Ministry of Housing,
Communities &
Local Government

Research into resistance to moisture in buildings

Using numerical simulation to assess moisture risk in new constructions

July 2019
PRP Architects LLP
Ministry of Housing, Communities and Local Government

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The document is prepared by Innovate at PRP Limited, part of PRP Architects LLP.

Contents

1. Background

It is a requirement of Part C of the Building Regulations that buildings, and people who use these buildings, are adequately protected from harmful effects of moisture. Approved Document C provides guidance on how to meet this requirement. However, much of this guidance was made before the energy performance requirements for buildings were improved in recent years and it is not certain that these recommendations are still appropriate. In addition, Approved Document C refers to a number of British Standards and other publications, but the usefulness and applicability of these documents, particularly in relation to retrofit works, required reviewing. It should be noted that this project focused specifically on moisture from precipitation, surface and interstitial condensation.

The Ministry of Housing, Communities and Local Government (MHCLG) commissioned PRP to carry out this research study, entitled *Research into resistance to moisture in buildings.*

The project was delivered in three main stages:

- **Stage One: Background research**
  Stage One covered all the background research activities required to inform the refinement of the analysis methodology and the parameters used for the analysis.

- **Stage Two: Detailed analysis of identified construction typologies**
  Stage Two involved the detailed analysis of the various construction types identified in Stage One for both new build and retrofit, including key thermal bridge junctions. In this stage, a number of software analysis packages and methodologies will be used to carry out a sensitivity analysis on each of the identified construction typologies:

  - Simplified Modelling based on *BS EN ISO 13788 (2012)* - the 'Glaser Method'
  - Standardised Modelling based on *BS EN 15026 (2007)* - with the use of a software package, WUFI (Wärme und Feuchte Instationär)
  - Multi-dimensional Thermal Modelling to *BS EN ISO 10211 (2007)* - with the use of THERM (for construction junctions only)

- **Stage Three: Simplified rules and recommendations**
  Stage Three involved the formulation of simplified rules and recommendations using the conclusions from the Stage Two work.

The outputs of this research are a series of eight reports, entitled:

- Research into resistance to moisture in buildings: Research Summary
- Research into resistance to moisture in buildings: Identification of common types of construction.
- Research into resistance to moisture in buildings: Using calculation methods to assess surface and interstitial condensation

- **Research into resistance to moisture in buildings: Using numerical simulation to assess moisture risk in new constructions**
- Research into resistance to moisture in buildings: Using numerical simulation to assess moisture risk in retrofit constructions. Part 1
- Research into resistance to moisture in buildings: Using numerical simulation to assess moisture risk in retrofit constructions. Part 2
- Research into resistance to moisture in buildings: Assessment of current moisture guidance
- Research into resistance to moisture in buildings: Simplified rules for reducing the risk of moisture

2. Moisture Assessment Methods and Risk Criteria

This report is the **Using numerical simulation to assess moisture risk in new constructions** report of the Research into resistance to moisture in buildings project.

2.1. Hazards associated with moisture risks in buildings

The presence of excess moisture can lead to health issues for occupants and damage to building fabric, and can cause the following problems:

- Mould Growth
  High internal relative humidity (RH) levels are favourable to surface mould growth and dust mites.

- Condensation
  Excess moisture can lead to both surface and interstitial condensation, which can lead to building fabric damage if organic or 'fragile' material (a material that degrades in the present of moisture, e.g. timber) is present.

- Damage due to high moisture content in materials
  Such conditions can promote rot in ‘fragile’ material (e.g. timber), which can lead to failure of building fabric elements including structural elements.

- Reduced performance of insulating materials
  High moisture content (from 80% of relative humidity levels, up to 100% where condensation occurs) can have a detrimental effect on the thermal performance of the material, as most insulation materials have a moisture-dependent thermal conductivity. Generally speaking, very high levels of moisture in insulation materials lead to a significantly poorer thermal conductivity.

- Frost damage
  When excess moisture is held in its liquid form in external surfaces of solid masonry walls, it will freeze in very cold conditions and cause damage to the masonry, particularly brickwork.

- Corrosion
  Corrosion of metallic compounds that are in contact with, or buried within, the wall. Corrosion occurs due to the presence of surface condensation on these compounds.

2.2. Assessment Methods

Currently the main guidance for moisture risk assessment standards in the UK are British Standard BS 5250 (2011): *‘Code of practice for control of condensation in buildings’* and a standardised modelling method BS EN ISO 13788 (2012):

'Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods'. These standards are useful in particular situations to provide an accurate moisture risk assessment. However, under certain conditions (described in paragraph 3.2.2), the limitations of these standards mean that currently they cannot provide a robust moisture risk assessment and cannot be relied on. This is where further modelling methods, such as BS EN 15026 (2007): *'Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation'*, are introduced.

It is therefore important to identify whether existing standards can be used with confidence to assess moisture risk and which construction typologies these standards are applicable to. Where existing standards can be seen to be insufficient it is important to clarify whether these standards need to be combined with other methodologies and form part of an expanded assessment.

Four different assessment methods used for this detailed analysis are listed in the sub-sections below, as explained in the Moisture Risk Assessment and Guidance document by Sustainable Traditional Buildings Alliance (STBA) and Department of Energy & Climate Change (DECC) (2014). The four different assessment methods can be regarded as a hierarchy of assessment; each assessment method has an increased complexity that requires more complex input data as well as a more in-depth understanding of the subject matter in order to carry out the assessment.

The choice of assessment method for each construction typology is explained within their respective results section.

2.2.1. Prescriptive Guidance BS 5250 (2011)

Prescriptive guidance is based on experience and details the commonly used applications for which there is good evidence of success over many years. BS 5250 (2011) is mainly based on prescriptive guidance.

2.2.2. Simplified Modelling to BS EN ISO 13788 (2012) (the 'Glaser Method')

The assessment method BS EN ISO 13788 (2012) is a one-dimensional steady-state assessment method predicting the risk of surface and interstitial condensation through a multi-layered structure occurring under specified environmental (monthly mean) conditions. This method only takes into account moisture transport via vapour diffusion alone.

The method has substantial limitations, such as the fact that it does not take into account any storage of moisture within the elements, or that the materials transport properties are not affected by moisture content. This means that an accurate moisture risk assessment will be limited to the build-ups where these aforementioned effects are considered negligible.

2.2.3. Standardised Modelling to BS EN 15026 (2007)

The BS EN 15026 (2007) assessment method is a one-dimensional transient modelling of heat and moisture flows through a multi-layered structure with complex transport properties. This method takes into account the heat and moisture storage, the latent heat affect, and any liquid and convective transport under realistic boundary and initial conditions (i.e. non-steady climate conditions both internally and externally).

Similarly to the BS EN ISO 13788 (2012) method, this method is limited to one-dimension assessment only and therefore junctions cannot be modelled. It also has some other limitations due to simplification around the modelling of air layers, as well as the lack of defined protocols and available data for materials, climate files, etc.

This assessment method is implemented in several software packages, including WUFI (Wärme und Feuchte Instationär), which is the software the most commonly used in the industry, and the one used for this stage of our research study.

2.2.4. Multi-dimensional Thermal Modelling to BS EN ISO 10211 (2007)

None of the hygrothermal assessment methods listed above is multi-dimensional and therefore none of them is able to assess moisture risks at junctions between different construction typologies. Surface condensation typically appears around junctions between materials due to low surface temperatures caused by any discontinuity of in the insulation layer. These moisture problems, mainly arising around junctions between different building elements, are called ‘connective effects’.

It is important to assess these junctions because surface condensation is also one of the main moisture risks that could lead to health issues for occupants and fabric damage. The effect of extra heat losses appearing around junctions can also be analysed with multi-dimensional thermal calculations using the methods specified in BS EN ISO 10211 (2007): '*Thermal bridges in building construction - heat flows and surface temperatures - detailed calculations'*.

BS EN ISO 10211 (2007) also refers to *BS EN ISO 6946 (2007) Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.* The parameters used in the multi-dimensional thermal modelling work follow the parameters listed in this standard.

2.3. Assessment risk criteria with transient hygrothermal modelling

Condensation risk criteria are clearly defined in BS EN ISO 13788 (2012). This assessment leads to a 'Pass / Fail' approach. This method models and calculates the amount of condensation or evaporation in a build-up on a monthly basis for each month of the year. The accumulated mass of condensed water over the twelve months is then compared to the total amount of evaporation during the year. The calculated amount of condensation presence within the build-up and its persistence are then analysed to check if there is any moisture accumulation, and consequently provide a 'Pass / Fail' status to the risk of condensation in the build-up.

However, there are no clear moisture risk assessment criteria (with moisture combining both liquid water and water vapour) with the use of BS EN 15026 (2007).

There is not a clear set of moisture risk assessment criteria agreed within the industry yet, especially as different build-ups, materials and applications will require different criteria. However, the Fraunhofer Institute offers some guidance criteria which can be used as general criteria. The following criteria are used for the analysis of this WUFI modelling work:

- Moisture must not accumulate over time
  This criteria is considered to be the most important one. Moisture content, i.e. water present in an element under its liquid or vapour form, must be able to dry out rather than accumulating within. If the moisture content in the building element keeps increasing (even slowly) without drying, then problems will arise sooner or later.

- RH levels at critical junctions should only ever rise above 80% for short periods of time (i.e. less than a month) to ensure good drying
  This criteria excludes any outer portion of wall directly affected by driving rain since it is outside. Although the outer layer gets wetter, it will also dry out more thoroughly because of its location.

- RH levels should drop below 80% within the first six months of simulation
  If it takes longer than the first six months of a WUFI simulation for RH levels to drop below 80% at the critical point of a build-up, the build-up is likely to be inadequate as constant high RH levels are likely to lead to moisture damage

Based on the above criteria, status of transient hygrothermal modelling cases are listed into three different categories in this report: 'pass', 'risky' or 'fail'.

2.4. Visualisation of results from multi-dimensional thermal modelling and transient hygrothermal modelling

Several outputs are used in this report in order to analyse the thermal performance of modelled junctions, as well as the hygrothermal performance of the modelled build-ups. The visualised outputs are listed and detailed below:

2.4.1. Internal Surface Temperature Factor f_{Rsi}

The internal surface temperature of a building envelope is directly linked to whether surface condensation and mould growth will occur. Surface condensation will occur when surface RH levels reach 100% on the surface of the element, whereas mould growth will occur when surface RH levels are kept high (typically higher than 80% for typical construction materials).

The internal surface temperature factor f_{Rsi} is used as a risk indicator for mould growth, and is effectively a ratio of the internal surface temperature to the external air temperature (see equation below):

$f_{Rsi} = (T_{si} – T_e) / (T_i – T_e)$
where:

- T_{si} = internal surface temperature (°C)
- T_i = internal temperature (°C)
- T_e = external temperature (°C)

Information Paper IP1/06: *'Assessing the effects of thermal bridging at junctions and around openings'* (2006) gives guidance on minimum critical temperature factors to avoid mould growth on surfaces (around thermal bridge junctions for instance), a minimum f_{Rsi} of 0.75 (i.e. 75%) is recommended for consistently heated buildings such as dwellings, residential buildings and schools.

For an internal temperature of 20°C and an external temperature of 0°C, meeting the minimum f_{Rsi} of 0.75 corresponds to having a minimum internal surface temperature of 15°C to avoid the risk of mould growth.

2.4.2. Graphs: Relative Humidity Levels

As listed in the risk assessment criteria in section 2.3, the next step will be to analyse the RH levels within a build-up (typically at interfaces between different layers) in order to assess the risk of interstitial condensation. For each typology, RH levels at the 'critical' junction, i.e. the junction being the most at risk of interstitial condensation, will be analysed.

RH levels at this junction will be monitored and displayed in a time-based graph, an example is shown in Figure 1. The x-axis represents time (in this case the 5-year modelling period) and the y-axis represents the RH levels at the critical junction (in percentage). In addition, the constant 80% RH level limit is displayed as a continuous red line, while the relaxed 95% RH level limit is displayed as a dotted red line.

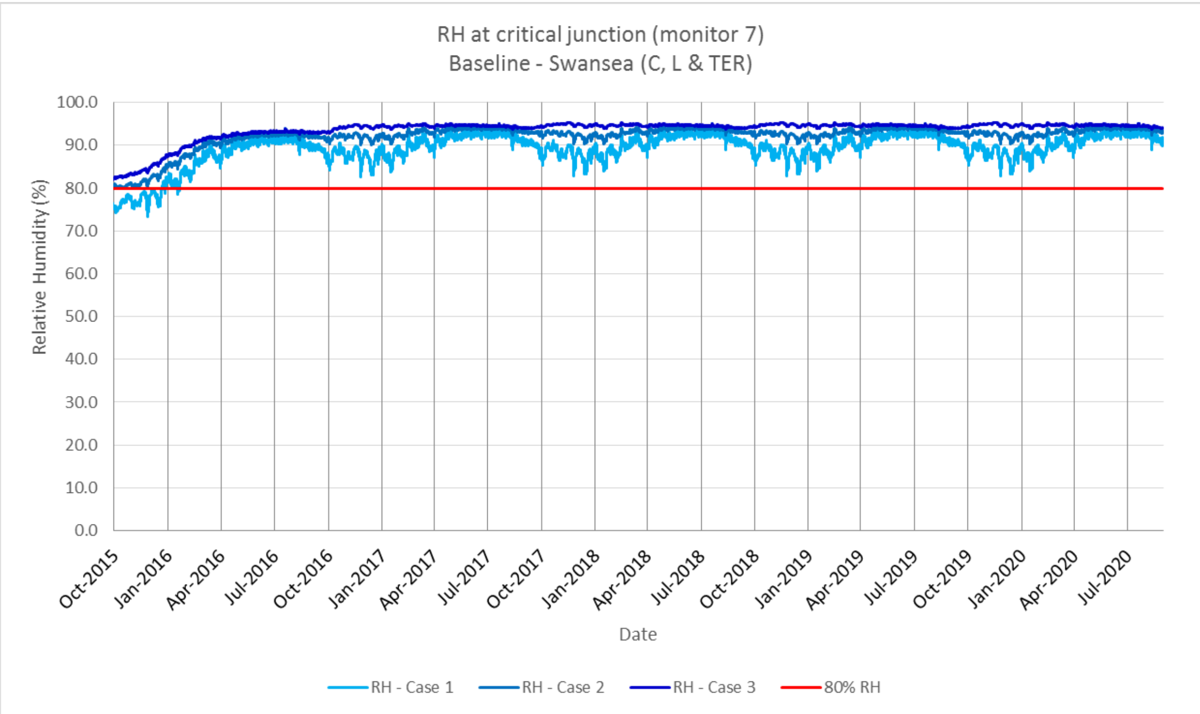


Figure 1: An example of an output graph for displaying RH at critical junction

2.4.3. Graphs: Water Content in Layers

In some particular cases, the water content present in certain layers will also be analysed. This analysis is related to the first moisture risk assessment criteria (as described in section 2.3) which states that moisture should not accumulate over time.

In the layer chosen for assessment, the water content is displayed on the y-axis (in kg/m^3) on a time-based graph (again the 5-year modelling period in this case), as shown in Figure 2.

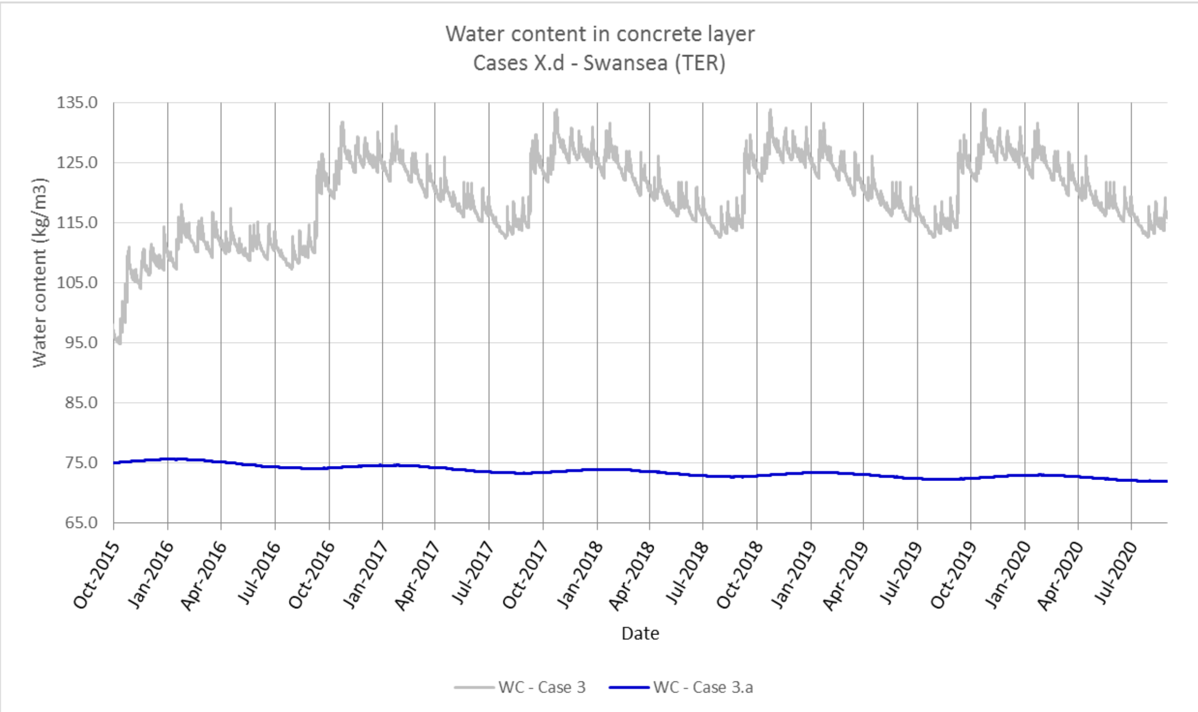


Figure 2: An example of an output graph for displaying water content in a particular layer

3. WUFI Model Input Parameters

As the standardised method BS EN 15026 (2007) is a more recent assessment method and due to its lack of protocols (which makes the interpretation of the results more difficult), all input data used commonly throughout all WUFI simulations in this research are listed in this section.

3.1. Materials

Physical properties of construction materials have a significant impact on the hygrothermal performance of a build-up. More specifically:

- porosity (w_{max})
- specific heat capacity (cp)
- thermal conductivity (λ)
- water vapour diffusion resistance factor (μ)
- moisture storage function, and suction & redistribution profiles (which are sometimes approximated in WUFI using the water absorption coefficient, called A-value)

There is currently a lack of tested / standardised material characteristics typically used in the UK construction industry. In the absence of such data, the material databases present in WUFI (Fraunhofer database, North-American database and others) are considered the best source of currently available data. Please refer to Appendix A for the exhaustive material list and their respective parameters used in the modelling.

Material types and thicknesses have been matched with Glaser simulated build-ups that were presented in the *Using calculation methods to assess surface and interstitial condensation* report.

3.2. Orientation, Inclination and Height

3.2.1. Orientation

Different parts of a building can be affected by very different micro-climates. In general, north-facing elevations can be subject to prolonged damp, as they are not exposed to the drying effect of the sun and they are usually sheltered from the drying effect of the wind. As a result, north façades tend to experience more stable conditions over time.

In contrast, fluctuations in temperature (due to solar radiations) and regular wetting and drying periods (due to the combined effects of wind, rain and solar radiations) means that south, west and south-west façades can suffer from accelerated rates of decay.

For this modelling work, the assumption is that the fluctuating conditions experienced on south-west façades are likely to be more detrimental to the hygrothermal performance of the build-up, compared to the constant damp experienced on north-facing façades. However, this assumption will not be true for all typologies as different typologies will be affected differently by these two different orientations. To analyse this, a sensitivity analysis with a change of orientation from south-west to north will be performed on specific typologies that could be particularly affected by constant damp related to a north-facing orientation.

All models (except explicitly stated) are oriented to face south-west, so as to model the most extreme scenario of wind-driven rain exposure and solar radiations. This is shown in section 3.5.1 – External Climate, displaying the characteristics of the weather files used, on which the wind-driven rain is the strongest from the south-west direction. The use of the south-west orientation is also the worst case for reverse diffusion due to this façade is experiencing the highest rate of solar radiations, which drives reverse diffusion in the summer.

3.2.2. Inclination

The following inclinations are used, depending on each element type:

- Floor: 0 degrees
- Wall: 90 degrees
- Pitched roof: 35 degrees
- Flat roof: 2 degrees

3.2.3. Height

All models have an assumed building height of less than 10m (described as low-rise buildings).

3.3. Surface Heat Transfer Coefficients

3.3.1. Surface Heat Transfer Coefficients

Surface heat transfer coefficients set in Table 1 below are used in the modelling, for unsheltered elements. They come from the calculation procedure set out in BS EN 15026 (2007) where possible, otherwise WUFI default settings are used.

Table 1: Surface Heat Transfer Coefficients

Heat flow direction	Downward	Horizontal	Upward
Rsi (internal)	0.172 m^2.K/W	0.131 m^2.K/W	0.099 m^2.K/W
Rse (external)	0.058 m^2.K/W	0.058 m^2.K/W	0.053 m^2.K/W

3.3.2. Adhering Fraction of Rain

Default values for adhering fraction of rain are used in the modelling, due to lack of standard protocol.

- Adhering fraction of rain – Exposed wall = 70%
- Adhering fraction of rain – Exposed roof = 100%
- Adhering fraction of rain – Protected build-up = 0%

3.4. Initial Conditions

3.4.1. Initial Moisture in Construction Typology

Initial moisture contents are taken in each layer of the build-up, set as typical built-in moisture for each material. This allows for appropriate built-in moisture levels in constructions using materials with significant built-in moisture at the time of construction (e.g. plasters, concrete or screed).

3.4.2. Initial Temperature in Construction Typology

The initial temperature in the material layers is taken as 20°C, and is constant throughout the build-up. Even if this is not a realistic case for the simulations (starting 1st October), a constant initial temperature profile tends to be adequate for all of our modelling cases since the temperature distribution adapts to the prevailing boundary conditions within a few hours in the simulation.

3.5. Boundary Conditions

3.5.1. External Climate

Location, aspect and the differing exposure of individual elevations to direct sun and wind-driven rain influence the hygrothermal performance of the construction type.

The modelling work aims at providing an overall view of the performance of each typology. Therefore, four locations and associated external conditions, representative of the four main UK wind-driven rain exposure zones as represented in Diagram 12 of Approved Document C, are used in the modelling.

- Zone 1 – London
- Zone 2 – Manchester
- Zone 3 – Bristol
- Zone 4 – Swansea

Due to the lack of approved / standardised weather files to be used in WUFI, synthetic weather files for a 'Design Reference Year' are created, following the procedure in BS EN 15026 (2007). The 'Design Reference Year' is constructed to cause the most severe conditions likely to occur once every ten years.

BS EN 15026 (2007) states that *'a more severe climate is usually required when problems caused by moisture movement within structures are being investigated'* showing the need to use a 'Design Reference Year', instead of a 'Typical Weather Year' (generally based on long-term measured average data).

In terms of data on which the 'Design Reference Year' is based, it is worth noting that most cases in moisture movement problems require analysis in cold winter weather, however some moisture damage is worst in warm humid summer conditions (reverse condensation). Therefore, the 'Design Reference Year' is designed to combine low temperatures and solar radiation with high relative humidities, for climates where the winter situation is the most critical (as described in Annex B of BS EN 15026 (2007)).

Table 2 summarises the main characteristics of the four weather files used for this modelling work.

Table 2: Main characteristics of the four weather files used

	Exposure Zones			
	Swansea (Zone 4)	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Mean Temperature (°C)	10.5	11.3	10.3	12.1
Mean RH (%)	84.0	77.0	79.0	71.0
Counter-Radiation Sum (kWh/m^2.year)	2,829.0	2,828.0	2,781.0	2,825.0
Mean Cloud Index (%)	0.73	0.76	0.75	0.78
Mean Wind Speed (m/s)	5.89	4.73	4.18	3.97
Normal Rain Sum (mm/year)	795.0	610.0	596.0	543.0

The counter-radiation sum is the total of the atmospheric and terrestrial counter radiations over a period of a year. Both radiations are long-wave radiations and taken into account in the night time radiation cooling, which is especially important for roof build-ups.

See Figure 3 for a snapshot of the weather file analysis from WUFI for the most severe weather file Zone 4 – Swansea. Since no weather file was available for Swansea, the weather file from Pembrey Sands, which is the closest location to Swansea, was chosen for the modelling. It is a slight over-estimation as Pembrey Sands is to the west of Swansea and is slightly more exposed to wind and rain. This location highlights the dominance of south-west wind-driven rain, compared to other orientations.

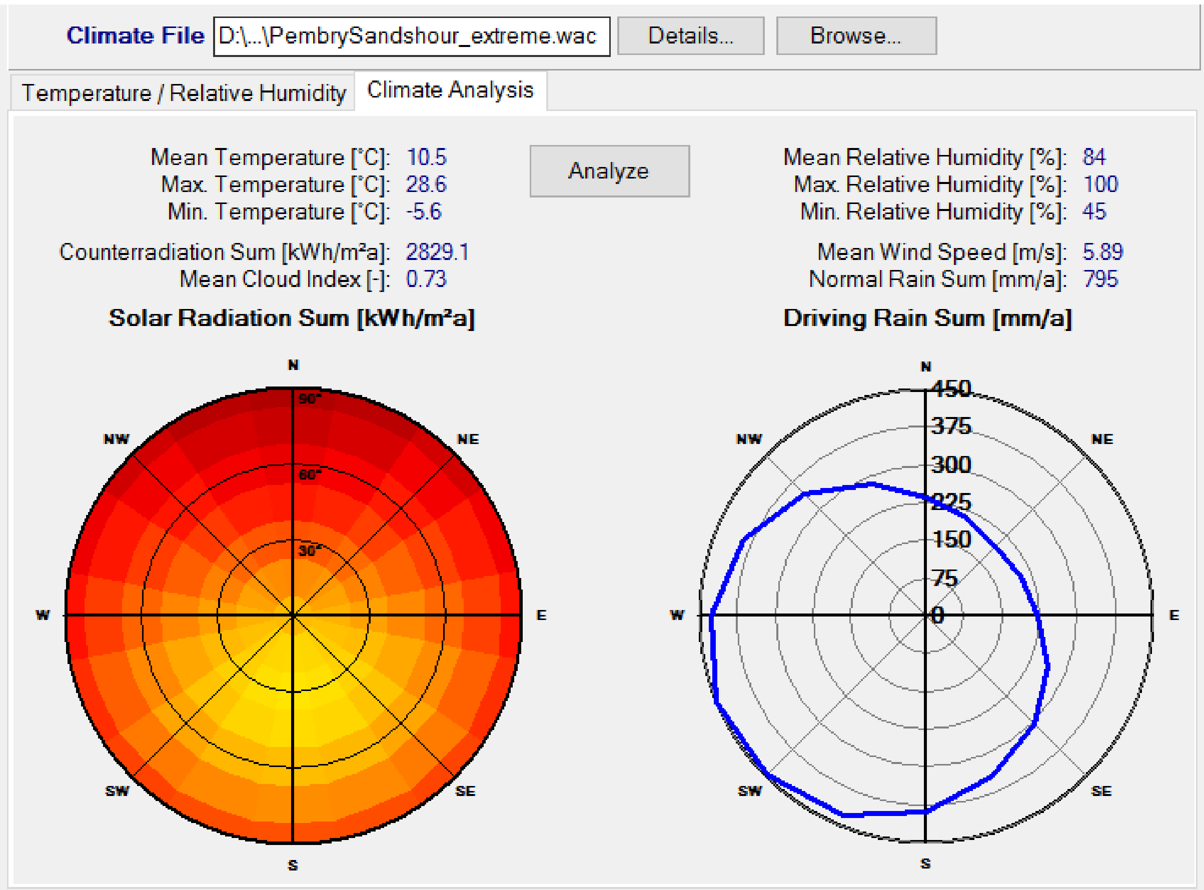


Figure 3: A snapshot of the weather file analysis from WUFI

This analysis from WUFI on the solar radiation sum is only comparative. The same colours on the solar radiation sum graphs are used for different weather files being analysed, but no legend is available to quantify solar radiations on different orientated façades. The software manual provides the following description: *'low values are displayed in dark red, medium values in yellow and high values in light blue'.*

3.5.2. Internal Moisture Conditions

Indoor conditions can play a significant role in the hygrothermal performance of a build-up. Indoor moisture loads are set in accordance to Annex C of BS EN 15026 (2007), where indoor conditions (temperature and relative humidity) are calculated based on external climate data (temperature). This simplified approach to determine indoor moisture conditions only applies to consistently heated buildings such as dwellings, residential buildings and schools.

For all models (except where explicitly stated in the sensitivity analysis), a 'normal' moisture load is used. This choice is made so as to analyse the hygrothermal performance of each typology without adding 'additional' stress due to poorer indoor conditions.

With the 'normal' moisture load condition, the indoor humidity is 30% for outdoor temperatures below -10°C, 60% for outdoor temperatures above 20°C and varying linearly with temperature for outdoor temperatures between these limits. With the ‘high’ moisture load condition, all humidity rates are 10% higher, i.e. varying linearly between 40% in winter (temperature less than -10°C) and 70% in summer (temperature greater than 20°C).

These two choices of indoor moisture condition are shown in Figure 4 and Figure 5:

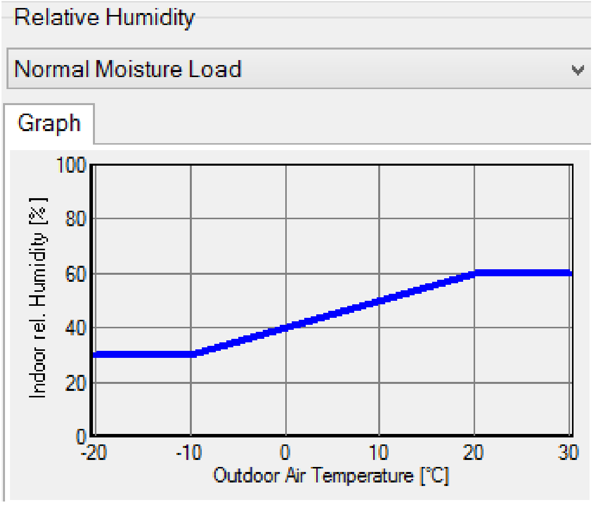


Figure 4: Normal moisture load

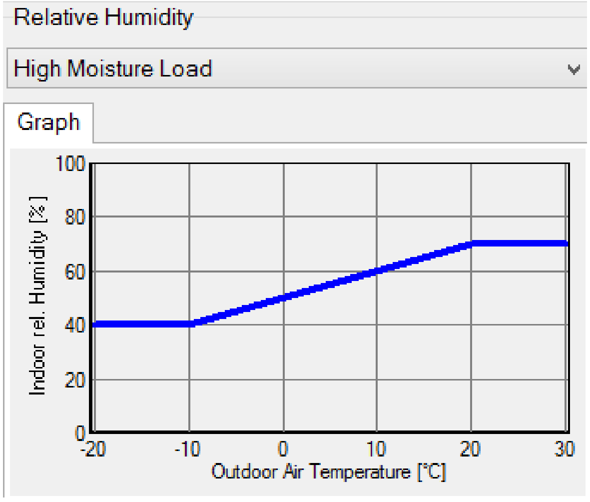


Figure 5: High moisture load

3.6. Other Modelling Parameters

All models are run for a simulation period of 5 years (or longer, should the construction type tested not reached equilibrium after 5 years), with a one-hour time increment and a start date of 1st October.

3.7. Modelling Limitations

For each simulation, a one-dimensional WUFI assessment includes the simulation of a specified build-up, using a location-specific climate file and includes assumptions on materials used (insulation, substrate and membranes), indoor conditions (moisture and temperature) and external conditions (moisture, temperature, rain, wind and solar radiations) for a set orientation and a set building height range.

These simulations are suitable for conditions where layers are not bridged, or where these bridging elements can be judged as insignificant hygrothermally.

However, there are a number of limitations worth noting:

- Build-ups
  the simulations are only considered representative of the main build-ups currently in the industry and cannot be extrapolated to cover every single possible build-up.

- Climate
  the climate files are generated from synthetic weather data. There is no agreed set of climate data ready for use with dynamic hygrothermal simulations in the UK currently.

- Standards
  While all the WUFI simulations and data analysis are carried out in accordance to BS EN 15026 (2007) and the STBA/DECC's guidance document, it is important to note that there are currently:
    - No protocols for use of BS EN 15026 (2007).
    - No protocols for non-standardised modelling to ASHRAE 160.
    - No protocols for non-standardised modelling for ABIS (As-built / In-service) conditions (as opposed to ‘theoretical’ conditions) and connective effects. Such modelling should aim to include effects like air leakage, thermal bypass, water ingress and other faults which could occur in practice.

- Two-dimensional modelling
  Two-dimensional simulation (which would be required to model junctions with ‘sensitive’ materials being present) is not included in this modelling work.

As such, any recommendations made as a result of modelling for this project can only be considered preliminary guidance as new protocols may vary from the approach taken here.

4. WUFI Modelling Scenarios

4.1. Baseline Scenario Variations

The baseline approach includes:

- Change in exposure zones (see Table 3)
- Change in build-up (i.e. insulation thickness) to meet target U-values as per *Using calculation methods to assess surface and interstitial condensation* report (see Table 4)

Table 3: 12 cases as the baseline approach

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

Table 4: Target U-values

	U-value backstops (W/m^2.K)		
Construction Type	**Part C**	**Part L**	**TER**
Floors	0.70	0.25	0.13
Walls	0.70	0.35	0.18
Roofs	0.35	0.25	0.13

Because each build-up is adjusted (using different insulation thicknesses) to match the target U-values listed above, the thickness of the insulation layers required in the WUFI models are sometimes unrealistic from a market availability perspective (such as extremely thin layers, i.e. thinner than 20mm).

This adjustment approach was used for the assessment, despite using unrealistic build-ups sometimes. It allows for equivalent comparison between the build-ups and the modelling still provides sufficient results for an accurate qualitative analysis of the impact of the insulation thickness on the hygrothermal performance of the build-up.

4.2. Additional Scenario Variations (Sensitivity Analysis)

Potential sensitivity analysis includes the following:

- Change in internal moisture load = Cases X.a
  Change in internal moisture load from 'normal' to 'high' following the guidance in BS EN 15026 (2007).

- Change in external surface performance = Cases X.b
  Introduction of additional moisture ingress through the external surface of the construction to simulate 'imperfect' construction, using the ASHRAE 160 method, with a rain penetration factor of 0.5%, 1% and 1.5% as a proxy for poor workmanship.

- Change in orientation = Cases X.c
  Change in orientation from ‘south-west’ (façade subject to the most extreme conditions in wind-driven rain and solar gains) to 'north' (façade in much more reduced / protected conditions regarding both wind-driven rain and solar gains) to analyse the impacts both solar gains and wind-driven rain have on the presence of diffusion in winter and reverse diffusion in summer

- Change in substrate and insulation materials = Cases X.d
  Change in material in WUFI build-up

- Other changes = Cases X.e
  Other changes deemed necessary or useful after analysis of baseline and additional scenarios, will be modelled

Additional scenario variations will be determined on a case-by-case basis. More scenarios will be modelled on construction types that are considered with the highest risk of condensation, where possible.

5. THERM Model Input Parameters

5.1. Geometry

5.1.1. All junction models are constructed following guidance from Multi-dimensional Thermal Modelling to BS EN ISO 10211 (2007, with the exception of window frames (see below).

5.1.2. Simplified Multi-dimensional Thermal Modelling to BS EN ISO 10077 (2006)

Where junctions incorporate window frames it is not necessary to follow a detailed methodology for glazing and frames since these elements can be simplified without material effect on the surface temperatures at the modelled junction. Therefore the effect of extra heat losses appearing around window junctions can be analysed with multi-dimensional thermal calculations using the methods specified in *BS EN ISO 10077-1 (2006) 'Thermal performance of windows doors and shutters - Calculation of thermal transmittance'.*

5.2. Materials

5.2.1. General

Materials used in THERM analysis are as closely matched to the materials used in the WUFI analysis, with the critical material value being thermal resistance.

Some materials require more detailed treatment, specifically brick layers.

5.2.2. Brick

Where an external brick is modelled as part of a wall structure the thermal resistance of the brick is modified to reflect the exposure of the brick (similarly to adjustments made in U-value calculations)

Brick Exposure	Description of situation	Thermal resistance (λ) (W/mK)
Wet	Below DPC	1.0
Exposed	External skin of wall	0.77
Protected	Inner leaf or behind retrofit EWI	0.56

5.2.3. Air gaps

Thermal resistance of unventilated airspaces have been nominally calculated using the formulas from appendix B of *BS EN ISO 6946 (2007) Building components and building elements - Thermal resistance and thermal transmittance* - Calculation method. For large spaces the calculation has been made utilising information from Table B.2 *from BS EN ISO 6946 (2007)*. For small spaces the calculation has been made utilising information from Section B.4 from *BS EN ISO 6946 (2007)*.

5.3. Boundary Conditions

5.3.1. Internal

Internal temperature is modelled at 20°C.

5.3.2. External

Suspended floor crawl space - Since a specific building is not being modelled a typical underfloor temperature of 3.2°C is assumed.

Unheated space - Sheltered spaces, e.g. unheated garages, are assumed to have a temperature of 6°C. Since the Internal Surface Temperature Factor (f_{Rsi}) will be higher in value when a lower external temperature is used, this is considered to be a suitably conservative assumption.

6. WUFI Modelling - Construction Types

The most common construction typologies have been chosen for the WUFI analysis, as shown in the table below. Results and analysis are included in Sections 8 to 28.

Table 5: New Build Typologies analysed

	Construction Type
N1	Suspended floor - insulated
N2	Ground bearing concrete floor - insulated above
N3	Ground bearing concrete floor - insulated below
N4	Concrete beam & block floor - insulated above
N5	Exposed Suspended floor - insulated
N6	Exposed concrete floor - insulated above
N7	Exposed concrete floor - insulated below
N8	Solid Wall - Internal insulation with a semi-porous finish
N9	Solid Wall - External insulation with a non-porous finish
N10	Solid wall- External and internal insulation with a non-porous finish (Insulated concrete formwork)
N11	Cavity wall – partial-fill with a semi-porous finish
N12	Cavity wall – full-fill with a semi-porous finish
N13	Timber-frame wall – with air gap and a semi-porous finish (e.g. facing brickwork)
N14	Timber frame wall – with air gap and a non-porous finish (e.g. render)
N15	Light Gauge Steel Frame (LGSF) – with air gap and a semi-porous finish (e.g. facing brickwork)
N17	Cold pitched roof (slates/concrete/clay tiles)
N18	Warm roof – slates / concrete / clay tiles
N19	Warm flat roof - timber
N20	Cold roof – timber deck
N21	Warm roof - concrete
N22	Inverted roof - concrete

7. Typology N1: Suspended floor - insulated

The N1 typology is a new-build ground suspended timber floor, with insulation installed in between (and in some cases below) timber joists.

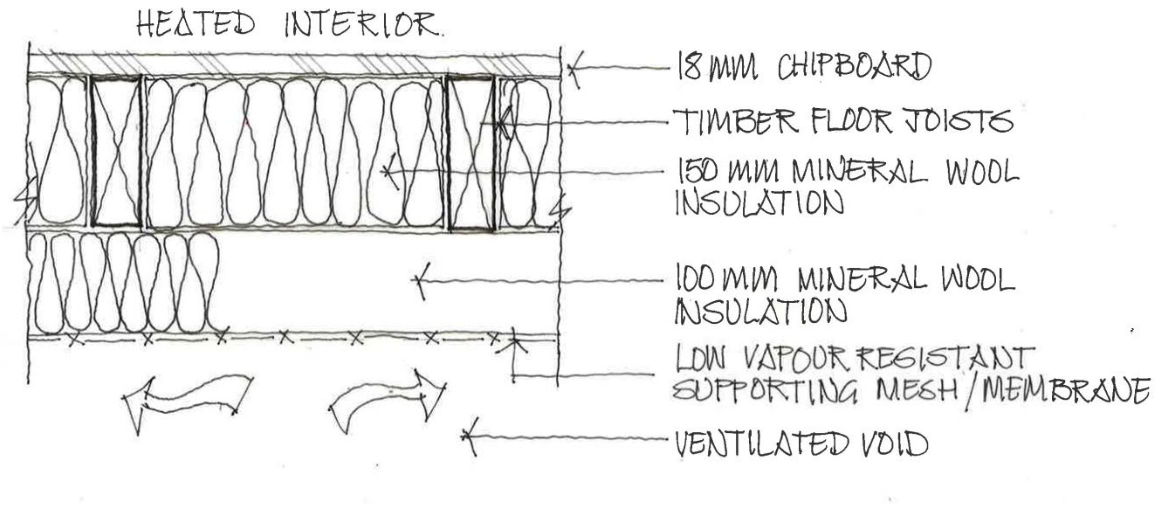


Figure 6: Illustration of the build-up of the typology (TER case)[1]

7.1. Assessment Method

As described in the STBA /DECC's Moisture Risk Assessment and Guidance (2014), *'floors of timber with a void beneath them should be ventilated to remove moisture'.* To follow prescriptive guidance in section F4.3 of BS 5250 (2011), the void is ventilated to outside, meaning that the external surface of the build-up is not exposed directly to rain, wind and solar radiations. Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method, as the main process driving moisture transfer in this build-up is vapour diffusion and the build-up is not exposed to wind-driven rain.

The results from the Glaser method analysis show that this build-up is considered to be a 'safe' build-up, with no risk of interstitial condensation. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

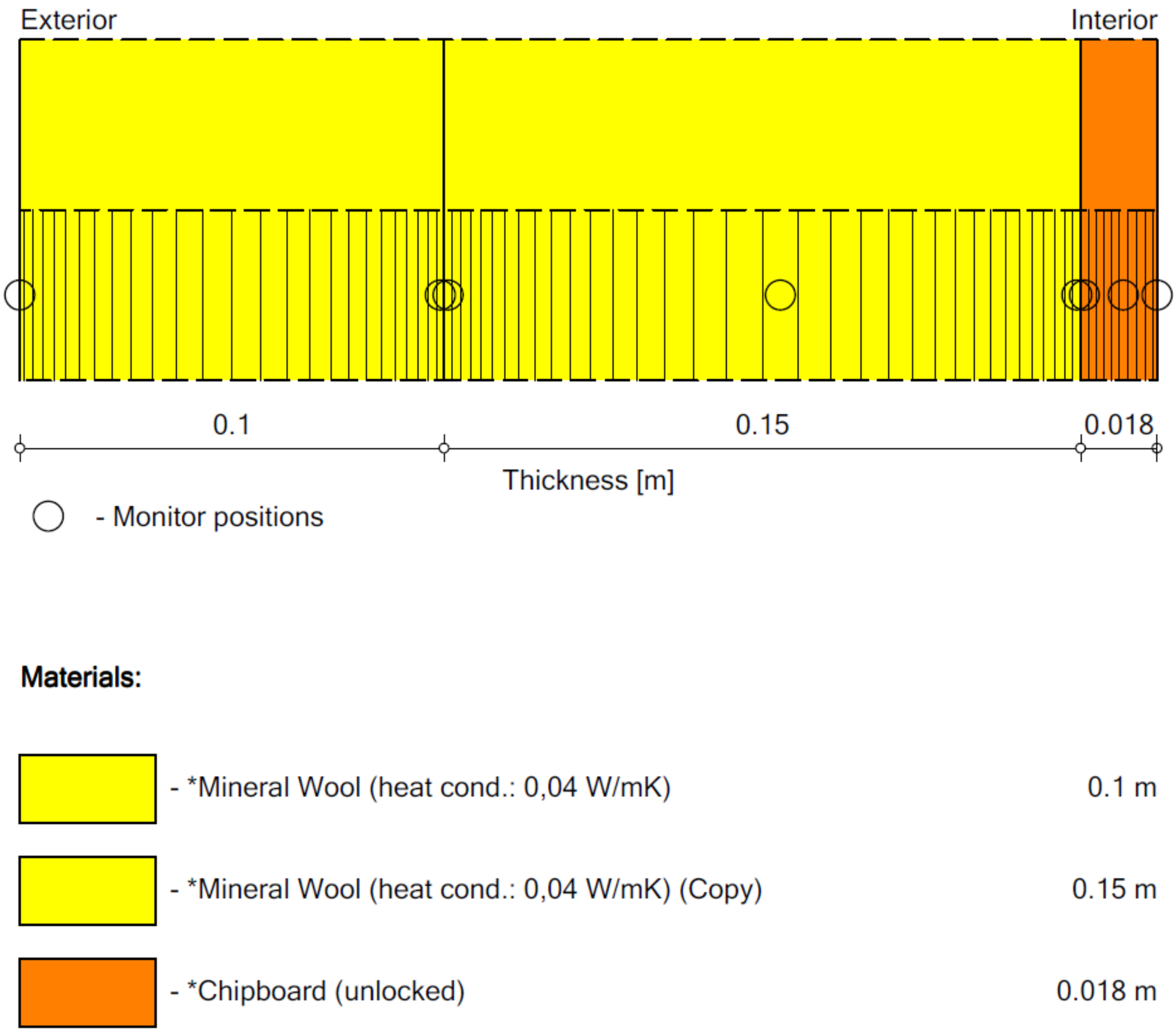
[1] Practicality of installation of low vapour resistant supporting mesh / membrane to be considered. This membrane is not present in the model as there will be negligible change to hygrothermal performance of the build-up.

7.2. Build-up

Please find below the build-up of the typology.

Build-Up:

- 18mm Chipboard
- 3mm // 120mm // 150mm mineral wool insulation (λ = 0.040 W/m.K) installed in between timber joists
- 0mm // 0mm // 100mm mineral wool (λ = 0.040 W/m.K) installed continuously below timber joists



7.3. Baseline Results

7.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 6: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

7.3.2. Critical / Monitored Junction

As mentioned previously, the build-up is protected from rain, wind and solar radiations, and should not present any moisture risks (as shown in the BS EN ISO 13788 (2012) calculations), meaning there is not a ‘critical’ junction per se.

The interface between the mineral wool insulation and the chipboard is not a particular importance, as it is possible to predict the RH profiles at this interface. This interface is located on the warm side of the insulation. As no vapour barrier (e.g. air and vapour control layer (AVCL), foil-facing layers, etc.) is present between this interface and the internal surface, the RH levels at this interface will mirror the internal RH conditions, with a small variation depending on the amount of insulation present in the build-up (the more insulation present in the build-up, the more negligible the increase in RH levels at the interface is). For these reasons, the graphs at this interface are not displayed in this report.

As the first mineral wool insulation layer is bridged with timber, a more useful junction to monitor is the underside of the joists. Due to the different U-value requirements, this junction is:

- Exposed (i.e. the external surface) in the Part C and Part L cases
- Covered by a continuous insulation layer in the TER case

7.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction – at the underside of the timber joists.

As this interface is not considered a ‘critical’ junction, only the results for the Swansea Zone (wind-driven rain exposure Zone 4) are displayed below, as cases in different exposure zones display similar RH profiles. In addition, only two out of the three cases are displayed below (Part L and TER), as conditions are similar at this junction in both Part C and Part L cases. For ease of the reading, the Part L case (case 2) is displayed in grey on the following graph, while the TER case (case 3) is displayed in dark blue.

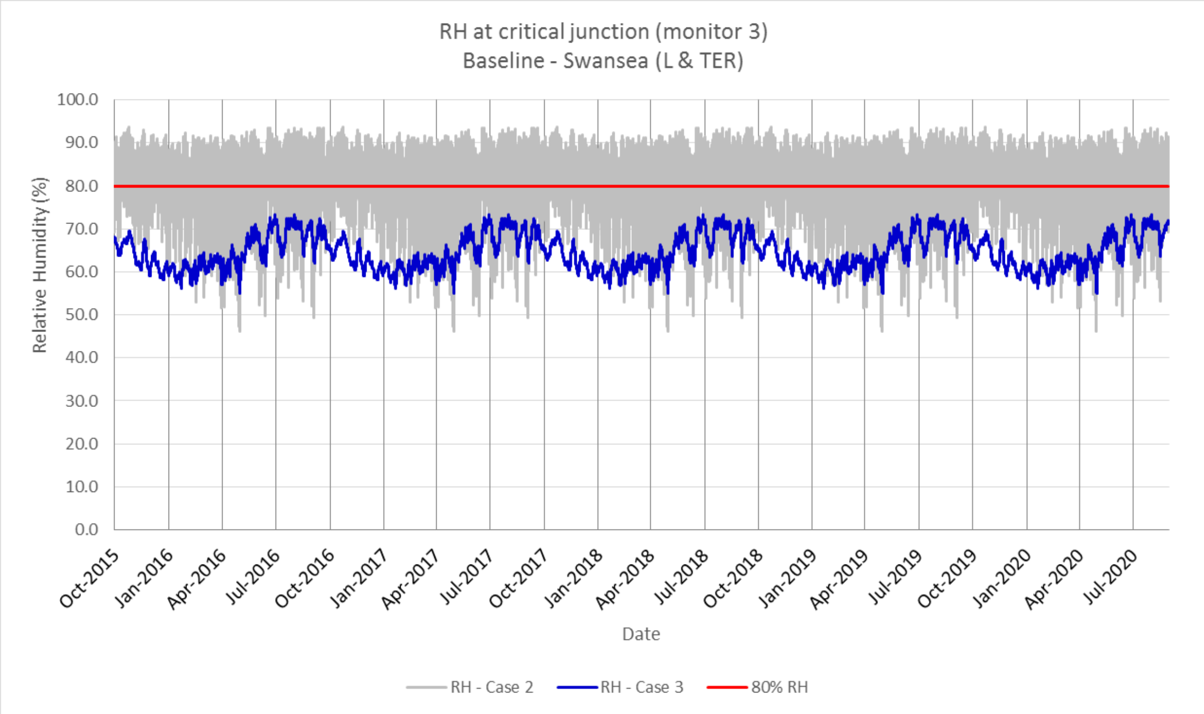


Figure 7: RH levels at monitored junction for Cases 2 and 3

7.3.4. Results Analysis

<u>RH Levels at the Monitored Junction</u>

In the Part L case, the monitored junction is located on the external surface. Consequently, the external temperatures and RH levels are 'assigned' to this surface, as boundary conditions. This explains the wide range in RH levels shown in the Part L (case 2) profile.

Similarly to the N11 typology (partial fill cavity wall) in section 17, in which a more in-depth analysis was undertaken on the results, the actual RH levels experienced on the external surface are not constantly kept above 80%. Large variations in RH levels happen on a daily basis. However, displaying the hourly data for a 5-year period on a single graph is slightly misleading and makes the RH levels on that surface appearing as if they were kept constantly above 80%.

It was also shown in the N11 in-depth analysis that RH levels in the insulation layer (compressible insulation – in both cases mineral wool) are quickly brought back from high RH levels (at the external surface) to 'safe' RH levels within the first couple of centimetres of this insulation layer.

In contrast, the RH levels at this junction in the TER case are much lower, kept well below the 80% RH limit.

The graph therefore shows the external surface of the timber joists as not in optimal conditions in the Part L case (i.e. where external conditions (temperature and RH) are 'forced' onto the external surface of the modelled build-up). As the RH levels often reach levels higher than 80%, which could have a detrimental effect on timber. The TER case (case 3) then shows that the installation of a continuous layer of insulation under the joists brings the RH levels at this interface to 'safe' levels, protecting the timber joists. This also improves the thermal performance of the whole build-up.

<u>Moisture risk assessment criteria</u>
As seen with the BS EN 13788 (2012) calculations, all scenarios are a 'pass' as they all do not accumulate moisture over time, with all interfaces displaying RH levels below the 80% limit (except towards the external surface, where external conditions (temperature and RH) are 'forced' onto the external surface of the modelled build-up). These results are summarised in the table below.

Table 7: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

The results are in line with the prescriptive guidance in BS 5250 (2011), and make sense as the build-up is a moisture-open build-up, without any vapour barriers which could lead to the accumulation of moisture if located in non-recommended locations.

<u>Effects of exposure zones and U-values</u>

As the build-up is not directly exposed to wind-driven rain and solar gains, the difference in exposure zone is minimal and does not have an effect on its hygrothermal performance.

As there is not a critical junction to monitor, a direct impact of the U-value on the build-up is not possible. However, the modelling shows that the timber joists, i.e. the element most at risk of moisture damage, is kept in more optimal conditions when an additional layer of continuous insulation is installed under the joists. This is due to the additional insulation increasing the temperature at this interface, which leads to lower RH levels.

7.3.5. Conclusions – Baseline

- Moisture-open build-up being safe
- Timber joists not in optimal conditions if no continuous layer of insulation installed under the joists. Better conditions (i.e. lower RH levels), as well as better thermal performance, with an additional insulation layer. The

practicality of installing this insulation layer would need to be considered further.

7.4. Sensitivity Analysis

7.4.1. Baseline versus BS 5250 (2011) Guidance

The baseline build-up differs slightly from the recommended build-up in BS 5250 (2011), which recommends a membrane with low vapour resistance (e.g. a breather membrane) to be installed on the cold side of the insulation.

A membrane with low vapour resistance (such as a breather membrane, modelled in other typologies with sd = 0.04m) is not a material being considered as a vapour retarder. It is a 'permeable' material, which will not obstruct the movement of moisture throughout the build-up. Therefore, the sensitivity analysis to match BS 5250 (2011) build-up is deemed unnecessary.

7.4.2. Airtightness and ABIS Conditions

It is important to note that the build-up modelled in WUFI is done in theoretical conditions, which means that the chipboard layer is continuous and plays the role of the airtightness layer. As highlighted in BS 5250 (2011), *'Airtightness is important both in terms of moisture transfer and heat loss, so an air barrier is essential'*.

No sensitivity analysis modelling is done in this report, in which air leakage is modelled through the chipboard layer to create a leaking airtightness layer. However, despite the absence of modelling, the impact of such conditions is known: this could lead to moisture-laden air making its way through the build-up and condensing within the build-up when it reaches its dew point. Therefore, particular case should be given around ensuring good airtightness in this build-up.

7.5. Conclusions

- Build-up 'safe' (though joists even 'safer' when presence of continuous insulation layer installed below the joists).

8. Typology N2: Ground bearing concrete floor - insulated above

The N2 typology is a new-build ground bearing concrete slab, with insulation installed above the slab.

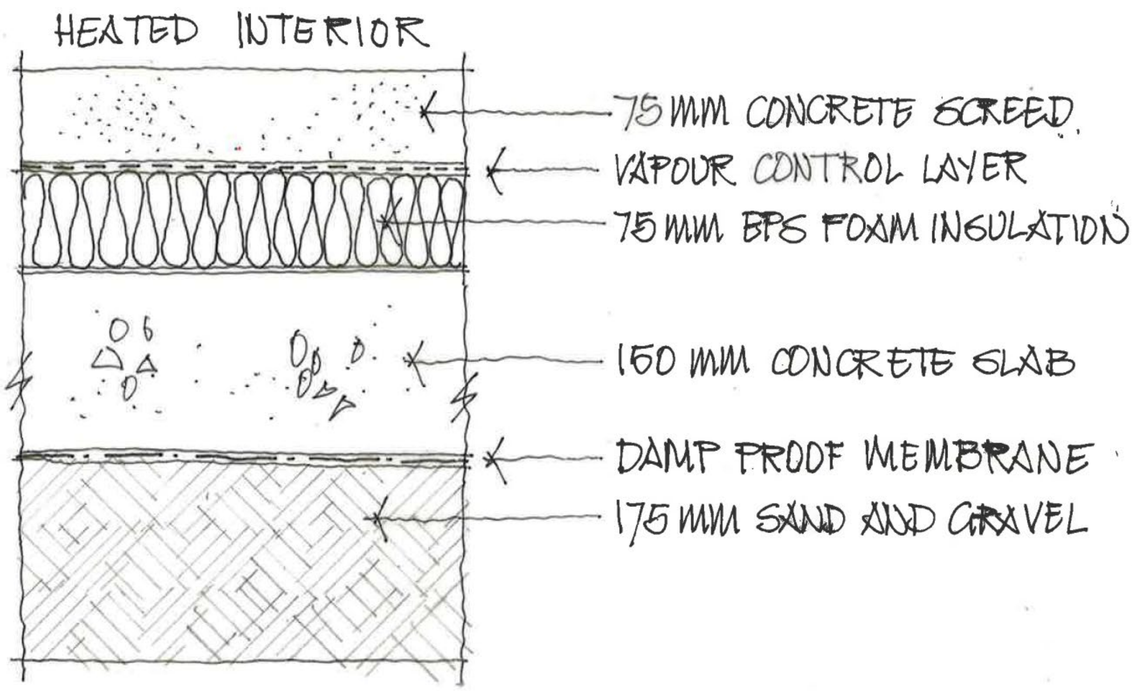


Figure 8: Illustration of the build-up of the typology (Part L case)

8.1. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 75mm concrete screed
- 0mm // 75mm // 230mm EPS foam insulation (λ = 0.040 W/m.K)
- 150mm concrete slab
- 1mm DPM (sd = 136m)
- 175mm sand and gravel

8.2. Assessment Method

No element of this construction type is exposed to either wind-driven rain or solar gains. This build-up is also protected from rising damp with the presence of the damp-proof membrane (DPM) layer below the slab, and subject to relatively constant external conditions (being in direct contact with the ground). Under these conditions, moisture transfer is mainly driven by vapour diffusion. Therefore, the build-up does not require dynamic simulation following BS EN 15026 (2007).

Prescriptive guidance in BS 5250 (2011) is also given for the construction of this floor type to avoid condensation. The current guidance from paragraph F.3 of BS 5250 (2011) states the following: *'If thermal insulation is installed above the floor slab, there is a risk of interstitial condensation occurring on the upper surface of the floor slab. To prevent that, an AVCL with a vapour resistance equivalent to that of the DPM should be laid over the thermal insulation'*.

Since this guidance is robust (as this is a very commonly used build-up, with good evidence of success over many years), and verified with the BS EN ISO 13788 (2012) assessment method, it is considered that there is no additional benefits to running this typology through transient hygrothermal modelling using WUFI. Therefore full WUFI analysis will not be used for this construction typology.

8.3. Connective Effects

8.3.1. Junction Modelling (ACD MCI-GF-01)

The previous paragraph highlights the absence of interstitial condensation risk, with build-ups following the guidance in BS 5250 (2011), though this guidance identifies a risk of surface condensation: *'On ground bearing floors, there is a risk of surface condensation forming, particularly at the junction with external walls and at external corners. That risk may be eliminated by providing adequate heating and ventilation of the occupied space. In order to avoid thermal bridging, thermal insulation should be provided to the edges of the slab build-up'*.

As connective effects around junctions play a much more significant role with this typology, a thermal bridging analysis using THERM was made of a N2 floor build-up (meeting Part C backstop U-value requirements) adjoining a typical partially-filled cavity wall (also meeting Part C thermal requirements). The model assesses the impact of the omission or inclusion of floor junction insulation to the requirements of the accredited construction detail (ACD) reference ACD MCI-GF-01 (Junction between ground bearing floor – insulation above slab – and partial-filled insulated cavity wall) on the corner surface temperature and risk of mould growth in this junction.

There are three items listed in ACD MCI-GF-01 in order to adhere to the standard:

- Ensure wall insulation is installed at least 150mm below the top of floor insulation.
- Floor insulation must tightly abut the blockwork wall.
- Ensure that partial fill insulation is secured firmly against the inner leaf of the cavity wall.

8.4. Results

8.4.1. Junction Modelling

Figure 9 illustrates the junction between an uninsulated floor type N2 (U-value ≥ 0.70 W/m.K) and an insulation wall type N11 (U-value ≥ 0.70 W/m.K), without junction insulation.

The lowest internal surface temperature (T_{si}) is 14.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.72, which indicates a risk of mould growth at this junction. This junction would not be compliant with Approved Document C at present since the ACD is not being followed.

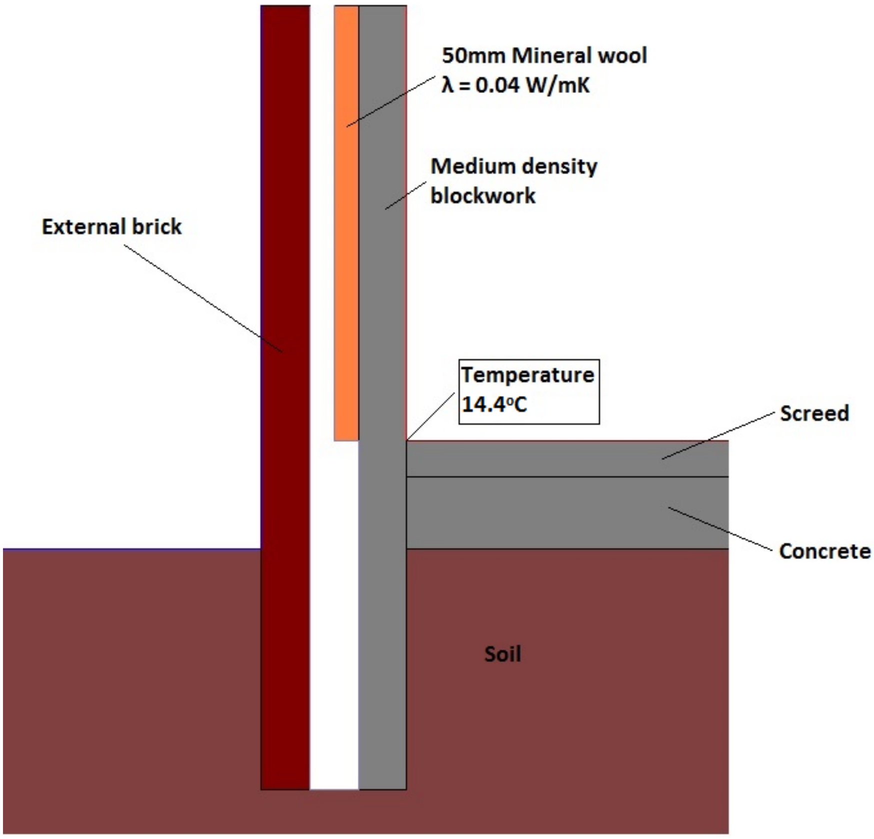


Figure 9: Junction between floor type N2 and wall type N11, with no junction insulation

Figure 10 illustrates the junction between an uninsulated floor type N2 (U-value ≥ 0.70 W/m.K) and an insulated wall type N11 (U-value ≥ 0.7 W/m.K), with junction insulation to ACD MCI-GF-01.

The lowest internal surface temperature (T_{si}) is 15.5°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.775, which indicates a low risk of mould growth conditions at this junction. This junction would be compliant with AD C at present since the ACD is being followed, however with an f_{Rsi} being only 3% better than recommended f_{Rsi}; this solution is considered a sub-optimal solution.

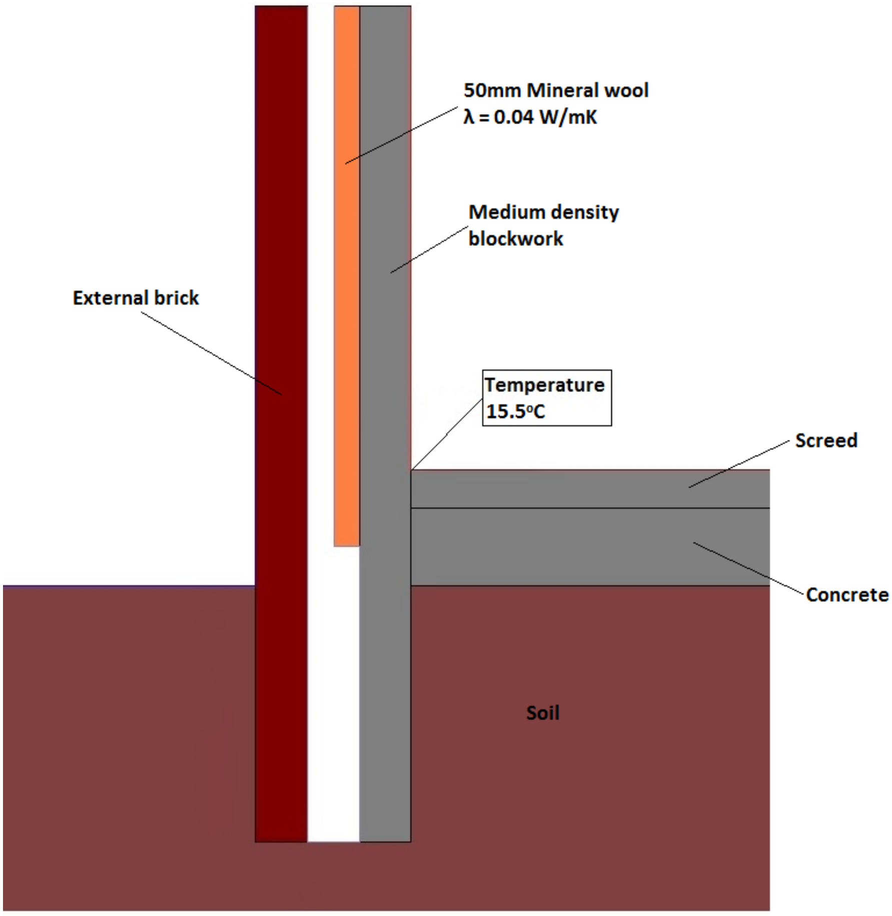


Figure 10: Junction between floor type N2 and wall type N11, with junction insulation to ACD MCI-GF-01

Since a risk of mould growth conditions is apparent at this junction, further analysis has been undertaken to assess the impact of increasing floor insulation to a Part L U-value target (0.25 W/m.K).

Figure 11 illustrates the junction between a floor type N2 (U-value ≥ 0.25 W/m.K) and an insulated wall type N11 (U-value ≥ 0.7 W/m.K), without junction insulation.

The lowest internal surface temperature (T_{si}) is 14.9°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.75, which indicates a risk of mould growth conditions at this junction. This junction would not be compliant with AD C at present since the ACD is not being followed.

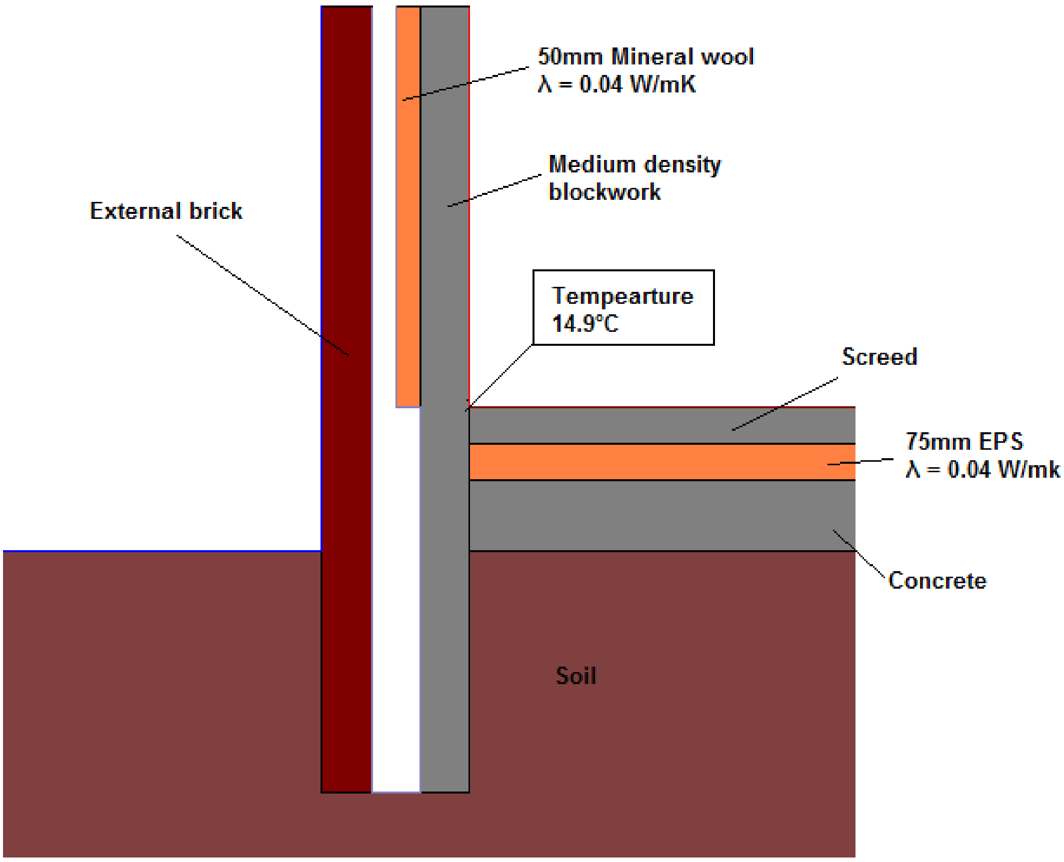


Figure 11: Junction between floor type N2 insulated to AD L and wall type N11, with no junction insulation

Figure 12 illustrates the junction between an insulated floor type N2 (U-value ≥ 0.25 W/m.K) and an insulated wall type N11 (U-value ≥ 0.7 W/m.K), with junction insulation to ACD MCI-GF-01.

The lowest internal surface temperature (T_{si}) is 16.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.82, which indicates a low risk of mould growth conditions at this junction. This junction would be compliant with AD C at present.

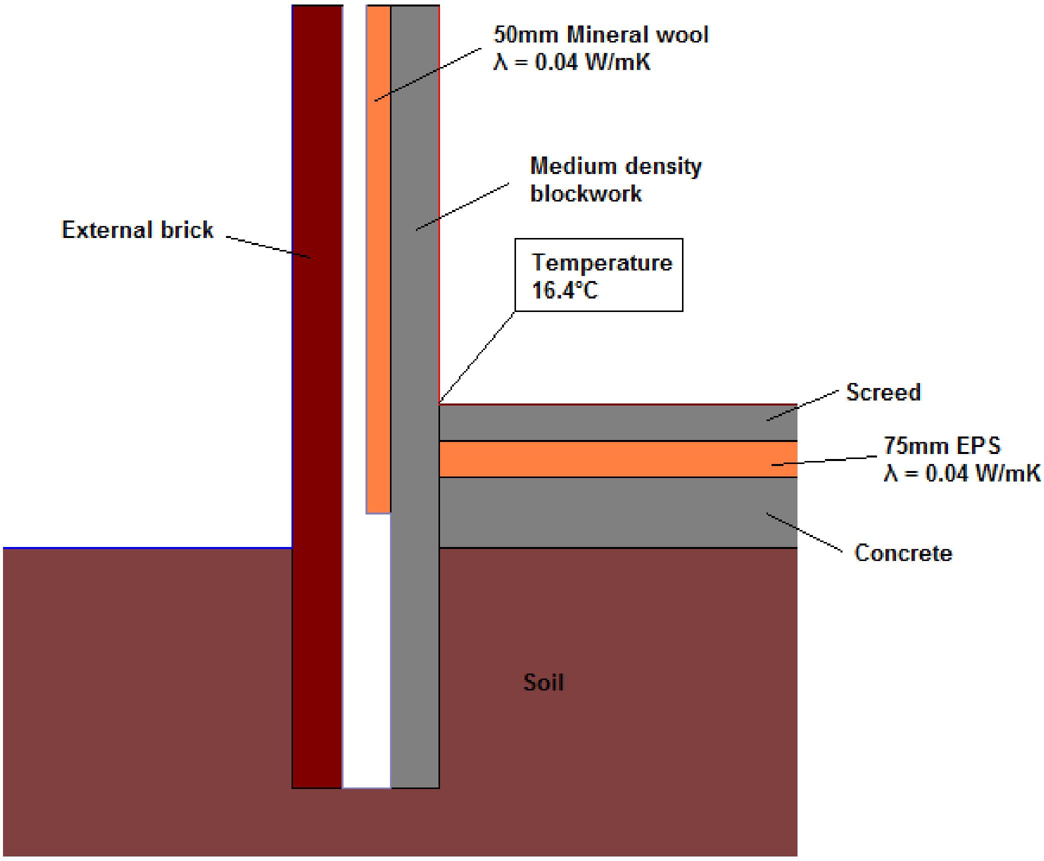


Figure 12: Junction between floor type N2 insulated to AD L and wall type N11, with junction insulation to ACD MCI-GF-01

8.4.2. Conclusions

It can be seen that not adhering to ACD MCI-GF-01 increases the risk of mould growth since the internal surface temperature factor f_{Rsi} is lower than 0.75, which is the current limit set in Building Regulations.

With the modelled conditions using a 20°C internal temperature (T_i) and 0°C external temperature (T_e), all surface temperatures (T_{si}) should have a minimum temperature of 15°C to avoid mould risk. The junction modelled in Figure 9 does not meet this criteria with an internal surface temperature T_{si} of 14.4°C.

Although adhering to ACD MCI-GF-01 increases the internal surface temperature factor f_{Rsi} above 0.75, the f_{Rsi} where both elements adhere only to the AD C elemental backstop U-values is only marginally above the critical temperature factor (f_{CRsi}) of 0.75.

