficients have been assumed to have the equivalent values to their respective standard resistances as found in Appendix A of Section 3 of the TGD of the 1991 Building Regulations, Part L[3] and are shown below

Table 7 4.1 Surface Resistances and Heat Transfer Coefficients

Building Element	**Surface**	**Resistance (m^2K/W)**	**h (W/m^2K)**
Exposed walls	outside	0 06	16 66
	inside	0 12	8 33
Roofs:	outside	0 04	25
	inside	0 10	10
Exposed floors	outside	0 04	25
	inside	0 14	7 1

Source: Department of Environment *Building Regulations 1991 Technical Guidance Document L Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991, p 13

These follow the assumptions made in the CIBSE Design Guide Section A3 and the first two assumptions necessitate the following

- No changes in air velocities occur at internal or external surfaces

- The heat transfer coefficients have been assumed to be unaffected by their position on a surface and only affected by the direction of heat flow.
- Heat transfer by radiation and convection at the surfaces of building elements has been assumed to be modelled by analogous thermal resistances which can be combined to give a surface resistance as follows:

$$R_s = \frac{1}{Eh_r + h_c}$$

where

R_s = surface resistance m^2K/W

$E = \Theta\, \varepsilon_1\, \varepsilon_2$ = emissivity factor

Θ= form (or shape) factor

ε_1, ε_2 = emissivities of the surfaces involved

h_r = radiative heat transfer coefficient $W/m^2\,K$

h_c = convective heat transfer coefficient $W/m^2\,K$

For building materials the emissivity have been assumed to have values of 0.9

7.4.1 Internal Heat Transfer Coefficients

- The air speed at the surface has been assumed not to be greater than 0.1 m/s
- The convective heat transfer coefficients have been assumed to depend only on the direction of the heat flow. That is upward, downward or horizontal

Table 7.4.2: Convective Heat Transfer Coefficient, h_c

Heat Flow Direction	**h_c / (W/m^2K)**
Horizontal	3.0
Upward	4.3
Downward	1.5
Average	3.0

Source CIBSE *CIBSE Design Guide Section A3* London, CIBSE, 1986, p. A3.6

- For standard surface resistances the shape factor has been multiplied by 6/5 (this factor is standard for heat transfer between a single surface area and its enclosing space, in this case a cubical room)[4]
- Surfaces have been assumed to have a temperature of 20°C

Table 7.4.3· Radiative Heat Transfer Coefficient and Temperature, h_r

Temperature of Surface / °C	**h_r/ (W/m^{2}K)**
-10	3 0
0	4 3
10	1 5
20	3 0

Source CIBSE *CIBSE Design Guide Section A3* London, CIBSE, 1986, p A-6

7 4 2 External Heat Transfer Coefficients

- The convective heat transfer coefficients have been assumed to be for turbulent air flows
- Shape factor for radiative heat transfer has been assumed to be unity
- It has been assumed that in winter heating design weather the walls receive little sunshine and the outside surface resistance is unaffected by orientation
- External surface resistances have been assumed to be for normal exposure conditions

7 4.3 Validity of Heat Transfer Coefficients

The calculation of heat flows for the thermal bridges has been based on the use of the standard internal heat transfer coefficients This has been carried out by calculating the heat transfer from the internal environment to the wall using Fourier's equation with the surface resistance as the thermal resistance and the ANSYS simulation surface temperatures

The heat transfer coefficients used in simulation were the normal heat transfer coefficients used in standard design practice A very accurate analysis would take into account all factors such as complex fluid flows but for the purposes of the project such an analysis was impracticable

The internal heat transfer coefficients values are assumed in the CIBSE Guide Section A3 to apply to surfaces at 20°C and to cubically shaped rooms These are commonly used values in standard practice and no corrections are made for changing surface resistances due to different shape factors and differing surface temperatures This has been assumed to make little difference to results since this problem does not affect well insulated rooms to a large degree However in the case of simulations for thermal bridges at different parts of a room, such as a wall corner at floor level, the heat transfer coefficients could be expected to be different An evaluation of the importance of the heat transfer coefficients can be taken into account by carrying out a sensitivity analysis of the thermal bridge by changing the heat transfer coefficients used in the simulation

For the particularly important thermal bridge of the bungalow foundation, external wall and floor the internal heat transfer coefficients have been decreased by 20% and the variation of bridge conductance was found not to be significant The bridge conductance with the decreased heat transfer coefficients was found to be 0 39 W/mK which represented a 4 8% decrease in the value of bridge conductance

7.5 Cavity

In the simulation of thermal bridges the following assumptions have been made regarding cavities, air gaps and air spaces

- Cavities have been assumed to be media with thermal resistance since the radiation and convection heat transfer across them is approximately proportional to the difference between the temperatures of the boundary surfaces

- The values of cavity resistance have been assumed to be equivalent to those in found in Tables A3 7 and A3 8 of the CIBSE Guide Design Data Volume A Section A3[5]
- Cavities have been assumed to be accurately modelled by materials with effective thermal conductivities and therefore comparable resistances to the values found in the CIBSE Guide Section A3

In consideration of the above the following assumptions have also been made

- It has been assumed that the thermal resistance of vertical airspaces increases as its thickness increases up to 25 *mm* and that for greater thicknesses the thermal resistance remains constant
- The effect of airspace ventilation has been assumed to be negligible and the airspace has been assumed to be essentially composed of static air in which turbulent and highly convective flows do not occur

These assumptions ignore turbulent fluid flow, convective and radiative effects which may occur within the cavities The disparity between reality and these assumptions can be significant Although these effects are important for the behaviour of the cavity they would be much less significant in regard to the thermal bridge conductance

For cavities within hollow blocks the simulation can be made more accurate by using orthotropic (i e having different physical properties in different directions) material properties The simulation of thermal bridges would have been too complicated by the complete simulation of such cavity behaviour

7 6 Material Properties

Construction materials have been assumed to be completely homogeneous and their thermal properties have been assumed to be as found in CIBSE Guide Section A3 Table A3 15[6] and the TGD Part L of the 1991 Building Regulations Conservation of Fuel and Energy

All properties of materials have been assumed to remain constant at all temperatures occurring during the heating season in Ireland The temperature variation during the heating season period to which the thermal bridges are submitted to has been assumed not to make significant differences when considering temperature related properties The materials have also been assumed to be isotropic (i e having same physical properties in all directions) The majority of materials found within constructions are isotropic although timber is an exception to this The heat loss that occurs at thermal bridges in many cases is so severe relative to other non-bridged sections of buildings that the change in calculation values due to including anisotropic and temperature dependent properties of materials has been assumed to be negligible

The conductivities of materials have also been assumed to have an average moisture content correction factor already included in their values With respect to this assumption the CIBSE Guide Section A3 notes that *'The thermal conductivity of a porous building material is determined by its density and, if moist, by the percentage of moisture in the pores '*

and

'It is less easy, however, to measure the thermal conductivity for masonry materials (brickwork and concrete) The chief difficulty is that many such materials contain appreciable amounts of moisture, either because they are hygroscopic and absorb moisture from the surrounding air or because they are exposed to rain Corrections for the moisture content of masonry materials are given in Appendix 3 '

In Appendix 3 of the CIBSE Design Guide Section A3 correction factors are given for different levels of moisture present in masonry The effect of increasing the thermal conductivity of the block below the dpc to simulate a material with moisture content of 25% has been carried out and was found not to be significant For the thermal bridge of foundation, external wall and ground floor, this was found to increase the bridge conductance by 29%, the revised bridge conductance being 0 53 W/mK

The most significant assumption has been that CIBSE Guide values represent accurately the properties of current construction materials Comparing the different conductivity values for cast concrete in the CIBSE Guide led to some doubt as to how accurate these values were The principal factor in having assumed these material property values as standard has been their use in the calculation of U values in the TGD of the 1991 Building Regulations

7.7 A Model as Represented in ANSYS

The dimensions and construction of the thermal bridges have been assumed to be generally as illustrated and in the NHGBS (National House Building Guarantee Scheme) Guide[7] and the Safehome Manual[8] and also complying to the 1991, Building Regulations This has been regarded as standard construction practice although construction practice is particular to each individual construction and development

In the simulation of individual thermal bridges, some aspects of the construction such as mortar joints, dpc, dpm, and ties have been considered not to affect the thermal behaviour of the bridge significantly For relatively unbridged sections of a construction affected by thermal bridges, it can be assumed that when two or more bridges are present together their own individual effect is separate and can be superimposed with the other to obtain the combined effect of the two bridges

The models of thermal bridges have been assumed to conform with perfect workmanship—Poor workmanship and aspects of real constructions which occur in practice such as small air gaps, unevenly laid blocks and deviations in building geometry have been completely ignored Many of these are likely to worsen thermal bridging effects

In some simulations, the complex shapes or thin layers present were simplified or ignored in order to make the simulation possible

7 8 Conclusion

The majority of assumptions that have been used in the analysis of thermal bridges have been those found in the CIBSE Design Guide Section A3 The most important of these were the assumptions regarding heat transfer coefficients which significantly simplified the analysis process Also significant was that for ease of analysis, the same temperatures were used for all thermal bridge simulations

References

1 Rohan PK *The Climate of Ireland* Dublin, The Stationary Office, 1986

2 CIBSE *CIBSE Guide Volume A Design Data Section A3* London, CIBSE, 1986

3 Department of Environment *Building Regulations 1991 Technical Guidance Document L Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991, p 13

4 CIBSE *CIBSE Guide Volume A Design Data Section A5* London, CIBSE, 1986, p A5-10

5 CIBSE *CIBSE Guide Volume A Design Data Section A3* London, CIBSE, 1986, p A3-8

6 Ibid, p A3-21

7 NHBGS *The NHBGS House Building Manual* Dublin, NHBGS, 1993

8 Concrete Development Group *The Safehome Manual* Dublin, Concrete Development, 1994

Chapter 8: Thermal Analysis of Thermal Bridges

Summary

In this chapter three thermal bridging examples are considered

1 Cavity wall with a thermal bridge

2 Thermal bridge from a bungalow

3 Thermal bridge from a semi-detached house

For the first thermal bridge example, three methods of analysis are used, the proportional area method, the finite difference method and the finite element method In the case of the two other examples the finite element method is only used Specific assumptions and boundary conditions are listed for each thermal bridge example

8.1 Example: Cavity Wall with a Thermal Bridge

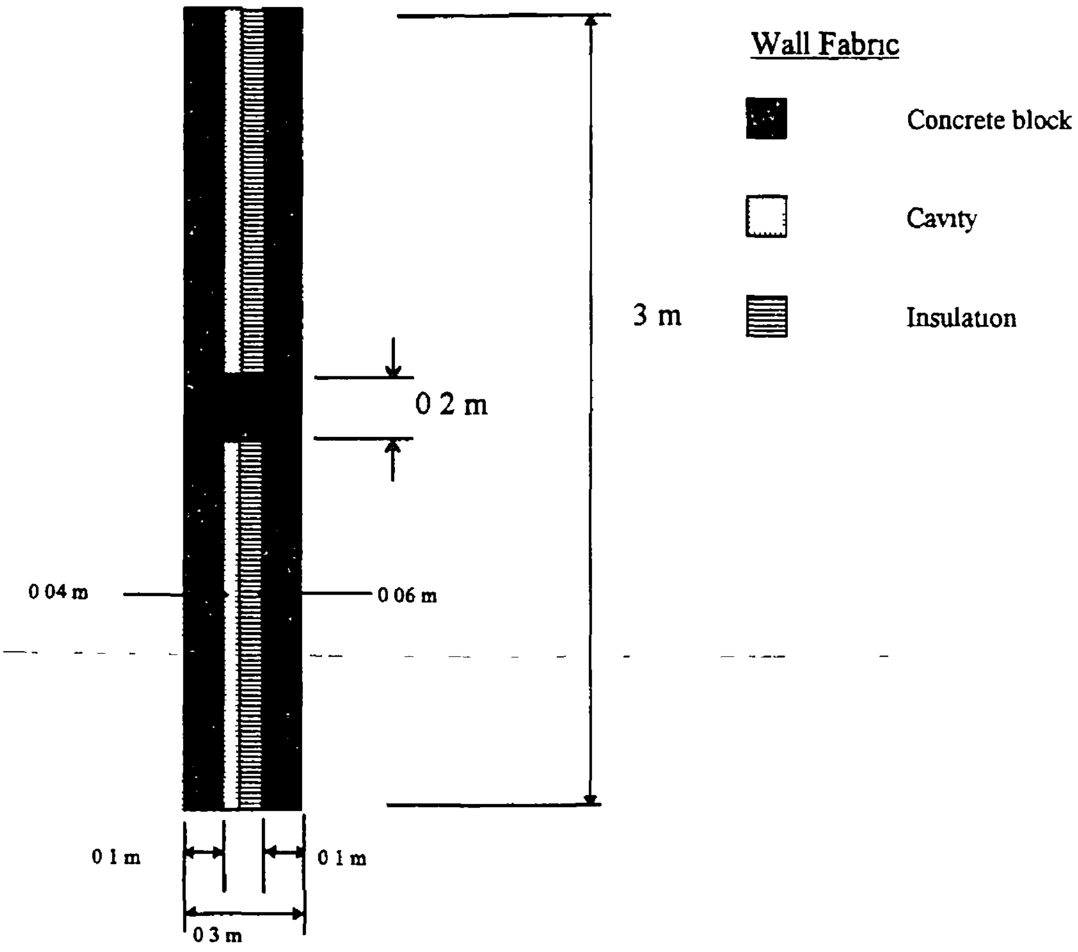


Figure 8 1 1: Cavity Wall with Thermal Bridge

8 1 1 Description

As an example to illustrate the different analysis methods, a cavity wall with a connecting solid component from the exterior wall to the interior wall was chosen This solid component constitutes a major heat flow path and is a thermal bridge The analysis is two dimensional as the bridge is a linear thermal bridge

8 1 2 Boundary Conditions and Data for Calculations

(i) Assumptions

1 Steady state conditions apply throughout the calculations
2 The cavity is treated like a material with an effective resistance of 0 18 m^2K/W
3 Uniform heat transfer coefficients apply on internal and external surfaces
4 Material properties and boundary conditions remain constant

(ii) Materials

1 Concrete block/bridge λ=1 4 W/mK (CIBSE Guide Table A 3 6)[1]
2 Insulation λ=0 035 W/mK (CIBSE Guide Table A 3 6)[1]

(Materials with these properties are also listed in Part L of the 1991 Building Regulations, Table 5)

(iii) Standard Resistances

Outside wall surface resistance, R_{so} = 0 06 m^2K/W (CIBSE Guide Table A 3 6)[2]
Cavity resistance, R_{cav} = 0 18 m^2K/W (CIBSE Guide Table A 3 7)[3]
Inside wall surface resistance, R_{si} = 0 12 m^2K/W (CIBSE Guide Table A3 5)[2]

(iv) Temperatures

Outside environmental temperature, t_{eo}=7° C
Inside environmental temperature, t_{ei}=17° C

8 1 3 Analysis using Methods as found in the TGD, Part L of the 1991, Building Regulations

Element	**λ (W/mK)**	**Δx(m)**	**R (m^2K/W)**
Outside Surface	----	----	0 06
Block	1 4	0 1	0 071
Cavity	0 2222 (effective)	0 04	0 18
Insulation	0 035	0 06	1 714
Block	1 4	0 1	0 071
Inside Surface	----	----	0 12
Total Resistance			2 216

Table 8 1.1· Thermal Elements with their Corresponding Conductivities and Resistances

The total resistance of the wall is calculated

$R_{Total} = R_{so} + R_B + R_{cav} + R_i + R_B + R_{si}$

$\Rightarrow R_{Total}$=0 06+0 071+0 18+1 714+0 071+0 12= 2 216 m^2 K/W

$\Rightarrow$ U = 0 45 W/m^2K

$\Rightarrow$ Q= U ΔT= 4 5 W/m^2

8 1 4 Calculation Method 1. CIBSE / Proportional Area Method

‘If both leaves and the cavity are bridged by a single element (e.g concrete column), the resistances of the bridged and unbridged elements should be combined in proportion to their areas ’

(CIBSE Guide Volume A Section A3, page A3-10)

$\Rightarrow U= P_1U_1+P_2U_2+$

Where

P_1= unbridged proportion of the total area

P_2= bridged proportion of the total area

$R_1 = R_{so} + R_B + R_{cav} + R_i + R_B + R_{si} = 2\ 216\ m^2\ K/W$

$\Rightarrow U_1 = 0\ 45\ W/m^2K$

$P_1 = 2\ 8/3 = 0\ 9333$

$R_2 = R_{so} + R_B + R_B + R_B + R_{si} = 0\ 3943\ m^2\ K/W$

$\Rightarrow U_2 = 2\ 54\ W/m^2K$

$P_2 = 0\ 2/3 = 0\ 0666$

$U = 0\ 9333 \times 0\ 45 + 0\ 0666 \times 2\ 54$

$\quad = 0\ 42 + 0\ 169$

$\quad = 0\ 589\ W/m^2K$

8 1.5 Calculation Method 2. Finite Difference Method

The model was meshed with a node spacing of 0 025m Each node was represented by an equation in a spreadsheet The majority of nodal equations were of the same form, different forms existing for nodes at material boundaries, lines of symmetry, corners etc These equations were derived initially by analysing nodes using an energy balance approach The nodal equations were solved by iteration in the spreadsheet

8 1 6 Calculation Method 3: Finite Element Method

This analysis was carried out using the finite element package ANSYS ANSYS is split up into three steps pre-processing, solution and post-processing In pre-processing the element type, mesh density, material properties and geometric properties of the model are specified The model was represented by two dimensional areas and was then meshed with a mesh density of 0 025m This is an automated process in ANSYS In the solution phase, the convection loads were specified by applying them to the corresponding lines on the model, the solution was then executed The analysis of results was carried out in the post-processing section were the nodes of the interior wall were selected for analysis

8.1.7 Results: Graphs

Inside Wall Surface

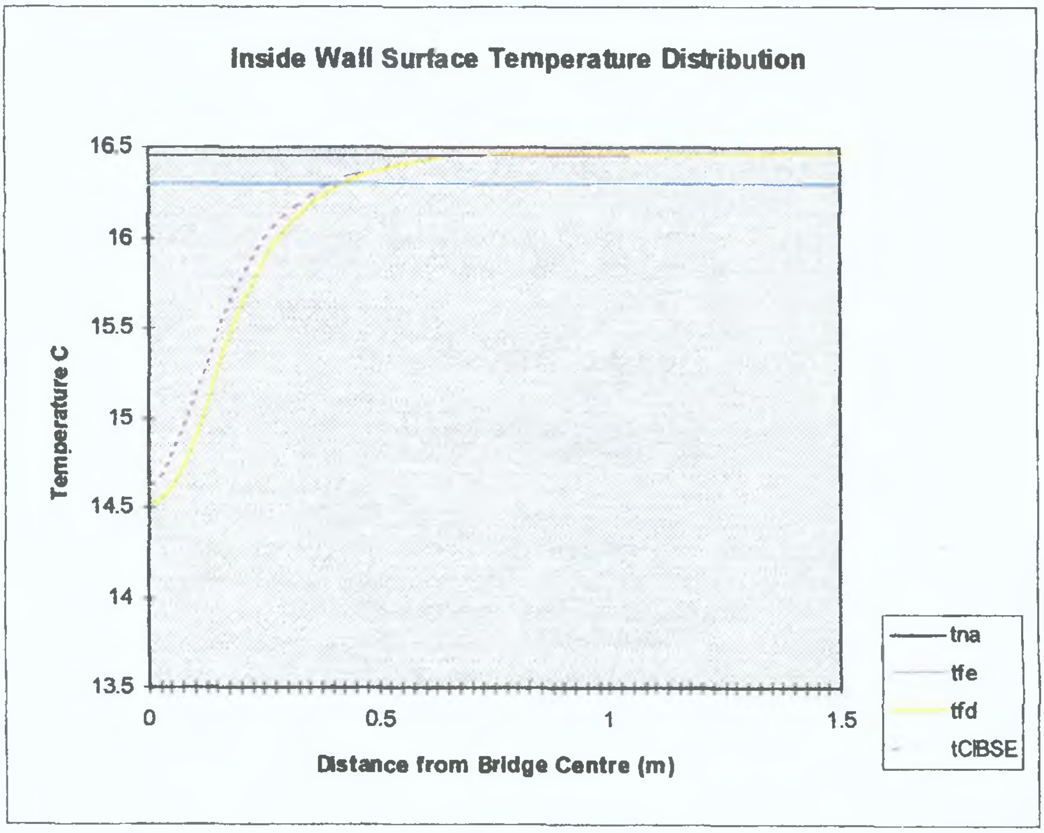


Figure 8.1.2: Graph of Inside Wall Surface Temperature Distribution and Distance from Bridge

Note: t_{na} is the temperature calculated using standard one dimensional analysis without taking account of the thermal bridge.

t_{fe} is the temperature calculated using the ANSYS program to simulate the thermal bridge.

t_{fd} is the temperature calculated using the finite difference method.

t_{CIBSE} is the temperature calculated using the proportional area method.

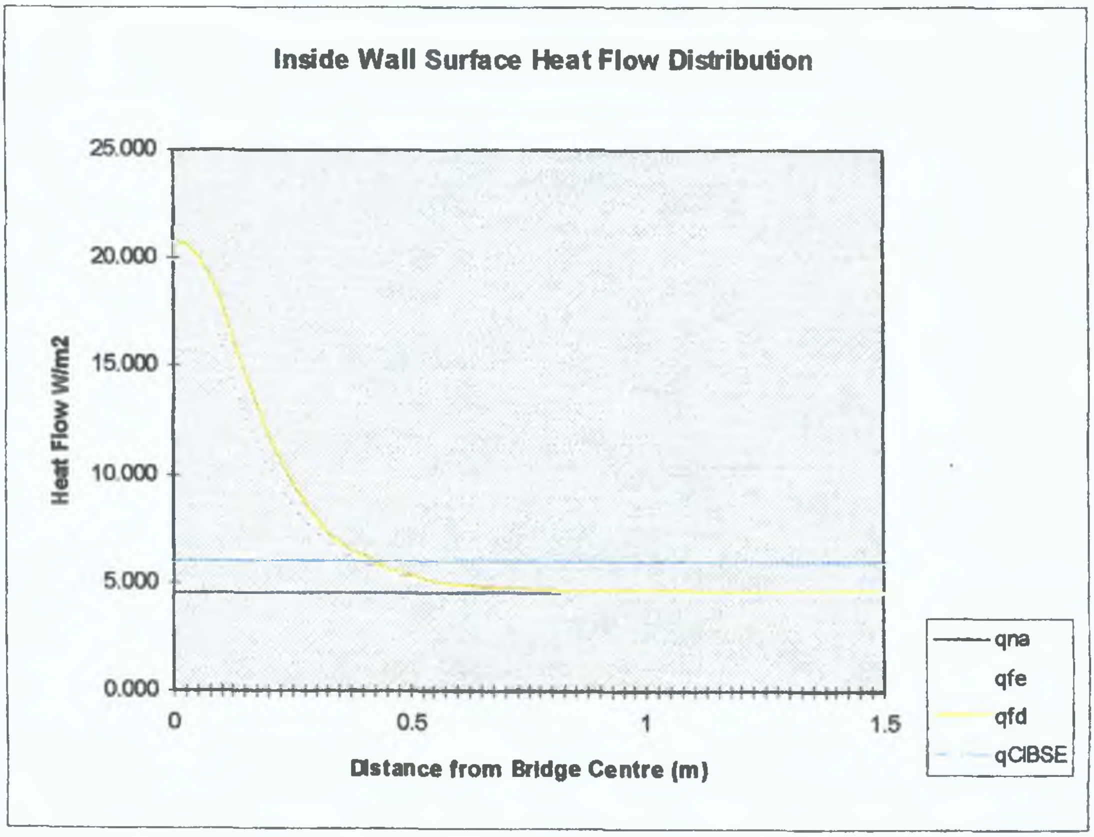


Figure 8.1.3: Graph of Inside Wall Surface Heat Flow Distribution and Distance from Bridge

Note: q_{na} is the heat flow calculated using standard one dimensional analysis without taking account of the thermal bridge.

q_{fe} is the heat flow calculated using the ANSYS program to simulate the thermal bridge.

q_{fd} is the heat flow calculated using the finite difference method.

q_{CIBSE} is the heat flow calculated using the proportional area method.

