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Airtightness and thermal bridging in buildings

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Cover image. ANMF House (Victorian Branch), Melbourne, by Bayley Ward. (Image: Earl Carter)

Abstract

All buildings should provide a durable enclosure, thermally comfortable interior, good indoor air quality and energy-efficient operation. These measures can largely be met through an airtight building envelope with adequate controlled ventilation and continuous insulation to address thermal bridging. This fundamental approach represents a step-change in how most Australian buildings – of all types – are currently designed and constructed.

This note provides strategies to reduce thermal bridging within a building's structure and achieve a high-quality airtight envelope. The note also considers the critical synergies between airtightness and effective ventilation for optimal indoor environment quality.

This note updates and replaces *Environment* Issue 03 October 2021 Airtightness and thermal bridging in buildings to reflect the minor commercial energy efficiency changes introduced into NCC 2022. Transition arrangements apply in some states and territories where NCC 2019 Section J clauses can still be used beyond the NCC 2022 adoption date of 1 May 2023. Refer to your jurisdiction's building authority for the relevant state and territory adoption dates.

Key words: Airtightness, condensation, controlled ventilation, insulation, thermal bridging.

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Introduction

Minimal requirements for energy-efficiency, amenity, and durability of buildings are mandated through the National Construction Code (NCC). The NCC 2019 energy-efficiency requirements significantly increased thermal performance of the building envelope and glazing performance stringency for Volume One; introduced condensation and weatherproofing management sections for all building classes and introduced air-sealing and thermal break requirements for all classes. Changes to Volume Two, in particular, followed findings that approximately a third of new and existing Australian houses suffer from condensation problems and moisture defects (Dewsbury et al. 2016), while measured air change rates of Australian houses revealed inadequate building sealing practices (Ambrose et al. 2013). The most recently published NCC 2022 changes build upon the initial provisions introduced in NCC 2019. The changes are intended to help further reduce condensation risk.

The effects of not considering airtightness and thermal bridging on the building's envelope leads to lost opportunities in the areas of improved health and comfort outcomes, material durability and energy efficiency.

When increasing airtightness, the provision of adequate ventilation needs to be addressed to avoid any consequences of condensation risks to the building and its occupants (refer to the Australian Building Codes Board's (ABCB) Condensation in Buildings Handbook, ABCB 2023). This note aims to increase the awareness and understanding of these issues, among others, and to show the importance of adequately accounting for their impact. The issues and recommendations relate equally to new build and existing projects and should be considered for renovation and upgrade projects.

Poor building sealing practices lead to a significant reduction of the overall thermal performance of a building. Gaps in the building envelope (the part of the building enclosure that has the role of physically isolating the inside of the building from the outside environment) allow air leakage, which can lead to moisture issues from condensation and water ingress, as well as excessive heat loss or gain. These issues contribute to inefficient energy use and poor indoor environment quality that affects occupant health and comfort. Likewise, poor thermal bridge detailing of the building envelope, depending on the climate, may lead to sub-standard performance. Thermal bridging creates localised temperature differences that can cause conditions conducive to mould growth and potential damage to the building structure, as well as unwanted heat loss or gain. With an increasing focus on improving our building stock in response to climate change, simple measures such as improving the building envelope should be regarded as essential.

The building envelope has a basic set of fundamental roles to play in our buildings – controlling the movement of rain, air, vapour, and heat, in that order of importance (Lstiburek 2007).

There should be a layer, or material(s), responsible for each of those functions. These are known as the control layers as shown in Figure 1. It is useful to break down the building envelope design and construction into its component parts to understand their function. It is also worth remembering that most materials do one thing very well, and rarely more than that. This note will cover the thermal and air control layers in detail. While vapour control is linked to air control, and can be delivered in the same control layer, it is outside the scope of this document and will be touched on only briefly.

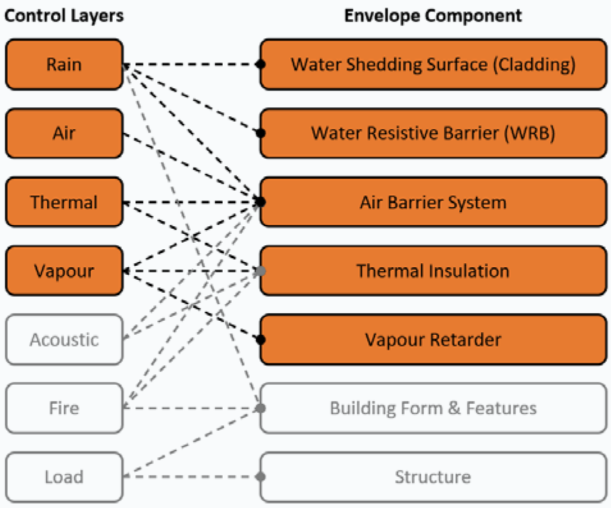

Figure 1. Relationship of control function to the critical barriers in a building (Adapted from: RDH Building Science Inc. 2017). Barriers of key interest to this note are highlighted.

Where any of these four control layers fail, a building's performance and durability are affected. Sometimes this may go unnoticed and can be catastrophic. Examples of catastrophic thermal and air control failures include mould-infested buildings. To be effective, the four control layers must wrap continuously around the building enclosure. At each junction in the building, it is imperative that the designer understands how the control layers are to be kept continuous. As construction details often intersect in three dimensions, thorough detailing is required. If these control layers are correctly implemented, airtightness can be ensured, and the negative impacts of thermal bridging avoided.

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Airtightness

The importance of airtightness in buildings

Airtightness is critical to building performance to minimise energy usage, ensure durability of materials, and to provide a thermally comfortable indoor environment. The building needs to be as airtight as possible with no holes, gaps, or other openings in the building envelope that allow uncontrolled leaks through the building envelope. To achieve an airtight construction there must be a continuous, identified air barrier around the building envelope. This airtightness line should be shown in the section detail drawings of the building (Figure 2).

The material(s) forming the airtight construction can be of many types, and though it is possible to deliver a well-connected and high-performing continuous barrier with a multitude of materials, simplicity is recommended. Materials must be carefully selected and clearly identified on project drawings and should be nominated as forming the air-barrier line, such as shown in Figure 2. Typical materials used include wet plaster, concrete, oriented strand boards (OSB) of minimum grade of 18mm OSB-3 (IBO 2009), and proprietary membranes manufactured specifically for the purpose of building sealing. Quality proprietary membranes should not be vapour impermeable, therefore allowing water vapour to pass through the membrane, while preventing the entry of liquid water. By contrast, there are products on the market which are manufactured from impermeable products (metal foils), perforated with tiny holes to allow the transfer of air and water vapour. However, the process of perforating the membrane also undermines its ability to withstand air and water penetration, making it unsuitable for use behind cladding materials.

Airtightness is useful in all Australian climates, whether cold and temperate or hot and humid.

In cool or cold climates, warm internal air containing high water vapour seeps through a gap or joint and cools down within the building structure, which may lead to interstitial condensation causing moisture damage. Therefore, the airtightness control layer should also have a vapour control function in these climates and be located on the interior facing surface of the insulation layer. In hot and humid Australian conditions, the external building envelope should resist vapour migration and heat flow through convection and diffusion. This is due to the high external dew point temperature in tropical climates, often up to 28°C,

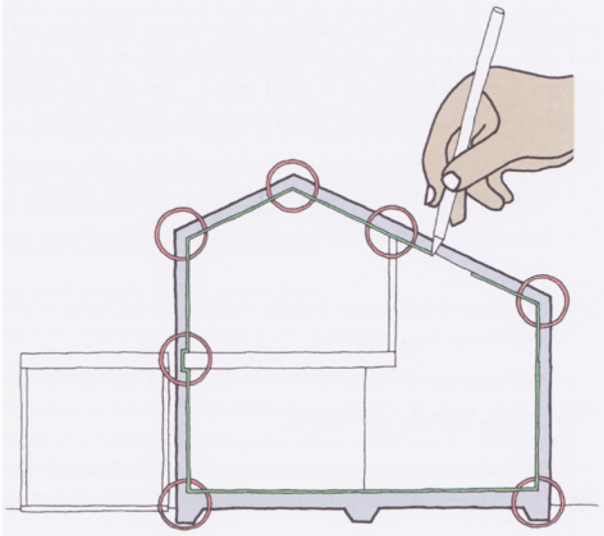


Figure 2. Tracing the airtightness layer with a pen in section shown in green. Areas circled in red need to be detailed carefully. (Source: Brimblecombe and Rosemeier 2017)

which can cause interstitial condensation in air-conditioned buildings if not prevented. In a tropical application, the airtightness barrier must also provide the function of a vapour barrier to prevent air transported water vapour, where the barrier should generally be located on the outside facing surface of the insulation layer. Further guidance on air conditioning, cooling and comfort in Australian hot humid tropical climates can be found in the Australian Institute of Refrigeration, Air conditioning and Heating (AIRAH) DA20 application manual (AIRAH 2016).