8.4.3. Recommendation

- N2/N3 are standardised floor build-ups, with high resistance to moisture
- Following AD C on both elements technically meet the current requirements, but results still very close to the 'risky' limit. So potential recommendation is to use ACD and AD L (rather than AD C) to ensure better performance
- However, advice around build-up not to be dissociated with junctions / connective effects (as decision on how to detail floor junctions can have a significant impact on the presence / absence of mould growth at corners – as seen through THERM modelling).
  So choices are to follow AD L, AND:
  • follow ACD MCI-GF requirements, or
  • use non-accredited junctions and do thermal bridging analysis to ensure $f_{Rsi} > 0.75$

9. Typology N3: Ground bearing concrete floor - insulated below

The N3 typology is a new-build ground bearing concrete slab, with insulation installed below the slab.

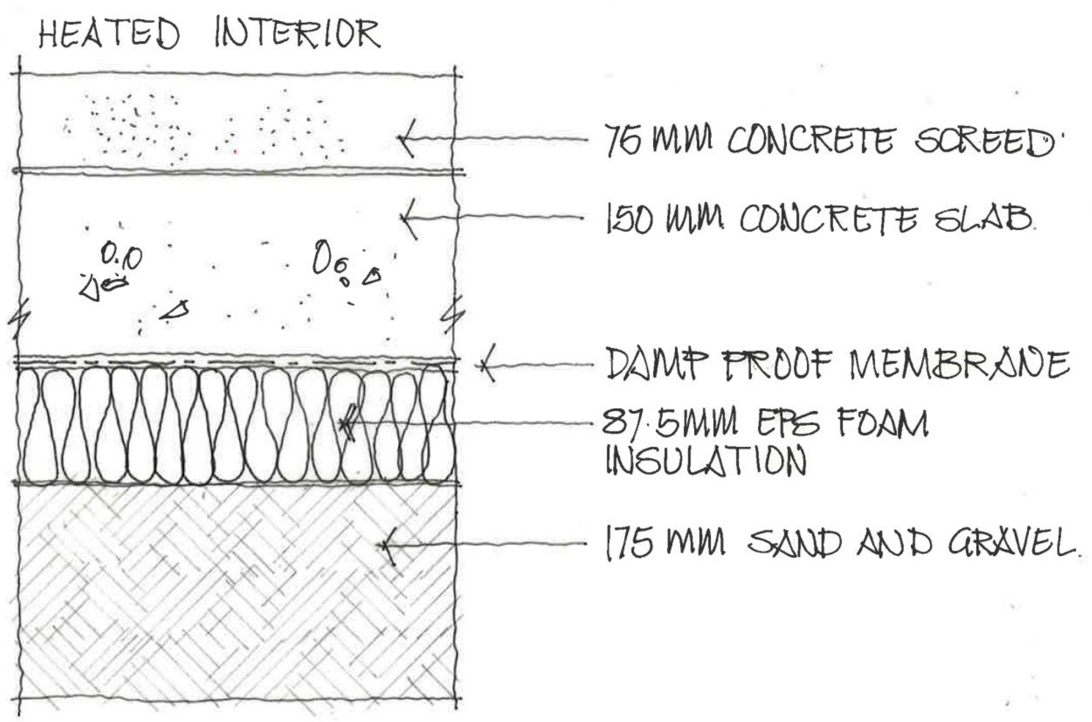


Figure 13: Illustration of the build-up of the typology (Part L case)

9.1. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 75mm concrete screed
- 150mm concrete slab
- 0mm // 87.5mm // 230mm EPS foam insulation (λ = 0.040 W/m.K)
- 1mm DPM (sd = 136m)
- 175mm sand and gravel

9.2. Assessment Method

No element of this construction type is exposed to either wind-driven rain or solar gains. This build-up is also protected from rising damp with the presence of the DPM layer below the slab, and subject to relatively constant external conditions (being in direct contact with the ground). Under these conditions, moisture transfer is mainly driven by vapour diffusion. Therefore, the build-up does not require dynamic simulation following BS EN 15026 (2007).

Since the guidance in BS 5250 (2011) is robust (as this is a very commonly used build-up, with good evidence of success over many years), and verified with the BS EN ISO 13788 (2012) assessment method, it is considered that there is no additional benefits to running this typology through transient hygrothermal modelling using WUFI. Therefore, WUFI analysis will not be used for this construction typology.

9.3. Connective Effects

9.3.1. Junction Modelling (ACD MCI-GF-02)

Similarly to construction type N2 above, there is an identified surface condensation risk with ground bearing floors, as listed in BS 5250 (2011): *'On ground bearing floors, there is a risk of surface condensation forming, particularly at the junction with external walls and at external corners. That risk may be eliminated by providing adequate heating and ventilation of the occupied space. In order to avoid thermal bridging, thermal insulation should be provided to the edges of the slab build-up'.*

As connective effects around junctions play a much more significant role with this typology, a thermal bridging analysis using THERM was made of an N3 floor build-up (meeting Part C backstop U-value requirements) adjoining a typical partially-filled cavity wall (also meeting Part C thermal requirements). The model assesses the impact of the omission or inclusion of junction insulation to the requirements of the accredited detail ACD MCI-GF-02 (Junction between ground bearing floor – insulation below slab – and partial-filled insulated cavity wall) on the corner surface temperature and risk of mould growth in this junction.

There are 4 items listed in ACD MCI-GF-02 in order to adhere to the standard:

- Install perimeter insulation with a minimum R-value of 0.75 m^2.K/W.
- Ensure wall insulation is installed at least 150mm below the top of floor insulation.
- Floor insulation must tightly abut the blockwork wall.
- Ensure that partial fill insulation is secured firmly against the inner leaf of the cavity wall

9.4. Results

9.4.1. Junction modelling

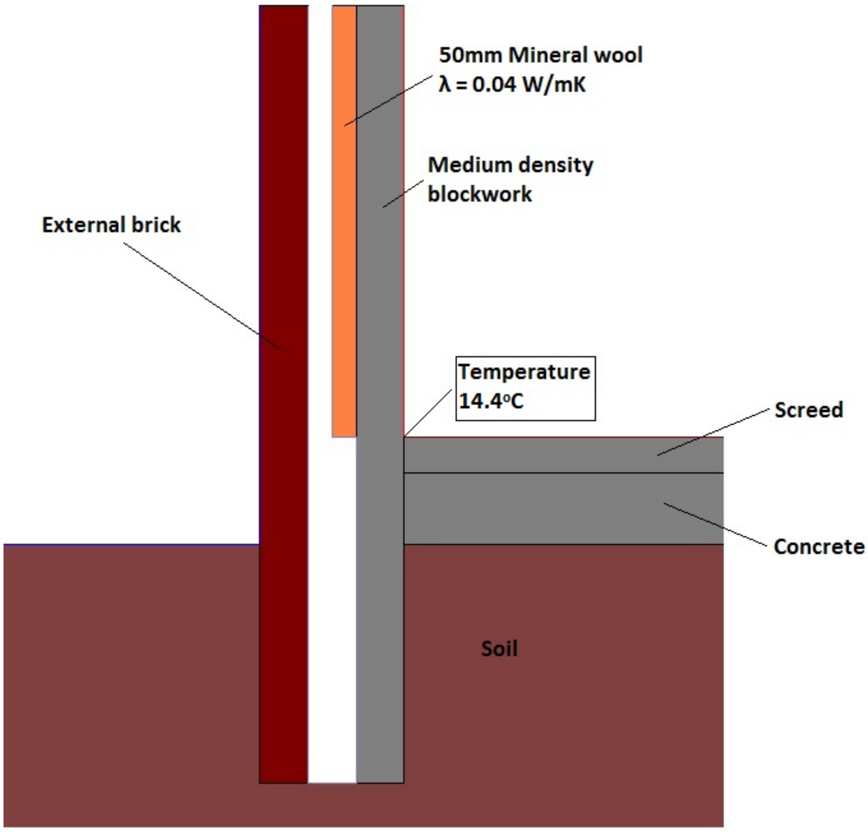


Figure 14 illustrates the junction between an uninsulated floor type N3 (U-value ≥ 0.70 W/m.K) and a partial-filled insulated cavity wall type N11 (U-value ≥ 0.70 W/m.K), without junction insulation.

This is effectively identical to the junction modelled for floor type N2 above. The lowest internal surface temperature (T_{si}) is 14.4°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.72, which indicates a risk of mould growth at this junction. This junction would not be compliant with AD C at present since the ACD is not being followed.

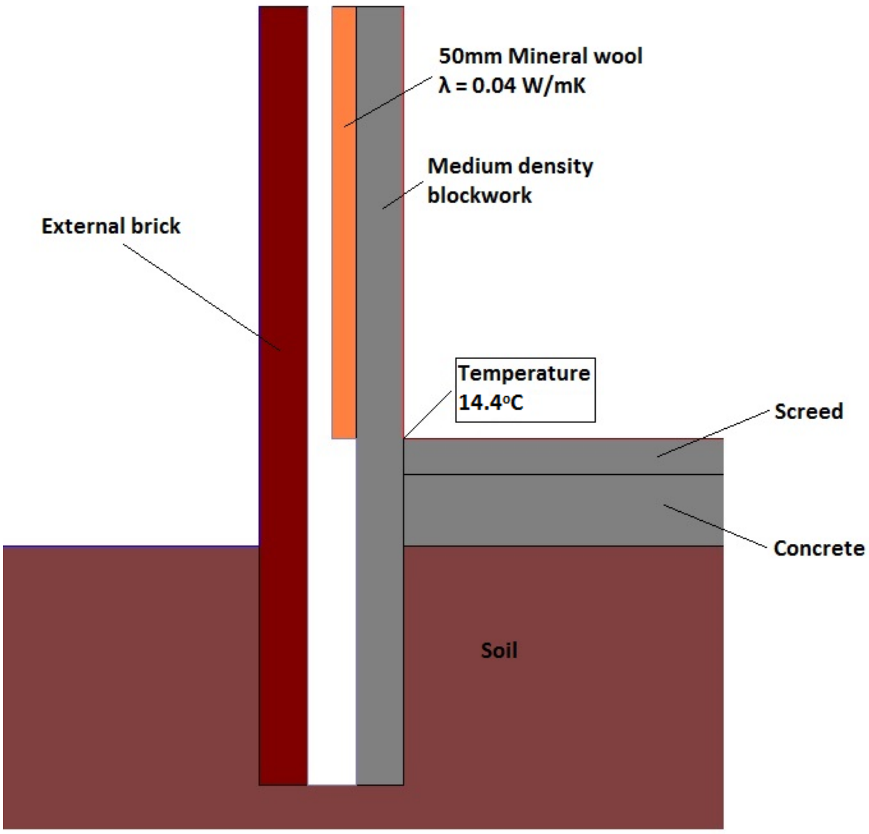


Figure 14: Junction between floor type N3 and wall type N11, with no junction insulation

Figure 15 illustrates the junction between an uninsulated floor type N2 (U-value ≥ 0.70 W/m.K) and a partial-filled insulated cavity wall type N11 (U-value ≥ 0.70 W/m.K), with junction insulation to ACD MCI-GF-02. The lowest internal surface temperature (T_{si}) is 15.8°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.79, which indicates a low risk of mould growth at this junction. This junction would be compliant with AD C at present since the ACD is being followed.

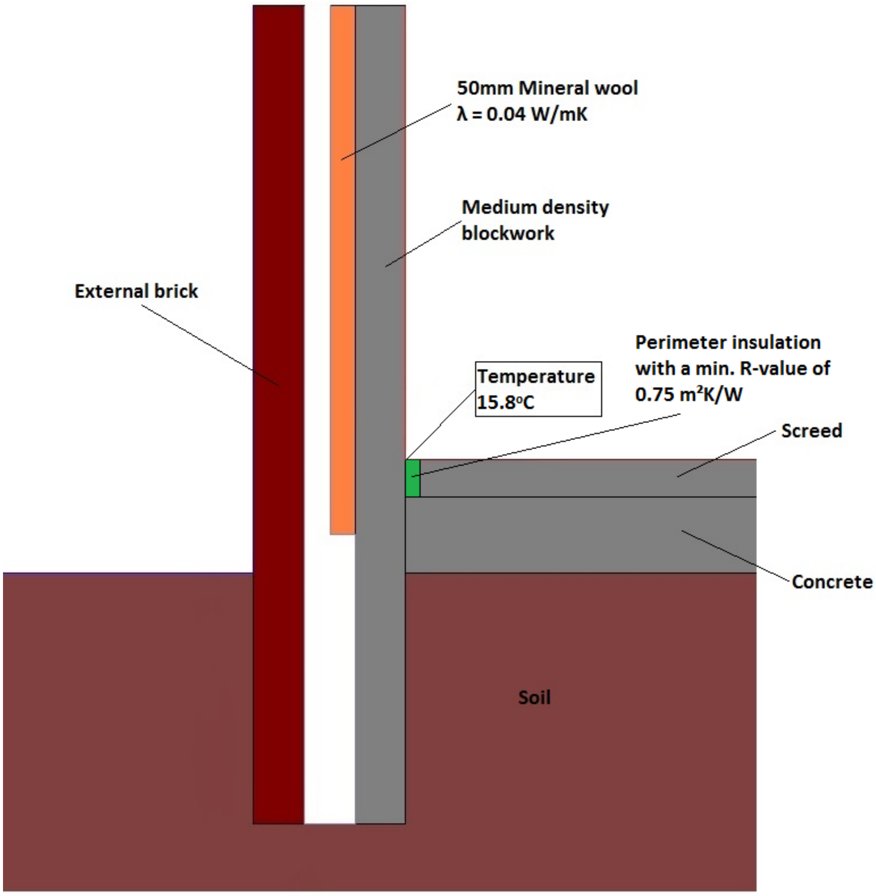


Figure 15: Junction between floor type N3 and wall type N11, with junction insulation to MCI-GF-02

Since a risk of mould growth conditions is apparent at this junction, further analysis has been undertaken to assess the impact of increasing floor insulation to a Part L U-value target (0.25 W/m.K).

Figure 16 illustrates the junction between an insulated floor type N3 (U-value ≥ 0.25 W/m.K) and a partial-filled insulated cavity wall type N11 (U-value ≥ 0.70 W/m.K), without junction insulation.

The lowest internal surface temperature (T_{si}) is 15°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.75, which indicates a risk of mould growth at this junction. This junction would not be compliant with AD C at present since the ACD is not being followed.

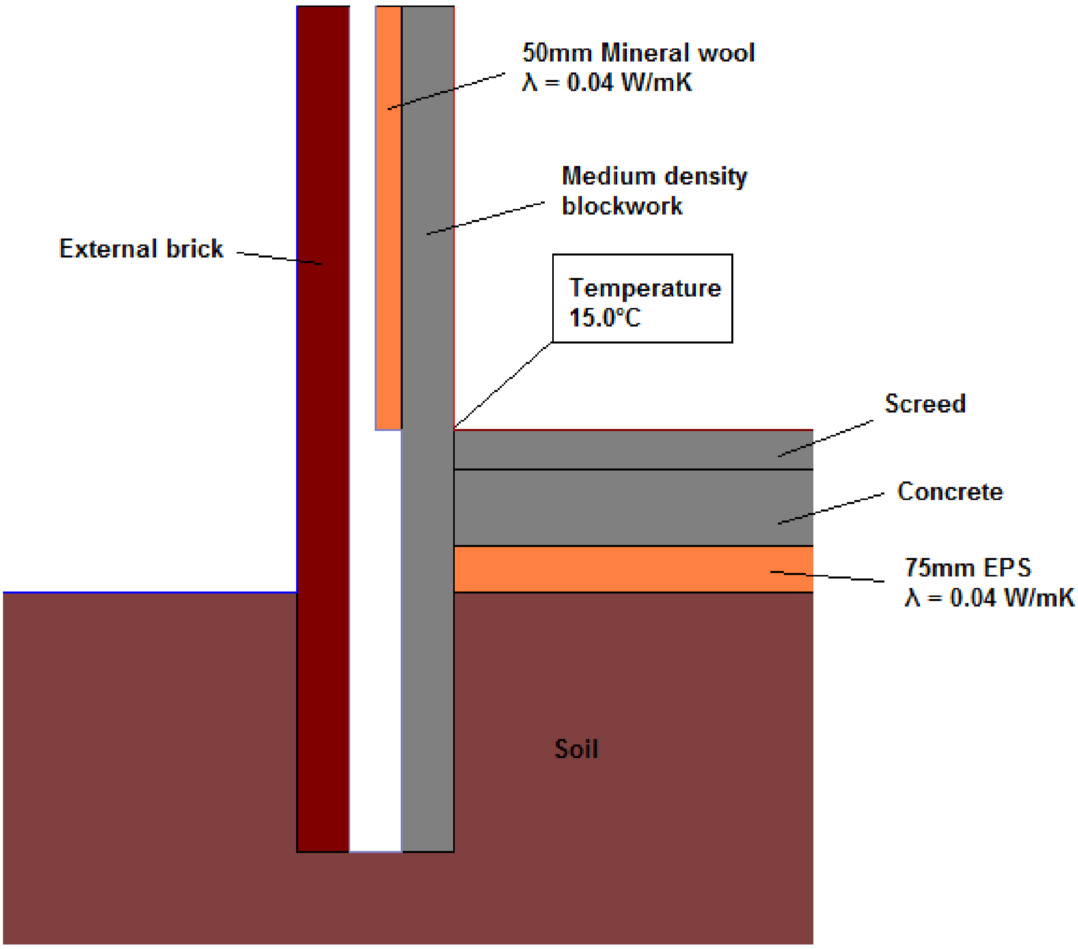


Figure 16: Junction between floor type N3 and wall type N11, with no junction insulation

Figure 17 illustrates the junction between an insulated floor type N3 (U-value ≥ 0.25 W/m.K) and a partial-filled insulated cavity wall type N11 (U-value ≥ 0.70 W/m.K), with junction insulation to ACD MCI-GF-02.

The lowest internal surface temperature (T_{si}) is 16.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.82, which indicates a low risk of mould growth at this junction. This junction would be compliant with AD C at present since the ACD is being followed.

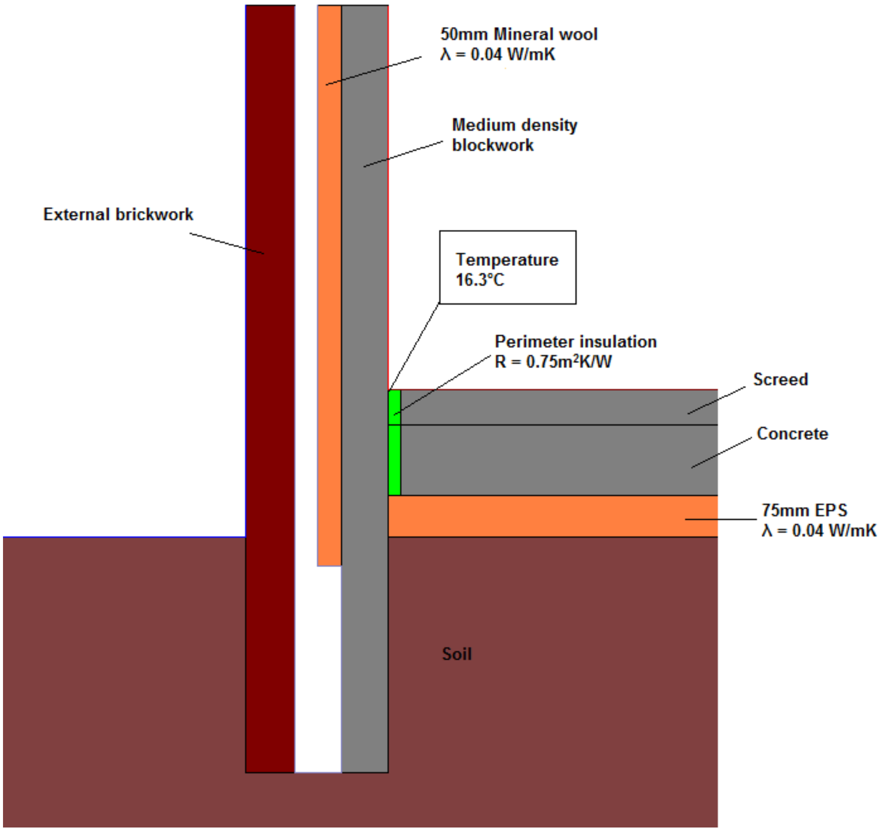


Figure 17: Junction between floor type N3 and wall type N11, with junction insulation to MCI-GF-02

9.4.2. Conclusions

It can be seen that not adhering to ACD MCI-GF-02 increases the risk of surface condensation since the internal surface temperature factor f_{Rsi} is lower than 0.75, which is the current limit set in Building Regulations.

With the modelled conditions using a 20°C internal temperature (T_i) and 0°C external temperature (T_e), all surface temperatures (T_{si}) should have a minimum temperature of 15°C to avoid mould risk. The junction modelled in Figure 9 does not meet this criteria with an internal surface temperature T_{si} of 14.4°C.

When the details within ACD MCI-GF-02 are followed, the resultant surface temperature factor (f_{Rsi}) of 0.79 indicates minimal risk of mould growth at this junction.

9.4.3. Recommendation

(All recommendations similar to N2)

- N2/N3 are standardised floor build-ups, with high resistance to moisture
- Following AD C on both elements technically meet the current requirements, but results still very close to the 'risky' limit. So potential recommendation is to use ACD and AD L (rather than AD C) to ensure better performance
- However, advice around build-up not to be dissociated with junctions / connective effects (as decision on how to detail floor junctions can have a significant impact on the presence / absence of mould growth at corners – as seen through THERM modelling).
  So choices are to follow AD L, AND:
  • follow ACD MCI-GF requirements, or
  • use non-accredited junctions and do thermal bridging analysis to ensure $f_{Rsi} > 0.75$

10. Typology N4: Concrete beam & block floor - insulated above

The N4 typology is a new-build concrete beam and block floor, with insulation installed above the beam and block and below the screed.

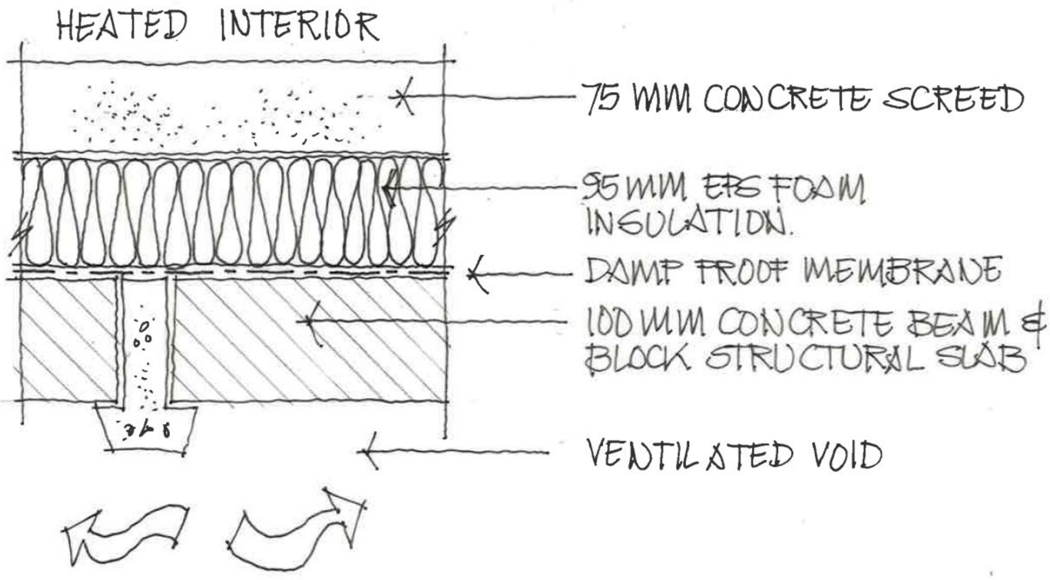


Figure 18: Illustration of the build-up of the typology (Part L case)

10.1. Assessment Method

The DECC/STBA Moisture Risk Assessment and Guidance (2014) states, *'floors of timber with a void beneath them should be ventilated to remove moisture'.* This is also mentioned in the prescriptive guidance in paragraph F4.2 of BS 5250 (2011). To follow prescriptive guidance in BS 5250 (2011), the void is ventilated to outside, meaning that the external surface of the build-up is not exposed directly to the elements (rain, wind and solar radiations).

As the concrete beam and block layer is only exposed to external temperatures and RH levels due to the ventilated subfloor, but without wind-driven rain or solar gains, the movement of moisture in this layer is driven by vapour diffusion. This mechanism is dealt with in the BS EN ISO 13788 (2012) calculation method, and therefore this method should be able to provide an accurate assessment of the hygrothermal performance of this build-up.

The results by the Glaser method show that this build-up is generally considered to be a 'safe' build-up. The calculation shows that interstitial condensation occurs during the winter season, but evaporates completely during the summer months.

Surface condensation was shown to occur only in the uninsulated case (Part C). This can be simply explained by the lack of insulation leading to a floor surface temperature not high enough to be above the dew point.

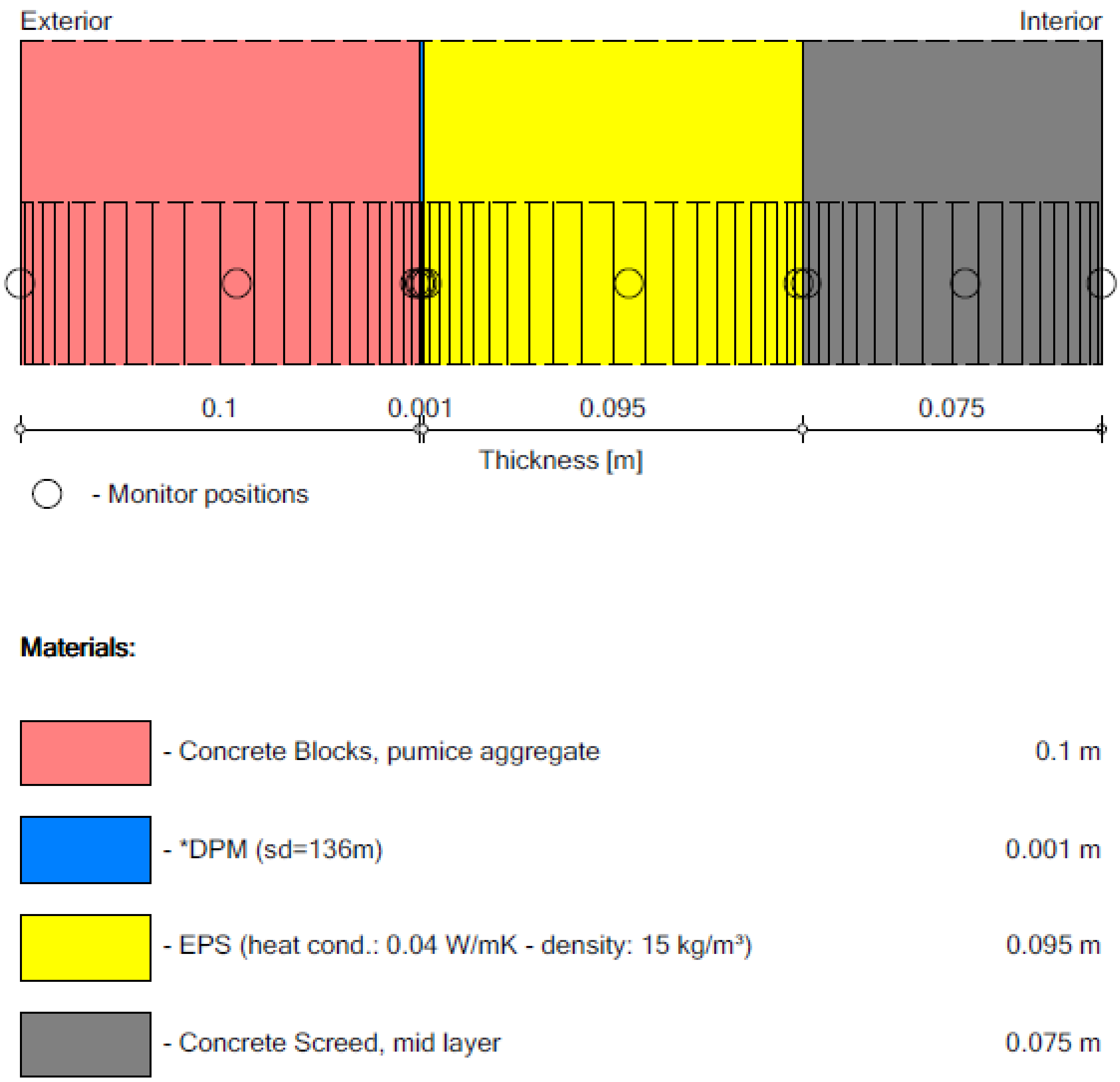
The results regarding the lack of interstitial condensation accumulating over the years will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

10.2. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 75mm sand cement concrete screed
- 0mm // 95mm // 230mm EPS insulation (λ = 0.040 W/m.K)
- 1mm DPM (sd = 136 - equivalent layer)
- 100mm Concrete beam & block



Prescriptive guidance in BS 5250 (2011) also specifies an AVCL between the screed and the insulation. This is not represented by the baseline model: the AVCL layer has been excluded as this not considered common industry practice.

10.3. Baseline Results

10.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 8: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

10.3.2. Critical Junction

For this typology, the focus is given on the RH levels at the interface of the cold concrete beam and block and the insulation (as mentioned in BS 5250 (2011)). A DPM is located between the beam and block floor and the insulation, therefore the RH levels will be monitored above the DPM, on the cold side of the insulation. Indeed, this interface is the location where moisture can get trapped; which means that the RH levels could rise higher than the recommended levels and lead to moisture risks.

This critical junction is correctly identified in the BS EN ISO 13788 (2012) assessment, but the presence of interstitial condensation in this calculation is not associated with the build-up failing, as the calculation shows that the interstitial condensation occurring at the critical junction evaporates during the summer.

10.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

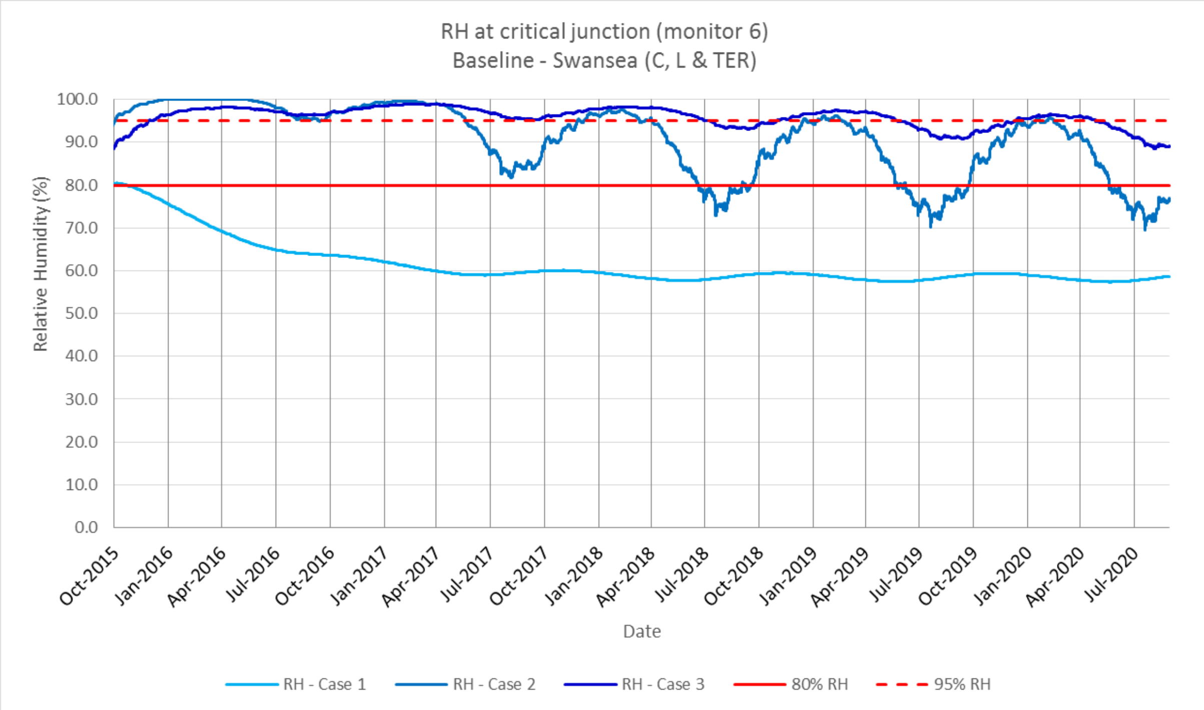


Figure 19: RH levels at critical junction for Cases 1, 2 and 3

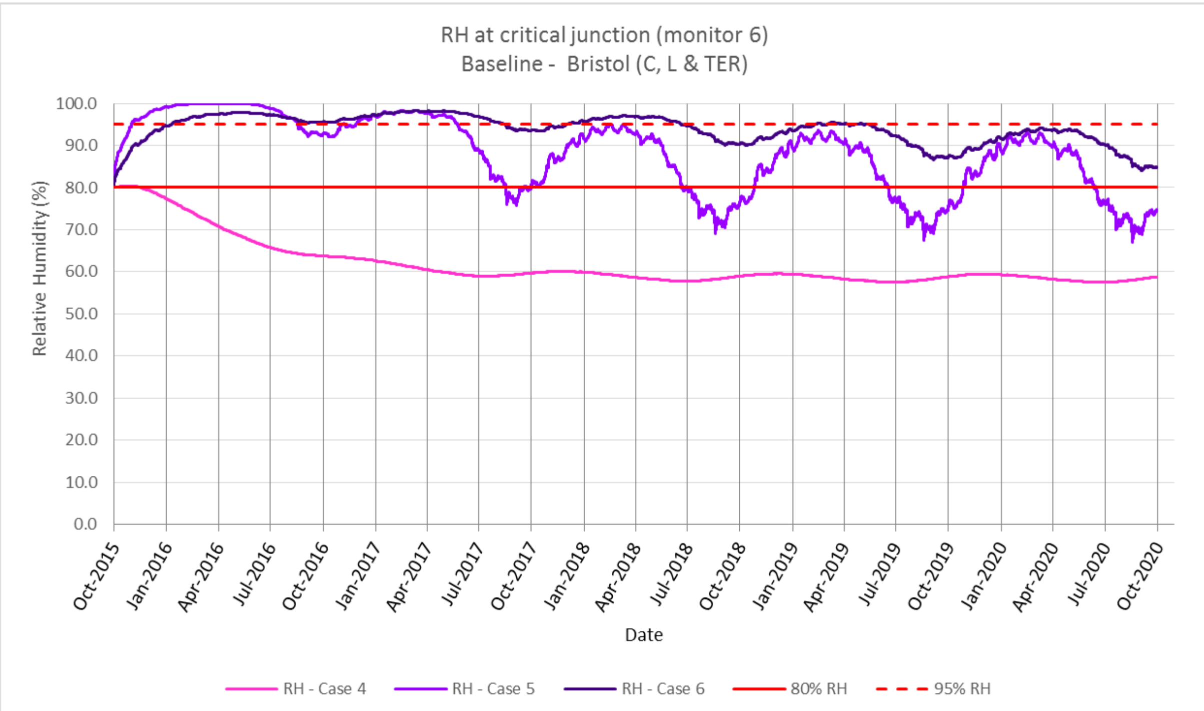


Figure 20: RH levels at critical junction for Cases 4, 5 and 6

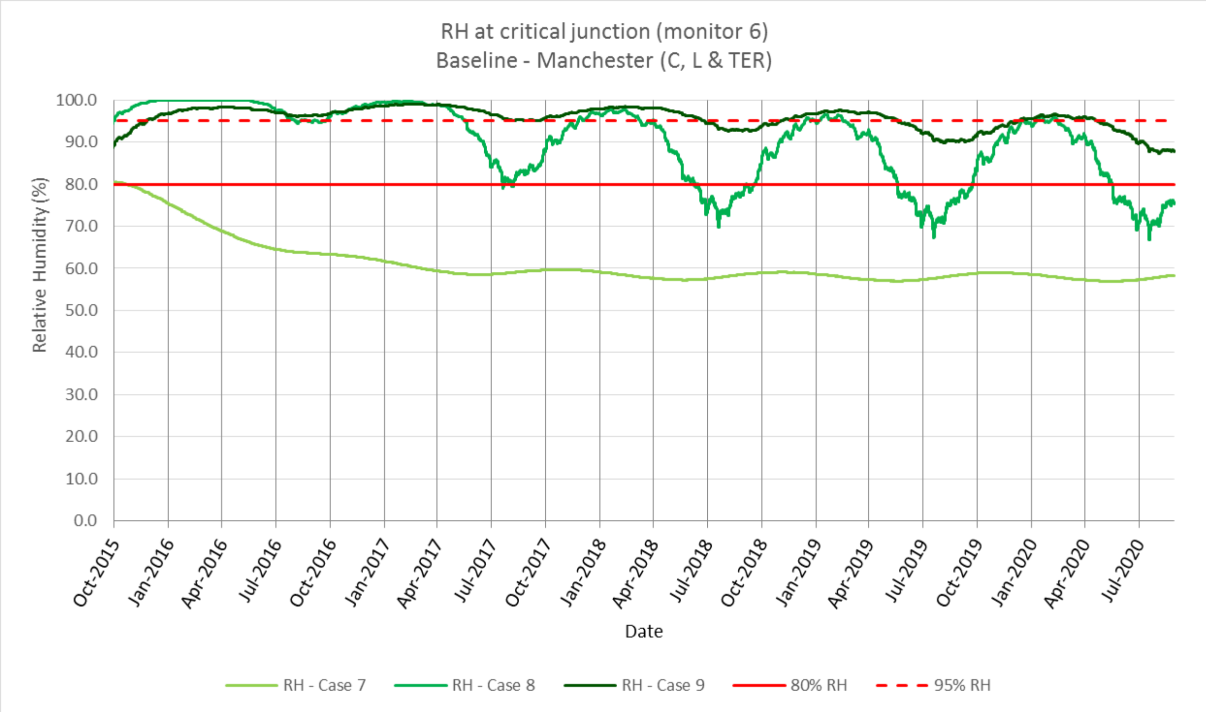


Figure 21: RH levels at critical junction for Cases 7, 8 and 9

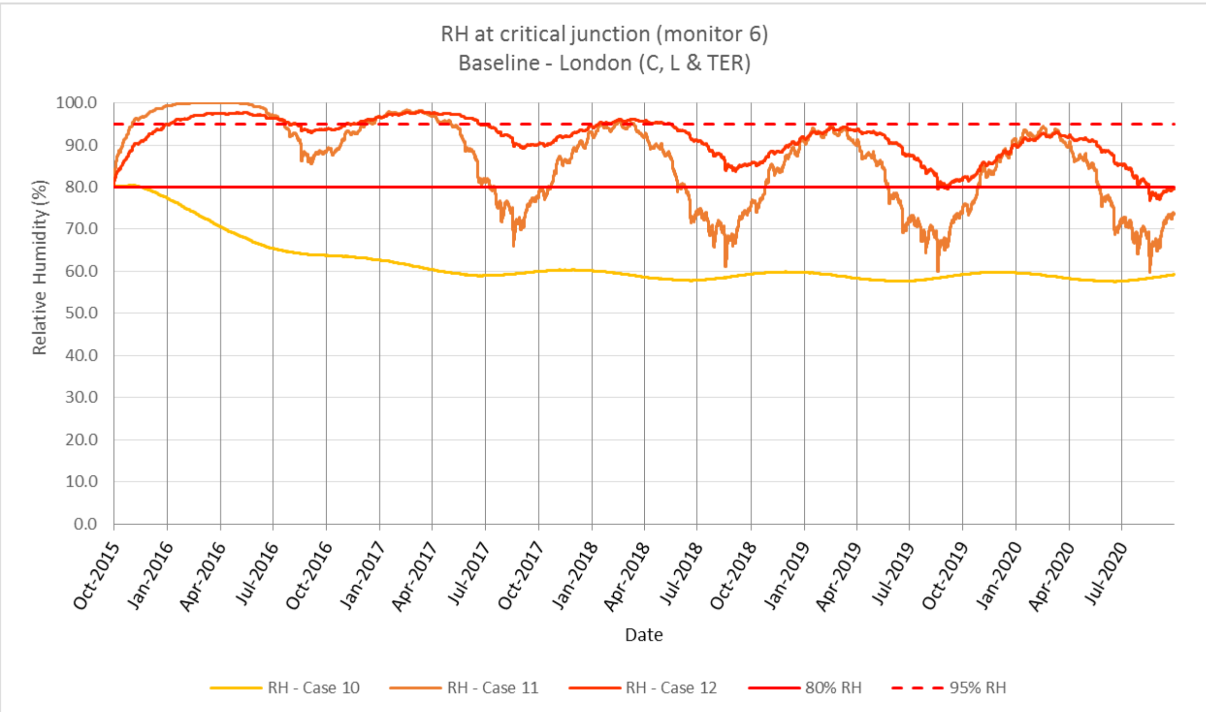


Figure 22: RH levels at critical junction for Cases 10, 11 and 12

10.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>
The moisture risk assessment criteria is normally set at 80% for the upper RH limit. However, this criteria can be relaxed here from 80% to 95% for this build-up at this monitored interface, as there is no significant food for mould growth, little to no air is (theoretically) in the build-up and RH peaks happen during winter (please refer to explanation in typology N19 for further details).

Only the uninsulated scenario appears to achieve equilibrium in the 5-year timeframe. Both insulated cases do not fully reach equilibrium within the modelling period, meaning a longer modelling period will be used to re-run these models as part of the sensitivity analysis.

The uninsulated case (Part C) displays RH levels drying towards equilibrium, always staying below the 80% threshold. This is due to the fact that the critical junction is warmer than in the insulated cases (due to the lack of insulation) and that the concrete screed layer is protected by the DPM and only exposed to the internal conditions – which are considered 'good' – therefore allowing the concrete screed to dry out. According to the moisture risk assessment criteria, these cases are considered a 'pass'. However, the thermal performance of a build-up is to be considered alongside its hygrothermal performance. In this case, this build-up displays a poor thermal performance, despite being resistant to moisture.

In contrast, both insulated scenarios (Part L and TER) display RH levels at the critical junction mainly above 95% RH for the first two years of the modelling period – with the presence of interstitial condensation (i.e. RH levels reaching 100%) during the first year. The RH profiles reduce slowly from the third year on, though they remain between 80% and 95% for the majority of the year. Although moisture is not accumulating over time, both insulated cases take more than six months to display RH levels below the recommended levels. Therefore, these cases are considered as a 'fail' according to the moisture risk assessment criteria. These high RH results seem to be mainly due to the 'initial' conditions, in which the concrete screed has very high water content. Moisture present in the concrete screed layer moves into the insulation and get trapped above the DPM, due to vapour diffusion in winter. After a few years of modelling, the RH levels at the critical junction display a more sinusoidal profile, slowly reaching equilibrium.

Despite the relaxation of the RH threshold from 80% to 95%, these results contradict BS EN ISO 13788 (2012) calculations. All insulated scenarios are a 'fail' as they exceed safe moisture levels for extended periods during the first few years of modelling, with RH levels above 95%. These results are summarised in the table below.

Table 9: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Fail
TER	Case 3 Fail	Case 6 Fail	Case 9 Fail	Case 12 Fail

Effects of exposure zones and U-values

As the build-up is not directly exposed to the elements, there is a very limited impact of different climatic conditions, meaning the hygrothermal performance of the build-up in different exposure zones is very similar. Therefore, any sensitivity analysis will be performed for one exposure zone only (Zone 4 – Swansea).

RH levels worsen as the target U-value increases. This is due to the thicker insulation layer keeping the critical junction at slightly colder temperatures (as the critical junction is located on the cold side of the insulation). In addition, the total water vapour resistance of the build-up increases with additional insulation, leading to slower moisture transfer (seen through the reduced amplitude of the sinusoidal profiles).

10.3.5. Conclusions – Baseline

The results showing high levels of moisture at the cold side of the insulation layer appears to support the prescriptive guidance in BS 5250 (2011) – section F.4.2 – to include an AVCL on the warm side of the insulation layer to prevent moisture reaching the cold point in the build-up. Therefore, this typology is considered a ‘fail’ following the moisture risk assessment criteria, but such RH levels might not be a problem if it is proven that the insulation material keep on performing while being kept for an extended period of time (two to four years) at RH levels above 95%.

These findings are contradictory with the findings from BS EN ISO 13788 (2012) assessment. This assessment seems to provide a false comfort, declaring the build-up as ‘safe’ due to the very small amount of condensation created and evaporating throughout the year.

10.4. Sensitivity Analysis – Extended time – 10 years

As both insulated baseline cases do not fully reach equilibrium, the first sensitivity analysis is to rerun the Swansea cases (cases 1, 2 and 3) for an extended period of 10 years.

10.4.1. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the baseline cases based in Swansea with an extended modelling period.

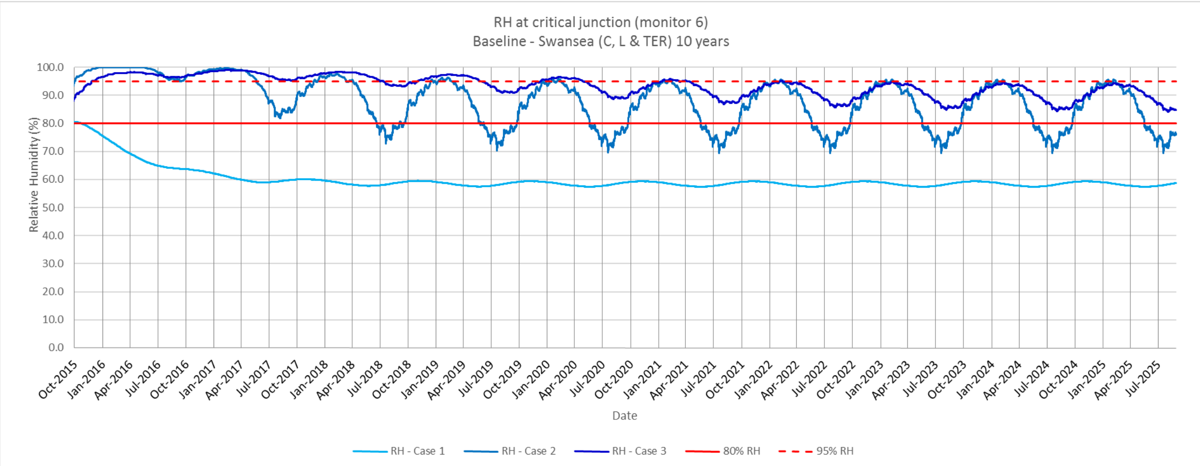


Figure 23: RH levels at critical junction for Cases 1, 2 and 3

10.4.2. Conclusions – Sensitivity Analysis Cases – 10 years

<u>Results</u>
The results confirm that equilibrium has been reached after 5 years and the conclusions for the baseline cases are valid / retained.

10.5. Sensitivity Analysis – Addition of AVCL / DPM [Cases X.d]

10.5.1. Baseline model versus BS 5250 (2011)

It is worth nothing that the baseline build-up differs from the build-up present in BS 5250 (2011), as no AVCL is included above the insulation layer in the baseline model (with the baseline model based on current typical construction practice).

<u>Presence / Absence of AVCL</u>

The current guidance from BS 5250 (2011) – paragraph F.4.2 – states the following: *'When insulation is applied above the slab, interstitial condensation is likely to occur on the upper surface of the slab. To avoid that risk, an AVCL should be laid between the thermal insulation and the floor finish and the space beneath the floor should be ventilated.'*

The location of the recommended AVCL is between the insulation and the concrete screed. In reality, it is likely for the characteristics of the AVCL to be similar to those of a DPM. Therefore, the second sensitivity analysis done here is to include a DPM in the build-up, located on the warm side of the insulation (in addition to the DPM already present in the build-up, below the insulation layer).

10.5.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones make no difference in the hygrothermal performance of the build-up, the cases in the worst exposure zones (i.e. Swansea - Zone 4) are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases):

Table 10: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

10.5.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with the DPM layer above the insulation) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

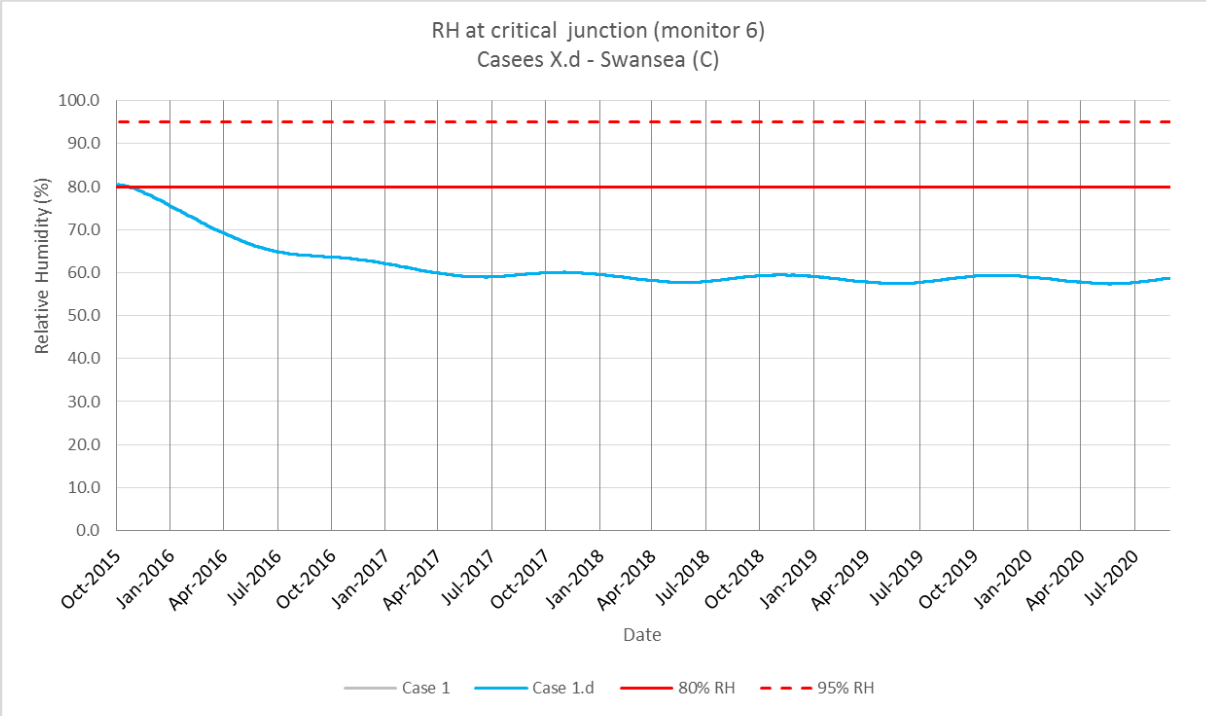


Figure 24: RH levels at critical junction for Cases 1 and 1.d

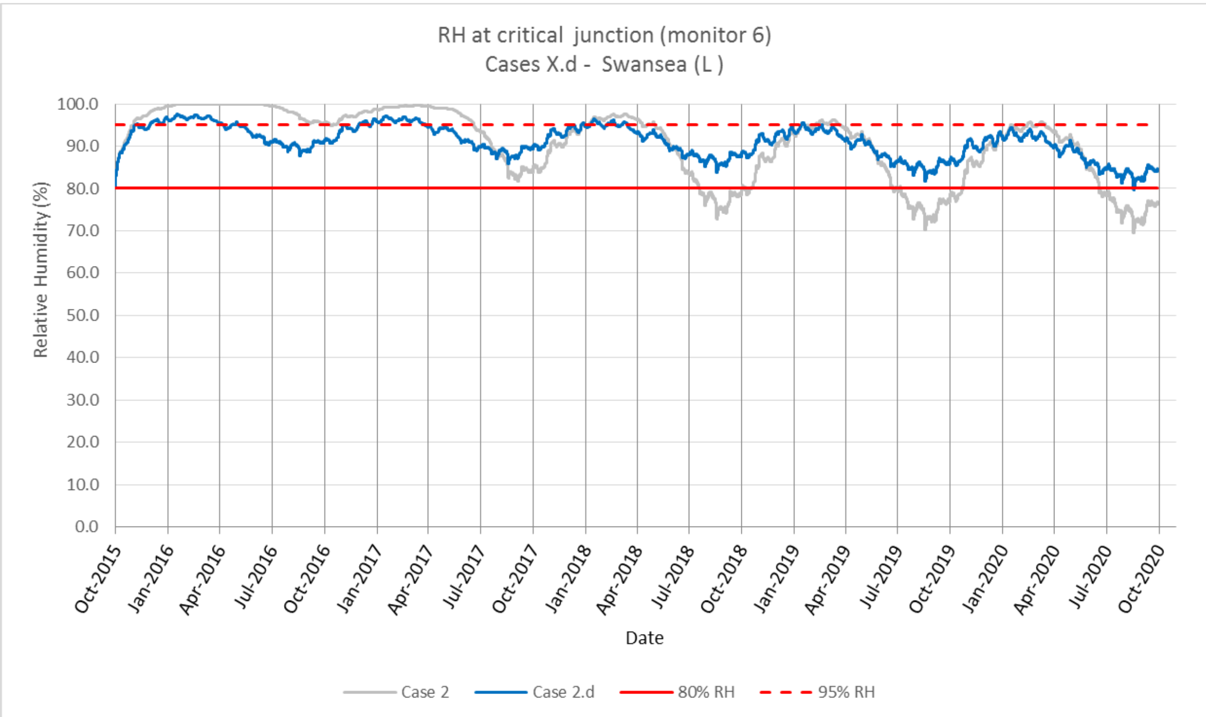


Figure 25: RH levels at critical junction for Cases 2 and 2.d

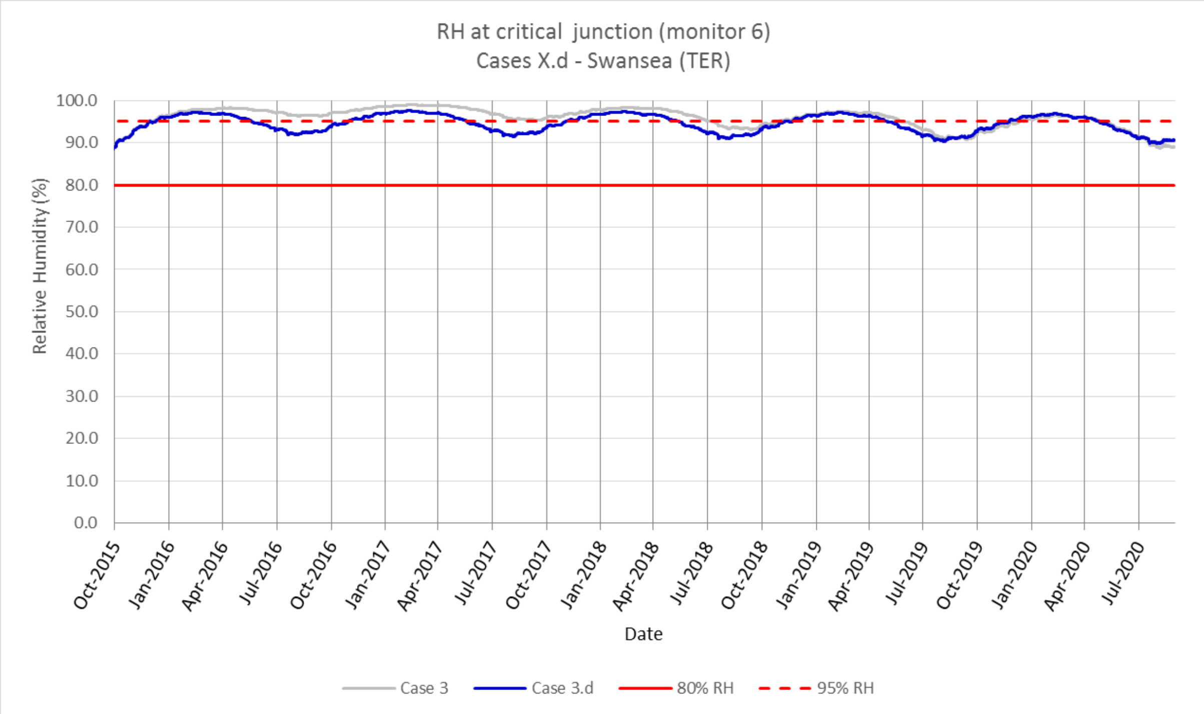


Figure 26: RH levels at critical junction for Cases 3 and 3.d

10.5.4. Conclusions – Sensitivity Analysis Cases X.d

Results

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 11: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Risky	-	-	-
TER	Case 3.d Fail	-	-	-

Moisture risk assessment criteria

Using the relaxed 95% RH criteria (as outlined in the baseline cases), the addition of the AVCL has no impact as there is no insulation in both the Part C cases, which is why the lines on the graph are not distinguishable.

With the Part L case, the AVCL makes the build-up more resistant to moisture and brings it closer to the ‘safe’ status. Despite the absence of interstitial condensation, there are still significant periods with RH levels above the 95% RH threshold, prior to the build-up reaching equilibrium. Therefore, the build-up is indicated as 'risky'.

With the TER case, reaching a lower / better U-value, the addition of the AVCL has little impact on the baseline model, particularly once the construction reaches equilibrium. The construction remains as risky as the baseline case, which is failing due to high RH levels for significant periods of time before the equilibrium is reached.

This suggests that the current BS 5250 (2011) recommendations may not be fully adequate for this construction, especially at low U-values, as it takes these cases several years to dry out to 'safe' conditions while the build-up might not perform to its full potential due to its insulation layer kept at high RH levels for long periods of time.

10.6. Conclusions

- BS EN ISO 13788 (2012) may not be adequate assessment method
- Robust typology (good resistance to moisture) if DPM is included as per BS 5250 (2011)
  • almost robust as, with 95% relaxed criteria, build-ups with insulation (Part L and Part C) considered 'safe' at equilibrium
  • not 100% 'robust', as all build-ups taking several years to achieve equilibrium and go below 'safe' RH levels

11. Typology N5: Exposed Suspended floor - insulated

The N5 typology is a new-build exposed suspended timber floor, with insulation installed in between (and in some cases below) timber joists.

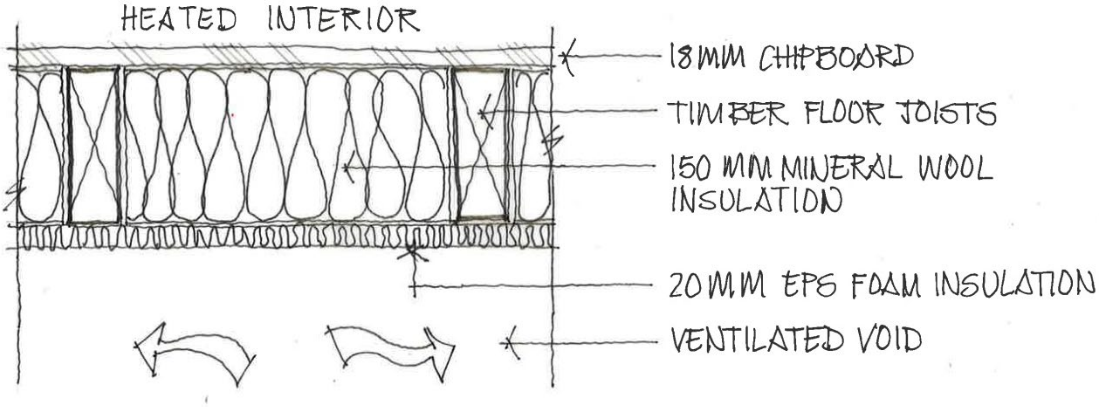


Figure 27: Illustration of the build-up of the typology (Part L case)

11.1. Assessment Method

The DECC/STBA Moisture Risk Assessment and Guidance (2014) states, *'floors of timber with a void beneath them should be ventilated to remove moisture'.* To follow prescriptive guidance in BS 5250 (2011) (section F.4.3), the void is ventilated to outside, meaning that the external surface of the build-up is not exposed directly to the elements (rain, wind and solar radiations). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method, as moisture movement is driven by vapour diffusion.

The results by the Glaser method show that this build-up is generally considered to be a 'safe' build-up.

Part C, with no continuous insulation layer installed below the joists, is similar to the N1 typology 'Suspended floor' and shows no risk of interstitial condensation.

For the Part L case, the calculation shows that interstitial condensation occurs during the winter season, but evaporates completely during the summer months. This risk disappears in the TER case, when the thickness of the insulation layer installed below the joists is increased. BS 5250 (2011) explains the occurrence of the interstitial condensation from the installation of a continuous rigid insulation layer under the joists, having a high vapour resistance than the mineral wool layer.

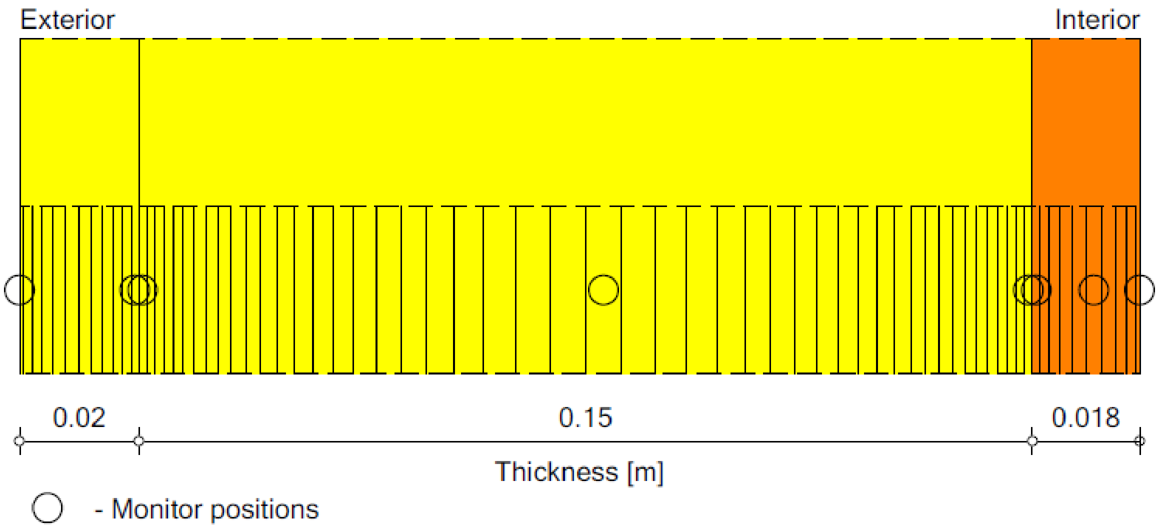
The results regarding the lack of interstitial condensation accumulating over the years will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

11.2. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 18mm Chipboard
- 51mm // 150mm // 150mm mineral wool insulation (λ = 0.040 W/m.K) installed in between timber joists
- 0mm // 20mm // 160mm EPS (λ = 0.040 W/m.K) below timber joists



Materials:

- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³) 0.02 m
- *Mineral Wool (heat cond.: 0,04 W/mK) 0.15 m
- *Chipboard (unlocked) 0.018 m

11.3. Baseline Results

11.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 12: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

11.3.2. Critical / Monitored Junction

As this build-up is a common construction in the current industry and considered ‘resistant’ to moisture, this build-up is not associated with a critical junction.

As interstitial condensation problems tend to appear at junctions, the interface between the mineral wool and the PU foam insulation was chosen, especially as timber joists bridge the mineral wool layer so the presence of ‘fragile’ material makes it even more important to monitor.

For this typology, the focus is therefore given on RH levels at the interface of the joists (although joists are not specifically modelled), and PU foam insulation (insulation layer installed below the joists), since this is the position within the structure where the presence of moisture could potentially get trapped and damage the structure.

In ‘perfect’ conditions (i.e. ‘normal’ internal moisture load, soffit in good condition, without additional water ingress due to leaks / poor drainage / etc.), the build-up is protected from the elements, and should not present any moisture risks (as currently shown with the BS EN ISO 13788 (2012) calculations).

11.3.3. Graphs at Monitored Junction

The graphs displayed below show the RH levels at the monitored junction, at the position where the lowest level of the floor joists. This location corresponds to the location at which the mineral wool and timber joists meet the insulation layer installed below the timber joists (PU foam in the model), for the Part L and TER cases. However, in the Part C case, no insulation is installed below the joists, as the mineral wool insulation present in between the joists is enough to provide the required U-value. Therefore, the ‘monitored’ junction for Part C cases (cases 1, 4, 7 and 10) corresponds to the ‘external’ monitor on the build-up and will display exactly the ‘external’ conditions applied to the model.

For these reasons, these Part C cases (cases 1, 4, 7 and 10) are shown in grey, as the monitored junction corresponds to the external conditions, which shows as 'noise' on the graphs.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

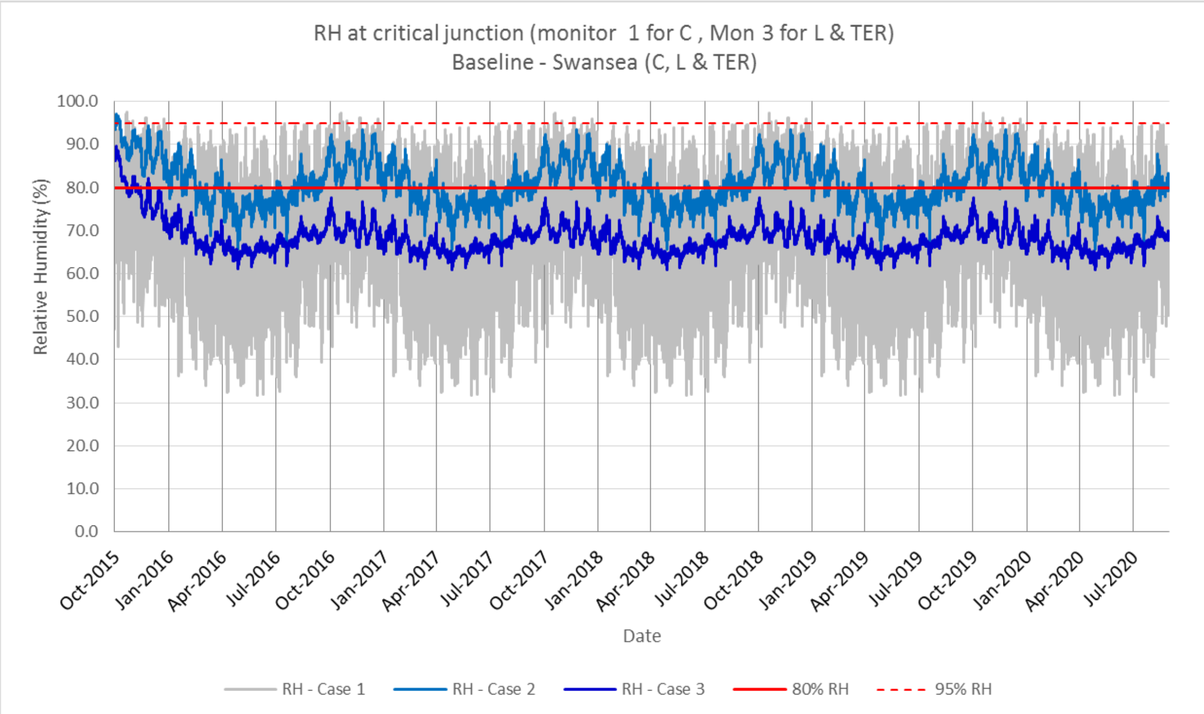


Figure 28: RH levels at monitored junction for Cases 1, 2 and 3

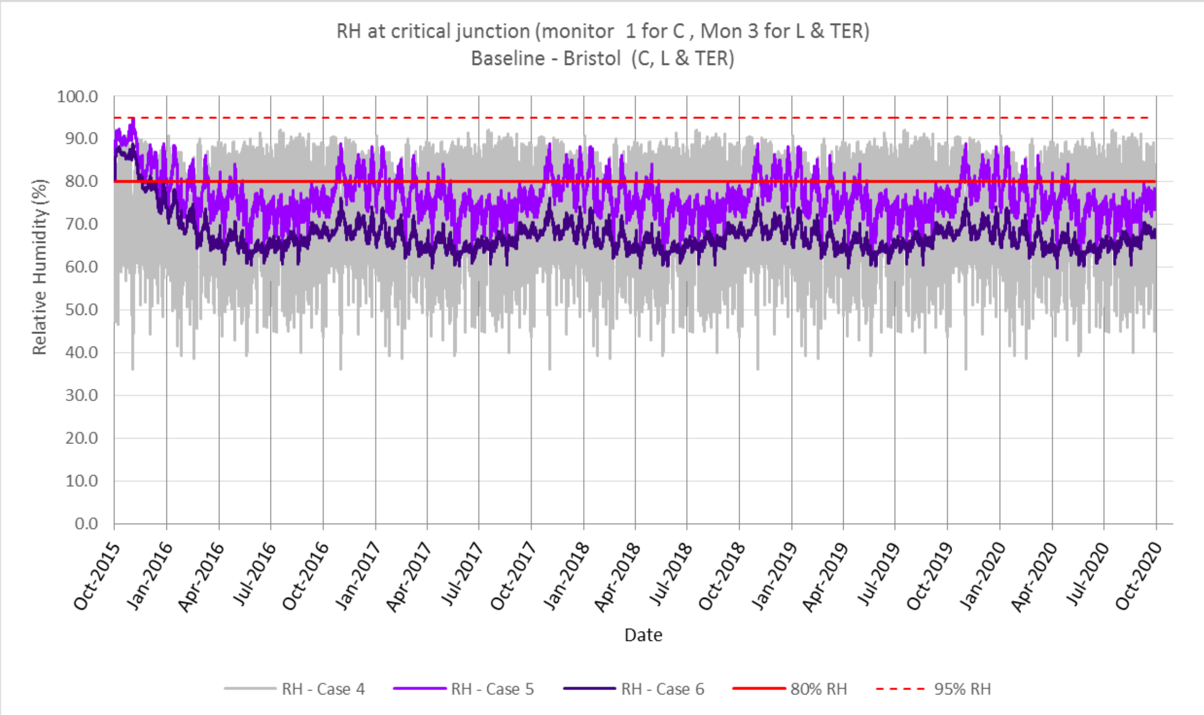


Figure 29: RH levels at monitored junction for Cases 4, 5 and 6

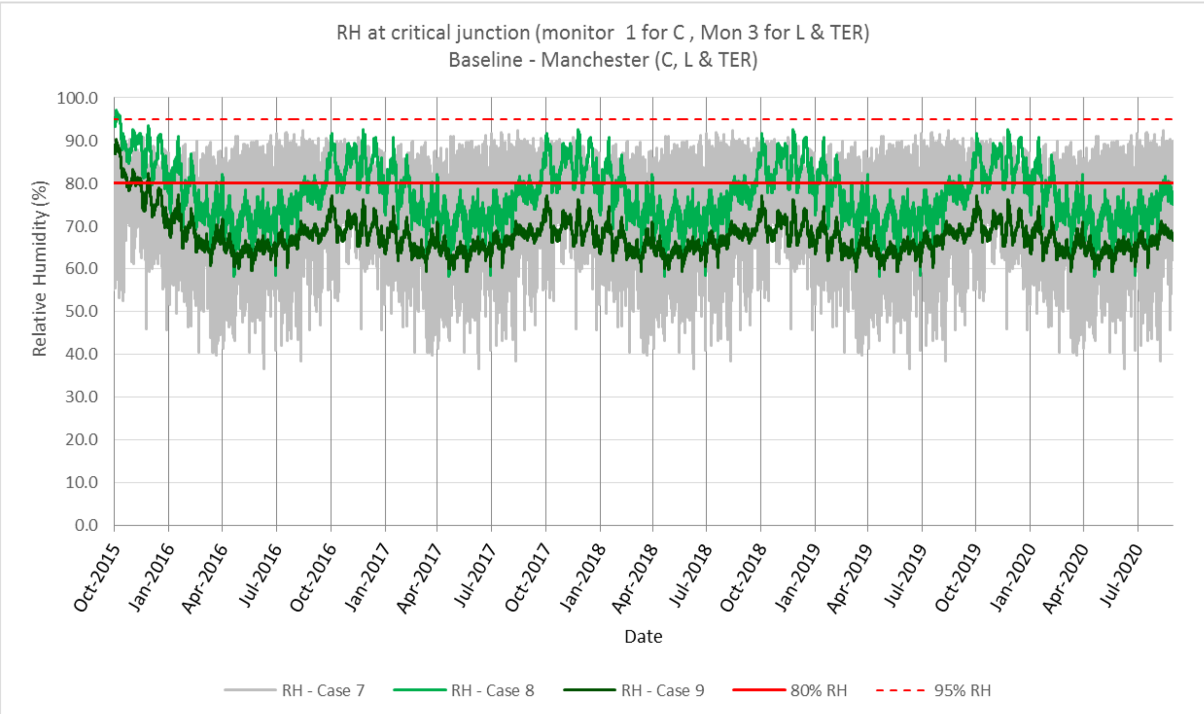


Figure 30: RH levels at monitored junction for Cases 7, 8 and 9

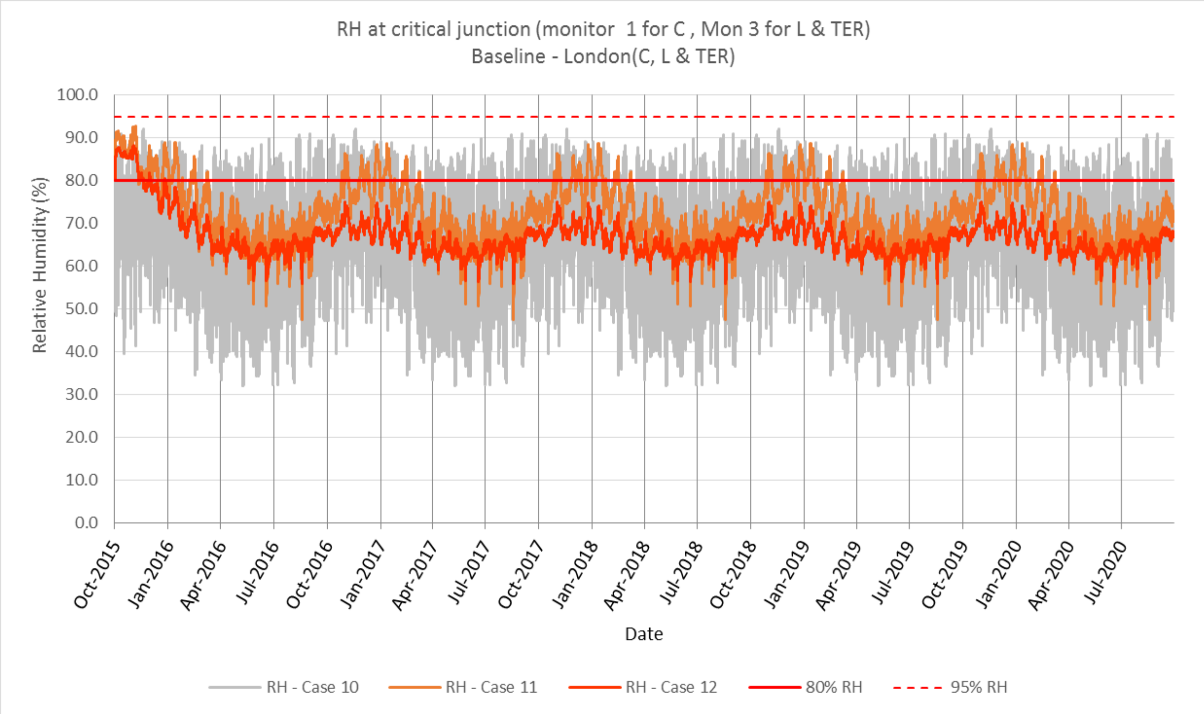


Figure 31: RH levels at monitored junction for Cases 10, 11 and 12

11.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

All scenarios achieve equilibrium (which means that moisture does not accumulate over time). However, all scenarios display different RH levels, with some being well within the recommended 80% RH limit and others above it.