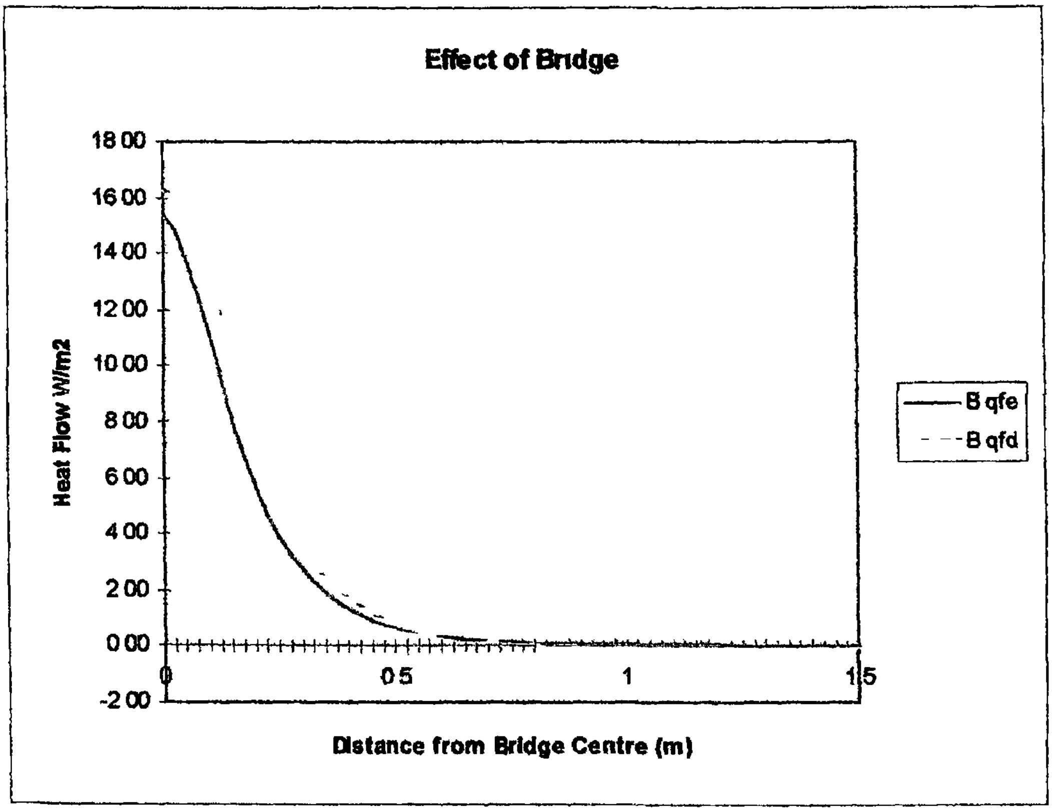


Figure 8.1 4: Graph of Effect of Bridge and Distance from Bridge

Note: B q_{fe} is the bridge effect (i e the difference between the heat loss of the construction affected by the bridge and the heat loss that the construction would normally incur) calculated using the ANSYS program to simulate the thermal bridge

B q_{fd} is the bridge effect calculated using the finite difference method

8 1 8 Results Summary

Wall Surface	**U-value (W/m^2K)**	**As % of U-value Building Regulations**
Nominal U value B Regulations (W/m^2K)	0 45	100
CIBSE Proportional Area Method U value	0 59	131
Averaged ANSYS U value (W/m^2K)	0 66	146
Averaged Finite Difference U value (W/m^2K)	0 69	153
Effect of bridge (CIBSE, W/m^2K)	0 14	31
Effect of bridge (ANSYS, W/m^2K)	0 21	46
Effect of bridge (Finite Difference, W/m^2K)	0 23	53
Bridge Conductance (ANSYS, W/mK)	0 63	

Table 8 1 2 Results of Analysis of Cavity Wall with a Thermal Bridge

8 1 9 Discussion

The ANSYS and finite difference U values in Table 8 1 2 were calculated from the averaged inside wall surface temperatures of the bridge The effect of the thermal bridge is very significant and affects the whole wall From the table and graph it can be seen that thermal bridging increases the U value by approximately 50% The bridge conductance is 0 63 W/mK (per metre run of wall)

8 2 Analysis of Bungalow Thermal Bridge with ANSYS

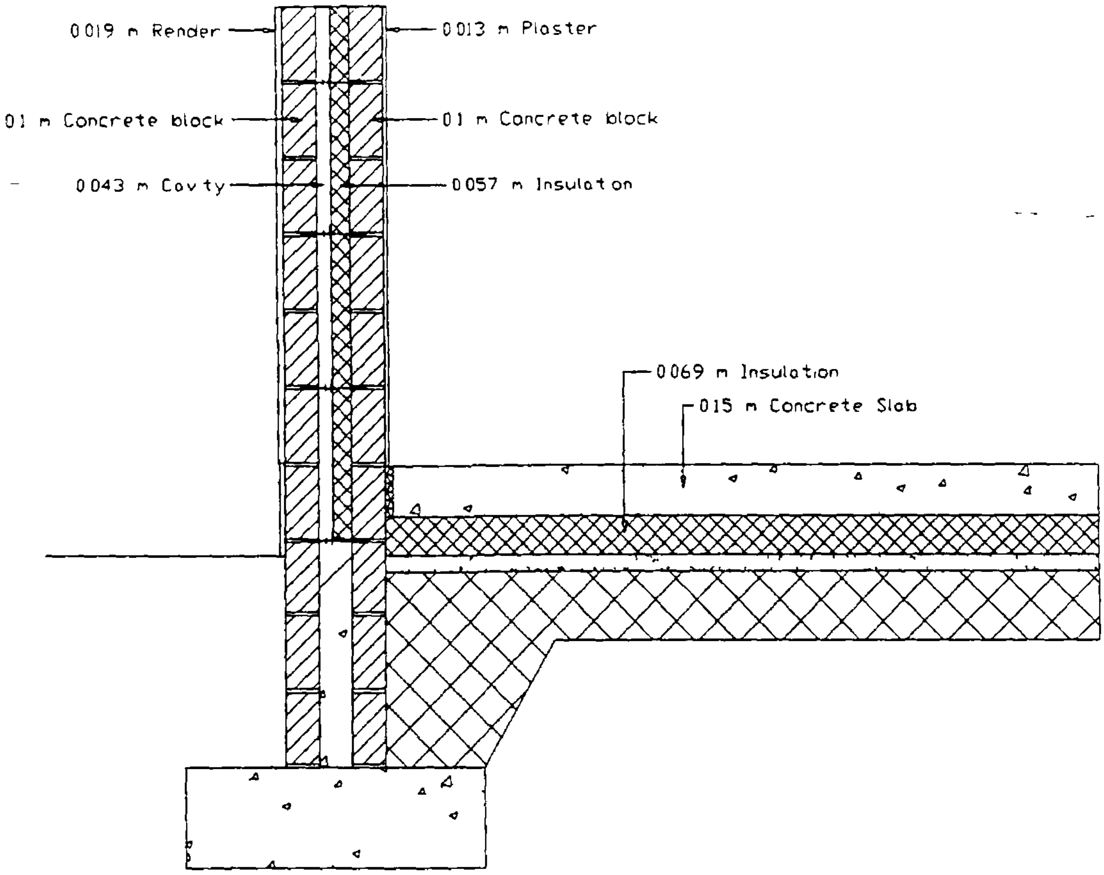


Figure 8.2 1 Bungalow Foundation, Floor and External Wall

8 2.1 Description

Figure 8 2 1 shows the thermal bridge which occurs at the junction of the external wall, floor and foundation The largest heat flow will be through the path which offers the least thermal resistance In this case, the path of least resistance follows downwards through the internal leaf of the wall to the foundation and external leaf, this is the major bridge which occurs in this construction There also exists a lesser bridge which is from the floor slab through the edge insulation to the internal leaf of the wall

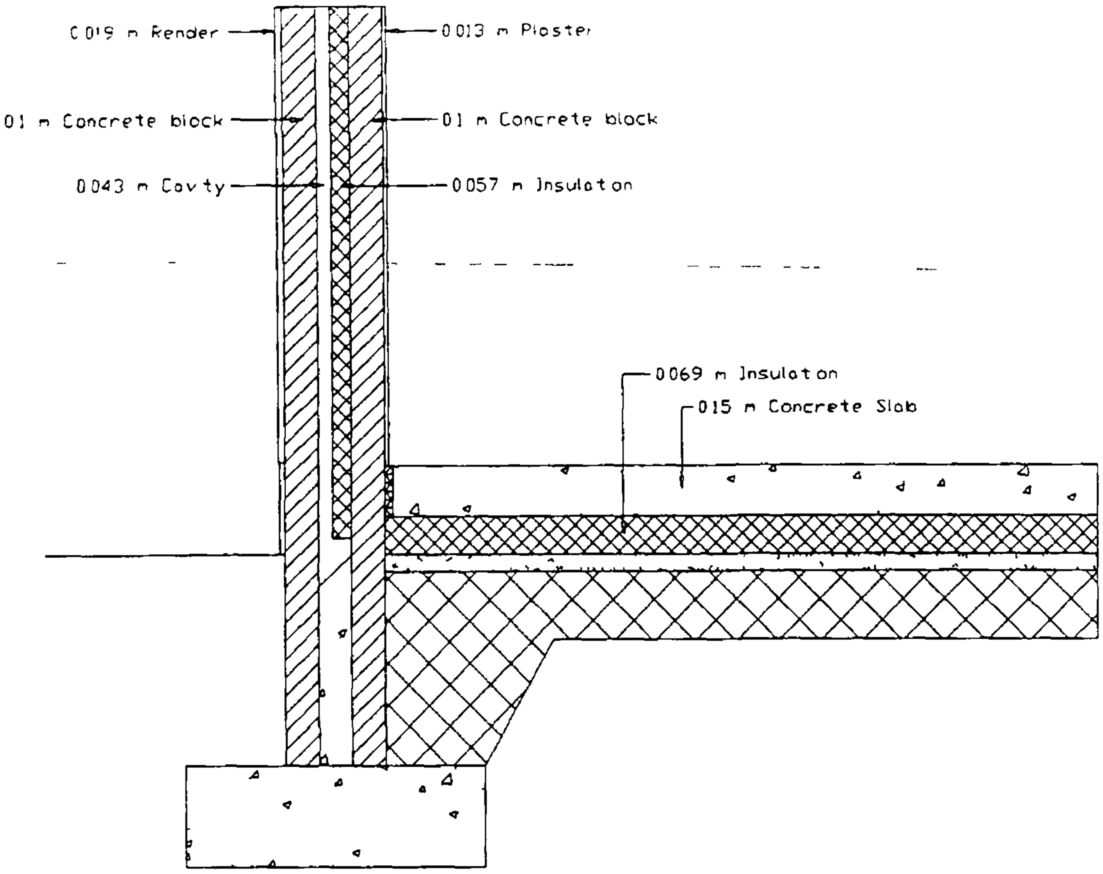


Figure 8.2.2. ANSYS Representation of Example 8 2

Figure 8 2 2 shows two dimensionally the bridge as it is represented in the ANSYS program In the ANSYS model wall ties, mortar joints, damp proof course, and damp proof membrane have been ignored Uniform thermal conductivities and heat transfer coefficients have been assumed and the insulation levels present have been chosen to meet standard or nominal U values found in the TGD of the 1991 Building Regulations, Part L

For the purpose of the simulation, an inside environmental temperature of 17°C and outside air temperature and ground temperature of 7°C[4] were used These values are arbitrary and any selected values can be used in the simulation

Using the surface heat transfer coefficients, the heat flow at the surfaces affected by the thermal bridge can be obtained These heat flows divided by the total temperature difference (10 °C in this case) yield the effective ANSYS U values

8.2.2 Boundary Conditions and Data for Calculations

(i) Assumptions

1. Steady state conditions apply throughout the calculations
2. The cavity is treated like a material with an effective resistance of 0.18 m^{2}K/W
3. Heat transfers coefficients remain uniform on all internal and external surfaces
4. Boundary conditions remain constant
5. Temperature of earth below foundation is 7°C
6. Wall ties, mortars joints, dpc and dpm are not considered within the model
7. The results are based on the average of the internal wall temperatures affected by the bridge
8. Materials properties are assumed to be isotropic, and have no variation with temperature or time
9. Moisture content is not considered in the calculations
10. The earth and hardcore are represented adequately by assumption 5

(ii) Materials

1. Render	λ=0.5 W/mK	(CIBSE Guide Table A 3.15)
2. Concrete block	λ=1.63 W/mK	(CIBSE Guide Table A 3.15)
3. Insulation	λ=0.035 W/mK	(CIBSE Guide Table A 3.15)
4. Plaster	λ=0.16 W/mK	(CIBSE Guide Table A 3.15)

(These thermal conductivities of these materials can also be found in the TGD of Part L of the 1991 Building Regulations, Table 5)

(iii) Surface Resistances

Outside wall surface resistance,	R_{so}=0.06 m^{2}K/W	(CIBSE Guide Table A 3.6)
Cavity resistance,	R_{cav}=0.18 m^{2}K/W	(CIBSE Guide Table A 3.7)
Inside wall surface resistance,	R_{si}=0.12m^{2}K/W	(CIBSE Guide Table A3.5)
Inside floor surface resistance,	R_{si}=0.14 m^{2}K/W	(CIBSE Guide Table A3.5)

(These resistances can be found in the TGD of Part L of the 1991 Building Regulations, Table 5) *(iv) Temperatures*

Outside environmental temperature $t_{eo}=7°\ C$

Inside environmental temperature $t_{ei}=17°\ C$

8.2.3 Calculation of Bridge Conductance for Wall, Floor and Foundation

Bridge Conductance = (Averaged ANSYS U value for wall× Wall height
+ Averaged ANSYS U value for floor× Floor width)
-(TGD Part L of the 1991 Building Regulations U value for wall× Wall height + TGD Part L of the 1991 Building Regulations U value for floor× Floor width)

⇒Bridge Conductance = $(0.648\ W/m^2K \times 1.55\ m + 0.516\ W/m^2K \times 1.515\ m)$
$-(0.449\ W/m^2K \times 1.55\ m + 0.448\ W/m^2K \times 1.515\ m)$

⇒Bridge Conductance = 1.786-1.373 = 0.41 W/mK

8.2.4 Results Summary

Bridge	**Wall, floor and foundation**	
Surface	**Inside Wall**	**Floor**
U value TGD Part L of the Building Regulations (W/m^2K)	0.449	0.448
Averaged ANSYS U value (W/m^2K)	0.648	0.516
Effect of bridge (ANSYS, W/m^2K)	0.175	0.068
Effect of bridge as % of 0.45 W/m^2K	44	15
Bridge Conductance (ANSYS, W/mK)	0.41	
Effect on 1m section of plane 2.5m high wall as %	36	

Table 8.2.1: Results of Analysis of Bungalow Thermal Bridge

8 2 5 Discussion

For the region of the wall affected by the bridge, the ANSYS U value is 0 648 W/m^{2}K or 44% greater than the nominal U-value of 0 45 W/m^{2}K The corresponding figure for the floor is 15% When both are combined there is an additional heat loss above that represented by the nominal values of U for wall and floor, this is given by the 'bridge conductance' of 0 41 W/mK (W/K per metre length of wall), also known as the 'linear thermal transmittance' This is quite significant It represents 36% of the nominal heat loss of a plane wall (no openings) 2 5 m high (corresponding to the typical bungalow wall height)

As the bridge extends around the full perimeter of the house, a heat loss coefficient of 20 5 W/K due to the bridge would result from a typical perimeter length of 50 m If the house has a total wall area of 100m^2, 20% glazing and a nominal wall U-value of 0 45 W/m^{2}K, the heat loss coefficient for the opaque wall is 80 m^2 × 0 45 W/m^{2}K or 36 W/K The bridge to the foundation is 57% of this value The bridge loss might also be compared with the glazing loss in the above example This would amount to 56 W/K for double glazing (U = 2 8 W/m^{2}K)

In actual construction, a skirting board would decrease the bridge loss, higher thermal conductivities below the damp proof course or using dry lining, would increase or decrease the effect Floor finish will also affect the bridge Usual practice of mounting radiator panels directly on external walls will have significance in terms of direct wall loss and through the bridge to foundation In some cases, it is the practice to place a screed over the floor slab and across the edge insulation, this would significantly increase the thermal bridge conductance (to 0 52 W/mK)

Finally, it must be noted that increasing levels of wall insulation increase the relative importance of this bridge

8 3 Analysis of Semi-Detached House Thermal Bridge with ANSYS

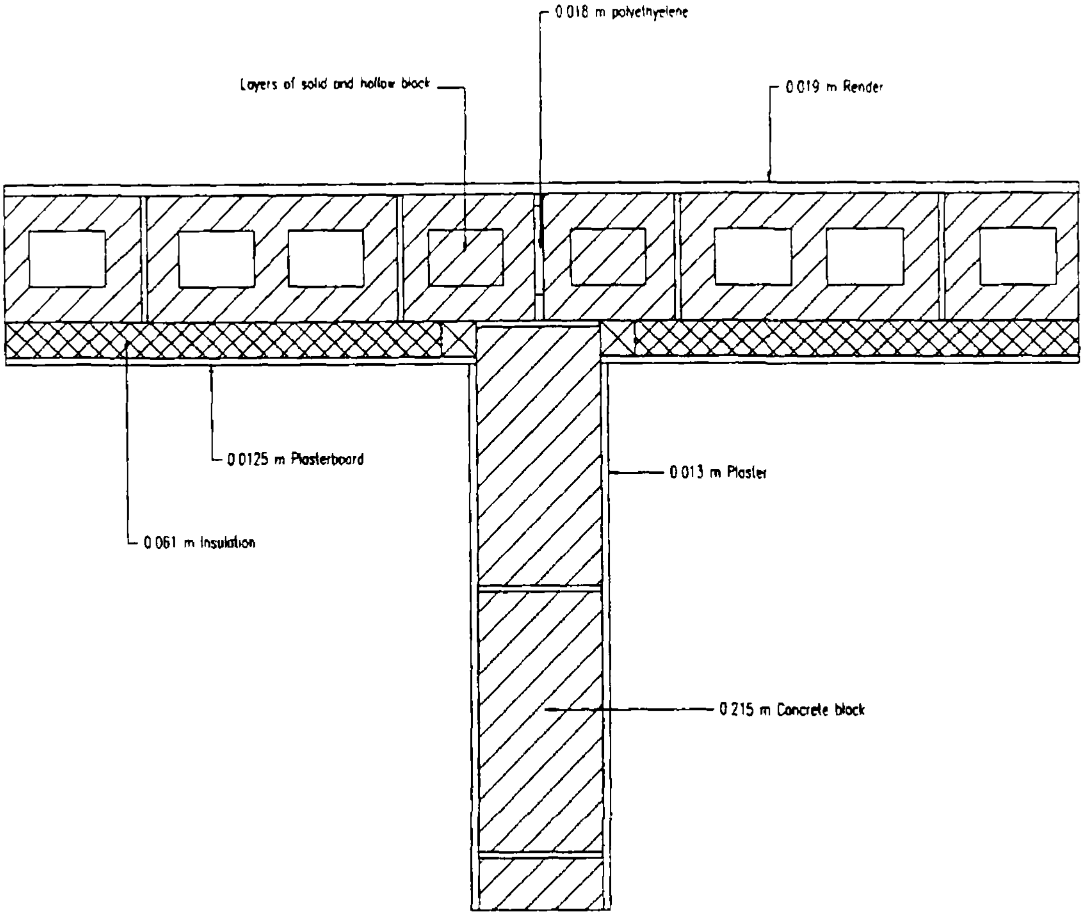


Figure 8.3.1 Party Wall of Two Adjoining Semi-Detached Houses

8 3 1 Description

The above diagram, Figure 8 3 1 illustrates the construction of a party wall between two adjoining semi-detached houses The junction of the party wall with external wall is uninsulated and this constitutes a major bridge The party wall is made up of high density concrete block which has a high thermal conductivity and therefore conducts heat away from both houses Mortar joints and wall ties are ignored (see Appendix A Figure A4 11 1)

8 3 2 Boundary Conditions and Data for Calculations

(i) Assumptions

1 Steady state conditions apply throughout the calculations

2 Uniform heat transfer coefficient apply on internal and external surfaces

3 Material properties and boundary conditions remain constant

4 Hollow block is approximated by a material with an effective conductivity

5 Bridge is assumed to be symmetrical about its axis

(ii) Materials

1 Render	λ=0 5 W/mK	(CIBSE Guide Table A 3 15)
2 Hollow block	λ=1 18 W/mK	(CIBSE Guide)
3 Insulation	λ=0 035 W/mK	(CIBSE Guide Table A 3 15)
4 Concrete block	λ=0 51 W/mK	(CIBSE Guide Table A 3 15)
5 Plaster	λ=0 16 W/mK	(CIBSE Guide Table A 3 15)

(iii) Standard Resistances

Outside wall surface resistance,	R_{si}=0 06m^{2}K/W	(CIBSE Guide Table A3 5)
Inside wall surface resistance,	R_{si}=0 12 m^{2}K/W	(CIBSE Guide Table A3 5)

(iv) *Temperatures*

Outside environmental temperature,	t_{eo}=7° C
Inside environmental temperature,	t_{ei}=17° C

8 3 3 Results Summary

Bridge	External Wall and Party Wall	
Surface	**External Wall**	**Party Wall**
U value Building Regulations (W/m^{2}K)	0 45	0
Averaged ANSYS U value (W/m^{2}K)	0 487	0 32
Effect of bridge (ANSYS,W/m^{2}K)	0 037	0 32
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	8	----
Bridge Conductance (ANSYS, W/mK)	0 42	

Table 8 3.1. Results of Analysis of Semi-Detached House Thermal Bridge

8 3.4 Discussion

This bridge is present for approximately a 4 8 m length This constitutes a heat loss of 2 W/K and can be considered as a serious thermal bridge

8 4 Conclusion

In the first example manual and computer methods of analysis have been used for thermal bridges The manual and computer results are significantly different (see Table 8 1 2) These differences between the results are explained by the higher degree of approximation in the manual analysis methods The computer methods take into account, to a much greater degree, the geometry of the bridge and the two-dimensional heat flows within it

In the second and third example we see two thermal bridges analysed using ANSYS The manual methods are unapplicable in this case Both bridges have significant thermal effects

References

1 CIBSE *CIBSE Guide Volume A Design Data Section A3* London, CIBSE, 1986, p A3-22

2 Ibid, p A3-7

3 Ibid, p A3-8

4 Rohan PK *The Climate of Ireland* Dublin, The Stationary Office, 1986

Chapter 9 Synopsis of Results

Summary

The results obtained from the simulation of thermal bridges by use of the ANSYS program are presented for the bungalow and the semi-detached house The results are compared with opaque fabric heat loss as calculated in the TGD of the 1991 Building Regulations[1] A detailed analysis of each thermal bridge is presented in Appendix A

9.1 Bungalow Thermal Bridges

The bungalow thermal bridging results are presented below

Table 9 1.1: Effect of Bungalow Thermal Bridges

Thermal Bridge	Bridge Conductance	Total Bridge Length (m)	Heat Loss Coefficient of Thermal Bridge (W/K)
1 Foundation, cavity wall and floor	0 41 (W/mK)	47 2	19 35
2 Foundation, partition wall and floor	1 08 (W/mK)	39	42 1
3 Window cill	0 16 (W/mK)	11 8	1 9
4 Window jamb	0 036 (W/mK)	18	0 65
5 Window lintel	0 504 (W/mK)	11 8	5 95
6 Cavity closer	0 26 (W/mK)	47 2	13
7 Wall corner	0 11 (W/mK)	9 6	1 06
8 Partition wall and external wall	0 08 (W/mK)	21 6	1 73
9 Tie	0 0009 W/K	n a	0 54
10 Uninsulated joists above ceiling	0 026 (W/mK)	269 5	7
11 Gable End Wall	0 473 (W/mK)	15 4	4 47
Total Heat Loss (due to thermal bridging)			97 8

The bridge conductance represents the heat loss per metre kelvin in the case of linear thermal bridges and heat loss per kelvin in the case of point thermal or three dimensional bridges In the case of linear thermal bridges the heat loss coefficient was calculated by multiplying the bridge conductance by the length of the bridge

The importance of the thermal bridging results are put in context in Table 9 1 2

Table 9.1.2: Effect of Bungalow Thermal Bridges in Comparison to Fabric Heat Loss

Building Component	**Fabric Heat Loss(W/K)**	**Fabric Heat Loss as % of Total Fabric Heat Loss for the Plane Sections of the Building**
Plane Sections of Building		
Walls	44 4	24
Windows	39 9	21
Doors	17 9	10
Ceiling	30 6	16
Floor	55 1	29
Total	**187.9**	100
Thermal Bridges	97 8	52

The Fabric Heat Loss was calculated using the conventional methods of calculation as found in the TGD Part L of the 1991 Building Regulations[1]

Figure 9 1 1 shows a comparison of thermal bridge heat loss and fabric heat loss as percentages of fabric heat loss Figure 9 1 2 shows sources of bungalow total fabric heat loss

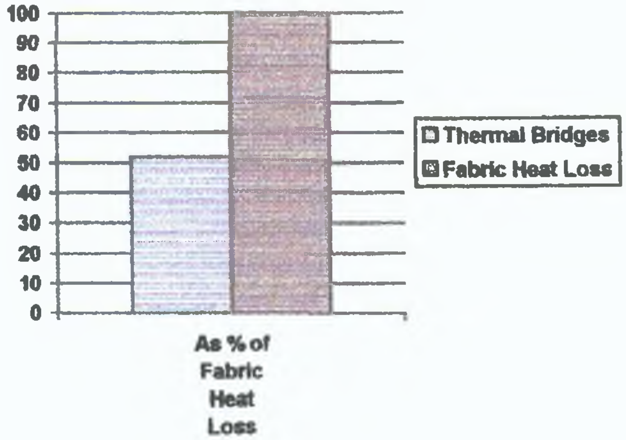


Figure 9.1.1: Comparison of Bungalow Thermal Bridge Heat Loss and Fabric Heat Loss