All measures to seal the building must be permanent and durable. These include construction materials or proprietary membranes and tapes that can ensure long-term adhesion and durability. Materials that may deteriorate during the life of the building or component part, eg a window seal, should be avoided. Airtightness is critical to building performance and must last as long as the building or component. Weather resistance membranes (also called 'pliable building membranes' in the NCC 2022) should protect against rain, wind, ultra-violet radiation and pollutants. The NCC 2022 also offers a Deemed-To-Satisfy (DTS) provision for condensation management for external wall construction; that the weather resistance membrane complies with AS/NZS 4200, installed in accordance with AS 4200.2, and is located on the external side of the primary insulation layer. Additionally, that the weather resistance membrane must have a vapour permeance of not less than the below, given in terms of climate zones as defined by the NCC 2022 for specific locations with similar climatic characteristics:

- 0.143 µg/N.s in climate zone 4 and 5
- 1.14 µg/N.s in climate zone 6, 7, and 8

Figure 3. Sealing pipes and ducts to the airtight membrane. (Source: pro clima 2021a)

Figure 4. Electrical power points to be sealed to the airtight membrane. (Source: pro clima 2021b)

It is now possible to computationally test the condensation management of a vapour permeable membrane in a construction assembly using dynamic simulations of coupled heat and moisture transfer. The NCC 2022 allows this modelling as a performance pathway under the condensation management section. The condensation management changes in the NCC 2022 builds upon the initial provisions introduced in NCC 2019. The changes are intended to help further reduce condensation risk. The AIRAH DA07 application manual (AIRAH 2020) is referenced; this manual sets out methodology guidance for how this modelling should be undertaken, including the input assumptions, and failure criteria limit (based on a mould growth index).

Other building components forming the building envelope such as windows, doors, and skylights used in an airtight building should achieve an airtightness class 3 in accordance with BS EN 12207:2016. Penetrations through the air barrier layer should be carefully detailed and are required to be well sealed up at the construction stage (Figures 3 and 4).

Measuring and controlling airtightness

A building's sealing can be accurately measured by carrying out an air-leakage or 'blower door' test (refer Figure 5). These tests are carried out across a wide range of pressures, both at pressurisation as well as at depressurisation, and the test result is read at 50 Pascals (Pa) pressure. During the test, the building should be as close to 'in use' mode as possible. The purpose of these tests is to induce air flow through the envelope, so that the envelope quality can be assessed. Locations where leaks are found should be sealed up to reduce the likelihood of the detrimental effects of uncontrolled air flow.

Testing a building's air change rate at different construction stages is useful to detect air leakage paths and defects inside the building envelope earlier.

Testing air change rates (ie using blower door tests) should be included in the building's specification and carried out by qualified airtightness testers, such as those registered with Air Tightness Testing & Measurement Association (ATTMA). Suggested blower door tests at different construction stages are shown in Table 1 over page.

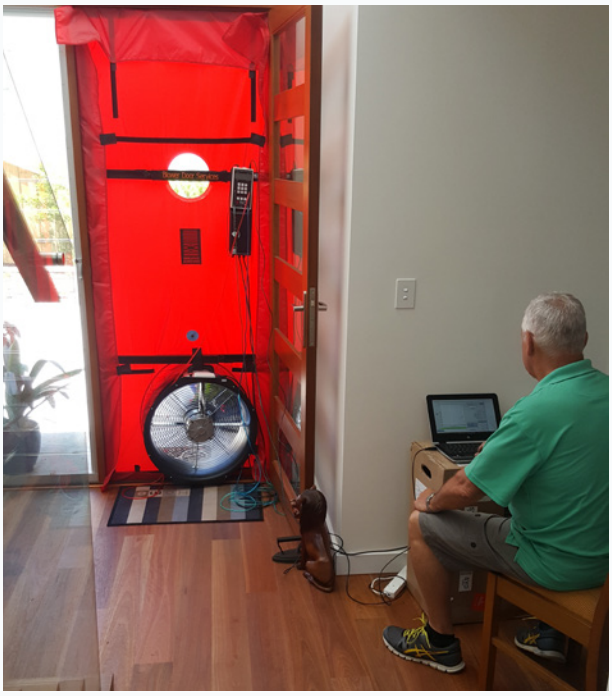


Figure 5. Installation of the fan for a blower door test. The fan is used to induce pressure in the building in two modes – pressurisation, or blowing air in, and depressurisation, or pulling air out. (Image: Blower Door Services n.d.)

Design activity	Recommendations across multiple dimensions
Initial airtightness test	On completion of the structural frame (when the dwelling has complete air barrier installed), with windows and external doors installed and fully sealed
Second airtightness test	After all services have been installed within the building envelope
Final airtightness test	On final completion

Table 1. Suggested stages when airtightness testing can be carried out. (Source: NHBC Foundation 2009)

Only by testing the building's airtightness, can the sealing quality of the building envelope be precisely assessed. There is currently no mandatory requirement for an airtightness test within NCC 2022 Volume Two. Without an airtightness test there is no guarantee that constructed buildings are satisfactorily sealed to achieve durability, healthy indoor environments, and significant energy savings. It is recommended that all new buildings undertake an airtightness test after construction to demonstrate that a sealing standard (air change rate) has been attained.

Airtightness testing of newly completed buildings is already a requirement in many countries, including the UK, Netherlands, France, Germany, Spain, USA, and Canada, to receive the final energy rating.

Air infiltration in Australia

Several studies (Ambrose et al. 2013; Ambrose and Syme 2016; Biggs et al. 1987) have highlighted the varying airtightness results achieved in the Australian building industry; calling for improvement in standards across multiple building typologies. While the NCC has included energy efficiency requirements since 2003 for Class 1 buildings and 2006 for other classes, specific requirements for building sealing have only been addressed using prescriptive qualitative measures that are difficult to enforce. Volumes One and Two of the NCC 2022 include an option for blower door testing to validate building sealing efforts. However, it remains to be seen how extensively this will be taken up. It is hoped that future iterations of the code move to mandatory testing, with increasingly stringent, climate-appropriate requirements, and remove the qualitative allowances.

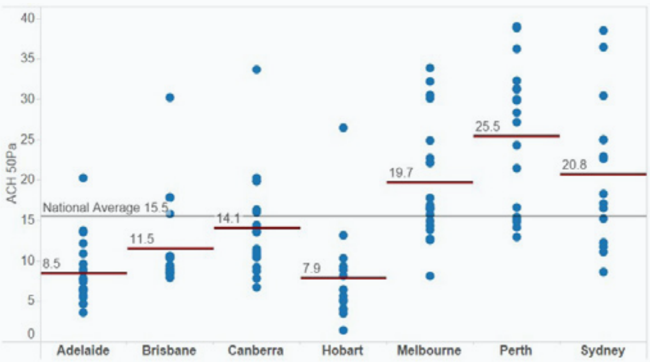


Figure 6. Australian airtightness test results (Source: Ambrose and Syme 2016). All houses (except Melbourne) were assumed to have been constructed to a 5-star NatHERS standard. The study indicated an average air change rate of 15.5 ACH@50Pa, with a number of houses recording above 30 ACH@50Pa.