The moisture risk assessment criteria is normally set at an 80% RH upper limit. This level is retained for this analysis, as ‘fragile’ materials are present, which could be damaged by high RH levels and the presence of mould. However, the risk of mould growth may be less important than it could be. The monitored junction is located between the mineral wool insulation and the PU foam insulation layers, so no air should be present in the ‘theoretical’ build-up.

The Part C cases (cases 1, 4, 7 and 10) have been excluded from the analysis, as the RH levels displayed represent exactly the external conditions applied to the build-up which means that the analysis is not necessary.

The graphs show that the Part L cases (cases 2, 5, 8 and 11) display RH levels oscillating above and below the 80% RH limit. As most cases (except in London) have RH levels above 80% occurring for periods of time appearing to be longer than a month, these cases are considered as ‘fail’ (except for London (case 11) where it is considered to be ‘risky’). It is worth noting that despite RH levels are higher than recommended, the risk of mould growth might be less important than it could be, for the additional reason that peaks in RH levels correspond with low temperatures (winter season), especially when the monitored junction is separated from the outside by only a 20mm layer of EPS insulation.

In contrast, all TER cases (cases 3, 6, 9 and 12) display RH levels well within the recommended levels, except after initial conditions where RH levels are above 80% but dry out within the first or second months of modelling. This means that these cases are considered as 'pass'. This is mainly due to the presence of a thick insulation layer present underneath the joists (and the monitored junction), keeping them warm and with lower RH levels.

Table 13: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 N/A	Case 4 N/A	Case 7 N/A	Case 10 N/A
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Risky
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

Effects of exposure zones and U-values

As the build-up is not directly exposed to the elements, there is a relatively limited impact of different climatic conditions, so the hygrothermal performance of the build-up is different exposure zones is similar. Therefore, any sensitivity analysis will be performed for one exposure zone only.

The effect of U-values is explained in the previous moisture risk assessment paragraph, showing that the RH levels for the Part C cases cannot be analysed, as they display the external conditions. The difference in U-value between Part L and TER cases is then visible. The more insulation is installed below the timber joists, the warmer the timber joists are kept and the lower the RH levels experienced at the monitored junction are. This finding goes alongside the same approach used to improve the overall thermal performance (U-value) by reducing / removing the thermal bridge created by the timber joists bridging the insulation.

Further Guidance from STBA/DECC's Moisture Risk Assessment and Guidance (2014)

The STBA/DECC's Moisture Risk Assessment and Guidance (2014) mentions the following recommendations regarding moisture-open build-ups: *'it is conventionally considered that condensation risk is avoided by adequate ventilation of the below-floor void, although minimal research exists on this subject.'*

This recommendation is fully followed in the baseline model (Part C).
The STBA/DECC's Moisture Risk Assessment Guidance (2014) mentions the following recommendations regarding moisture-closed build-ups: '*it will be important to consider the relative vapour resistance of the different layers in the floor above the void, using the BS EN ISO 13788 procedure, to reduce the risk of surface and interstitial condensation.'*

The baseline build-up does not show any risks of interstitial condensation. However, this is due to the fact that materials with relatively similar vapour resistance performances are used in the build-up, as no AVCL, foil-facing layers or other vapour retarders are being used in the build-up. If such materials were to be included in the build-up, the conditions at the monitored junction will be different and the hygrothermal performance of the build-up will change.

11.3.5. Conclusions – Baseline

- This is a common build-up
- Different hygrothermal performance depending on the build-up (presence or absence of continuous insulation underneath the joists)
  • If fully moisture-open build-up, then no risk of trapping moisture and if joists are exposed, then ventilation should avoid joists to be at risk of rotting
  • If presence of continuous rigid insulation installed underneath the joists, then the thicker the continuous insulation layer is, the better the conditions in which the timber joists are kept

11.4. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of foil layers on both sides of the continuous rigid insulation layer

11.4.1. Addition of foil layers on both side of the continuous rigid insulation layer

As rigid foam insulation used in this construction commonly has foil layers, additional sensitivity cases have been analysed to assess the impact of adding foil layers to both sides of the rigid insulation layer onto the hygrothermal performance of the build-up.

A foil layer is added on both sides of the continuous rigid insulation layer present in the baseline build-up. Please note that this sensitivity analysis does not apply to the Part C case, as no continuous rigid insulation is present below the joists in this case (as the insulation is only installed in between the timber joists).

11.4.2. Sensitivity Analysis Cases

As the impact of the different exposure zones has already been assessed in the baseline cases, this sensitivity analysis is done only in the most extreme exposure zone, Zone 4 - Swansea.

The two cases are set across the Zone 4 wind-driven rain exposure zone, meeting the two target U-values (as per baseline cases).

Table 14: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

11.4.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction (which is the same as to the baseline cases); at the interface of the joists / mineral wool insulation layer, and the continuous PU foam insulation layer installed below the joists for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with foil layers) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

The Part C case is not displayed below, as there is no distinction between the sensitivity analysis and the baseline cases, as no continuous rigid insulation is installed below the joists.

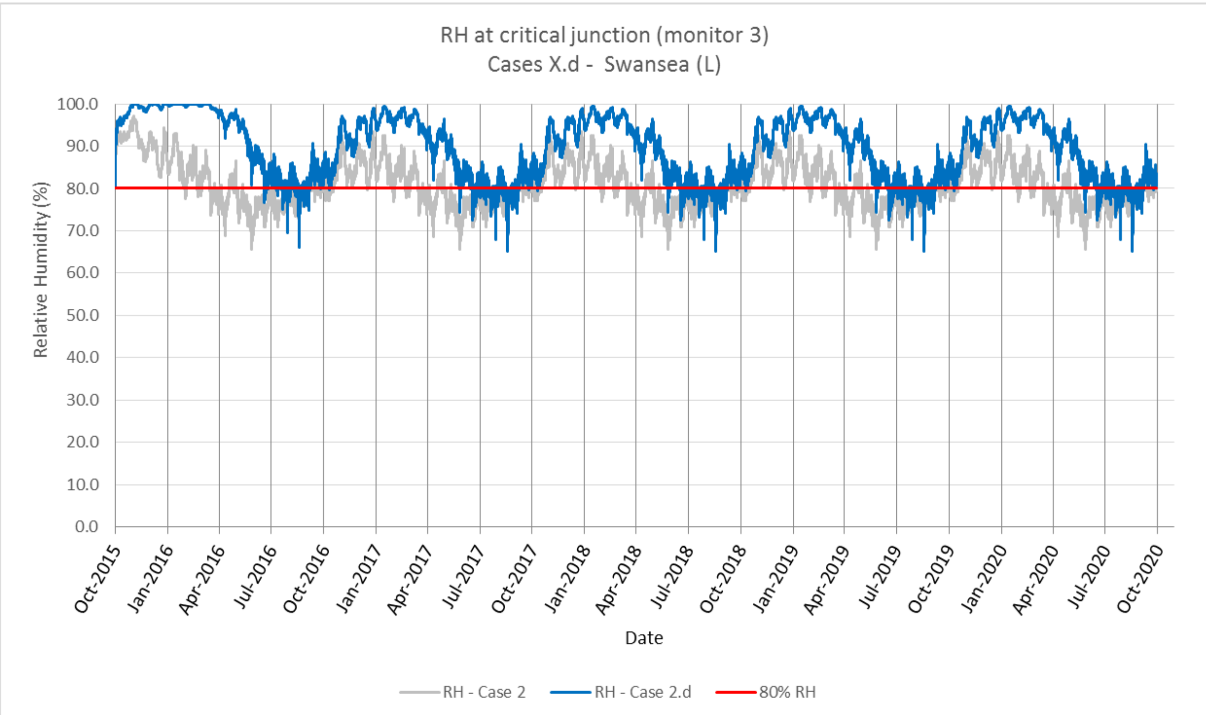


Figure 32: RH levels at monitored junction for Cases 2 and 2.d

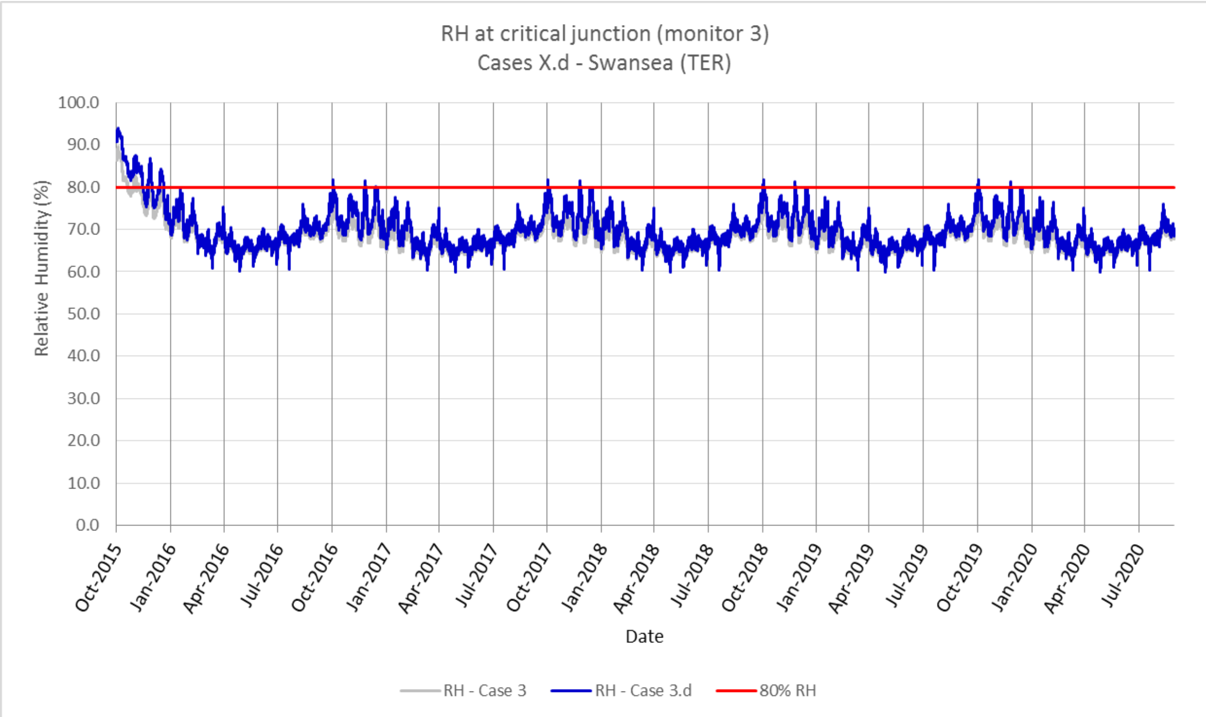


Figure 33: RH levels at monitored junction for Cases 3 and 3.d

11.4.4. Conclusions – Sensitivity Analysis Cases X.d

The results show that all the modelled sensitivity cases perform worse than their baseline cases. The presence of the foil layers on both sides of the continuous rigid insulation increases notably the total vapour resistance of the build-up. This added resistance is located directly on the outside of the bottom of the joists (monitored junction), meaning that moisture travelling from inside to outside will accumulate more at this junction, compared to the baseline conditions. This leads to increased RH levels at the monitored junction.

This added resistance, making the travelling of moisture more difficult through the entire build-up, can also be seen with the offset (delay) of a few months in the peaks in the RH profiles.

All sensitivity analysis cases are displaying worse performance than their baseline cases. As the status for baseline case 2 (Part L) was a ‘fail’, the sensitivity analysis case 2.d (Part L) status is also a ‘fail’. Indeed, the RH levels are kept above 80% for most of the year. The increase in RH levels between the baseline and the sensitivity analysis is also clearly visible on the graph (with an increase of RH peak levels by about 10%).

The difference between the sensitivity analysis case and the baseline is a lot less visible on the TER case. The status of the sensitivity analysis case remains a ‘pass’ despite the slight increase in RH levels. This is due to the fact that the more insulation is installed below the joists, the warmer the temperature at which the bottom of the joists is kept (leading to lower and safer RH levels).

<u>Results</u>

Table 15: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L	Case 2.d Fail	-	-	-
TER	Case 3.d Pass	-	-	-

The graphs show that the use of insulation which includes foil layers (being considered as vapour retarders) only has a small detrimental effect on the hygrothermal performance of the build-up. This type of insulation is commonly used in the building industry.

<u>Effects of U-values</u>
The graphs show that the small detrimental effect of the addition of the foil layers on both sides of the insulation is decreasing the thicker the external insulation layer is. This is linked to the fact that the more insulation is installed below the joists, the warmer the temperature at which the critical junction is kept.

It seems that the detrimental effect of the addition of the foil layers on both sides of the insulation can be disregarded as soon as the external insulation layer reaches a certain percentage of the total insulation thermal resistance.

In this case, only extreme cases are tested, with a very thin rigid insulation layer (20mm in Part L case) and a very thick rigid insulation layer (160mm in TER case). It might be worth modelling cases with intermediate rigid insulation thicknesses, to assess at which point the whole build-up can be declared a 'pass' (with or without the presence of foil layers on the sides of the insulation).

11.5. Sensitivity Analysis – Change in Ventilation of soffit [Cases X.e]

11.5.1. Baseline model versus BS 5250 (2011)

BS 5250 (2011) describes categories of floors (section F.2) as follow, including:
(b) 'suspended floors of structural concrete or timber with a void beneath them; such floors may separate a conditioned space from an unconditioned space, such as a loading bay, parking space, garage or void'

It is worth noting that neither BS 5250 (2011) nor the baseline model account for circumstances where the external surface cannot be ventilated. An example of this circumstance is where the floor type is above a garage, where fire risk management means that the soffit cannot be ventilated.

<u>Ventilated / Unventilated Soffit</u>

BS 5250 (2011) does not offer specific guidance for this scenario, although it is stated (section F.4.3): *'when thermal insulation is applied between the joists, it should not be supported on a material which offers a vapour resistance higher than that of the thermal insulation. If an external soffit of high vapour resistance is provided, an AVCL should be installed on the warm side of the insulation and a ventilated void not less than 50 mm deep should be provided between the thermal insulation and the soffit'.*

Therefore, the first sensitivity analysis done here is to model an unventilated air gap, with the addition of a soffit material (now part of the WUFI build-up).

11.5.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones make relatively little difference in the hygrothermal performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases):

Table 16: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.e	-	-	-
Part L	Case 2.e	-	-	-
TER	Case 3.e	-	-	-

11.6. Conclusions

- BS EN ISO 13788 is generally an adequate assessment method as this build up is not exposed to wind driven rain
- Robust typology (good resistance to moisture – from experience) except in certain circumstances where either the external surface is unventilated and / or an additional layer of insulation with a higher vapour resistivity than that between the joists is used. e.g. where soffits are attached directly to the underside of the build-up (e.g. above a garage)
- Foil layers present on both sides of the rigid insulation layer have a detrimental effect. But only visible / detrimental to the hygrothermal performance of the build-up when only thin thicknesses of insulation are installed below the joists. More research is needed in this area to assess the tilting point at which the presence of foil does not make a significant difference / does not change the status of the build-up (staying as ‘pass’)

Typology N6: Exposed concrete floor - insulated above

The N6 typology is a new-build exposed concrete slab, with insulation installed above the slab.

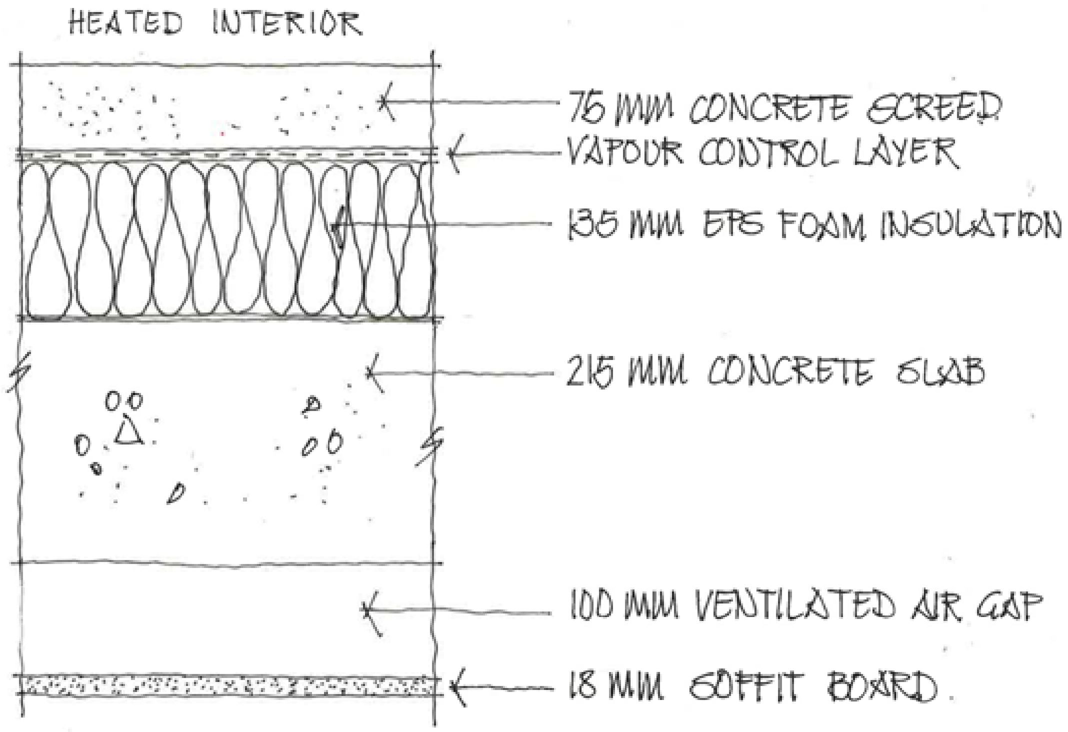


Figure 34: Illustration of the build-up of the typology (Part L case)

11.7. Assessment Method

The STBA's/DECC's Moisture Risk Assessment and Guidance (2014), *'floors of structural concrete with a void beneath them should be ventilated to remove moisture'.* This is also mentioned in the prescriptive guidance in section F.4.2 of BS 5250 (2011).

As the concrete slab layer is therefore partially exposed (underside concrete is submitted to external temperatures and RH levels due to the ventilated gap between the concrete slab and the cladding, but without wind-driven rain or solar gains), the movement of moisture in this build-up is driven by vapour diffusion. This mechanism is dealt with in the BS EN ISO 13788 (2012) calculation method, and therefore this method should be able to provide an accurate assessment.

The results by the Glaser method show that this build-up is generally considered to be a 'safe' build-up. The calculation shows that interstitial condensation occurs during the winter season, but evaporates completely during the summer months.

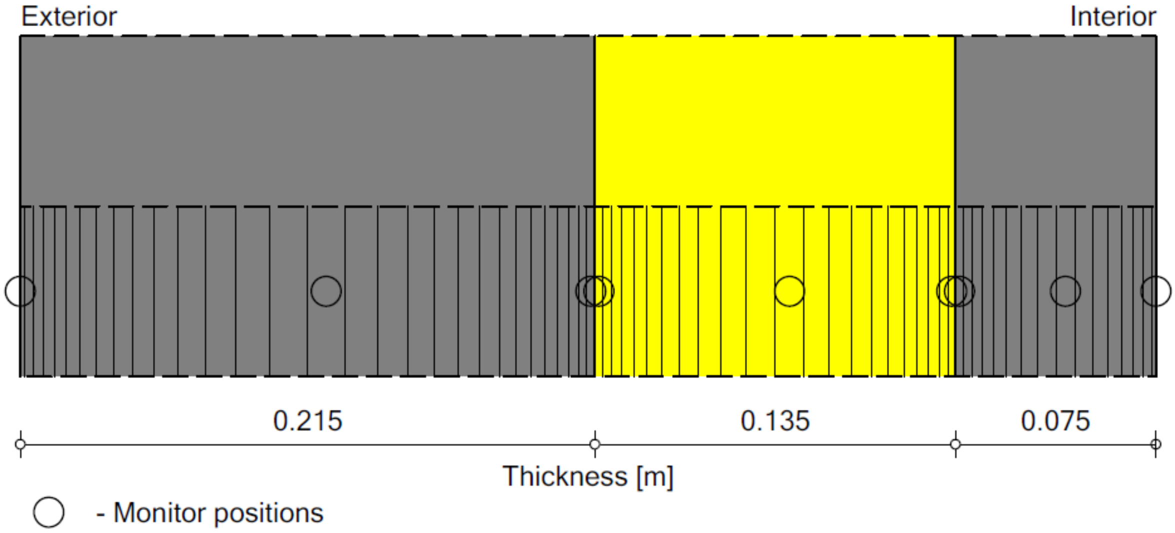
The results regarding the lack of interstitial condensation accumulating over the years will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

11.8. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 75mm concrete screed
- 31mm // 135mm // 282mm EPS foam insulation (λ = 0.040 W/m.K)
- 215mm concrete slab
- 100mm ventilated air gap with stainless steel ceiling hangers *(considered outside of the WUFI build-up)*
- 18mm PVC cladding *(considered outside of the WUFI build-up)*



Materials:

	- Concrete, C35/45	0.215 m
	- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	0.135 m
	- Concrete Screed, mid layer	0.075 m

11.9. Baseline Results

11.9.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 17: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

11.9.2. Critical Junction

For this typology, the focus is given on RH levels at the interface of the cold concrete screed and insulation. Indeed, paragraph F.4.2 in BS 5250 (2011) states that *'when insulation is applied above the slab, there is no risk of surface condensation but interstitial condensation is likely to occur on the upper surface of the slab. To avoid that risk, an AVCL should be laid between the thermal insulation and the floor finish'*. This critical junction is correctly identified in the BS EN ISO 13788 (2012) calculation.

11.9.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

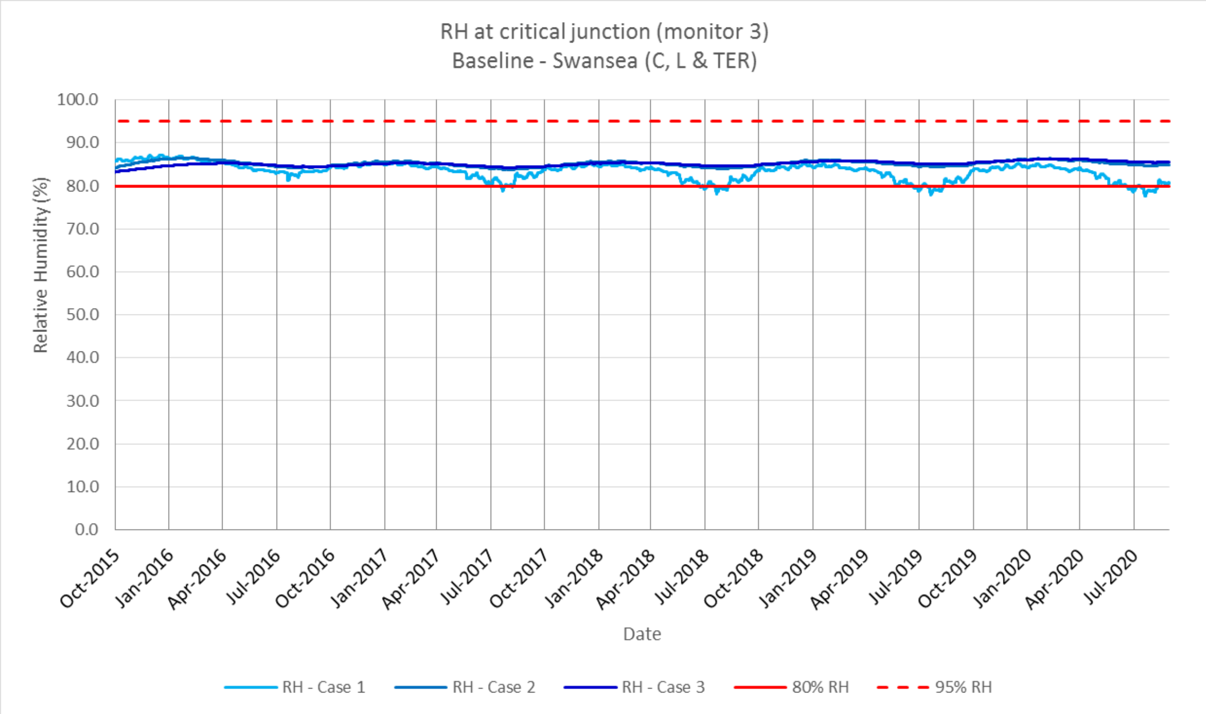


Figure 35: RH levels at critical junction for Cases 1, 2 and 3

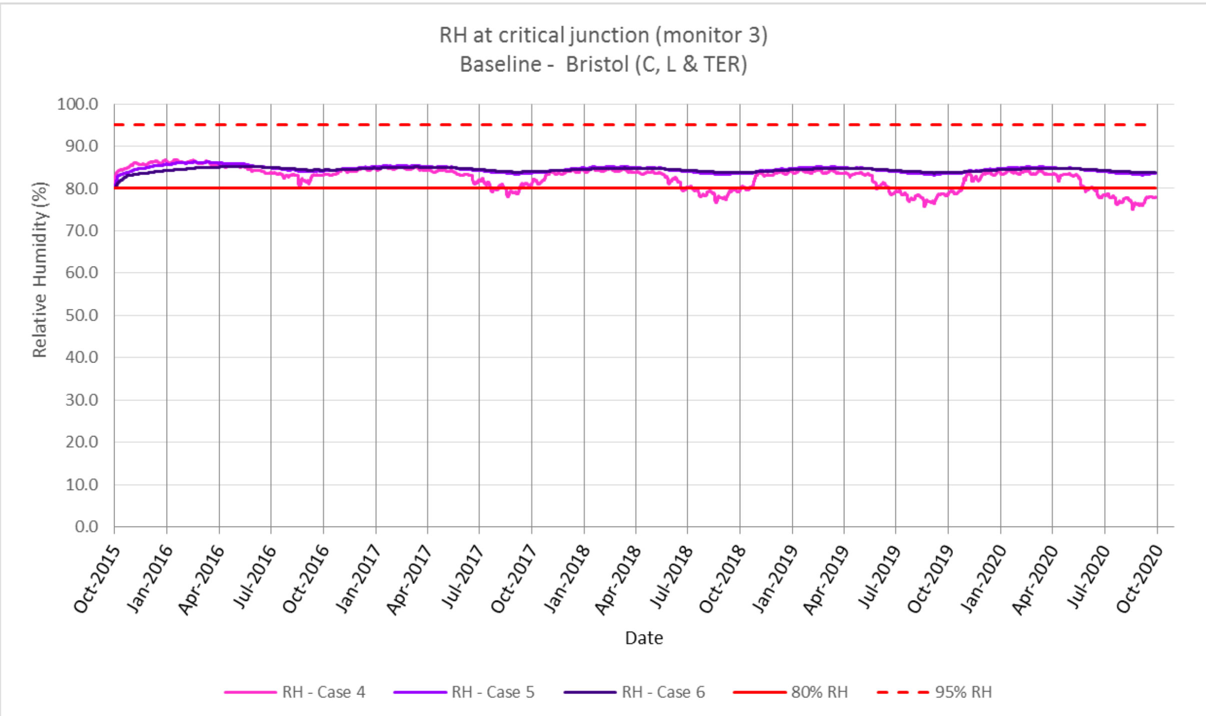


Figure 36: RH levels at critical junction for Cases 4, 5, and 6

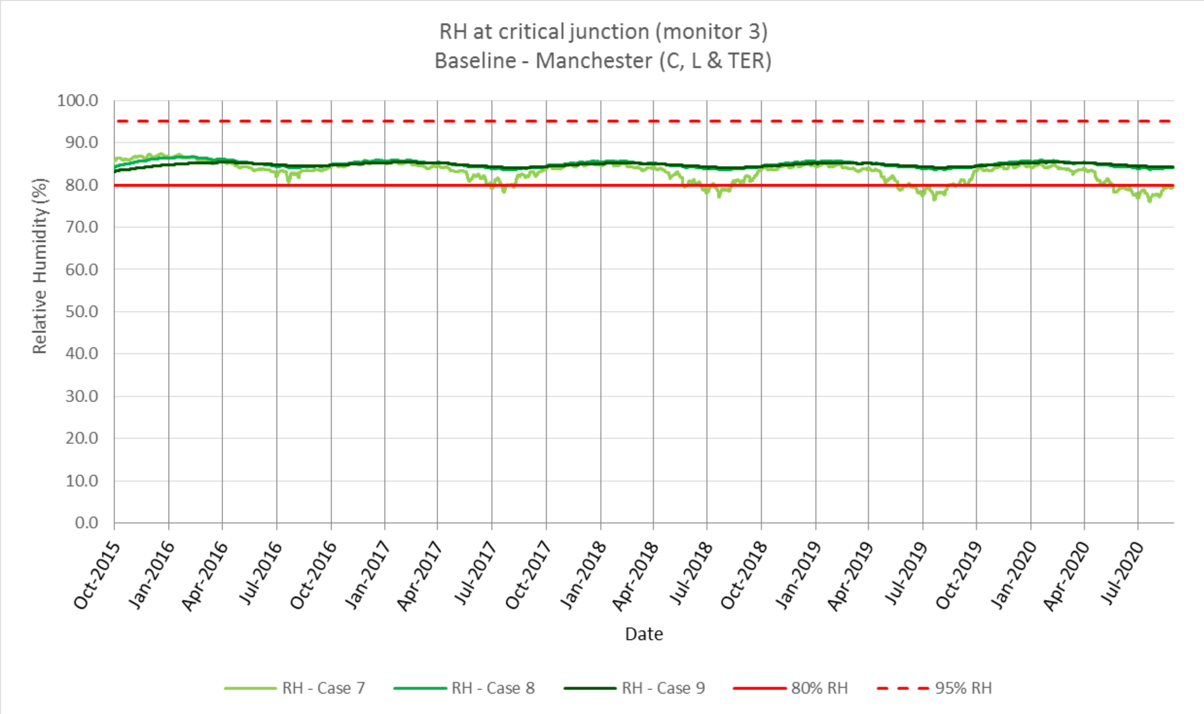


Figure 37: RH levels at critical junction for Cases 7, 8 and 9

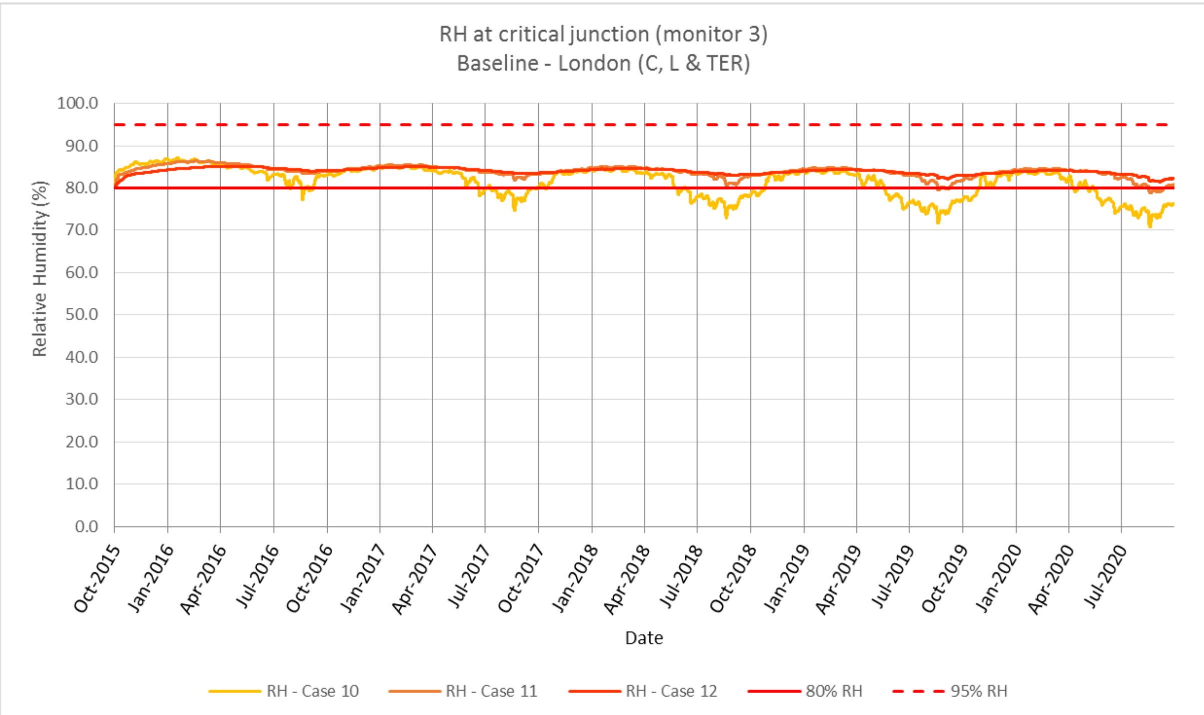


Figure 38: RH levels at critical junction for Cases 10, 11 and 12

11.9.4. Results Analysis

<u>Moisture risk assessment criteria</u>

All scenarios achieve equilibrium (moisture does not keep on accumulating over time). All scenarios display RH levels at the critical junction between 80% and 85%.

The moisture risk assessment criteria is normally set at an 80% RH upper limit. However, this criteria can be relaxed here from 80% to 95% for this build-up at this interface, as there is no significant food for mould growth, little to no air is in the build-up (in theory) and RH peaks happen during winter (please refer to explanation in typology N19 for further details).

As such all scenarios are considered as "pass" as there is no risk of interstitial condensation and RH levels are kept within acceptable levels. These results are summarised in the table below.

Table 18: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in line with current practice in the industry, where this build-up is commonly used and considered safe / resistant to moisture.

Effects of exposure zones and U-values

As the build-up is not directly exposed to the elements, there is a very limited impact of different climatic conditions so the hygrothermal performance of the build-up in different exposure zones is very similar. Therefore, any sensitivity analysis will be performed for one exposure zone only.

RH levels are fairly similar to across the three target U-values. However, RH levels in the thinner insulation case (Part C) are slightly lower than the other cases. This is due to air being able to handle more moisture at higher temperature, with a thinner insulation layer keeping the critical junction at slightly warmer temperatures (as the critical junction being located on the cold side of the insulation).

11.9.5. Conclusions - Baseline

In accordance with current best practice in the industry, this typology is found to be resistant to moisture, as the RH levels at the critical junction are within the ‘safe’ and recommended RH levels and there is no risk of interstitial condensation, independently to the wind-driven rain exposure zone the build-up is located in and the amount of insulation installed above the slab.

The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation accumulates over time in this build-up at the critical junction.

11.10. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of an AVCL

11.10.1. Baseline model versus BS 5250 (2011)

The baseline build-up differs from the build-up present in BS 5250 (2011), as no AVCL is included above the insulation layer in the baseline model (with the baseline model based on current typical construction practice).

Presence / Absence of AVCL

The current guidance from paragraph F.4.2 of BS 5250 (2011) states the following: *'When insulation is applied above the slab, interstitial condensation is likely to occur on the upper surface of the slab. To avoid that risk, an AVCL should be laid between the thermal insulation and the floor finish and the space beneath the floor should be ventilated.'*

Therefore, the first sensitivity analysis done here is to include an AVCL (sd = 2m) in the build-up, located on the warm side of the insulation – installed between the insulation layer and the concrete screed.

11.10.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones make no difference in the hygrothermal performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 - Swansea) are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 19: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

11.10.3. *Graphs at Critical Junction*

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

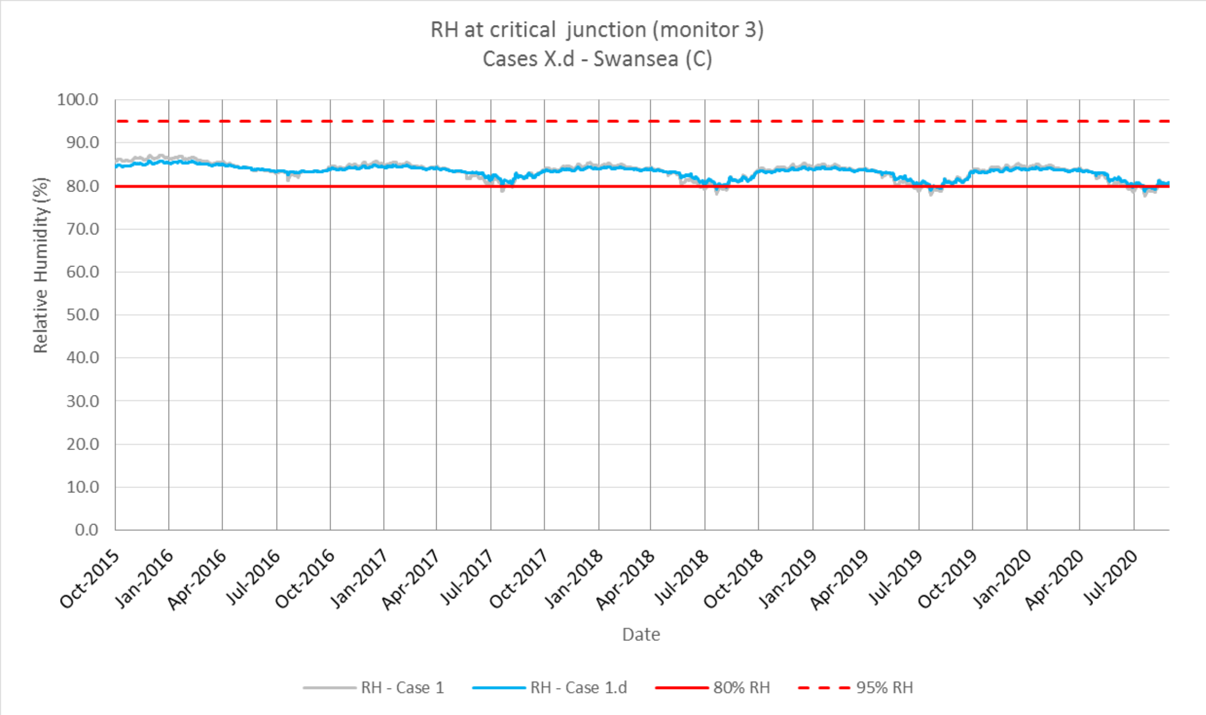


Figure 39: RH levels at critical junction for Cases 1 and 1.d

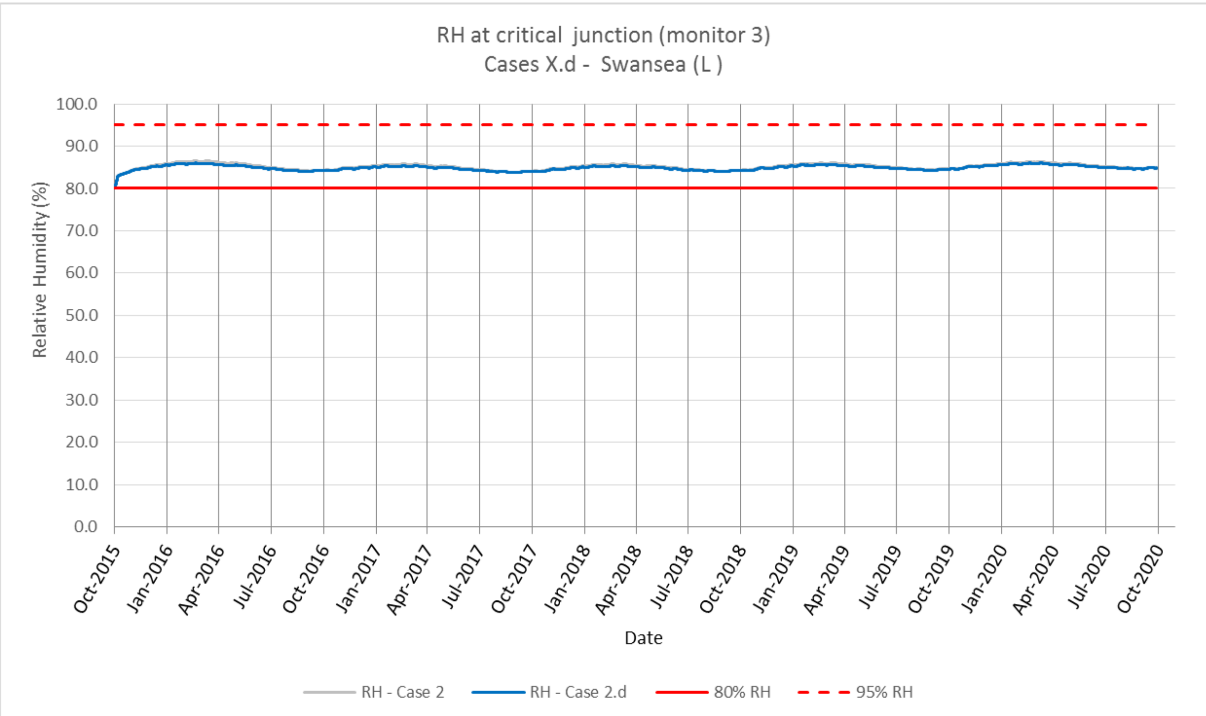


Figure 40: RH levels at critical junction for Cases 2 and 2.d

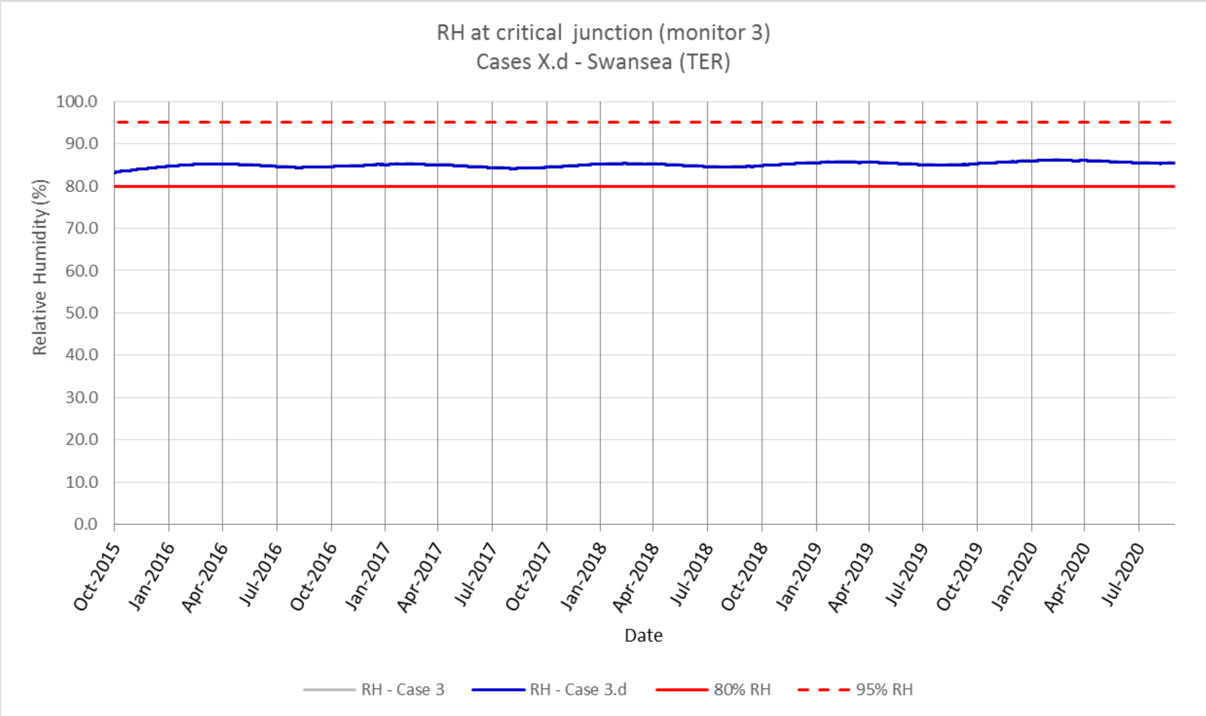


Figure 41: RH levels at critical junction for Cases 3 and 3.d

11.10.4. Additional case – added foil layers on insulation

As the rigid foam insulation used in this construction commonly has foil layers, additional runs were done to assess the impact of adding foil layers to both sides of the rigid insulation. It is much more common for PU foam insulation to have foil layers on both sides of the insulation layer compared to EPS insulation. In order to change only one input data variable at the time, the foil layers were added on both sides of the baseline insulation layer, i.e. EPS. However, as EPS and PU foam insulation have fairly similar characteristics in terms of vapour resistance, it is expected that the results will be similar and will depict the impact of a foil-facing rigid insulation accurately.

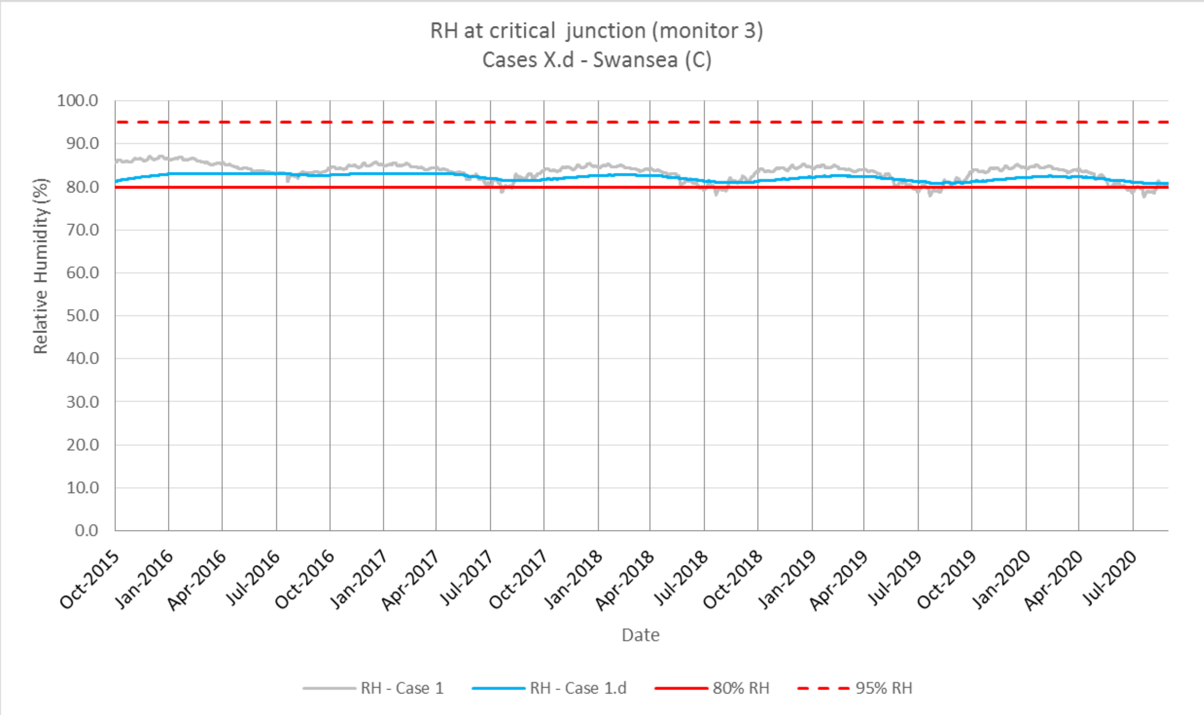


Figure 42: RH levels at critical junction for Cases 1 and 1.d

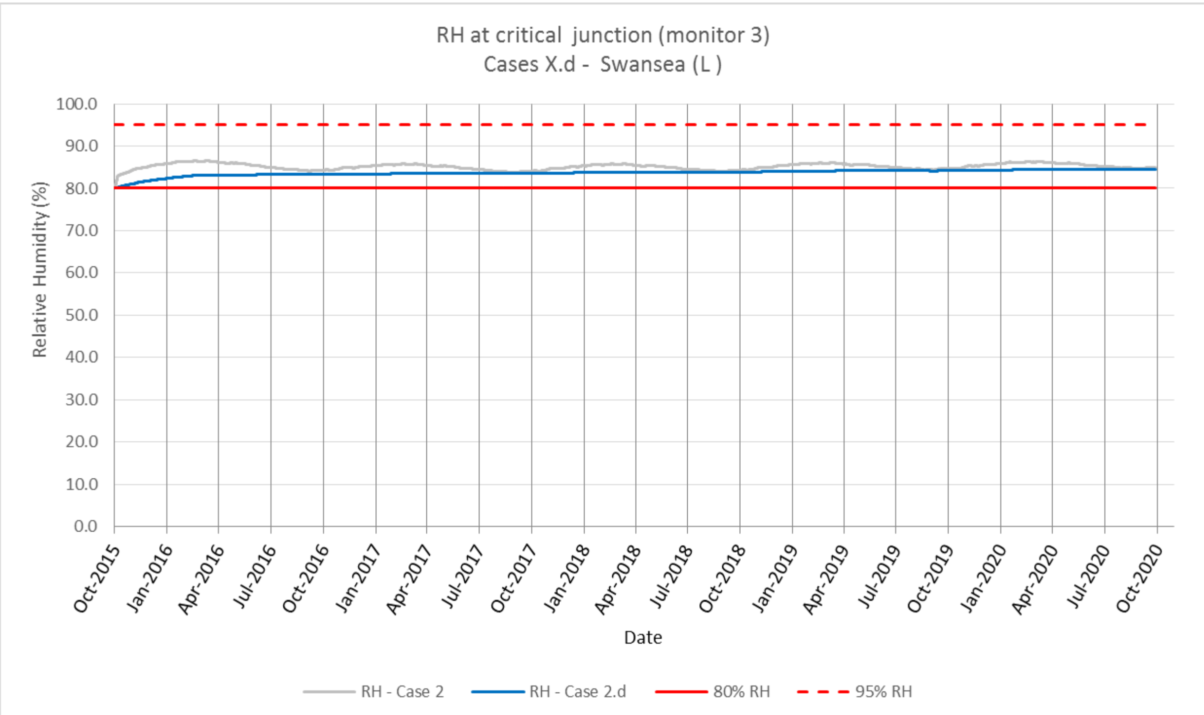


Figure 43: RH levels at critical junction for Cases 2 and 2.d

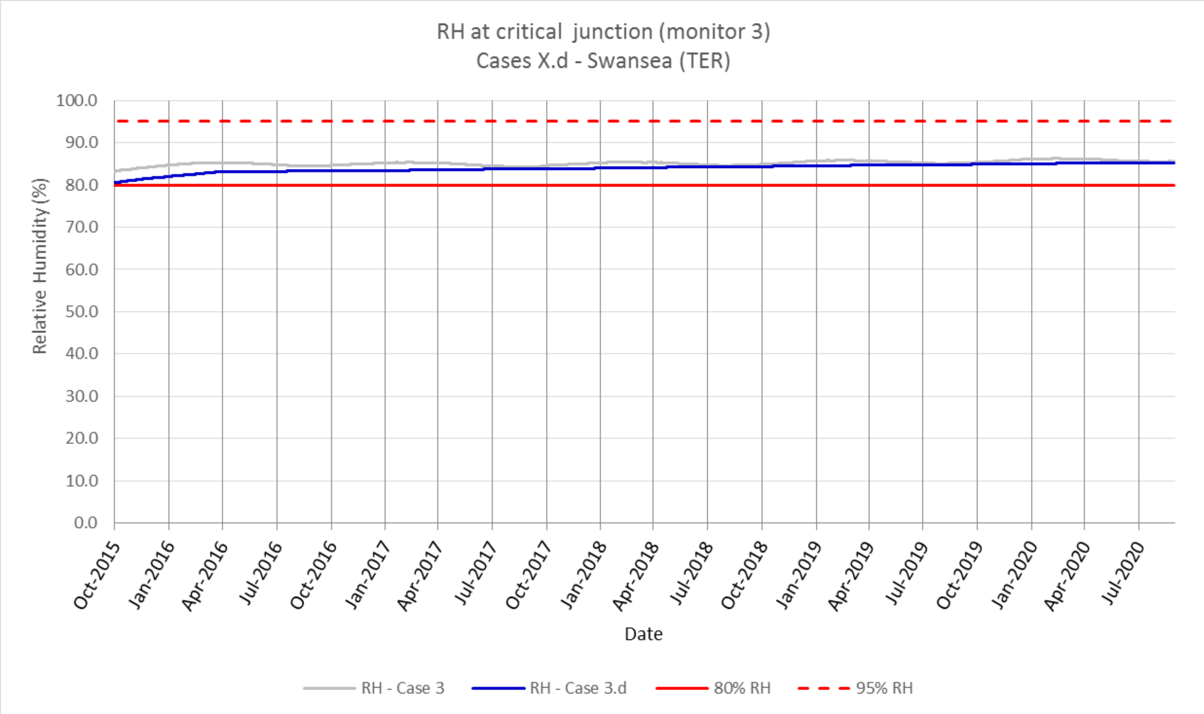


Figure 44: RH levels at critical junction for Cases 3 and 3.d

The results, as shown in the graphs above, indicate that having the foil layers on both sides of the insulation has a very small impact on the RH profiles at the critical junction. As the foil layers are more vapour resistant and provide more protection to the insulation layer, the RH profiles have a similar RH average value, but the amplitude of the sinusoidal is reduced (the profiles are flatter) due to this added vapour resistance.

11.10.5. Conclusions – Sensitivity Analysis Cases X.d

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 20: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

<u>Moisture risk assessment criteria</u>

All the modelled sensitivity cases pass the moisture risk assessment criteria that are listed in section 2.3. The statuses of these cases are identical to the baseline results, as all the sensitivity analysis cases show minor impacts compared to the baseline cases (due to the addition of an AVCL on the warm side of the insulation layer, or due to the rigid insulation being modelled with foil layers on both sides). This is due to both the concrete screed and concrete slab layers already have a significant vapour resistance and vapour storage capacity, which control the moisture content at the critical junction. The addition of these AVCL or foil layers does not represent a significant change.

11.11. Conclusions

- BS EN ISO 13788 is an adequate assessment method
- This is a robust typology, it has good resistance to moisture, and it is not directly exposed
- BS 5250 recommendation may not be as efficient as thought

12. Typology N7: Exposed concrete floor - insulated below

The N7 typology is a new-build suspended concrete slab, with insulation installed below the slab.

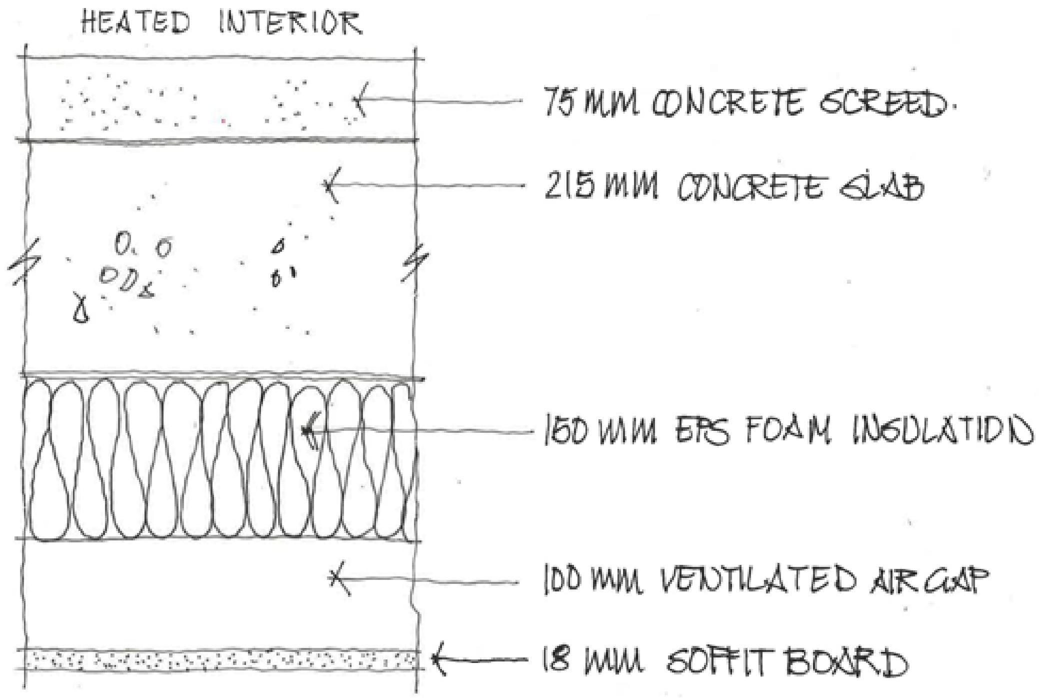


Figure 45: Illustration of the build-up of the typology (Part L case)

12.1. Assessment Method

The STBA/DECC's Moisture Risk Assessment and Guidance (2014) states, *'floors of structural concrete with a void beneath them should be ventilated to remove moisture'.* This is also mentioned in the prescriptive guidance in section F.4.2 of BS 5250 (2011).

As the build-up is therefore partially exposed (the insulation layer is submitted to external temperatures and RH levels due to the ventilated gap between the insulation and the cladding, but without wind-driven rain or solar gains), the movement of moisture in this build-up is driven by vapour diffusion. This mechanism is dealt with in the BS EN ISO 13788 (2012) calculation method, and therefore this method can be used to provide an accurate assessment.

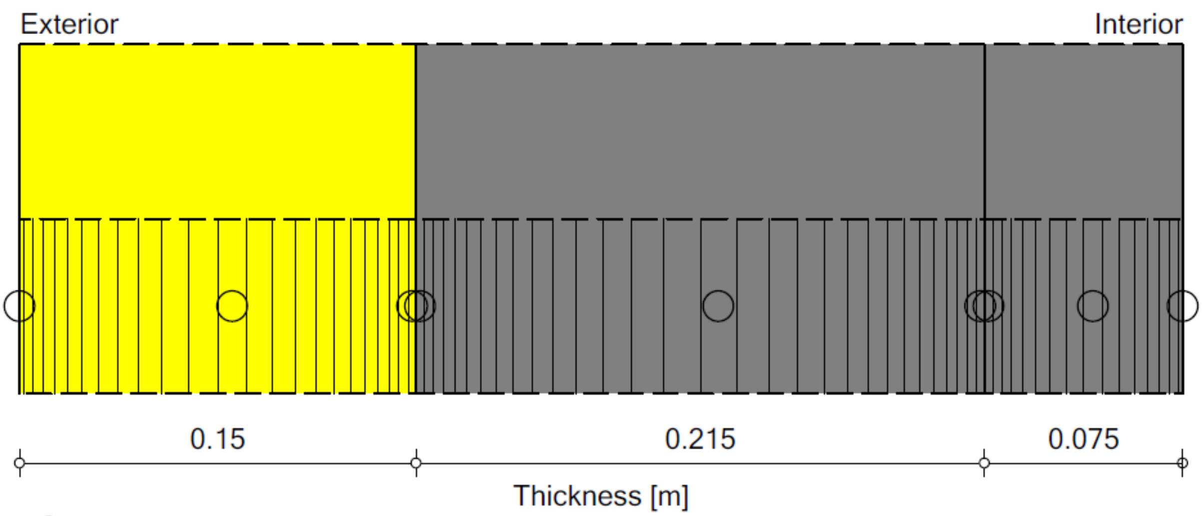
The results by the Glaser method show that this build-up is considered a 'safe' build-up, with no risk of interstitial condensation. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

12.2. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 75mm concrete screed
- 215mm concrete slab
- 40mm // 150mm // 326mm EPS foam insulation (λ = 0.040 W/m.K)
- 100mm ventilated air gap with stainless steel ceiling hangers *(considered outside of the WUFI build-up)*
- 18mm PVC cladding *(considered outside of the WUFI build-up)*



○ - Monitor positions

Materials:

(yellow)	- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	0.15 m
(grey)	- Concrete, C35/45	0.215 m
(grey)	- Concrete Screed, mid layer	0.075 m

12.3. Baseline Results

12.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 21: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

12.3.2. Monitored Junction

In this typology, the interface between the insulation and the concrete layer is located on the warm side of the insulation, so this junction should not be at risk as its temperature is constantly kept above the dew point. However, this is the only interface worth monitoring in this typology, to verify that no moisture is accumulating at this junction.

12.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction, at the interface between the insulation layer (warm side) and the concrete slab.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

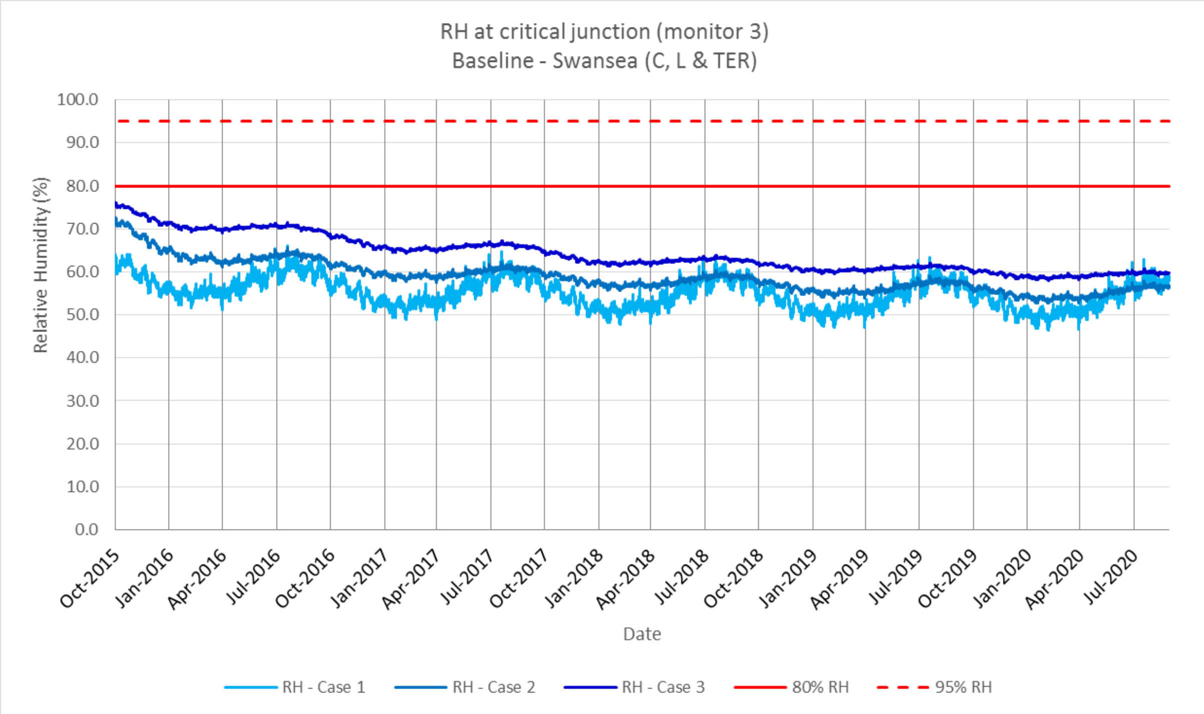


Figure 46: RH levels at monitored junction for Cases 1, 2 and 3

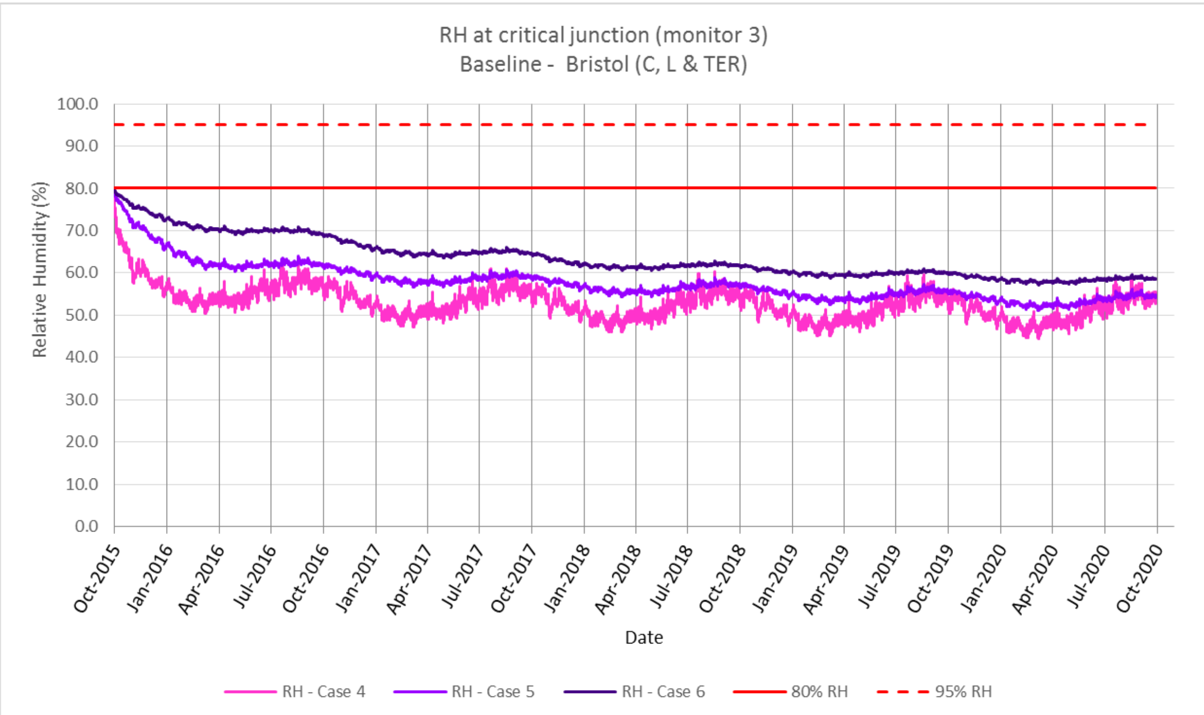


Figure 47: RH levels at monitored junction for Cases 4, 5 and 6

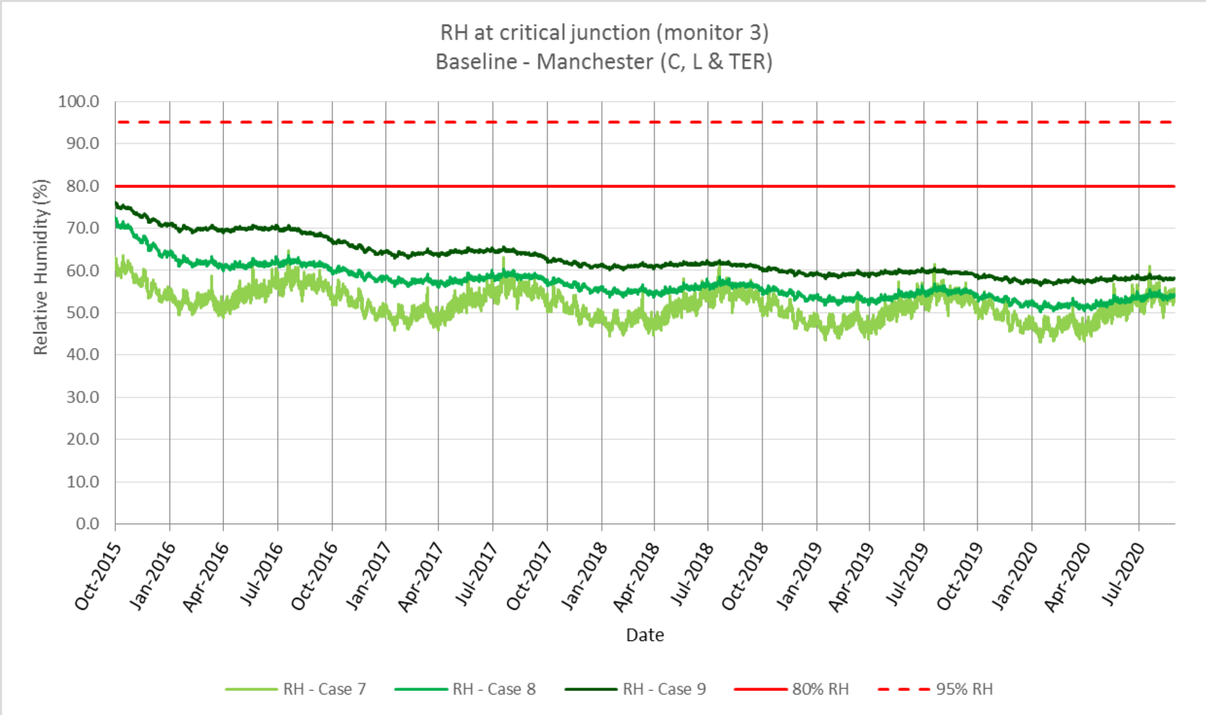


Figure 48: RH levels at monitored junction for Cases 7, 8 and 9

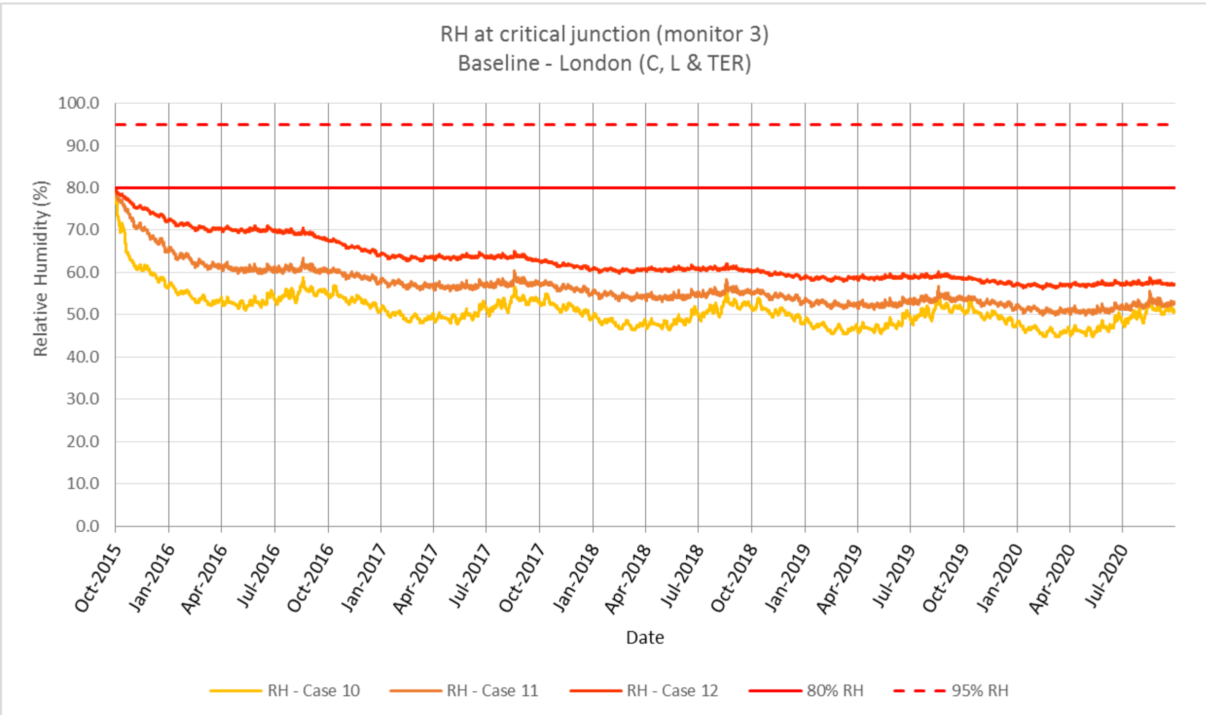


Figure 49: RH levels at monitored junction for Cases 10, 11 and 12

12.3.4. Results Analysis

Moisture risk assessment criteria
All scenarios achieve equilibrium, with all cases drying out towards equilibrium and moisture not accumulating over time. All scenarios also display RH levels below the 80% threshold at the monitored junction (as predicted, due to the location of the monitored junction on the warm side of the insulation).