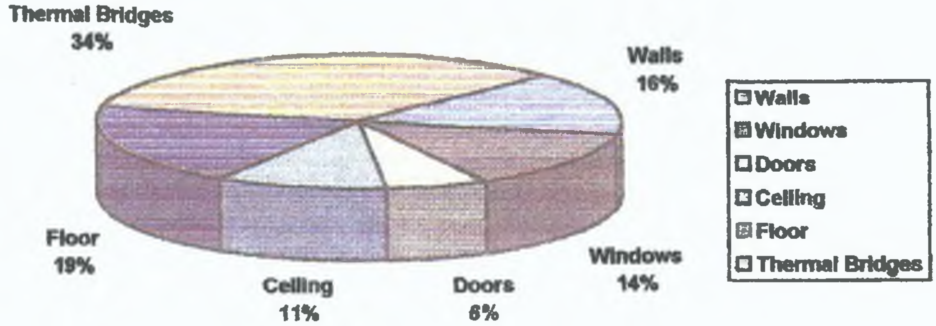


Figure 9.1.2: Sources of Bungalow Total Fabric Heat Loss

9 2 Semi-Detached House Thermal Bridges

The thermal bridging results for the semi-detached house are presented in Table 9 2 1

Table 9.2 1 Effect of Semi-Detached House Thermal Bridges

Thermal Bridge	**Bridge Conductance**	**Total Bridge Length (m)**	**Total Heat Loss of Thermal Bridge (W/K)**
1 Foundation, external wall and floor	0 293 (W/mK)	21 2	6 2
2 Foundation, partition wall and floor	1 08	6	6 48
3 Partition wall and external wall	0 247 (W/mK)	2 4	0 59
4 Stud partition wall and external wall	0 085	14 4	1 22
5 Window cill	0 232	9 49	2 2
6 Window jamb	0 145	15 82	2 29
7 Window lintel	0 168	9 49	1 59
8 Wall corner	0 146	19 2	2 8
9 Party wall to foundation	0 56 (W/mK)	7 4	4 14
10 Party wall to attic	0 33 (W/mK)	7 4	2 44
11 Party wall and external wall	0 42 (W/mK)	4 8	2 02
12 Uninsulated wall at first floor level	0 69	21 2	14 63
13 Uninsulated joists above ceiling	0 026 (W/mK)	111	2 9
14 Battens	0 056 (W/mK)	148 8	8 33
Total Heat Loss Coefficient			57 8

The fabric heat loss was calculated using the conventional methods of calculation as found in the TGD Part L of the 1991 Building Regulations[1]

Table 9 2 2 lists fabric heat losses as a percentage of the fabric heat loss of the building

Table 9 2 2. Effect of Semi-Detached House Thermal Bridges in Comparison to Fabric Heat Loss

Building Component	**Fabric Heat Loss (W/K)**	**Fabric Heat Loss as % of Fabric Heat Loss for the Plane Sections of the Building**
Plane Sections of Building		
Walls	40 18	32
Windows	32 22	26
Doors	17 94	14
Ceiling	12 75	10
Floor	22 95	18
Total	**126**	100
Thermal Bridges	57 8	46

Figure 9 2 1 is a comparison of thermal bridge heat loss and fabric heat loss as percentage of fabric heat loss Figure 9 2 2 shows sources of total fabric heat loss including thermal bridging

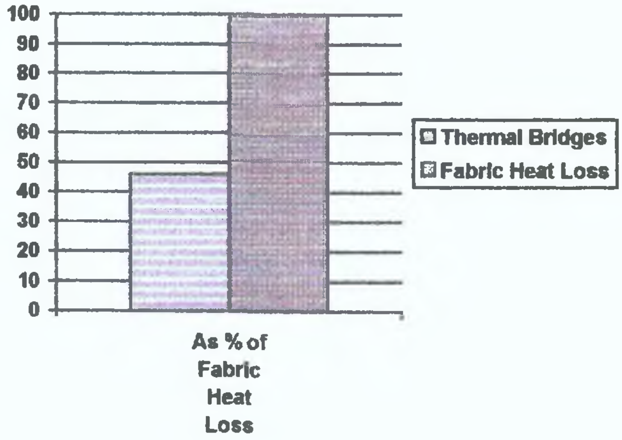


Figure 9.2.1: Comparison of Semi-Detached Thermal Bridge Heat Loss and Fabric Heat Loss

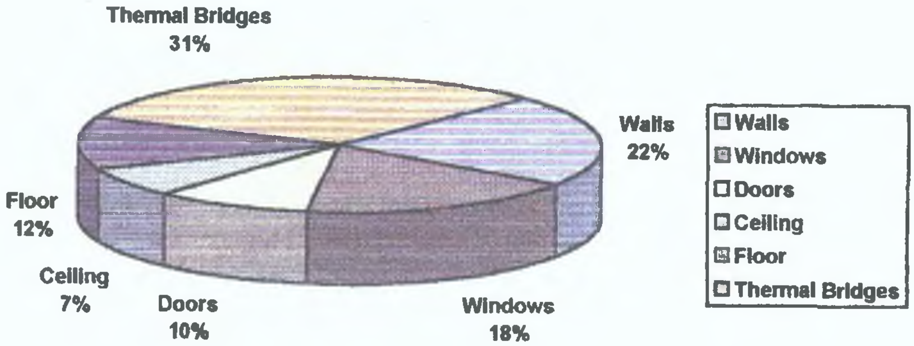


Figure 9.2.2: Sources of Semi-Detached Total Fabric Heat Loss

9 3 Conclusion

Thermal bridges represented 52% as a percentage of fabric heat loss in the bungalow As a percentage of total fabric heat loss this represented 34% Thermal bridges in the semi-detached house represented 46% as a percentage of fabric heat loss As a percentage of total fabric heat loss this represented 31%

References

1 Department of the Environment *Building Regulations 1991 Technical Guidance Document L Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991

Chapter 10. Discussion

The principal thermal bridges in the bungalow were the foundation, cavity wall and floor, the foundation, partition wall and floor and the cavity closer at eaves level Together, they represented 76% of thermal bridging heat loss in the bungalow Some of these principal thermal bridges were found to increase the nominal U-values of the building elements which they affected by up to 50% In the bungalow the fabric heat loss coefficient based on conventional analysis[1] was found to be 188 W/K The heat loss coefficient due to thermal bridging was 98 W/K which represents 52% of fabric heat loss calculated using conventional methods, and 34% of fabric heat loss inclusive of thermal bridging effects The total heat loss coefficient inclusive of infiltration / ventilation losses, thermal bridges and opaque fabric heat loss was 384 W/K for the bungalow Thermal bridging represents 25% of this figure

The total semi-detached house heat loss coefficient was 265 W/K and thermal bridging represents 22% of this figure The principal thermal bridges present in the semi-detached house were the foundation, external wall and floor, the foundation, internal wall and floor, the uninsulated wall at first floor level and the battens, these bridges represented 62% of thermal bridging heat loss These bridges significantly altered the nominal U-values of constructions which they affected (for example, the party wall to foundation increases the nominal U-value of the floor by 20%) In the semi-detached house the fabric heat loss coefficient based on conventional analysis was 126 W/K The heat loss coefficient due to thermal bridging was 57 8 W/K which represents 46% of conventionally calculated fabric heat loss, and 31% of heat loss inclusive of thermal bridges The heat loss due to thermal bridging was 3% more as a proportion of total heat loss in the semi-detached house than in the bungalow Although thermal bridging as a percentage of total heat loss is approximately the same in the bungalow as in the semi-detached house, the bungalow mainly loses heat due to thermal bridging through the ground floor and ceiling constructions while the semi-detached house principally loses heat due to thermal bridging heat through the wall fabric

The proportion of total heat loss due to thermal bridging was 25% and 22% in the bungalow and semi-detached house respectively Assuming that one off and estate developments represent 30% and 70% respectively of total annual residential construction, and that the semi-detached house and bungalow chosen in this study are completely representative of residential construction, then the percentage of total heat loss due to thermal bridging can be assumed to be approximately 23% of total heat loss in modern housing

It is important to note that old houses are relatively poorly insulated in comparison to new houses, and therefore the percentage heat loss due to thermal bridging should represent a lower proportion of total heat loss than in modern housing Renovation and maintenance accounts for approximately 50% of total residential construction output[2] and therefore some old houses should be insulated to modern standards Taking into account these factors, the percentage heat loss due thermal bridging can be assumed to be less than the 23% figure when considering the complete housing stock and therefore a percentage heat loss due to thermal bridging of approximately 5% has been assumed

Commercial and public buildings are significantly different to housing and are very diverse in type and style They have generally in their constructions a great proportion of heavy structural elements and sometimes finned elements which can be important thermal bridges Assuming the same general assumptions for housing apply to commercial and public buildings, and that at least the same proportion of heat loss due to thermal bridging is present, the percentage heat loss due to thermal bridging in public and commercial buildings can be assumed to be approximately 5% This heat loss percentage is important primarily in terms of energy needed for space heating Assuming similar figures apply to Ireland as in the UK, space heating represents 61% of domestic energy consumption[3] and 60% of energy consumption in public and commercial buildings[4] Residential and commercial energy consumption in 1994 was approximately 2 million tonnes of oil equivalent and 1 million tonne of oil equivalent respectively[5] The 5% heat loss due to thermal bridging represents 3% of total energy consumption in residential and commercial buildings This represents approximately 1% of total national final energy consumption (i e total energy consumption excluding energy used in producing secondary energy[6], such as in the generation of electricity) in the country This approximate figure serves to illustrate that thermal bridging is a very important source of energy loss in buildings

The current conventional analysis of buildings using one-dimensional heat flow largely ignores thermal bridging This is particularly true with the analysis examples found in the Technical Guidance Document of the 1991 Building Regulations[7] With an ideal analysis tool, the objective should be to carry out as accurate an analysis as practically possible Now with the ever increasing computer calculation power and decreasing computer prices a new degree of computer simulation of buildings and thermal bridges is possible It can be generally accepted that the greater the level of accuracy of a simulation the better, but it is still also important to offset increases in accuracy with increases in costs and computer time and to use the most practical solution available

This trend of using complex computer models is occurring in all fields of analysis such as engineering, medicine, mathematics, architecture and is irreversible As they represent 10% of heat loss thermal bridges are quite important The current Building Regulations are successful in achieving the aim of conserving fuel and energy and introducing insulation into building construction when twenty years ago this was not standard practice Many aspects of buildings such as thermal bridges require special analysis and therefore the possibility of including individual sections in Technical Guidance Document, Part L[1] to deal with such topics would be useful to designers The TGD, Part L and Section A3 of the CIBSE Design guide, Volume A are useful tools for the thermal analysis of a buildings but to a limited extent for thermal bridges Therefore guidance on the use of computer methods and packages should be given

Thermal bridging is very difficult to avoid once the construction of the building has been completed. Preventative measures are the most successful and therefore to rely on builders using good construction practice as given in the NHBGS House Building Manual[8] or in the BRE's paper Thermal Insulation avoiding risks[9] would not be as successful as giving more stringent directions in the Technical Guidance Document of Part L of the Building Regulations. Thirteen percent of heat loss due to thermal bridging in a building as found in the calculations would justify such a change.

'Lintels, jambs and cills associated with window, rooflight and door openings may be counted as part of the window, rooflight and door opening area or as part of the roof, wall or floor in which the opening occurs. However, in no case should the U value of a lintel, jamb or cill exceed 0 9 W/m^{2}K'

(Section 0 13,b)[10]

If the U values of openings as mentioned above or of any section of the building as regarded from the internal environment were specified to have the same U value as that of a surrounding area such as a wall or floor this would reduce significantly the effects of thermal bridges. This would apply only in terms of one dimensional hand calculations. That is, that no section of wall, floor, ceiling should be seen to have a higher U value than the nominal U value using the one dimensional calculation methods.

The use of catalogues of standard thermal bridges is a way in which thermal bridges could be taken into account without detailed analysis in construction design. A catalogue could be provided within the TGD of the Building Regulations and values for thermal bridges could then be used to calculate the overall U values of constructional elements. The principle disadvantages in using such a catalogue of thermal bridges are the danger of ignoring condensation, the degree of possible error if a thermal bridge with different properties is encountered and the possibility that the catalogue would be misapplied.

The most practical solution involving the use of thermal bridging values in the calculation of U values would be the use of a specialised program such as Kobra This program could be used purely as a database which would give a detailed analysis of thermal bridges including analysis on condensation risk The Department of the Environment could suggest the use of such software in the TGD of the Building Regulations, and provide standard thermal bridges from Irish construction practice in the program which could then be made available to the public for general use

Although the finite element method used in the ANSYS program is recommended by the CIBSE Guide, the use of ANSYS as a common analysis tool of thermal bridge is limited The high cost, the fact that ANSYS is not explicitly designed to analyse building elements and that it is difficult to learn to use and to customise for analysis of standard constructions, makes it impractical for common use It also difficult to make simple alterations once a model has been inputted and a computer system more powerful than the average computer system is needed to run the ANSYS program The ANSYS program has more possibilities of being a useful tool in the analysis of specific problems affecting thermal bridges such as radiation and air movement in cavities It could be possibly used by a consultancy

The CIBSE Guide methods for analysing thermal bridges calculate average resistance values for simple non-homogeneous constructions which are generally walls such as a wall with plasterboard on battens or a wall containing cavity blocks These methods do not take into account fully the geometric properties of a thermal bridge under consideration or of the complex heat flows occurring within such a bridge They cannot be used for analysing the effects of a temperature distribution on a bridge The CIBSE Guide analysis assumes that heat flows follow predetermined one dimensional paths as in the proportional are method This means that the CIBSE Guide methods have a higher degree of approximation than methods such as the finite element method These methods offer very little flexibility in the analysis of different problems and cannot be applied to the majority of complex thermal bridges The CIBSE Guide methods of analysis are useful only when manual calculations can be carried out They can be considered valuable when making rough estimates, but for the construction industry where computers are now ubiquitous, they are inadequate methods In summary, the CIBSE Guide methods are unable satisfactorily to analyse thermal bridges with complex heat flows

The TGD of Part L of the 1991 Building Regulations use steady-state analysis methods Throughout the construction industry, building insulation requirements are calculated on a steady-state basis The CIBSE manual methods of assessment of thermal bridges are necessarily steady-state Thus it is appropriate that the detailed analysis of the complex heat flows in thermal bridges should initially be on a steady-state basis This has been the case throughout the simulation of thermal bridges in this study

Progressively, more sophisticated evaluation of thermal bridges will require transient analysis Inherently, this will have to be integrated with transient analysis of the whole or part of the building It is clear that transient analysis will require much more complex models and will take a significantly longer time in the simulation analysis process than the comparable steady-state analysis Only for special problems and special research, such as for assessing condensation and mould growth in buildings is it likely that transient analysis of thermal bridges will be used

Condensation and mould growth can be the most serious consequences of thermal bridging This affects predominantly houses which have very little energy input and houses which have been poorly built A significant proportion of houses in the UK suffer from condensation problems[11] and this affects mainly low income groups A typical household can generate between 7 and 14 litres per day of moisture from activities such as washing, cooking, taking showers, heating, perspiration and breathing[12] Building materials absorb moisture when the internal environment is cold and release moisture when the internal environment is warm The moisture within a building can circulate from warmer areas to colder areas such as unheated bedrooms This happens by diffusion, air movements due to infiltration and thermal currents due to convection The occupants of a building can participate in this process by leaving open the doors of rooms where moisture is produced such as the kitchen or bathroom If no adequate ventilation exists or if openings for ventilation are not used in order to allow moisture to escape, this can result in condensation Other important factors are the internal temperatures, the presence of thermal bridges and any other factors affecting the building's overall thermal performance January to March is the coldest period of the year and can be assumed to be the most dangerous in terms of condensation risk and obviously would be the most appropriate period for the analysis of thermal bridges Condensation at thermal bridges can be avoided if the internal surface temperature remains above the dewpoint temperature The adding of insulation at particular point in a building affected by condensation without correct analysis can make matters worse This is one reason the simulation of thermal bridges is very important A method of characterising the importance of thermal bridges in condensation terms is by using a temperature difference ratio (TDR)[13]

$$\text{TDR} = \frac{\text{Internal air temperature} - \text{thermal bridge temperature}}{\text{Internal air temperature} - \text{External air temperature}}$$

The TDR is used in conjunction with the table below

Table 10.1: Thermal Bridge Condensation Category and TDR

Thermal Bridge Condensation Category	**TDR**
Negligible	< 0 15
Moderate	0 15 - 0 2
Severe	0 2 - 0 3
Unacceptable	> 0 3

Source. Roaf S / Hancock M, Energy Efficient Building, London, Blackwell, 1992, p 181

For the bungalow thermal bridge of foundation, external wall and ground floor the TDR determined from the temperature distribution of a standard simulation is 0 3 This means that in January weather there would be a possibility of prolonged condensation

There is significant risk of mould growth if there is prolonged condensation Moulds are fungi which spread through the air by means of a great number of spores Fungi are found on nearly all decaying matter Therefore, their spores are found nearly everywhere and most importantly within buildings To grow, mould needs only oxygen, temperatures at or above 0°C, an organic material such as dust to feed on, and water The most important factor influencing mould growth within a building is the presence of water Mould can grow on any material including glass at relative humidities of 95% and over[14] Any thermal bridge giving rise to high local relative humidities or condensation for a prolonged period, will cause mould growth In this study the principal objective has been the thermal evaluation of bridges A comprehensive evaluation of condensation / mould growth risks would require a separate study, which would appear to be justified by the results here obtained

References

1 Department of the Environment *Building Regulations 1991 Technical Guidance Document L Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991, p 13

2 Department of the Environment *Construction Industry Review 94 Outlook 95* Dublin, The Stationary Office, 1995, p 53

3 Dunster JE *Energy use in the housing stock* Garston, BRE, 1994

4 Moss SA *Energy consumption in public and commercial buildings* Garston, BRE, 1994

5 Department of Transport, Energy & Communications *Energy In Ireland 1980-1994 A Statistical Bulletin* Dublin, Department of Transport, Energy & Communications, p 16

6 Ibid, p 12

7 CIBSE *CIBSE Guide Volume A Design Data Section A3* London, CIBSE 1986

8 NHBGS *NHBGS House Building Manual* Dublin, NHBGS, 1993

9 BRE *Thermal insulation avoiding risks* London, HMSO, 1994

10 Department of Environment p 5

11 Garratt J / Nowak F *A guide to the causes of, and remedies for, surface condensation and mould in traditional housing* Garston, BRE, 1991, p 1

12 Ibid, p 18

13 Roaf S / Hancock M Energy Efficient Building, London, Blackwell, 1992, p 181

14 Garratt J / Nowak F p 18

Chapter 11. Conclusions and Recommendations

Thermal bridges were found to represent 25% and 22% of total heat loss (including infiltration loss) in the bungalow and semi-detached house respectively The fabric heat loss due to thermal bridging was 98 W/K and 58 W/K for the bungalow and semi-detached house respectively As a percentage of fabric heat loss calculated using the conventional methods this represented 52% for the bungalow and 46% for the semi-detached house These values represent a reasonably high percentage (1%) of national total final energy consumption The results obtained show that thermal bridging is an important consideration for the energy efficiency of buildings, and a consideration which should be given much more attention in the Building Regulations[1]

The nominal U value of walls, floors and ceilings can be effectively increased by up to 50% by important thermal bridges This means that, without calculations to take into account the effects of thermal bridging, the construction elements of buildings can have greater U values than the maximum nominal U values indicated in the Building Regulations and their Technical Guidance Document, and thereby not achieve the required thermal resistance objectives of the Building Regulations

The significant proportion of heat loss due to thermal bridging and the occurrence of thermal bridges can be only prevented before the completion of construction Certain types of bridges such as ties are almost impossible to prevent This suggests that thermal bridges can only be treated on an individual basis and that computer simulation is required if suspicions exist that a thermal bridge will cause problems More generally it is logical to assume that regions within the building structure with an inhomogeneous U value (using analysis as found in the TGD of the Building Regulations Part L[1]) will have a greater risk of being severe thermal bridges than regions with homogeneous U values Imposing a requirement of homogeneous U values (calculated using the standard methods and a recommended heat flow path) within a building would reduce significantly thermal bridging and reinforce good building practice although necessarily more difficult

Alternatively, a catalogue of standard thermal bridges could be used to obtain effective insulation requirements for a building This method has the danger of not preventing the occurrence of condensation Another alternative would be to use a program such as the Kobra program which produces a detailed analysis of a thermal bridge (including an assessment of condensation risk), and which can be effectively used as a database of thermal bridges, and is also easy to use The main advantages over using a catalogue is that changes can be made to the existing thermal bridges within the database and new thermal bridges added to the database with relative ease

Methods of avoiding risks with insulation and preventing thermal bridges should be included within the TGD of the Building Regulations so that thermal bridging problems would be more often take into account in the design of buildings

A simple increase in the insulation levels in buildings will not eliminate thermal bridges but will make their effects relatively more important A requirement that thermal bridges should be taken into account in U-value calculations would probably be the most useful step in preventing the occurrence of thermal bridges in buildings, and reducing the effects of thermal bridging

Despite generally increased levels of insulation in buildings there still remains significant risk of condensation and mould growth A comprehensive evaluation would appear to be justified

References

1 Department of Environment *Building Regulations 1991 Technical Guidance Document L Conservation of Fuel and Energy* Dublin, The Stationary Office, 1991

Appendix A ANSYS Simulation of Thermal Bridges

A1 Introduction

This Appendix contains the information pertinent to the simulation of each thermal bridge This information is presented in the form of a report for each thermal bridge The assumptions, boundary conditions and data generally used throughout all the simulation of thermal bridges are listed below Assumptions, boundary conditions and data which apply uniquely to a particular thermal bridge are listed with the summary/report of that thermal bridge The thermal bridge reports of the bungalow foundation, cavity wall and floor and the semi-detached party wall and external wall are also found within the main body of the thesis, they are repeated here for completeness It is important to note ANSYS U value refers to the section of the construction element affected by the bridge

A2 General Simulation Data

A2.1 Assumptions

- Steady state conditions apply throughout the calculations
- Heat transfer coefficients remain uniform on all internal and external surfaces
- Boundary conditions remain constant
- Materials properties are assumed to be isotropic, and have no variation with temperature or time
- Cavities are modelled as solid materials with resistances equivalent to those found in Tables A3 5 to A3 8 of the CIBSE Design Guide Section A3
- Hollow block walls are modelled as walls composed of a solid material with a thermal conductivity of 1 18 W/mK
- Wall ties, mortar joints, dpc and dpm are not considered within the model (wall ties are considered separately)
- All building elements found in the thermal bridges are assumed to be dry unless otherwise noted

- The results are based on the average of the internal surface temperatures affected by the thermal bridge
- Temperatures of earth and hardcore below foundation level are assumed to be equal to the external ambient temperature

A2 2 Materials

The thermal conductivities of these materials are taken from the CIBSE Design Guide Tables A 3 15 and A 3 22 and page A 3-9

Material	**Thermal Conductivity (W/mK)**
Render	0 5
Concrete Block (Heavyweight)	1 63
Concrete Block (Mediumweight)	0 51
Mortar (Outer Leaf)	0 8
Mortar (Inner Leaf)	0 9
Insulation	0 035
Plasterboard	0 16
Plaster	0 16
PVC	0 16
Softwood	0 13
Hardwood	0 15
Chipboard	0 15
Plywood	0 14
Screed	0 41
Cast Concrete	1 13
Earth	2 1
Hardcore (Limestone)	1 5 (dry)

A2 3 Standard Resistances

The thermal resistance values used in the simulations were taken from tables A3 5, A3 6, A3 7, A3 8 of the CIBSE Design Guide A summary of the values generally used is presented below

Type of Resistance	**Resistance (m^2K/W)**
Inside Surface	
For Horizontal Heat Flow Wall Surface Resistance	0 12
For Upward Heat Flow Floor/Ceiling Surface Resistance	0 1
For downward heat flow Floor/Ceiling Surface Resistance	0 14
Outside	
Wall Surface	0 06
Roof Surface	0 04
Cavity	
Cavity < 0 025 m×<0 2 m	0 18
Cavity 0 095 m × 0 13 m	0 20