Acknowledging that a very small percentage of houses that comply with energy efficiency regulations do so through a performance solution, the vast majority of new or significantly renovated houses are constructed to meet the star rating requirements of the National House Energy Rating Scheme (*NatHERS*) to show compliance with the NCC. The NatHERS software does not explicitly define a level of airtightness. An average value for new Australian houses is considered to be 15 air changes per hour (ACH) at 50 Pascals (50Pa) pressure difference (Ambrose and Syme 2016). If windows and doors are properly sealed, the value might be closer to 10 ACH@50Pa. The GBCA Green Star Homes Standard requires a minimum of 3-7 $m^3/hr.m^3$ (air permeability) at 50 Pascals for eligibility of its airtightness credit, depending on the climate (GBCA 2021). This level of air infiltration still far exceeds the international best practice of 0.6 ACH required for Passivhaus-certified constructions. Note that the air permeability metric is roughly equivalent to the ACH metric for residential-sized buildings.

Australian air change study test results (Ambrose et al. 2013; Ambrose and Syme 2016; Biggs et al. 1987) are much higher compared to new houses in many countries, including the UK, USA, and Canada. Figure 6 indicates the test results of 134 houses tested as part of a study performed through the CSIRO (Source: Ambrose et al. 2016). The best performing Australian city was Hobart, with an average rate of 7.9 ACH@50Pa which is still higher than the maximum allowed rates in many countries.

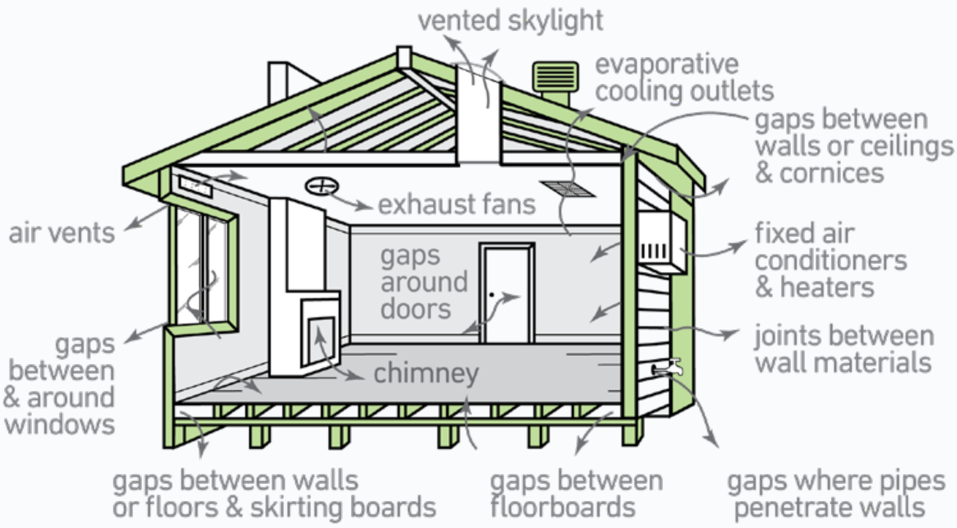


Figure 7. Infiltration sources within houses. (Sustainability Victoria 2021)

Air permeability testing is now allowed as a verification method for demonstrating compliance for the thermal performance pathway. However, this should be mandated for all new buildings in future NCC updates. A target value of 10 ACH@50Pa would correspond with minimum values for houses set in the UK. Local testing results, including those above, show that air change rates under 10 can be readily achieved.

In its present form, a NatHERS model does not allow a user to consider a target air change rate under accreditation mode but includes a standard assumption in the modelling algorithm. These standard assumptions do not depend on the construction type or quality but are rather calculated based on the hourly wind speed from the weather files multiplied by a stack and wind infiltration factor (Chen 2013).

The ability to incorporate target air change results into the NatHERS simulations would lead to increased awareness and an increase in the number of projects that target better building sealing to improve star ratings. A subsequent requirement for a blower door test to validate as-built performance (in combination with an industry push for as-built regulation) would lead to improved building performance.

It is crucial to note that effective ventilation, especially in combination with building sealing, should be understood. If a building is constructed in an airtight manner, mechanical ventilation should be installed to avoid poor indoor air and environment quality (NHBC Foundation 2009). This is generally accepted in most countries where requirements are set for airtightness and mechanical ventilation, and especially for residential buildings. Where the air permeability is less than 5 $m^3/hr.m^2$ at 50 Pa pressure, the NCC specifies that a mechanical ventilation system must be provided that can be manually overridden and provides outdoor air either continuously or intermittently (H6V3 of Volume Two 2022 and J1V4 of Volume One 2022).

However, as there is currently no mandatory requirement to test buildings with a blower door test, there is no way to know if this air permeability threshold is passed.

Common air leakage paths in buildings

There are many possible sources of draughts (gaps in the building envelope). Some of the most common are shown in Figure 7.

Leakages can be found during blower door testing as described above. Thermal imaging can be used to indicate both thermal bridges and air leaks, when employed during a blower door test or when pressurisation occurs such as during high winds (Figure 8). Thermal imaging can be especially useful in spaces with high ceilings or otherwise inaccessible places.

Building air leakage should be verified with Method 1 of AS/NZS ISO 9972. Refer to Appendix A for example working in the 'Airtightness calculation using Method 1 of AS/NZS ISO 9972' section.

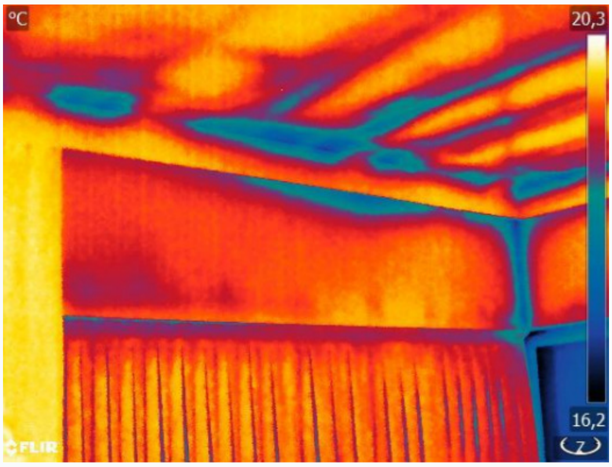


Figure 8. Air leakage at wall to ceiling junction with temperature differentials between inside and out. (Image: Vijver et al. 2014)

NCC requirements for airtightness

NCC 2022 Volume Two specifies that compliance with H6P1 is verified for residential dwellings when a building envelope is sealed at an air permeability of not more than 10 $m^3/h.m^2$ at 50 Pa reference pressure; however, "best endeavours" sealing is still compliant where a home uses NatHERS software to demonstrate compliance (NCC, Vol Two 2022). While NCC Volume One also allows air sealing as a verification method for demonstrating compliance for the performance pathway J1P1(e) and P1P2. This air permeability rate is verified when the envelope is sealed in accordance with Method 1 of AS/NZS ISO 9972. Australian air-permeability limits for different building classifications, as set in the NCC, are as follows (ABCB 2022, p 437):

- Class 2 or 4: 10 $m^3/h.m^2$ at 50Pa
- Class 5, 6, 8, 9a and 9b, in climate zone 1, 7 and 8: 5 $m^3/h.m^2$ at 50Pa
- Class 3 or 9c, or class 9a ward area, in climate zone 1, 3, 4, 6, 7 and 8: 5 $m^3/h.m^2$ at 50Pa

These targets are set as objectives, however, verification of whether a building actually meets these targets is not always required.

The importance of adequate ventilation in buildings

The strategy for ensuring airflow into and out of a building should be known during building design. Whether this is natural ventilation, with a consideration of occupant behaviour and reliability, or mechanical, the control of airflow is crucial to performance and indoor environment quality.

Relying on uncontrolled air leakage through cracks and gaps in the building envelope for the provision of fresh air is an unsuitable strategy. The notion that 'buildings that breathe' is good for occupants and performance is misleading.

It carries the implication that an unknown path or method for ensuring sufficient air quality or flow could be adequate. Buildings for human occupation should not be designed in this way.