As such, all scenarios are considered as "pass" as there is risk no risk of mould or interstitial condensation at the monitored junction. These results are summarised in the table below.

Table 22: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in line with current practice in the industry.

Effects of exposure zones and U-values

As the build-up is not directly exposed to the elements, there is a very limited impact of different climatic conditions so the hygrothermal performance of the build-up in different exposure zones is very similar. Therefore, any sensitivity analysis will be performed for one exposure zone only.

Differences in RH levels between U-values are noticeable on the baseline graphs. RH levels are shown consistently lower with higher / poorer U-values. These results seem counterintuitive: it is expected for higher / poorer U-values to have higher RH as the monitored junction is not kept as warm as with lower / better U-values.

However, the monitored junction is the interface between the insulation and the warm concrete slab. With the concrete slab having a high capacity to store moisture, the concrete slab starting with relatively ‘wet’ initial conditions and the thicker insulation layer providing a higher vapour resistance to the build-up, the TER case (lower / better U-value) takes a much longer period to reach equilibrium. It is suspected for RH levels at equilibrium to be very similar between the three cases (based on the three target U-values), except some small difference in the amplitude of the sinusoidal RH profiles during the winter season.

12.3.1. Conclusions - Baseline

In accordance with current best practice in the industry, this typology is found to be resistant to moisture, as the RH levels at the monitored junction are within the 'safe' and recommended RH levels and there is no risk of interstitial condensation, independently to the wind-driven rain exposure zone the build-up is located in and the amount of insulation installed above the slab.

The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up.

12.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change from rigid to compressible insulation

12.4.1. Baseline model versus BS 5250 (2011)

The baseline build-up differs from the build-up present in BS 5250 (2011). The insulation shown on the drawing of the build-up is annotated as *'compressible thermal insulation, which normally has a low vapour resistivity',* which is typically associated with air-based insulating materials such as mineral wool. As the insulation used in the baseline build-up is EPS foam, classified as rigid insulation, in the first sensitivity analysis for this build-up the insulation material will be changed to mineral wool.

Presence / Absence of AVCL

The current guidance from paragraph F.4.2 of BS 5250 (2011) states the following: *'If an external soffit of high vapour resistance is provided, an AVCL should be installed on the warm side of the insulation and a ventilated void of not less than 50mm deep should be provided between the thermal insulation and the soffit.'*

However, this is commonly ignored in common building practice as it is impractical to build. Each sensitivity analysis was also done with only one variable changed from the baseline, to be able to assess the impact of each change. As such, the AVCL has not been modelled here.

12.4.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones only have a little effect on the performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 - Swansea) are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 23: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

12.4.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the warm side of the insulation layer, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with mineral wool) are displayed as a coloured line, while their respective baseline cases (with EPS foam) are displayed with a grey line.

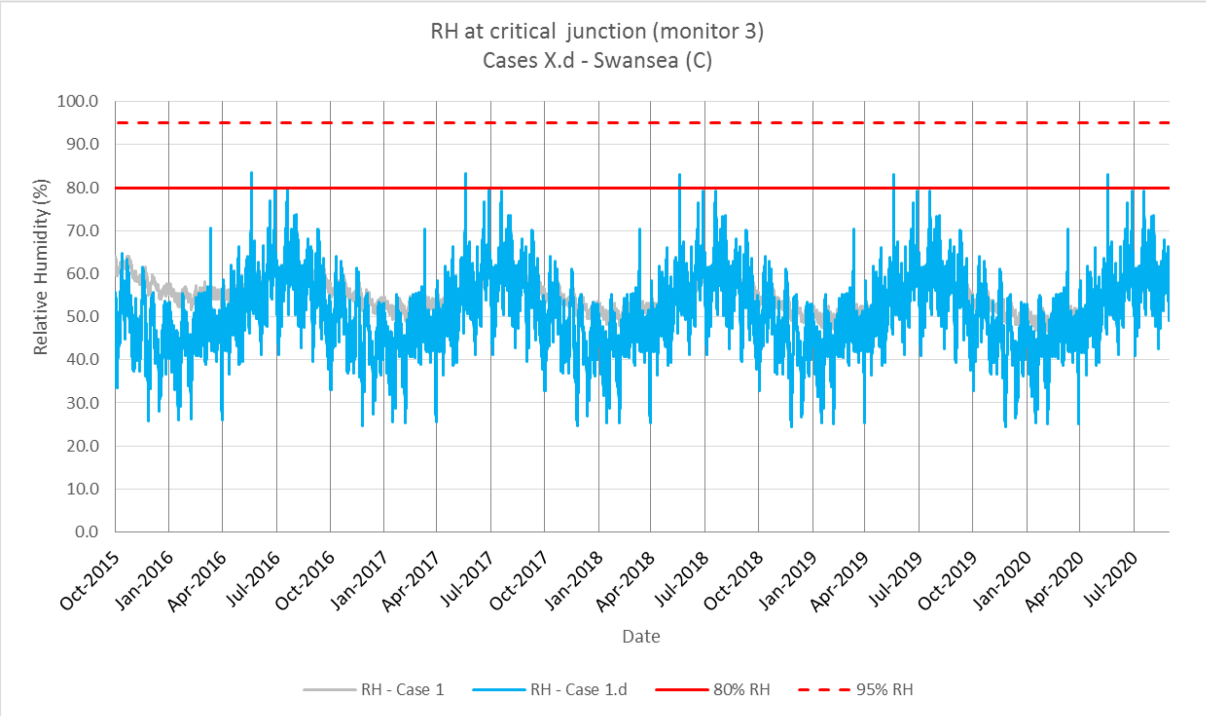


Figure 50: RH levels at critical junction for Cases 1 and 1.d

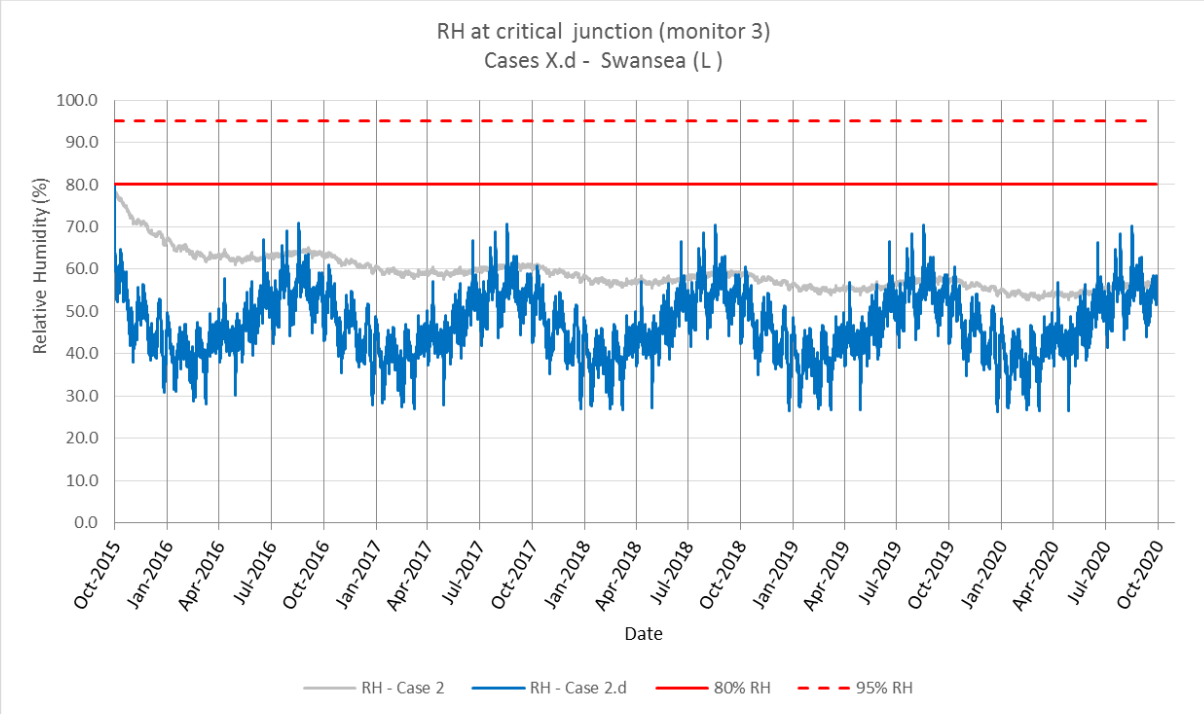


Figure 51: RH levels at critical junction for Cases 2 and 2.d

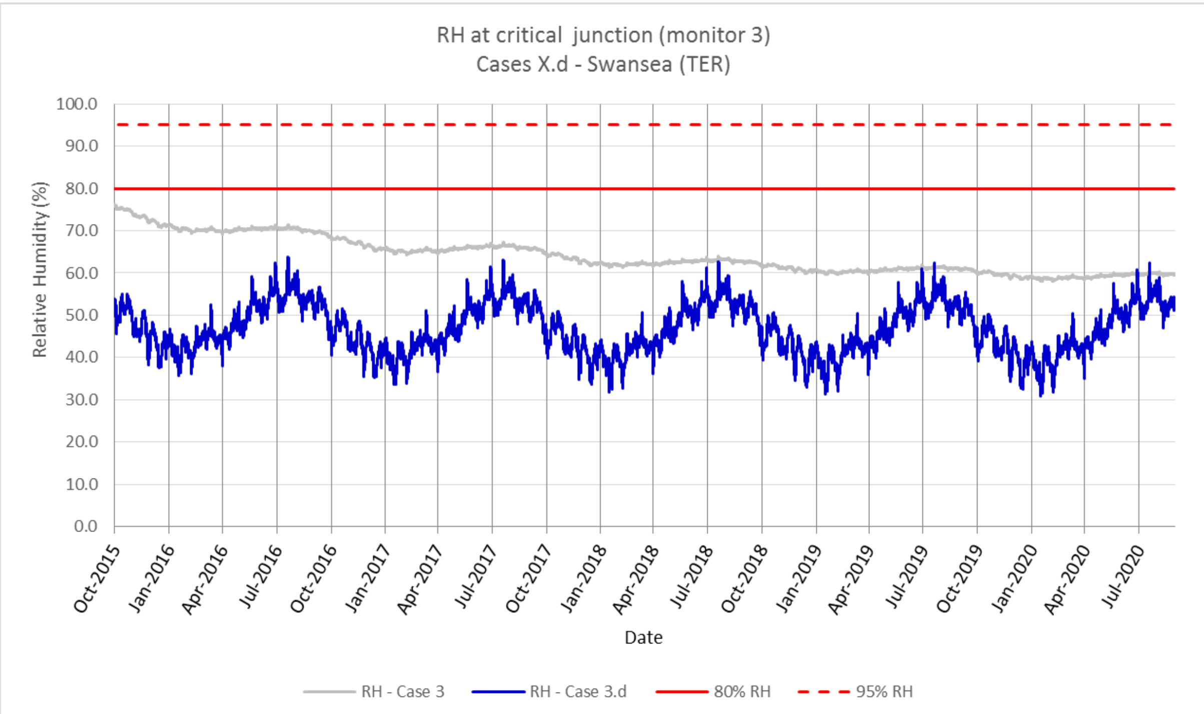


Figure 52: RH levels at critical junction for Cases 3 and 3.d

12.4.4. Conclusions – Sensitivity Analysis Cases X.d

<u>Results</u>

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 24: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

Moisture risk assessment criteria

The graphs show that all cases modelled with mineral wool pass easily and perform better than their baseline cases (modelled with rigid insulation). The increased variability / amplitude in RH levels that are shown in these graphs (compared to the respective baseline cases), is due to the vapour resistance of the build-up being lower with mineral wool insulation, as opposed to the EPS insulation (which was in the baseline cases).

These results show that all cases still have a 'pass' status since the baseline the baseline build-ups are already classified as "pass" in every case where the sensitivity analysis case is made more moisture-open (no vapour retarder / barrier is added).

AVCL requirement

The requirement for an AVCL with impermeable cladding, as per recommendation in BS 5250 (2011), would seem to be redundant, due to the low moisture levels indicated. This would be the case as long as the cladding is well ventilated.

12.5. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of foil layers on both side of the rigid insulation layer

12.5.1. Addition of foil layers

As rigid foam insulation often has in practice foil layers on both sides, the second sensitivity analysis for this build-up is to add these layers to the insulation layer present in the baseline cases.

12.5.2. *Sensitivity Analysis Cases*

As the baseline cases showed that the exposure zones only have a little effect on the performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 - Swansea) are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 25: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

12.5.3. *Graphs at Critical Junction*

All graphs displayed below show the RH levels at the critical junction (which is the same as to the baseline cases), on the warm side of the insulation layer, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with foil layers on both sides of the rigid insulation) are displayed as a coloured line, while their respective baseline cases (without foil) are displayed with a grey line.

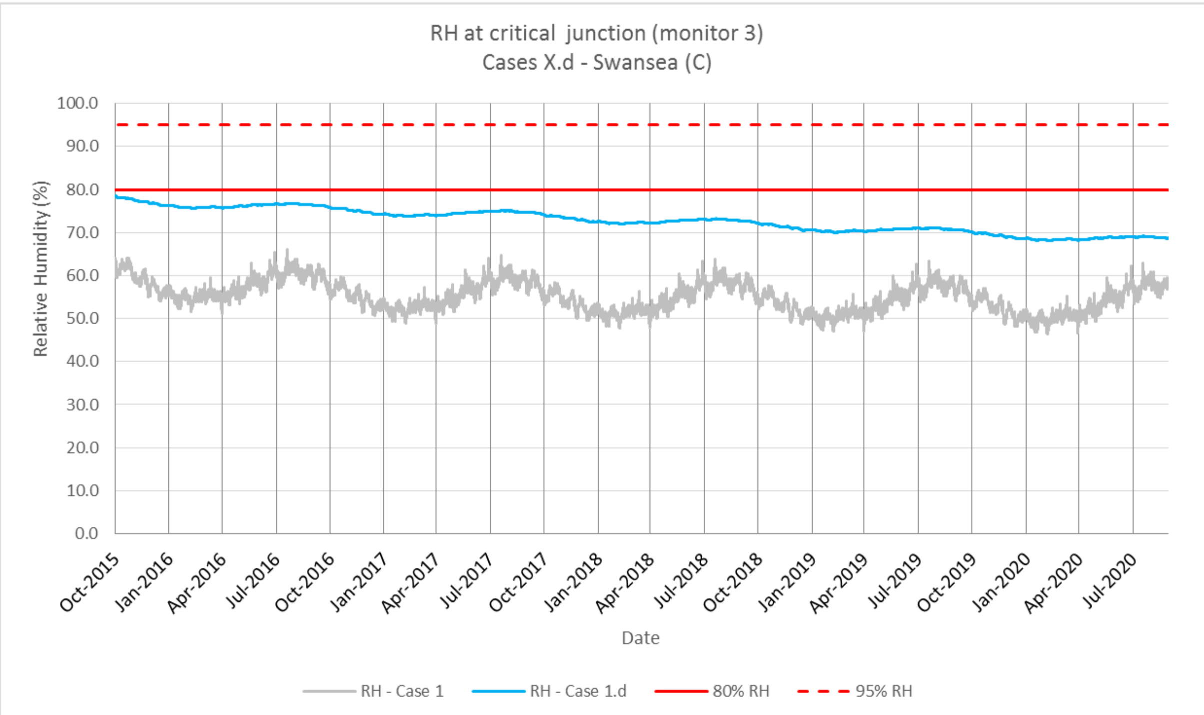


Figure 53: RH levels at critical junction for Cases 1 and 1.d

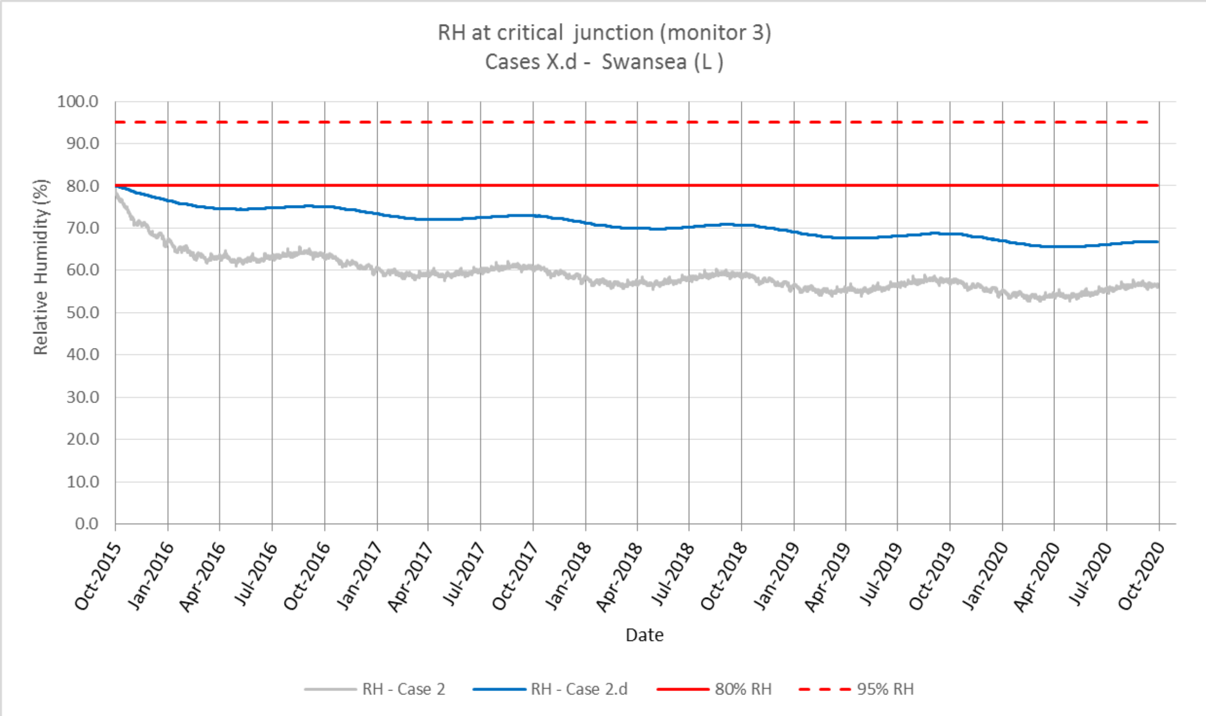


Figure 54: RH levels at critical junction for Cases 2 and 2.d

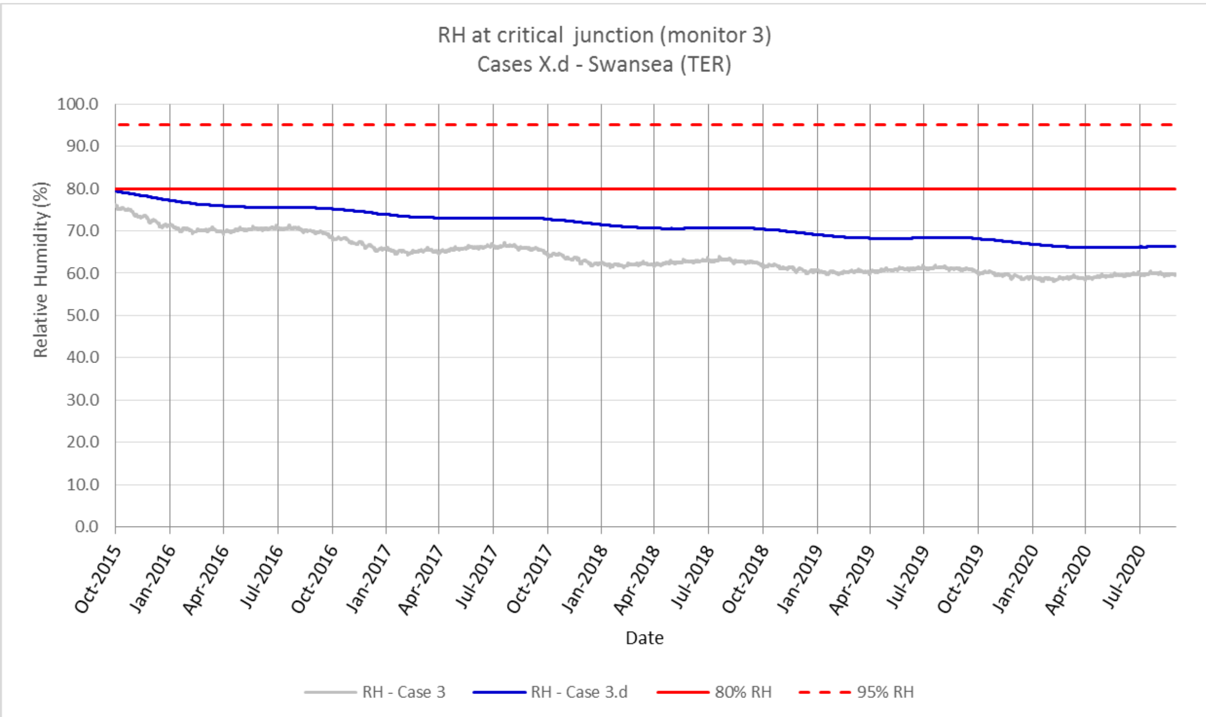


Figure 55: RH levels at critical junction for Cases 3 and 3.d

12.5.4. Conclusions – Sensitivity Analysis Cases X.d

Results

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 26: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

Moisture risk assessment criteria

The graphs show that all cases modelled with foil-facing insulation have slightly worse performance compared to their respective baseline cases. Higher RH levels are displayed at the critical junction, showing that it takes the build-up a much longer period to dry towards equilibrium. This is due to the increased vapour resistance of the build-up due to the addition of the two foil layers (which have a very high vapour resistance diffusion factor).

Despite the higher RH levels displayed in these cases, all RH levels are kept throughout the modelling period well within the 'safe' RH levels. This means that the addition of the foil layers onto the insulation layer does not change the status of the build-up in terms of moisture risks.

AVCL requirement

The requirement for an AVCL with impermeable cladding, as per recommendation in BS 5250 (2011), would seem to be redundant, due to the low moisture levels indicated. This would be the case as long as the cladding is well ventilated.

12.6. Conclusions

- BS EN ISO 13788 is an adequate assessment method
- Robust typology (good resistance to moisture)
- Baseline with EPS = ‘pass’
- Sensitivity analysis with foil layers on both sides of the insulation shows a slightly worse hygrothermal performance of the build-up, which take longer to dry out to equilibrium
- Compressible insulation without AVCL means that the build-up is more moisture-open, making it even safer (as the moisture does not get trapped)
- BS 5250 (2011) recommendation that an AVCL is needed is needed on the warm side of the insulation (if a high vapour resistance soffit is provided and well ventilated) seems to be redundant, as results showing ‘safe’ build-up already

Notes:

- No moisture problem being inherent to the build-up. But build-up used in ‘poor’ situations (such as basement car parks and store / dwellings above).
- So high risk of thermal bridging (due to the concrete structure) cast as 1 structure – not thermally broken (despite some being inside and some being outside of the thermal envelope)
- Possibility for RH conditions in basement / car parks poorer than typical (exhaust fans from occupied space / poor ventilation / etc.)
- Therefore a potential for mould growth / surface condensation

13. Typology N8: Solid Wall - Internal insulation with a semi-porous finish

The N8 typology is a new-build solid concrete wall, insulated internally with closed-cell insulation.

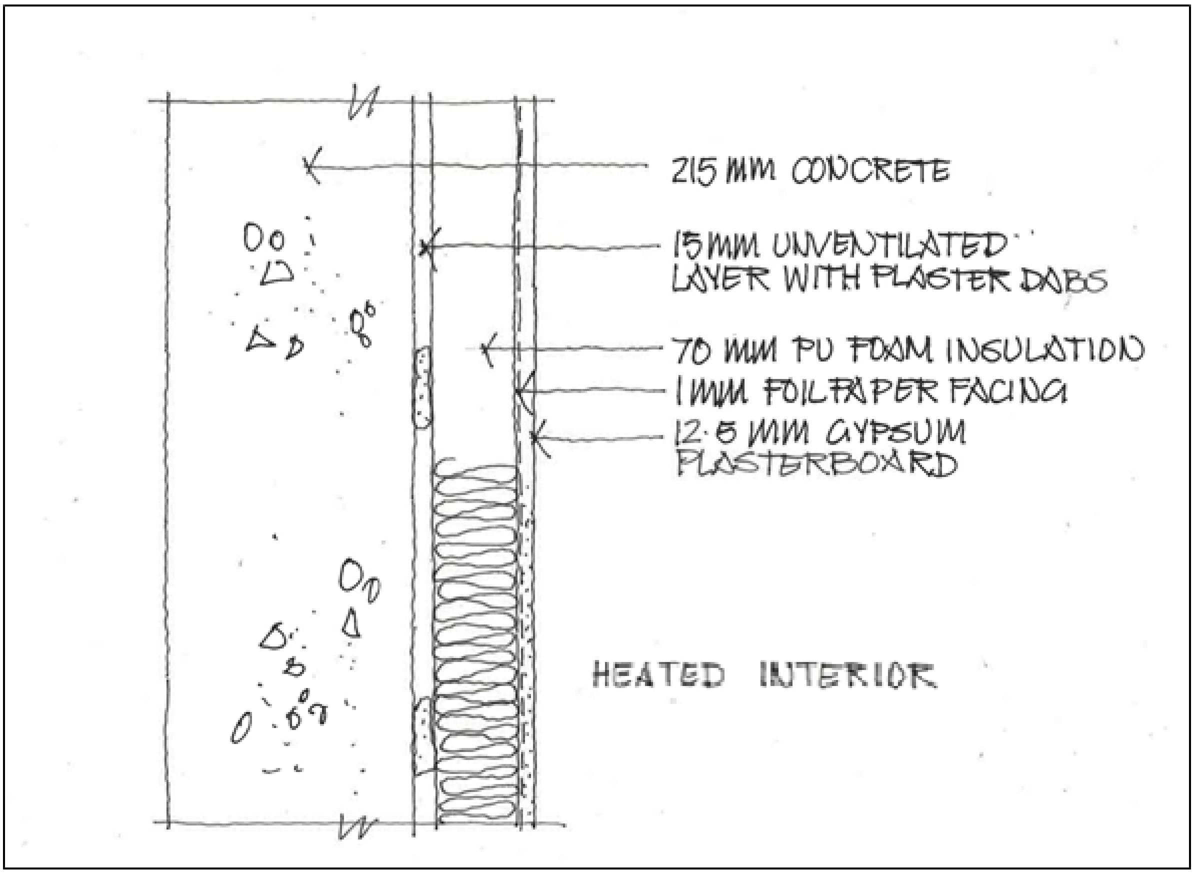


Figure 56: Illustration of the build-up of the typology (Part L case)

13.1. Assessment Method

As the concrete layer is exposed, the storage of moisture in this layer plays an impact on the hygrothermal performance of the build-up, as well as the exposure of its external surface to wind-driven rain and solar gains throughout the year. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment. Indeed, the analysis of this build-up with the Glaser method identifies the correct critical junction but provides false comfort declaring the build-up as ‘safe’ due to the very small amount of condensation created and evaporating throughout the year.

Similarly, the STBA/DECC's ‘Moisture Risk Assessment and Guidance’ (2014) notes that *‘the advice given on Internal Wall Insulation onto solid masonry walls in section G3.1.4 of BS 5250 (2011) is now considered incorrect (rather than just incomplete).’*

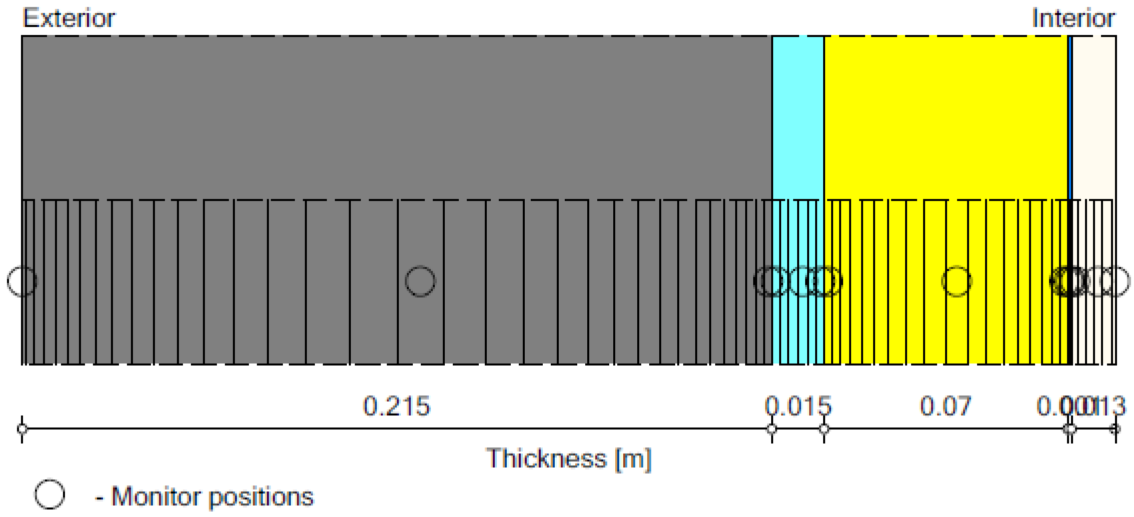
Due to the limitations of previous methods to assess accurately the hygrothermal performance of this build-up, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

13.2. Build-up

Below is the build-up of the typology, as modelled in WUFI.

Build-Up:

- 215mm concrete
- 15mm unventilated air layer with plaster dabs
- 29mm // 70mm // 150mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm foil paper facing (sd = 14m)
- 12.5mm gypsum plasterboard



Materials:

	- Concrete, C35/45	0.215 m
	- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
	- PU (heat cond.: 0,025 W/mK)	0.07 m
	- *foil facing / vapour retarder (sd=14m) (unlocked)	0.001 m
	- Gypsum Board	0.013 m

13.3. Results

13.3.1. Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 27: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

13.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the insulation and the solid wall. Indeed, this interface is the location where moisture gets trapped, meaning RH levels raise higher than recommended and lead to a greater risk of mould growth and condensation.

13.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

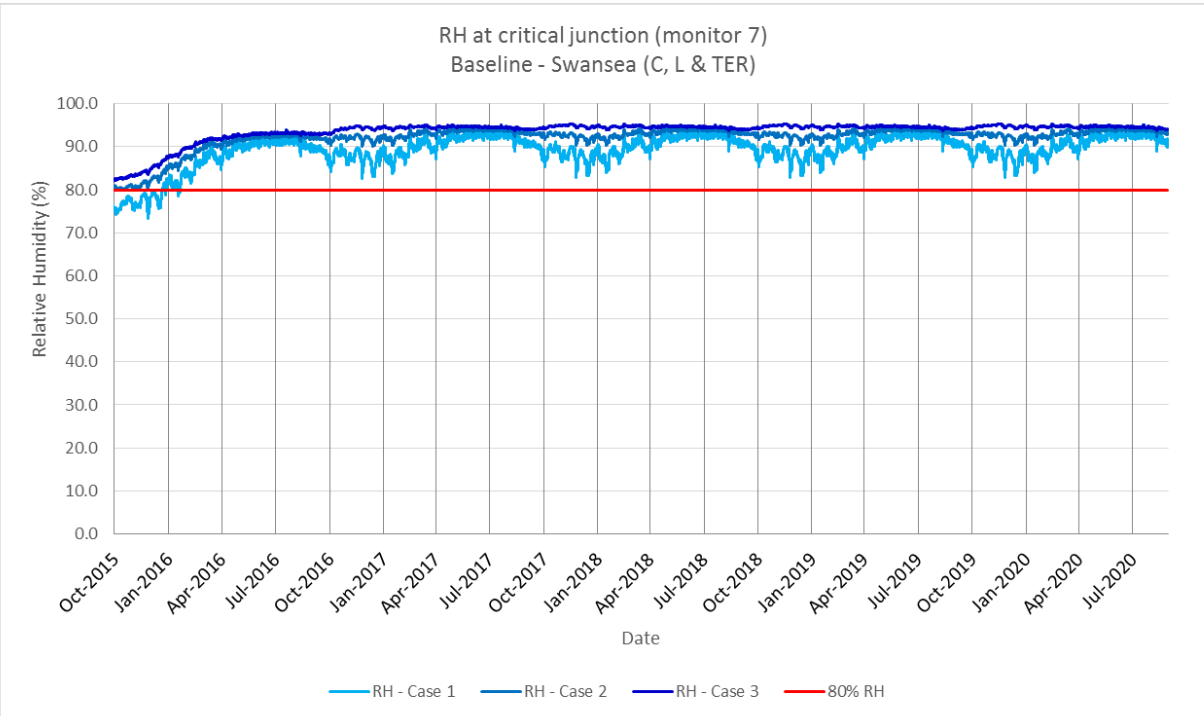


Figure 57: RH levels at critical junction for Cases 1, 2 and 3

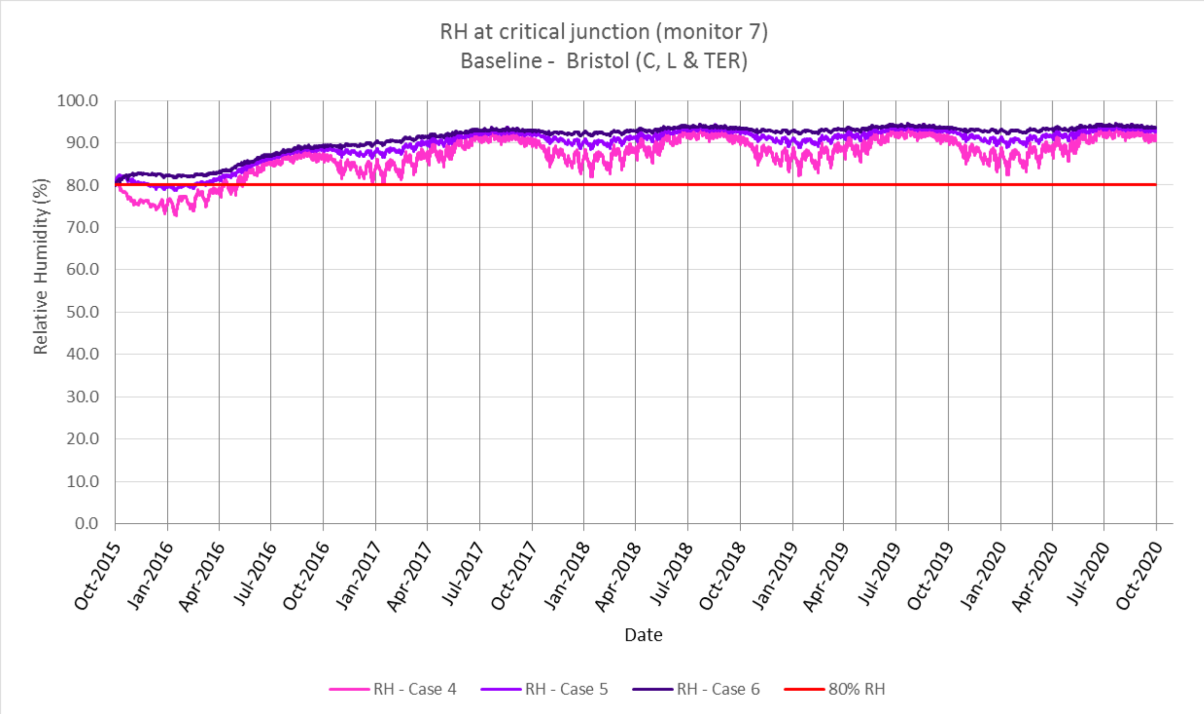


Figure 58: RH levels at critical junction for Cases 4, 5 and 6

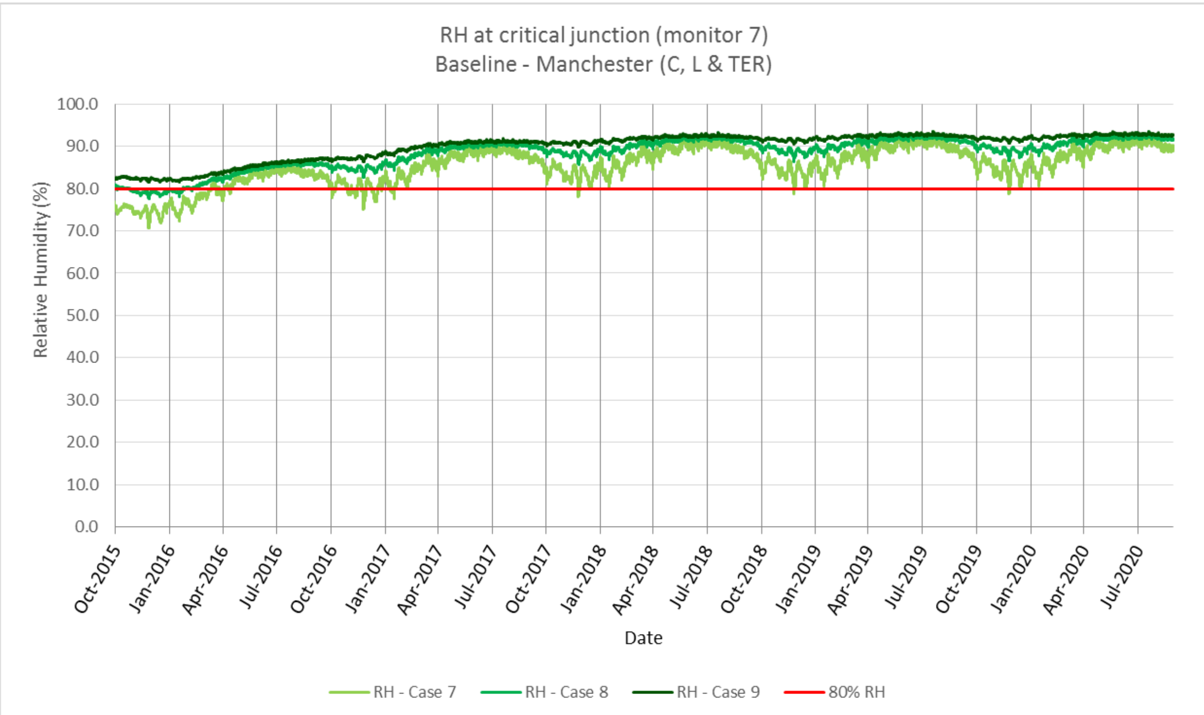


Figure 59: RH levels at critical junction for Cases 7, 8 and 9

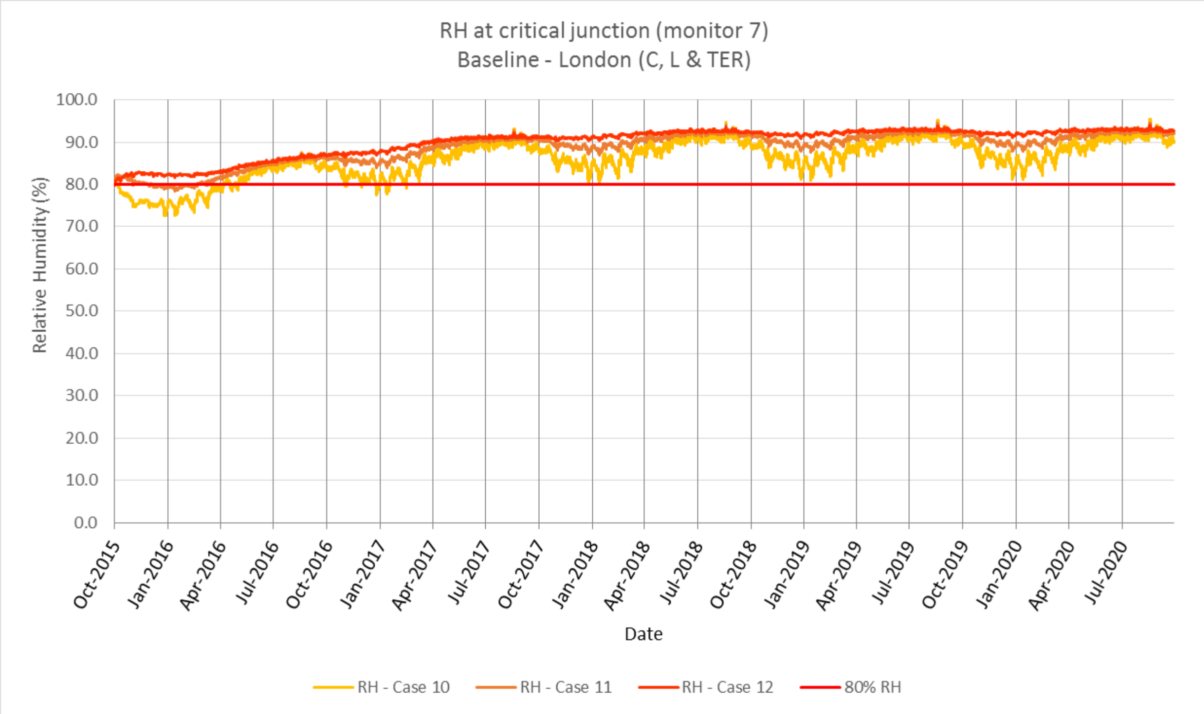


Figure 60: RH levels at critical junction for Cases 10, 11 and 12

13.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

All scenarios achieve equilibrium; therefore moisture does not keep on accumulating over time. However, all scenarios display RH levels well above 80% (80% being the threshold of where moisture risks, in particular conditions favourable to mould growth, start occurring). So all scenarios are considered as "fail". These results are summarised in the table below.

Table 28: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Fail	Case 4 Fail	Case 7 Fail	Case 10 Fail
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Fail
TER	Case 3 Fail	Case 6 Fail	Case 9 Fail	Case 12 Fail

These findings are in line with current concerns in the industry, as it is known this is a build-up with a high moisture risk.

The main moisture source creating problems in a solid wall build-up is rain penetration from outside. As the wall, in this scenario, is not protected, moisture (as liquid water) penetrates deeper into the build-up in winter via capillary action due to wind-driven rain reaching the façade. Similarly, moisture (as water vapour) is also pushed back into the build-up in summer due to reverse diffusion (see definition in Glossary). However, with a closed-cell insulation layer covered by a foil layer (acting like a VCL – if continuous) present on the inside on the solid wall, the moisture has nowhere to go and creates unfavourable conditions – leading to build-up failure – at the critical junction.

In addition, the graphs show that the higher RH levels correspond with higher temperature periods, which indicates a direct and significant risk of mould growth at this critical junction.

Effects of exposure zones and U-values

The effect of wind-driven rain exposure zones can be seen on the graphs but it only has a medium impact, due to the build-up being a very risky build-up to start with.

The graphs also show that the cases with higher (i.e. poorer) U-values have a slightly better RH profile during winter. This is linked to the fact that, as the insulation layer is thinner, the wall is kept warmer and therefore RH levels are lower (due to the air being able to handle a larger amount of absolute humidity the warmer it gets).

Finally, all three scenarios, independently to the insulation thickness, demonstrate the same RH peaks in summer, much higher than 80%, leading to system failure. These peaks demonstrate the process of ‘reverse condensation’, driving the moisture back into the fabric (i.e. in the opposite direction to vapour diffusion in winter). Indeed, if the outer leaf of the wall is heated by solar gain, the water vapour it contains is carried deeper into the fabric due to vapour diffusion and is at risk of condensing on the cooler interface of the masonry with the internal insulation layer. This phenomenon mainly occurs on south-facing façades, where there is direct sunshine radiating on the façade.

13.3.5. Conclusions - Baseline

As all the baseline scenarios fail quite significantly, independently of the amount of insulation present on each build-up or in which wind-driven rain exposure zone the build-up is located in, this typology (exposed concrete solid walls with closed-cell insulation applied internally) appears to be a very risky build-up and therefore cannot be recommended – as this exact build-up – as a safe method of construction in terms of resistance to moisture.

13.4. Sensitivity Analysis – Change in Orientation [Cases X.c]: North-facing walls

13.4.1. Sensitivity Analysis Cases

As the build-up is exposed to the wind-driven rain, which has a significant impact on its hygrothermal performance, the first sensitivity analysis is to change the orientation of the façade. With this sensitivity analysis, the orientation of the façade is changed from South-West to North. The build-up on a South-West facing orientation experiences more wind-driven rain but benefits from greater solar gains (allowing it to dry out quicker). In comparison, a build-up on a North facing orientation experiences less wind-driven rain, which is beneficial to its hygrothermal performance. However, the lack of solar gains leads to a reduction in drying capabilities, which is detrimental to its hygrothermal performance.

The overall impact of the change of orientation is difficult to predict, as it is the balance between the (beneficial) reduction in wind-driven rain and the (detrimental) reduction in solar gains that will inform the change in hygrothermal performance of the build-up.

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the three target U-values (as per baseline cases):

Table 29: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.c	Case 4.c	Case 7.c	Case 10.c
Part L	Case 2.c	Case 5.c	Case 8.c	Case 11.c
TER	Case 3.c	Case 6.c	Case 9.c	Case 12.c

13.4.2. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases. The graphs are displayed for the two most extreme zones: Zone 4 – Swansea and Zone 1 – London.

The sensitivity analysis cases are displayed as a coloured line (blue for Zone 4 – Swansea and orange for Zone 1 – London), while their respective baseline cases are displayed with a grey line. Within each colour, the darker the colour, the higher / better the U-value is.

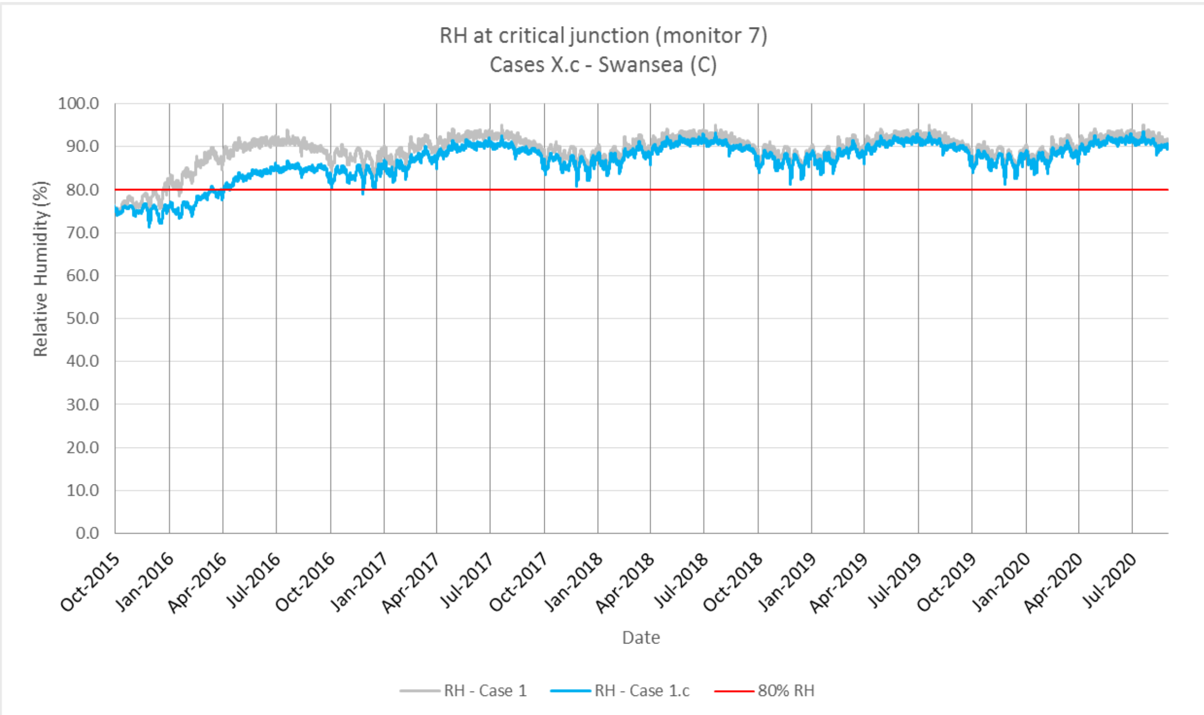


Figure 61: RH levels at critical junction for Case 1 and 1.c

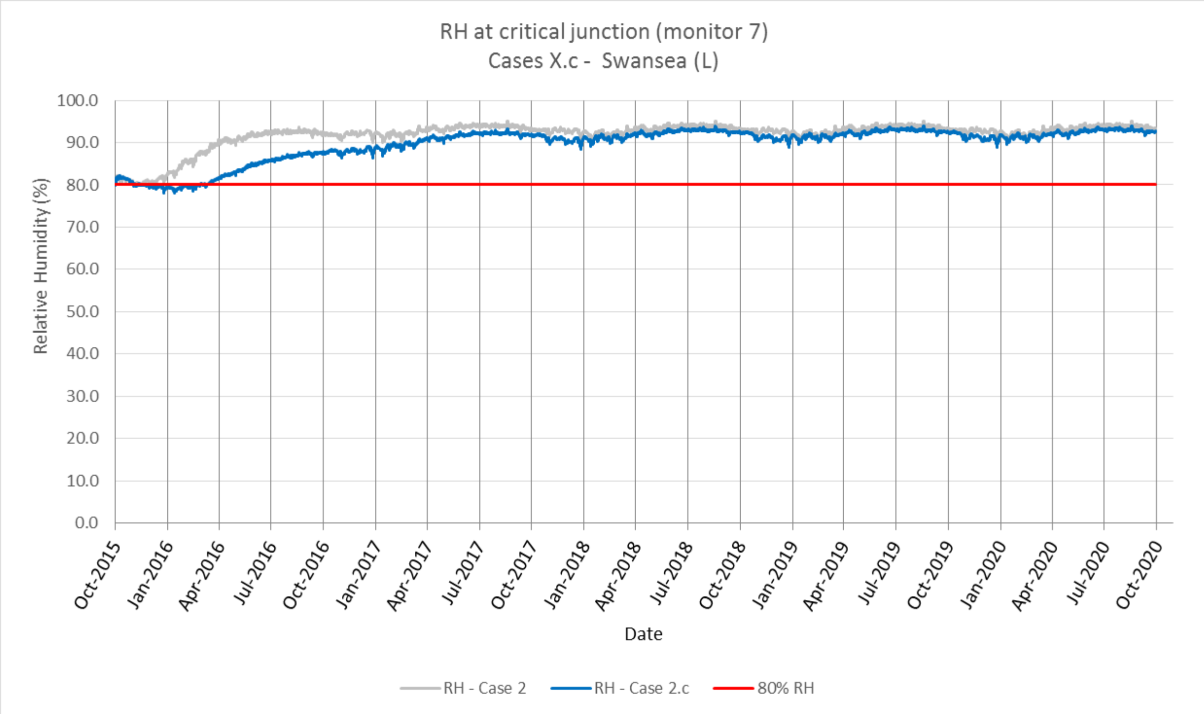


Figure 62: RH levels at critical junction for Cases 2 and 2.c

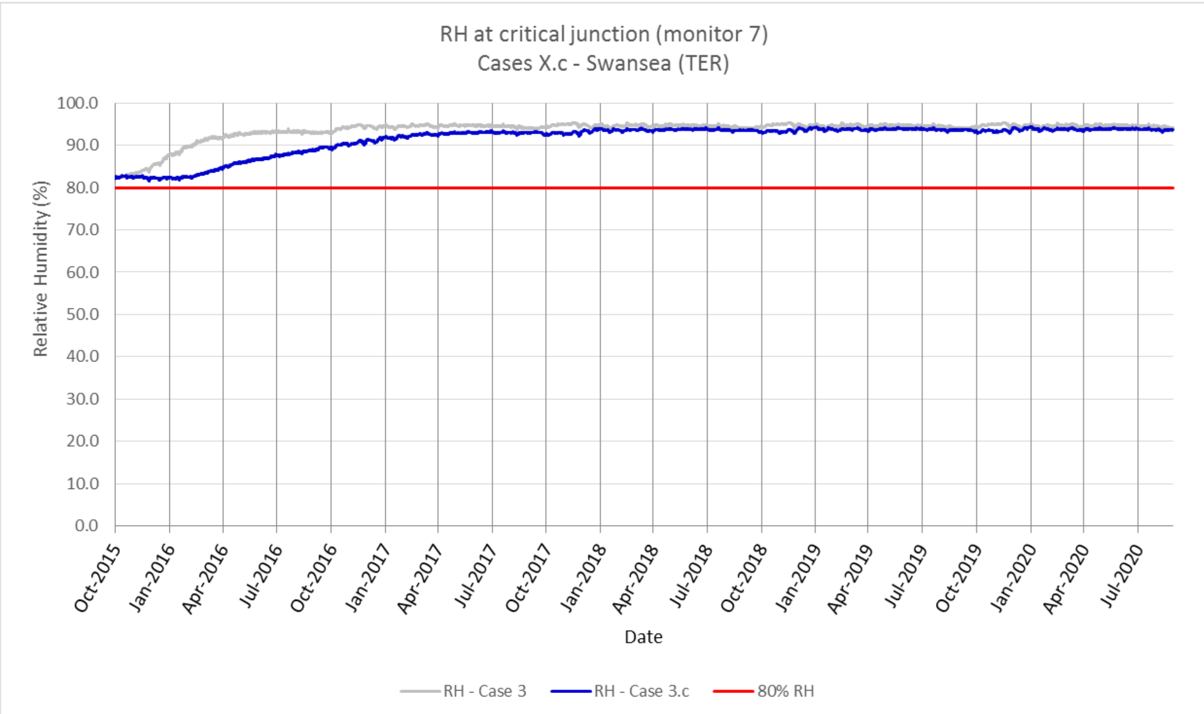


Figure 63: RH levels at critical junction for Cases 3 and 3.c

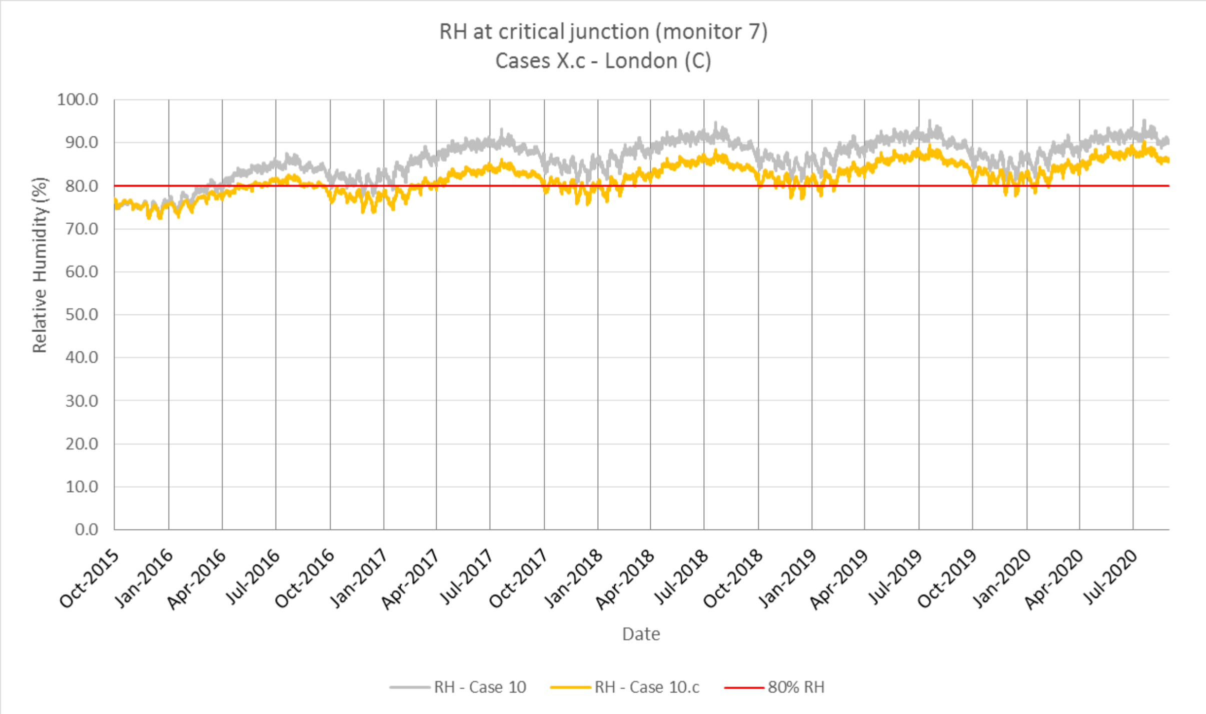


Figure 64: RH levels at critical junction for Cases 10 and 10.c

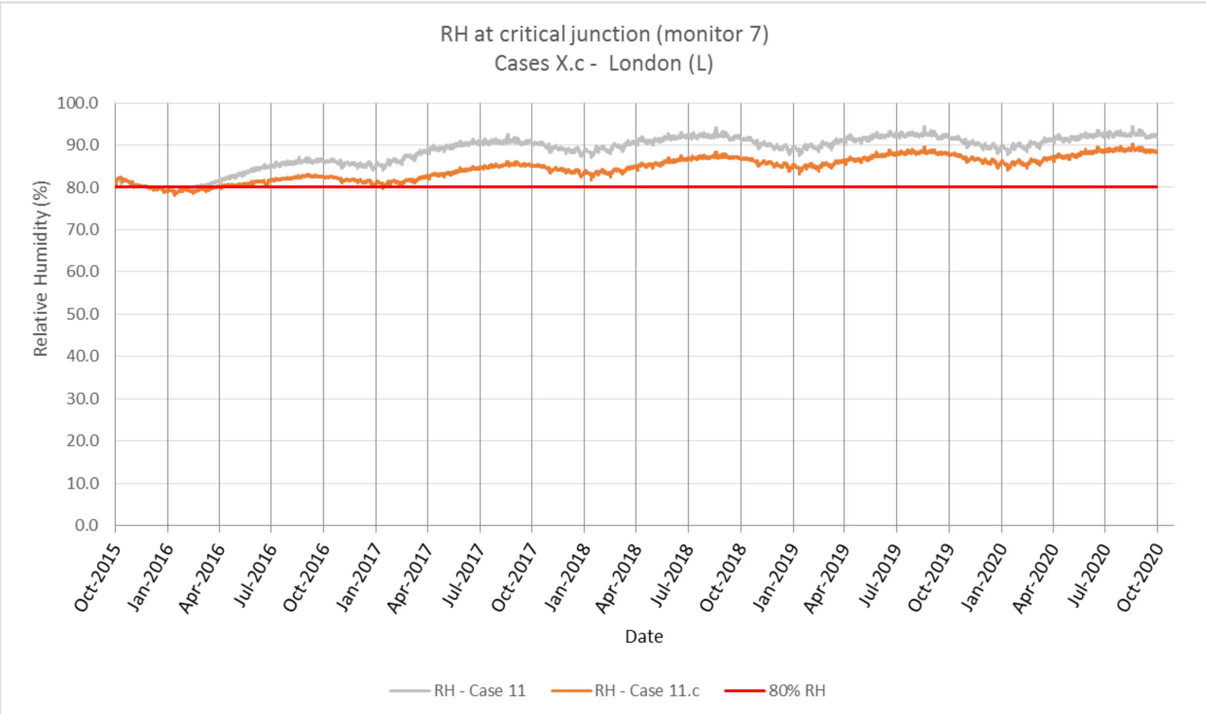


Figure 65: RH levels at critical junction for Cases 11 and 11.c

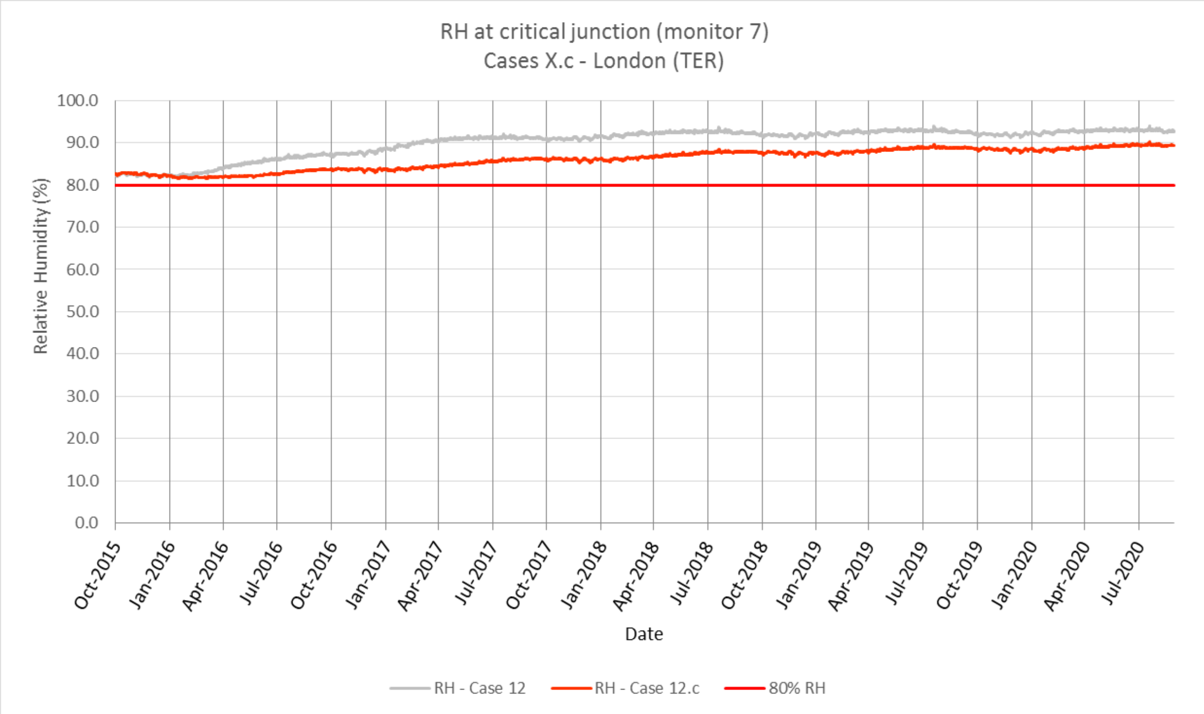


Figure 66: RH levels at critical junction for Cases 12 and 12.c

13.4.3. Conclusions – Sensitivity Analysis Cases X.c

<u>Moisture risk assessment criteria</u>

The graphs show that all cases modelled in this sensitivity analysis perform slightly better than their respective baseline cases. However, this improvement is not sufficient enough to change the status of these cases – they are still all considered as 'fail'. Indeed, all cases display RH levels higher than 80% at the critical junction, for (most of) the entire year.

<u>Effects of exposure zones</u>

The graphs show that, in the most extreme exposure zones (Zone 4 – Swansea), the overall beneficial impact of the change in orientation is only temporary. After 3 to 4 years, the RH profiles between the baseline and the sensitivity cases at the critical junction are almost identical (independently to the amount of insulation present in the build-up). This beneficial effect appears more permanent in zones where there is less wind-driven rain (Zone 1 – London), where the decrease in RH levels at the critical junction between the baseline and the sensitivity cases is maintained throughout the modelling period.

Results
The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 30: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.c Fail	Case 4.c Fail	Case 7.c Fail	Case 10.c Fail
Part L	Case 2.c Fail	Case 5.c Fail	Case 8.c Fail	Case 11.c Fail
TER	Case 3.c Fail	Case 6.c Fail	Case 9.c Fail	Case 12.c Fail

These graphs show that, on average, the reduction in wind-driven rain and the reduction in solar gains have a small beneficial impact on the hygrothermal performance of the build-up. However, this improvement is not significant enough to improve the build-up's status from 'fail' to 'pass'.

These results show that this build-up remains a risky build-up that is prone to high risks of mould growth, and therefore cannot be considered robust to resistance to moisture, regardless of the build-up's orientation. These results also highlight that a South-West orientation typically is the orientation which will display the worst hygrothermal performance, and should therefore be the one modelled / analysed if this build-up is considered at a design stage.

13.5. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of a water-resistant external render

13.5.1. Sensitivity Analysis Cases

As the baseline build-up fails for all cases, due to the wind-driven rain reaching the external surface and penetrating the build-up, the first sensitivity analysis is to improve the build-up's resistance to moisture by introducing an additional external layer – silicone render – on the bare concrete wall. Per definition, this will reduce the amount the wind-driven rain penetrating the build-up and therefore should have a beneficial impact on its performance.

As the baseline cases showed that the exposure zones only have a medium effect onto the performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis. The 3 cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases):

Table 31: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

13.5.2. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

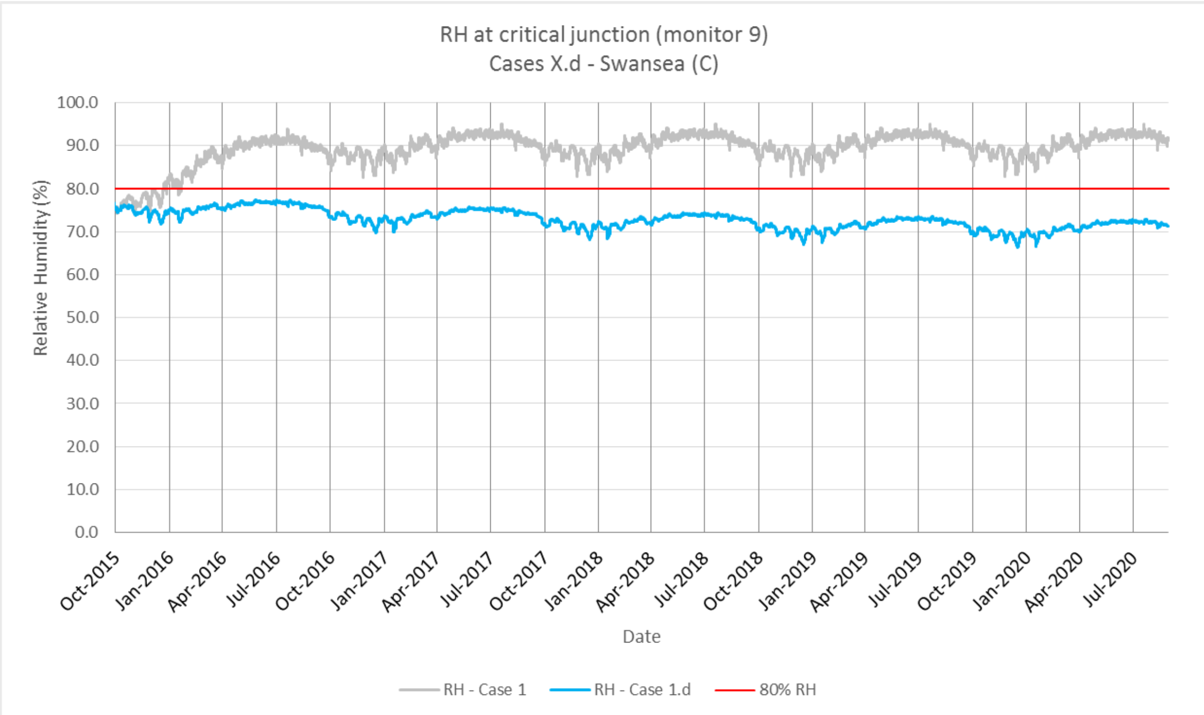


Figure 67: RH levels at critical junction for Cases 1 and 1.d

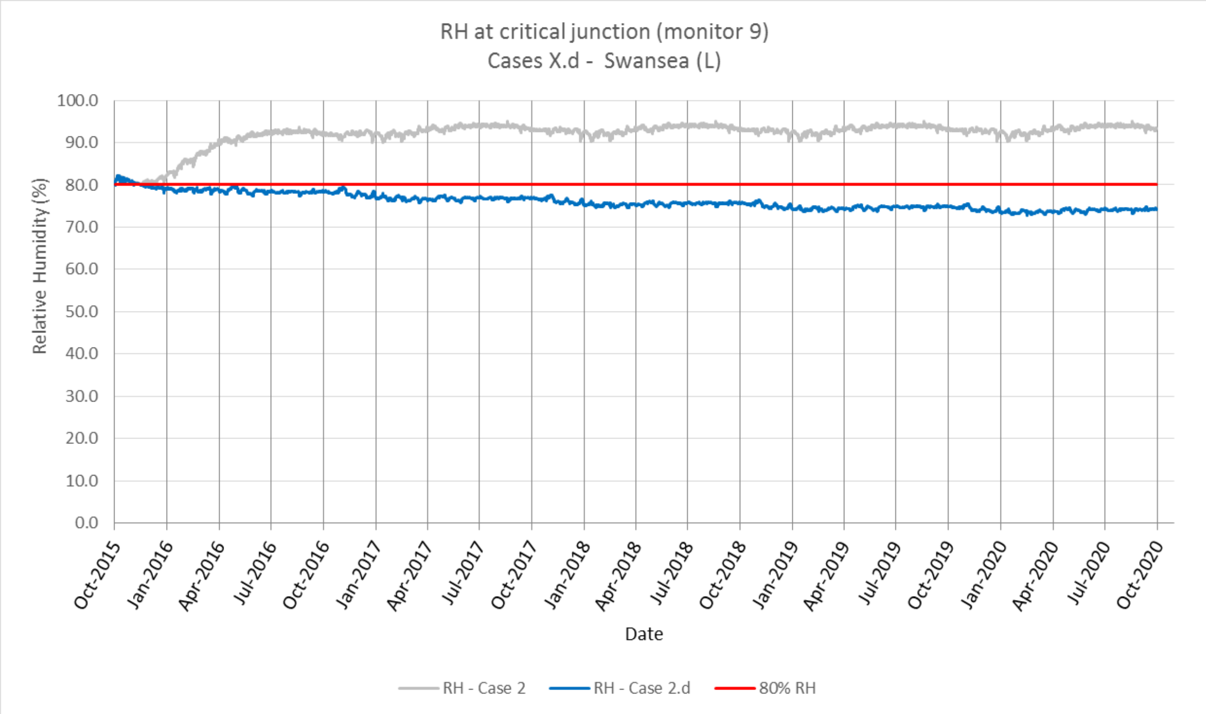


Figure 68: RH levels at critical junction for Cases 2 and 2.d

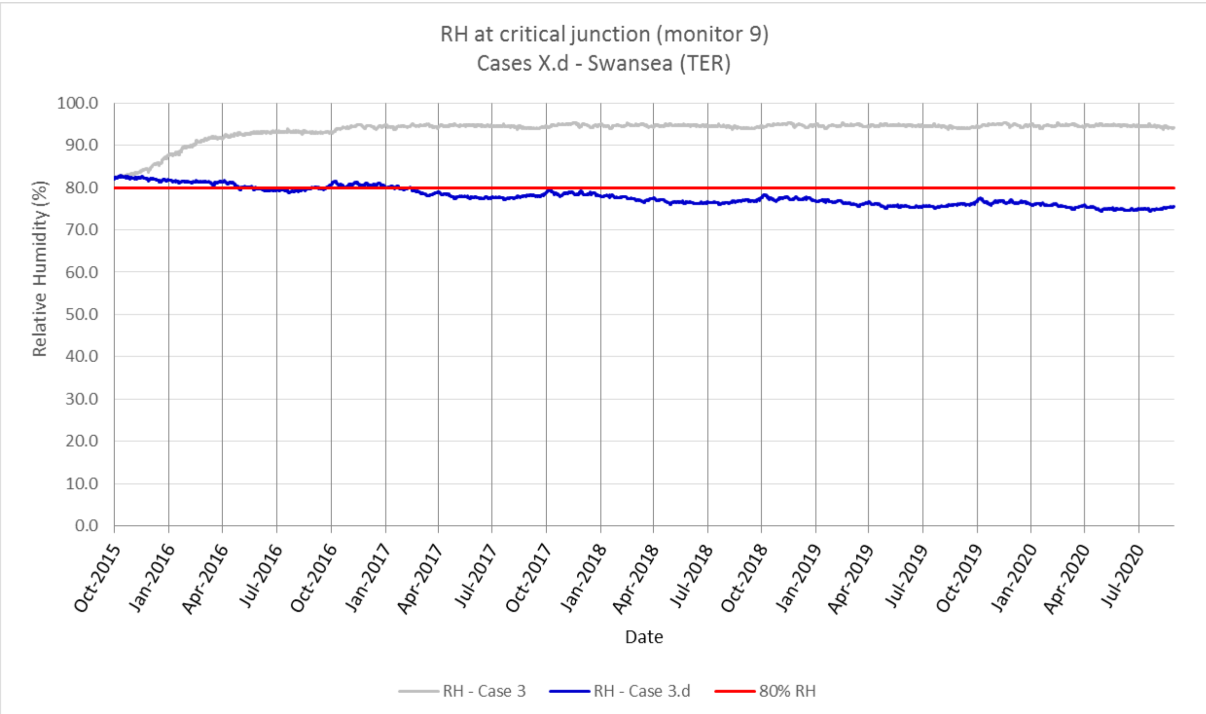


Figure 69: RH levels at critical junction for Cases 3 and 3.d

13.5.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform better than their respective baseline cases.