A3 Bungalow Thermal Bridges

The Bungalow thermal bridges analysed are listed below

1 Foundation, cavity wall and floor

2 Foundation, partition wall and floor

3 Window cill

4 Window jamb

5 Window lintel

6 Cavity closer at eaves level

7 Wall corner

8 Partition wall and external wall

9 Wall tie

10 Uninsulated joists above ceiling

11 Gable end wall

A3 1 Bungalow Thermal Bridge 1 Foundation, Floor and External Wall

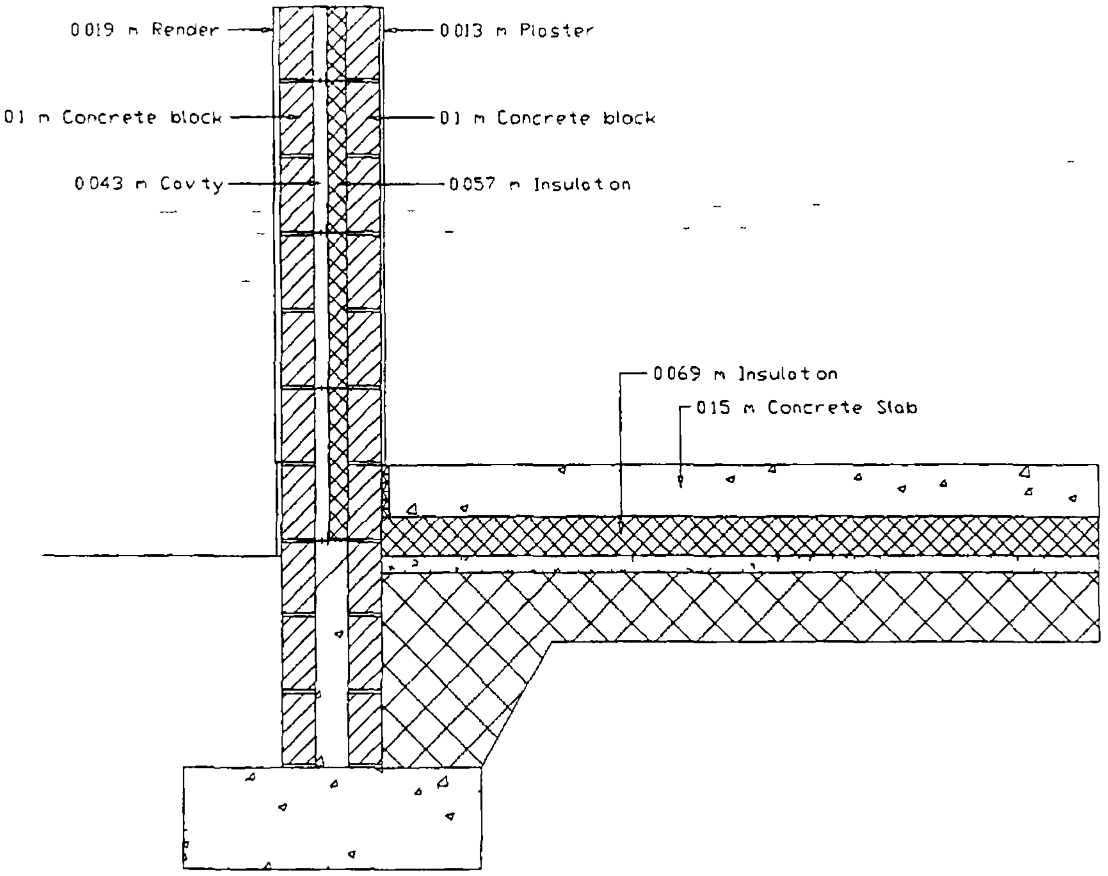


Figure A3 1 1 Bungalow Foundation, Floor and External Wall

A3 1 1 Description

Figure A3 1 1 shows the thermal bridge which occurs at the junction of the external, floor and foundation (see section 8 2 for an extensive description and discussion of this bridge)

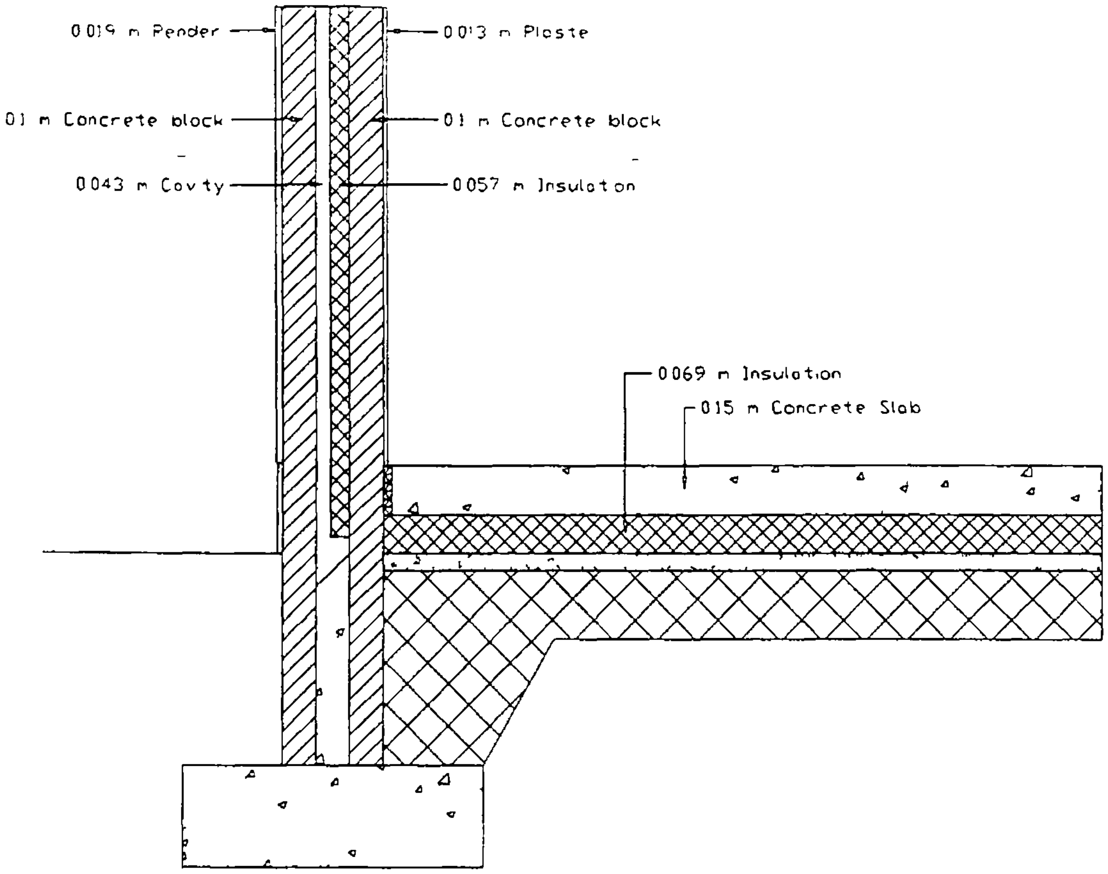


Figure A3 1.2 ANSYS Representation of Foundation, External Wall and Ground Floor

A3 1 2 Results

Bridge	**Wall, floor and foundation**	
Surface	**Inside Wall**	**Floor**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 449	0 448
Averaged ANSYS U value (W/m^{2}K)	0 648	0 516
Effect of bridge (ANSYS,W/m^{2}K)	0 175	0 068
Effect of bridge as % of 0 45 W/m^{2}K	44	15
Bridge Conductance (ANSYS, W/mK)	0 41	
Effect on 1m section of plane 2 5m high wall as %	36	

A3 1 3 Discussion

For the region of the wall affected by the bridge, the ANSYS U value is 0 65 W/m^{2}K or 44% greater than the nominal U-value of 0 45 W/m^{2}K The corresponding figure for the floor is 15% As the bridge length for a typical bungalow is approximately 47 m, this is a very significant thermal bridge

A3 2 Bungalow Thermal Bridge 2 Foundation, Partition Wall and Floor

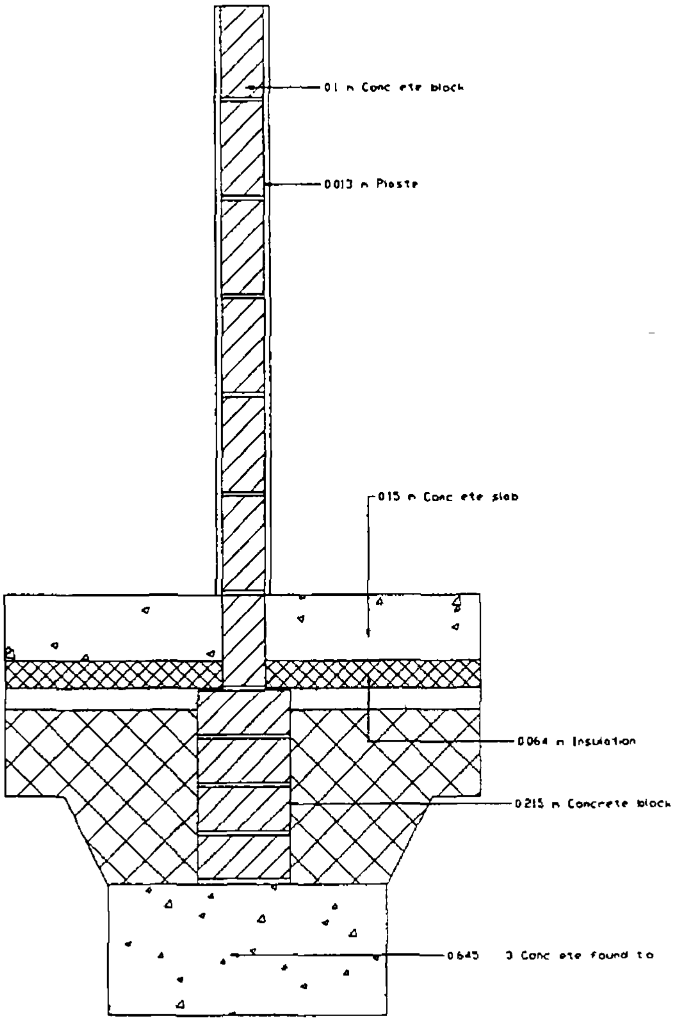


Figure A3 2 1 Foundation, Partition Wall and Floor

A3 2 1 Description

The bridge under consideration (see Figure A3 2 1) occurs at the junction of the internal walls with the floor and foundation There are two paths of low thermal resistance present, one following the wall directly downwards and the other along the concrete slab to the wall This bridge is a linear thermal bridge

In Figure A3 2 2, it can be seen that the bridge was assumed to be symmetrical for the purposes of simulation

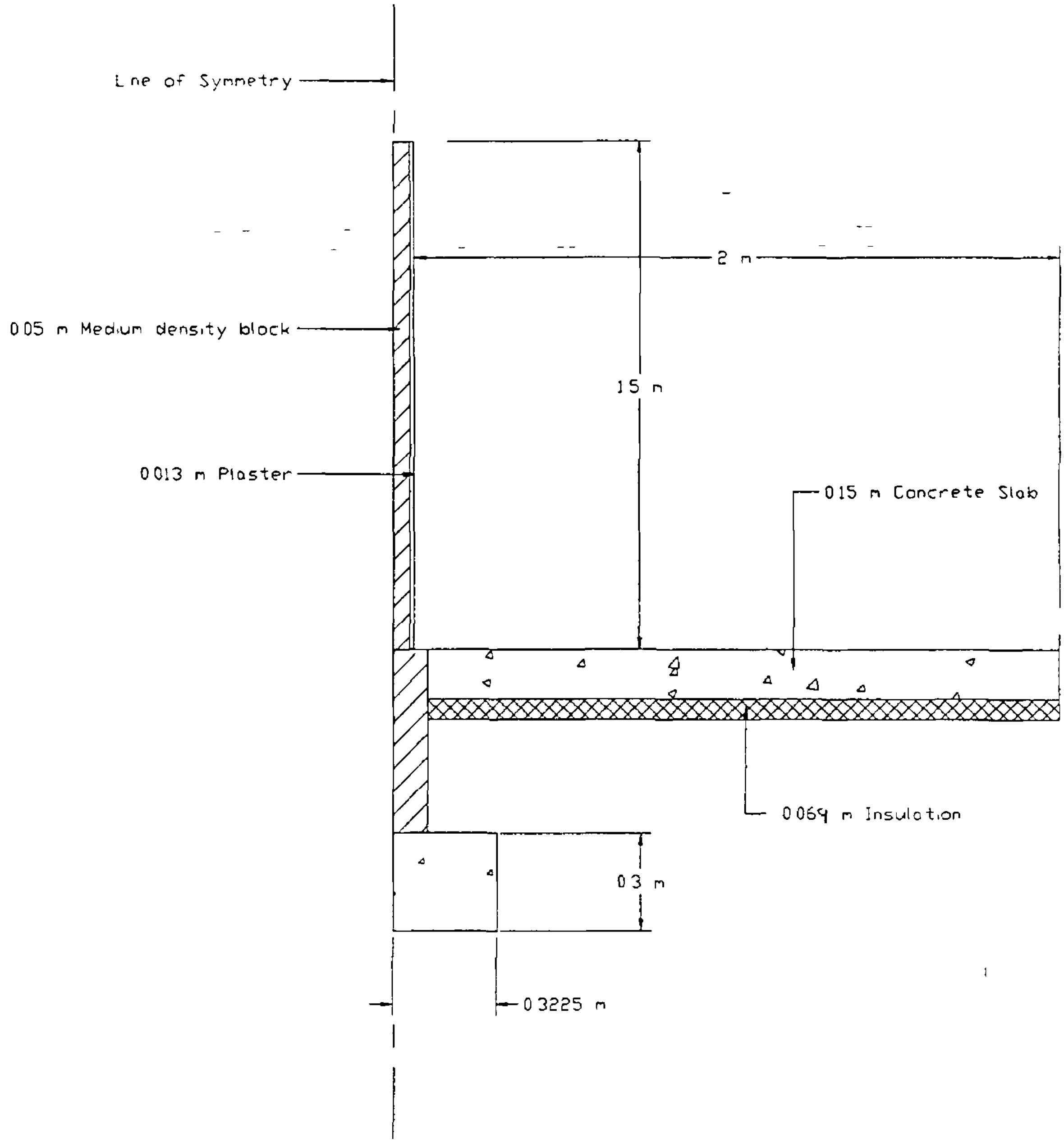


Figure A3 2 2 ANSYS Representation of Bungalow Foundation, Floor and Partition Wall

A3 2 1 Results

Bridge	**Wall and Floor**	
Surface	**Partition Wall**	**Floor**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0	0 45
Averaged ANSYS U value (W/m^{2}K)	0 648	0 525
Effect of bridge (ANSYS, W/m^{2}K)	0 648	0 525
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	-----	17
Bridge Conductance (ANSYS, W/mK)	1 08	

A3 2 3 Discussion

The bridge conductance of the bridge is 1 08 W/mK This bridge is very significant since there are approximately 40 m of partition walls in the bungalow

A3 3 Bungalow Thermal Bridge 3 Window Cill

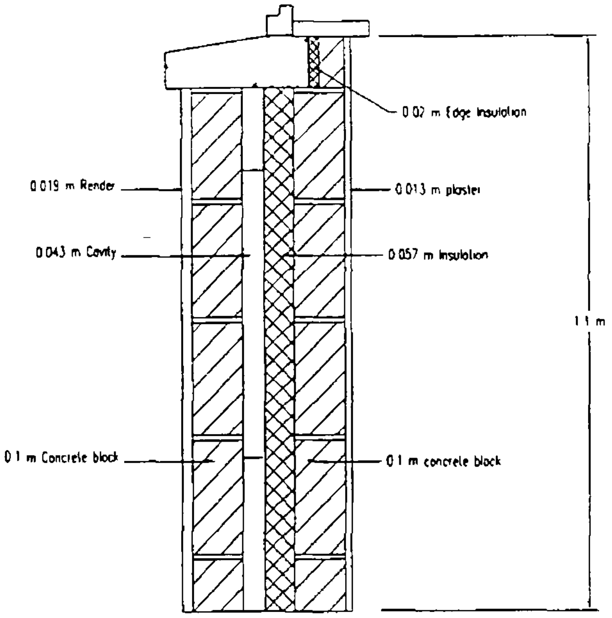


Figure A3 3 1 Bungalow Window Cill

A3 3 1 Description

Figure A3 3 1 shows the bungalow window cill This bridge is assumed to be a linear thermal bridge

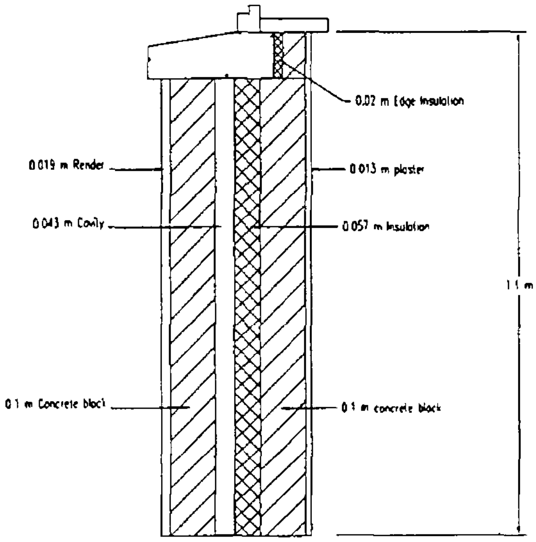


Figure A3 3 2 ANSYS Representation of Bungalow Window Cill

Figure A3 3 2 shows how the bridge is represented in ANSYS Standard internal and external heat transfer coefficients apply on window cill and top surrounds

A3 3 2 Results

Bridge	**Window Cill**	
Surface	**Inside Wall**	**Cill**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 448	0
Averaged ANSYS U value (W/m^{2}K)	0 485	0 72
Effect of bridge (ANSYS, W/m^{2}K)	0 037	0 72
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	8	-----
Bridge Conductance (ANSYS, W/mK)	0 16	

A3 3 3 Discussion

The bridge conductance is 0 16 W/mK which is significant

A3 4 Bungalow Thermal Bridge 4 Window Jamb

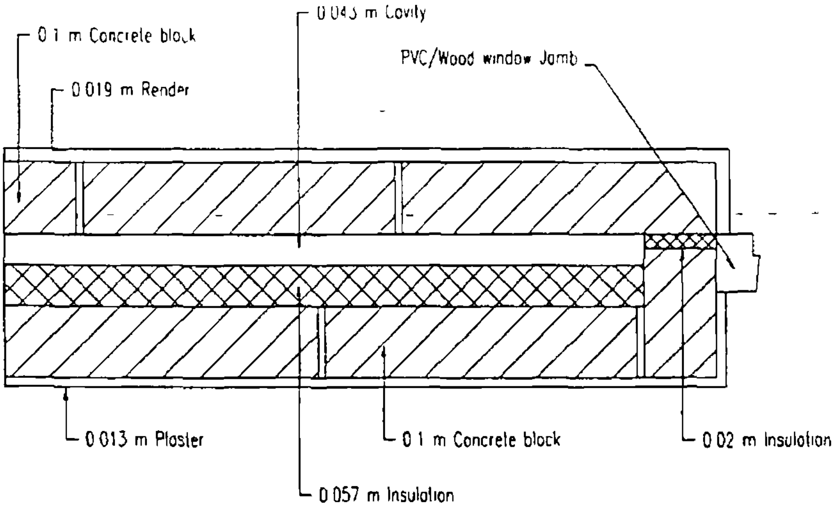


Figure A3 4 1: Bungalow Window Jamb

A3 4 1 Description

This bridge (see Figure A3 4 1) is well suited to two dimensional analysis A path of low thermal resistance can be found in the wall beside the jamb This path has an approximate thermal resistance of 1 m^2K/W, the rest of the wall has an approximate thermal resistance of 2 2 m^2K/W This means that the region directly beside the jamb is losing heat at at least twice the rate of a standard cavity wall

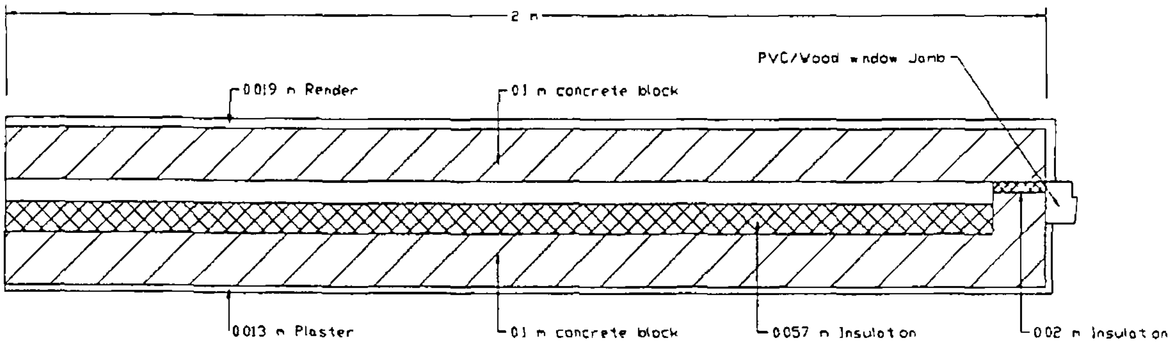


Figure A3 4 1 ANSYS Representation of Bungalow Window Jamb

Uniform heat transfer coefficients on internal surfaces and external surfaces of window jamb and surrounds are assumed Glazing is assumed to have no effect on the calculation

A3 4 2 Results

Bridge	**Window Jamb**
Surface	**Inside Wall**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 441
Averaged ANSYS U value (W/m^{2}K)	0 469
Effect of bridge (ANSYS,W/m^{2}K)	0 028
Effect of bridge as % of U value= 0 45 W/m^{2}K (ANSYS)	6
Bridge Conductance (ANSYS, W/mK)	0 036

A3 4.3 Discussion

The bridge affects the wall for a distance of 1 m Over this distance it increases the U value of the wall by 6 % The bridge conductance is 0 036 W/mK This bridge is therefore not very severe

A3 5 Thermal Bridge 5 Bungalow Window Lintel

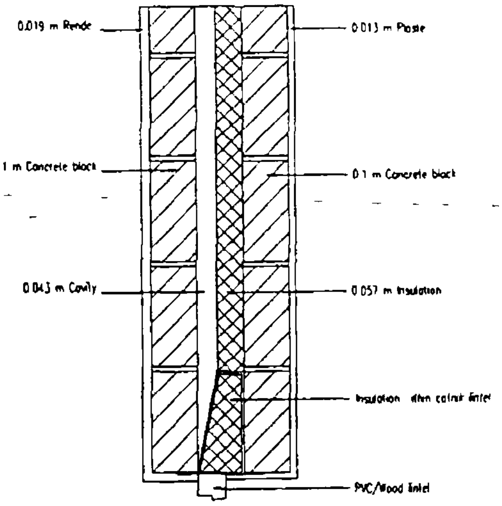


Figure A3 5 1. Bungalow Window Lintel

A3 5 1 Description

This bridge (Figure A3 5 1) occurs at the top horizontal sections of windows

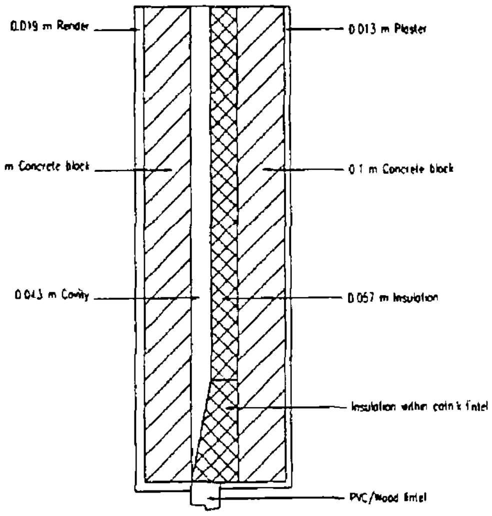


Figure A3 5.2 ANSYS Representation of Window Lintel

The lowest thermal resistance path in this bridge is found through the base of the metal 'catnik' lintel The base of the 'catnik' lintel is made up of several pieces of welded perforated galvanised steel This base has thicknesses varying from 2 mm to 4 mm

Assumed in this analysis was a 2 mm thick plate with an effective thermal conductivity of 30 W/mK running underneath the blockwork Standard heat transfer coefficients were utilised for the different surroundings

A3 5 3 Results

Bridge	**Window Lintel**	
Surface	**Inside Wall**	**Lintel**
U value TGD Part L of the Building Regulations (W/m²K)	0 449	0
Averaged ANSYS U value (W/m²K)	0 772	1 182
Effect of bridge (ANSYS, W/m²K)	0 323	1 182
Effect of bridge as % of U value = 0 45 W/m²K (ANSYS)	72	-----
Bridge Conductance (ANSYS, W/mK)	0 504	

A3 5.3 Discussion

The bridge conductance is 0 504 W/mK, which makes this bridge very significant

A3 6 Bungalow Thermal Bridge 6 Cavity Closer

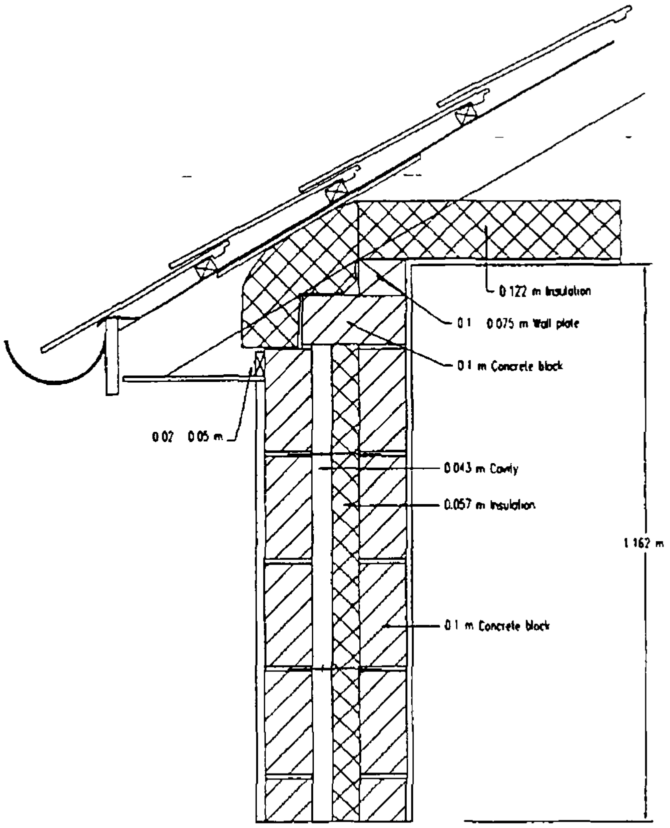


Figure A3.6 1. Bungalow Cavity Closer

A3 6 1 Description

The cavity closer (see Figure A3 6 1) provides a heat flow path of low thermal resistance and bridges the inner leaf of the wall and the ceiling This bridge occurs at the top of cavity walls and is therefore carried the full perimeter of the bungalow (i e for an average bungalow there is 47 2 m of bridge)