This note only briefly explores strategies for ensuring adequate ventilation, though the importance of ensuring adequate ventilation in buildings of all types should not be understated.

Mechanical ventilation with heat recovery

Airtight construction needs to be considered in conjunction with ventilation strategies to maintain adequate indoor air quality. In the extremely well sealed Passivhaus (or Passive House) construction, a mechanical ventilation with heat recovery (MVHR) unit is typically used to ensure the supply of fresh air, while also re-using the heat energy or "coolth" of exhausted indoor air.

Mechanical ventilation can be used to ensure designed airflows are achieved, thus maintaining good air hygiene for occupants. This reduces the risk of elevated relative humidity and therefore moisture accumulation.

A MVHR system exhausts internal air that is extracted from rooms — such as kitchens, bathrooms, and toilets — where heat, moisture, and unwanted smells are produced. Before this air is expelled outside, it passes through a heat exchanger where the heat energy is transferred to the incoming fresh air, therefore eliminating the need to completely heat or cool the fresh air as it enters the building (Figure 9). In mild weather, when the outside air is within a comfortable range, some MVHR systems can automatically activate a summer bypass to help keep the building comfortable by not recovering heat. In this situation, the fresh air and exhaust air flows bypass the heat exchanger. The filtered incoming air will then be the same temperature as the outside air. It is also worth noting that if the external temperature is considered comfortable, occupants can open any number of windows if desired, however, this is not required for the supply of fresh air.

In hot weather, when the outside air is hotter than the exhaust indoor air, the MVHR will help keep the building cool by recovering 'coolth'. For this to happen, the air flows need to go through the heat exchanger. The MVHR effectively recovers 'coolth' instead of heat, to cool the outside air as it enters the building. This reduces the cooling load of the building, just as a MVHR unit reduces the heating load when it is cooler outside (Burrell 2018). In some hot and humid climates, if is often beneficial to install an enthalpy recovery ventilation (ERV) exchanger, rather than a heat recovery ventilation (HRV) exchanger. ERVs can be useful in hot and humid climates to recover otherwise-expended energy comprising of heat (sensible energy), in addition to humidity (latent energy). The addition of the latent

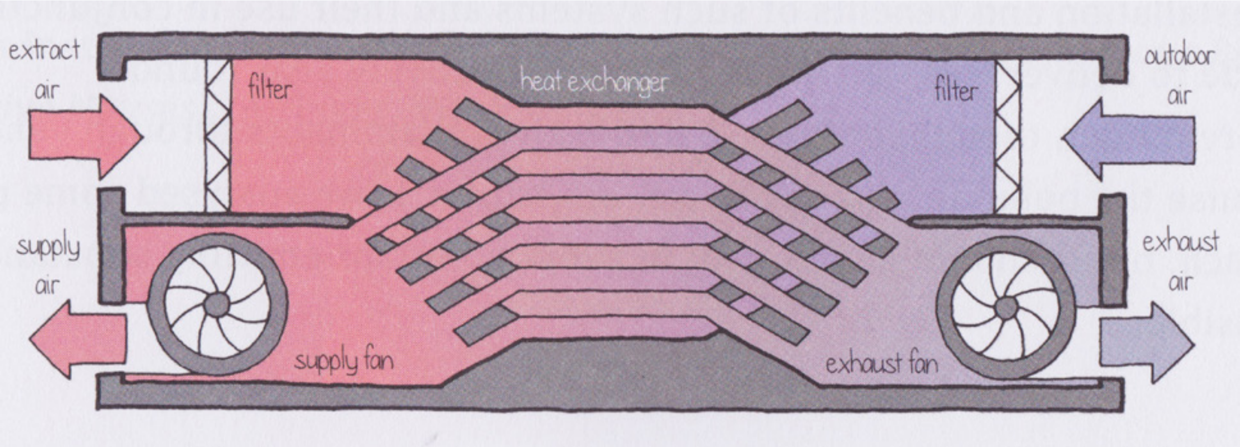


Figure 9. Schematic of a basic heat recovering system. (Source: Brimblecome and Rosemeier 2017)

energy recovery in an ERV reduces the required cooling energy demand for dehumidification in hot and humid climates.

The benefits of a MVHR system are many, including:

- Constant supply of the correct amount of fresh air to all habitable rooms, reducing carbon dioxide levels and removing the cause and perception of stuffiness and tiredness.
- Extraction of moisture-laden air from bathrooms, utility rooms and kitchens, ventilating harmful gases and smells.
- Lowering humidity levels, reducing mould and fungus that may appear over time, as well as decreasing dust and mite levels.
- Reducing the heating and cooling demand in buildings.

Thermal bridging

Definition and types

It is still relatively uncommon for building designers to undertake a thermal bridging assessment in their project, or to be aware of the impact of thermal bridging on thermal performance. Research has shown that thermal bridging in conventional construction may reduce the insulation effectiveness by as much as 40% (Morrison and Hershfield 2011).

A thermal bridge is a localised area of the building envelope where the heat flow is different (usually increased) in comparison with adjacent areas.

Thermal bridging can be accounted for using a psi-value (ψ) in units W/mK to describe the effects of the thermal bridge, quantifying the heat loss relative to the design without the thermal bridge. This might occur where, for example, a metal component (high conductivity) sits adjacent to an insulative material (low conductivity). In this example, the metal is a thermal bridge, or the path of least resistance, where heat flows at a much higher rate than through the adjacent material.

A common detail of a wall with a timber stud and metal studs are shown in Figure 10, where both studs are at 600mm centres. Each timber stud causes a psi-value

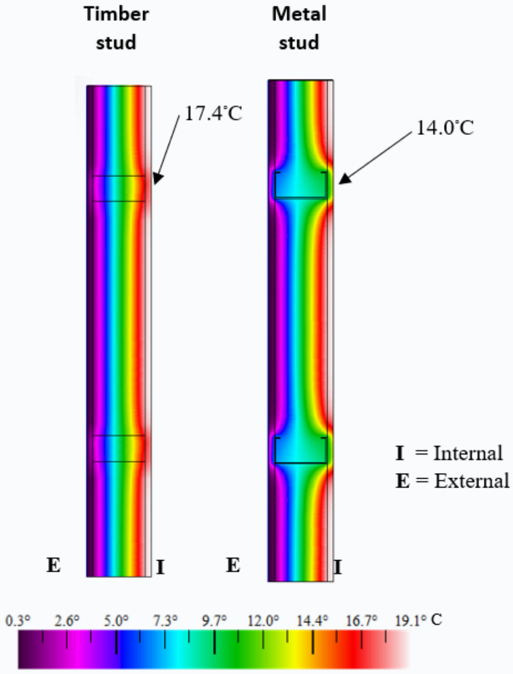


Figure 10. The thermal bridging impact of using timber studs (left) or metal studs (right) in a common 90mm stud wall. Boundary conditions modelled as a heating-dominated climate. (Image: Author)