All cases show the build-up slowly drying out towards equilibrium. All cases also display RH levels at equilibrium within recommended RH levels (i.e. below 80%). These 'safe' levels are reached very rapidly on both Part C and Part L cases. However, for the TER case, it takes more than 6 months for the RH levels to reduce to the 80% levels, which is considered 'risky' in the moisture risk assessment criteria.

Results

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section3.3:

Table 32: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d (Risky) Fail	-	-	-

These results show that the upgraded build-up with external render is made safer in terms of hygrothermal performance, compared to the baseline build-up. However, despite significantly improving its performance, this additional render layer is not a sufficient enough solution to ensure the 'safe' performance of the build-up in every case, as the thickness of the insulation and the characteristics of the render will make the results vary.

The wind-driven rain penetrating the concrete layer is the main source of moisture which is leading to the failure of the build-up. Analysing the water content in this layer between the baseline and the improved case will show how much improvement is obtained through the installation of the external render.

The graph below displays the water content in the concrete layer for the TER case in Zone 4 – Swansea . As per other sensitivity modelling, the case X.d tested here is displayed as a coloured line against its respective baseline case, displayed with a grey line. Please note that the vertical axis is adjusted for ease of reading.

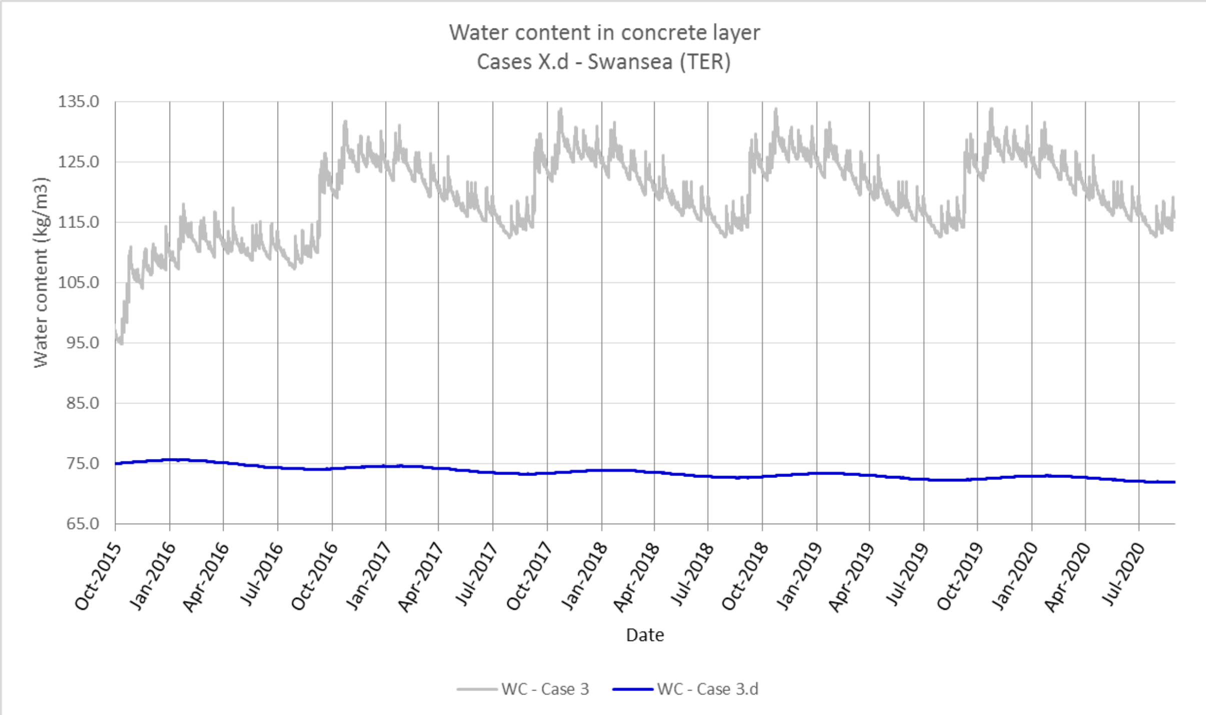


Figure 70: Water content in concrete layer for Cases 3 and 3.d

The graph shows that the water content throughout the years in the concrete layer is significantly reduced in the improved case, which explains the decrease in RH levels at the critical junction and therefore the improvement in the hygrothermal performance of the build-up.

Effects of exposure zones and U-values

The effect of the U-value levels is visible on the graphs, with better U-value cases taking longer to dry out towards equilibrium from higher RH levels initial conditions. This is due to the fact that, with similar boundary conditions, moisture movements will be slower through a much thicker insulation layer (compared to thinner insulation layers for the cases with poorer U-values).

13.6. Sensitivity Analysis – Change in Material [Cases X.d]

13.6.1. Baseline model versus BS 5250 (2011)

It is worth nothing that the baseline build-up differs from the build-up present in BS 5250 (2011). The insulation shown on the drawing of the build-up is annotated as *'compressible thermal insulation, which normally has a low vapour resistivity',* which is typically associated with air-based insulating materials such as mineral wool. In contrast, the insulation used in the baseline build-up is PU foam, classified in the rigid insulation category. Therefore, the insulation material will be changed from PU foam to mineral wool in the second sensitivity analysis for this build-up.

As mineral wool is a flexible and breathable material, no air gap will be present (in theory) between the structural concrete layer and the mineral wool layer (which differs again from the baseline build-up).

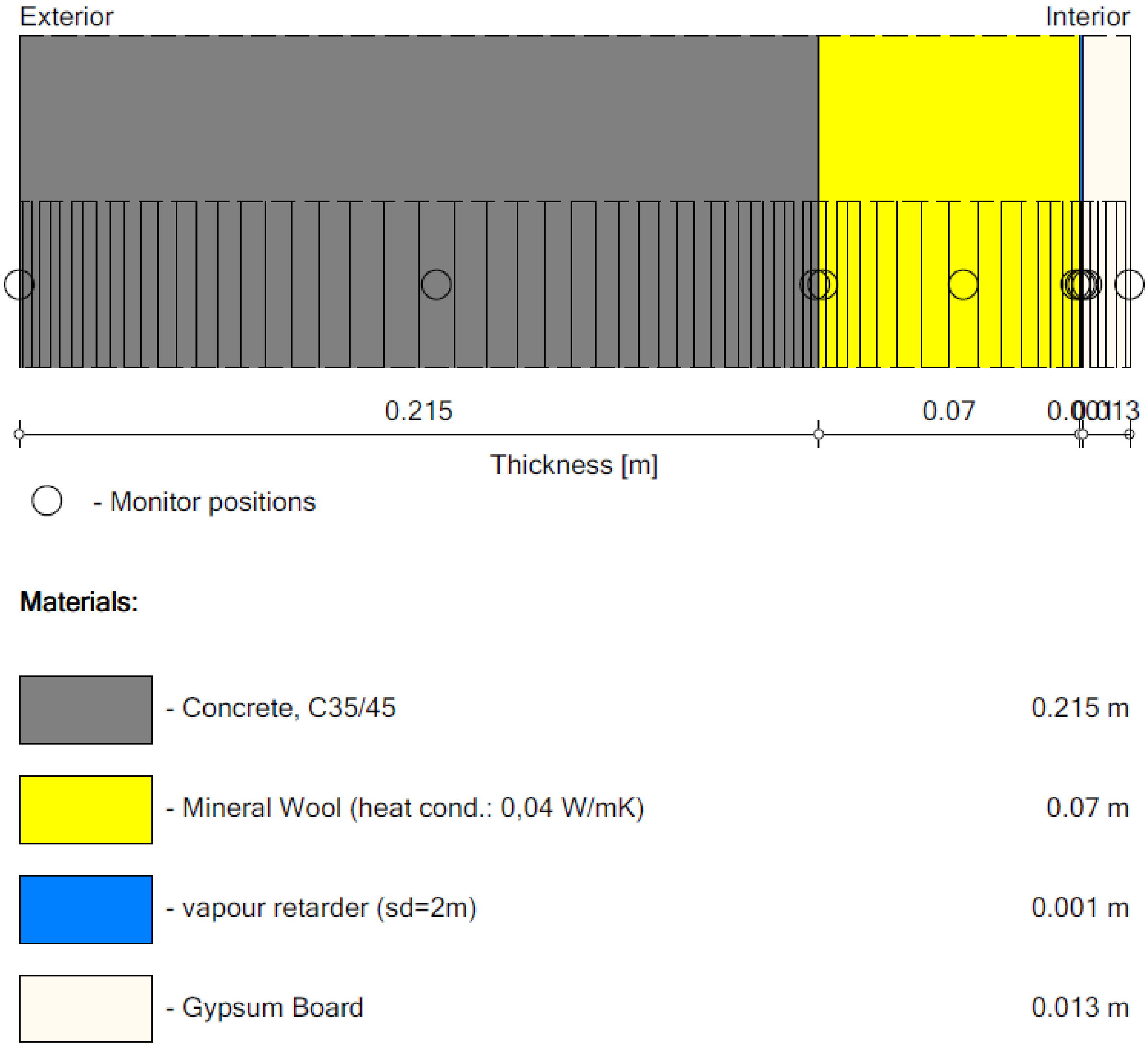
Presence / Absence of AVCL

The current guidance from paragraph G.3.1.4 of BS 5250 (2011) states the following: *'Internally applied thermal insulation isolates the heated interior from the masonry, which will therefore be cold, producing a risk of interstitial condensation behind the thermal insulation. To prevent that, an AVCL should be applied on the warm side of the thermal insulation.'*

However, this recommendation is debated in the industry. Therefore, both cases (with and without an AVCL) are modelled, so that a comparison can be drawn from the modelling.

Build-Up:

- 215mm concrete
- 29mm // 70mm // 150mm mineral wool insulation (λ = 0.040 W/m.K)
- 1mm AVCL (sd = 2m) – ONLY IN CASES WITH AVCL
- 12.5mm gypsum plasterboard



13.6.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones only have a medium effect onto the performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis. The six cases (three cases with AVCL and three without AVCL) are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

- Cases with AVCL

Table 33: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

- Cases without AVCL

Table 34: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d (without AVCL)	-	-	-
Part L	Case 2.d (without AVCL)	-	-	-
TER	Case 3.d (without AVCL)	-	-	-

13.6.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

- Cases with AVCL

The sensitivity analysis cases (with mineral wool with AVCL) are displayed as a coloured line, while their respective baseline cases (with PU foam) are displayed with a grey line.

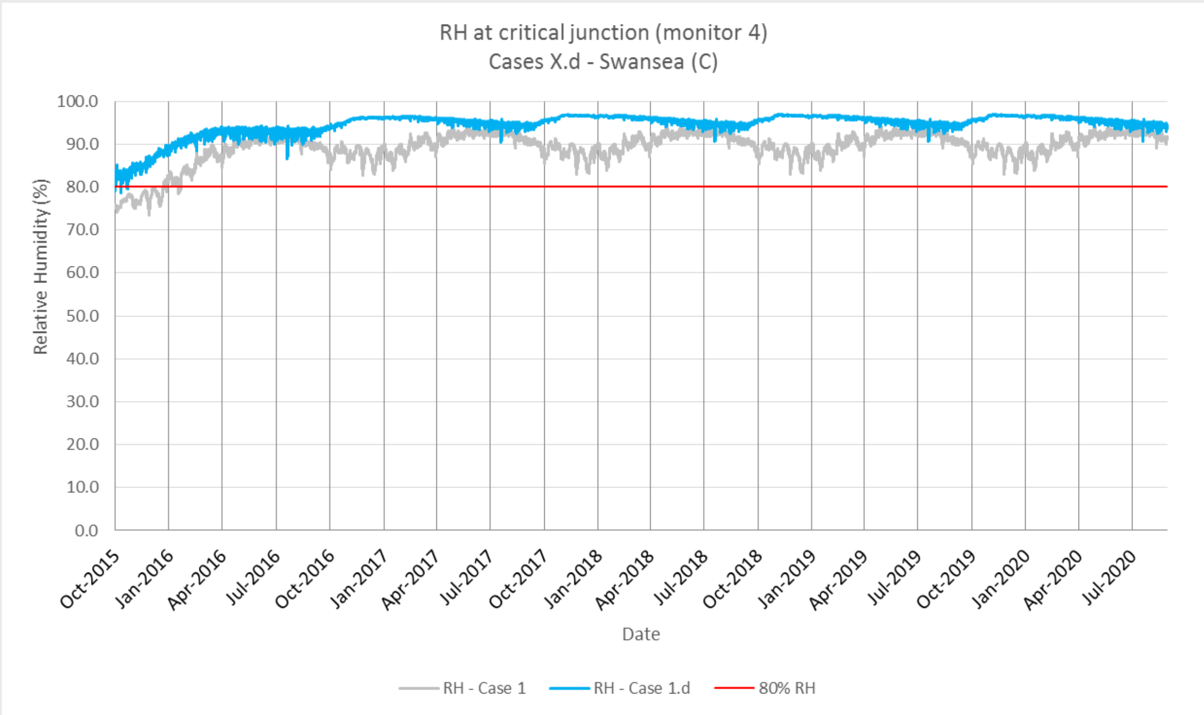


Figure 71: RH levels at critical junction for Cases 1 and 1.d (with AVCL)

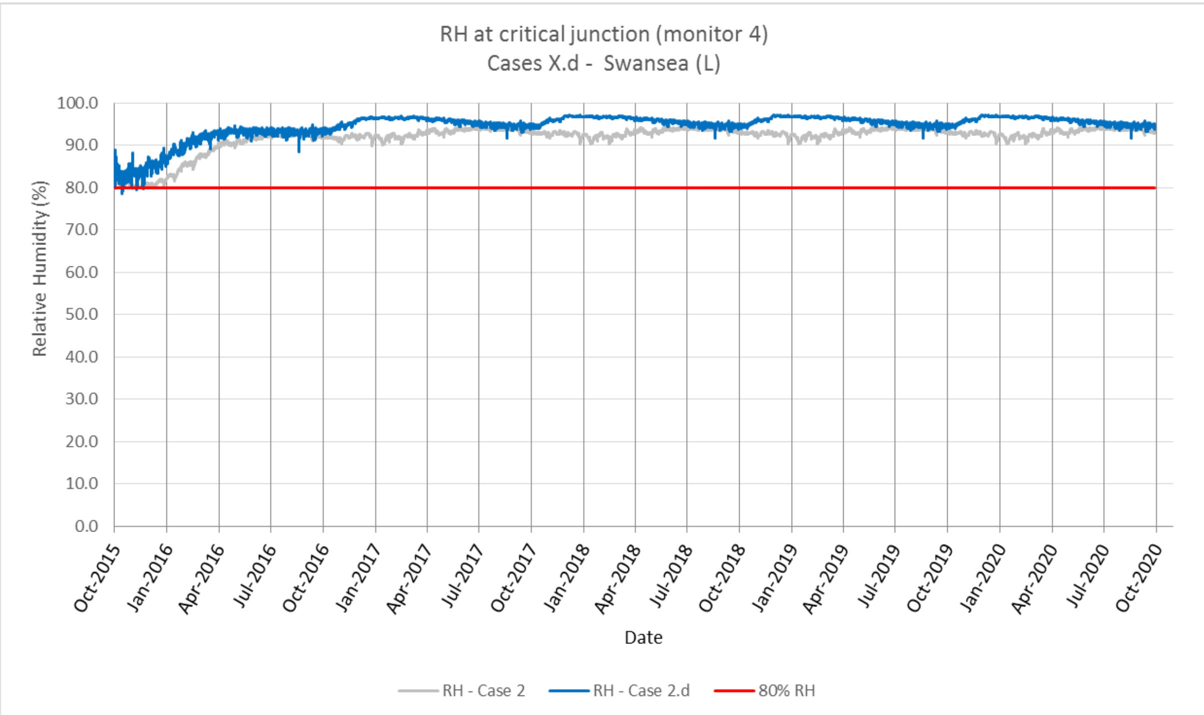


Figure 72: RH levels at critical junction for Cases 2 and 2.d (with AVCL)

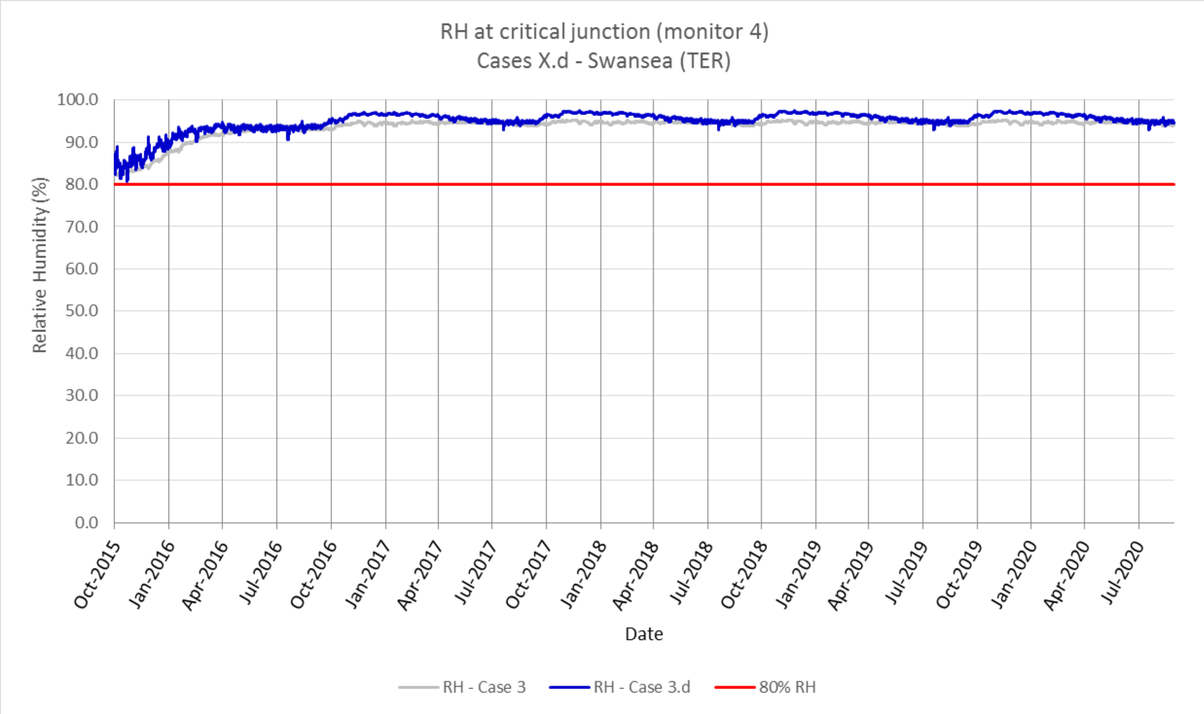


Figure 73: RH levels at critical junction for Cases 3 and 3.d (with AVCL)

- <u>Cases without AVCL</u>

The sensitivity analysis cases (mineral wool without AVCL) are displayed as a coloured line, while the previous sensitivity analysis cases (mineral wool insulation with AVCL) are displayed with a grey line.

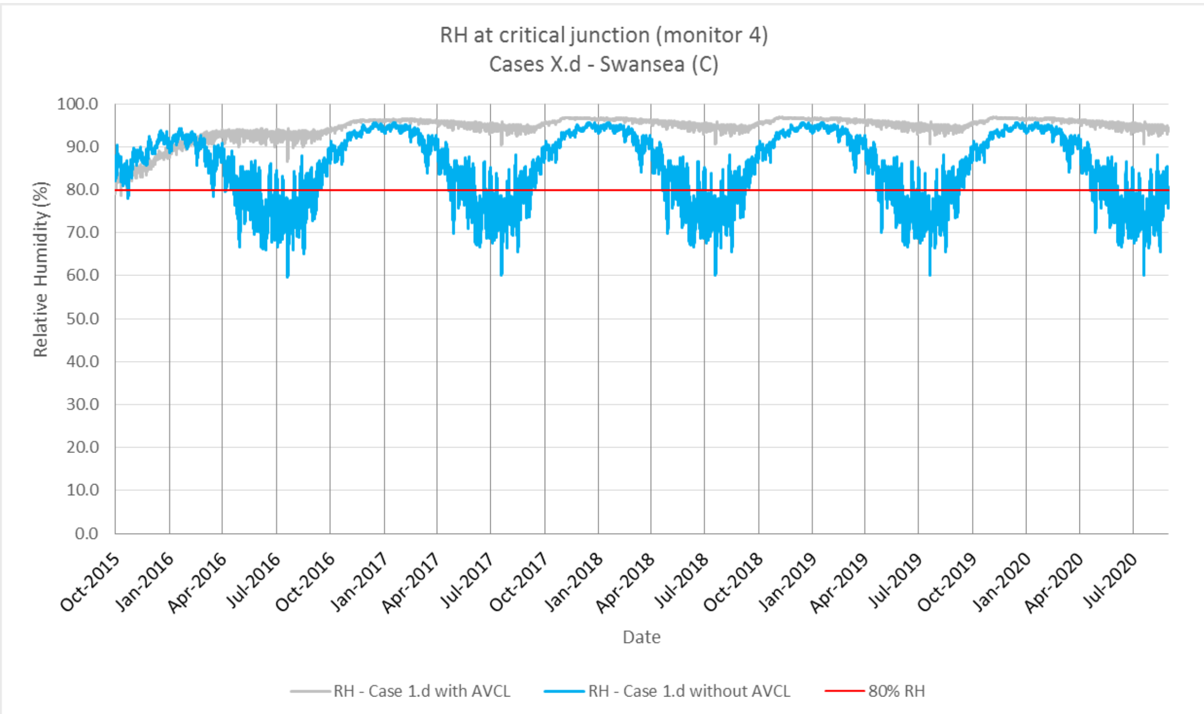


Figure 74: RH levels at critical junction for Cases 1.d (with AVCL) and 1.d (without AVCL)

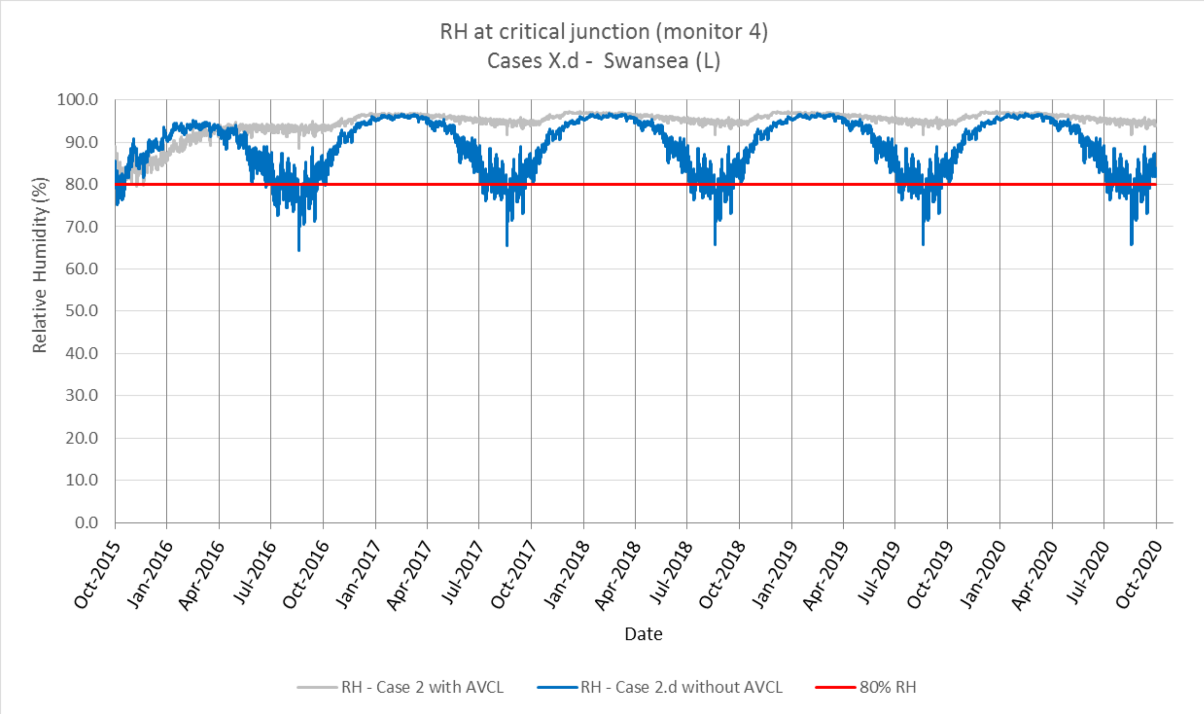


Figure 75: RH levels at critical junction for Cases 2.d (with AVCL) and 2.d (without AVCL)

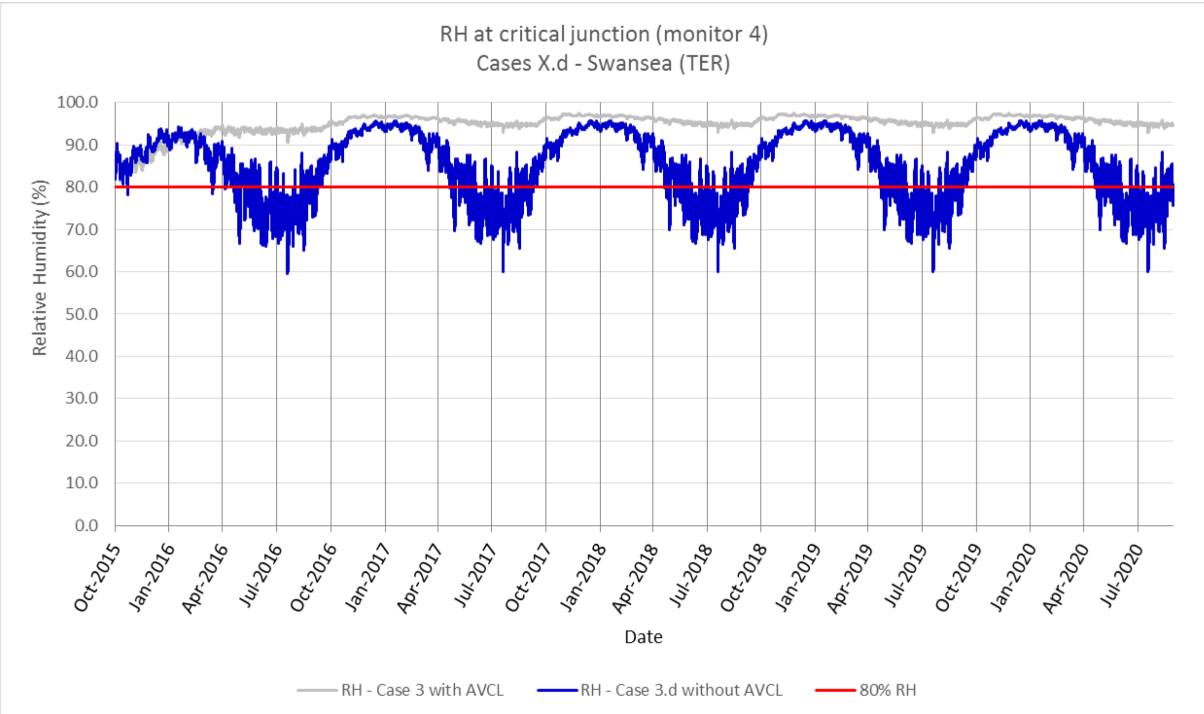


Figure 76: RH levels at critical junction for Cases 3.d (with AVCL) and 3.d (without AVCL)

13.6.4. Conclusions – Sensitivity Analysis Cases X.d

Results

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

- Cases with AVCL

Table 35: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d (with AVCL) Fail	-	-	-
Part L	Case 2.d (with AVCL) Fail	-	-	-
TER	Case 3.d (with AVCL) Fail	-	-	-

Moisture risk assessment criteria

The graphs shows that all cases modelled with mineral wool and AVCL perform slightly worse that their baseline cases (rigid insulation).

RH levels at the critical junction are higher in the sensitivity analysis cases, and their profiles are slightly different from the baseline cases. The RH profiles of the sensitivity analysis cases displays directly the conditions experienced by the concrete layer, with a rapid rain intake during the wet season (starting October) and then a slow drying out during the rest of the year. By comparison, the baseline cases RH levels have a smoother profile, as the rigid insulation is not directly in contact with the concrete layer (due to a small 15mm unventilated air gap created by the dot-and-dab fixing system). As the rigid insulation does not have the capacity to store much moisture and acts as a moisture 'barrier', the peaks in RH levels are also offset, as the baseline models suffer from reversed condensation shown by peaks in RH levels happening during the summer with moisture pushed through the build-up towards the critical junction and getting trapped there.

The baseline cases displayed high RH levels, significantly above the 80% RH limits. With this sensitivity analysis displaying slightly worsen conditions, all sensitivity cases with mineral wool and AVCL all fail. Therefore, this build-up does not present any advantages and cannot be considered safer compared to the baseline build-up.

- Cases without AVCL

Table 36: Summary of results

	Exposure Zones			
Target U-values	Swansea (Zone 4)	Bristol (Zone 3)	Manchester (Zone 2)	London (Zone 1)
Part C	Case 1.d (without AVCL) Fail	-	-	-
Part L	Case 2.d (without AVCL) Fail	-	-	-
TER	Case 3.d (without AVCL) Fail	-	-	-

Moisture risk assessment criteria

The graphs show that all cases modelled without the presence of an AVCL in the build-up perform better than the similar sensitivity case with the AVCL included in the build-up (as well as their respective baseline cases). RH levels at the critical junction of the build-up without AVCL are always equal or lower than the RH levels in the build-up with AVCL.

However, despite presenting lower RH levels at the critical junction, the modelled cases still display RH levels much higher than the set 80% limit for 9 months (around the winter period) of the year, when reaching equilibrium. The risk of mould growth is not the main concern, as mineral wool and concrete are not materials providing ample source of food for mould growth, and air should not be present at this interface as mineral wool is a very flexible and should be installed in a tight fit to the concrete. However, the fact that the mineral wool is to be installed in a tight fit with the concrete and the plasterboard layer means that moisture will be forced into the build-up (compared to moisture draining on the surface if a cavity is present). The presence of additional moisture in the material has then detrimental effect on the thermal performance of the material. So, all cases without a AVCL are still considered a ‘fail’ due to the RH levels, mainly higher than the recommended 80% level as well as the detrimental effect the high RH levels have on the thermal performance of the mineral wool at this interface.

As a conclusion, all cases with mineral wool (instead of PU foam) with or without AVCL cannot be considered ‘safe’ build-ups without any additional improvements. It is worth noting that the build-up without AVCL performs better – reaching lower RH levels during the summer months through a drying process thanks to a fully moisture-open build-up – and is therefore the preferred build-up on which to implement further improvements to make it a ‘safe’ build-up.

13.6.5. Further Sensitivity Analysis Cases X.d

To assess the impact of installing a render finish externally on the preferred mineral wool build-up mentioned in the previous paragraph, an additional sensitivity analysis case is modelled with the following build-up:

- 15mm silicon resin render
- 215mm concrete
- 29mm // 70mm // 150mm mineral wool insulation (λ = 0.040 W/m.K) installed in between timber studs
- 12.5mm gypsum plasterboard

As the reduction in water ingress in the concrete layer plays a significant role (please refer to first sensitivity analysis in this typology), and exposure zones and U-values play a much minor role, only the case 1.d for Swansea – Part C is displayed below. The additional sensitivity analysis case (mineral wool with render) is displayed as a coloured line, while the previous sensitivity analysis case (mineral wool without render) is displayed with a grey line.

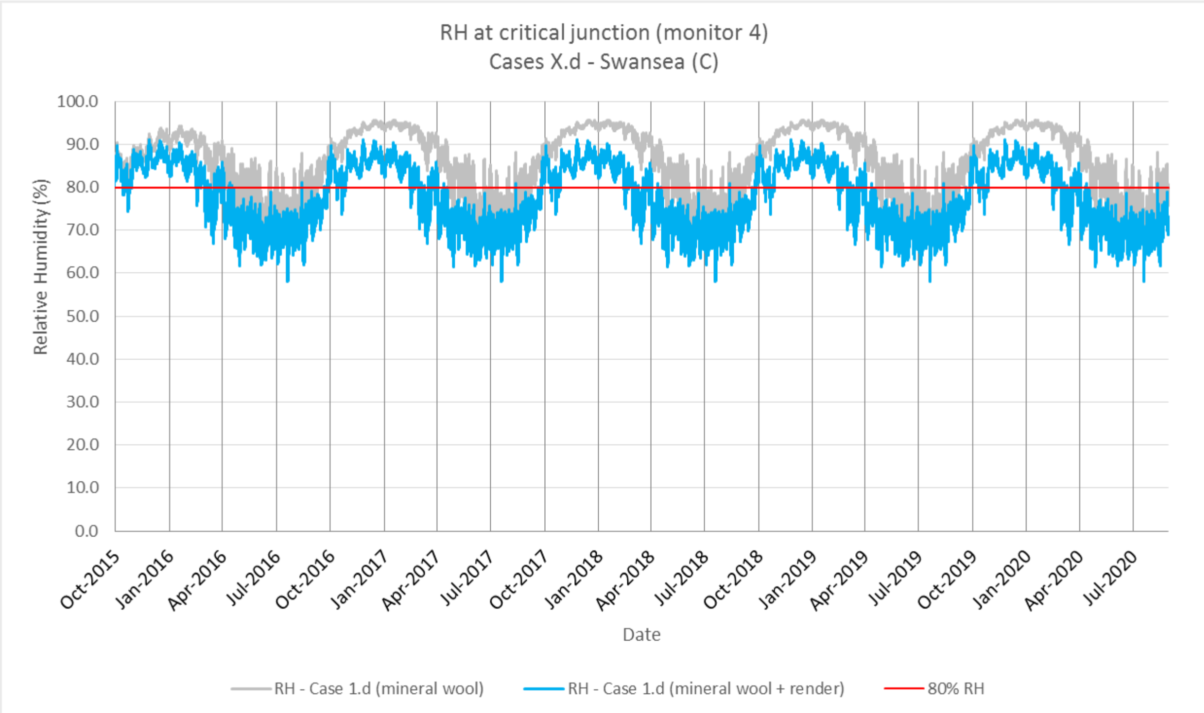


Figure 77: RH levels at critical junction for Cases 1.d (mineral wool) and 1.d (mineral wool + render)

The positive effect of the render, reducing the water ingress into the build-up, shows a direct and constant reduction of about 8% in the RH levels at the critical junction. This is still not enough to bring the build-up to a fully 'safe' status but the hygrothermal performance of the build-up is still significantly improved. With more research by refining the characteristics of the render (thickness, vapour resistivity, etc.), it might be possible to ensure this build-up to always perform safely.

13.7. Conclusions

- BS EN 15026 is the only adequate method (though still not standardised)
- Build-up very risky in ‘theoretical’ conditions
- Build-up performance significantly improved with additional external layer (to reduce wind-driven rain ingress in the concrete layer)
- BS EN 5250 guidance not up-to-date as change from rigid to breathable insulation offers no significant improvements and the presence of AVCL does not seem to improve the hygrothermal performance of the build-up
- Need to add ‘improvement’ measures (good render, change in insulation material: wood fibre and inclusion of ‘clever’ membrane, etc.) to move towards a more systematic ‘safe’ hygrothermal performance of the build-up

14. Typology N9: Solid Wall - External insulation with a non-porous finish

The N9 typology is a new-build solid concrete wall, insulated externally with closed-cell insulation with a non-porous finish.

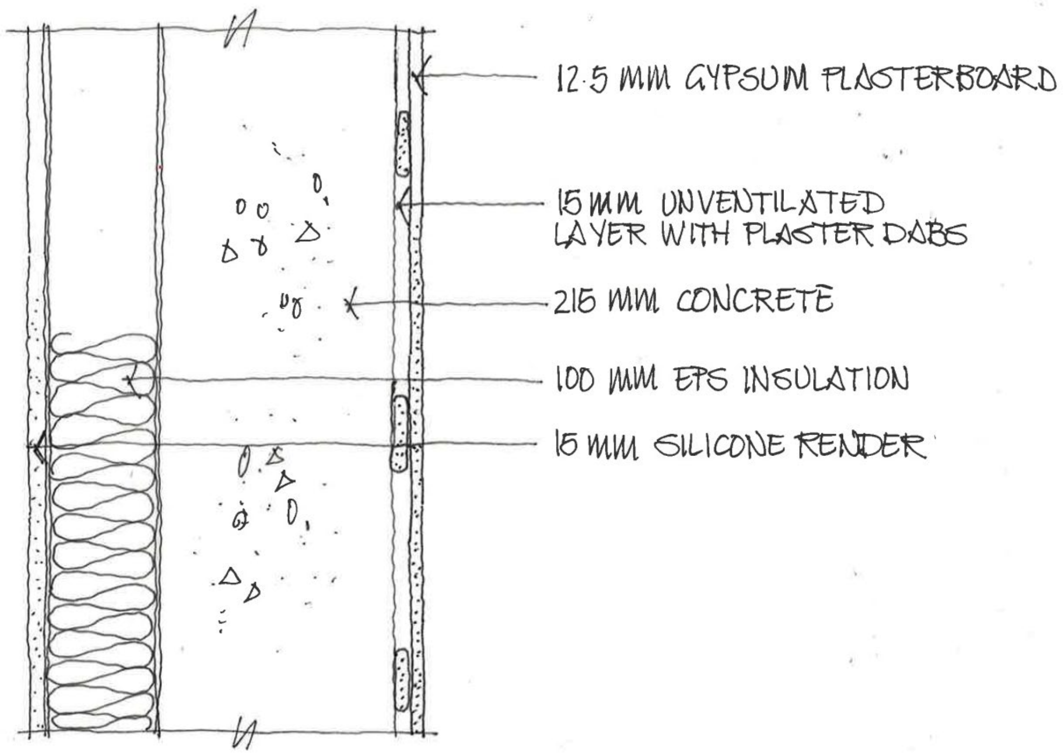


Figure 78: Illustration of the build-up of the typology

14.1. Assessment Method

The build-up contains porous materials having the capacity to store moisture, however, the porous material (concrete layer)'s external surface is not directly exposed to the elements (rain, wind and radiations). Therefore, the BS EN ISO 13788 (2012) assessment method is valid for this typology.

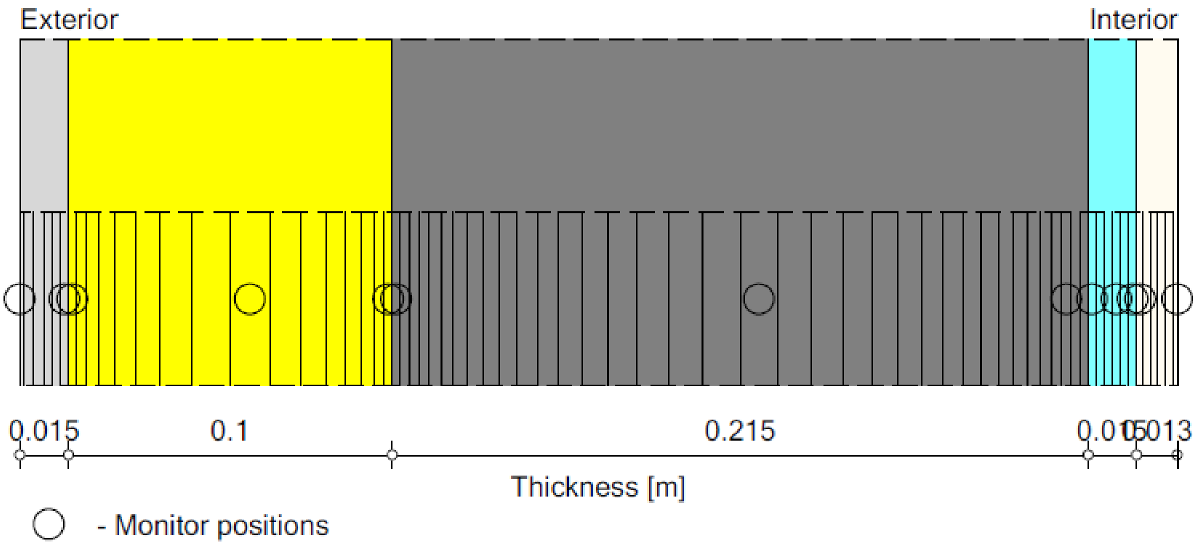
The results by the Glaser method show that this build-up is considered a 'safe' build-up, with no risk of interstitial condensation. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

14.2. Build-up

Below is the build-up of the typology, as modelled in WUFI.

<u>Build-Up:</u>

- 15mm silicone render
- 43mm // 100mm // 220mm EPS insulation (λ = 0.040 W/m.K)
- 215mm concrete layer
- 15mm unventilated air layer with plaster dabs
- 12.5mm gypsum plasterboard



Materials:

	- Silicon Resin Finishing Coat	0.015 m
	- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	0.1 m
	- Concrete, C35/45	0.215 m
	- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
	- Gypsum Board	0.013 m

14.3. Baseline Results

14.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set below.

Table 37: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

14.3.2. Critical / Monitored Junction

Moisture problems tend to be exacerbated at interfaces, as they are locations at which moisture can accumulate or get trapped. In this case, as the interface between the insulation and the concrete layer is located on the warm side of the insulation, this junction should not be at risk as its temperature is kept above the dew point. But this is the interface monitored in this typology, as this is the interface at which moisture could get trapped.

14.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction – interface between the insulation and the concrete layer, interface being on the warm side of the insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

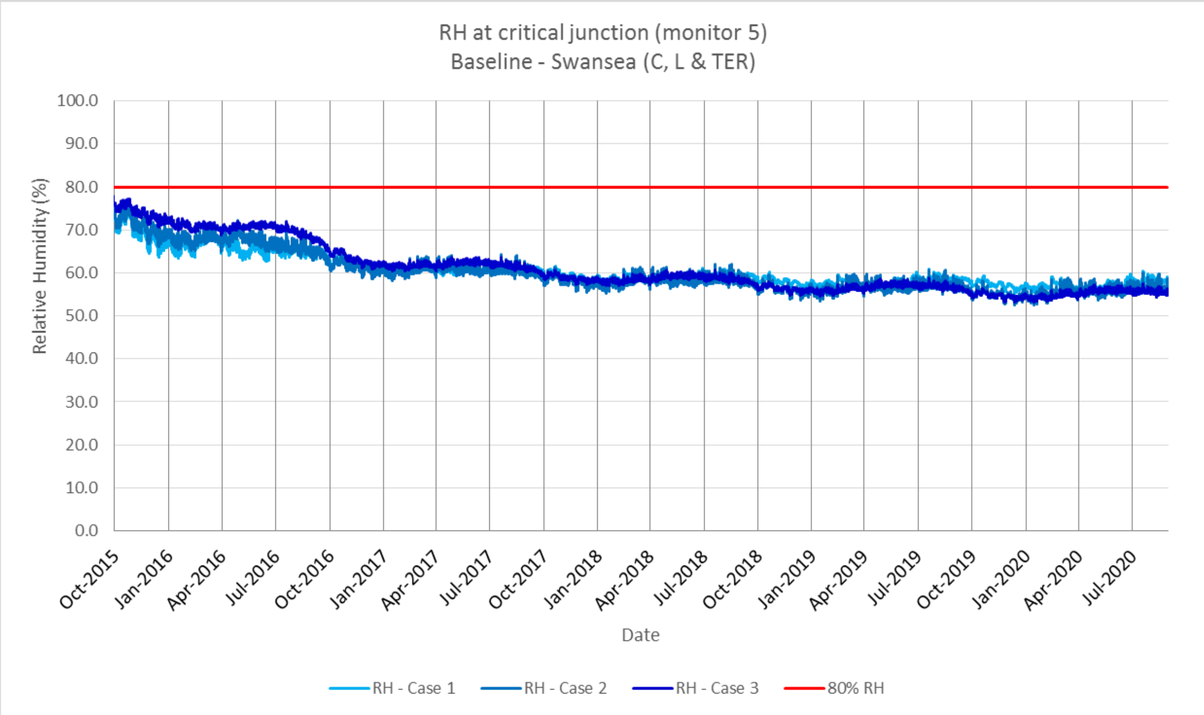


Figure 79: RH levels at critical junction for Cases 1, 2 and 3

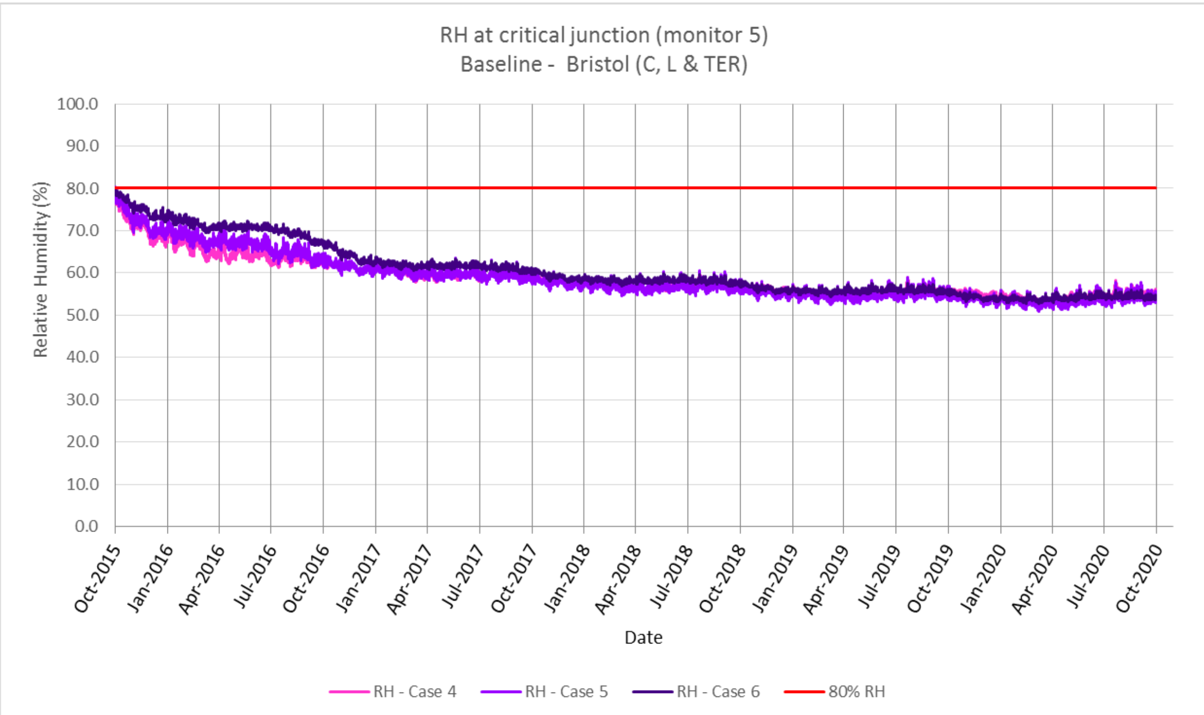


Figure 80: RH levels at critical junction for Cases 4, 5 and 6

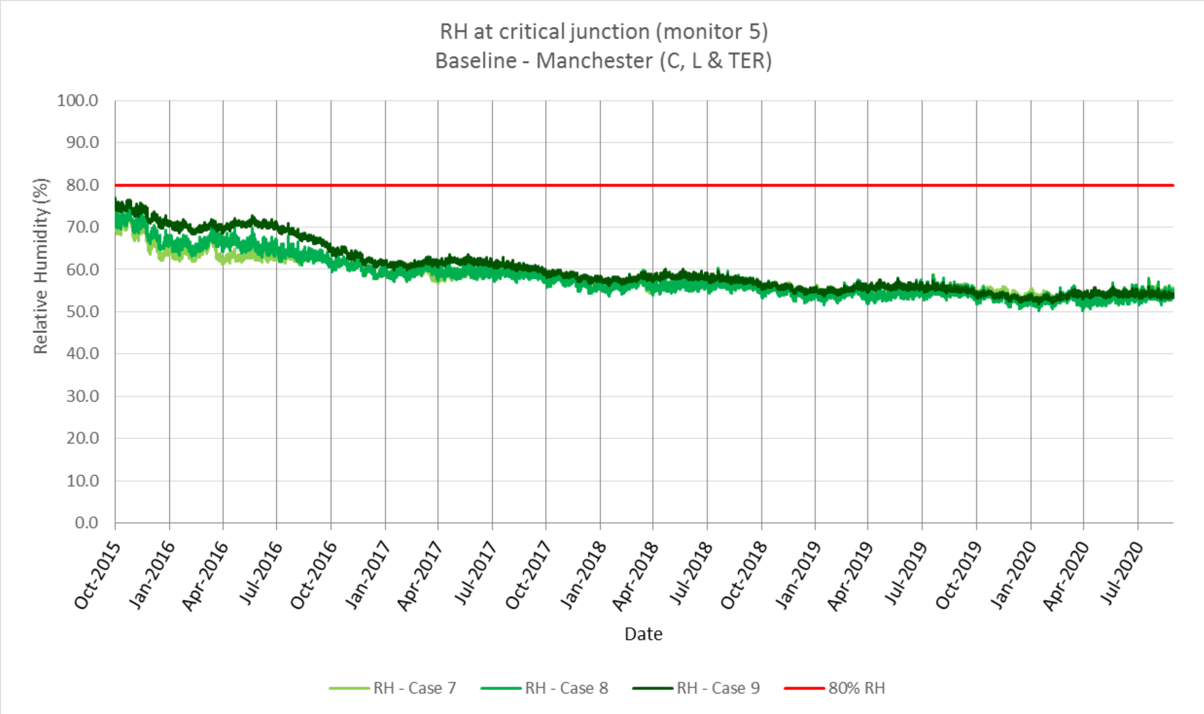


Figure 81: RH levels at critical junction for Cases 7, 8 and 9

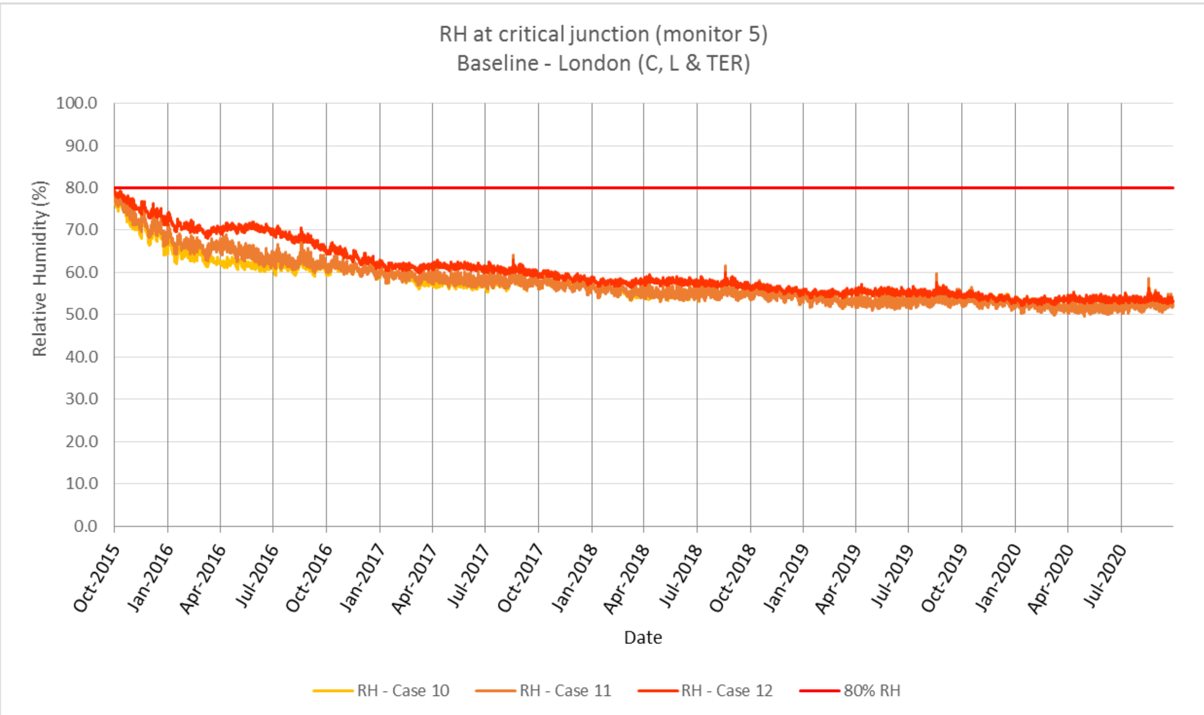


Figure 82: RH levels at critical junction for Cases 10, 11 and 12

14.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

As predicted, all scenarios are a ‘pass’ as they do not accumulate moisture, they are drying out towards equilibrium and have RH levels well below 80% (after initial conditions). These results are summarised in the table below.

Table 38: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in line with current practice in the industry, as this is one of the typologies considered highly resistant to moisture (when installed adequately).

<u>Effects of exposure zones and U-values</u>

The effect of wind-driven rain exposure zones is almost undistinguishable on the graphs, as all RH levels at the monitored junctions look similar for all cases, with RH levels well within the ‘safe’ RH levels. This confirms that this typology is considered good regarding its resistance to moisture.

The effect of the U-value levels is slightly visible on the graphs, with better U-value cases taking longer to dry out towards equilibrium from wetter initial conditions. This is due to the fact that, with similar boundary conditions, moisture movements will be slower through a much thicker insulation layer (compared to thinner insulation layers for the cases with poorer U-values).

14.3.5. Conclusions - Baseline

In accordance with current best practice in the industry, this typology is found to be resistant to moisture, as independently to the wind-driven rain exposure zone the build-up is located in and the amount of insulation installed externally, the RH levels at the monitored junction are well within the ‘safe’ and recommended RH levels. This is due to the fact that this interface between the insulation and the concrete layer is kept above the dew point, as a result of the insulation layer.

The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up

14.4. Sensitivity Analysis – Change in Internal Moisture Load [Cases X.a]

14.4.1. Sensitivity Analysis Cases

One of the most common sensitivity analysis performed in this modelling work is regarding the change in internal moisture load, from typical to poorer conditions (called 'high' moisture load) following the BS EN 15026 (2007) procedure (described in Annex C of BS EN 15026 (2007)).

As the baseline cases showed that the difference in exposure zones does not have an impact on the hygrothermal performance of the build-up, only cases for Zone 4 – Swansea are modelled in this sensitivity analysis, as set below.

Table 39: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.a	-	-	-
Part L	Case 2.a	-	-	-
TER	Case 3.a	-	-	-

14.4.2. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the junction where potential problems could be seen, at the interface between the insulation and the concrete layer, for the three cases located in Zone 4.

For these results, the sensitivity analysis cases X.a tested here (i.e. high moisture load) are displayed as a coloured line against their respective baseline cases, displayed with a grey line.

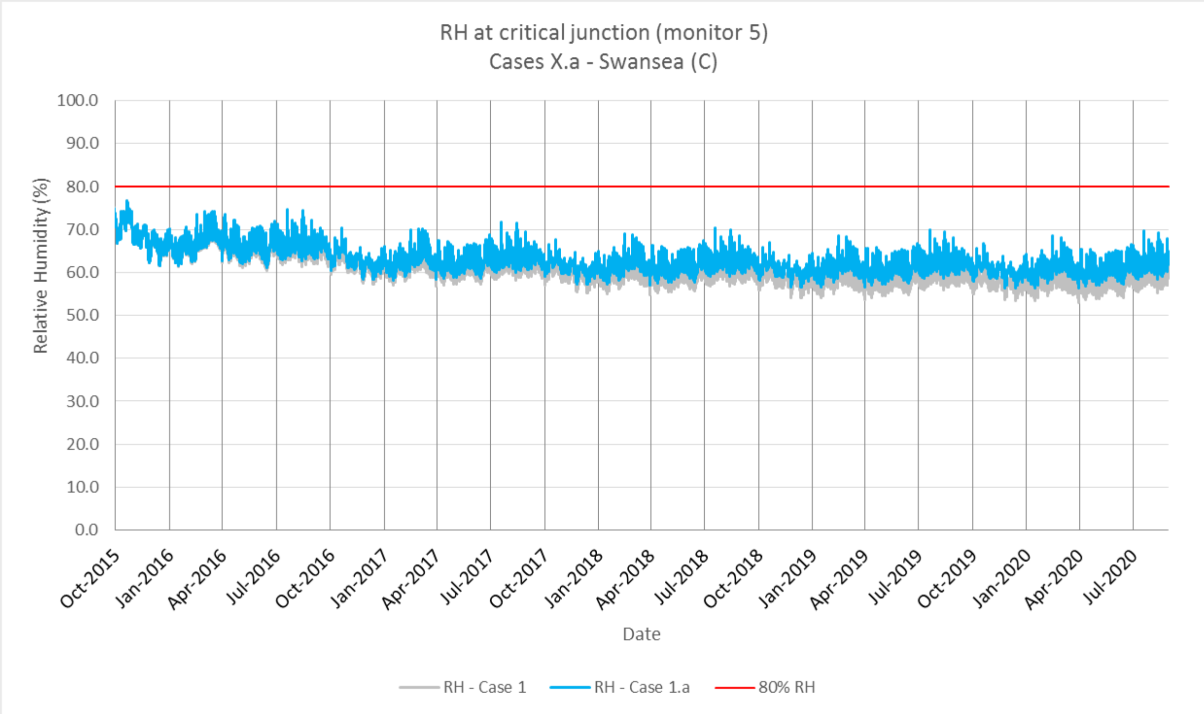


Figure 83: RH levels at critical junction for Cases 1 and 1.a

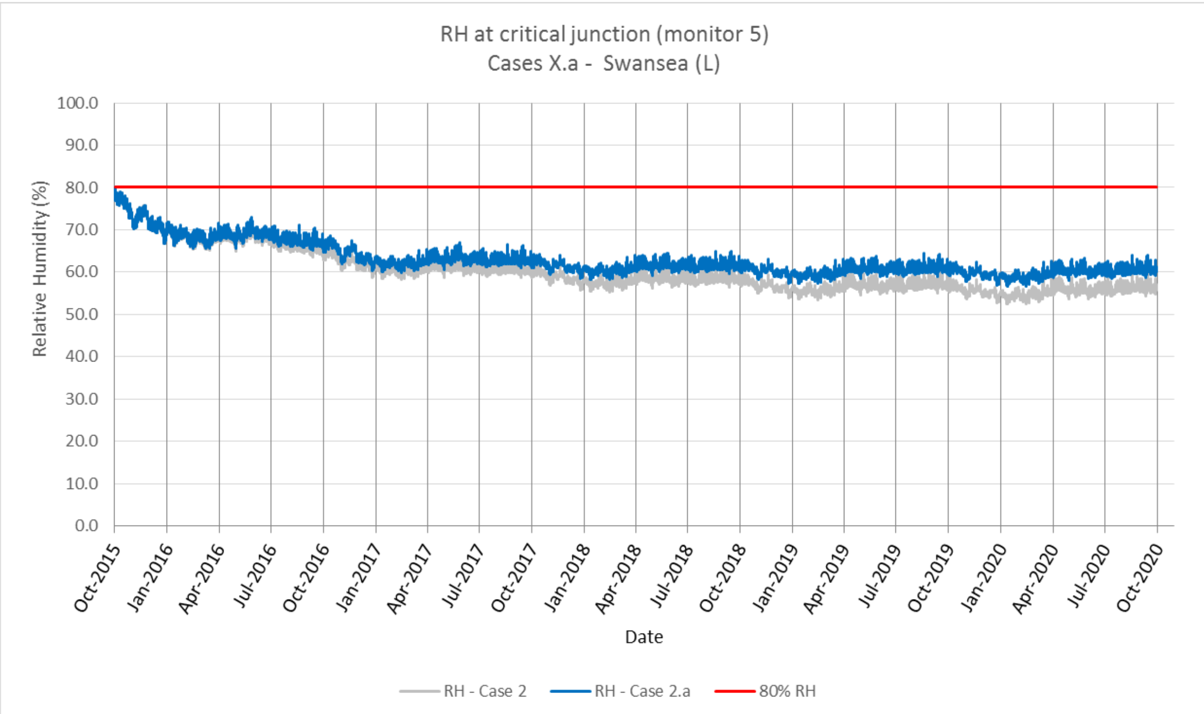


Figure 84: RH levels at critical junction for Cases 2 and 2.a

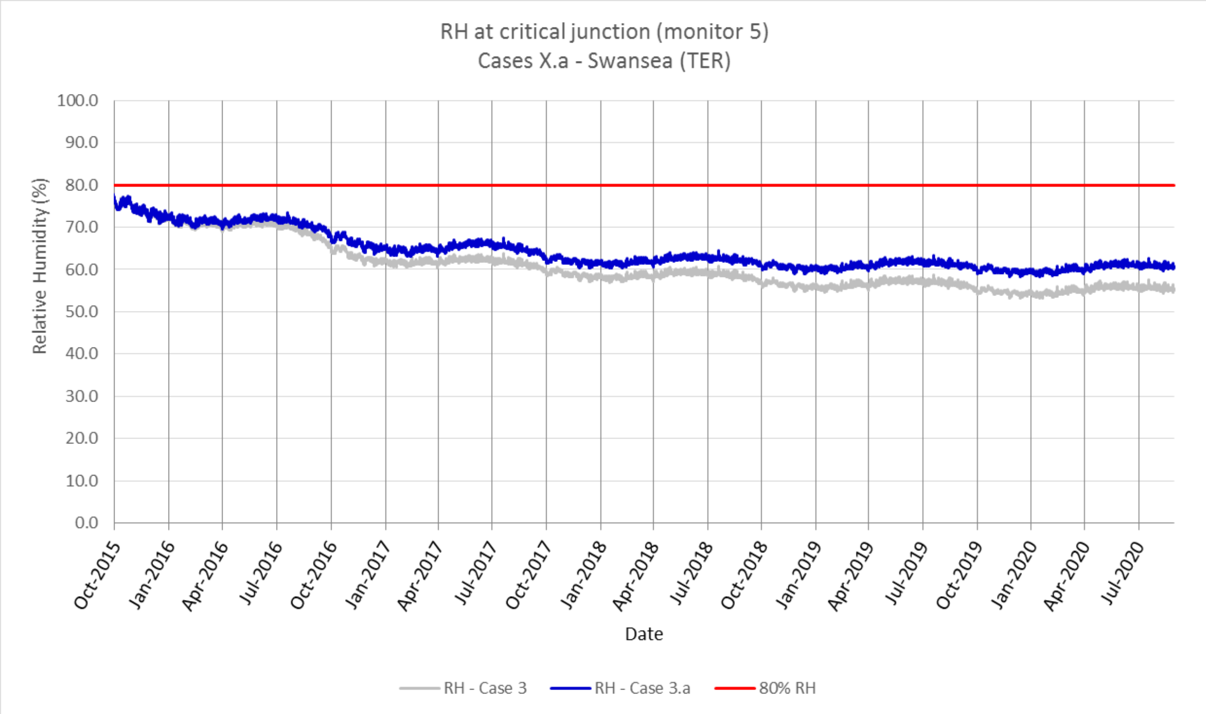


Figure 85: RH levels at critical junction for Cases 3 and 3.a

14.4.3. Conclusions – Sensitivity Analysis Cases X.a

<u>Moisture risk assessment criteria</u>

As predicted – due to the deterioration of indoor conditions, the graphs show that the cases modelled in this sensitivity analysis X.a perform worse compared to the baseline cases. All cases simulated here still pass, though the effect of higher internal moisture load is directly visible at the monitored junction, where an increase of internal RH levels by 10% leads to an increase of RH levels at the monitored junction between 3% and 6% (while remaining well within recommended RH levels below 80%).

Results

The table below summarises the performance of each case modelled (as well as non-simulated cases, where results are listed by deduction), following the moisture risk assessment criteria listed in section3.3:

All cases are considered a ‘pass’, as they do not accumulate moisture and the build-up slowly dries towards an equilibrium (equilibrium now slightly higher than in the baseline cases, due to poorer internal moisture conditions), which is still within recommended RH levels.

Table 40: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.a Pass	Case 4.a Pass	Case 7.a Pass	Case 10.a Pass
Part L	Case 2.a Pass	Case 5.a Pass	Case 8.a Pass	Case 11.a Pass
TER	Case 3.a Pass	Case 6.a Pass	Case 9.a Pass	Case 12.a Pass

Effects of ‘high’ moisture load (internal conditions)

Similarly to other sensitivity analyses regarding the deterioration of indoor conditions, the increase of RH levels at the monitored junction is not significant enough in this sensitivity analysis to change the status of the simulations from ‘pass’ to ‘risky’ / ‘fail’ but it is important to remember that the conditions described as ‘high’ moisture load following BS EN 15026 (2007) are not considered the most extreme internal conditions a building could be in – likely due to very poor ventilation, higher occupancy, etc.

This typology is a one of the safer typologies regarding resistance to moisture, with this build-up reaching RH levels at equilibrium much lower than RH levels setting the ‘pass’/’risky’ limit. In addition, any intermittent peaks in RH levels are also attenuated by the ability of the concrete layer to store high levels of moisture, which makes this build-up even safer.

Therefore, the deterioration of internal conditions has a detrimental effect on the hygrothermal performance of the build-up, which is directly visible at the monitored junction. So it is likely that the deterioration of internal moisture conditions will, starting at a certain level (likely to be extremely high for this typology), lead to the failure of the build-up.

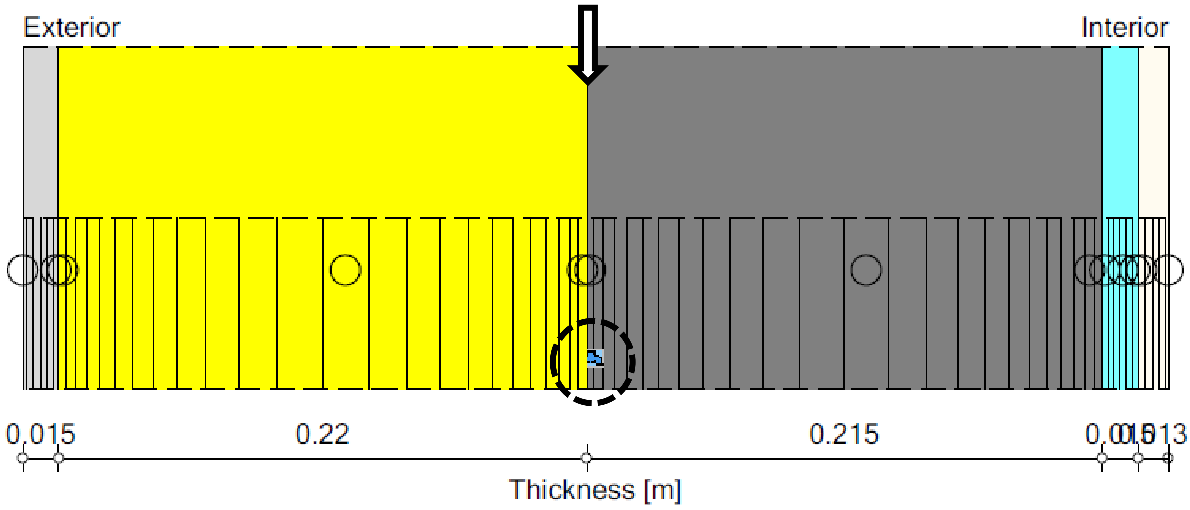
14.5. Sensitivity Analysis – Change in Workmanship [Cases X.b]

14.5.1. Sensitivity Analysis Cases

The next sensitivity analysis undertaken on this typology assesses the impact of poor workmanship, through the use of non-standardised modelling using the ASHRAE 160 method.

ASHRAE 160 is the first standard which does not assume perfect workmanship and postulates that a perfect build-up does not exist in practice. Therefore, under ASHRAE 160, this is modelled with hygrothermal modelling done with additional water ingress. This additional moisture source is modelled as an additional fraction of wind-driven rain penetrating the build-up, through a rain penetration factor of 1%. However, care is needed on the use of the 1% rain penetration factor. This figure, used in the ASHRAE 160 method, has never been validated outside of the US, and therefore a bracketing approach – using scenarios with a 0.5%, 1% and 1.5% rain penetration factor – is considered a more robust approach to get a good insight when considering the effects of moisture ingress on the performance of this typology.

For this sensitivity analysis, this additional moisture source is located behind the insulation (in the outer 5mm of the layer behind the insulation). This location was chosen to represent one of the critical positions for water ingress with this build-up – water ingress around window installations (as shown on the following build-up).



◯ - Monitor positions

- Heat/Moisture source/sink positions

Materials:

- Silicon Resin Finishing Coat	0.015 m
- EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	0.22 m
- Concrete, C35/45	0.215 m
- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
- Gypsum Board	0.013 m

As the baseline cases showed that the difference in exposure zones does not have an impact on the hygrothermal performance of the build-up, only cases for Zone 4 – Swansea are modelled in this sensitivity analysis, as set out below.

Table 41: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.b (0.5%) Case 1.b' (1.0%) Case 1.b'' (1.5%)	-	-	-
Part L	Case 2.b (0.5%) Case 2.b' (1.0%) Case 2.b'' (1.5%)	-	-	-
TER	Case 3.b (0.5%) Case 3.b' (1.0%) Case 3.b'' (1.5%)	-	-	-

14.5.2. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the same monitored junction where potential problems could be seen, at the interface between the insulation and the concrete layer, for the TER cases (chosen out of the 3 cases) located in Zone 4.

For these results, the sensitivity analysis cases X.b tested here (i.e. poor workmanship) are displayed as grey lines (the darker the line, the higher the rain penetration factor) against the respective baseline case, displayed with a coloured line.

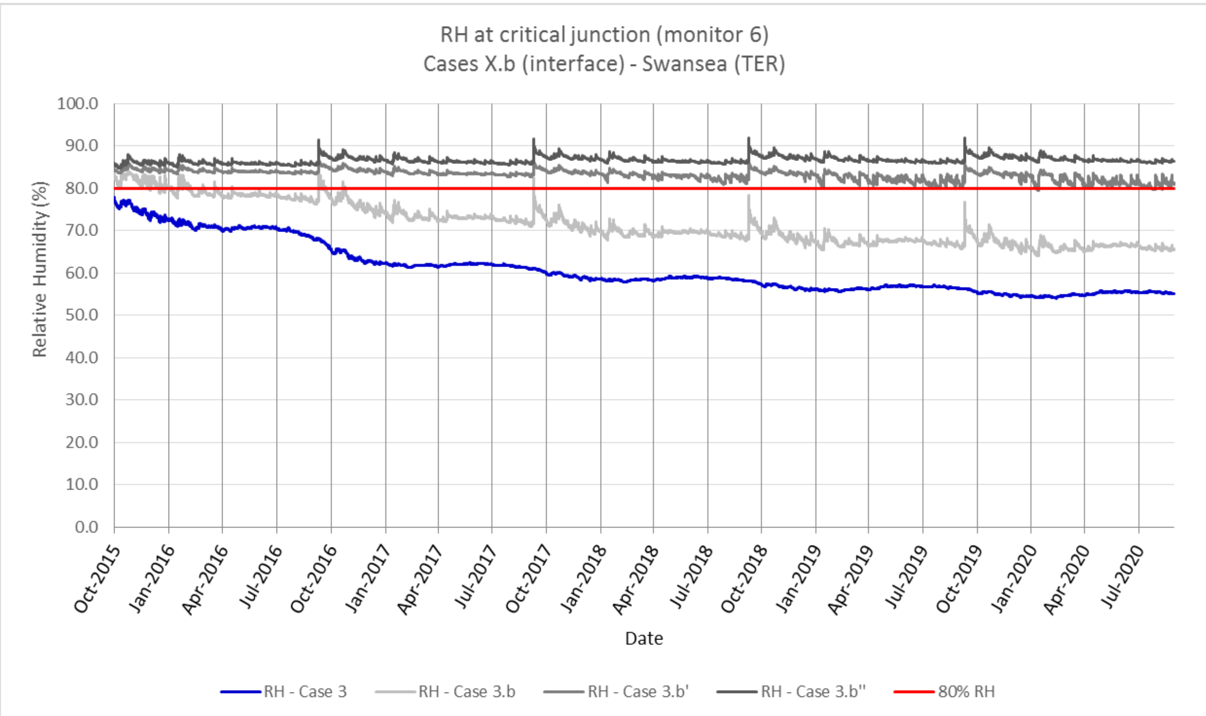


Figure 86: RH levels at critical junction for Cases 3, 3.b, 3.b' and 3.b''

14.5.3. Conclusions – Sensitivity Analysis Cases X.b

Moisture risk assessment criteria

As suspected, the deterioration of workmanship modelled through additional moisture source penetrating the build-up, has a detrimental effect on the hygrothermal performance of the build-up.

The higher the rain penetration factor (i.e. the higher the percentage of additional water ingress entering the build-up), the more at risk the build-up is. A 0.5% rain penetration factor for the moisture source is enough to raise the RH levels at the monitored junction by about 10%. As the baseline build-up has a robust performance with very low RH levels at the monitored junction, this 10% increase in RH levels is not enough to cause moisture risk to the build-up, i.e. for the build-up to fail the assessment. However, with a rain penetration factor of 1% and above, the RH levels at the monitored junction are above recommended RH levels, leading to the failure of the build-up.