The model is simulated as shown in Figure A3 6 2 The insulation at the top of the closer has been included in the model

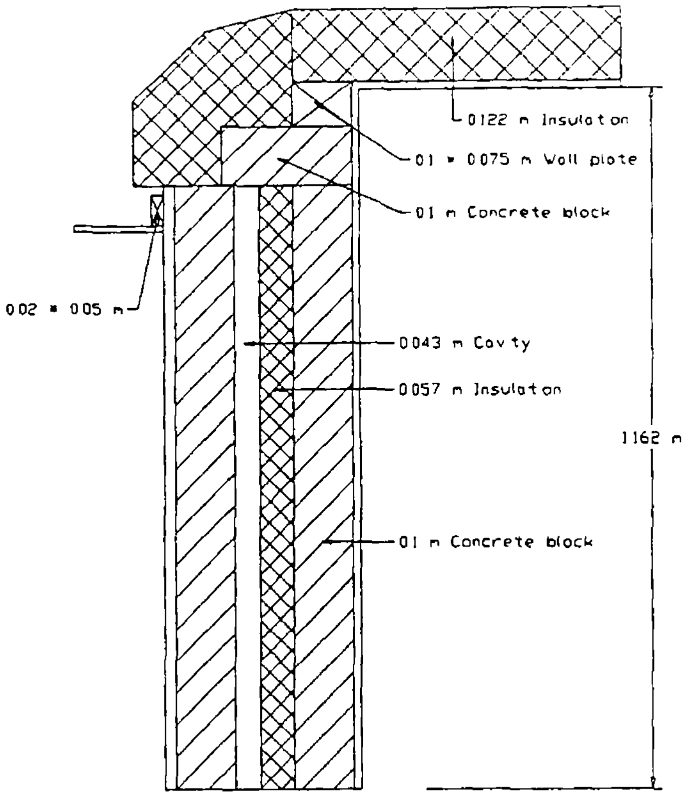


Figure A3.6.2 ANSYS Representation of Bungalow Cavity Closer

A3.6.2 Results

Bridge	**Cavity Closer**	
Surface	**Wall**	**Ceiling**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0.45	0.213
Averaged ANSYS U value (W/m^{2}K)	0.66	0.242
Effect of bridge (ANSYS,W/m^{2}K)	0.21	0.029
Effect of bridge as % of U value= 0.45 W/m^{2}K (ANSYS)	47	14
Bridge Conductance (ANSYS, W/mK)	0.275	

A3.6.3 Discussion

This bridge constitutes an 13 W/K heat loss coefficient for a standard bungalow which is very significant

A3 7 Bungalow Thermal Bridge 7 Wall Corner

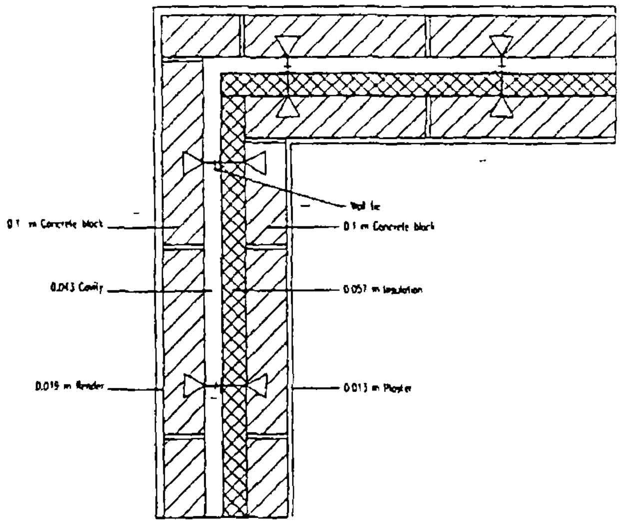


Figure A3 7 1 Bungalow Wall Corner

A3 7 1 Description

This thermal bridge occurs at corners of the external wall of a building Surprisingly, even though the wall may be well insulated, there is a bridge effect

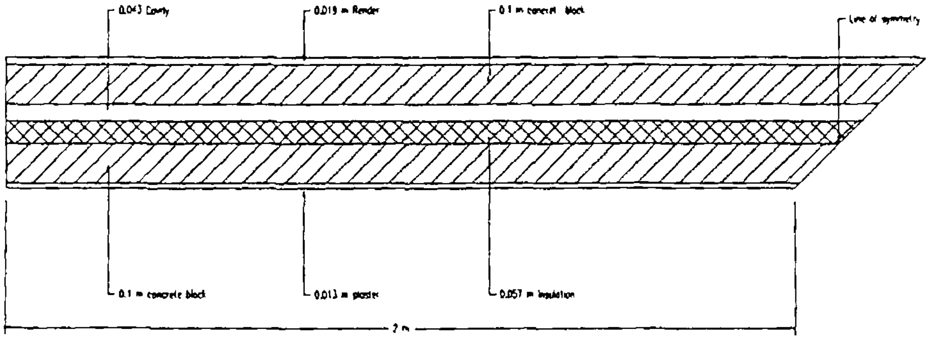


Figure A3 7 2 ANSYS Representation of Wall Corner

Figure A3 7 2 shows how the wall corner was modelled in ANSYS It was assumed to be fully symmetrical and consequently only half of the corner was modelled

A3 7 2 Results

Bridge	**Wall Corner**
Surface	**Inside Wall**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 449
Averaged ANSYS U value (W/m^{2}K)	0 497
Effect of bridge (ANSYS,W/m^{2}K)	0 048
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	11
Bridge Conductance (ANSYS, W/mK)	0 11

A3 7 3 Discussion

In a standard bungalow, heat loss due to this bridge amounts to 1 06 W/K

A3 8 Bungalow Thermal Bridge 8 Wall Junction

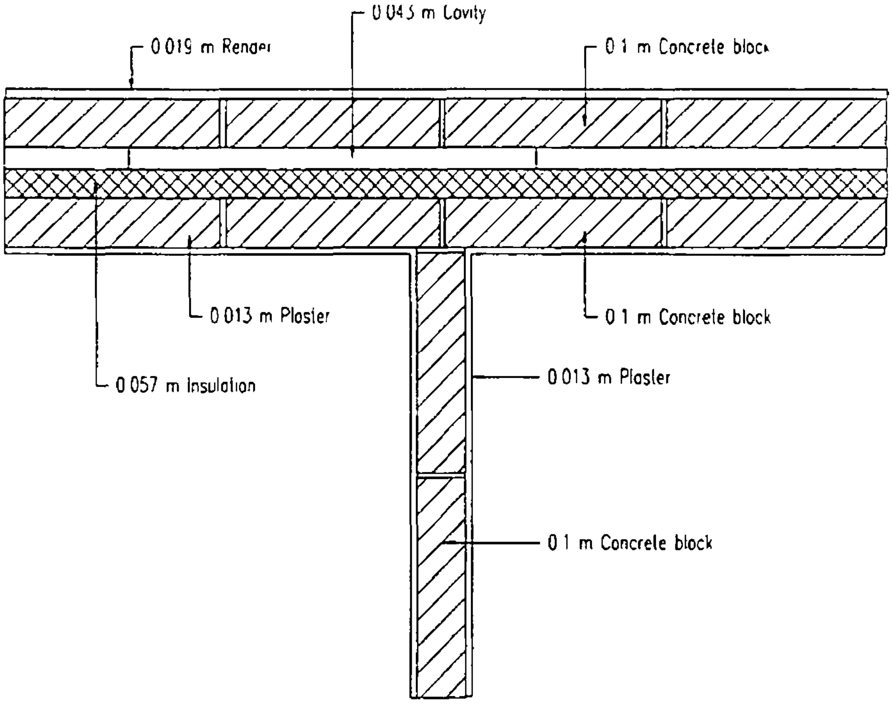


Figure A3 8 1 Bungalow Partition Wall and External Wall

A3 8 1 Description

This bridge (see Figure A3 8 1) occurs where the internal walls meets the external wall This occurs regularly throughout the building

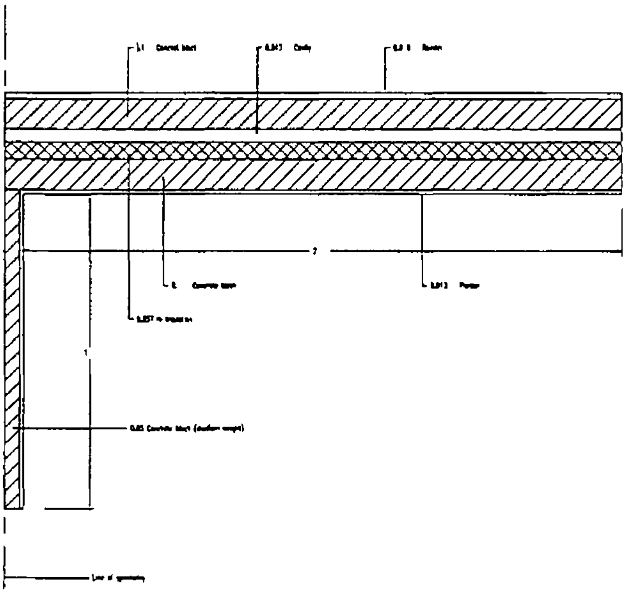


Figure A3 8 2 ANSYS Representation of Bungalow Partition Wall and External Wall

Figure A3 8 2 shows how the bridge is modelled in ANSYS

A3 8 2 Results

Bridge	**Wall and Partition Wall**	
Surface	**External Wall**	**Partition Wall**
U value TGD Part L Building Regulations (W/m^{2}K)	0 448	0
Averaged ANSYS U value (W/m^{2}K)	0 447	0 047
Effect of bridge (ANSYS,W/m^{2}K)	-0 001	0 047
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	0	-----
Bridge Conductance (ANSYS, W/mK)	0 08	

A3 8 3 Discussion

This bridge conductance is not very significant The bridge can result in a heat loss coefficient of 1 73 W/K in a standard bungalow

A3 9 Thermal Bridge 9 Bungalow Wall Tie

A3 9 1 Description

The bridge under consideration is the cavity wall tie There are approximately 600 of these present in an average bungalow Three dimensional analysis is necessary to completely simulate this bridge The current model assumes the tie to be accurately modelled by a circular rod of 0 004 m in diameter Because of the wall tie's small cross sectional area, the effect of the tie on wall thermal behaviour should be very small The ANSYS model (see Figure A3 9 2) was axi-symmetric

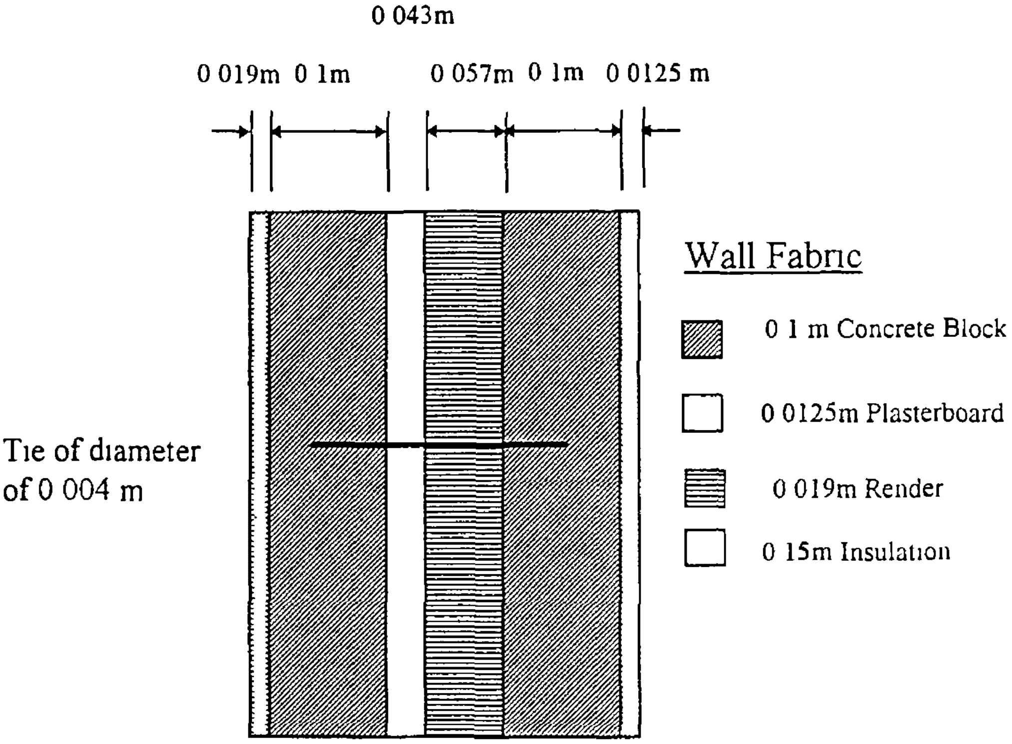


Figure A3 9 1 Bungalow Wall Tie

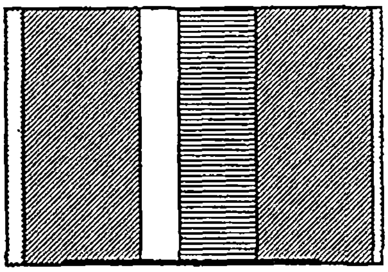


Figure A3 9 1 ANSYS Representation of Bungalow Wall Tie

A3.9.2 Results

Bridge	**Wall Tie**
Surface	**Wall**
U value TGD Part L Building Regulations (W/m^{2}K)	0 45
Averaged ANSYS U value (W/m^{2}K)	0 45176
Effect of bridge (ANSYS,W/m^{2}K)	0 0176
Effect of bridge as % of U value= 0 45 W/m^{2}K (ANSYS)	4
Bridge Conductance (ANSYS, W/K)	0 0009

A3 9 4 Discussion

A tie's individual effect is negligible, but when there are up to 600 present in a bungalow they can have a small effect on heat loss (0 54 W/K)

A3 10 BungalowThermal Bridge 10 Uninsulated Joists

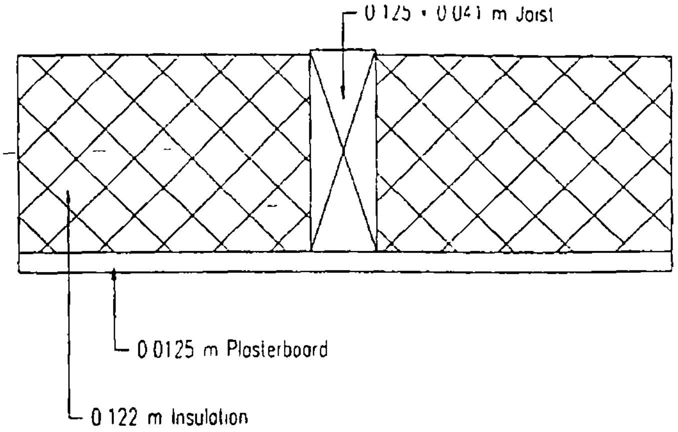


Figure A3 10 1· Bungalow Joist

A3 10.1 Description

This thermal bridge occurs in the ceiling The exposed joists have a greater thermal conductivity than the insulation, and therefore a region of greater heat loss exists around the joists The path of low themal resistance is formed through the plasterboard and joist (see Figure A3 10 1) The ANSYS model is represented exactly as shown in Figure A3 10 1 The boundary conditions within the roof space were calculated using a standard summation of resistances for the roof structure

A3 10 2 Results

Bridge	**Joist and Ceiling**
Surface	**Ceiling**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 263
Averaged ANSYS U value (W/m^{2}K)	0 35
Effect of bridge (ANSYS,W/m^{2}K)	0 087
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	33
Bridge Conductance (ANSYS, W/mK)	0 026

A3 10 3 Discussion

The total heat loss for a standard bungalow due to this bridge is 7 W/K (assuming that joists occur at 0 45 m centres) This bridge increases the U value of the ceiling by approximately 23%

A3 11 Bungalow Thermal Bridge 11 Gable End Wall

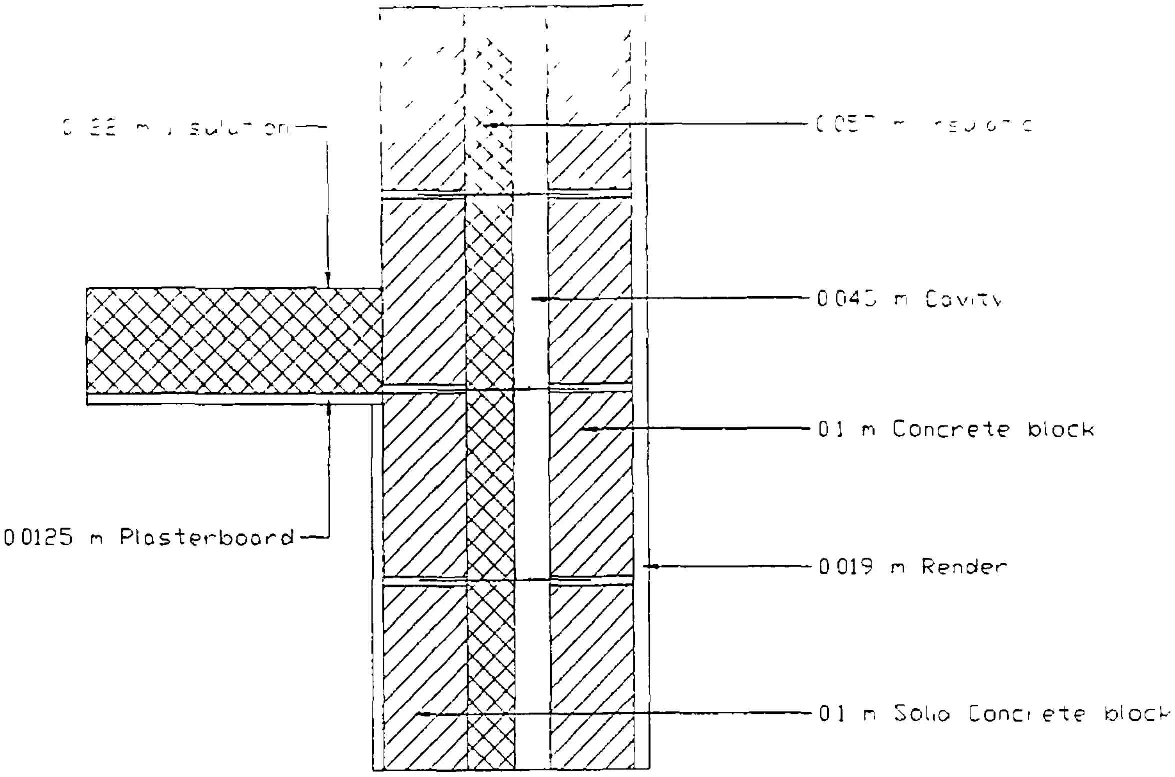
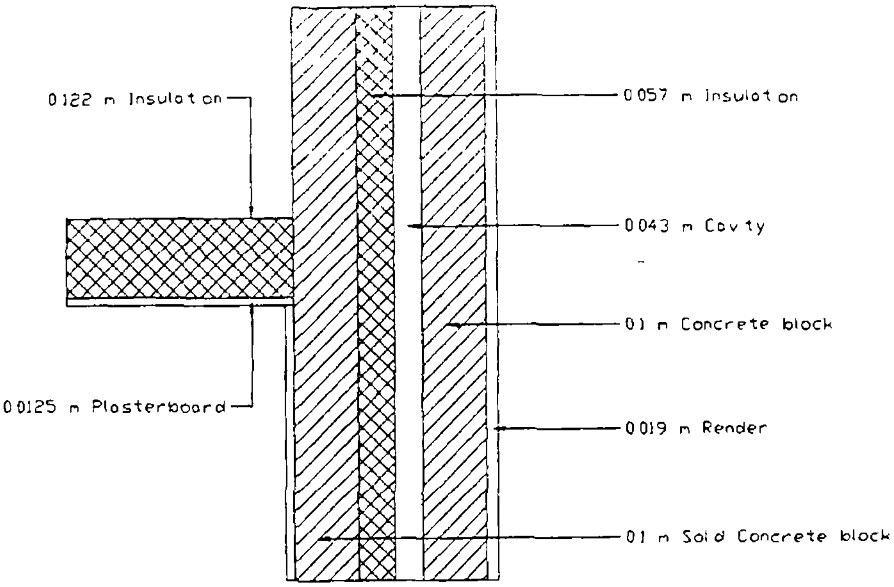


Figure A3 11 1 Bungalow Gable End Wall

A3 11 1 Description

This bridge occurs at the junction between the gable end wall and the ceiling The inner leaf of the gable end wall gives a direct path for heat flow between the internal environment and the loft space Since, there is a reasonably large area of wall at a lower temperature in the loft space this bridge should be significant It affects primarily the upper inner wall surface and the ceiling The ANSYS representation of the bridge is shown in Figure A3 11 2



A3 1 1 Results

Bridge	**Gable End Wall**	
Surface	**Wall**	**Ceiling**
U value TGD Part L of the Building Regulations (W/m²K)	0 45	0 263
Averaged ANSYS U value (W/m²K)	0 64	0 465
Effect of bridge (ANSYS, W/m²K)	0 19	0 202
Effect of bridge as % of U value= 0 45 W/m²K (ANSYS)	42	77
Bridge Conductance (ANSYS, W/mK)	0 29	

A3 11 3 Discussion

This bridge is very significant with a conductance of 0 29 W/mK It affects the wall over a length of 1 258 m and the ceiling over a distance of 1 16 m Over these distances the U values of the ceiling and wall are significantly increased The bridge occurs over a length of 15 4 m and results in a heat loss coefficient of 4 47 W/K for the standard bungalow

A4 Semi-Detached House Thermal Bridge

1 Foundation, external wall and floor

2 Foundation, partition wall and floor

3 Partition wall and external wall

4 Stud partition wall and external wall

5 Window cill

6 Window jamb

7 Window lintel

8 Wall corner

9 Party wall to foundation

10 Party wall to attic

11 Party wall and external wall

12 Uninsulated external wall at first floor level

13 Uninsulated joists above ceiling

14 Battens

A4 1 Semi-Detached House Thermal Bridge 1 Foundation, Floor and Wall

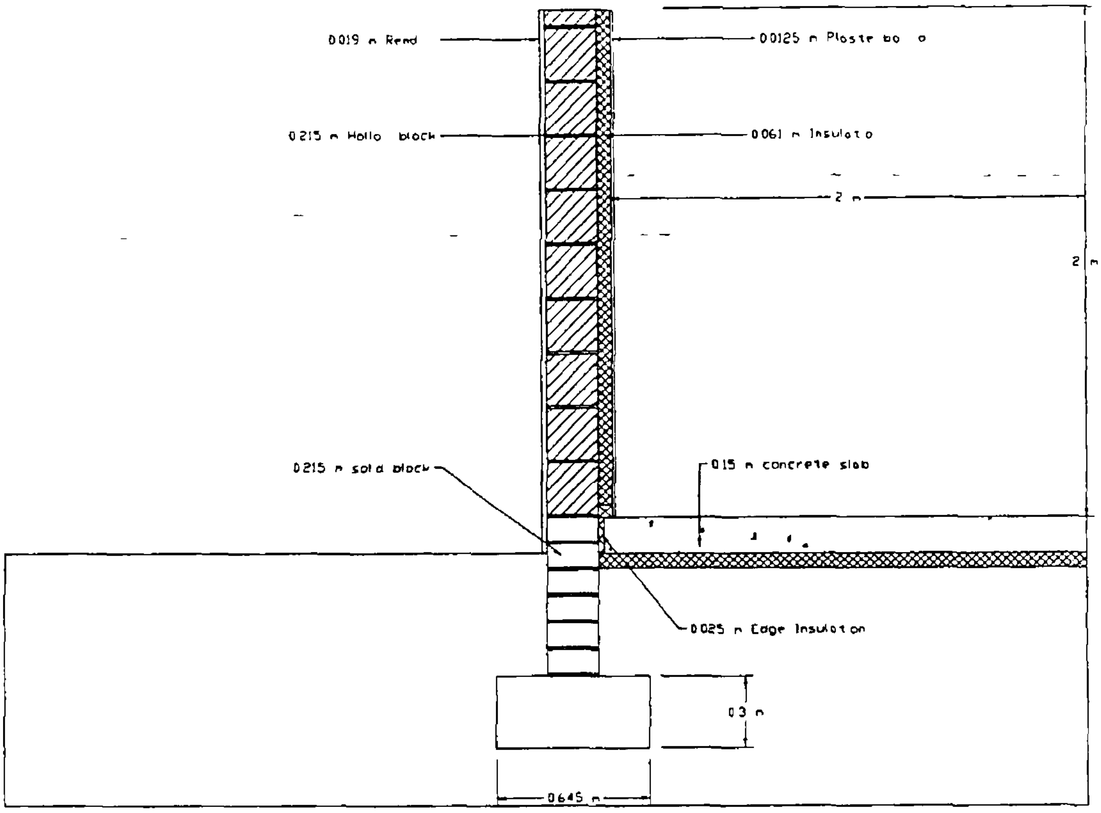


Figure A4.1 1 Semi-Detached House Foundation, Floor and External Wall

A4 1 1 Description

This bridge (see Figure A4 1 1) occurs as a combination of the external wall, floor and foundation The corner has a thermal bridging effect on both the external wall and the floor The internal insulation should reduce the effect of this bridge, even if the insulation envelope is broken by the timber ground The main path of low thermal resistance in this bridge, occurs from the concrete floor slab through the edge insulation