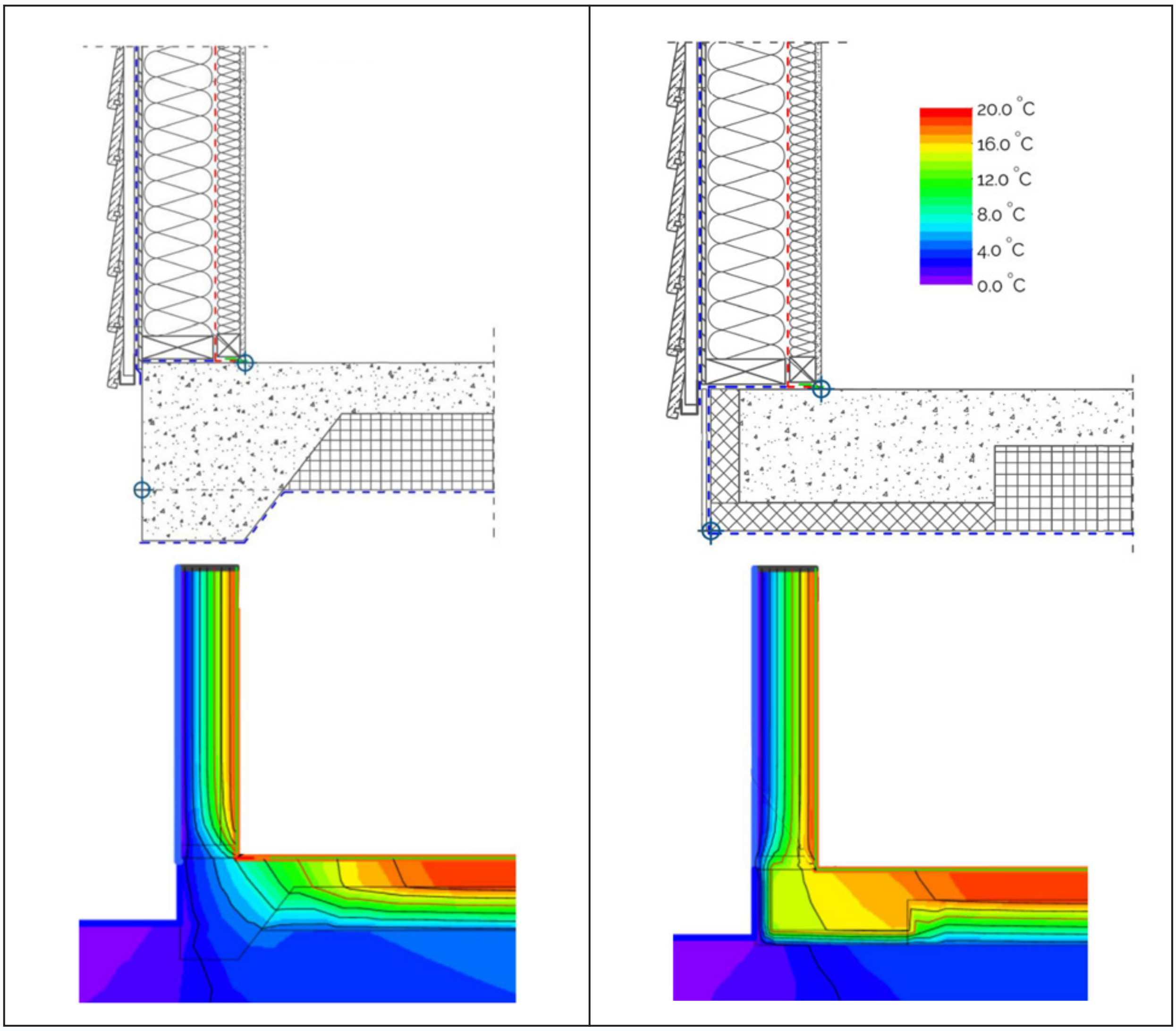


Figure 11. Insulation missing at the perimeter of the concrete slab (left) leads to a psi-value of 0.778 W/mK. In comparison an improved slab detail with continuous perimeter insulation (right) results in a significantly lower psi-value of 0.15 W/mK. The right diagram depicts the warm interior with the red and yellow surface, while the left diagram clearly shows lower surface temperatures at the corner leading to greater risk of moisture accumulation in the building envelope (Source: Quinn 2021). Cladding and flashing should be installed to the outside face of the perimeter insulation to ensure the materials longevity.

of 0.033 W/mK which produces a system R-value of 2.14 m^2K/W, while each metal stud causes a psi-value of 0.165 W/mK which produces a much lower system R-value of 1.28 m^2K/W. In this case, the metal studs show far greater thermal conductivity, effectively causing an overall thermal performance decrease of 60 % due to the increased heat flow from inside to outside. This example shows an often-neglected factor – the influence of the structure in the thermal control layer. Thermal bridging is just as important in cooling dominated climates; however, the heat flow direction is reversed.

Thermal bridges work in both directions – inside to outside and vice versa. Heat always flows from where there is more heat to less. So, when the interior of a building is warmer than outside, heat flows from inside to out, and the opposite occurs when interior conditions are cooler than outside. This presents an issue in two areas: energy consumption and building indoor environment quality (IEQ). IEQ issues may become apparent when low interior surface temperatures cause mould, due to increase relative humidity at the cool surfaces.

Unwanted energy flows affect the internal condition to the point that they must be overcome with active systems, eg if substantial heat is lost in winter, a heater needs to replace that heat for the interior to be comfortable. IEQ issues arise when temperature and humidity factors combine, presenting conditions that may lead to mould, condensation, and material degradation.

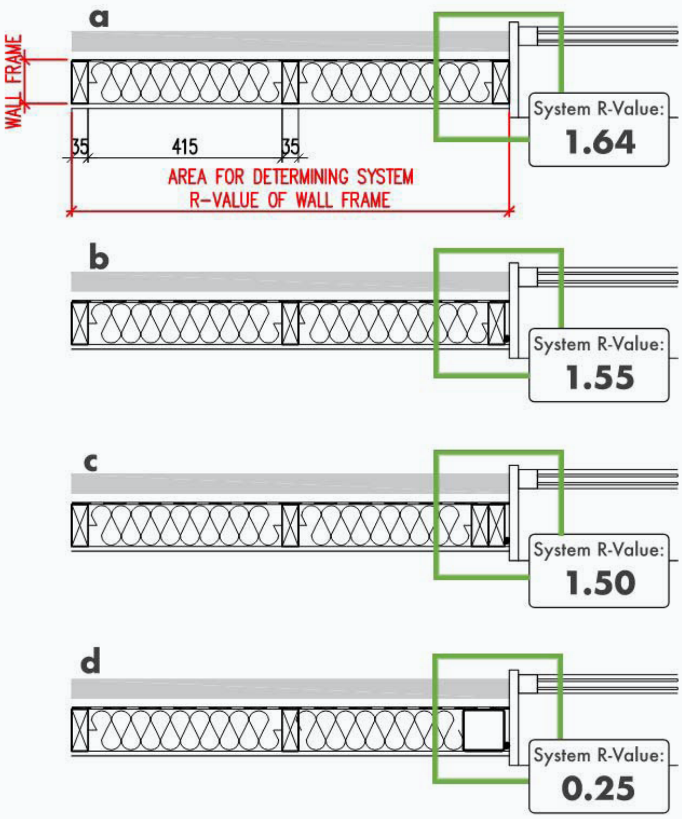
There are two different types of thermal bridges: geometric and construction.

Geometric thermal bridges

A geometric bridge is found where the geometry of a building is non-uniform, ie where a dimension or direction change occurs. This could be where materials of the same or different conductivities meet, or at corners, where building elements head in varying directions. In these scenarios, heat flow becomes non-uniform resulting in a thermal disruption called a bridge.

Examples include:

- External wall corners
- Eave junctions
- Ground floor and external wall junctions
- Around windows and wall openings



a	Softwood framing (90x35mm), double top plate, bottom plate and noggin per panel.
b	Similar to a, with 10mm construction air gap between reveal and frame by backer rod.
c	Similar to b, with double stud, as commonly constructed.
d	Double stud replaced with steel square hollow section (3mm wall thickness).

Figure 12. Thermal bridging impact on the system R-value for different junction construction types (Source: Law 2021). Section detail of interest highlighted in green.

The geometry of the building envelope can cause increased energy loss in a specific location, as shown in Figure 11 (refer page 9), between the ground floor slab and wall junction.

Geometric thermal bridging is unavoidable; however, it increases with the complexity of the building form and use of many different materials. In other words, simplicity is key, or at least beneficial.

Construction thermal bridges

A construction thermal bridge exists where a material, gap or building component penetrates through the insulation layer, conducting heat energy faster than the insulation.

Examples include:

- Rafters that break through the building envelope.
- Steel or timber studs or joists within the insulation zone.
- Cantilevered structure breaking through the building envelope.
- Lintels that interrupt the cavity insulation.
- Gaps between layers of insulation.

Construction thermal bridges can be easily minimised or avoided with careful design details, see reducing thermal bridges below. For Passivhaus buildings, the heat loss for all construction thermal bridges must be planned and calculated for. Figure 12 shows the bridging effect using softwood timber framing, where the total system R-value is dramatically decreased when the timber stud is replaced by a steel column.