In addition, as the monitored junction is located behind the insulation, the temperature at which the interface is kept is relatively warm throughout the year, i.e. during the peaks of RH levels. It is also unlikely for the walls and insulation boards to be perfectly flat, which could lead to the presence of air gaps. This means that although the presence of food for mould spores is not ideal, this interface displays the right conditions to promote mould growth. However, this might not be an issue as important as in other cases (such as with internal wall insulation (IWI)) as the risk of mould growth is located in the outer side of the concrete layer (i.e. outside of the structure).

In both sensitivity analysis cases with a rain penetration factor of 0.5% and 1%, the total water content in the build-up decreases slowly with time before reaching equilibrium. In contrast, the worst case of this sensitivity analysis (with a 1.5% rain penetration factor) has its total water content profile continuously increasing. This means that the first moisture risk assessment criteria is not met anymore and that this case has reached the tilting point of the build-up’s moisture risks.

The water content in the insulation layer is also demonstrating higher levels than seen in the baseline case. The typical water content in EPS is set at 1.79 kg/m^3 and reduces around a range of 0.9 kg/m^3 to 1.7 kg/m^3 (throughout the seasons) when reaching equilibrium. In contrast, the case X.b’’ with the 1.5% rain penetration factor shows water content ranging 3 kg/m^3 to 4.5 kg/m^3, which is much higher than in the baseline case. This increase in water content in the insulation will also have a detrimental effect on the insulating capability of the insulation, as EPS is a material modelled in WUFI with a moisture-dependent thermal conductivity.

Results

The table below summarises the performance of each case modelled, following the moisture risk assessment criteria listed in section 2.3:

Table 42: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.b (0.5%) Pass Case 1.b' (1.0%) Risky Case 1.b'' (1.5%) Fail	-	-	-
Part L	Case 2.b (0.5%) Pass Case 2.b' (1.0%) Fail Case 2.b'' (1.5%) Fail	-	-	-
TER	Case 3.b (0.5%) Pass Case 3.b' (1.0%) Fail Case 3.b'' (1.5%) Fail	-	-	-

Effects of additional water ingress (due to poor workmanship)

All cases with a 0.5% rain penetration factor are considered a 'pass' whilst worsening the build-up performance. All cases with a 1% and 1.5% rain penetration factor are considered 'fail' (with one scenario considered only 'risky') as RH levels are kept above recommended levels and moisture starts accumulating in the build-up for the 1.5% rain penetration factor scenario.

The deterioration of external conditions via the introduction of additional water ingress in the build-up at critical junctions (e.g. around window installations in this sensitivity analysis) has a significant detrimental effect on the hygrothermal performance of the build-up.

14.6. Sensitivity Analysis – Change in Material [Cases X.d]: Change from rigid to compressible insulation

14.6.1. Baseline versus BS 5250 (2011) Guidance

It is important to note that this build-up does not reflect the build-ups that are recommended in BS 5250 (2011). Two build-ups are currently presented in BS 5250 (2011):

Build-up #1: 'EWI with low vapour resistance protective finish'

The build-up is drawn as follow:

- Internal finish
- AVCL (if required)
- Concrete structure
- Compressible insulation (which is described as normally having a low vapour resistivity)
- Low vapour resistance protective finish

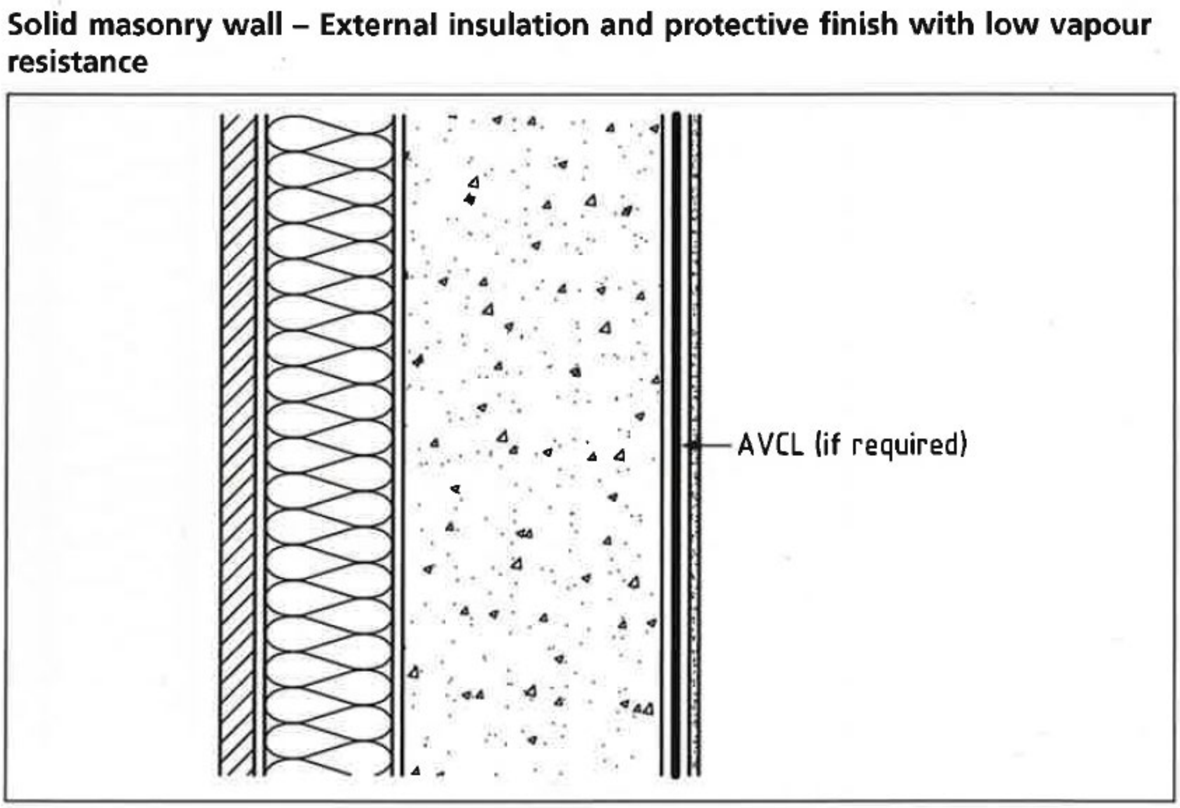


Figure 87: Illustration of the build-up of the typology (Figure G.1, Solid masonry wall - external insulation and protective finish with low vapour resistance, BS 5250 (2011)

Please note that there is not a clear definition of a low vapour resistance protective finish in the BS 5250 (2011) guidance, but only a comment in the text stating that a render and a ventilated cladding are considered low vapour resistance protective finishes.

Paragraph G3.1.2 of BS 5250 (2011) states that *'dependent upon the thickness and composition of the wall, the insulant and the protective layer, there is a risk of interstitial condensation and a condensation risk analysis should be performed to determine whether an internal AVCL is needed'*

<u>Build-up #2: 'EWI with high vapour resistance protective finish'</u>

The build-up is drawn as follow:

- Internal finish
- Concrete structure
- AVCL
- Rigid insulation (which is described as normally having a high vapour resistivity)
- Ventilated cavity
- High vapour resistance protective finish

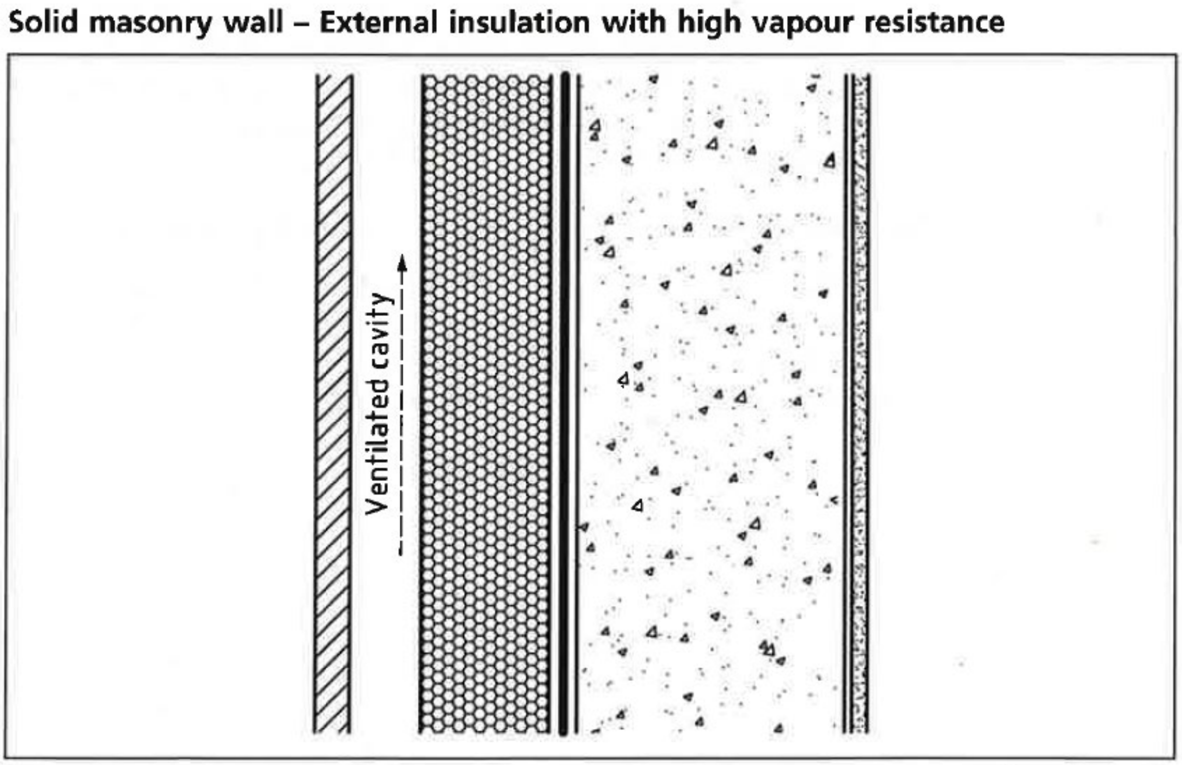


Figure 88: Illustration of the build-up of the typology (Figure G.2, Solid masonry wall - external insulation with high vapour resistance, BS 5250 (2011))

Due to a highly vapour resistant finish, the guidance recommends for a ventilated cavity to be installed between the finish and the insulation layer. This means that the build-up (from the insulation to the interior finish) is not directly exposed to the exterior climate anymore (wind-driven rain, solar radiations and wind). This typology is already known to be one of the most robust typologies regarding moisture resistance and the fact that the build-up #2 is now not directly exposed to the exterior climate only makes this build-up even safer. Therefore, it seems unnecessary to model the build-up #2 to assess its hygrothermal performance and the sensitivity analysis done here will focus on build-up #1.

14.6.2. Sensitivity Analysis Cases

In this sensitivity analysis, the rigid insulation layer (EPS) is replaced with compressible insulation. As the data in the WUFI database regarding compressible insulation materials used for EWI might not be adequate (due to small number of materials available in the WUFI database), data was taken directly from one of the main UK stone wool EWI insulation suppliers.

As the baseline cases showed that the build-up passed in the worst exposure zones (i.e. Zone 4 – Swansea), these cases are the only cases modelled in this sensitivity analysis.

The three cases are set across the Zone 4 wind-driven rain exposure zone, matching the three target U-values (as per baseline cases) as set out below.

Table 43: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

14.6.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the same monitored junction, at the interface between the insulation and the concrete layer, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

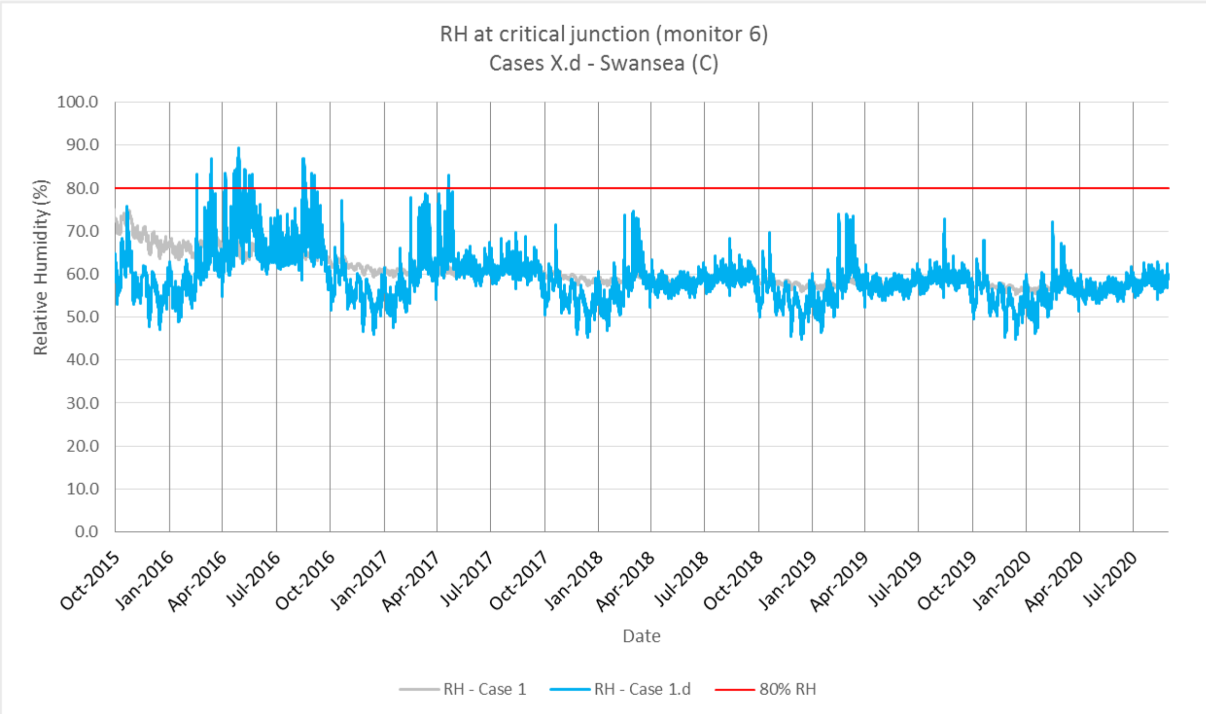


Figure 89: RH levels at monitored junction for Cases 1 and 1.d

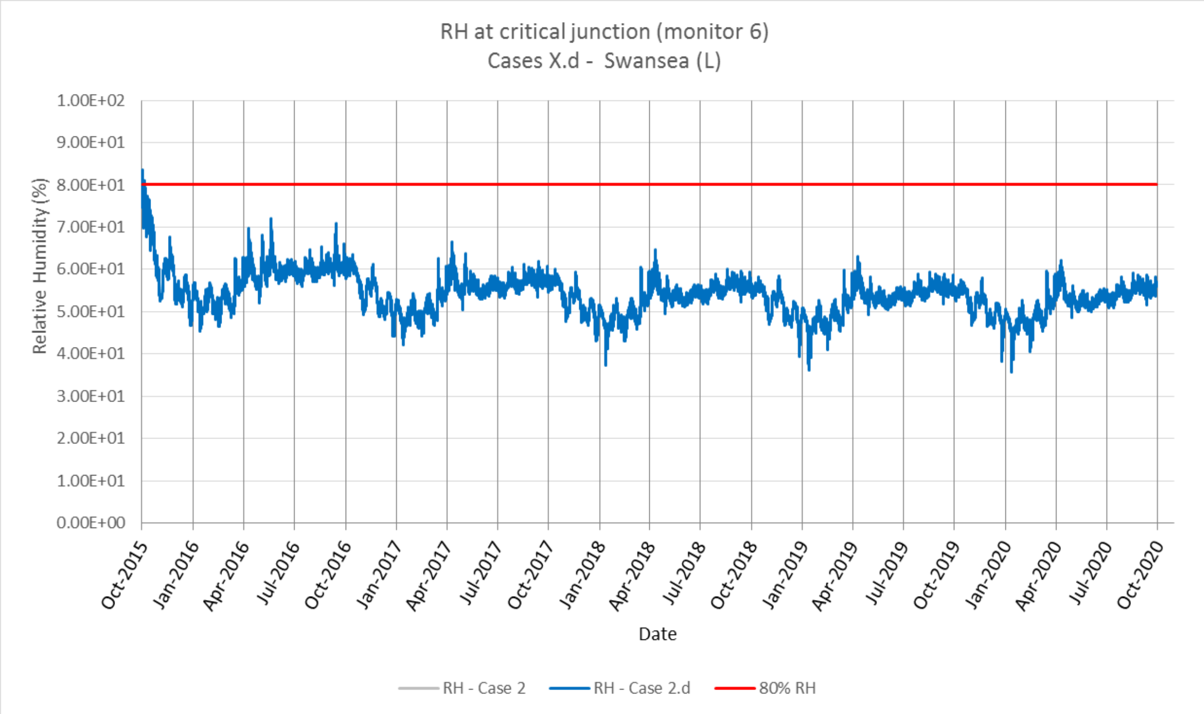


Figure 90: RH levels at monitored junction for Cases 2 and 2.d

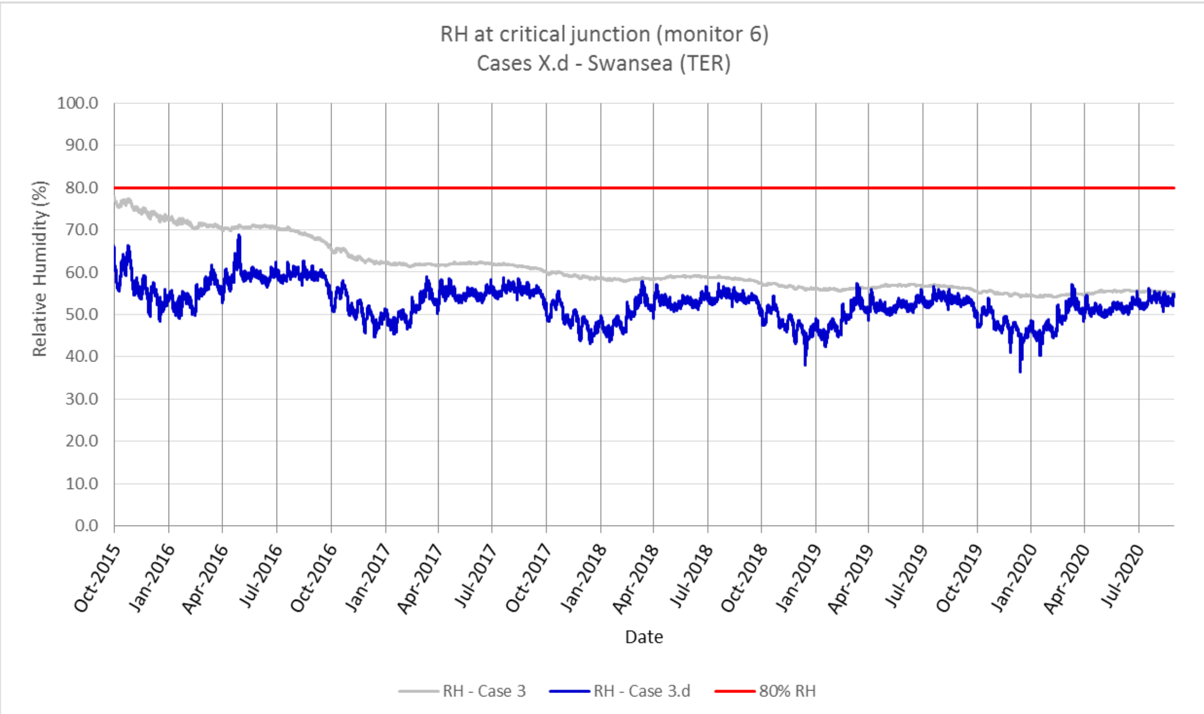


Figure 91: RH levels at monitored junction for Cases 3 and 3.d

14.6.4. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

In this sensitivity analysis, moisture does not accumulate in the build-up and RH levels are kept below the 80% RH threshold for the entire modelling period, similarly to the baseline cases. The RH profiles display a different compared to the baseline, due to the different characteristics (especially vapour resistance diffusion factor) between the rigid EPS insulation (baseline) and the stone wool insulation (sensitivity analysis).

Results

Table 44: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

The change of insulation type does not have an effect on the hygrothermal performance of the build-up regardless of its insulation thickness.

14.7. Conclusions

- Build-up very safe in ‘theoretical’ conditions
- Deterioration of indoor conditions directly reflected at critical junction – pushing the build-up closer to ‘risky’ / ‘fail’ → MEDIUM effect / link
- Deterioration of external conditions / workmanship (tested here around window installations) reflected at monitored junction → STRONG effect / link so build-up less ‘robust’ than others. Need to follow ‘best practice’ installation guidance
- BS EN ISO 13788 (2012) has potential for being a sufficient method to assess the performance of EWI build-up (no need for BS EN 15026 (2007) if proper ‘best practice’ guidance for design and installation followed)

15. Typology N10: Solid wall- External and internal insulation with a non-porous finish (Insulated concrete formwork)

The N10 typology is a new-build solid Insulated concrete formwork wall, insulated internally and externally with closed-cell insulation with a non-porous finish.

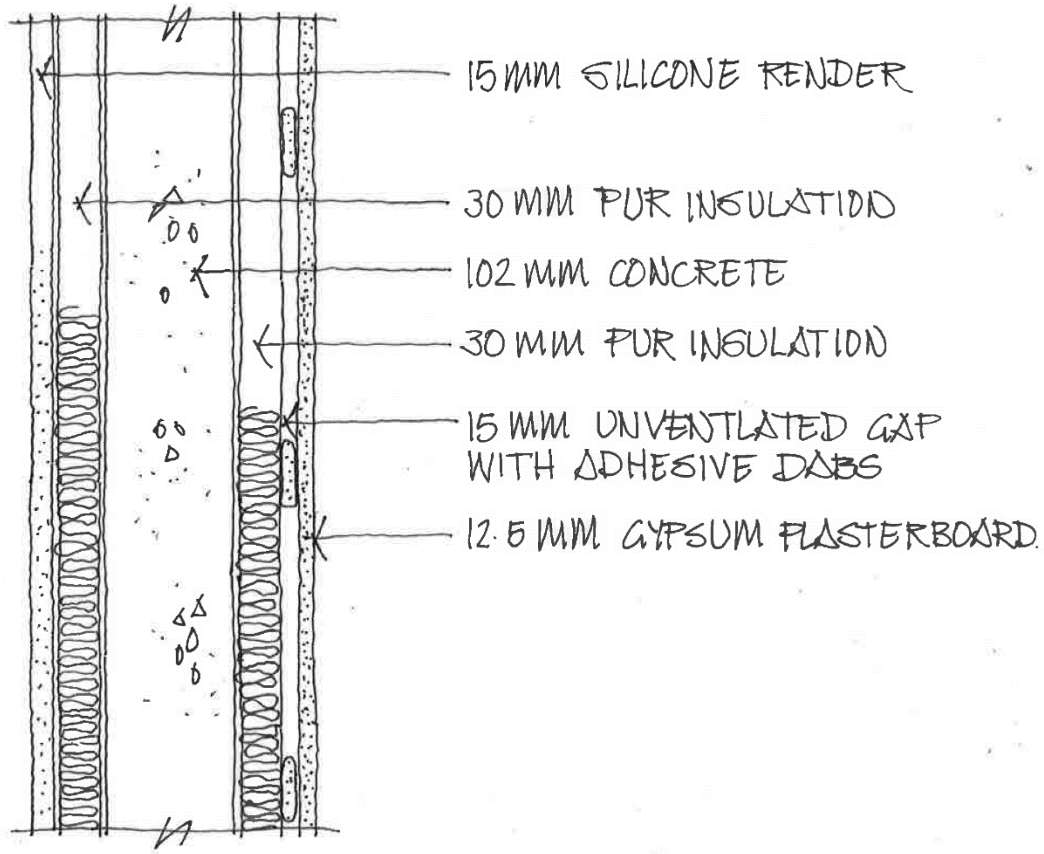


Figure 92: Illustration of the build-up of the typology (Part L case)

15.1. Assessment Method

The build-up contains porous materials (concrete layer) having the capacity to store moisture. However, the porous material's external surface is not directly exposed to the elements (rain, wind and radiations), due to the protection provided by the external insulation layer as well as the water resistant external finish. This means that the BS EN ISO 13788 (2012) assessment method is valid for this typology.

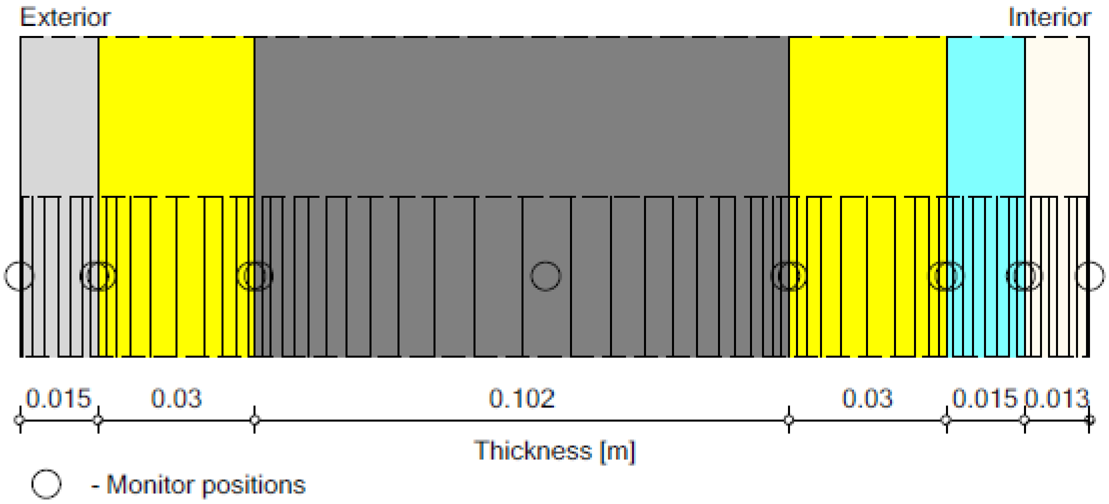
The results by the Glaser method show that this build-up is considered a ‘safe’ build-up, with a lack of interstitial condensation. This will be confirmed with some modelling done following the BS EN 15026 (2007) assessment method.

15.2. Build-up

Below is the build-up of the typology, as modelled in WUFI.

Build-Up:

- 15mm silicone render
- 14mm // 30mm // 65mm PUR insulation (λ = 0.025 W/m.K)
- 102mm concrete layer
- 14mm // 30mm // 65mm PUR insulation (λ = 0.025 W/m.K)
- 15mm unventilated air layer with plaster dabs
- 12.5mm gypsum plasterboard



Materials:

	- Silicon Resin Finishing Coat	0.015 m
	- PU (heat cond.: 0,025 W/mK)	0.03 m
	- Concrete, C35/45	0.102 m
	- PU (heat cond.: 0,025 W/mK)	0.03 m
	- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
	- Gypsum Board	0.013 m

15.3. Baseline Results

15.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set below.

Table 45: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

15.3.2. Critical Junction

Moisture problems tend to be exacerbated at interfaces, as they are locations at which moisture can accumulate or get trapped.

The critical junction is not identified in BS 5250 (2011), being located on the inner surface of the concrete layer. Therefore, all graphs will display RH levels at the interface between the concrete layer and the cold side of the internal insulation layer.

As half of the insulation is located externally to this critical junction, it is expected for the critical junction to be kept at temperatures above the dew point and therefore to not display risky levels of moisture.

15.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction – the interface between the concrete layer and the internal insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

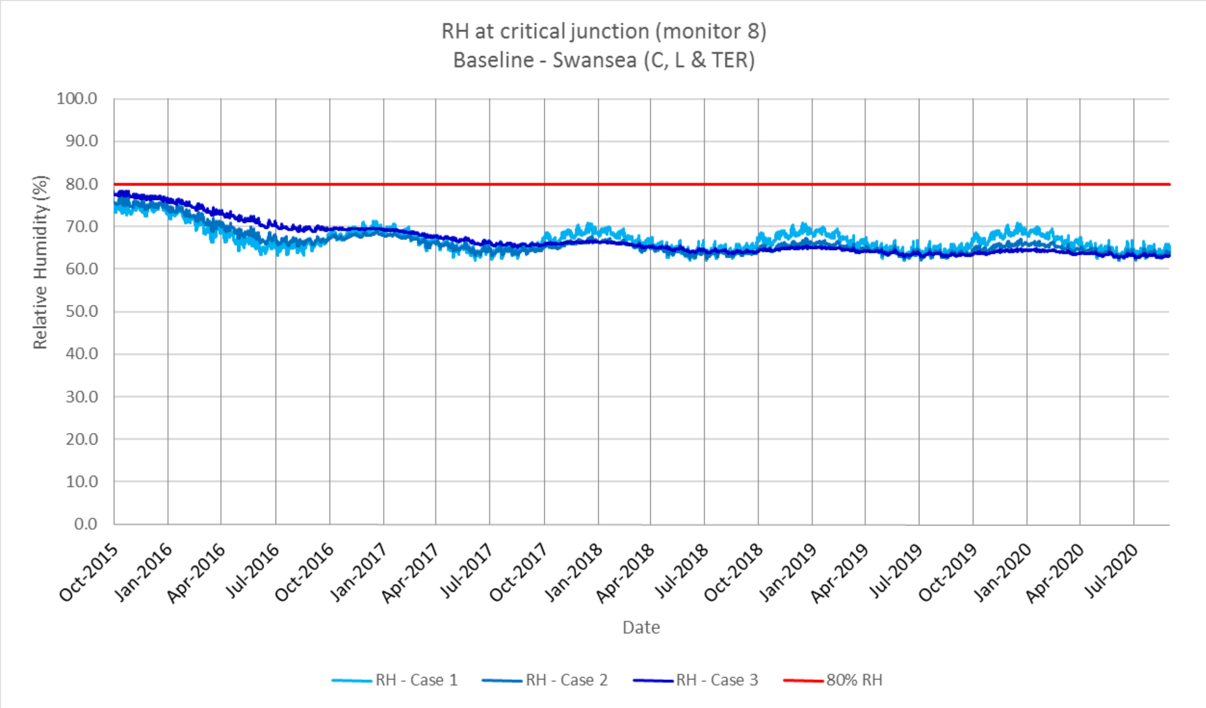


Figure 93: RH levels at critical junction for Cases 1, 2 and 3

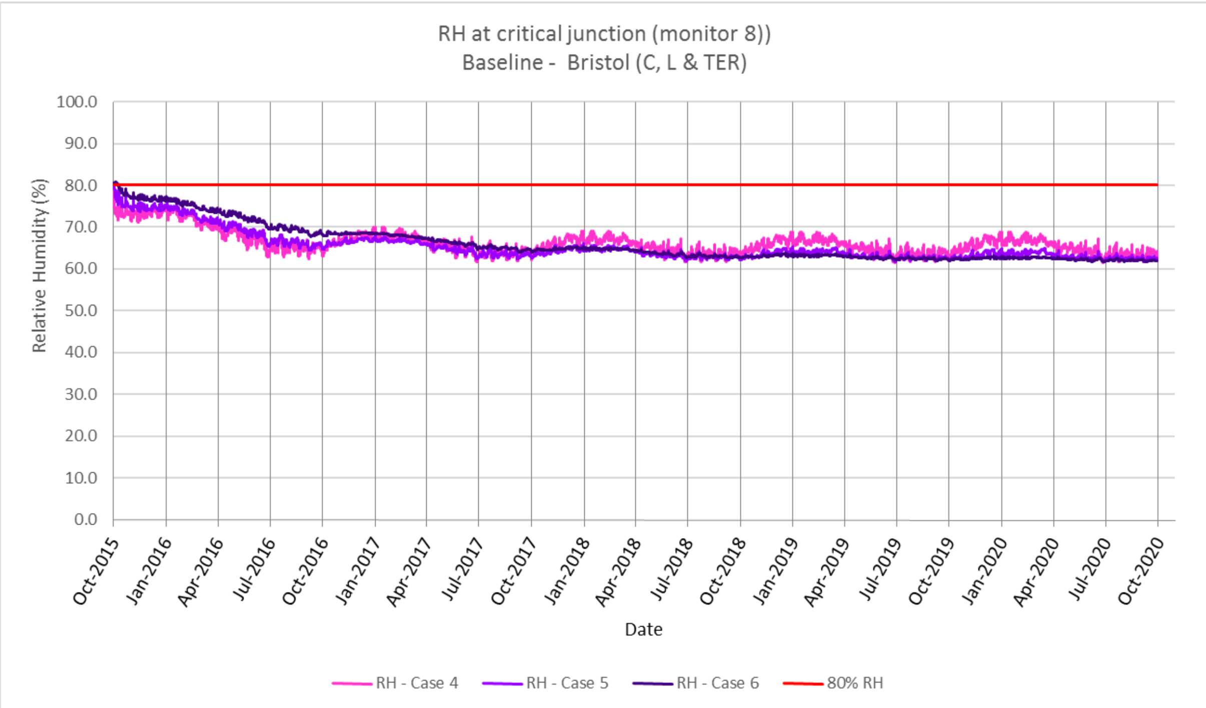


Figure 94: RH levels at critical junction for Cases 4, 5 and 6

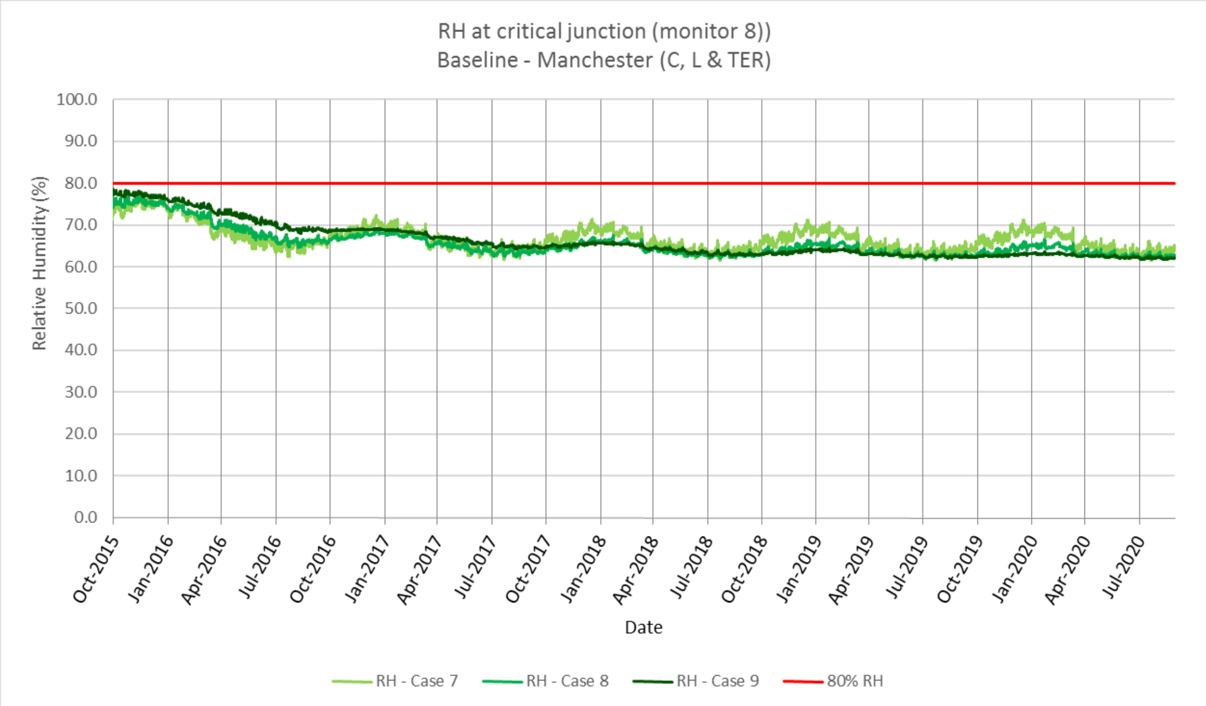


Figure 95: RH levels at critical junction for Cases 7, 8 and 9

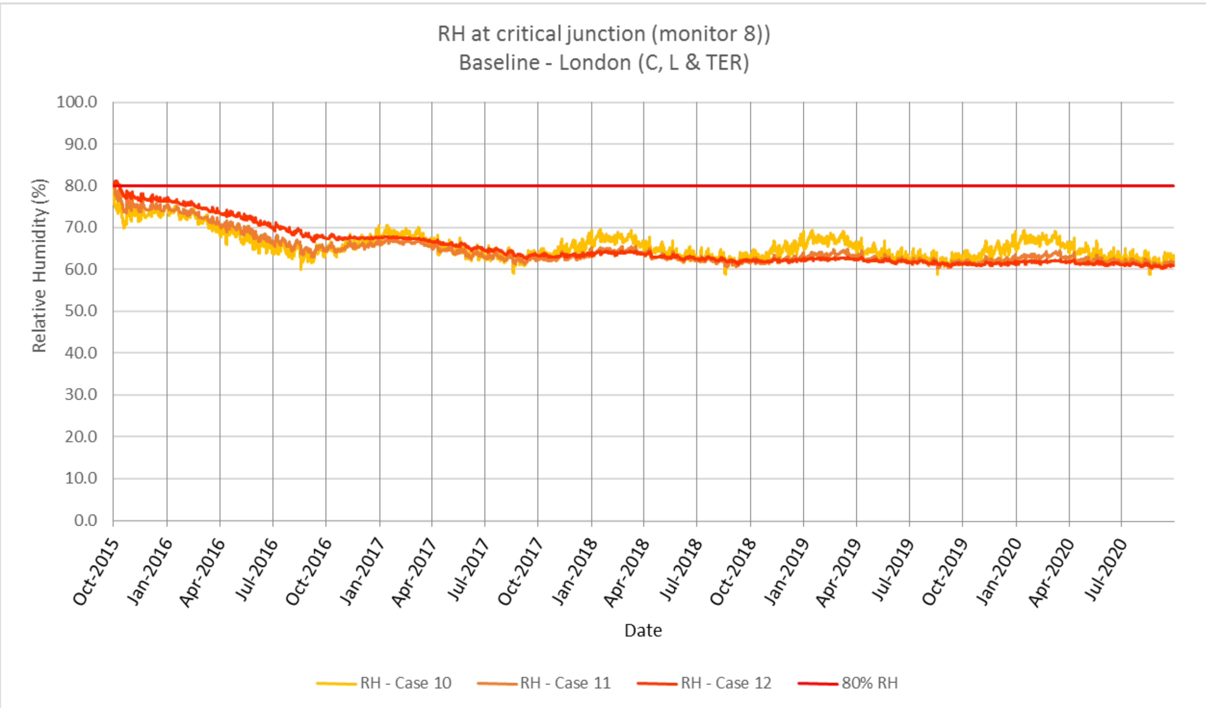


Figure 96: RH levels at critical junction for Cases 10, 11 and 12

15.3.4. Results Analysis

Moisture risk assessment criteria

As expected, all scenarios are a 'pass' as they do not accumulate moisture over time, they are drying out towards equilibrium and have RH levels well below 80% (after initial conditions). These results are summarised in the table below.

Table 46: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in line with current practice in the industry, as this is one of the typologies considered highly resistant to moisture (when installed adequately).

Effects of exposure zones and U-values

The effect of wind-driven rain exposure zones is almost undistinguishable on the graphs, as RH profiles are similar for all cases, with RH levels well within the 'safe' RH levels. This confirms that this typology is considered good regarding its resistance to moisture.

The effect of the U-value levels is slightly visible on the graphs, with lower / better U-value cases taking slightly longer to dry out towards equilibrium from wetter initial conditions and also restricting summer / winter variation. The smoother RH profile of these lower / better U-value cases is due to the fact that, with similar boundary conditions, moisture movements will be slower through a much thicker insulation layer (compared to thinner insulation layers for the cases with poorer U-values).

Additional Guidance in BS 5250 (2011)

BS 5250 (2011) highlights that condensation risk analysis is important for this construction as it states that: '*there is a risk of interstitial condensation occurring if:*

a) asymmetrical formwork is installed with the thinner layer of insulation to the outside of the concrete core; and/or
b) the vapour resistance of any externally applied finish is greater than that of any internally applied finish'

In the baseline model, the insulation is kept symmetrical, spread equally between the internal and the external insulation layers. Therefore, the first condition is met and findings are in accordance with the BS 5205 (2011) recommendation.

In the baseline model, the vapour resistance of both the internal and external layers are as follow:

- Internal = Gypsum Plaster: 0.62 MNs/g
- External = Silicone render: 5.55 MNs/g

These figures show that the second recommendation listed in BS 5250 (2011) is not respected, as the vapour resistance of the external finish is greater than the one of the internal finish. However, the graphs show that the critical junction is not displaying risky RH levels.

After analysis of the build-up, it seems that comparing the vapour resistance between the internal and external layers might not be as useful and necessary as comparing to each other the vapour resistances of adjacent layers on the outside and on the inside of the concrete. Indeed, the concrete layer is the layer with the highest vapour resistance in the baseline case (with 125 MNs/g) and it is likely to always be the case in all ICF construction. The insulation layers have a vapour resistance less important than the concrete but more important than the finishes (with 7.5 MNs/g for the Part L case – 30mm insulation on each side).

As no AVCL / vapour barriers are present in this build-up and that the most vapour resistant layer is the concrete layer, this shows that any moisture penetrating in the build-up will be able to dry out following the way it entered (i.e. moisture coming from the indoor environment will be able to dry out towards the inside, and similarly for moisture from the outside).

15.3.5. Conclusions - Baseline

In accordance with current best practice in the industry, this typology is found to be resistant to moisture, as the RH levels at the monitored junction are well within the 'safe' and recommended RH levels, independently to the wind-driven rain exposure zone the build-up is located in or the amount of insulation installed on each side of the concrete.

The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up, at the critical junction.

15.4. Sensitivity Analysis – Asymmetrical insulation

15.4.1. BS 5250 (2011) Recommendations

As noted previously, BS 5250 (2011) states that *'there is a risk of interstitial condensation occurring if asymmetrical formwork in installed with the thinner layer of insulation to the outside of the concrete core'.*

No sensitivity analysis modelling is done in this report, in which the formwork is modelled asymmetrically, with the thinner layer of insulation being installed on the outside of the concrete core. However, despite the absence of modelling, the impact of such conditions is known: moisture travelling through the build-up is likely to accumulate at the critical junction, on the inner surface of the concrete core. The concrete layer remains the layer with the highest vapour resistance in the build-up. But, as more insulation is installed on the inside than on the outside of the concrete core, the critical junction is kept at lower temperature, which will have the effect of increasing RH levels. This will lead to the build-up's failure, once the RH levels pass the 95% RH threshold.

Further modelling could be undertaken in these conditions, to provide additional guidance in BS 5250 (2011) as to detail what is the limiting ratio of insulation to be installed respectively internally and externally, while keeping the build-up 'safe'.

15.5. Conclusions

- Build-up very safe in 'theoretical' conditions
- BS EN ISO 13788 has the potential for being a sufficient method to assess the performance of build-up (no need for BS EN 15026 if 'best practice' guidance for design and installation followed)

16. Typology N11: Cavity wall – partial-fill with a semi-porous finish

The N11 typology is a new-build partial-fill cavity wall with a semi-porous finish (e.g. facing brickwork).

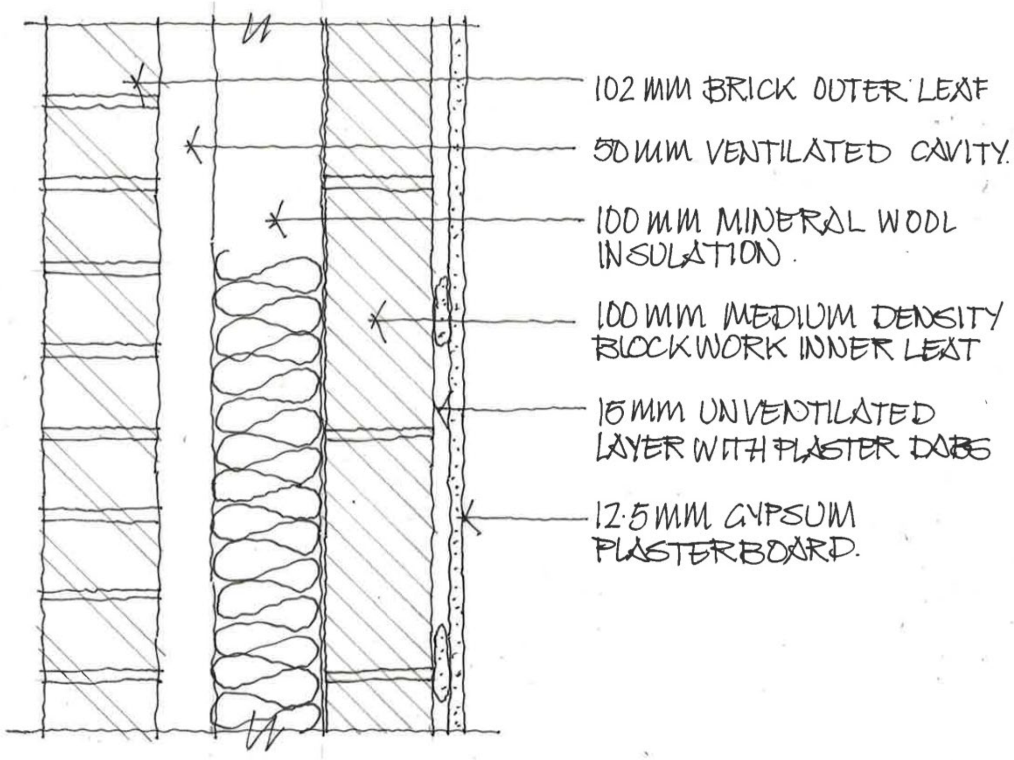


Figure 97: Illustration of the build-up of the typology (Part L case)

16.1. Assessment Method

As BS 5250 (2011) states in the cavity wall section (G.3.2.1), *'masonry walls of stonework, brickwork, blockwork or concrete may incorporate a cavity, the primary function of which is to prevent the transmission of rainwater to the interior. Rainwater might well penetrate the external skin of masonry, reducing its thermal resistance, and provision should be made for such moisture to drain out of the cavity.'*

To follow prescriptive guidance, the cavity is ventilated to the outside, to allow any moisture present in the cavity to be drained out. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the outer surface of the insulation to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method.

The results by the Glaser method show that this build-up is generally considered to be a ‘safe’ build-up. The calculation shows that interstitial condensation occurs during the winter season, but evaporates completely during the summer months.

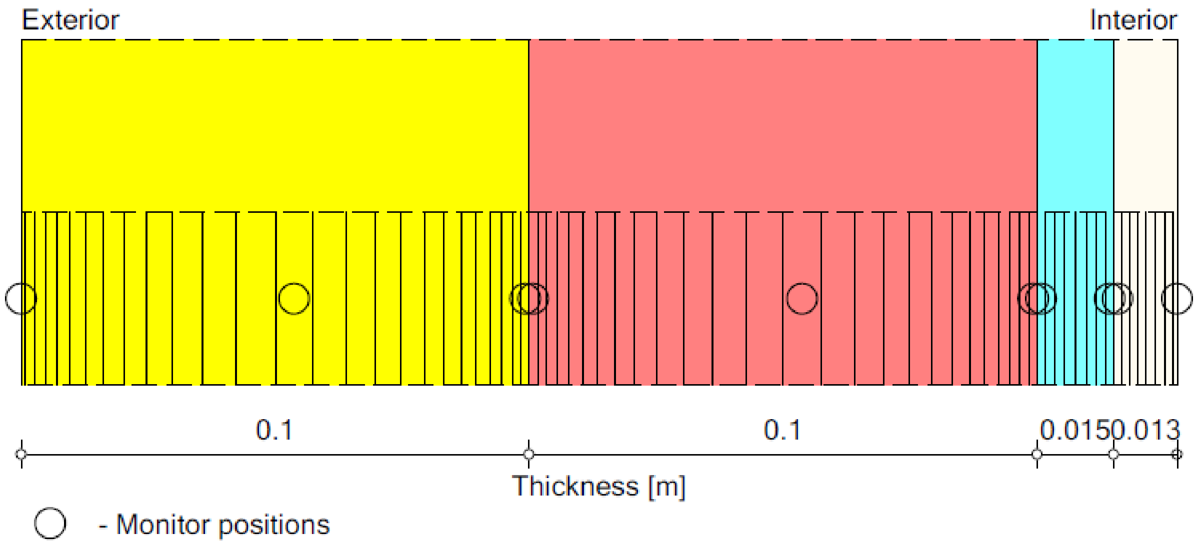
The results regarding the lack of interstitial condensation accumulating over the years will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

16.2. Build-up

Please find below the build-up of the typology.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 50mm // 100mm // 130mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm unventilated layer with plaster dabs
- 12.5mm gypsum plasterboard



Materials:

- *Mineral Wool (heat cond.: 0,04 W/mK) (unlocked) — 0.1 m
- *Medium density blockwork (unlocked) — 0.1 m
- *Air Layer 15 mm; without additional moisture capacity (unlocked) — 0.015 m
- Gypsum Board — 0.013 m

<u>WUFI Input Parameters</u>

As the cavity is considered ventilated, both the brick outer layer and the air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the insulation) is exposed to different external conditions due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity

16.3. Baseline Results

16.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 47: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

16.3.2. Monitored Junction

In 'perfect' conditions (i.e. 'normal' internal moisture load, outer brick layer in good conditions, without additional water ingress due to leaks / poor drainage / etc.), the build-up is protected from the elements, and should not present any moisture risks (as shown with the BS EN ISO 13788 (2012) calculations), meaning there is not a 'critical' junction per se.

This is confirmed by BS 5250 (2011) stating that *'any interstitial condensation which might occur will do so on the inner surface of the external skin, where it is unlikely to cause damage to non-hygroscopic insulation, or insulation which does not fill the cavity.'*

The only interface which could be monitored is the interface between the insulation and the inner blockwork layer. However, RH levels at the interface can already be predicted as:

- This interface is on the warm side of the insulation, with the only remaining layers internally being blockwork and gypsum plasterboard. These materials being materials which do not significantly block moisture transfer. This means that the RH levels at this interface will roughly mirror internal conditions applied to the model (i.e. safe RH levels ranging from 30% to 60%).
- In addition, no AVCL or other vapour retarder membranes are present in the build-up, meaning that moisture diffusion is not obstructed in any way. So, accumulation of moisture, which can potentially lead to moisture damage, will not happen at this interface.

16.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction – at the interface between the insulation and the inner blockwork layer.

As this interface is not considered a ‘critical’ junction, only the results for Zone 4 – Swansea are displayed below, as cases in different exposure zones display similar RH profiles. As per previous typologies, each zone is associated with a colour (blue for Zone 4). Within each colour, the darker the colour, the higher / better the U-value is.

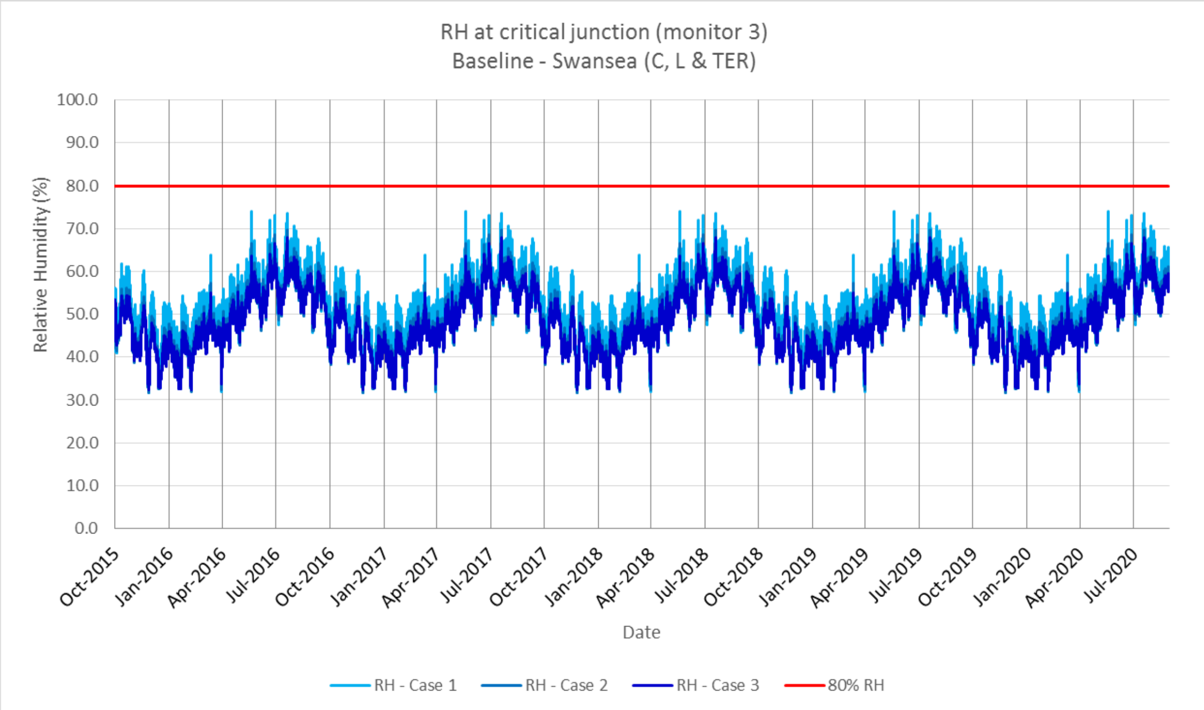


Figure 98: RH levels at monitored junction for Cases 1, 2 and 3

16.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

As seen with the BS EN ISO 13788 (2012) calculations, all scenarios are a ‘pass’ as they all reach equilibrium so they do not accumulate moisture over time, and have RH levels well below 80%. This is true of the RH levels at the monitored junction (showed in the previous graph), but this is also true of RH levels monitored in the insulation layer (except towards the external surface, where external conditions – temperature and RH – are ‘forced’ onto the external surface of the modelled build-up). These results are summarised in the table below.

Table 48: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in line with current practice in the industry, as this is one of the typologies considered highly resistant to moisture (when installed correctly).

Effects of exposure zones and U-values

The effect of wind-driven rain exposure zones is slightly visible on the graphs (graphs not displayed in this report) – with lower average RH levels in less exposed zones. However, this is directly due to different external (and consequently internal) conditions. This difference in exposure zones will not have an impact on the hygrothermal performance of the build-up, as the modelled build-up is sheltered from direct wind-driven rain.

Logically, RH levels are very slightly higher with poorer U-values. This is due to the temperature at the monitored interface (warm side of the insulation, with the blockwork) being slightly cooler, and therefore being able to handle less moisture.

16.3.5. Conclusions – Baseline

- Build-up sheltered from the elements and moisture-open so theoretically safe
- Safe results similar to BS EN ISO 13788 calculations
- There is some uncertainty when:
  1. Conditions of the insulation in contact with the cavity
  2. If the cavity is poorly / not ventilated?
  3. Buildability / workmanship / thermal bypass? ABIS or in-situ thermal performance not modelled in WUFI

16.4. Sensitivity Analysis – RH Levels in the Insulation Outer Layer [Baseline]

As the cavity is a ventilated cavity, the outer surface of the insulation is submitted to external temperature and RH (but without wind-driven rain). Mineral wool insulation is a vapour-open material, letting the passage of moisture through. A closer examination is therefore carried out on the RH levels in the outer layer of the insulation, as external conditions with high RH levels may have a detrimental effect on the insulation performance.

The RH levels in the insulation layer are monitored in 4 locations:

- About 1mm from the outer insulation surface (monitor 2)
- About 10mm from the outer insulation surface (monitor 5)
- About 20mm from the outer insulation surface (monitor 8)
- In the middle of the insulation layer (about 75mm from the outer insulation surface - monitor 13)

The results are displayed in the graphs below for the Swansea – TER case (case 3). The three monitors close to the outer surface (2, 5 and 8) are displayed in light blue (the lighter the blue, the deeper in the insulation the monitor is), while the monitor located right in the middle of the insulation (monitor 13) is displayed in dark blue.

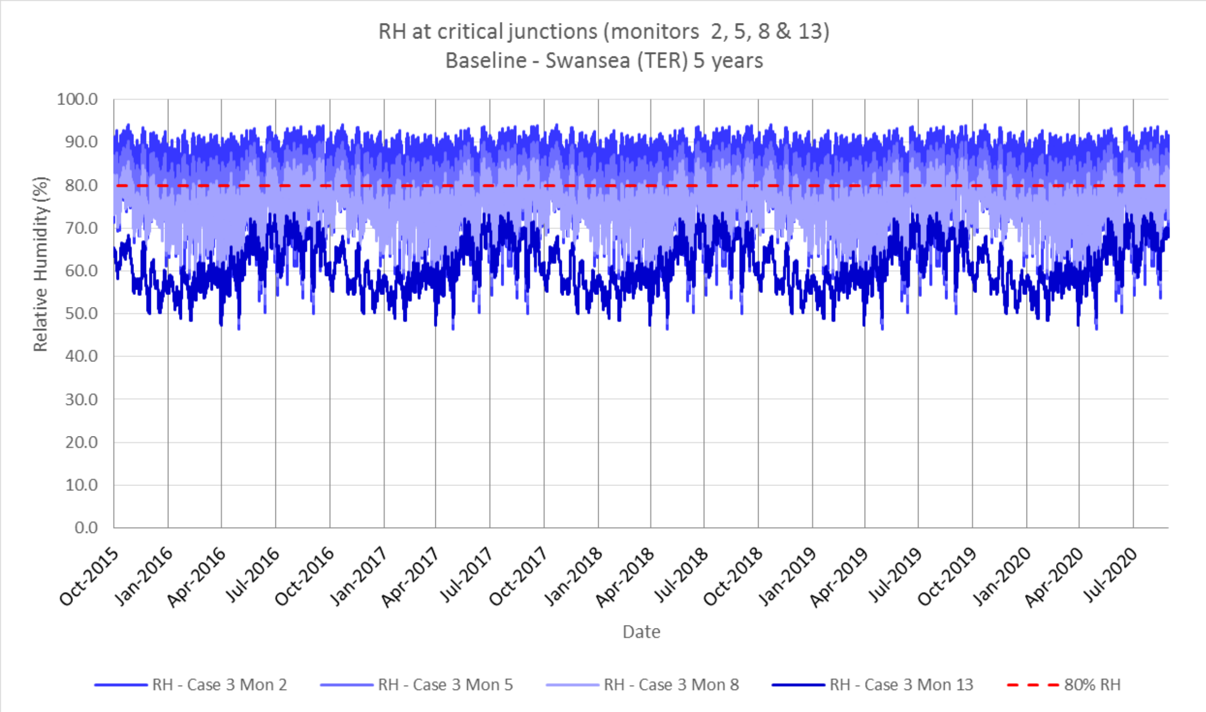


Figure 99: RH levels at monitored junctions for Case 3 (monitors 2, 5, 8 and 13) over a period of 5 years

This graph shows that the middle of the insulation is kept at very 'safe' RH levels (well below 80%), while the outer surface of the insulation seems to be kept at constant and very high RH levels.

In reality, the outer surface of the insulation is not kept constantly at very high RH levels. It only seems to be the case due to the amount of data that is displayed in the graphs (5 years of hourly data). The following graphs display the same results over a shortened period of respectively 1 year and 1 month.

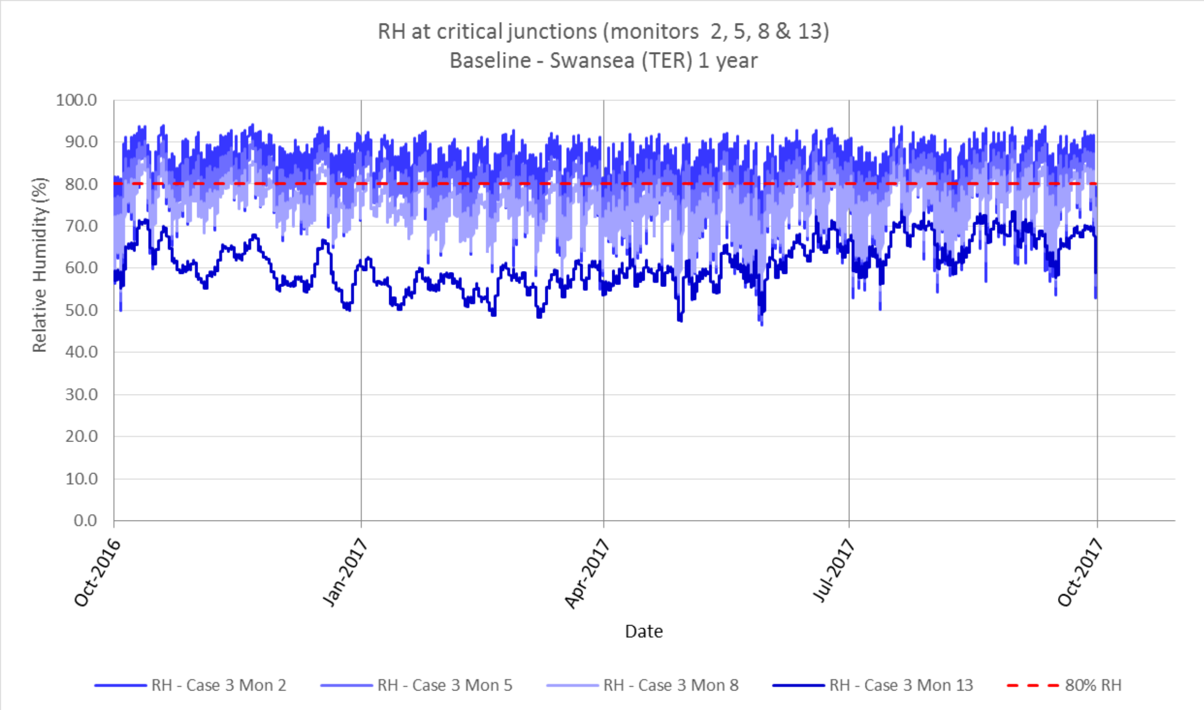


Figure 100: RH levels at monitored junctions for Case 3 (monitors 2, 5, 8 and 13) over a period of 1 year

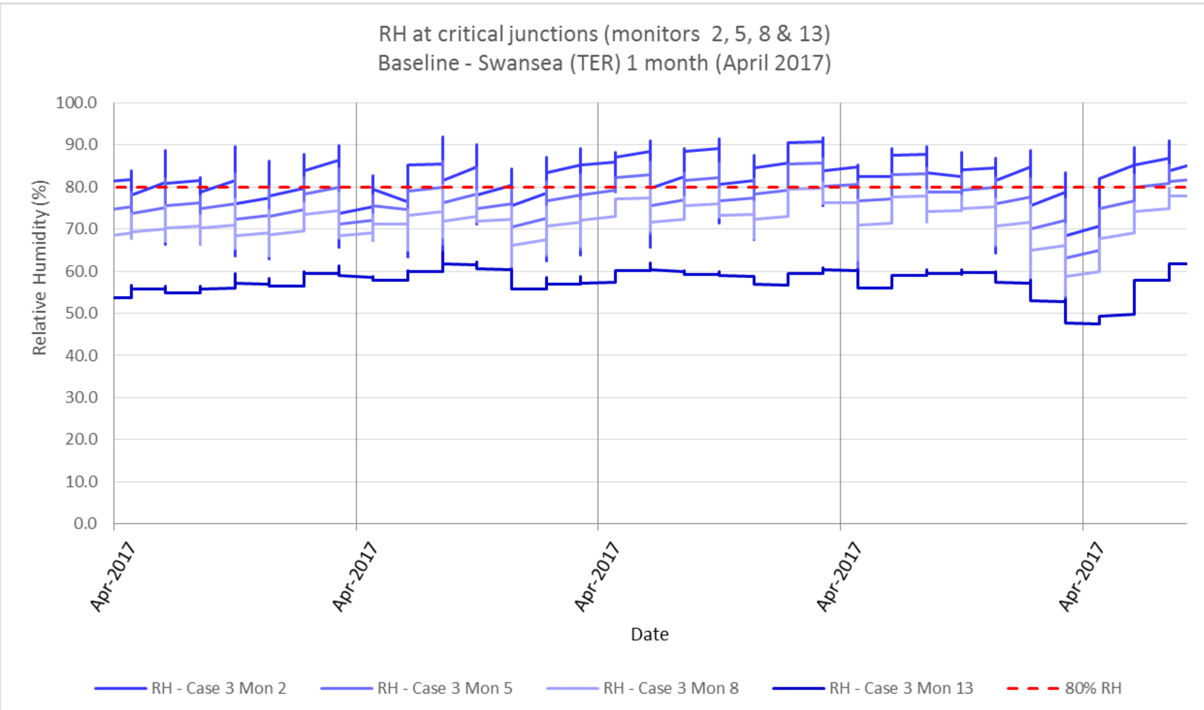


Figure 101: RH levels at monitored junctions for Case 3 (monitors 2, 5, 8 and 13) over a period of 1 month

These graphs show that on average, the RH levels of the monitor located around 20mm from the outer surface of the insulation are kept below the 80% RH threshold for the majority of the time. RH levels above the 80% threshold only occur over relatively short periods of time (shorter than a month). This means that, in the theoretical build-up, the insulation layer is performing well overall. However, the last 10mm of the insulation layer displays high RH levels, which is not a significant problem in terms of mould growth (due to the lack of food for mould growth present at that location and the isolation from the indoor environment) but may have a detrimental effect on the overall thermal performance of the insulation.

Research on the impact of moisture content in the thermal performance of insulation materials is not part of this work. However there is some work already available showing that some materials, like mineral wool, have a moisture-dependent thermal conductivity λ. Consequently, the presence of higher moisture content (compared to typical conditions) in these materials has a detrimental effect on the thermal performance on the whole build-up.

16.5. Sensitivity Analysis – Change in Material [Cases X.d]: Change from compressible to rigid insulation

16.5.1. Sensitivity Analysis Cases

Both types of insulation (compressible and rigid) are displayed in the build-up shown in BS 5250 (2011), as shown below. As such, to match the build-ups shown, rigid types of insulation were modelled as a sensitivity analysis.

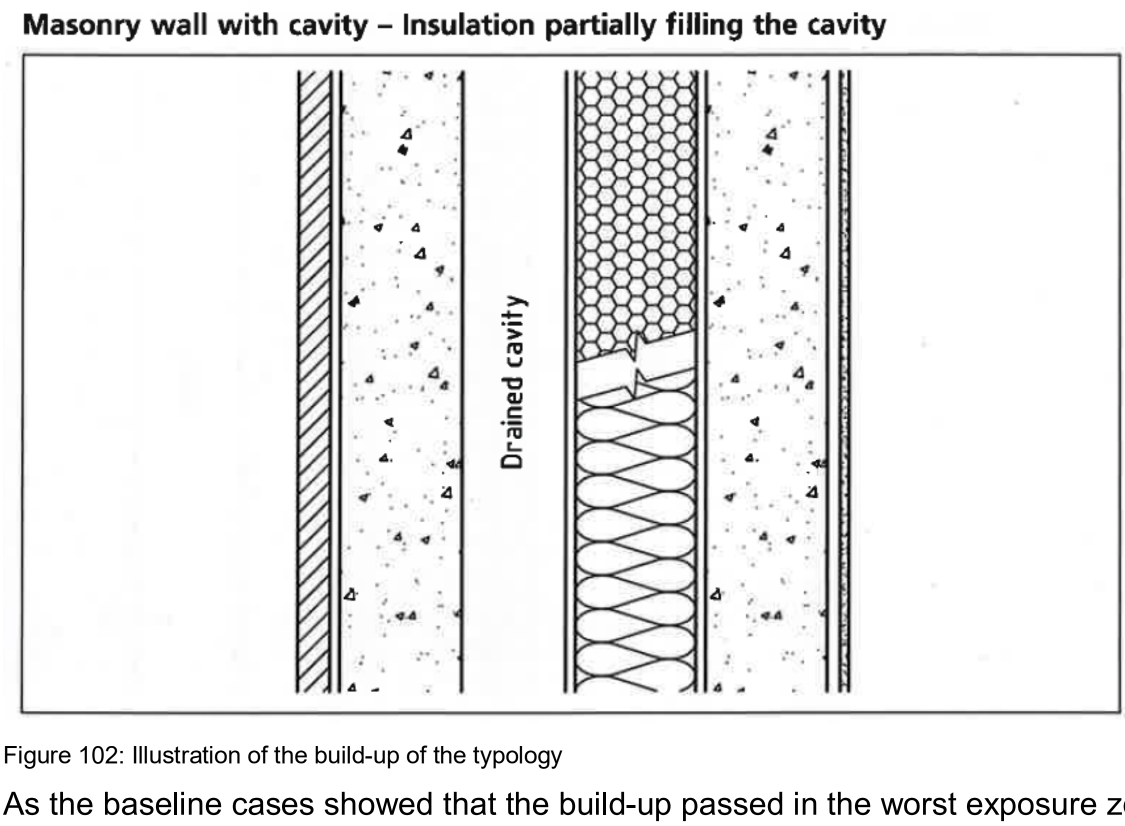


Figure 102: Illustration of the build-up of the typology

As the baseline cases showed that the build-up passed in the worst exposure zones (i.e. Zone 4 – Swansea). These cases are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, matching or exceeding the three target U-values (as per baseline cases) as set out below.