The ANSYS representation of this bridge can be seen in Figure A4 1 2 It is important to note that the timber ground is maintained within the ANSYS model

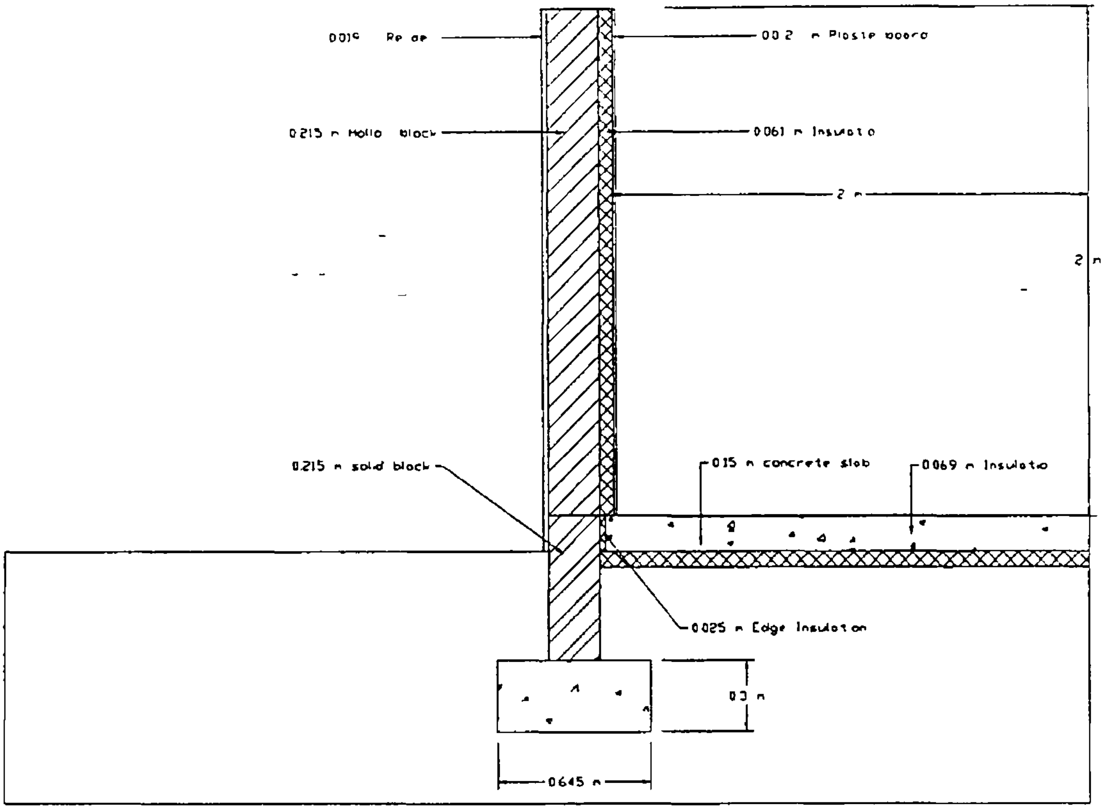


Figure A4 1 2 ANSYS Representation of Semi-Detached Foundation, Floor and Wall

A4 1 2 Results

Bridge	**Foundation, Floor and Wall**	
Surface	**Wall**	**Floor**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 45	0 45
Averaged ANSYS U value (W/m^{2}K)	0 56	0 73
Effect of bridge (ANSYS, W/m^{2}K)	0 11	0 28
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	24	62
Bridge Conductance (ANSYS, W/mK)	0 293	

A4 1 3 Discussion

The bridge conductance is 0 293 W/mK which makes this bridge severe The bridge affects an internal length of approximately 21 2 m in the semi-detached house and therefore has a heat loss coefficient of 6 2 W/K

A4 2 Semi-Detached House Thermal Bridge 2 Foundation, Partition Wall and Floor

A4 2 1 Description

At the junction between a solid internal wall and a ground floor, the wall goes straight through the ground floor slab and insulation to the foundation, which makes an uninterrupted heat flow path and a thermal bridge The bridge is made serious because there is normally no edge insulation at the sides of the concrete slab This bridge has the same construction as the equivalent bridge in the bungalow

A4 2 2 Discussion

The bridge has a conductance of 1 08 W/mK Its incidence, however in the semi-detached house is lower than in the bungalow (approximately 6 m) and results in a heat loss coefficient of 6 48 W/K For a more detailed analysis and diagrams of the construction see section A3 2 Bungalow Thermal Bridge 2

A4 3 Semi-Detached House Thermal Bridge 3 Solid Partition Wall and External Wall

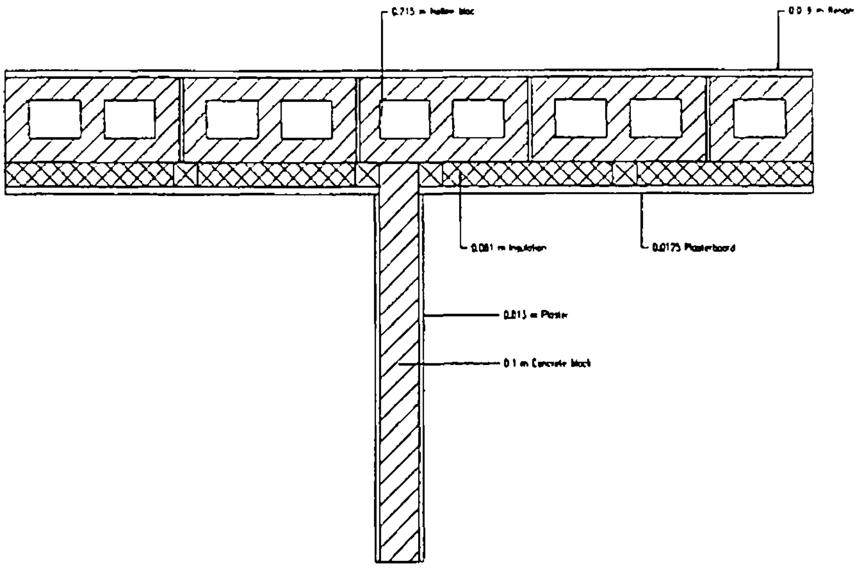


Figure A4 3 1 Semi-Detached House Solid Partition Wall and External Wall

A4 3 1 Description

At the junction between the external and a solid partition wall, there is generally no insulation present which creates a thermal bridge (see Figure A4 3 1)

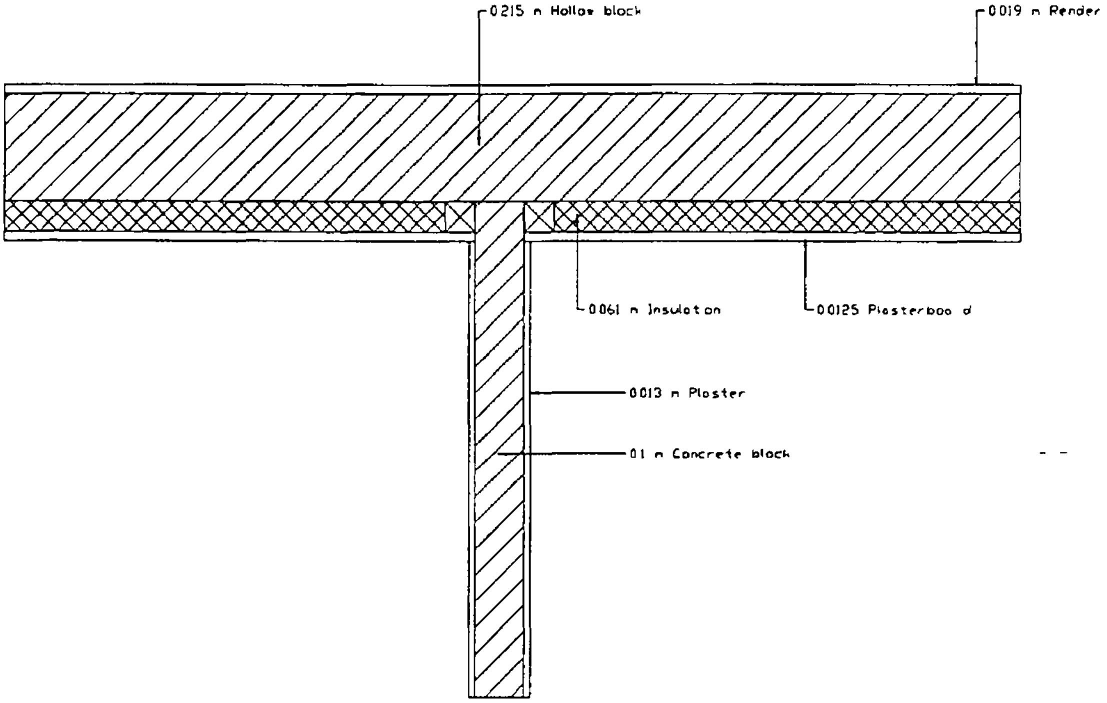


Figure A4 3 2 ANSYS Representation of Solid Partition Wall and External Wall

A4 3 2 Results

Bridge	**Wall and Partition Wall**	
Surface	**External Wall**	**Partition Wall**
U value Building Regulations (W/m^{2}K)	0 449	0
Averaged ANSYS U value (W/m^{2}K)	0 462	0 217
Effect of bridge (ANSYS,W/m^{2}K)	0 013	0 217
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	3	-----
Bridge Conductance (ANSYS, W/mK)	0 247	

4 3 3 Discussion

Internal partitions walls affects 2 4 m of wall within the semi-detached house The solid partition wall results in a heat loss coefficient of 0 494 W/K

A4 4 Semi-Detached House Thermal Bridge 4 Stud Partition Wall and External Wall

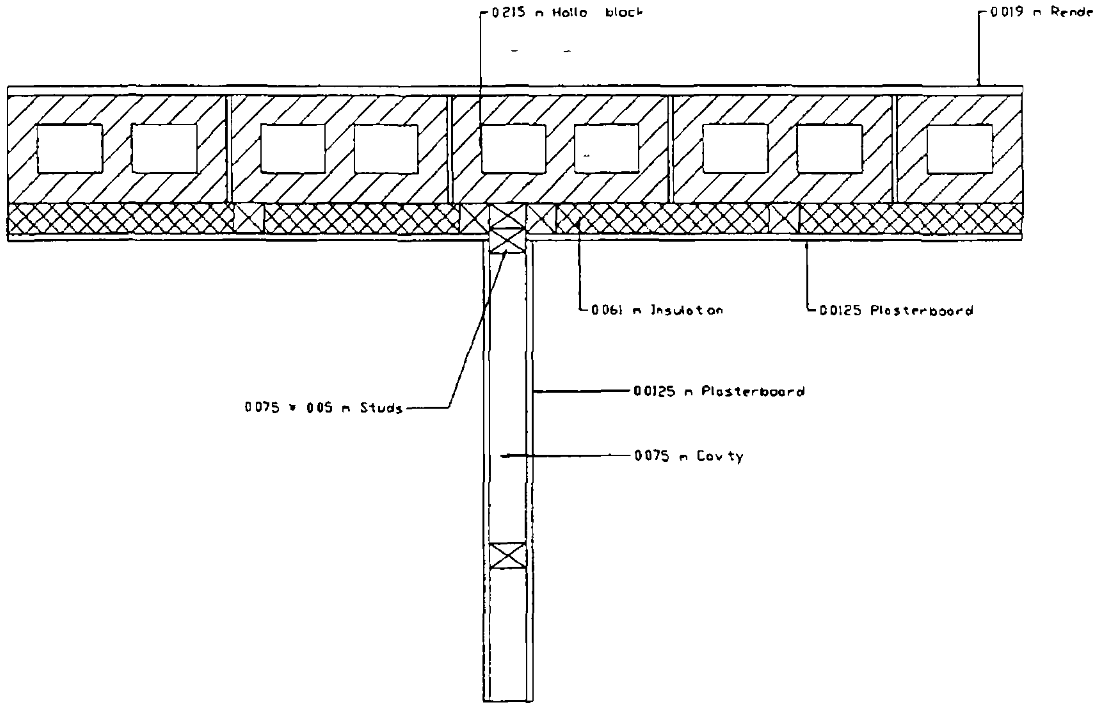


Figure A4 4 1: Semi-Detached House Partition Wall and External Wall

A4 4 1 Description

At the junction between the external and a stud partition there is generally timber studs or battens present and no insulation which creates a thermal bridge (see Figure A4 4 1) The presence of battens on either side of the stud partition make the thermal bridging effect worse and leave a reasonably wide path of low thermal resistance Figure A4 4 2 shows how the bridge is modelled in ANSYS

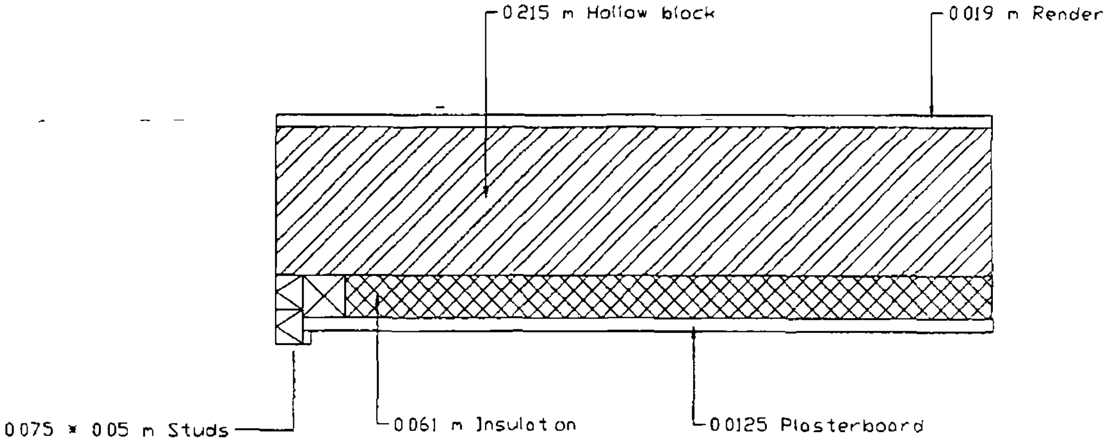


Figure A4 4 2 ANSYS Representation of Partition Wall and External Wall

The bridge was assumed to be symmetrical about its axis and a heat transfer coefficient of 6 W/m^{2}K was used to model the effect of the stud partition wall

A4 4 2 Results

Bridge	Wall and Stud Partition Wall
Surface	**External Wall**
U value Building Regulations (W/m^{2}K)	0 449
Averaged ANSYS U value (W/m^{2}K)	0 508
Effect of bridge (ANSYS, W/m^{2}K)	0 059
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	13
Bridge Conductance (ANSYS, W/mK)	0 085

4 4 3 Discussion

Internal partitions walls represent very significant thermal bridges within the semi-detached house This bridge is present for 14 4m in the semi-detached house and results in a heat loss of 1 22 W/K

A4 5 Semi-Detached House Thermal Bridge 5 Window Cill

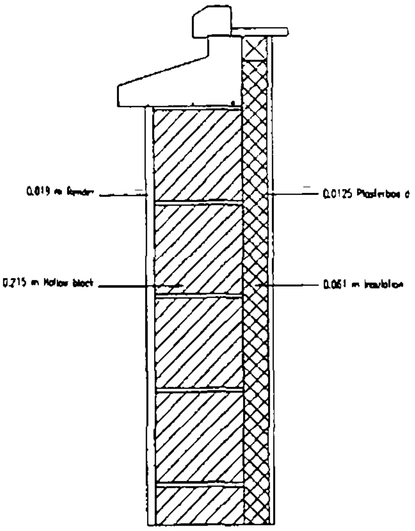


Figure A4 5.1: Semi-Detached House Window Cill

A4 5 1 Description

This thermal bridge occurs at the horizontal bottom sections of windows in the house (see Figure A4 5 1) The bridge should not have a very a severe affect as it is insulated internally

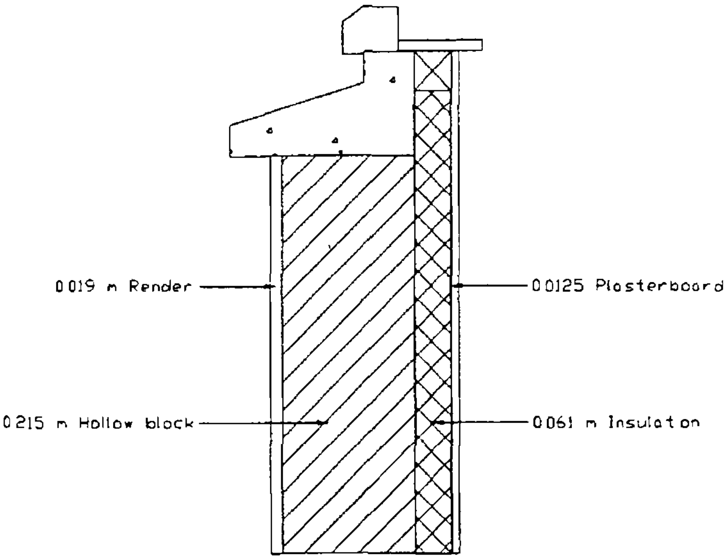


Figure A4 5 2 ANSYS Representation of Semi-Detached Window Cill

Figure A4 5 2 shows how the thermal bridge is represented in the ANSYS program

A4 5 2 Results

Bridge	**Window Cill**	
Surface	**Wall**	**Cill**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 45	0
Averaged ANSYS U value (W/m^{2}K)	0 473	1 262
Effect of bridge (ANSYS, W/m^{2}K)	0 023	1 262
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	5	-----
Bridge Conductance (ANSYS, W/mK)	0 232	

A4 5 3 Discussion

The bridge is present within the semi-detached house for 9 49m and has a bridge conductance of 0 232 W/mK The bridge results in a heat loss coefficient of 2 2 W/K

A4 6 Semi-Detached House Thermal Bridge 6 Window Jamb

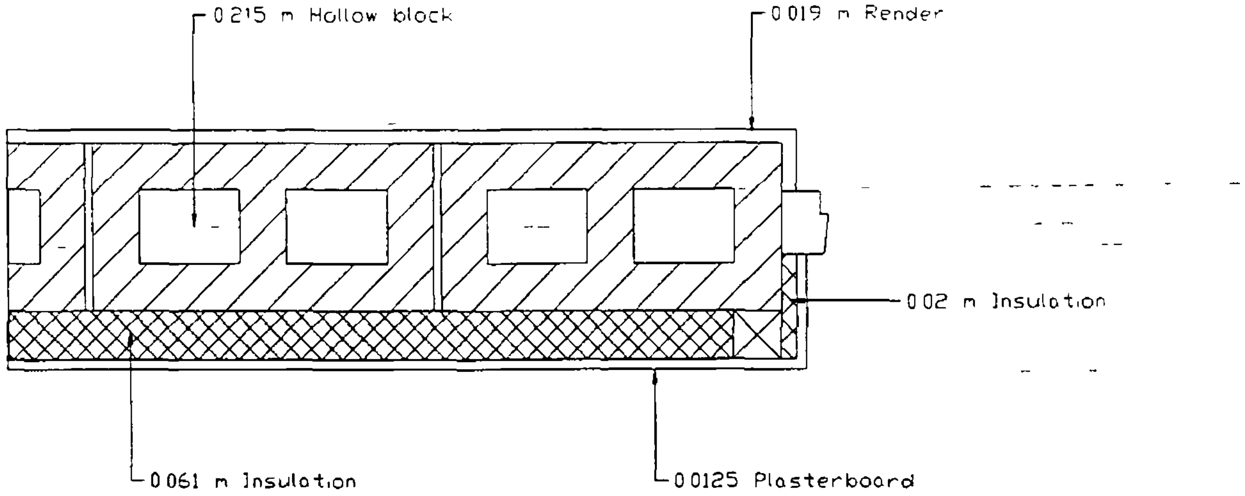


Figure A4 6 1. Semi-Detached Window Jamb

A4 6 1 Description

This bridge (see Figure A4 6 1) occurs at the vertical parts of windows and its importance depends on the amount of windows present in a building

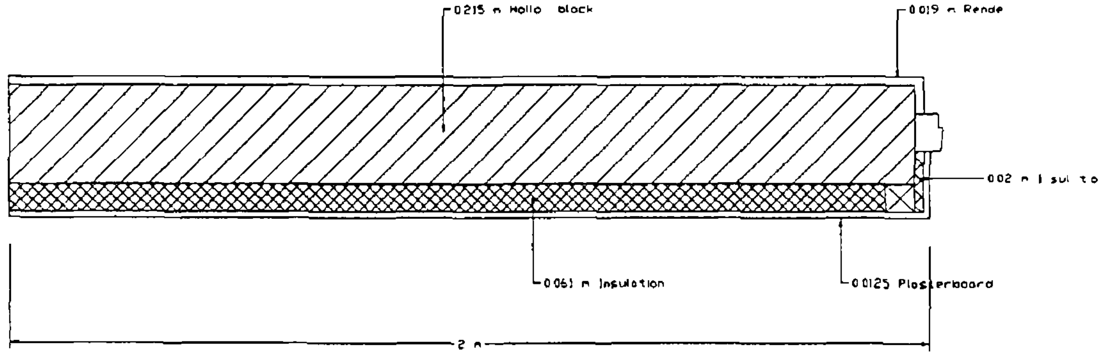


Figure A4.6 1 ANSYS Representation of Semi-Detached Window Jamb

The ANSYS representation of the thermal bridge can be seen in Figure A4 6 1

A4 6 2 Results

Bridge	**Window Jamb**
Surface	**Wall**
U value TGD Part L of the Building Regulations (W/m²K)	0 449
Averaged ANSYS U value (W/m²K)	0 592
Effect of bridge (ANSYS, W/m²K)	0 143
Effect of bridge as % of U value = 0 45 W/m²K (ANSYS)	32
Bridge Conductance (ANSYS, W/mK)	0 145

A4 6 3 Discussion

The bridge has a conductance of 0 145 W/mK This results in heat loss coefficient of 2 29 W/K, which is significant

A4 7 Semi-Detached House Thermal Bridge 7 Window Lintel

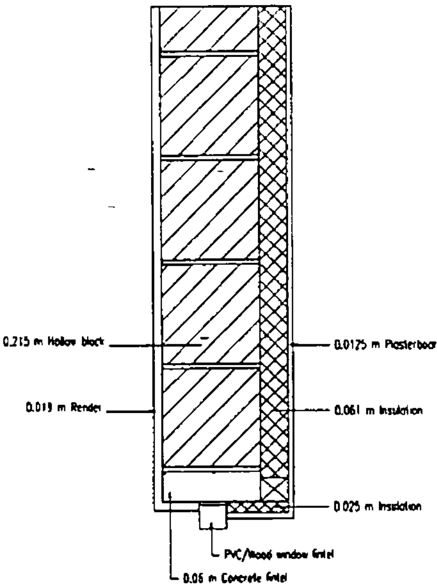


Figure A4 7 1 Semi-Detached Window Lintel

A4 7.1 Description

This thermal bridge occurs obviously at windows and its importance depends on the number and size of windows present in a house

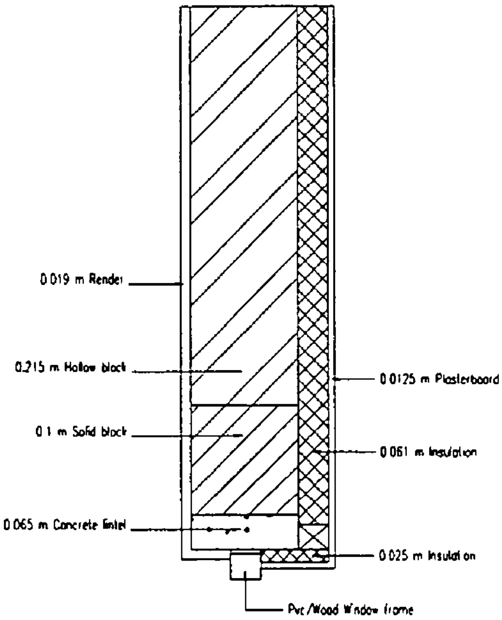


Figure A4 7 2 ANSYS Representation of Semi-Detached Window Lintel

Figure A4 7 2 shows how the bridge is represented in ANSYS

A4 7 2 Results

Bridge	**Window Lintel**
Surface	**Wall**
U value TGD Part L of the Building Regulation (W/m^{2}K)	0 45
Averaged ANSYS U value (W/m^{2}K)	0 576
Effect of bridge (ANSYS, W/m^{2}K)	0 126
Effect of bridge as % of U value= 0 45 W/m^{2}K (ANSYS)	28
Bridge Conductance (ANSYS, W/mK)	0 168

A4 7 3 Discussion

The bridge has a conductance of 0 168 W/mK and results in a heat loss coefficient of 1 59 W/K