Combined thermal bridges

The two types of thermal bridges (geometric and construction) can be accounted for in two ways: linear (2D) or point (effectively 3D):

- Linear thermal bridges occur where disruption in the continuity of the insulation layer transpires along a certain length of the building envelope. Examples include an external wall-to-wall connection (Figure 13). Energy losses incurred by a linear thermal bridge are expressed by the linear thermal transmittance ψ (psi-value) in units W/mK.
- Point thermal bridges occur at a specific point only. Typical examples include facade fixings (eg pins, bolts) and penetrations. The energy losses incurred by point thermal bridges are quantified by the point thermal transmittance χ (chi-value) in units W/K.

Thermal bridge-free design

For optimal efficient design, thermal bridge-free construction effectively has a net zero effect, ie the net heat losses due to thermal bridging amount to zero, or near zero. In the Passivhaus Standard, thermal bridge-free design is achieved when the sum of the heat losses from all the thermal bridges does not increase the building's net heat loss (Passipedia 2019). In other terms, thermal bridge-free construction can be defined by Equation 1, as the sum of the psi-value and chi-value contributions being smaller than or equal to zero.

$$\Sigma\, \psi \cdot l + \Sigma \chi \leq \ 0$$

Equation 1. Definition for thermal bridge-free construction, where psi-value = ψ [W/mK], chi-value = χ [W/K], and length = l [m].

When thermal bridge-free construction is achieved, the impact of thermal bridge heat losses can be omitted from calculations. However, to understand whether the net impact is close to zero it is usually necessary to calculate, or use known or approved details such as the high-performance construction details handbook published by PHINZ (Quinn 2021).

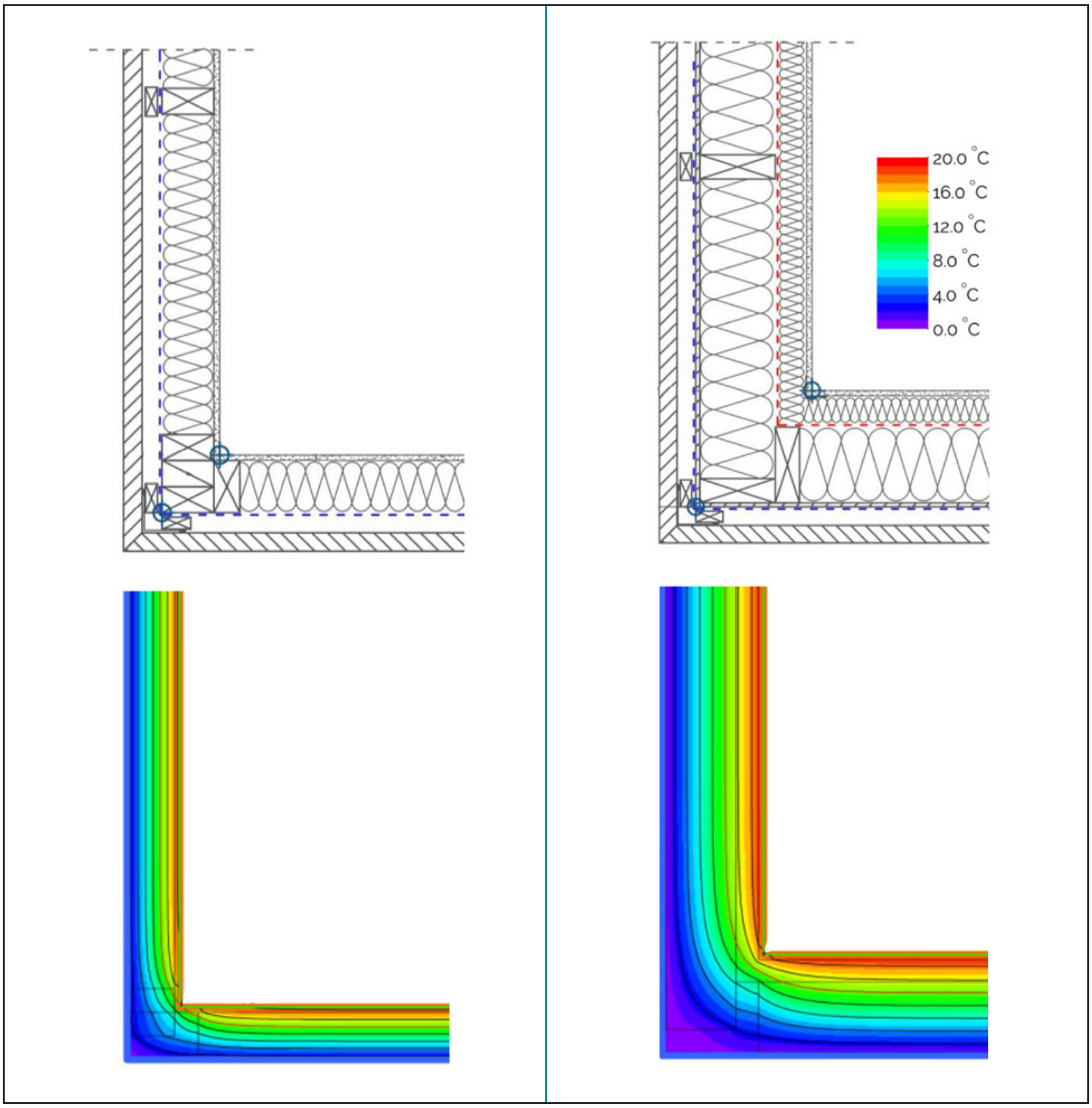


Figure 13. A concentration of timber studs in the external wall-to-wall corner (left) leads to a psi-value of 0.021 W/mK. In comparison an improved wall-to-wall detail with a reasonable timber stud concentration and insulated service cavity (right) results in a significantly lower psi-value of -0.059 W/mK. The right diagram depicts the warm interior with the red surface, while the left diagram clearly shows lower surface temperatures at the corner leading to greater risk of moisture accumulation. (Source: Quinn 2021)

While not completely necessary, thermal bridge-free design is possible and should be addressed during the design phase as early as possible. This action will mitigate the adverse effects of thermal bridging: energy losses, reduced comfort, and the risk of building envelope deterioration due to moisture accumulation. While calculation tools are required to account for thermal bridges, resources are rapidly increasing in availability to facilitate and support these calculations. An example working of a thermal bridge calculation is included in Appendix A.

Reducing thermal bridges

There are many thermal bridge-free construction details available to reduce or eliminate thermal bridging, depending on the location and construction type of the building (Whale 2016, IBO 2009). The aim is to create a continuous thermal break within the building envelope or to reduce the number of building components with higher conductivity that cross from the exterior to the interior. Some methods for reducing thermal bridges include:

- A continuous thermal insulation layer physically separated as much as possible from the structural line. The structure is commonly a thermal bridge and separating these layers is good practice to reduce bridging (Figure 14).
- Staggering structural or supporting elements, eg the use of staggered studs in a double-stud wall construction.
- Installing rigid insulation elements, such as wood fibre panels or foam boards
- Reducing the framing factor by eliminating unnecessary framing members, and/or increasing spacing of structural components, such as studs, floor joists or ceiling joists (refer Figure 13).
- Ensuring the use of good quality insulation materials and proper insulation installation without leaving gaps and compressing insulation.
- High quality installation of external doors and windows, where insulation abuts neatly with the frame and a metallic structure does not penetrate through the insulation layer.
- Installing windows with consideration for thermal performance of the frames (eg, thermally broken aluminium, timber) and warm-edge glazing spacers (ie, should not be aluminium).

In most instances, proprietary products are available that can provide thermal breaks, even for structural elements. Consideration of local availability, carbon impact of global import and cost, among other factors, is important.