Table 49: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

16.5.2. Graphs at monitored junctions

All graphs displayed below show the RH levels at the monitored junction (which is the same as the baseline cases), i.e. on the warm side of the insulation layer, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

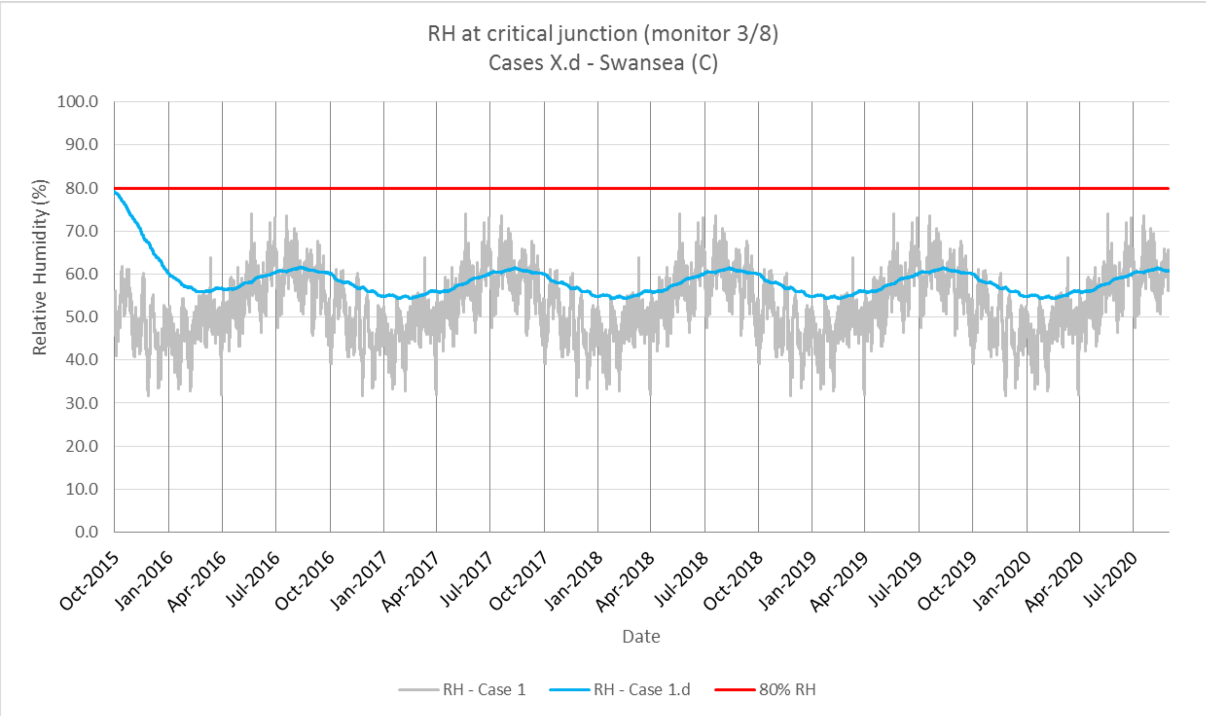


Figure 103: RH levels at monitored junction for Cases 1 and 1.d

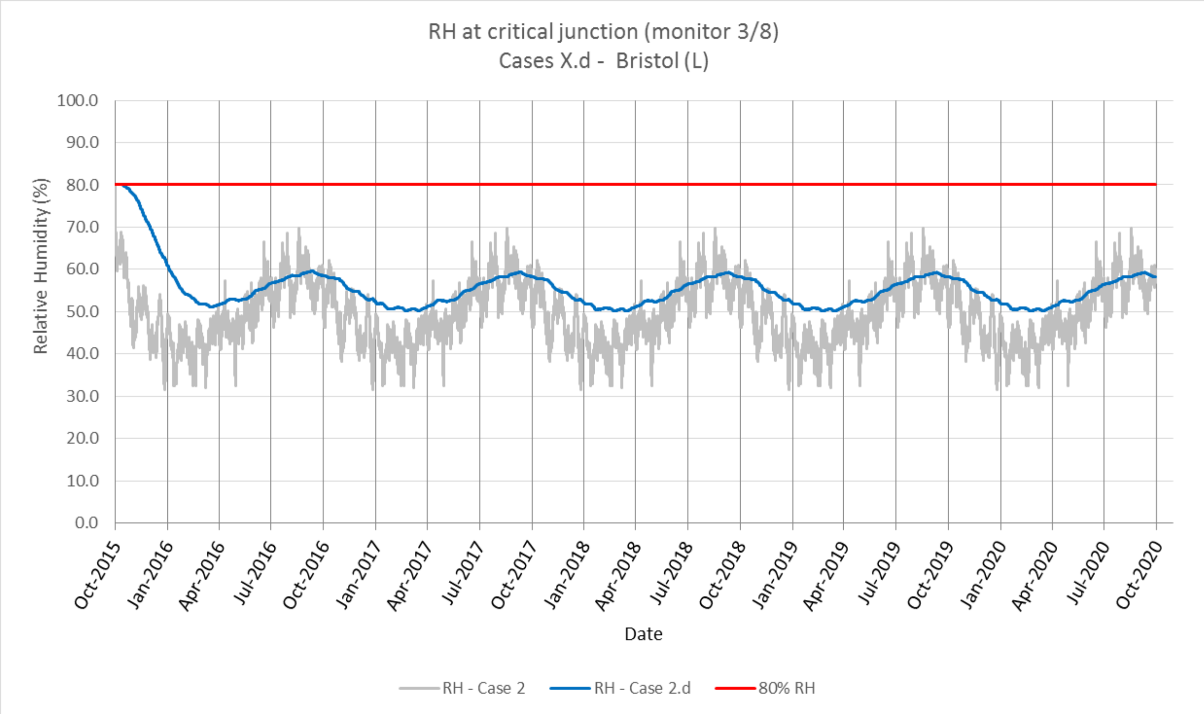


Figure 104: RH levels at monitored junction for Cases 2 and 2.d

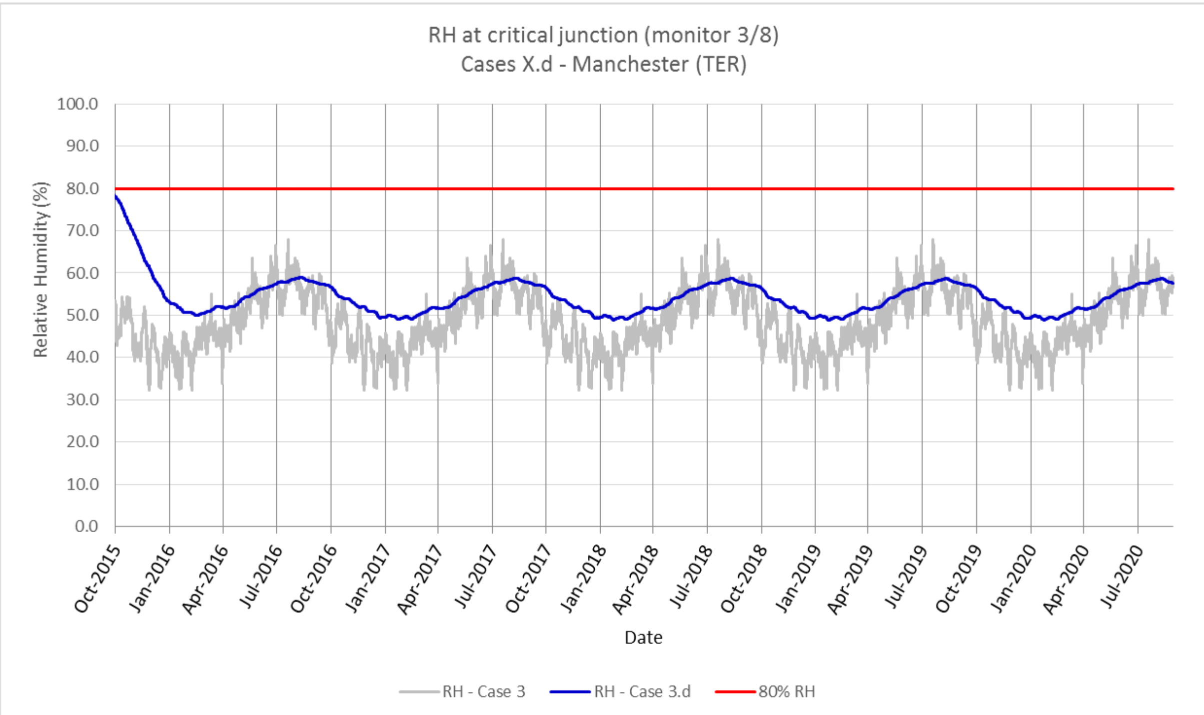


Figure 105: RH levels at monitored junction for Cases 3 and 3.d

16.5.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The insulation layer modelled is still protected (not directly exposed to the elements) and similarly to the baseline, moisture does not accumulate in the build-up. These conditions do not change if the compressible insulation layer (mineral wool) is switched to a rigid insulation layer. The presence of foil-facing layers on both surfaces of the rigid insulation layer simply keeps the insulation drier, with less moisture allowed to diffuse through it.

- This may have a beneficial impact on the outer surface of the insulation, as the insulation might be kept drier closer to this surface (and therefore performing better thermally)
- The presence of this foil-facing layer on the inner surface of the insulation (at the interface with the inner blockwork layer) means that moisture diffusion is made more difficult and the internal RH levels are mirrored at this interface with a much smoother profile (compared to the case with the compressible insulation)
- Condensation can occur on the surface of the insulation due to the low-emissivity finish

Rigid Insulation without Foil Layers

The presence of the foil layers has a minor impact to the hygrothermal performance of the build-up. The graph below shows the RH levels at the interface between the insulation and the inner blockwork layer for the Swansea – TER case (case 3) where the foil layers are removed. The baseline is displayed in grey, while the sensitivity analysis case in colour.

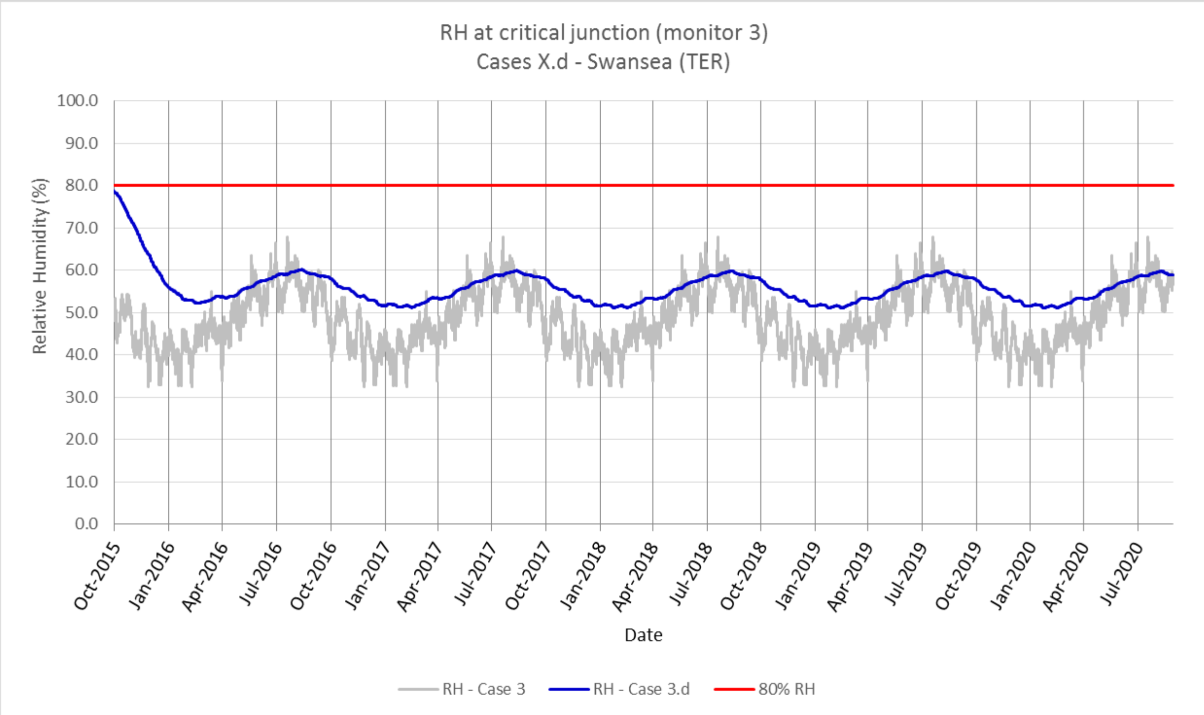


Figure 106: RH levels at monitored junction for Cases 3 and 3.d with no foil layers

Results

Figure 107: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

The change of insulation type does not have a significant effect on the hygrothermal performance of the build-up regardless of its insulation thickness.

Buildability

In general, rigid boards are considered a more difficult material to work with in terms of cavity wall insulation product. It is important to note that the model does not account for poor fitting of rigid insulation boards, which can allow air circulation behind the board (i.e. thermal bypass). This may affect the thermal performance of the build-up (overall U-value), but should not affect its hygrothermal performance which will remain satisfactory, as long as there are no moisture related construction faults (e.g. rubbles in cavity, incorrectly installed wall ties).

16.6. Sensitivity Analysis – Change in Material [Cases X.e]: Unventilated Cavity

16.6.1. Sensitivity Analysis Cases

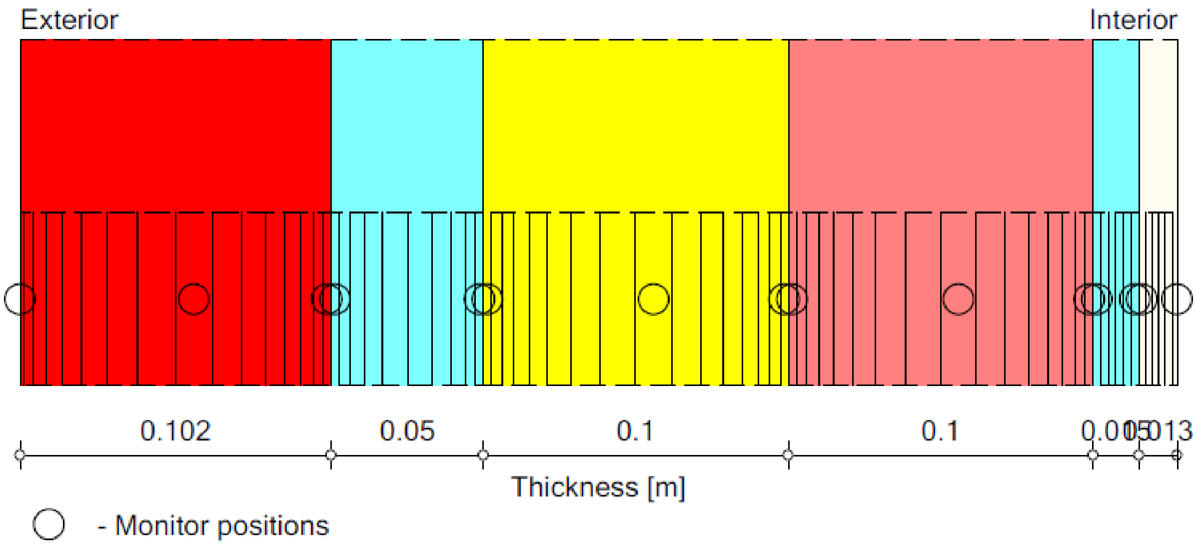
As stated in BS 5250 (2011), *'provision should be made for such moisture to drain out of the cavity'*. However, no exact indication / physical characteristics are given as to what constitutes adequate ventilation in the cavity. The guidance also suggests that the absence of ventilation would be detrimental to the correct hygrothermal performance of the build-up, as any moisture or surface condensation accumulating in the cavity will not be drained out.

The next sensitivity analysis assesses the build-up's performance with the cavity changed from ventilated to be unventilated. This is unlikely to be a correct representation of the reality, where it is more likely for cavities to be partially ventilated / under-ventilated (rather than unventilated). However, by modelling an unventilated cavity, this sensitivity analysis represents the worst case scenario. It is also worth noting that WUFI is not able to model 'ventilated' or 'slightly-ventilated' cavities, so no transient modelling with partially ventilated could have been possible.

<u>Build-up:</u>

The new build-up is as follow (as both the outer brick layer and the cavity are reintroduced in the WUFI model):

- 102mm brick outer leaf
- 50mm unventilated air gap
- 50mm // 100mm // 130mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm blockwork inner leaf
- 15mm unventilated layer with plaster dabs
- 12.5mm gypsum plasterboard



Materials:

- Solid Brick, hand-formed	0.102 m
- Air Layer 50 mm; without additional moisture capacity	0.05 m
- *Mineral Wool (heat cond.: 0,04 W/mK) (unlocked)	0.1 m
- *Medium density blockwork (unlocked)	0.1 m
- *Air Layer 15 mm; without additional moisture capacity (unlocked)	0.015 m
- Gypsum Board	0.013 m

As explained in the next typology (section 18.2 – Full-fill cavity wall N12), a worst case scenario was chosen for the brick in the absence of available properly tested data for existing UK bricks, stones and plasters. Therefore, a brick with a high-absorption was chosen in the WUFI model as a worst case scenario.

As the baseline cases showed that the exposure zones only have a small effect onto the performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis. The 3 cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases):

Table 50: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.e	-	-	-
Part L	Case 2.e	-	-	-
TER	Case 3.e	-	-	-

16.6.2. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction (which is the same as the baseline cases), on the warm side of the insulation layer for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

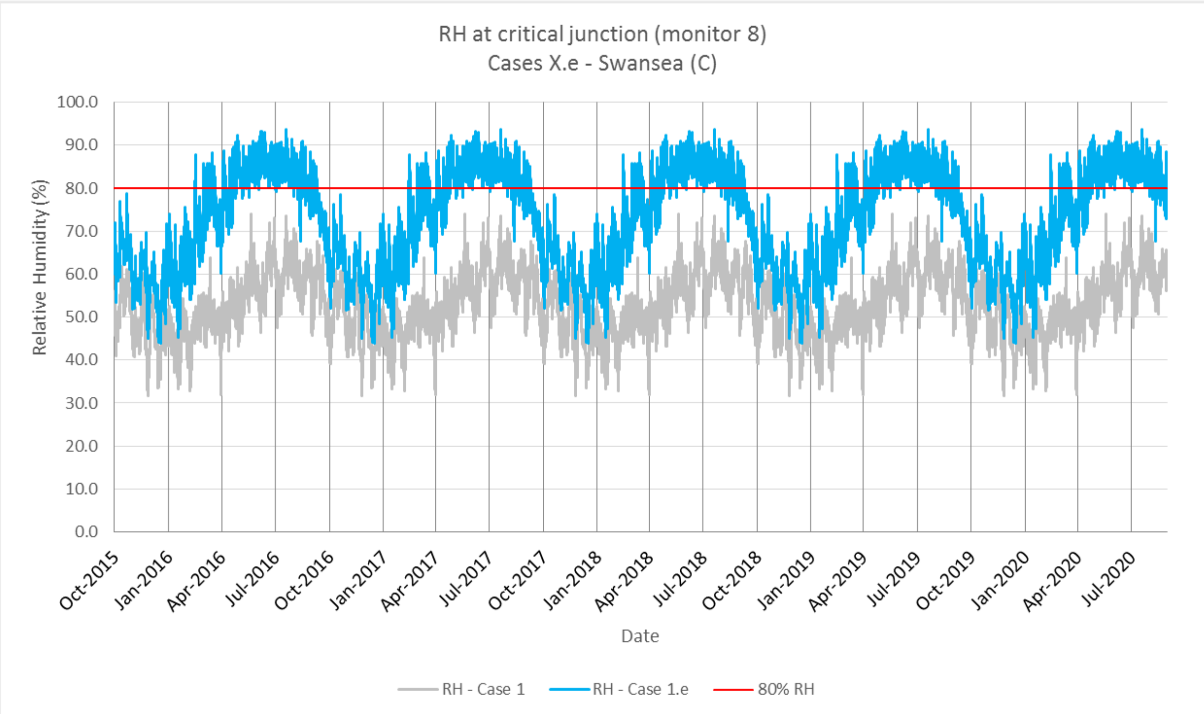


Figure 108: RH levels at monitored junction for Cases 1 and 1.e

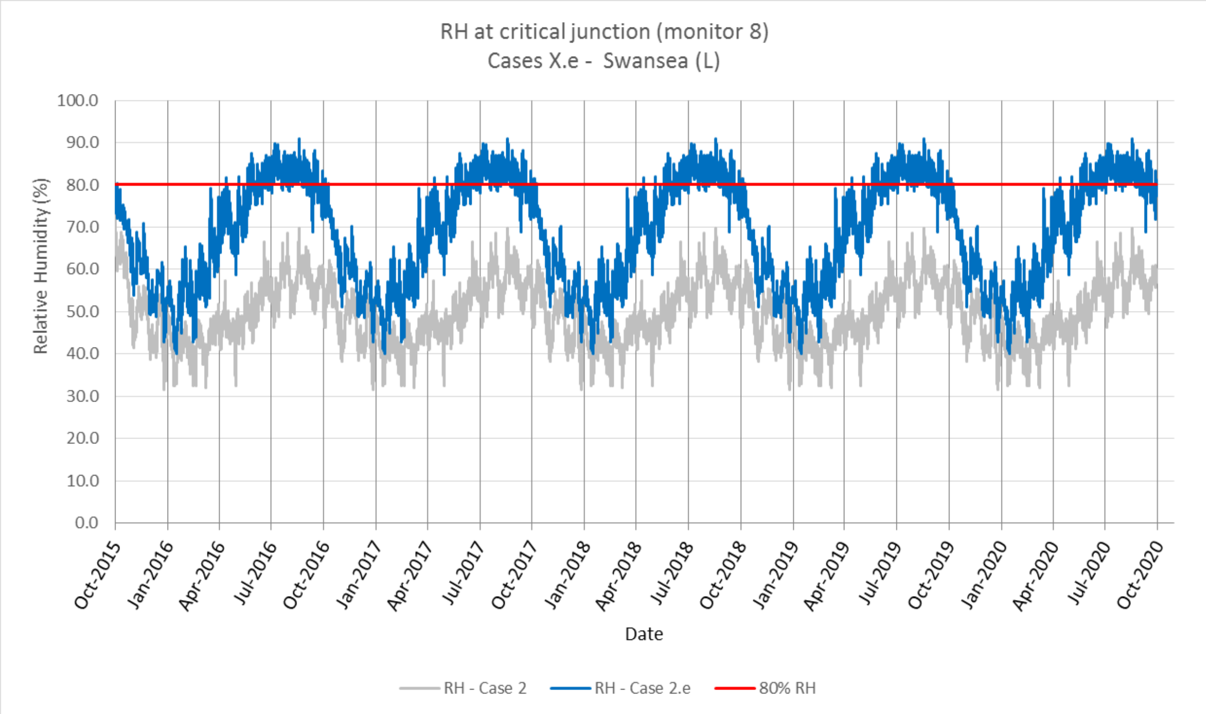


Figure 109: RH levels at monitored junction for Cases 2 and 2.e

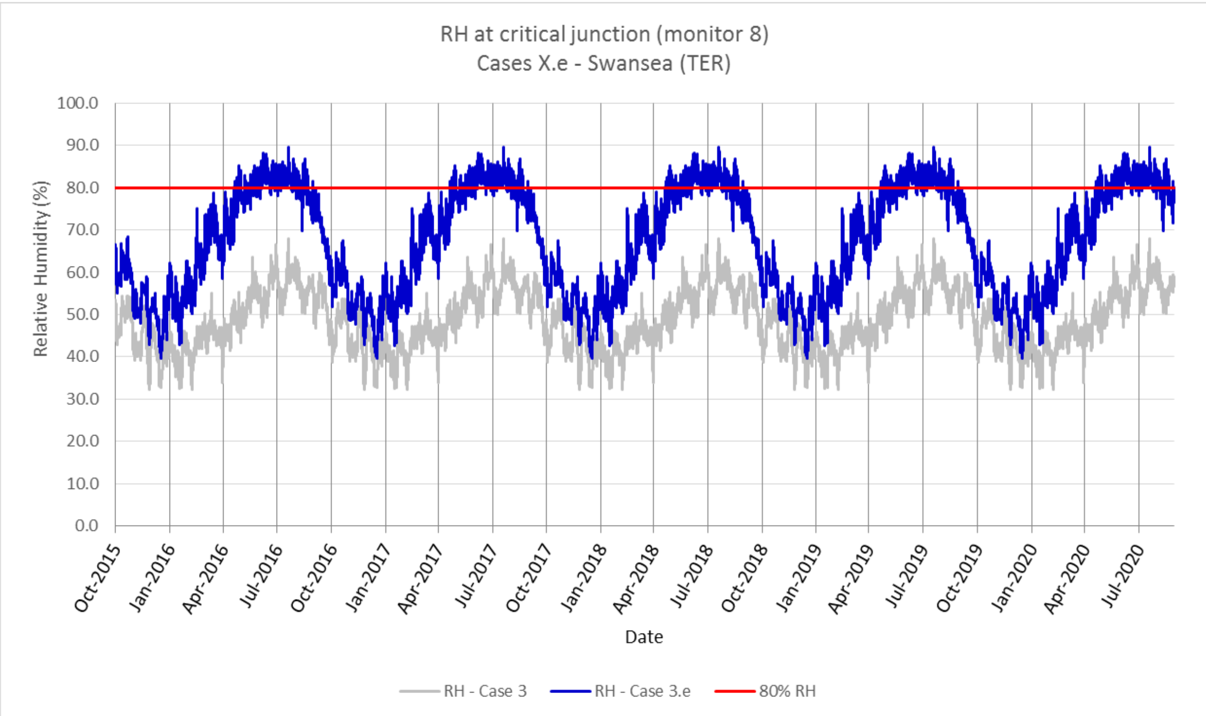


Figure 110: RH levels at monitored junction for Cases 3 and 3.e

16.6.3. Conclusions – Sensitivity Analysis Cases X.e

Moisture risk assessment criteria

The graphs show that all cases modelled in this sensitivity analysis perform significantly worse than their respective baseline cases.

Despite the monitored junction declared in theory as 'safe' conditions, the graphs show that RH levels on the warm side of the insulation rise above the 80% RH threshold for periods up to several months during the summer season.

RH peaks that are visible during the summer season can be explained through the process of reverse diffusion. Moisture present in the outer brick layer is driven inwards into the build-up, as a result of solar radiations on the façade.

The 80% RH threshold could be questioned, as in theory there should not be any presence of food for mould growth at this interface between the warm side of the insulation and the inner blockwork. However, all other conditions for the risk of mould growth are present, i.e. high RH levels, adequate temperature (as high RH levels occur during the summer season) and air (as it is highly likely for air to be present at this interface due to the difficulty to build a 'perfect' insulated cavity wall). So the 80% RH threshold appears to be more appropriate than a more relaxed 95% RH threshold.

Results

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 51: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.e Fail	-	-	-
Part L	Case 2.e Fail	-	-	-
TER	Case 3.e Fail	-	-	-

These results show that if the build-up is pushed to its extreme, with a cavity considered fully unventilated, the RH levels at the monitored junctions are pushed from 'safe' to 'risky' levels and it could lead to mould growth. This confirms the prediction that the lack of adequate ventilation in the cavity has a significant detrimental effect on the hygrothermal performance of the build-up, as suggested in the prescriptive guidance BS 5250 (2011).

Risk of Surface Condensation

The 'critical' junction at which condensation is likely to occur is identified as the inner surface of the outer brickwork layer in the prescriptive guidance from BS 5250 (2011). As this surface is now included in the WUFI model (as the cavity is considered unventilated), RH levels on this surface are monitored and displayed in the graph below.

As all RH profiles are similar, independently to the amount of insulation installed in the cavity, the graph displays the RH level on the inner side of the outer blockwork layer for the TER case in Zone 4 – Swansea.

As the monitored RH levels for this location is not available for the baseline (location technically outside of the modelled WUFI build-up), only the sensitivity analysis case is displayed on the graph below, as a coloured line.

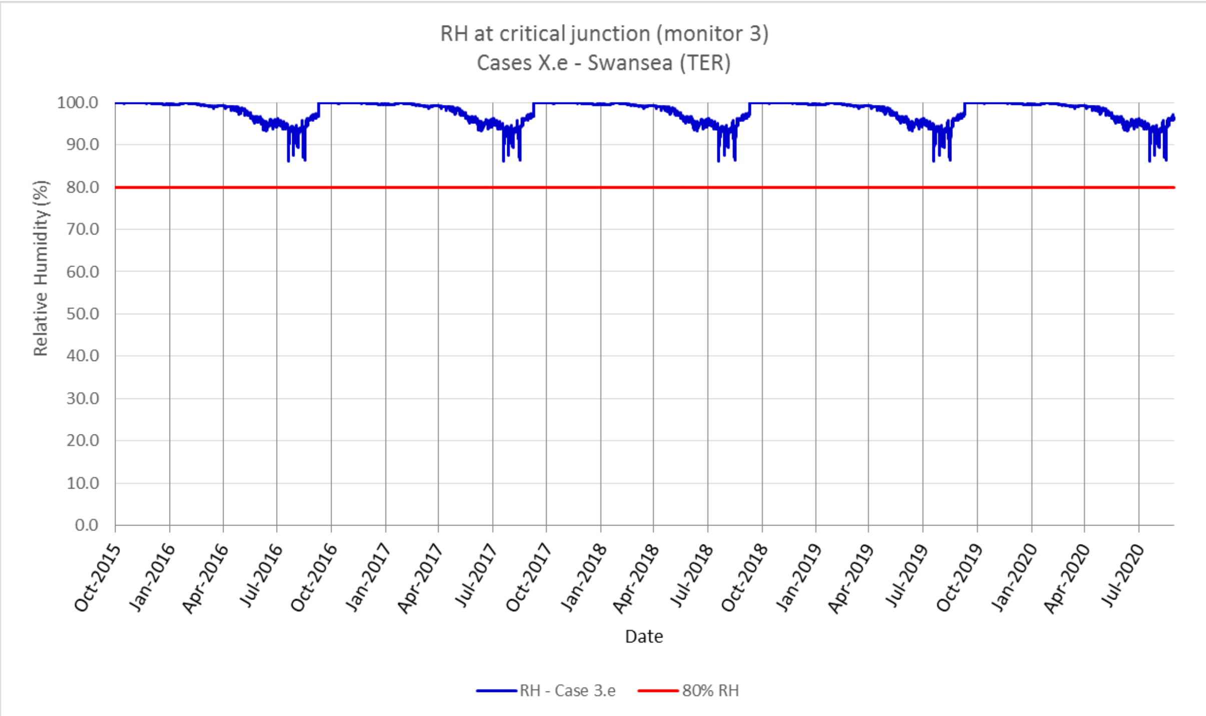


Figure 111: RH levels at critical junction for Case 3.e

The graph above confirms the risk of surface condensation on the inner surface of the outer brickwork layer, as RH levels are close to / reaching the 100% level for about six months in the year, during the winter season.

As mentioned before, the modelling of an unventilated cavity is pushing the build-up to extreme conditions and is likely not to be an accurate representation of the reality. However, this sensitivity analysis shows the worst case scenario, if the cavity was unventilated, and provides a useful understanding of the amplitude of the detrimental impact non-adequate ventilation in the cavity has on the hygrothermal performance of the partial-fill cavity wall build-up.

16.7. Discussion on Workmanship & Buildability

Workmanship and buildability have always been a major question with partial-fill cavity wall and thermal performance. Indeed, the thermal performance of the cavity wall is significantly reduced as soon as thermal bypass happens in the cavity. However, a ‘perfect’ cavity wall is a difficult build-up to achieve in practice, as any gaps behind the insulation (due to the insulation being poorly installed or due to the wall not presenting a flat surface), or any gaps in between boards (due to the insulation boards not installed tightly together) will lead to cold air present in the cavity infiltrating the insulation layer, reducing its performance in these locations.

These conditions are not included in the WUFI modelling, as the modelling uses a theoretical build-up which has been built to ‘good practice’. Despite not being able to model thermal bypass in WUFI, it is known that air convection through the insulation will carry more moisture than moisture typically travelling through the build-up due to vapour diffusion. This additional moisture carried around by convection is also at risk of condensing if correct conditions are met.

Thermal bypass in cavity walls is a common problem and is mainly related to additional heat losses and thermal bridging effects (which could lead to surface condensation / mould growth). In addition, it is likely for moisture risks to increase with the addition of thermal bypass / convection through the insulation.

It is worth noting that despite not presenting moisture management risks in the analysis, N11 might not be considered as a safe build-up due to the issues highlighted above.

Similar to N22, it is impossible to obtain ‘bad’ results with WUFI modelling. Workmanship (thermal bypass) trial in WUFI model with additional moisture source (located at insulation / blockwork interface) with ‘infiltration’ category. But results still similar to baseline case (with RH levels under 80%), possibly due to the air / additional moisture source kept at ‘warm’ temperature – rather than infiltration of external ‘cold’ air.

16.8. Conclusions

- Build-up sheltered from the elements and moisture-open so theoretically safe
- Safe results similar to BS EN ISO 13788 calculations
- Outer layer of the insulation in the cavity experiencing high RH levels, which may have an effect of the thermal performance of the insulation
- Unventilated cavity (build-up pushed to the extreme) has a significant detrimental effect on the hygrothermal performance of the build-up. All modelled cases failing due to high RH levels at normally ‘safe’ junctions
- Buildability / workmanship playing a significant role (due to the very high risk of thermal bypass). But difficult to model these non-ideal conditions in WUFI

17. Typology N12: Cavity wall – full-fill with a semi-porous finish

The N12 typology is a new-build full-fill cavity wall, with brick and block layers.

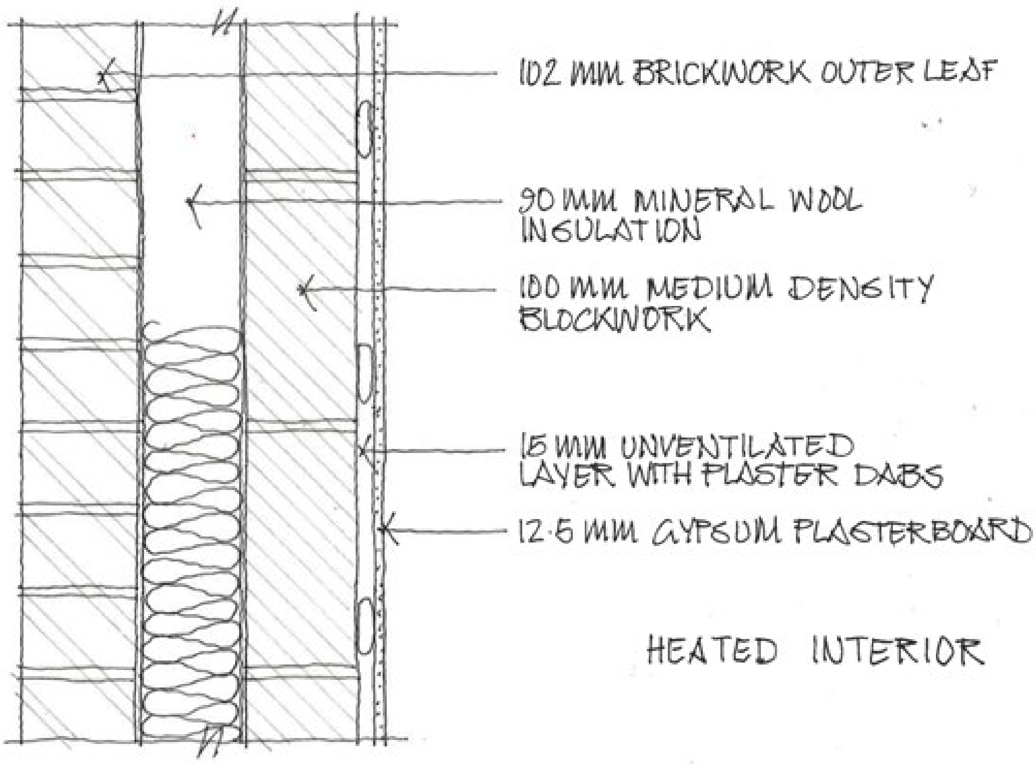


Figure 112: Illustration of the build-up of the typology (Part L case)

17.1. Assessment Method

As the outer brick layer is exposed (and fully part of the build-up, contrary to the previous N11 typology), the storage of moisture in this layer as well as the exposure of its external surface to wind-driven rain and solar gains throughout the year plays an impact on the hygrothermal performance of the build-up,. As these elements need to be taken into account but fall outside of the scope of the BS EN ISO 13788 (2012) assessment method, this method cannot be used to provide an accurate assessment. Indeed, the analysis of this build-up with the Glaser method identifies the correct critical junction but provides false comfort declaring the build-up as ‘safe’ due to the very small amount of condensation created and entirely evaporating throughout the year.

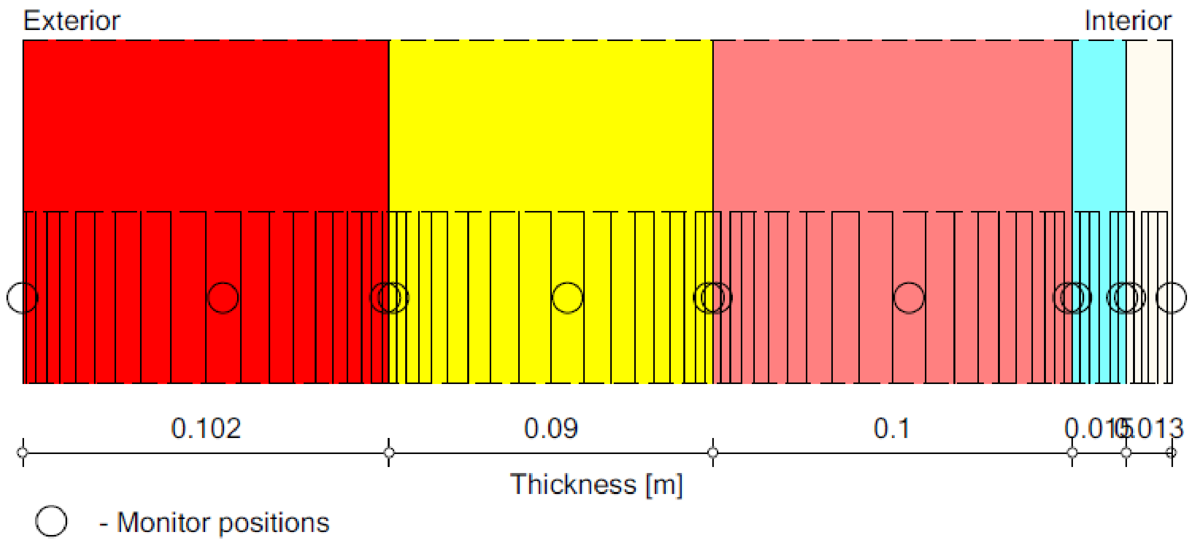
Due to the limitations of previous methods to assess accurately the hygrothermal performance of this build-up, this typology will be assessed with the BS EN 15026 (2007) assessment method using WUFI modelling.

17.2. Build-up

Please find below the build-up of the typology.

<u>Build-Up:</u>

- 102mm brick outer lead
- 50mm // 90mm // 150mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm medium density blockwork inner leaf
- 15mm unventilated layer with plaster dabs
- 12.5mm gypsum plasterboard



Materials:

(red)	- Solid Brick, hand-formed	0.102 m
(yellow)	- Mineral Wool (heat cond.: 0,04 W/mK)	0.09 m
(pink)	- *Medium density blockwork (unlocked)	0.1 m
(cyan)	- *Air Layer 15mm; without additional moisture capacity (unlocked)	0.015 m
(cream)	- Gypsum Board	0.013 m

Material Physical Properties

While the relevant material properties of the modern construction materials are reasonably consistent and well understood (e.g. gypsum board, rigid insulation, etc.), there is currently a lack of properly tested data for existing UK bricks, stones and plasters.

As this work is generic (no tested data is available), bricks already available in the existing WUFI Pro Fraunhofer database were assumed and selected as being the nearest matches to existing solid brick walls. These selections were done to obtain a suitable range of data to model brick walls.

In the absence of data, it is considered best to opt for conservative assumptions. In this situation, this means that the brick chosen to be used in this modelling is a less 'performing' brick in terms of moisture, i.e. a more 'absorbent' brick.

Default Brick

The "Solid Brick, hand-formed" from the Fraunhofer IBP database of materials was selected during the setting out of the methodology for this modelling work. This brick is a higher density, less porous brick with a high A-value (0.300 kg/m²√s) – refer to Appendix A. The selection of this brick was based on a paper which tested the A-value of a typical London Brick Fletton brick at 0.32 kg/m²√s (Rirsch & Zhang, 2012). This is one of the few known moisture tests of a UK brick with publicly available results.

It is worth noting that this is a type of brick not commonly used in the industry anymore on new-build constructions. However, in the absence of what is considered a 'typical' brick in the industry, including its full physical properties, the decision was taken to use this brick as the default brick in this modelling work. This is also one of the most absorbent bricks in the Fraunhofer WUFI database and therefore gives a good representation of "worst case scenario" in terms of brick characteristics.

Sensitivity Analysis

As the brick's physical characteristics play a significant role in the hygrothermal performance of this build-up, in addition to the lack of data available for UK bricks, the first sensitivity analysis is carried out with a substitution of the default bricks by two additional bricks with different physical characteristics (density, porosity and water absorption coefficient).

17.3. Baseline Results

17.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set below.

Table 52: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

17.3.2. Monitored Junction

Prescriptive guidance BS 5250 (2011) states that *'applying thermal insulation within a wall cavity risks compromising the primary function of the cavity, namely the avoidance of rainwater penetration.'* This shows that the build-up is likely to be prone to moisture risks.

The critical junction is correctly identified by the BS EN ISO 13788 (2012) calculation, also by BS 5250 (2011): *'any interstitial condensation which might occur will do so on the inner surface of the external skin'.* Therefore, all graphs will display RH levels at the interface between the brick outer layer and the cold side of the insulation layer.

17.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction, which is at the inner face of the outer brick layer (i.e. interface between the brick layer and the insulation layer).

As per previous typologies, each zone is associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

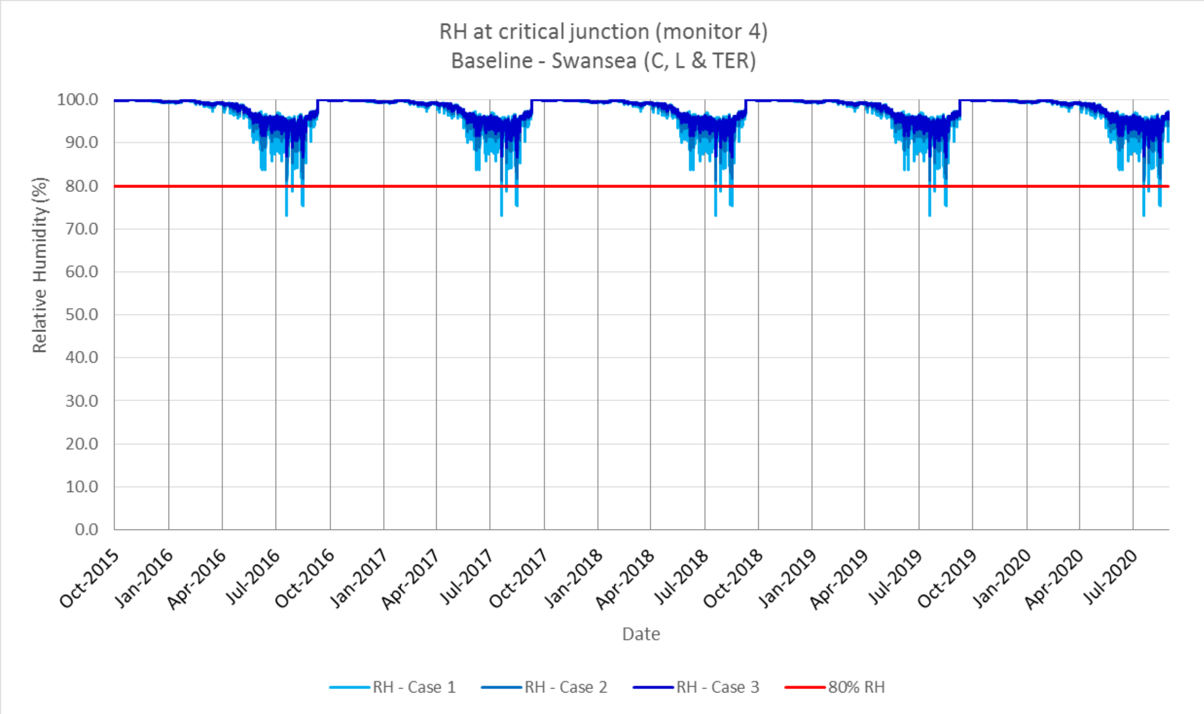


Figure 113: RH levels at monitored junction for Cases 1, 2 and 3

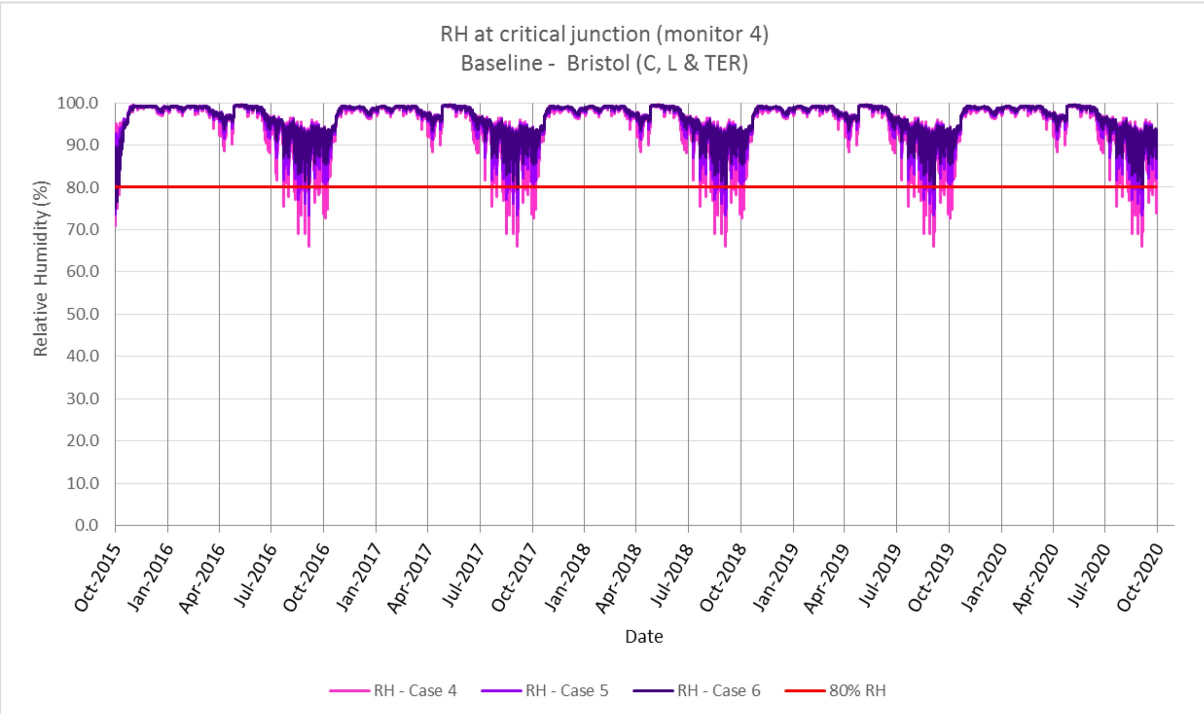


Figure 114: RH levels at monitored junction for Cases 4, 5 and 6

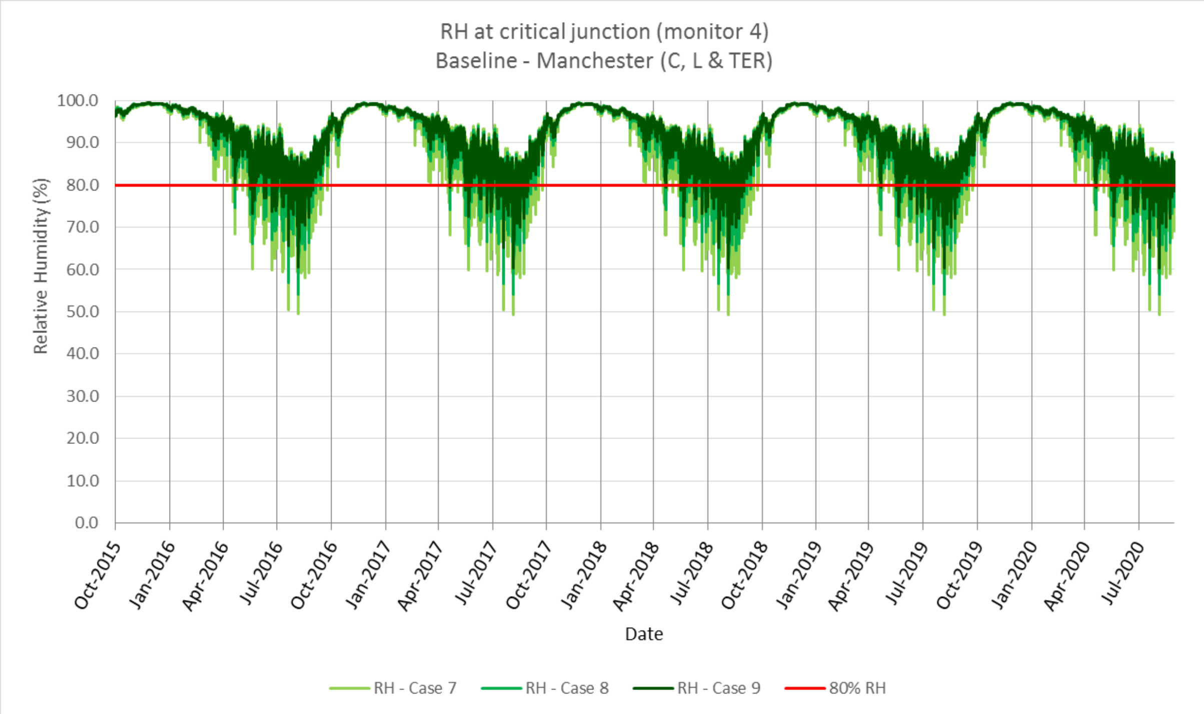


Figure 115: RH levels at monitored junction for Cases 7, 8, and 9

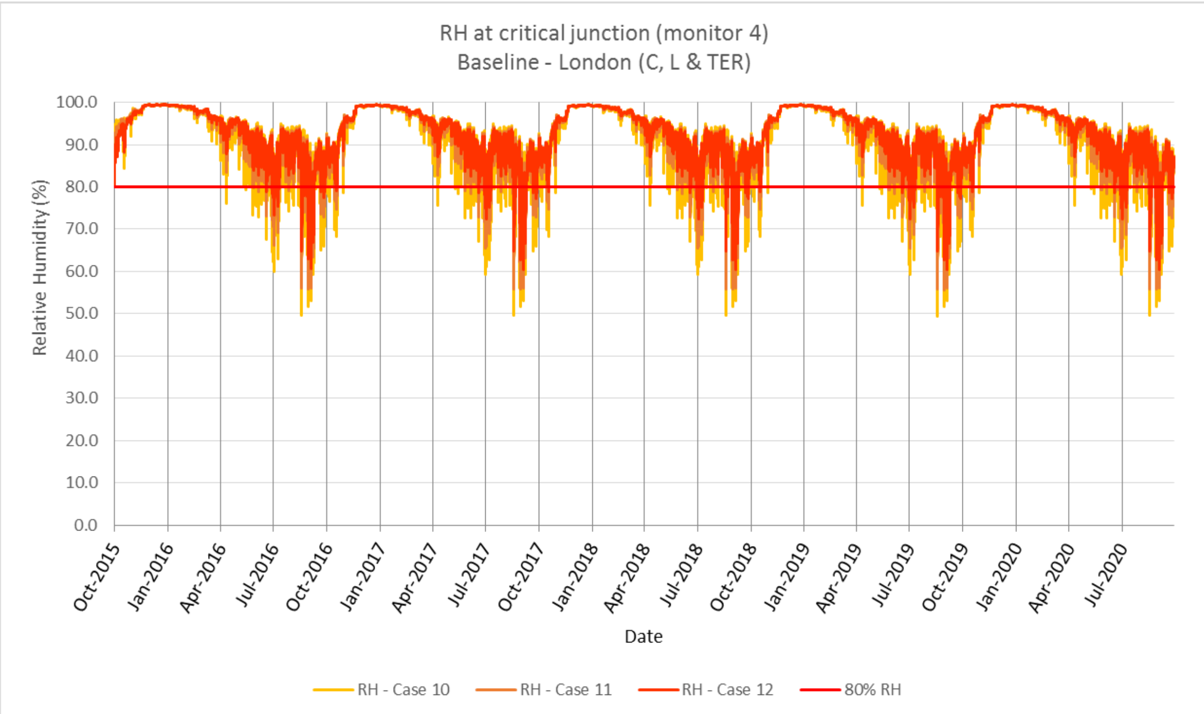


Figure 116: RH levels at monitored junction for Cases 10, 11, and 12

17.3.4. Results Analysis

Moisture risk assessment criteria

All cases reach equilibrium very quickly, but all of them display RH levels well above 80%. In addition to high RH levels, some cases (Part C, Part L and TER in Swansea) display the presence of interstitial condensation, with RH levels reaching 100%. So all cases are considered as "fail". These results are summarised in the table below.

Table 53: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Fail	Case 4 Fail	Case 7 Fail	Case 10 Fail
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Fail
TER	Case 3 Fail	Case 6 Fail	Case 9 Fail	Case 12 Fail

These findings are not in line with current practice in the industry, as this build-up is normally known to be a robust build-up when used under recommended conditions.

The main moisture source creating problems in a solid wall build-up is rain penetration from the outside. As the external wall, in this build-up, is not protected, moisture (as liquid water) penetrates deeper into the build-up in the winter via capillary action due to wind-driven rain reaching the façade. As the insulation is installed directly in contact with the outer brick layer, the cold side of the insulation is exposed to the conditions experienced by the inner surface of the brickwork. However, it is worth noting that this baseline analysis is done using the worst case scenario regarding the physical characteristics of the brick material, which means that the effect might be less visible in the sensitivity analysis when 'better-performing' bricks (in terms of moisture properties) are used.

This also raises the question of the actual thermal performance of the outer part of the insulation layer, which is exposed to very high RH levels. For example, mineral wool, like most full-filled cavity wall insulation materials, has a moisture-dependent thermal conductivity.

Risk of Mould Growth

Independently to which exposure zone the build-up is located in, all cases display extremely high RH levels (RH levels > 95%) for several months a year. All the conditions for mould growth are not met at this interface. Indeed, these periods of high RH levels are centred around the winter season (which does not promote mould growth), food for mould growth should also not be abundant and air should not be present at this interface.

However, RH levels are still mainly above 80% throughout the year (including the summer season, when this promotes mould growth). In addition, the subject of buildability with cavity walls has been raised with the N11 typology (partial-fill cavity wall). It is possible for a small air gap to be present in between the outer brickwork layer and the insulation for diverse buildability reasons (insulation being squashed and not expanding through the whole cavity, insulation not being thick enough, etc.). It is also likely for mould growth to find a food source (even if not abundant), which means all the conditions for mould growth could be met at this interface.

However, if mould growth was to occur, as its location is isolated from the indoor environment there would be no significant consequences to the build-up or the health of building occupants.

Risk of Interstitial Condensation

The graphs show that the cases located in Swansea present the risk of interstitial condensation several months a year. This confirms this risk, as highlighted by BS 5250 (2011) and BS EN ISO 13788 (2012).

However, this is not considered a significant risk, as cavity wall insulation such as mineral wool is generally a non-hygroscopic material, which means that the material does not possess the ability to attract and hold water molecules from its surrounding materials. In addition, full-fill cavity wall constructions typically include weep holes located at the base of the wall, which allow any condensation happening at this interface to be evacuated, as to avoid its accumulation.

Therefore, the presence of interstitial condensation is not as detrimental as it could be, due to the fact that safe removal mechanisms are included in the build-up.

Effects of exposure zones and U-values

The difference in U-values between different cases is almost unnoticeable. This seems coherent, as the conditions on the inner surface of the outer brick layer are mainly driven by the conditions the external brick façade is exposed to (such as wind-driven rain and solar gains) rather than the conditions present on the warm side of the critical junction.

The difference in exposure zones is visually noticeable on the graphs, as they show clearly that build-ups in zones that are more exposed to wind-driven rain display on average higher RH levels, as well as a more prolonged period during which interstitial condensation occurs. This finding is as predicted, since the hygrothermal performance of exposed brick walls is directly affected by the external conditions.

17.3.5. Additional Monitored Junction

As the baseline cases demonstrate that a full-fill cavity wall presents some moisture risks, it is useful to monitor the RH levels at a second location within the build-up, this time on the warm side of the insulation. If the build-up is to be considered ‘safe’, the interface between the insulation layer and the inner blockwork layer situated on the warm side of the insulation should be kept at warm temperatures and ‘safe’ RH levels.

As the monitored junction is now located on the warm side of the insulation, the impact of different exposure zones is less noticeable on the RH levels of the junction, with all RH profiles being similar (with only a minor difference in exact RH levels). Therefore, only the cases for Zone 4 – Swansea are displayed below.

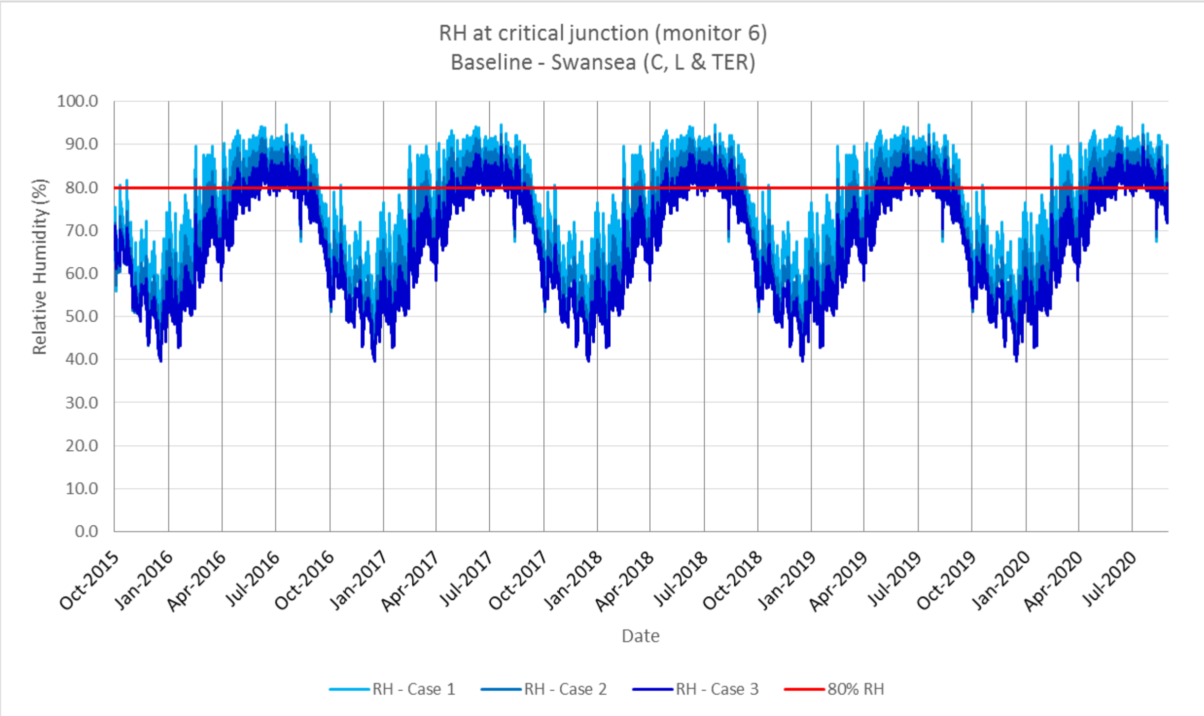


Figure 117: RH levels at additional monitored junction for Cases 1, 2 and 3

The graph shows that RH levels reach above the 80% threshold for several months during the summer season. These RH profiles can be explained by reversed condensation due to solar gains reaching the façade. Indeed, when the outer leaf is heated by sunshine, the water vapour it contains is carried across deeper into the fabric due to vapour diffusion and is at risk of accumulating on the cooler interface of the inner leaf. This phenomenon occurs on south-facing façades, where there is direct sunshine radiating on the façade.

<u>Risk of Mould Growth</u>

Interstitial condensation is not a risk at this interface, as the graph shows that RH levels are kept below 90%. However, the risk of mould growth is higher, as RH levels are kept above 80% during the summer season and temperatures are adequate for mould growth. The lack of abundant food and air should not promote mould growth, but it is possible for these conditions to be met in practice – if the build-up was built without replicating ‘perfect’ theoretical conditions.

17.3.6. Conclusions – Baseline

- This build-up is heavily used in the industry

- Due to the limitations of BS EN ISO 13788 and the build-up with porous material exposed to the elements (wind-driven rain and solar gains), then there is a need for BS EN 15026 assessment method
- The build-up's hygrothermal performance is heavily linked to exposure zone: the more exposed the build-up is, the higher the RH levels experienced (up to 100% RH leading to interstitial condensation) on the inner surface of the outer brickwork
- There is a presence of interstitial condensation, though this is not a significant issue as the interstitial condensation is accounted for and interstitial condensation removal process is included in build-up
- There is a question about the thermal performance of the insulation when constantly submitted to high RH levels (> 80%)
- The risk of mould growth on the outer and inner surfaces of the insulation is not considered highly significant (due to lack of abundant food and air). However, possibility for 'non-perfect' build-up in practice (ABIS conditions), which could mean the presence of food and air for mould growth (which is not directly in contact with the internal environment, but not recommended on the inner surface of the insulation).

STBA / DECC's guidance
'There is the possibility that the insulation will bridge the cavity allowing moisture from driving rain to penetrate to the inner leaf. However, if the outer leaf is in good repair and the insulation has been properly installed, the risk is negligible, except in conditions of extreme driven rain'

This is an extract from the STBA / DECC's guidance, which is the latest guidance on this build-up. It is suggesting that this build-up is safe except in extreme driven rain (i.e. Zone 4). Prolonged rain has been predicted as part of the climate change. Since more rainfall is likely to mean more wind-driven rain, it may have a greater impact in future.

17.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change in Brick Physical Characteristics

17.4.1. Brick Physical Characteristics

This typology includes a porous material (the outer brick layer) being exposed to wind-driven rain and solar gains. The transient modelling of other typologies (N8 – solid wall with IWI) indicates that the physical characteristics of the brick play a significant role on the hygrothermal performance of the build-up. Therefore, the first sensitivity analysis is carried out with a change in the physical characteristics of the brick, where two additional bricks are tested in addition to the baseline model.

- Baseline Brick: Hand-formed brick (high absorption)

As explained in section 16.2, the default brick chosen for the baseline model is considered to be a conservative choice, due to the poor performance of the brick (porosity, water absorption coefficient). This conservative approach is taken because of a lack of available data for UK building materials. This brick can be described as high absorption, and is likely not to represent the characteristics of bricks used in new-build buildings currently in the industry.

To assess the impact of brick characteristics onto the hygrothermal performance, two additional bricks (considered lower absorption) were chosen as alternatives for the first sensitivity analysis. Below are a short summary of their characteristics:

- Sensitivity 1: Solid Brick Masonry

The first lower absorption brick is chosen with a similar density and porosity to the default brick, while having a lower water absorption coefficient (0.11 kg/m²√s instead of 0.32 kg/m²√s).

- Sensitivity 2: Aerated Clay Brick (650 kg/m^3)

The second lower absorbent brick was chosen with much lower density (linked to a higher porosity) compared to the two previous bricks, and has a mid-range A-value of 0.097 kg/m²√s.

17.4.2. Sensitivity Analysis Cases

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the three target U-values (as per baseline cases), for each of the two bricks tested in this sensitivity analysis:

Table 54: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	Case 4.d	Case 7.d	Case 10.d
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
TER	Case 3.d	Case 6.d	Case 9.d	Case 12.d

17.4.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases. The graphs are displayed for the sensitivity cases across the four exposure zones.

The results show that the RH profiles are very similar between the Part C, Part L and TER cases, independently for each exposure zone. The minor difference in RH levels ranges from slightly lower RH levels in Part C cases and slightly higher with TER cases, with a variation between all cases within 2% to 3%.

As the RH profiles are very similar between the cases for each exposure zones, only the Part L cases are displayed in the following section for each exposure zone. The sensitivity analysis cases are displayed as a coloured line (blue for Swansea, purple for Bristol, green for Manchester and orange for London), while their respective baseline cases are displayed with a grey line.

- <u>Sensitivity 1: Solid Brick Masonry</u>

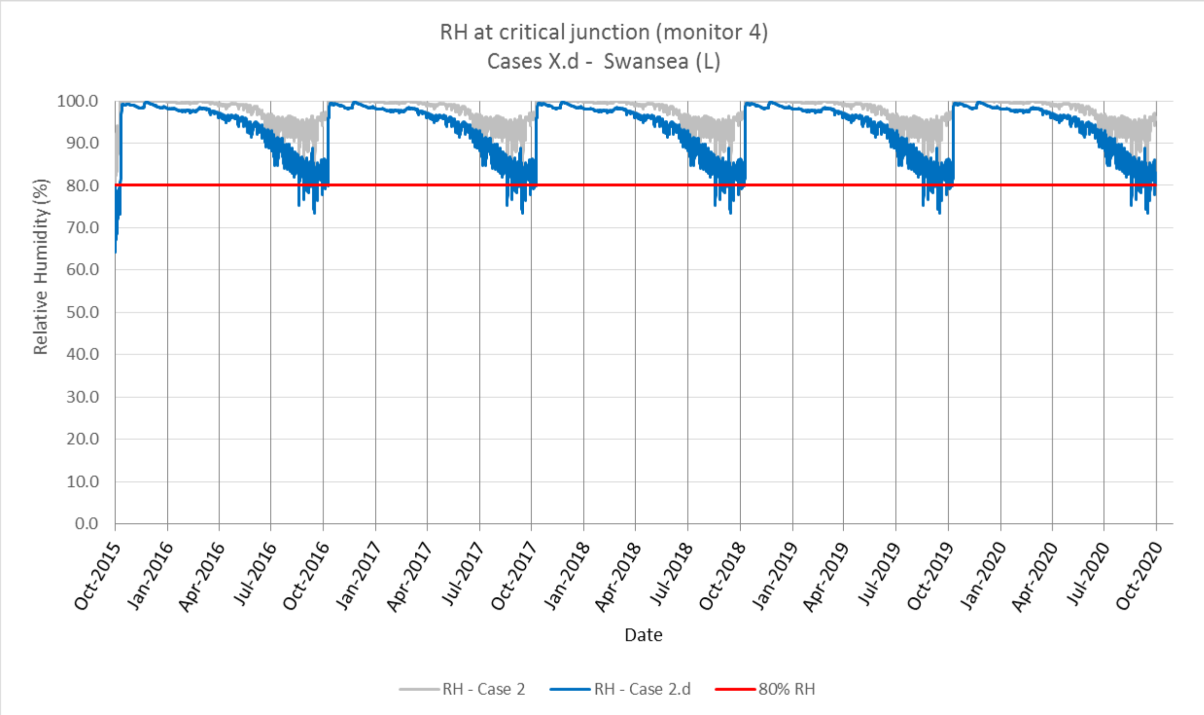


Figure 118: RH levels at critical junction for Cases 2 and 2.d

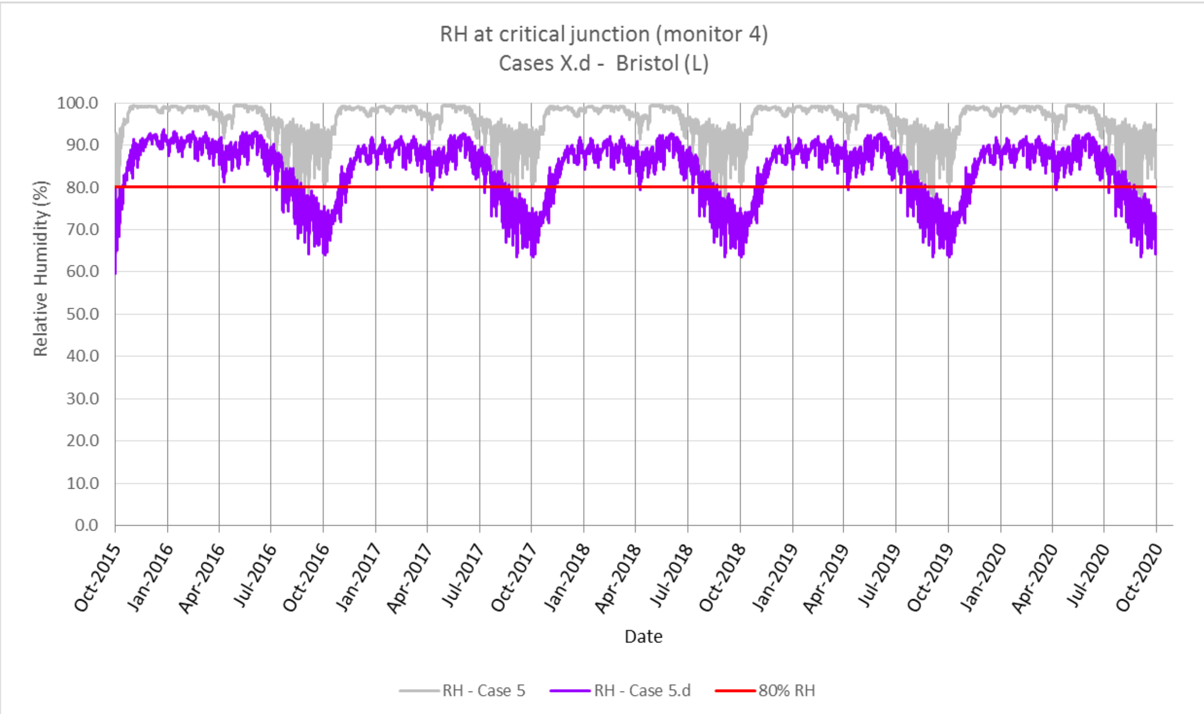


Figure 119: RH levels at critical junction for Cases 5 and 5.d

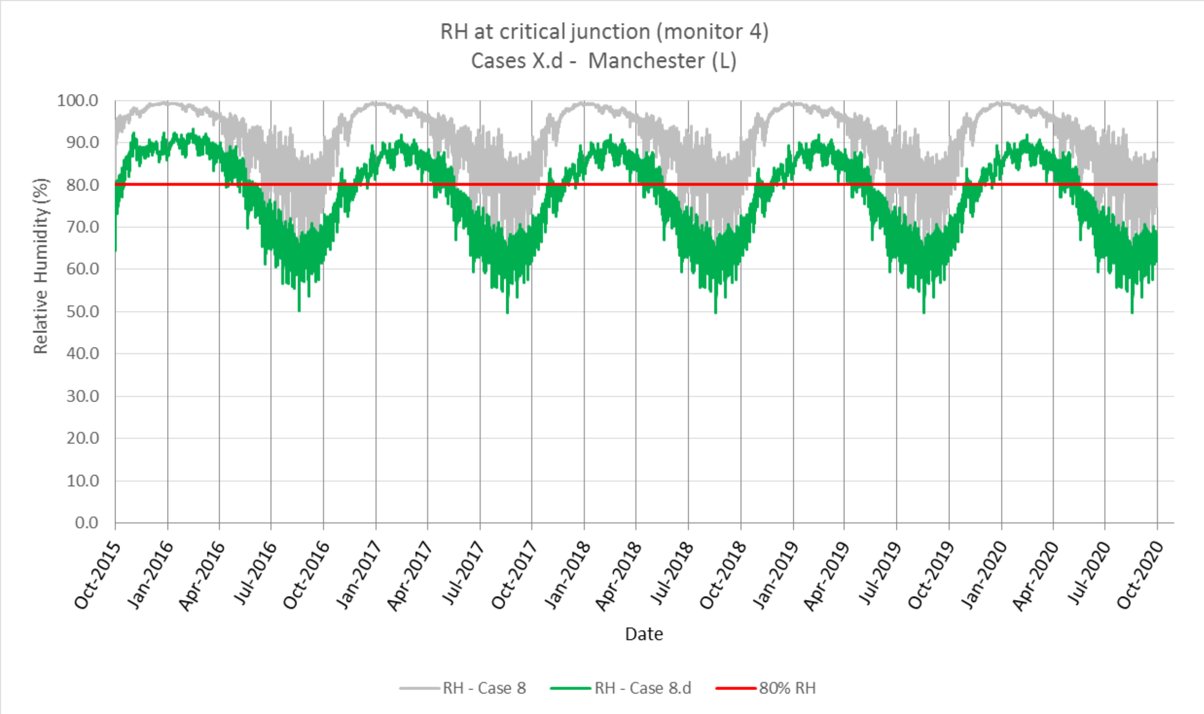


Figure 120: RH levels at critical junction for Cases 8 and 8.d

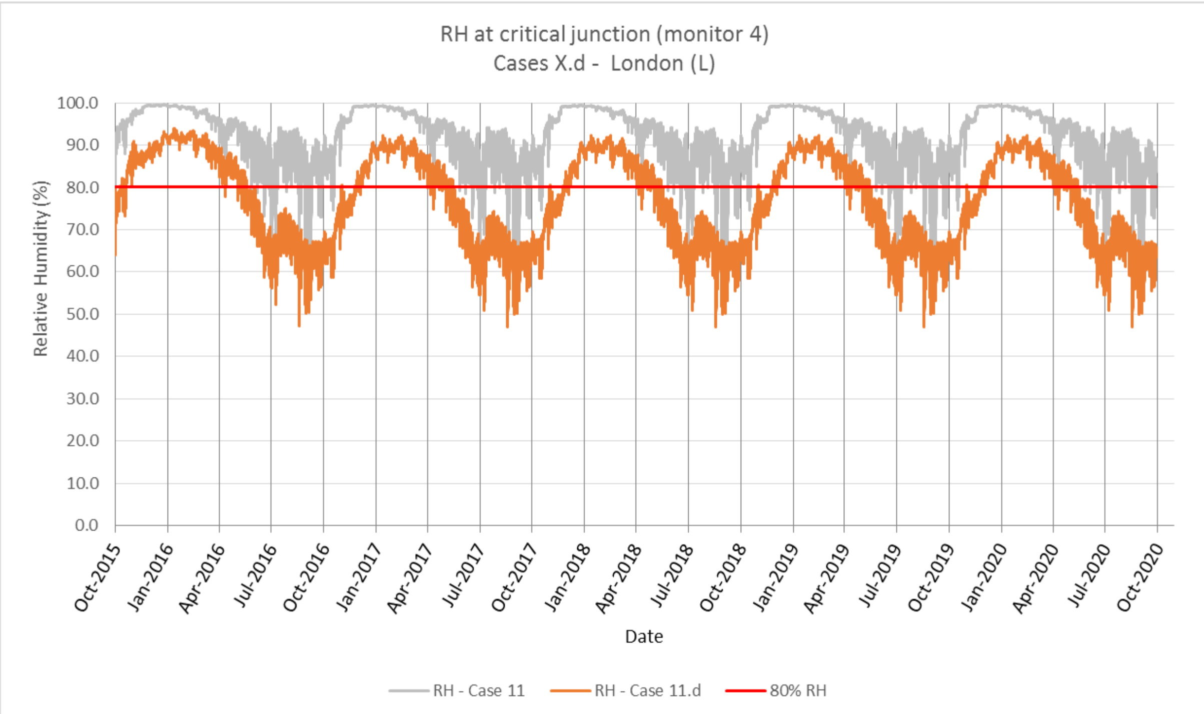


Figure 121: RH levels at critical junction for Cases 11 and 11.d

- <u>Sensitivity 2: Aerated Clay Brick (650 kg/m^3)</u>

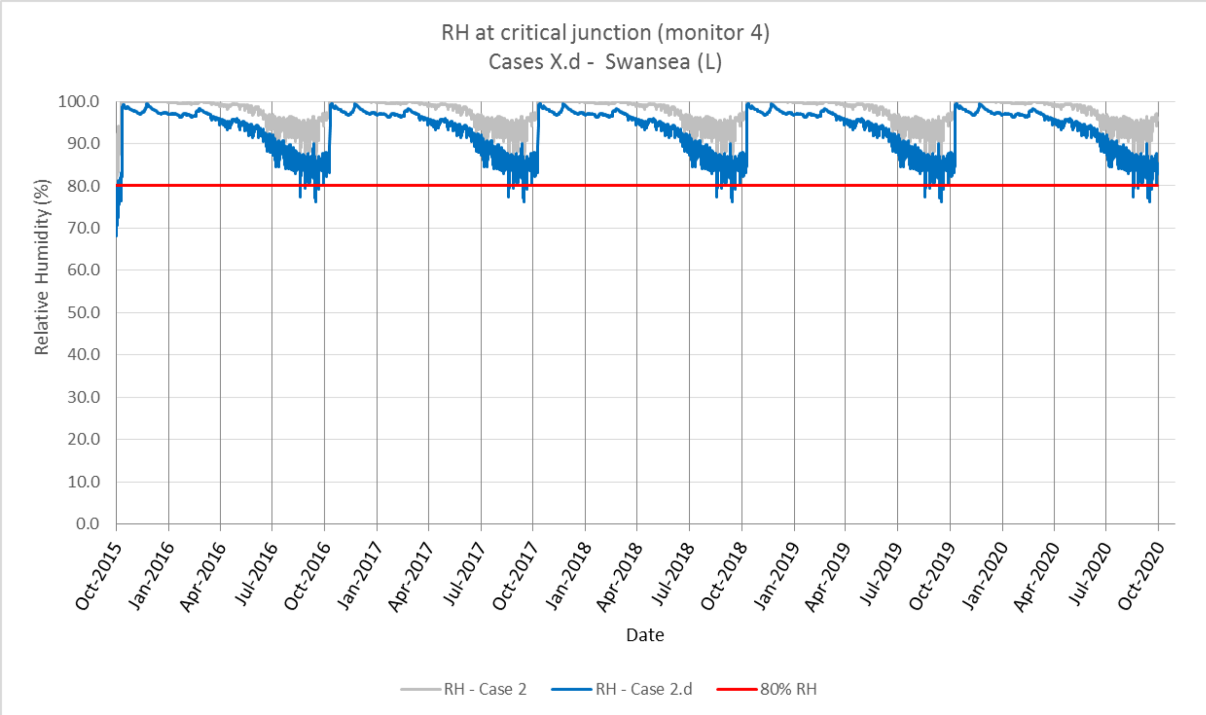


Figure 122: RH levels at critical junction for Cases 2 and 2.d

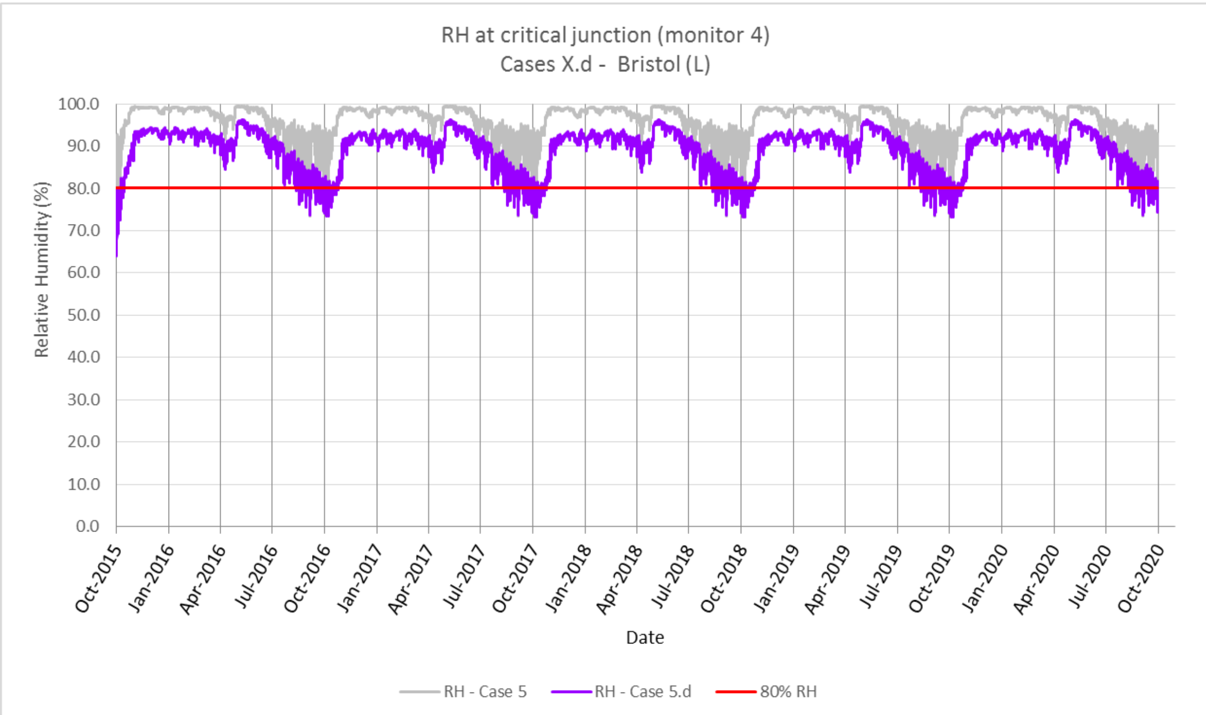


Figure 123: RH levels at critical junction for Cases 5 and 5.d

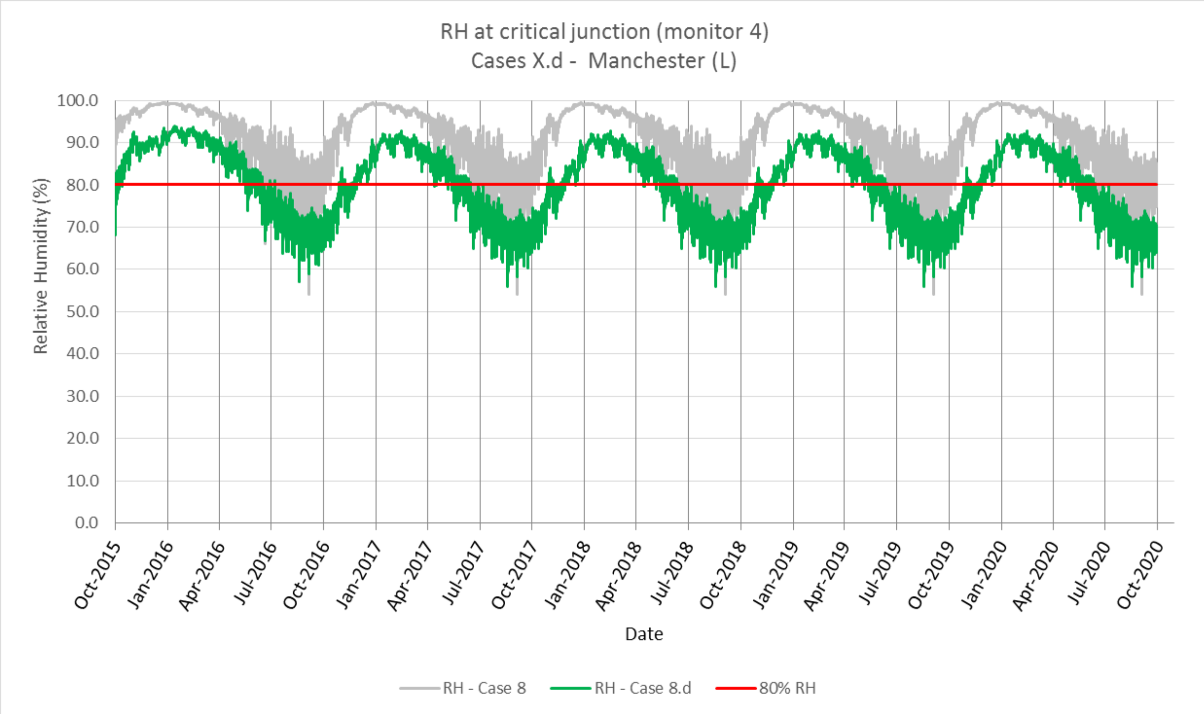


Figure 124: RH levels at critical junction for Cases 8 and 8.d

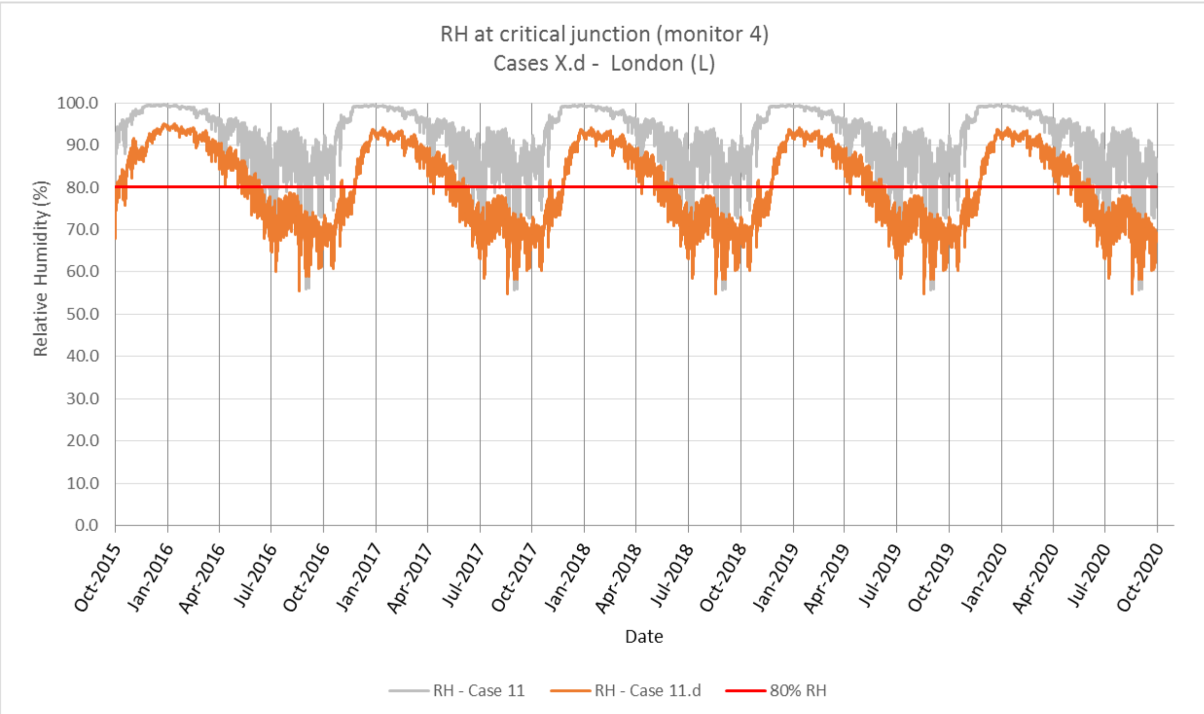


Figure 125: RH levels at critical junction for Cases 11 and 11.d

17.4.4. Conclusions – Sensitivity Analysis Cases X.d

<u>Moisture risk assessment criteria</u>

The graphs show that all cases modelled in this sensitivity analysis perform better than their respective baseline cases, as the RH profiles in the sensitivity analysis are consistently lower than their respective baseline. The decrease in RH levels is in the range of 10% for Zones 1, 2 and 3, and ranging 3% to 10% for Zone 4.