A4 8 Semi-Detached House Thermal Bridge 8 Wall Corner

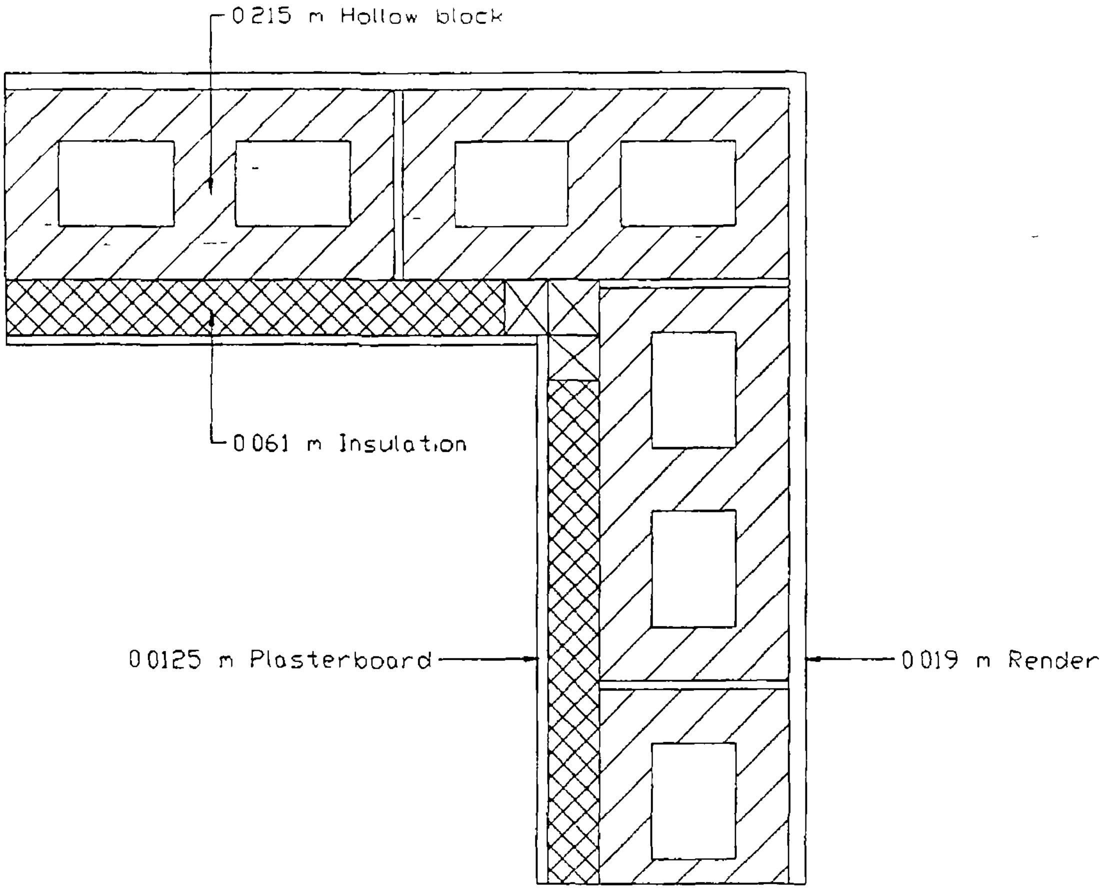


Figure A4 8 1. Semi-Detached House Wall Corner

A4 8 1 Description

This thermal bridge occurs at corners (see Figure A4 8 1) A path of low thermal resistance is present at the corner due to the geometry and presence of three battens with higher thermal conductivity than the insulation The ANSYS representation of the bridge can be seen in Figure A4 8 2

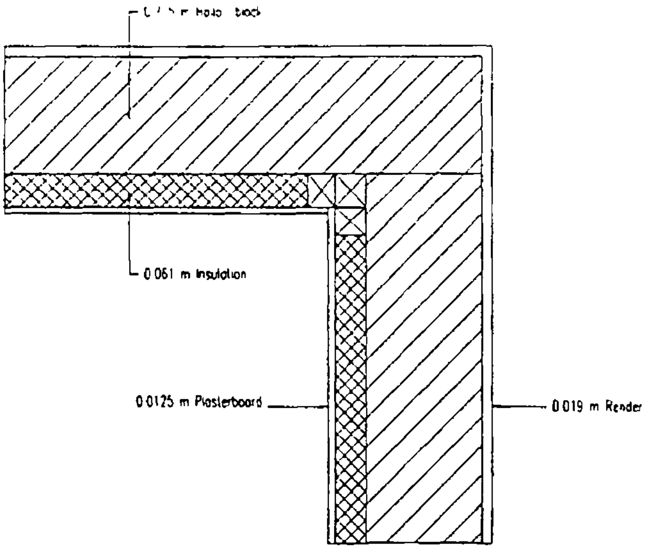


Figure A4.8.2 ANSYS Representation of Semi-Detached Wall Corner

A4.8.2 Results

Bridge	**Wall Corner**
Surface	**Wall**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0.45
Averaged ANSYS U value (W/m^{2}K)	0.564
Effect of bridge (ANSYS, W/m^{2}K)	0.114
Effect of bridge as % of U value = 0.45 W/m^{2}K (ANSYS)	20
Bridge Conductance (ANSYS, W/mK)	0.146

A4.8.3 Discussion

The bridge has a conductance of 0.146 W/mK and is present for 19.2m in the semi-detached house. The bridge results in a heat loss coefficient of 2.8 W/K

A4 9 Semi-Detached House Thermal Bridge 9 Party Wall to Foundation

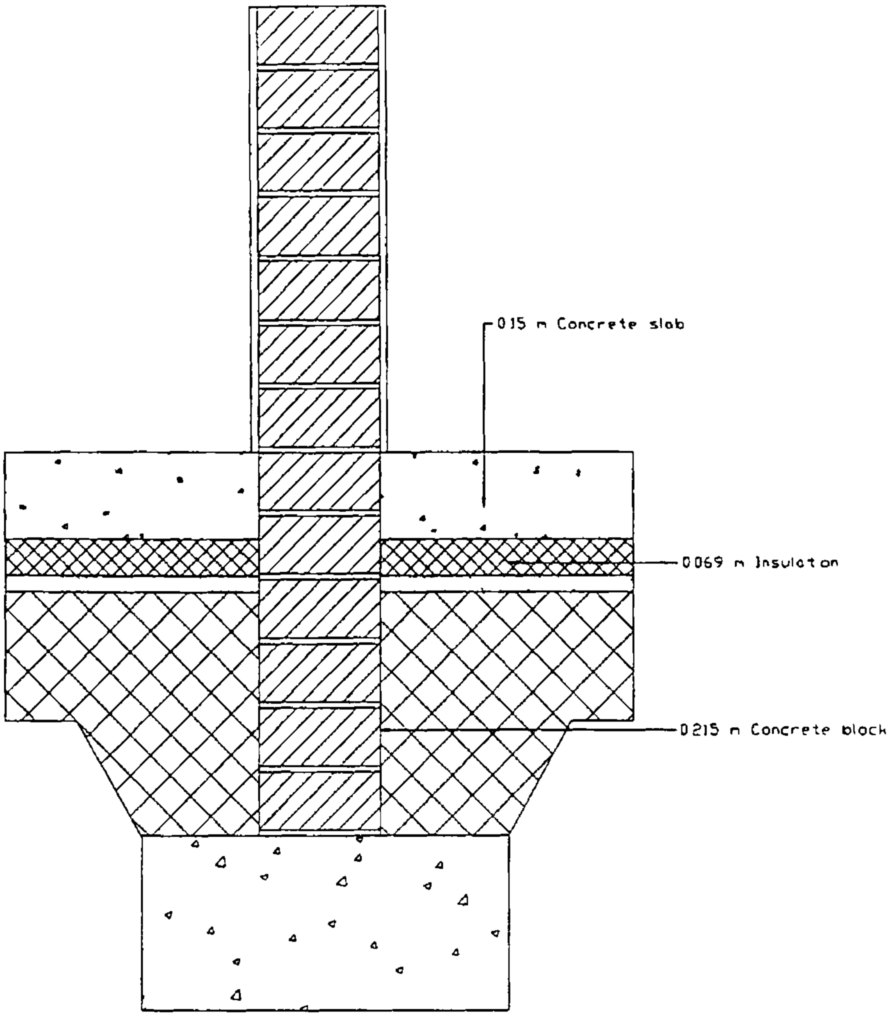


Figure A4 9 1· Semi-Detached House Party Wall to Foundation

A4 9 1 Description

The 0 215 m thick solid block wall is uninsulated as it passes through the ground floor to the foundation (see Figure A4 8 1) Typically, in the construction there is no edge insulation between the ground floor concrete slab and the party wall Therefore, this bridge provides a significant path of low thermal resistance to the foundation Figure A4 8 2 shows the ANSYS representation of the thermal bridge It has been assumed to be symmetrical about its axis

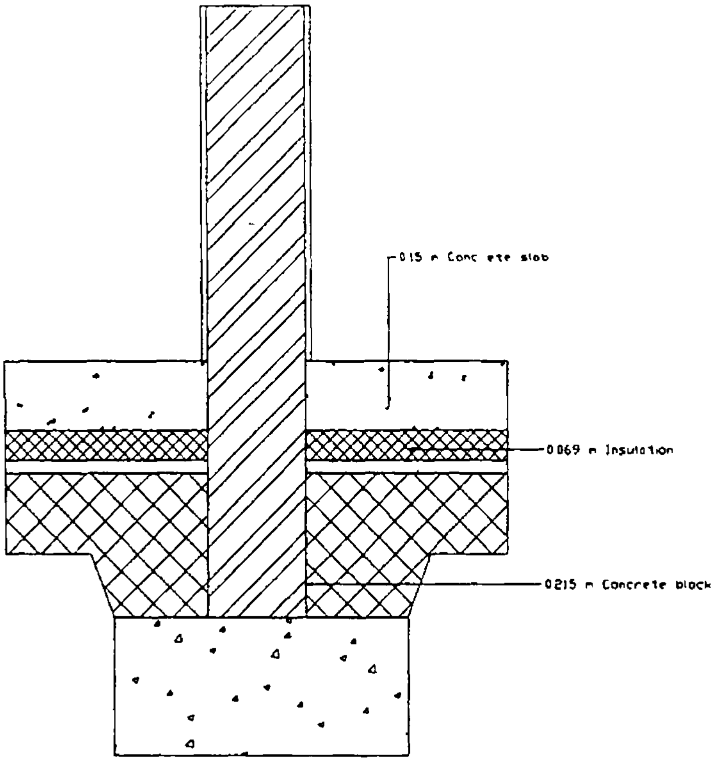


Figure A4.9 2 ANSYS Representation of Semi-Detached House Party Wall to Foundation

A4 9 2 Results

Bridge	**Party Wall to Foundation**	
Surface	**Floor**	**Party Wall**
U value Building Regulations (W/m^{2}K)	0 45	0
Averaged ANSYS U value (W/m^{2}K)	0 8	0 528
Effect of bridge (ANSYS,W/m^{2}K)	0 35	0 528
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	78	-----
Bridge Conductance (ANSYS, W/mK)	0 56	

A4 9 3 Discussion

The bridge conductance is 0 56 W/mK (an equivalent bridge conductance also affects the other semi-detached house within the construction) The bridge length is 7 4 m and therefore the bridge has a heat loss coefficient of 4 14 W/K The bridge is very severe

A4 10 Semi-Detached House Thermal Bridge 10 Party Wall to Attic

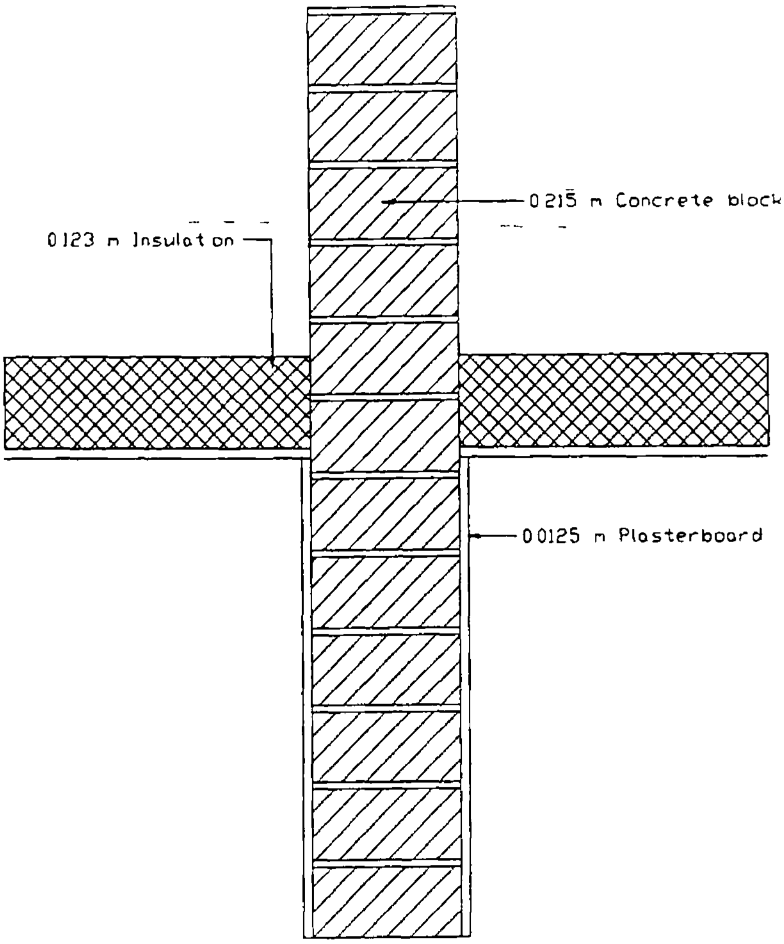


Figure A4 10 1. Semi-Detached House Party Wall to Attic

A4 10 1 Description

The 0 215 m thick party wall (see Figure A4 10 1) extends through ceiling level into the attic space The party wall in the attic space is uninsulated and since the attic space is cooler than the internal residential environment thermal bridging occurs The bridge affects both houses of a typical semi-detached construction The bridge is represented in ANSYS as shown in Figure A4 10 2 and is assumed to be symmetrical about its axis

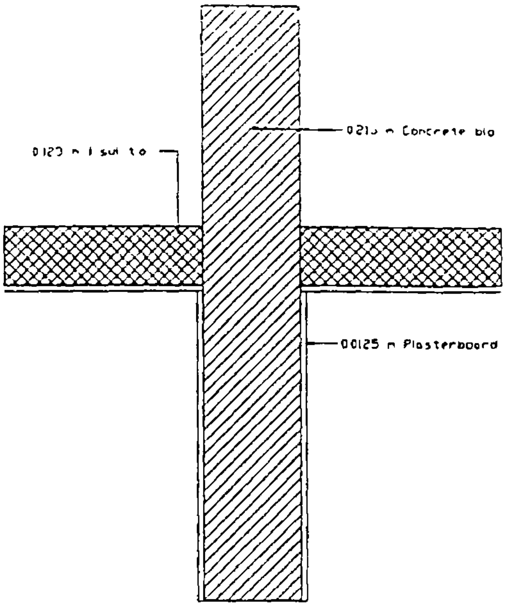


Figure A4 10 1 Semi-Detached House Party Wall to Attic

A4 10 2 Results

Bridge	**Party Wall to Attic**	
Surface	**Party Wall**	**Ceiling**
U value Building Regulations (W/m²K)	0	0 263
Averaged ANSYS U value (W/m²K)	0 262	0 45
Effect of bridge (ANSYS,W/m²K)	0 262	0 187
Effect of bridge as % of U value= 0 45 W/m²K (ANSYS)	-----	71
Bridge Conductance (ANSYS, W/mK)	0 33	

A4 10 3 Discussion

This thermal bridge is very severe and has a bridge conductance of 0 33 W/mK The bridge affects approximately 7 4 m of the semi-detached house, this represents a heat loss coefficient of 2 44 W/K

A4 11 Semi-Detached House Thermal Bridge 11 Party Wall and External Wall

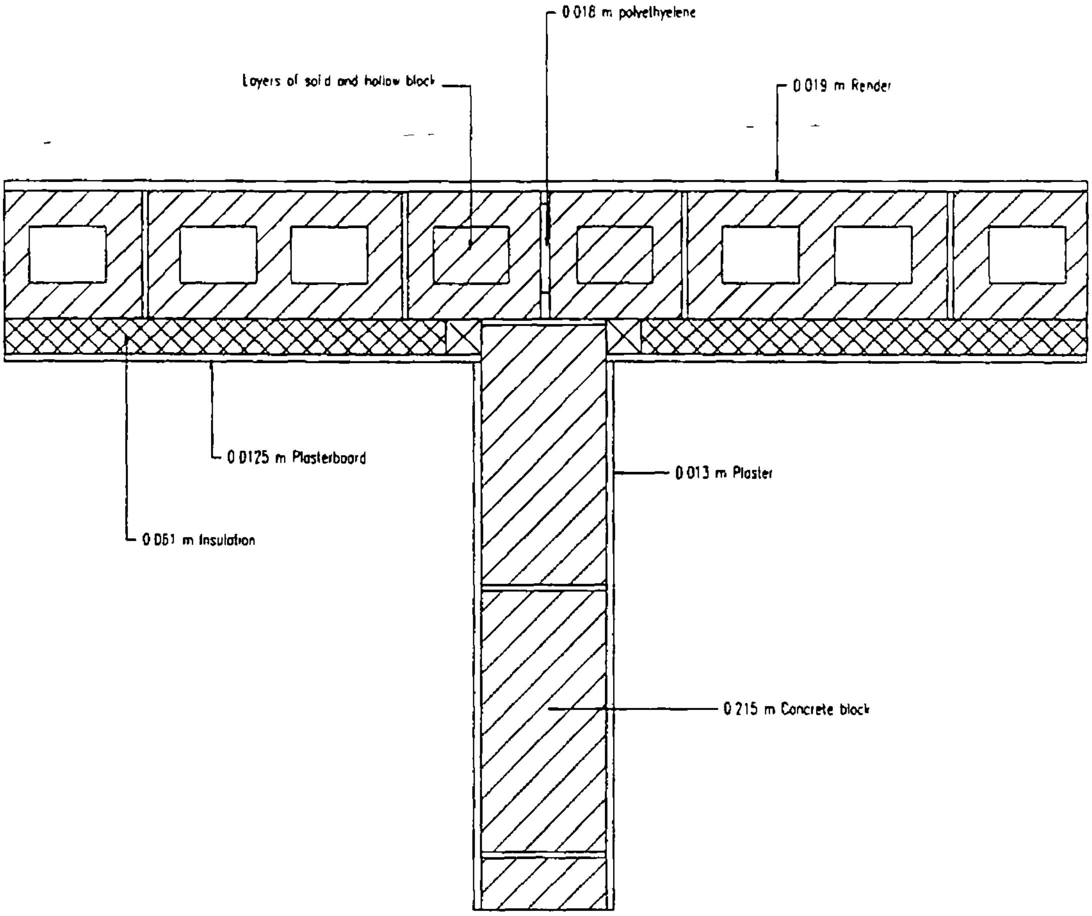


Figure A4 11 1. Party Wall of Two Adjoining Semi-Detached Houses

A4 11.1 Description

The above diagram Figure A4 11 1 illustrates the construction of a party wall between two adjoining semi-detached houses The junction of the party wall with the external wall is uninsulated and this constitutes a major bridge The party wall is made up of solid high density concrete block which has a high thermal conductivity and therefore conducts heat away from both houses to the external wall Mortar joints and wall ties are ignored Figure A4 11 2 shows the ANSYS representation of the party wall and the external wall

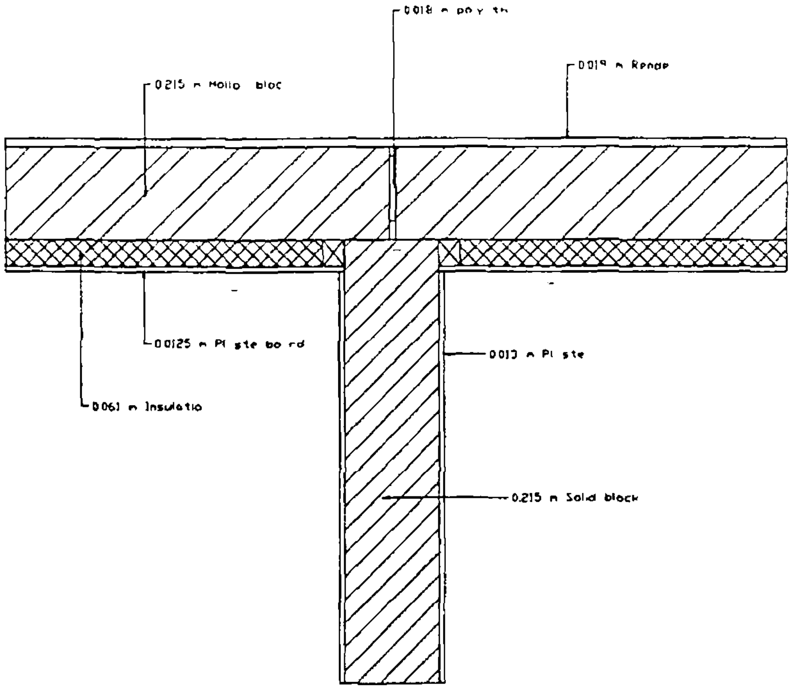


Figure A4 11 2 ANSYS Representation of Semi-Detached Party Wall and External Wall

A4 11.2 Results

Bridge	**External Wall and Party Wall**	
Surface	**External Wall**	**Party Wall**
U value Building Regulations (W/m^{2}K)	0 45	0
Averaged ANSYS U value (W/m^{2}K)	0 487	0 32
Effect of bridge (ANSYS, W/m^{2}K)	0 037	0 32
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	8	-----
Bridge Conductance (ANSYS, W/mK)	0 422	

A4 11 3 Discussion

This bridge is present for approximately a 4 8 m length This constitutes a heat loss coefficient of 2 03 W/K and can be considered as a serious thermal bridge

A4 12 Semi-Detached House Thermal Bridge 12 Uninsulated External Wall at First Floor Level

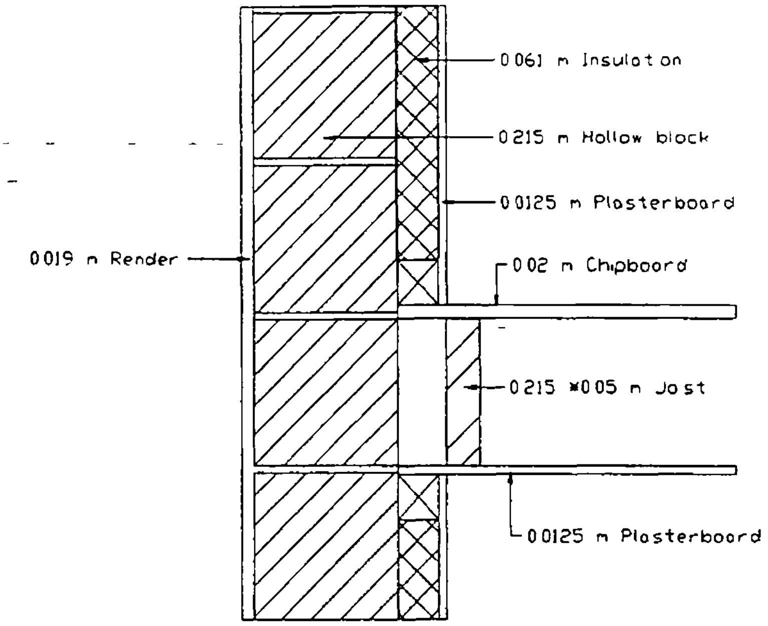


Figure A4 12 1 Semi-Detached Uninsulated Wall at First Floor Level in the Direction of the Joists

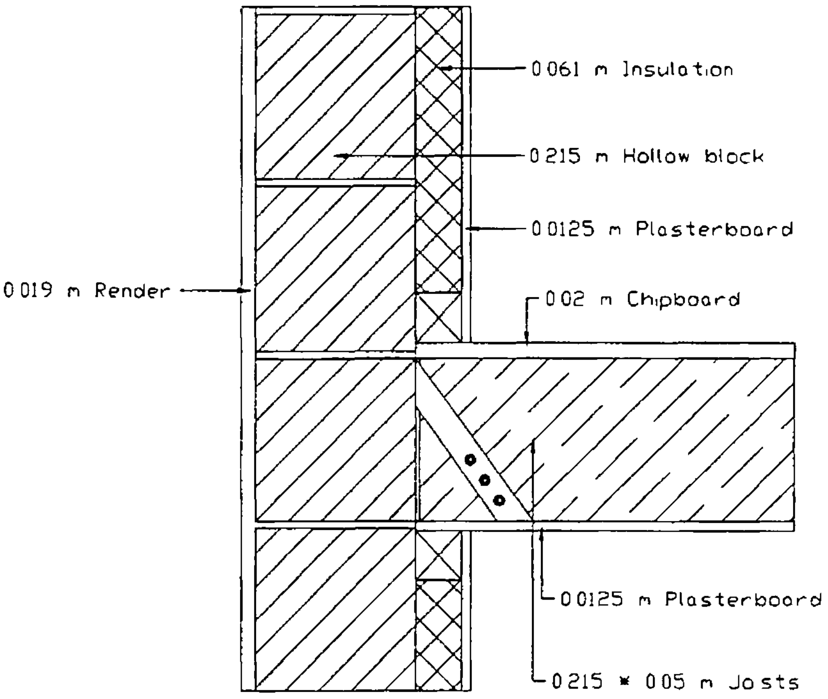


Figure A4 12 2 Semi-Detached Uninsulated Wall at First Floor Level in the Direction of the Joists