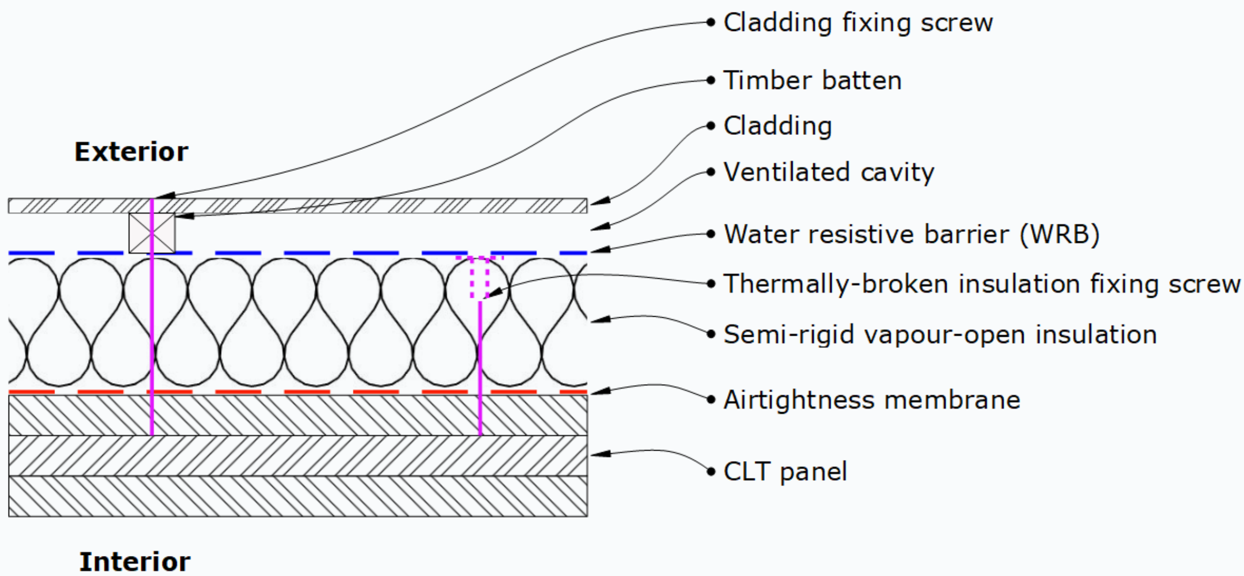


Figure 14. Cross-laminated timber structure with external insulation layer is a good example of a structural material with minimal thermal bridging due to the low thermal conductance of the structural timber. The depiction of the airtightness and weathertightness membranes should also be noted. (Image: Author)

NCC requirements for thermal bridging

Thermal bridging is addressed in the Housing Provisions Standard 2022, where it is required that any wall cladding or sheet roofing directly attached to a metal stud requires a thermal break with an R-value of 0.2 m^2K/W installed between all points of contact between the external material and metal frame. The NCC 2022 also includes an allowance for thermal bridging in accordance with AS/NZS 4859.2 in the Housing Provisions Standard for external wall and external floors, while NCC 2022 Volume One calls for the same standard to be used for roofs, floors, and walls. Spandrel panels must be determined according to Specification 38 of the NCC 2022 Volume One. In the Housing Provisions Standard, DTS provisions give several approaches to address thermal bridging for metal-framed roofs.

The standard AS/NZS 4859.2 calls for thermal bridging to be addressed using the NZS 4214 method. The NZS 4214 method is a simplified method that area-weights the thermal conductance of the material. However, it should be noted that this does not account for true thermal bridging effects, where the increase in heat transfer due to thermally conductive materials creates a path of least resistance, which can only be modelled using a finite-element heat-transfer analysis.

Conclusion

This note outlines the critical synergies between airtightness, thermal bridging, and effective ventilation. A focus on delivering an airtight envelope and reducing the effects of thermal bridging is essential to improve building performance. Positive outcomes of these measures include better durability, improved indoor environment quality for occupants and substantial benefits to energy efficiency and operational costs. This note also highlights the need to address adequate ventilation alongside increased airtightness to avoid the risks of condensation, mould, compromised IEQ and building material degradation.

As the NCC moves to recognise performance metrics relating to airtightness, thermal bridging and build quality, the standard of construction will necessarily rise to meet it. This is in keeping with other developed nations in reducing unnecessary building energy losses, and increasing the indoor environmental quality, comfort, and resilience of the built environment.

Relevant standards and clauses

Airtightness

NCC Volume One 2022: J1V4, building envelope sealing.
The NCC J1V4 verification method for building envelope sealing must be verified using AS/NZS ISO 9972. The air-permeability rate must be tested in accordance with Method 1.

AS/NZS ISO 9972 (Method 1)
This standard specifies the use of mechanical pressurisation or depressurisation of a building to measure the resulting air flow rates over a range of indoor-outdoor static pressure differences.

NCC Volume One and the Housing Provisions Standard 2022
General requirements are specified for building sealing in Volume One, Section J5 and the Housing Provisions, section 13.4. Ceilings, walls, floors, and any openings such as a window frame, door frame, roof light frame or the like must be constructed to minimise air leakage. Where windows, doors, roof lights must be sealed. Exhaust fans, chimneys and evaporative coolers must include a self-closing damper.

Thermal insulation and continuity

NCC Volume One 2022: J3D5 roof thermal breaks and J3D6 wall thermal breaks.
A minimum thermal break of R-Value 0.2 is to be used if a wall or roof interior lining is directly fixed to a metal frame.

NCC Housing Provisions Standard 2022
A thermal break with an R-value of 0.2 is defined as expanded polystyrene strips greater than or equal to 12 mm thickness and timber greater than or equal to 20 mm.

NCC Volume Two 2022: 13.2.3 Roofs and External Walls
Where a ceiling or wall lining is directly fixed to metal purlins or metal studs, a thermal break, consisting of a material with an R-value of greater or equal to 0.2 must be installed. The purpose of the thermal break is to ensure that the thermal performance of the metal framed roof or wall is comparable to that of a similar roof or wall with timber purlins or timber studs.

AS/NZS 4859.2 2018: Thermal insulation materials for buildings: Part 2 Design.
This standard specifies calculation and total R-values of building constructions, including reflective and non-reflective airspaces, for the purpose of designing building components to be used in thermal insulation systems. In section 10.2 for thermal bridging, it refers to standard NZS 4214 as the method to be used to calculate the total thermal resistance of a building component, including the thermal resistance of thermal bridging materials.

NZS 4214 2006: Methods of determining the total thermal resistance of parts of buildings.
In section 5.7 thermal bridges, thermal bridges are determined by a simplified calculation. A worked example is provided for the transformation method for metal frame sections.

EN ISO 10211 2017: Thermal bridges in building construction.
This standard sets out the specifications for a three-dimensional and two-dimensional geometrical model of a thermal bridge and the numerical calculation of:

- Heat flows to assess the overall heat loss from a building, and;
- Minimum surface temperatures to assess the risk of surface condensation.

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Appendix A – example working calculations

Thermal bridge calculation using ISO 10211

A time-consuming thermal bridge analysis can be avoided by ensuring the design is thermal bridge-free, where the insulation layer is not penetrated and runs continuously around the building envelope.

Thermal bridge calculations must be undertaken with software; it is not possible to calculate manually due to the computational complexity involved. It is recommended to use building physics specialists where this is required. A psi-value can be assessed using two-dimensional finite-element heat conduction software such as THERM or FLIXO. The Passivhaus Standard uses the reference EN ISO 10211, where the minimum internal temperature is also assessed with the same standard to ensure condensation does not occur on the internal surface.

Working example for psi-value calculation

The psi-value can be calculated with Equation 2 below, where L_{2D} is the thermal coupling coefficient obtained from a two-dimensional heat conduction software. If L_{2D} is given as 0.67 W/K, the U-value of each side of wall element without the steel beam is 0.39 W/m^{2}K, and the length of each side of the steel element is 0.5 m. This gives a psi-value of 0.28 W/mK due to the steel column shown in Figure 15. This means that an additional heat loss of 0.28 watts would results per degree difference between the inside and outside for each meter of the steel column, when compared to this same assembly without the steel column.

$$\psi = L_{2D} - (U_1 \cdot l_1 + U_2 \cdot l_2)$$
$$\psi = 0.67 - (0.39 \cdot 0.5 + 0.39 \cdot 0.5) = 0.28\ W/mK$$

Equation 2. Psi-value calculation for two elements. (Source: British Standards Institution 2017)

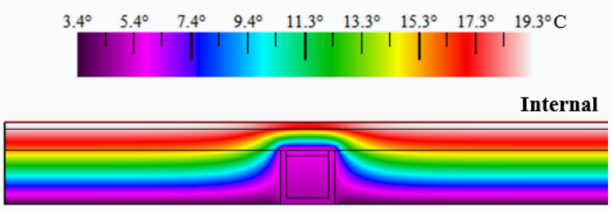

Figure 15. Steel column in an external wall in section with the colour legend. (Image: Author)

The total heat transfer through the building can be quantified using a U-value for each of the external building assemblies, such as floors, walls, ceiling, windows, and doors. The psi-value provides a useful metric to account for elements that are not included using a U-value calculation.

Chi-values can be found using the same approach as psi-values. However, they require the use of three-dimensional finite-element heat conduction analysis, as they are single points of heat flow and not divided by any length.

Airtightness calculation using Method 1 of AS/NZS ISO 9972

Building air leakage should be verified with Method 1 of AS/NZS ISO 9972. It involves area calculation, building preparation, test procedure, and reporting of the air leakage.

Envelope area calculation

The part of the building measured includes all rooms that are intended to be heated, cooled, or ventilated. The envelope area, A_E, is the total area of all floors, walls, and ceilings, bordering the internal volume (Equation 3). Internal dimensions are used to calculate this area. Internal walls, floors, cavities, or furniture volumes should not be subtracted.

In the simplified example below (Figure 16), the internal dimensions are 10 m by 12 m. If the floor-to-ceiling height is given as 3 m, this is 372 m^2 of internal envelope area.

$$A_E = \underset{(wall\ sections)}{(12 \cdot 3 \cdot 2 + 10 \cdot 3 \cdot 2)} + \underset{(floor\ \&\ ceiling)}{(12 \cdot 10 \cdot 2)} = 372\ m^2$$

Equation 3. The envelope area, A_E, is the total area of all floors, walls, and ceilings, bordering the internal volume.

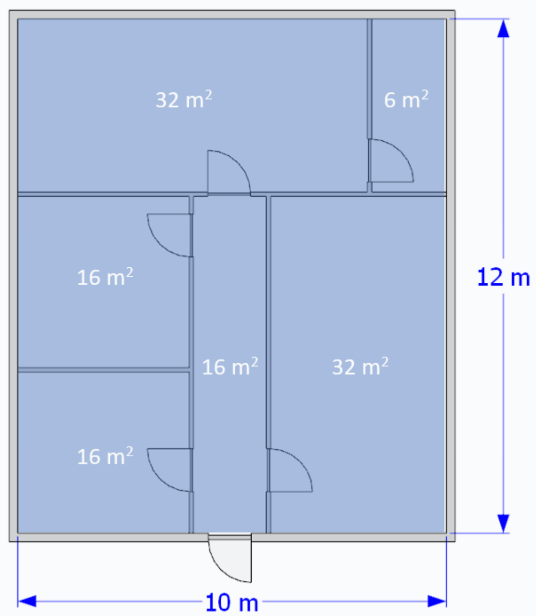

Figure 16. Representation of internal floor area for volume calculation. (Source: International Standard Organisation 2015)

Building preparation
The building is prepared by closing natural ventilation openings. This includes any windows, doors, and trapdoors in the envelope, and sealing the mechanical ventilation or air conditioning openings.

Test procedure
The environmental conditions of temperature and wind force should be noted, and blower door equipment calibrated to ensure that any pressure differences between the inside and outside of the building are accounted for. The test is then carried out with the blower door equipment by taking measurements of air flow rate and the pressure difference between the indoor and outdoor. It is the blower door consultant's responsibility to ensure the correct number of measurement points are taken at both pressurisation and depressurisation, that the readings are within the allowances, and that the envelope area calculation is correct. Full testing requirements and methods should be checked in the standard AS/NZS ISO 9972.

Reporting the results
The readings from the blower door test should be calculated as air flow rate in m^3/h (Figure 17). The two points where 50 pascals (on the x-axis) intercepts with the pressurisation and depressurisation lines are averaged to give an airflow rate of 1000 m^3/h in this example.

To calculate the air permeability rate at the reference pressure difference of 50 Pa, the air permeability rate is divided by the internal envelope area as shown in Equation 4.

$$q_{E50} = \frac{q_{50}}{A_E}$$

Equation 4. Air permeability rate (Source: ISO 9972, 2015)

For our example, this gives 1000 m^3/h divided by 372 m^2, resulting in an air permeability rate of 2.7 m^3/h.m^2 at 50Pa. If we assume this example is a residential dwelling, then it would meet the NCC 2022 regulation of 10 m^3/h.m^2 at 50 Pa, however verification of this target is not required.

Note: the Passivhaus Standard methodology uses the air change rate (equation 5), which is the airflow rate divided by internal volume (excluding internal wall volumes). The internal volume can be calculated as 354 m^3 ((32 + 6 + 16 + 16 + 16 + 32) · 3m). For the same example, this gives 1000 m^3/h divided by 354 m^3, resulting in an air change rate of 2.8 /h at 50Pa. Therefore, this example would not be compliant with the Passivhaus standard air change rate limit of 0.6 ACH at 50Pa.

$$n_{50} = \frac{q_{50}}{V}$$

Equation 5. Air permeability rate (Source: ISO 9972, 2015)

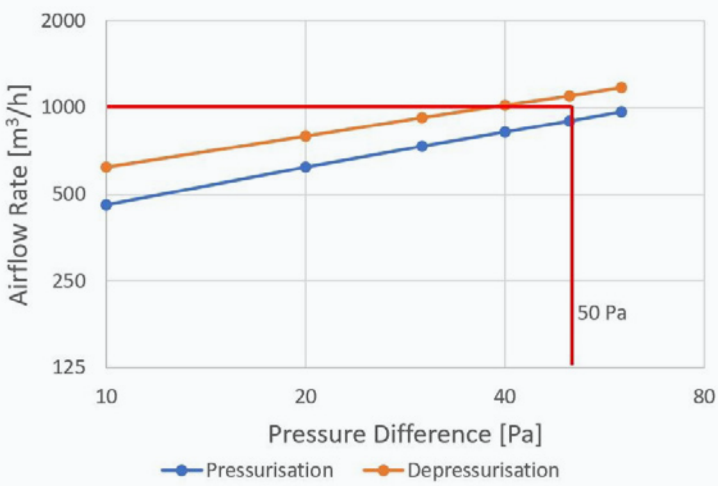

Figure 17. Example air leakage graph. The blower door results are graphed in terms of pressure difference in pascals (Pa) using the method of least squares regression to produce a line for both the pressurisation points (blue line) and depressurisation points (orange line). (Source: ISO 9972, 2015)

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Clare Parry is the sustainability director at Development Victoria. With experience ranging across traditional sustainability roles, and training as a mechanical engineer, Clare seeks to provide advice on improving health, comfort, and efficiency outcomes for our built environment with a focus of building physics and first principles system design. Clare believes that our buildings should serve us without detracting from the living systems we are a part of and seeks to harness opportunities and consider constraints to deliver a lower carbon, more systems-integrated outcome. Clare's favourite part of any project is challenging assumptions about how things 'should' be done; habits are hard to break, and silos are the norm.

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Senior Consultant at HIP V. HYPE, Marcus seeks to develop the potential positive impacts in each project that he undertakes. He does this by augmenting the technical capabilities of the Better Buildings team, through his specialisation in ultra-low energy building design, which he sees as a fundamental step for progressing towards net-zero carbon emission buildings and a vibrant society. Marcus' role includes building energy modelling, occupant comfort analysis, passive design optimisation, thermal envelope and fenestration design, and identification and remediation of interstitial and surface moisture risks. He completed his PhD at the University of Queensland, researching solutions for net-zero energy multi-storey buildings with cross-laminated timber facades located in hot and humid Australian climates.

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