A4 12 1 Description

In speculative housing where the first floor comes in contact with the external wall, insulation of the external wall is neglected and this creates a severe thermal bridge, additionally the joists are supported on metal straps mounted in the walls It is assumed that there is a continuous band of uninsulated wall around the house as shown in Figure A4 12 3 The heat transfer coefficient within this space at the wall is assumed to be 6 W/m^{2}K

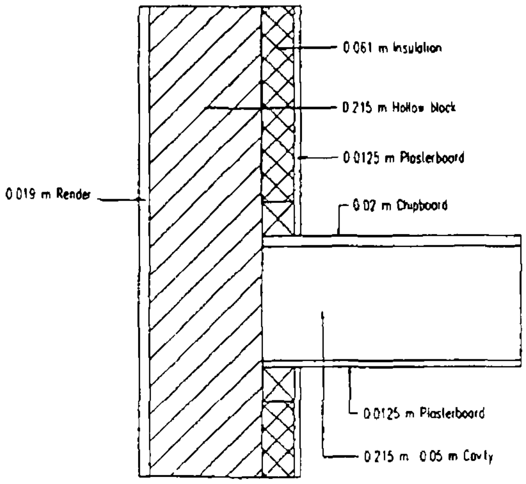


Figure A4 12 3 Semi-Detached Uninsulated Wall at First Floor Level

A4 12 2 Results

Bridge	**Uninsulated Wall at First Floor Level**
Surface	**Wall**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 45
Averaged ANSYS U value (W/m^{2}K)	0 766
Effect of bridge (ANSYS, W/m^{2}K)	0 316
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	70
Bridge Conductance (ANSYS W/mK)	0 69

A4 12 3 Discussion

The bridge has a conductance of 0 69 W/mK The bridge length is 21 2 m and results in a heat loss coefficient of 14 63 W/K The thermal bridge is severe

A4 13 Semi-Detached House Thermal Bridge 13 Uninsulated Joists

A4 13 1 Description

This thermal bridge (see Figure A4 13 1) occurs at the ceiling under the roof The exposed joists have a greater thermal conductivity than the insulation, thus a region of greater heat loss exist around the joists The roofspace was assumed to be at 8 9°C, which was based on the ratio of the standard resistances of the insulated ceiling and tiled roof

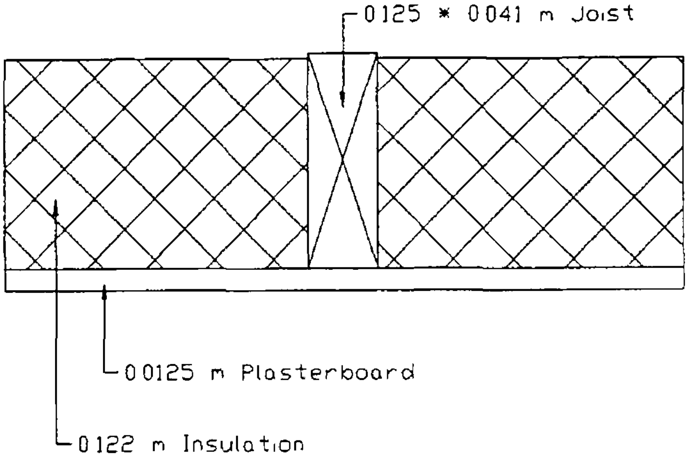


Figure A4 13 1 Semi-Detached House Uninsulated Joists

A4 13 2 Results

Bridge	**Joist**
Surface	**Ceiling**
U value TGD Part L of the Building Regulations (W/m^{2}K)	0 263
Averaged ANSYS U value (W/m^{2}K)	0 35
Effect of bridge (ANSYS,W/m^{2}K)	0 087
Effect of bridge as % of U value = 0 45 W/m^{2}K (ANSYS)	33
Bridge Conductance (ANSYS, W/mK)	0 026

A4 13 3 Discussion

This bridge is very similar to the equivalent bridge found in the bungalow The bridge conductance is 0 026 W/mK The bridge length is 111 m for the complete ceiling and results in a heat loss coefficient of 2 9 W/K

A4 14 Semi-Detached House Thermal Bridge 14 Battens

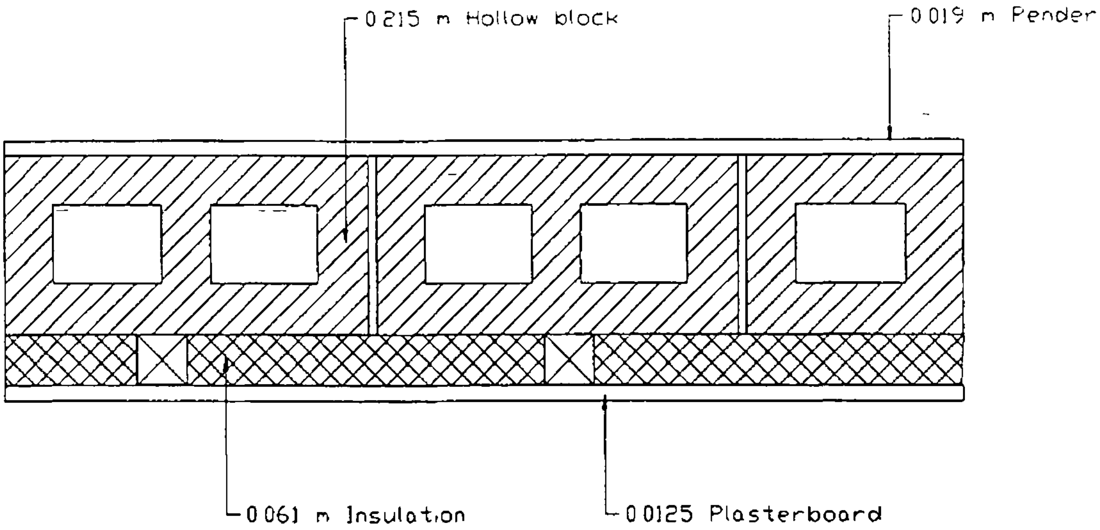


Figure A4 14 1 Semi-Detached House Battens

A4 14 1 Description

The batten (see Figure A4 14 1) breaks the insulation and creates a path of low thermal resistance

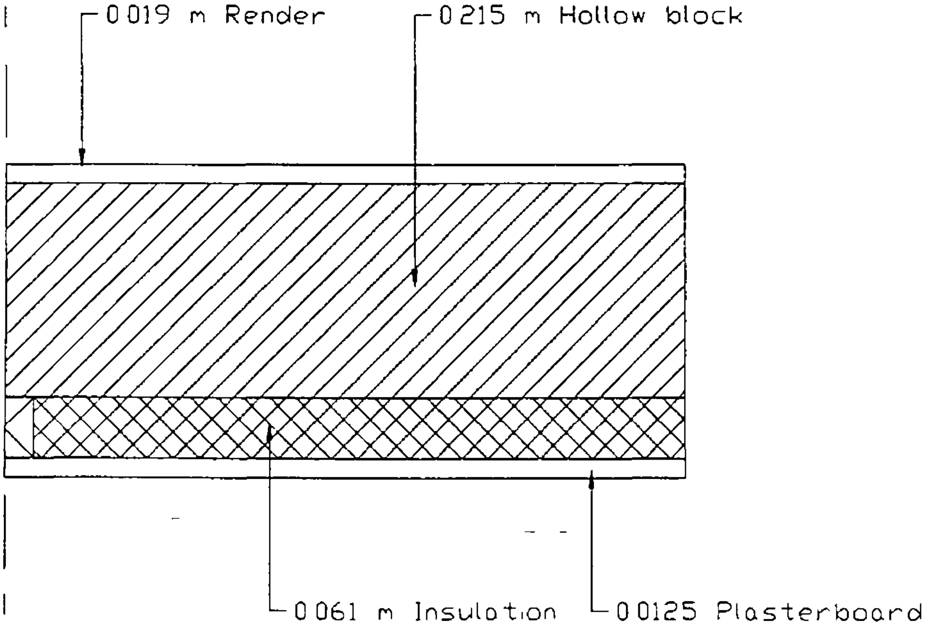


Figure A4 14 1 ANSYS Representation of Semi-Detached House Batten

The ANSYS representation of the semi-detached house batten is shown in Figure A4 14 1 This bridge has been assumed to be symmetrical about its axis

A4 14 2 Results

Bridge	**Battens**
Surface	**Wall**
U value TGD Part L of the Building Regulations (W/m^2K)	0 45
Averaged ANSYS U value (W/m^2K)	0 489
Effect of bridge (ANSYS, W/m^2K)	0 039
Effect of bridge as % of U value = 0 45 W/m^2K (ANSYS)	9
Bridge Conductance (ANSYS, W/mK)	0 056

A4 14 3 Discussion

The bridge has a conductance of 0 023 W/mK Its effect is negligible when considering an individual batten but considering all the battens present within a semi-detached house with a total bridge length of 148 8 m, the heat loss coefficient for the bridge is 8 33 W/K which is very significant

Appendix B 'Private Housebuilding' Statistics 1989-1993

Source An Foras Forbartha / Environmental Research Unit *Private Housebuilding Surveys* Dublin, Department of Environment, 1989-1993

B1 Estate Housing Survey 1989-1993

Floor Area

The average floor area in estate housing was 102m^2 The largest single percentage of houses had areas between 80-100m^2 These houses made up 43% of estate houses surveyed over the period 1989-1993 and 47% in 1993 Houses with areas of 100-125m^2 occupy the second largest percentage within the period 1991 to 1993 with a percentage of 40% There are four main groups of surface area of estate housing which are

Areas (m^2)	**1993**
1 <80m^2	9%
2 80-100m^2	47%
3 100-125m^2	41%
4 125-160m^2	3%

Table B1 1 Size of Houses by Percentage

Table B1 1 implies that several different areas could be used for estate reference houses and that the area used should be within area groups 2 and 3 For the reference house the average area of 102m^2 was used

House Type

In the survey there are only three relevant house types detached, semi-detached and terraced, of these the semi-detached house type constituted 68% of houses surveyed in 1993 and 60% over the period 1989-1993 Clearly, the reference selected would be a semi-detached house

Number of Storeys

93% of estate houses surveyed over the period 1989-1993 had two storeys with 95% of houses in 1993 The reference house selected has two storeys

Number of Bedrooms

Over the period 1989-1993, 55% of houses had three bedrooms, 38% had four bedrooms

Ground Floor Construction

The ground floor construction of estate houses was predominately concrete (99% of houses surveyed)

First Floor Construction

There are two types of first floor construction, predominantly timber T&G (tongued and grooved) construction (71% of houses surveyed) and chip board construction (20%)

Roof Construction

Roof construction in the survey has always predominantly been trussed construction (77% of houses surveyed) The rest of houses surveyed used framed roof construction

Roof Covering

99% of houses in the survey used tiles

External Wall Fabric

There are two types of external wall fabric which were important in the survey cavity and hollow block The latter has been increasing while the former has been decreasing in use over the last five years, respectively they represent 43% and 45% of houses surveyed

Extent of Brickwork Facing

Most houses had 30% of brickwork (or a slightly lower percentage) at the front of the house

Applied External Wall Finish

There were three kinds of external wall finish Rough Cast (13%), Nap (57%), Dry Dash (26%) Although the majority of houses surveyed used Nap as their wall finish, looking further at the statistics shows that both rough cast and dry dash are on the increase while Nap is on the decrease, decreasing from 62% in 1989 to 52% in 1993

Internal Wall Finish

The are two significant types of wall finish in the survey hard wall (38%) and dry lining (58%)

Internal Wall Covering

The principal wall covering was wall paper which was used in 61% of houses surveyed Paint was used in 37% of houses

Window Type

14% of estate houses surveyed had soft wood windows, hard woods were used by 61% of houses and PVC in 13% of houses In this case the trends are important and the use of hard woods although predominant have dropped from 67% in 1990 to 54% in 1993 while the use of PVC has increased from 11% in 1990 to 19% in 1993

It is clear from trends that PVC windows will be used extensively in future estate housing

Glazing Type

Single glazing was used in 56% of houses surveyed and 44% of houses had double glazing Here, it is important to examine the trends since single glazing use has been reduced from a percentage of 76% in 1989 to 35% in 1993, more than a 50% drop This contrast with the trend in double glazing, where its use has increased from 24% in 1989 to 65% in 1993 This figure is likely to increase in the future and it can be assumed that double glazing will be used in nearly all new estate housing

Roof Insulation Material

94% of houses surveyed used mineral fibre rolls for roof insulation, 98% of houses used them in 1993

Floor Insulation Material

99% of houses surveyed in 1993 used expanded polystyrene or polyurethane insulation and 98% over the total period surveyed

Wall Insulation Material

In 1993 43% of houses surveyed used expanded polystyrene and 56% used mineral fibre rolls, over the total period the percentages were 60% and 37% respectively

Wall Insulation Method

In 1993 internal and cavity part fill wall insulation methods were used 65% and 31% respectively, in estate houses surveyed

Miscellaneous

99% of houses surveyed in 1993 had one bath 82% had between two and three toilets and wash hand basins Only 70% of houses had showers Of the houses surveyed, 18% had a garage

B2 Single Housing Survey 1989-1993

It is important to note that this survey was carried out for only six rural counties

Floor Area

The average floor area in single housing was 142m^2 The single most significant group of houses (20%) was that with areas of 121-125m^2 The second most important group of houses (16%) had areas in the range of 161-200m^2 The number of houses surveyed were spread very evenly along the whole range of area values, but the most representative group would be houses with areas between 111m^2 and 125m^2

House Type

In the survey there were several relevant house types detached, bungalow, split-level and dormer The respective percentages of houses surveyed were 19%, 56%, 1% and 23% Therefore, the predominant house type was the bungalow

Number of Storeys

Since most of the houses surveyed were bungalows it is obvious that most of the houses had only one storey Those with two storeys accounted for 43% of houses although this figure includes dormers

Number of Bedrooms

33% of houses surveyed had 3 bedrooms and 51% had 4 bedrooms

Ground Floor Construction

The ground floor construction of single houses was generally concrete (99% of houses surveyed)

First Floor Construction

The first floor construction in the houses surveyed with first floors was timber T&G construction

Roof Construction

Framed roof construction accounted for 75% of houses surveyed The other 25% of houses used trussed roof construction

Roof Covering

47% of houses in the survey used tiles and 53% used slates

Extent of Brickwork Facing

84% of houses surveyed had no brickwork facing 6% had complete(100%) external brickwork facing and a remaining 6% had front (30%) brickwork facing

Applied External Wall Finish

Between 1989 and 1991 63% of houses used nap external wall finish, 7% used rough cast and 16% used dry dash

Internal Wall Finish

For 1991, 91% of houses had hard wall finishes

Internal Wall Covering

There were no statistics in the survey on this aspect

Window Type

Although hardwood was used in 30% of houses surveyed and PVC in 16%, these percentages give a false picture Hardwood in 1989 was used in 41% of houses surveyed, and fell to 23% in 1993 while PVC was unused in 1989 and in 1993 was window type in houses built will be PVC as can be seen in Figure B2 1 (the not shown category represents houses within the survey, whose window type was not determined)

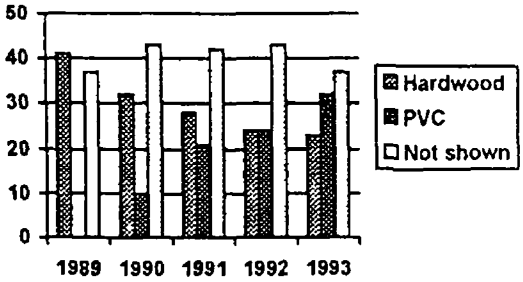


Figure B2 1. Percentage Use of Window Types

Glazing Type

Overall, 55% of houses surveyed used single glazing and 29% of houses surveyed used double glazing These statistics are misleading if it is taken into account that in 1989, 78% of houses used single glazing and in 1993 this figure has fallen to 35% and that double glazing has doubled in use from 22% in 1989 to 44% in 1993 Double glazing was the predominant glazing type in single building in 1993 (see Figure 2 2)

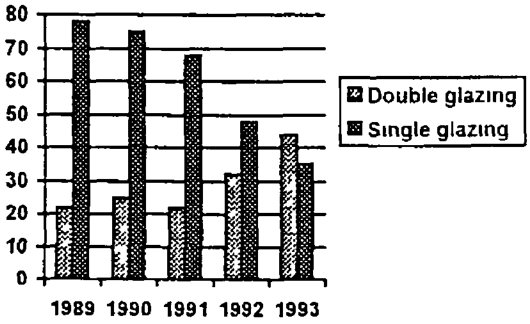


Figure 2 2 Percentage Use of Glazing

Number of Fireplaces

54% of houses surveyed had one fireplace 43% of houses had two fireplaces

Roof Insulation

84% of houses surveyed had roof insulation (100 mm)

Floor Insulation

82% of houses surveyed had floor insulation

Wall Insulation

85% of houses surveyed had wall insulation

Wall Insulation Method

In 1993, 99% of houses surveyed had cavity walls

Miscellaneous

95% of single surveyed in 1993 had one bath 65% of houses had 2 to 3 toilets and 63% had also two to three toilets 52% of houses surveyed in 1993 had a utility room

Appendix C House Specifications

C1 Bungalow

C1 1 Description of House

The house is a one storey building which has been built as a one off development The house is comprised of three bedrooms and one bathroom and of a kitchen-dining room, sitting room and lobby There are three windows on the front of the house and four windows at the back There are two external doors There is one fireplace located in the sitting room on an internal wall

C1.2 Dimensions

Externally	16 5×8 3 m
Internally	15 9×7 7 m
Floor to Ceiling Height	2 4 m
Floor Area (ignoring internal partitions)	122 43 m^2
House Volume	293 83 m^3

C1 2.1 Dimensions of External Openings

Table C1 2 1 External Openings of Bungalow

	External Openings			
Position	**Windows**		**Doors**	
	Dimensions (m)	**Area (m^2)**	**Dimensions (m)**	**Area (m^2)**
Front	2 035×1 13	2 3	2 035×2 03	4 13
	2 035×1 13	2 3		
	2 035×1 13	2 3		
Back	1 36×1 13	1 54	0 910×2 03	1 85
	1 36×1 13	1 54		
	0 91×1 13	1 03		
	0 91×1 13	1 03		
	1 125×1 13	1 27		
Total Window Area		13 31	Total Door Area	5 98

Total Area of Openings (Windows and Doors) 19 29 m^2

C1 3 Bungalow Construction

C1 3 1 Walls

External Walls Cavity wall construction

Components 0 013 m of internal plaster, 0 1 m inner leaf of dense concrete block, 0 1 m cavity comprised of 0 057 m insulation and 0 043 m air gap, 0 1 m outer leaf of dense concrete block, 0 019 m external render

Internal Partition Walls. 0 1 m solid block construction

Components 0 013 m of plaster, 0 1 m of dense concrete block, 0 013 m of plaster

C1 3 2 Floor

Floor Concrete slab-on-ground construction

Components. 0 025 m edge insulation, 0 15 m powerfloated concrete slab, 0 069 m insulation, 0 025 m sand blinding, 0 15 m hardcore

C1 3 3 Roof

Roof Pitched tiled roof with 0 123 m insulation

C1 3.3 Windows

Windows Double glazed with hardwood frames

C2 Semi-Detached House

C2 1 Description of House

The house is half of a two storey building which is partitioned with a thick party wall The house is comprised of three bedrooms, an upstairs bathroom, a kitchen-dining room, a sitting room and a lobby There are three windows on the front of the house and four windows at the back There are two external doors There is one fireplace located in the sitting room at the party wall

C2 2 Dimensions

Externally	7 55×8 05 m
Internally	6 9×7 4 m
Floor to Ceiling Height	2 4 m
Floor Area (ignoring internal partitions)	102 m^2 (51 m^2 × 2)
House Volume	244 8 m^3

C2 2 1 External Opes

Table C2 2 1· External Openings of Semi-Detached House

	External Openings			
Position	**Windows**		**Doors**	
	Dimensions (m)	**Area (m^2)**	**Dimensions (m)**	**Area (m^2)**
Front	1 5×1 13	1 695	2 035×2 03	4 13
	1 5×1 13	1 695		
	1 5×1 13	1 695		
Back	1 36×1 13	1 54	0 91×2 03	1 85
	1 36×1 13	1 54		
	1 36×1 13	1 54		
	0 91×1 13	1 03		
Total Window Area		10 74	Total Door Area	5 98

Total Area of Openings (Windows and Doors) 16 72 m^2

C2 3 Semi-Detached House Construction

C2 3 1 Walls

External Walls Hollow block construction

Components 0 0125 m of plasterboard, 0 061 m wooden battens, 0 061 m insulation, 0 215 hollow concrete block, 0 019 m external render

Internal Partition Walls

Ground Floor Solid block construction

Components 0 013 m of plaster, 0 1 m of dense concrete block, 0 013 m of plaster

First Floor Stud partition construction

Components. 0 0125 m of plasterboard, 0 075 m battens, 0 0125 m of plasterboard

C2 3.2 Floor

Floor Concrete slab-on-ground

Components· 0 025 m edge insulation, 0 15 m powerfloated concrete slab, 0 069 m Insulation, 0 025 m sand blinding, 0 15 m hardcore

C2 3 3 Roof

Roof Pitched tiled roof with 0 123 m insulation

C2 3.3 Windows

Windows Double glazed with wooden frames

Appendix D General Heat Loss Calculations

D1 Bungalow

D1 1 Fabric Heat Loss

Table D1 1 Bungalow Fabric Heat Loss

Building Element	Area (m^2)	U value (W/m^{2}K)	Heat Loss Coefficient (W/K)
Ceiling	122 43	0 25	30 6
Floor	122 43	0 45	55 1
Walls	98 71	0 45	44 4
Windows	13 31	3	39 93
Doors	5 98	3	17 94

The Heat Loss Coefficients shown in Table D1 1 were calculated using the following formula

Heat Loss Coefficient = Area × U value

D1 2 Infiltration / Ventilation Losses

Total Bungalow Volume = $7\ 7 \times 15\ 9 \times 2\ 4 = 293\ 83\ \text{m}^3$

$$q = \dot{M} c_p(\Delta t) = \rho \dot{V} c_p(\Delta t)$$

Where N = 1 (Airchanges per hour)

$\rho = 1\ 2\ \text{kg/m}^3$ (Density of air)

$c_p = 1000$ J/kgK (Specific heat capacity of air)

$\dot{M}$ = Mass flow rate

$\dot{V}$ = Volumetric flow rate

Δt = Temperature difference between inside and outside air

$$\Rightarrow q = \rho \frac{NV}{3600} c_p(\Delta t) = \frac{NV}{3} \Delta t$$

$$\Rightarrow \text{Heat Loss Coefficient} = \frac{NV}{3} = \frac{293\ 83}{3} = 97\ 94 \approx 98\ \text{W / K}$$

D2 Semi-Detached House

D2 1 Fabric Heat Loss

Table D2 1 Semi-Detached House Fabric Heat Loss

Building Element	**Area (m^2)**	**U value (W/m^2K)**	**Heat Loss Coefficient (W/K)**
Ceiling	51	0 25	12 75
Ground Floor	51	0 45	22 95
External Walls	89 28	0 45	40 18
Windows	10 74	3	32 22
Doors	5 98	3	17 94

The Heat Loss Coefficients shown in Table D2 1 were calculated using the following formula

Heat Loss Coefficient = Area × U value

D2 2 Infiltration / Ventilation Losses

Total Semi-Detached House Volume = 2 × (6 4×7 4×2 4) = 244 8 m^3

$$q = \dot{M} c_p(\Delta t) = \rho \dot{V} c_p(\Delta t)$$

Where N = 1 (Airchanges per hour)

$\rho = 1\ 2\ Kg/m^3$ (Density of air)

$c_p = 1000\ J/K$ (Specific heat capacity of air)

$\dot{M}$ = Mass flow rate

$\dot{V}$ = Volumetric flow rate

Δt = Temperature difference between inside and outside air

$$\Rightarrow q = \rho \frac{NV}{3600} c_p(\Delta t) = \frac{NV}{3} \Delta t$$

$$\Rightarrow \text{Heat Loss Coefficient} = \frac{NV}{3} = \frac{244\ 8}{3} = 81\ 6 \approx 82\ W/K$$

Appendix E The Chimney and Fireplace in Reference Houses

The chimney and fireplace are potentially significant thermal bridges if they are generally unused during the heating season They may be unused because of a separate central heating system In the case of the chimney, it provides an uninsulated heat flow path from the internal environment to the outside air in the chimney and to the loft, for both the bungalow and the semi-detached house large heat transfer surfaces are involved The fireplace provides an uninsulated heat flow path through its foundation Estimates of the bridge conductance are of the order of 8 W/K and 6 W/K for the chimney and fireplace respectively

For this study, the chimney and fireplace have been assumed to be in normal use in the bungalow and the semi-detached house during the heating season and thus not to constitute thermal bridges Higher temperatures due to their operation have been assumed not to affect other thermal bridges

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