However, this improvement in hygrothermal performance is not important enough, as it does not bring RH levels at the critical junction below the 80% RH threshold for most of the year. This means that all cases have the same status as those in the baseline assessment and are labelled as 'fail' in accordance with the moisture risk assessment criteria listed in section 2.3.

Effects of brick characteristics

The graphs show that both bricks give very similar results, despite some of their different characteristics (especially their porosity). The second brick (aerated clay brick) is three times more porous than the first brick tested in the sensitivity cases. This difference is seen on the graphs with the steepness of the increase in RH levels during the wet season (October to January). With the second brick being much more porous, the RH levels increase more rapidly during the wet season, as this brick has a larger potential for water intake on a daily basis during the wet season.

Both bricks have their water absorption coefficient, called 'A-value', being very similar. Therefore, it seems that the A-value is one of the key characteristics of the brick, having a direct and key impact on the hygrothermal performance of the build-up: the lower the A-value, the more resistant to moisture a build-up is.

Results

The table below summarises the performance of the modelled cases (for both types of bricks modelled in the sensitivity analysis), following the moisture risk assessment criteria listed in section 2.3:

Table 55: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Fail	Case 4.d Fail	Case 7.d Fail	Case 10.d Fail
Part L	Case 2.d Fail	Case 5.d Fail	Case 8.d Fail	Case 11.d Fail
TER	Case 3.d Fail	Case 6.d Fail	Case 9.d Fail	Case 12.d Fail

These graphs show that, on average, the change in brick characteristics has a significant impact on the hygrothermal performance of the build-up. The main variable is the brick water absorption coefficient 'A-value', with a lower A-value having a direct beneficial impact on the build-up's performance. A lower porosity (normally linked to a higher density) can also improve the hygrothermal performance, as a lower porosity reduces the amount of water uptake from wind-driven rain into the build-up.

However, this improvement is not significant enough to improve the build-up's status from 'fail' to 'pass'. These results show that this build-up remains a risky build-up and is prone to high RH levels, which could lead to mould growth and/or a reduction in thermal performance.

17.5. Sensitivity Analysis – Change in Orientation [Cases X.c]: North-facing walls

17.5.1. Sensitivity Analysis Cases

As the build-up is exposed to the wind-driven rain, which has a significant impact on its hygrothermal performance, the second sensitivity analysis is to change the orientation of the façade. With this sensitivity analysis, the orientation is changed from South-West to North. As explained in typology N8 (solid wall with IWI), the build-up on a South-West facing orientation experiences more wind-driven rain but benefits from greater solar gains (allowing it to dry out quicker). In comparison, a build-up on a North facing orientation experiences less wind-driven rain, which is beneficial to its hygrothermal performance. However, the lack of solar gains leads to a reduction in drying capabilities, which is detrimental to its hygrothermal performance.

The overall impact of the change of orientation is difficult to predict, as it is the balance between the (beneficial) reduction in wind-driven rain and the (detrimental) reduction in solar gains that will inform the change in hygrothermal performance of the build-up.

The sensitivity analysis cases are set across the 4 wind-driven rain exposure zones, meeting the three target U-values (as per baseline cases):

Table 56: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.c	Case 4.c	Case 7.c	Case 10.c
Part L	Case 2.c	Case 5.c	Case 8.c	Case 11.c
TER	Case 3.c	Case 6.c	Case 9.c	Case 12.c

17.5.2. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases. The graphs are displayed for the sensitivity cases across the four exposure zones.

The sensitivity analysis cases are displayed as a coloured line (blue for Swansea, purple for Bristol, green for Manchester and orange for London), while their respective baseline cases are displayed with a grey line. Within each colour, the darker the colour, the higher / better the U-value is.

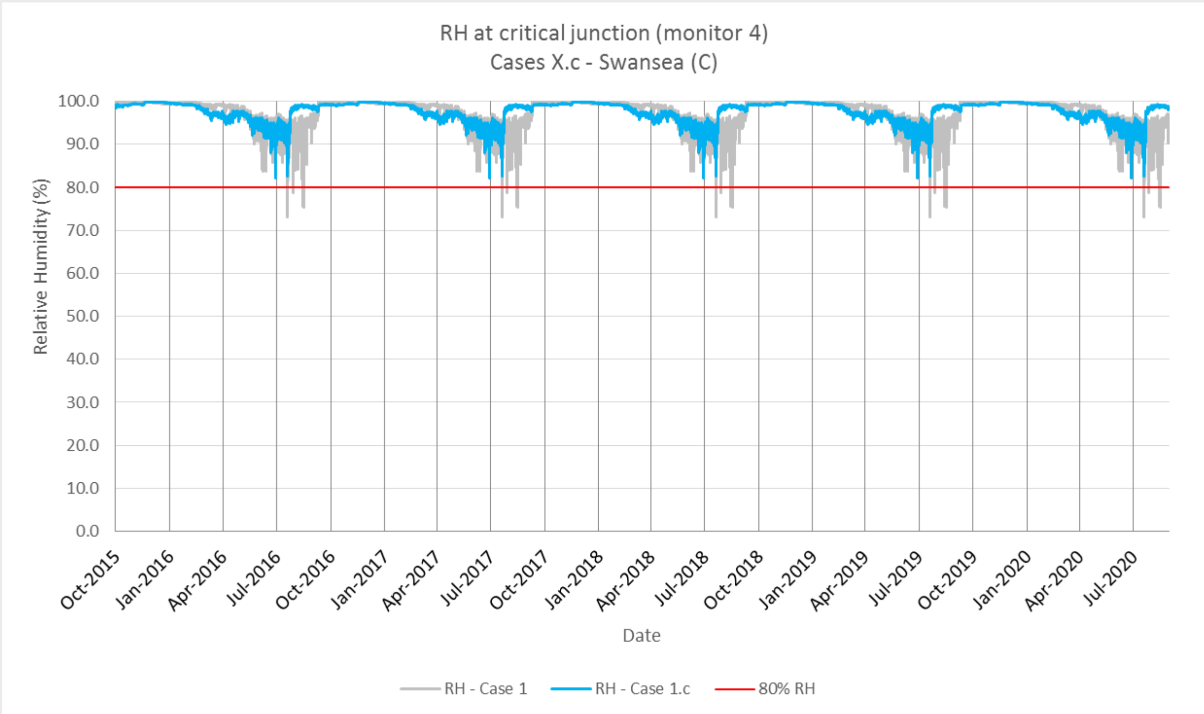


Figure 126: RH levels at critical junction for Cases 1 and 1.c

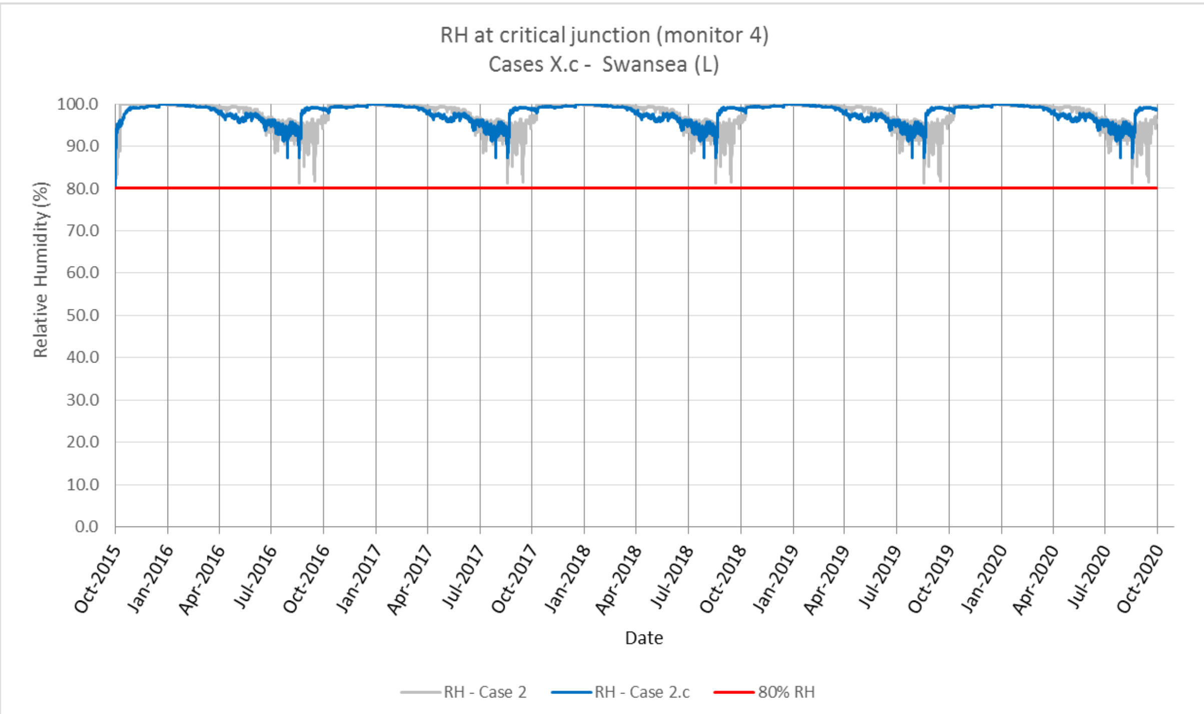


Figure 127: RH levels at critical junction for Cases 2 and 2.c

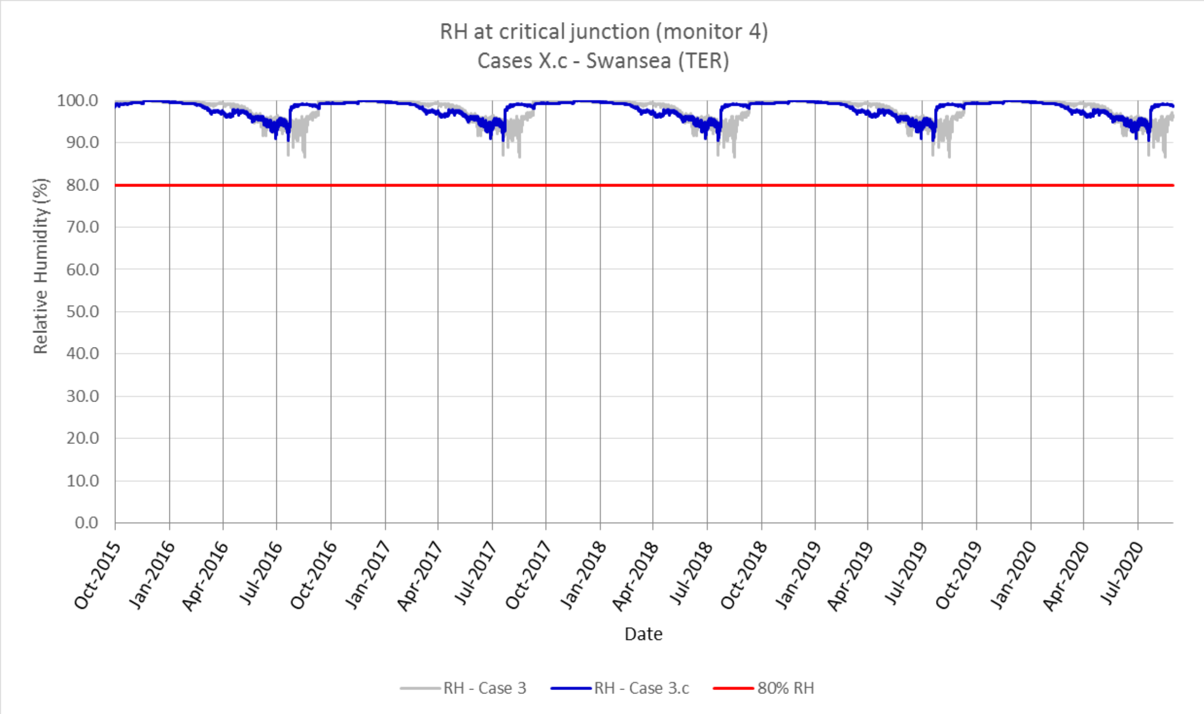


Figure 128: RH levels at critical junction for Cases 3 and 3.c

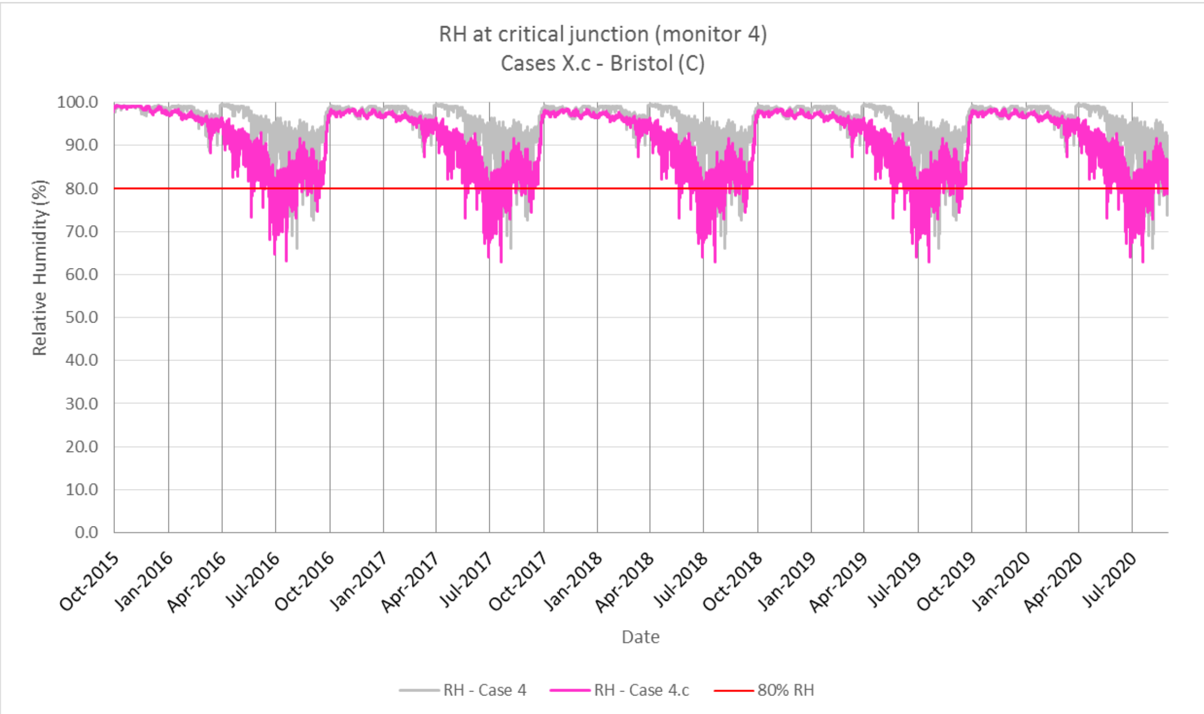


Figure 129: RH levels at critical junction for Cases 4 and 4.c

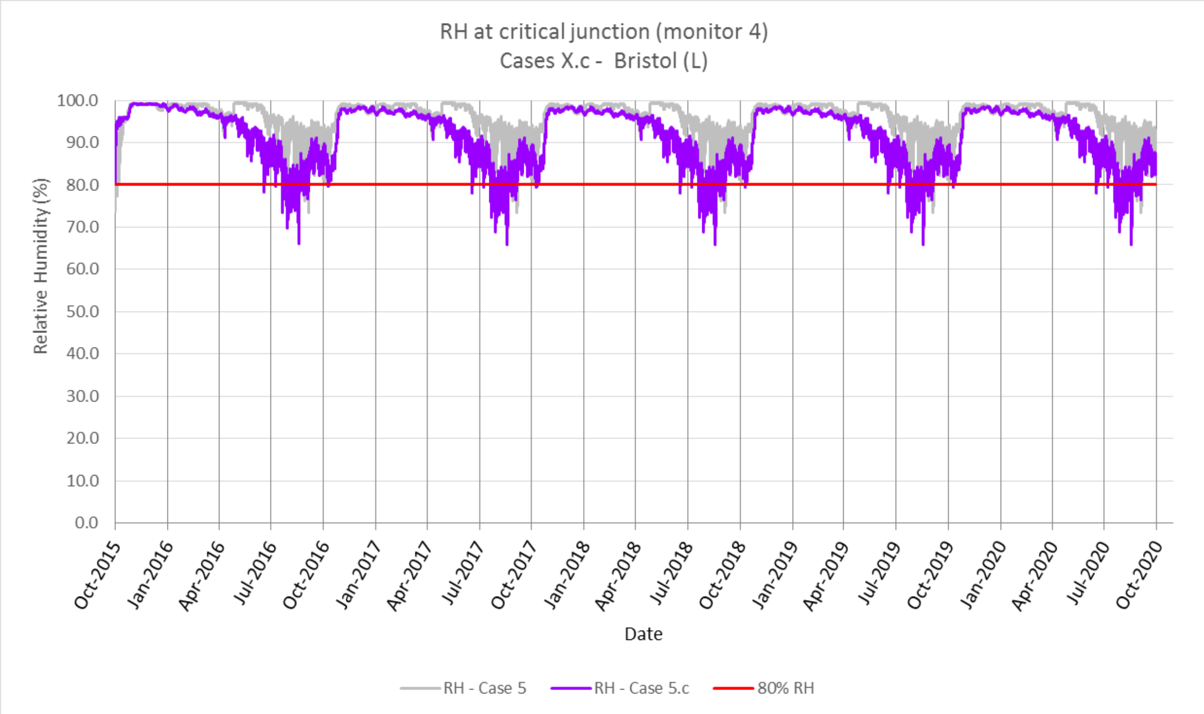


Figure 130: RH levels at critical junction for Cases 5 and 5.c

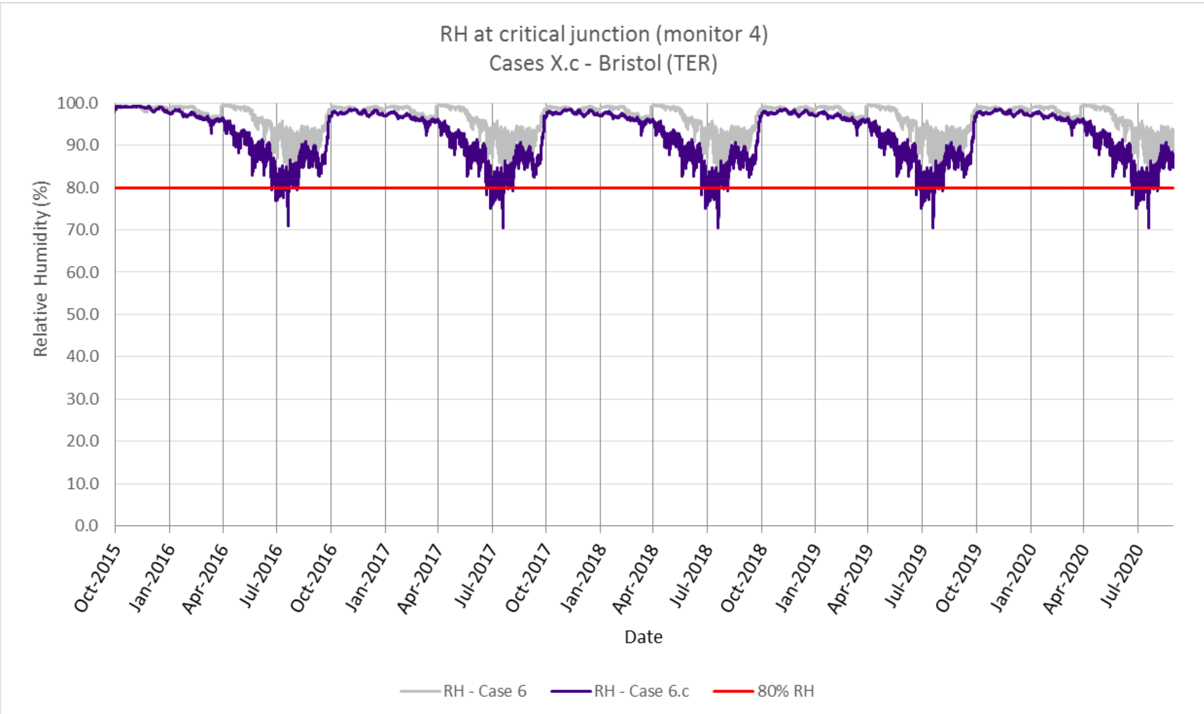


Figure 131: RH levels at critical junction for Cases 6 and 6.c

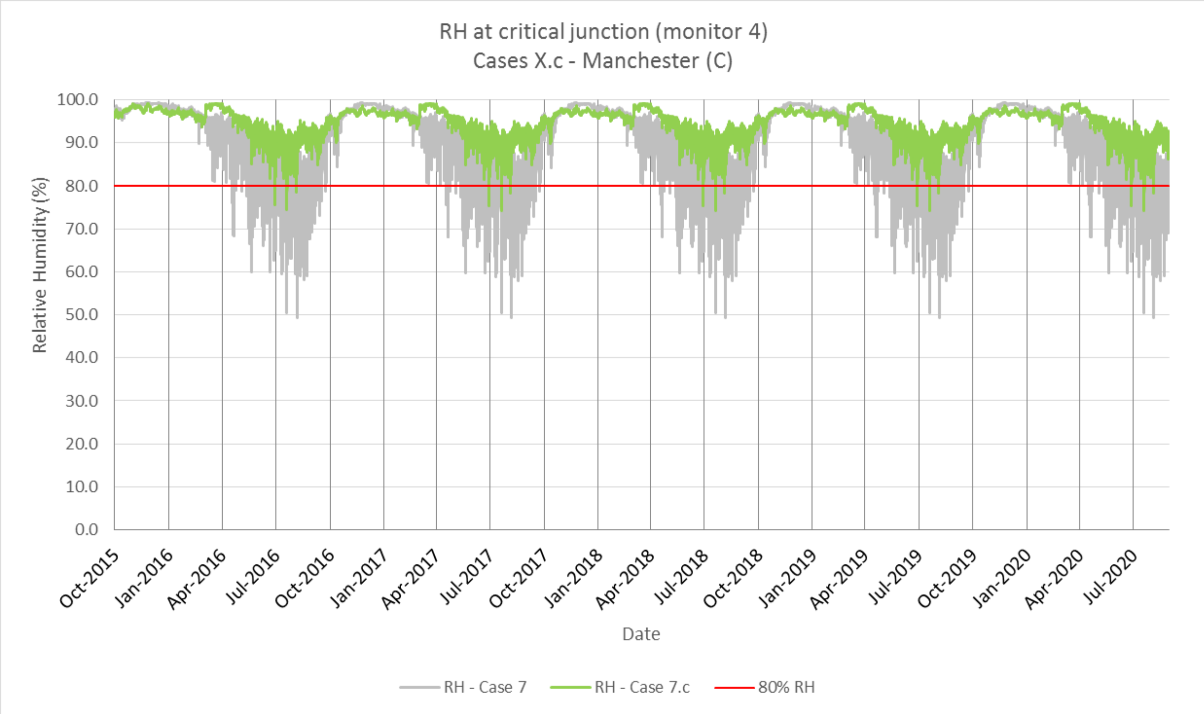


Figure 132: RH levels at critical junction for Cases 7 and 7.c

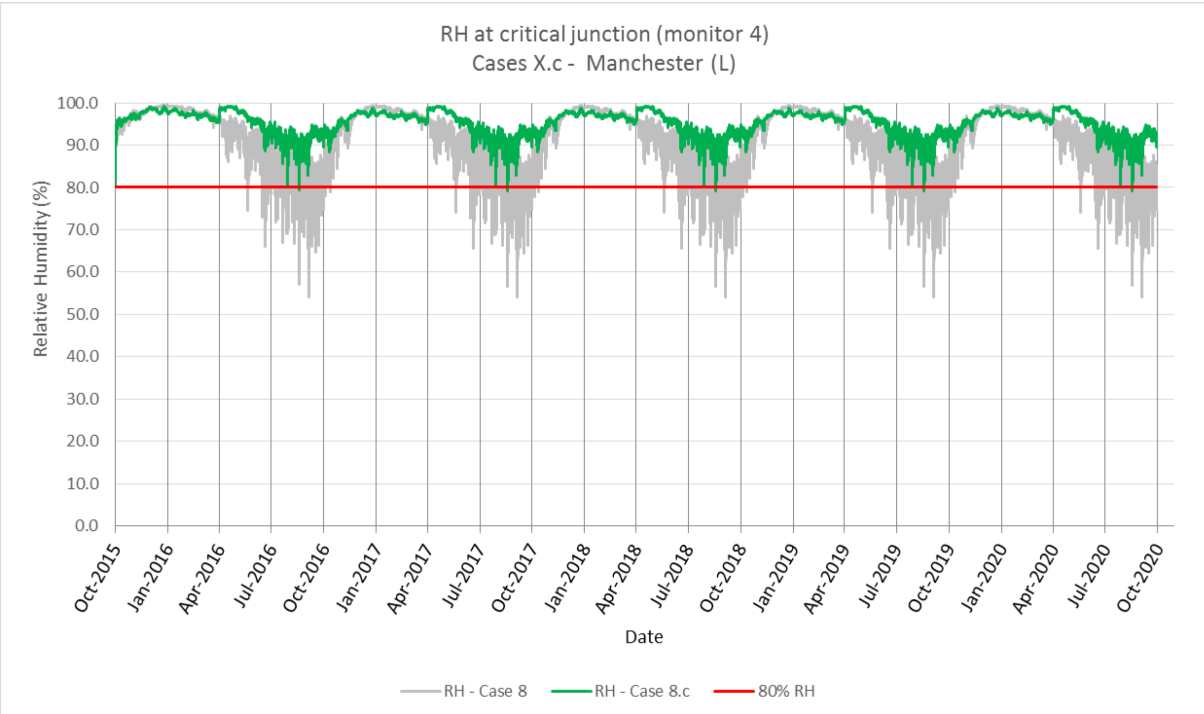


Figure 133: RH levels at critical junction for Cases 8 and 8.c

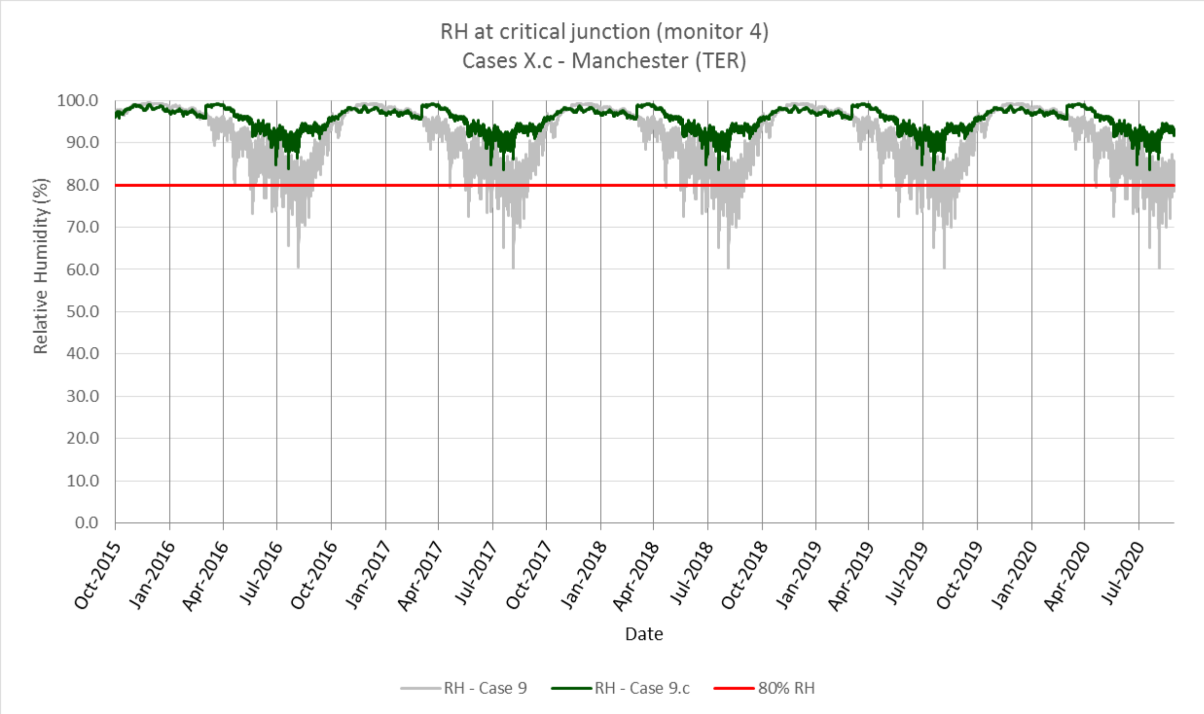


Figure 134: RH levels at critical junction for Cases 9 and 9.c

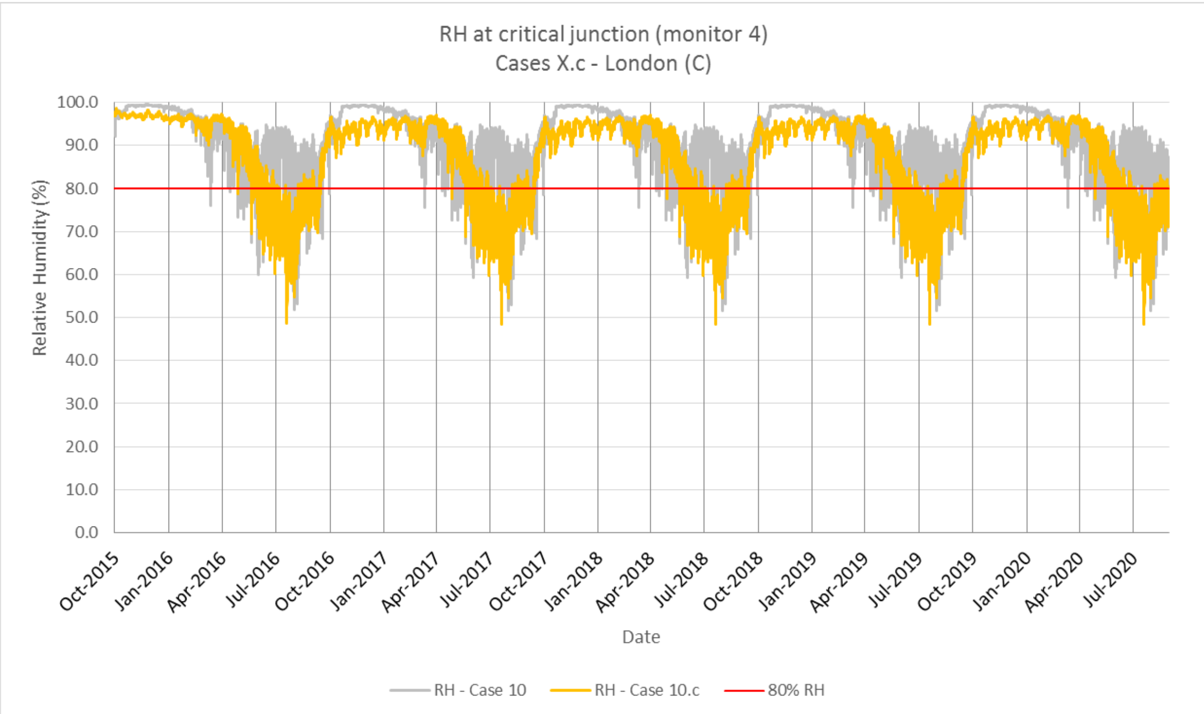


Figure 135: RH levels at critical junction for Cases 10 and 10.c

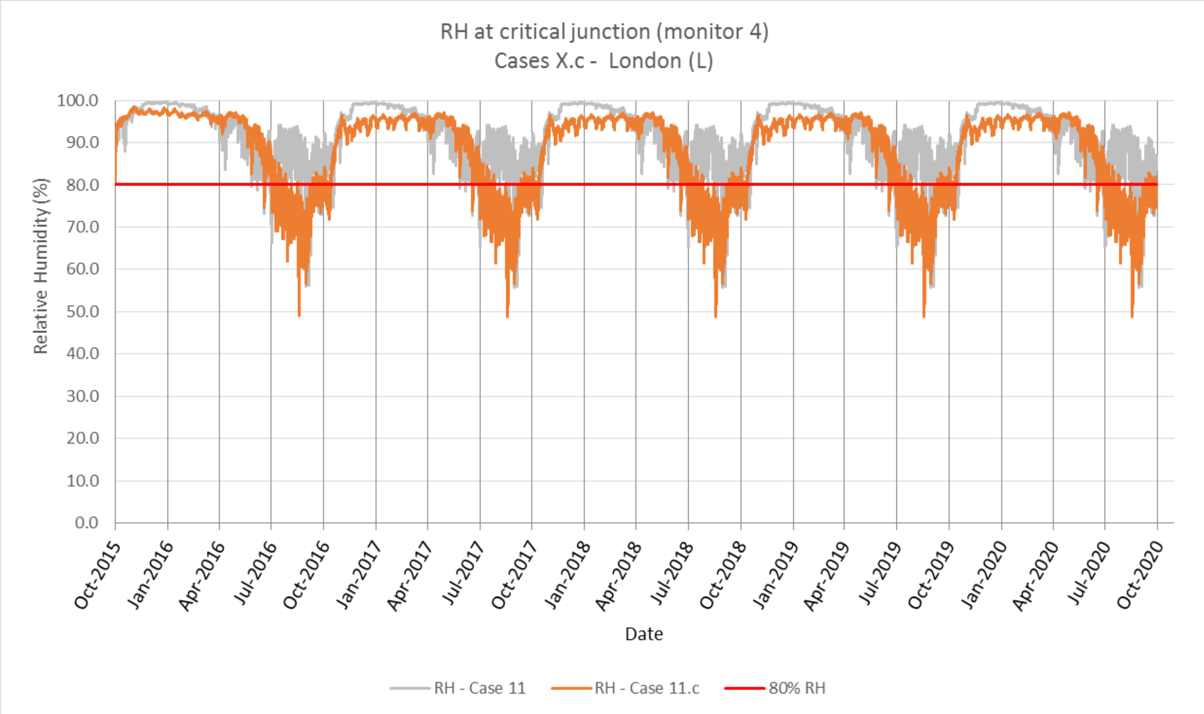


Figure 136: RH levels at critical junction for Cases 11 and 11.c

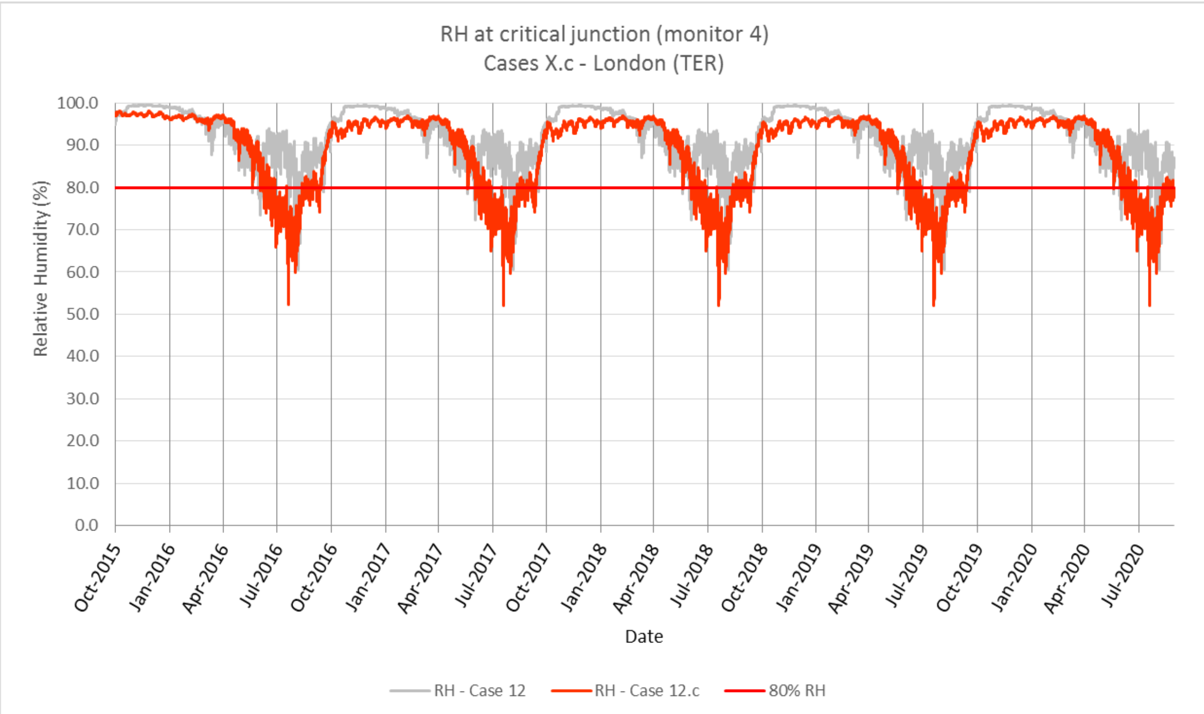


Figure 137: RH levels at critical junction for Cases 12 and 12.c

17.5.3. Conclusions – Sensitivity Analysis Cases X.c

<u>Moisture risk assessment criteria</u>

The graphs show that all cases modelled in this sensitivity analysis perform (on average) similarly or slightly better than their respective baseline cases, with the exception of the three cases in Manchester (as shown in green in the graphs above). These 3 cases in Manchester (i.e. Cases 7, 8 and 9) display a worse hygrothermal performance when compared to their respective baselines.

However, this improvement in hygrothermal performance, which is present only in some cases, is minimal and does not bring RH levels at the critical junction below the 80% RH threshold for most of the year. This means that all cases have the same status as those in the baseline assessment and are labelled as 'fail' with the moisture risk assessment criteria listed in section 2.3.

Effects of exposure zones

The graphs show that, in the most extreme exposure zone (Zone 4 – Swansea), the hygrothermal performance of the build-up is unchanged despite the change in orientation. The RH levels at the critical junction are kept around similar levels, with the RH profiles displaying an offset in time (with the wet season starting slightly early with the north orientation, compared to the south-west orientation).

The graphs for both Zone 3 – Bristol and Zone 1 – London cases show that the reduction in wind-driven rain and the reduction in solar gains have a small overall beneficial impact on the hygrothermal performance of the build-up. This beneficial effect appears to be kept throughout the modelling period, therefore changing the equilibrium RH profiles.

In contrast, the graphs for the Zone 2 – Manchester cases are the only cases displaying worse RH levels at the critical junction, compared to the baseline cases. This shows that, in these conditions, the reduction in wind-driven rain is not enough to compensate for the reduction in solar gains, leading to a small detrimental impact on the hygrothermal performance of the build-up.

Results

The table below summarises the performance of the modelled cases, following the moisture risk assessment criteria listed in section 2.3:

Table 57: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.c Fail	Case 4.c Fail	Case 7.c Fail	Case 10.c Fail
Part L	Case 2.c Fail	Case 5.c Fail	Case 8.c Fail	Case 11.c Fail
TER	Case 3.c Fail	Case 6.c Fail	Case 9.c Fail	Case 12.c Fail

These graphs show that, on average, the reduction in wind-driven rain and the reduction in solar gains due to the change in orientation can have a different impact on the hygrothermal performance of a build-up, depending on the wind-driven rain exposure zones / weather conditions the build-up is in.

On average, it appears that a change in orientation from South-West to North may have none to a small beneficial impact on the hygrothermal performance of the build-up (though this is not the case for the modelling cases in Zone 2 – Manchester). However, this improvement (only present in certain cases) is not significant enough to improve the build-up's status from 'fail' to 'pass'.

These results show that this build-up remains a risky build-up and is prone to high risks of mould growth, and therefore cannot be considered robust to resistance to moisture, regardless of the build-up's orientation . These results also highlight that a South-West orientation might not typically be the orientation which will display the worst hygrothermal performance, and therefore both south-west and north orientations should be considered / modelled this build-up is considered at a design stage.

17.6. Sensitivity Analysis – Change from compressible to rigid insulation

Rigid insulation is also commonly used in the industry in this type of build-up. No sensitivity analysis modelling is done in this report, in which the insulation type is changed from compressible to rigid insulation, as the build-up is quite different due to the presence of a small air gap to allow for drainage of any moisture present in the cavity.

Further modelling could be undertaken in these conditions, to assess the hygrothermal performance of a full-fill cavity wall with rigid insulation.

17.7. Conclusions

- This build-up is used often in the industry
- The impact of exposure zones and orientation and building conditions (ABIS) is large

Build-up not highly risky (mainly experiencing high RH levels and presence of interstitial condensation – then adequately removed, rather than suffering from accumulation of moisture) but does not appear to be the most robust build-up regarding resistance to moisture.

18. Typology N13: Timber-frame wall – with air gap and a semi-porous finish (e.g. facing brickwork)

The N13 typology is a new-build timber frame wall with an air gap and a semi-porous finish (e.g. facing brickwork). The thermal performance of the build-up is improved with the use of IWI (internal wall insulation) on the internal side of the timber frame.

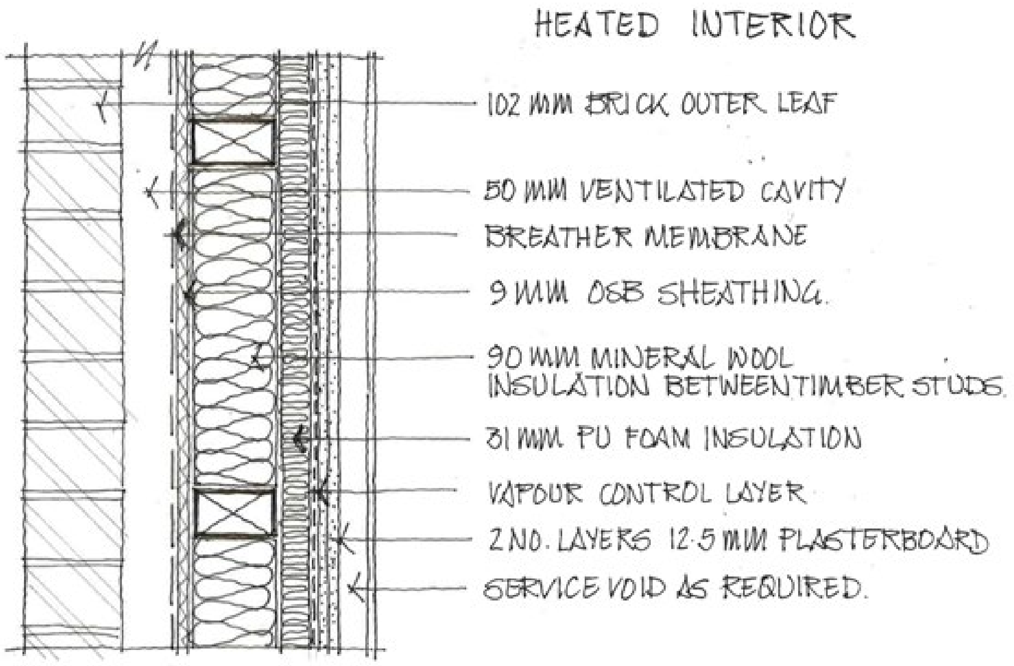


Figure 138: Illustration of the build-up of the typology (Part L case)

18.1. Assessment Method

As BS 5250 (2011) states in the general framed wall section (G.4.1), *'there is a risk of interstitial condensation occurring behind impermeable external finishes or cladding: to avoid that, a vented space should be provided immediately behind the finish or cladding'.*

To follow prescriptive guidance, the cavity behind the brick finish is ventilated to the outside, to allow any moisture present in the cavity to be removed. This means that the outer brick layer is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the breather membrane (on the cold side of the frame) to the internal finish.

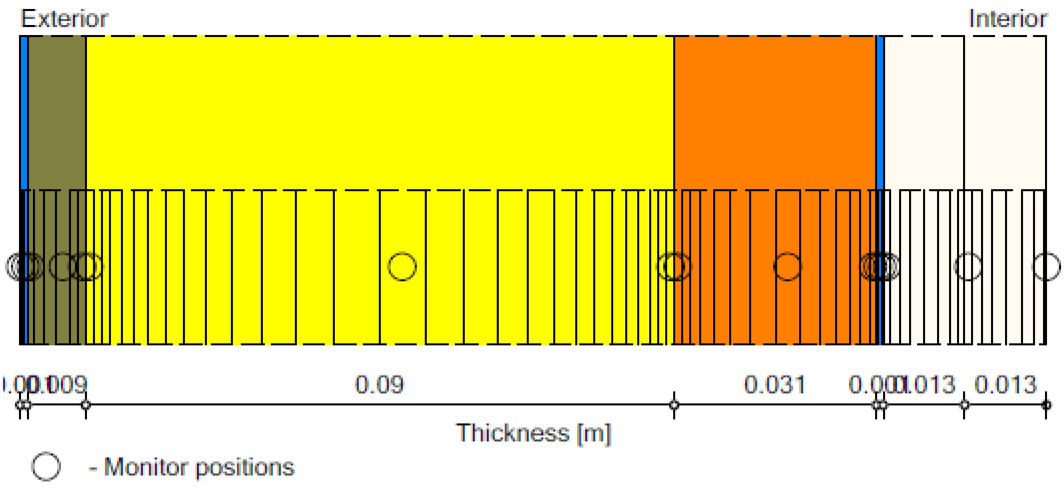
As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method. The results by the Glaser method show that this build-up is considered a ‘safe’ build-up, with no risk of interstitial condensation. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

18.2. Build-up

Please find below the build-up of the typology.

Build-Up:

- 102mm brick outer leaf *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 90mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 0mm // 31mm // 100mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard



Materials:

- *weather resistive barrier (sd=0,04m) (unlocked)	0.001 m
- Oriented Strand Board (density 615 kg/m³)	0.009 m
- Mineral Wool (heat cond.: 0,04 W/mK)	0.09 m
- PU (heat cond.: 0,025 W/mK)	0.031 m
- vapour retarder (sd=2m)	0.001 m
- Gypsum Board	0.013 m
- Gypsum Board	0.013 m

<u>WUFI Input Parameters</u>

As the cavity is considered ventilated, both the brick outer layer and the air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the breather membrane) is exposed to different external conditions due to the outer brick layer acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the timber frame)

- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the ‘sheltered’ condition in the cavity

18.3. Baseline Results

18.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 58: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

18.3.2. Critical Junction

Prescriptive guidance BS 5250 (2011) paragraph G.4.1 states that *‘there is a risk of interstitial condensation occurring on the inner surface of any sheathing applied directly to the outside of the framing’.* Therefore, all graphs will display RH levels at the interface between the OSB (sheathing) and the cold side of the insulation layer.

This critical junction is not identified by the BS EN ISO 13788 (2012), as the calculation shows no presence of interstitial condensation in the build-up throughout the year.

18.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, at the interface between the OSB (sheathing) and the cold side of the insulation layer.

As per previous typologies, each zone is associated with a colour (blue for Zone 4). Within each colour, the darker the colour, the higher / better the U-value is.

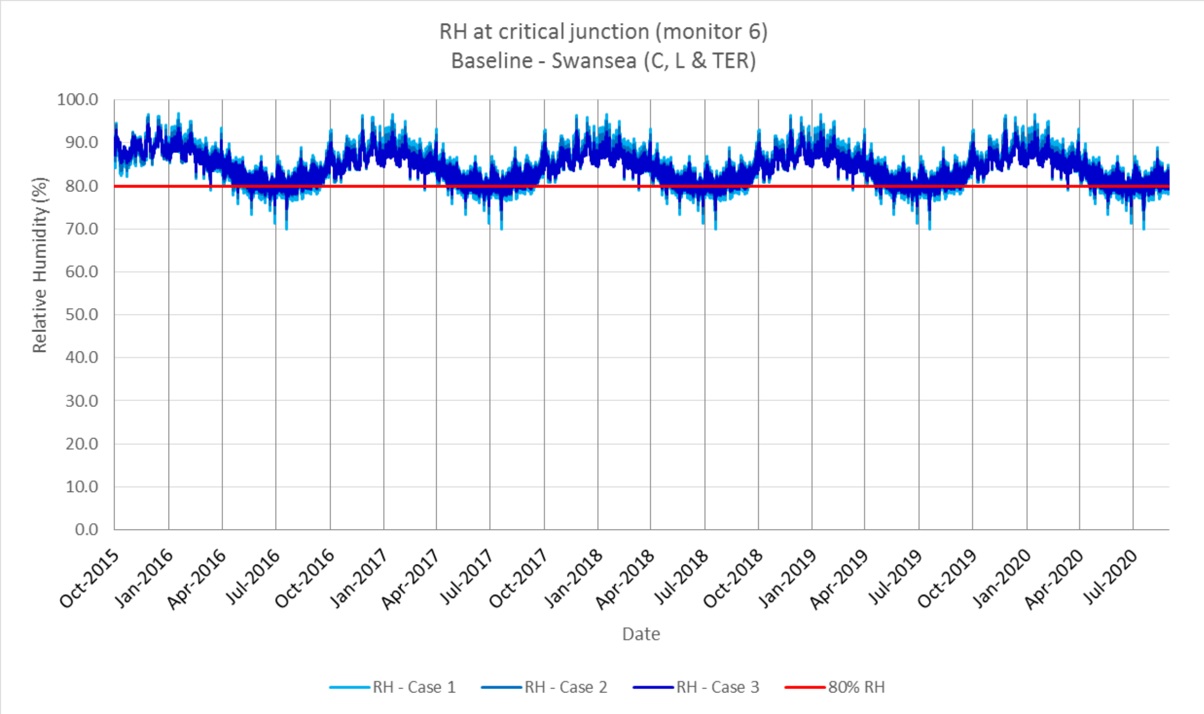


Figure 139: RH levels at critical junction for Cases 1, 2 and 3

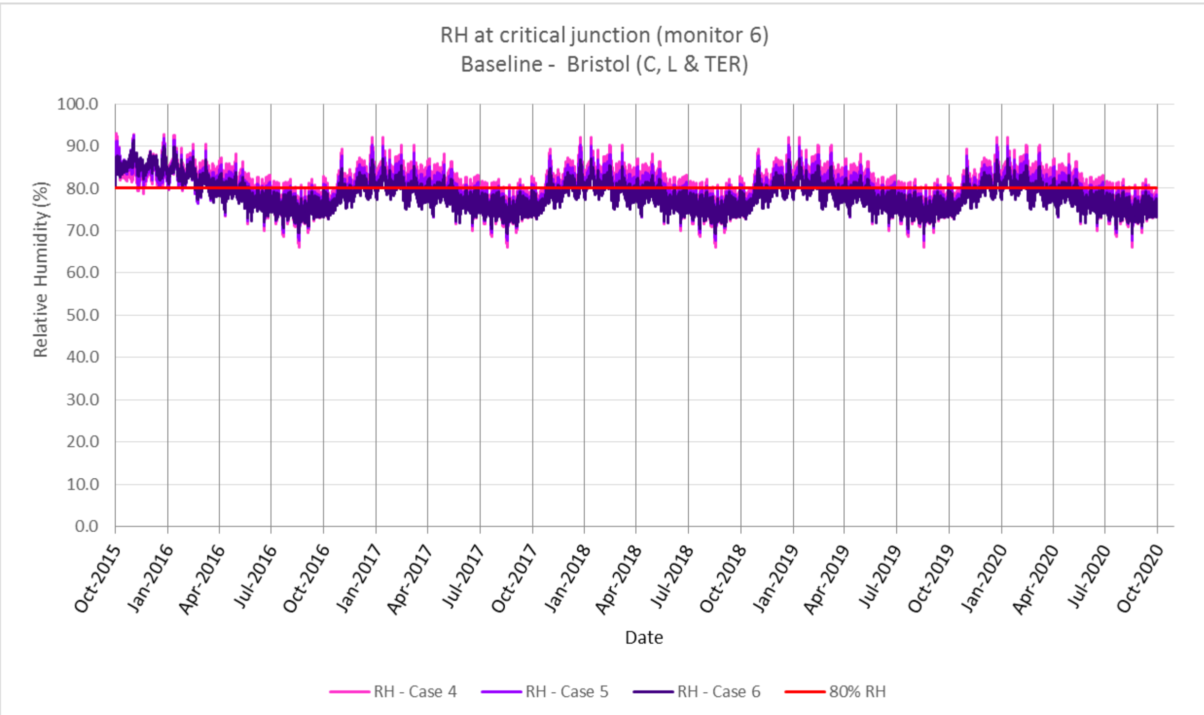


Figure 140: RH levels at critical junction for Cases 4, 5 and 6

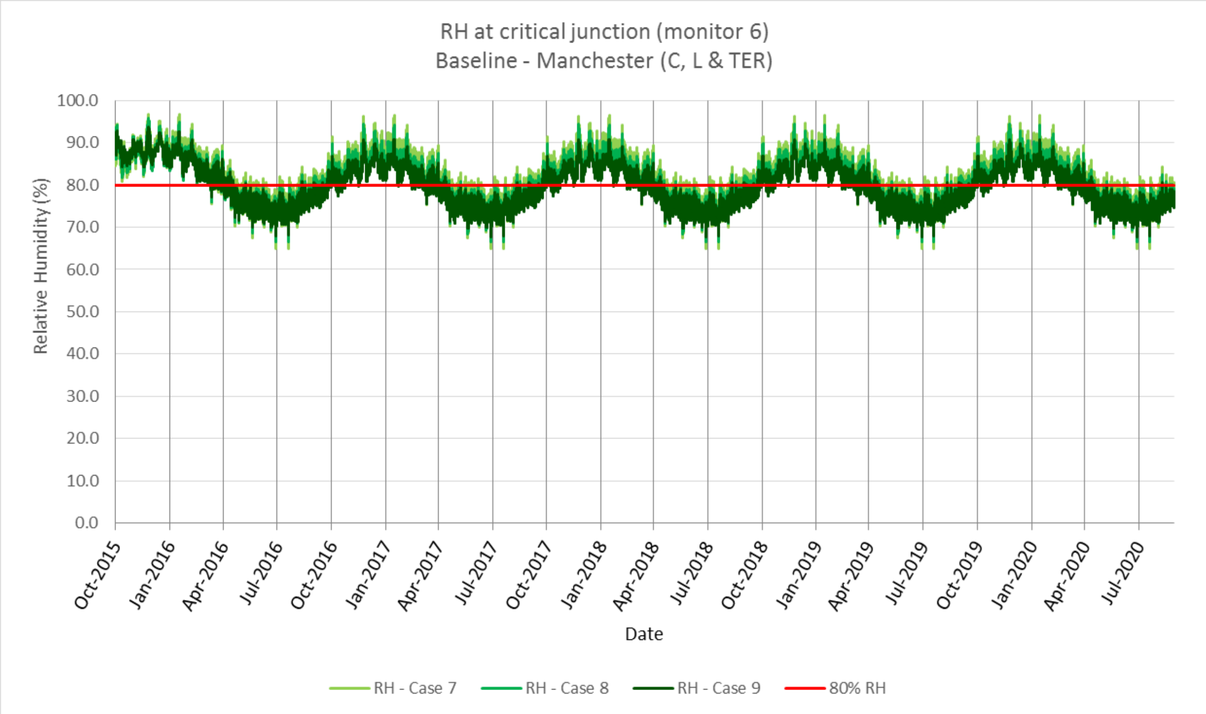


Figure 141: RH levels at critical junction for Cases 7, 8 and 9

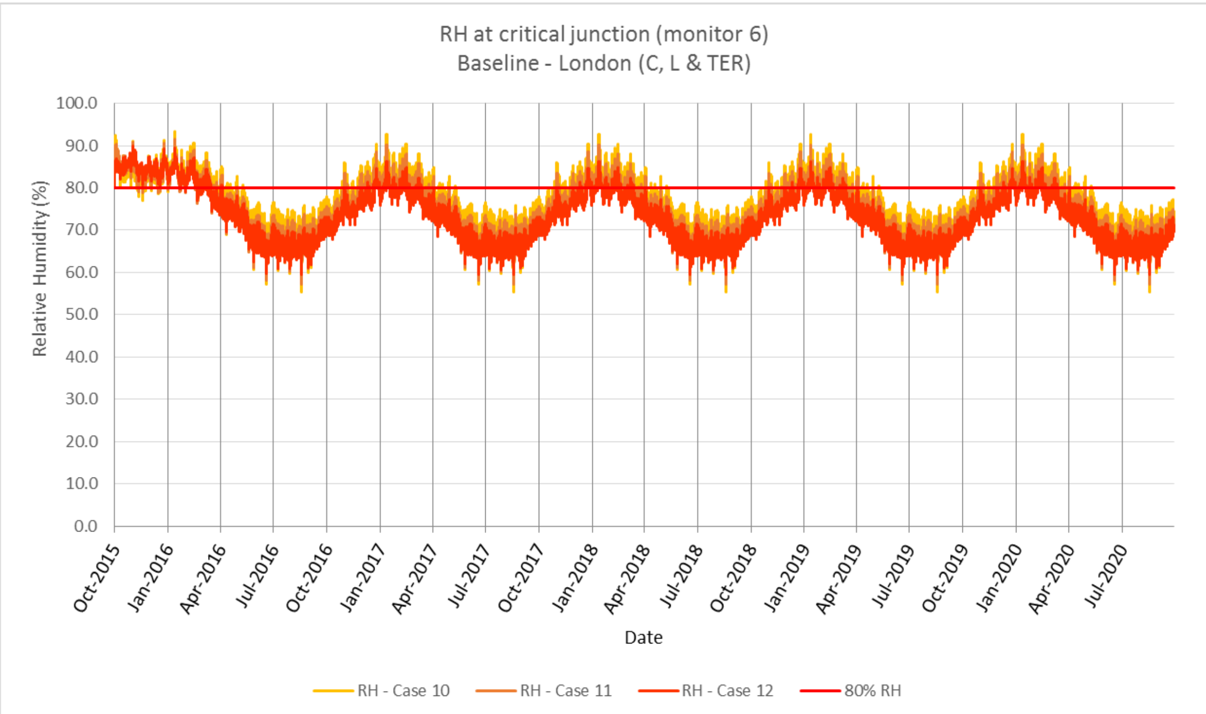


Figure 142: RH levels at critical junction for Cases 10, 11 and 12

18.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

None of the cases display risks of interstitial condensation, as in all cases, the RH levels are most of the time kept below 90%. This is in line with the BS EN ISO 13788 (2012) calculations.

All cases achieve equilibrium, but all of them display intermittent RH levels above the 80% RH threshold. Unfortunately, this threshold cannot be relaxed to 95%, as the interface includes fragile materials (timber studs and OSB), RH levels are sometimes kept high in summer and timber being an organic material, is adequate food for mould spores. In addition, constant high RH levels in the timber might also lead to its deterioration over time.

As some cases (Part C, Part L and TER in Swansea, Bristol and Manchester) display RH levels above 80% for long periods of time (the majority of the year). For this reason, these cases are considered a 'fail'. The three cases in London display lower RH levels, which means that RH levels above 80% occur for shorter periods of time. This means that these cases are considered 'risky' rather than 'fail'.

Table 59: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Fail	Case 4 Fail	Case 7 Fail	Case 10 Risky
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Risky
TER	Case 3 Fail	Case 6 Fail	Case 9 Fail	Case 12 Risky

<u>Risk from Mould Growth</u>

Despite the risk of mould growth being present, this risk might not be as significant as it could be. The build-up is considered easily buildable, due to the ease of installing adequately flexible insulation in between timber studs. This should lead to the absence of air at this critical junction, due to the additional installation of the breather membrane externally to the OSB / sheathing.

However, great care is needed to ensure that the sheathing and the breather membrane are installed properly, as cracks and gaps in these layers would lead to the presence of air (which is the only missing requirement at the critical junction for mould growth) and they are likely to have a detrimental effect on the hygrothermal performance of the build-up.

Such build-up is considered good practice within the industry for resistance to moisture. However, these findings show that the build-up is prone to moisture risks, meaning they are not in line with BS EN ISO 13788 (2012) calculations and industry beliefs.

<u>Effects of exposure zones and U-values</u>

The effects of exposure zones are visible on the graphs. This difference in RH levels at the critical junction due to exposure zones is a direct consequence of the different external conditions in the synthetic weather files. Indeed, external conditions in less exposed zones display lower external RH levels than in more exposed zones.

The difference in U-value is almost unnoticeable on the graphs. This seems in line with what is expected, as:

- the critical junction is located on the cold side of the insulation layer, and a minimum of 90mm of mineral wool insulation between timber studs is present in each case, meaning the critical junction is kept at relatively similar temperatures throughout all cases
- the amount of moisture at the critical junction is mainly driven by vapour diffusion and mainly limited by the presence of the AVCL on the warm side of the insulation (independently to the different thicknesses of insulation present in different cases)

<u>AVCL and Vapour Resistance</u>

Prescriptive guidance BS 5250 (2011) also mentions that *'to avoid [the risk of interstitial condensation on the inner surface of any sheathing applied directly to the outside of the framing], an AVCL with a vapour resistance of at least double that of the sheathing should be provided on the warm side of the insulation, behind the internal surface finish'*.

In the baseline cases, an AVCL is present on the warm side of the insulation, while the sheathing is OSB. With the characteristics of each material, the vapour resistance of the AVCL and the OSB are as follow:

- Vapour resistance of AVCL = 10 MNs/g (with sd = 2m)
- Vapour resistance of OSB = 7.875 MNs/g (with μ = 175 and 9mm thickness)

These results show that the recommendation from BS 5250 (2011) is not met in the baseline build-up. In order to meet the recommendation, the AVCL characteristics should be increased to reach sd = 3.15m. It is also quite common for the sheathing to be ply, which has a much higher vapour resistance diffusion factor (μ = 700), compared to OSB. If ply was used as sheathing, the AVCL characteristics should be further increased to reach sd = 12.6m (as 9mm ply has a vapour resistance of 31.5 MNs/g) to respect the recommendation in BS 5250 (2011).

18.3.5. Conclusions – Baseline

- The build-up is sheltered from the elements and moisture driven by vapour diffusion, with AVCL on the warm side of the insulation, so this is theoretically safe
- Results opposed to BS EN ISO 13788 (2012) calculations; the critical junction showed RH levels above 80%, mainly above 80% in most cases (except for London cases 10, 11 and 12):
  - could lead to potential damage in timber after long term constant high RH levels (and risk of mould growth if air present at critical junction, due to poor workmanship)
  - these results are in contradiction with thinking in the industry

18.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change in AVCL characteristics

18.4.1. Baseline model versus BS 5250 (2011)

The baseline build-up does not fully follow the recommended build-up present in BS 5250 (2011), as the AVCL included between the insulation layer and the plasterboard in the baseline model should have a higher vapour resistance (more precisely, a vapour resistance of at least double that of the sheathing), as stated in the previous section.

<u>Improvement in AVCL</u>

Therefore, the first sensitivity analysis done here is to include an AVCL of an sd-value of 3.15m (instead of sd = 2m) in the build-up, located on the warm side of the insulation, and installed between the insulation layer and the plasterboard in order to match the requirements of BS 5250 (2011).

18.4.2. Sensitivity Analysis Cases

The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 60: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

18.4.3. Graphs at Critical Junction (sd = 3.15m)

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL with sd = 3.15m) are displayed as a coloured line, while their respective baseline cases (with ACVL with sd = 2m) are displayed with a grey line.

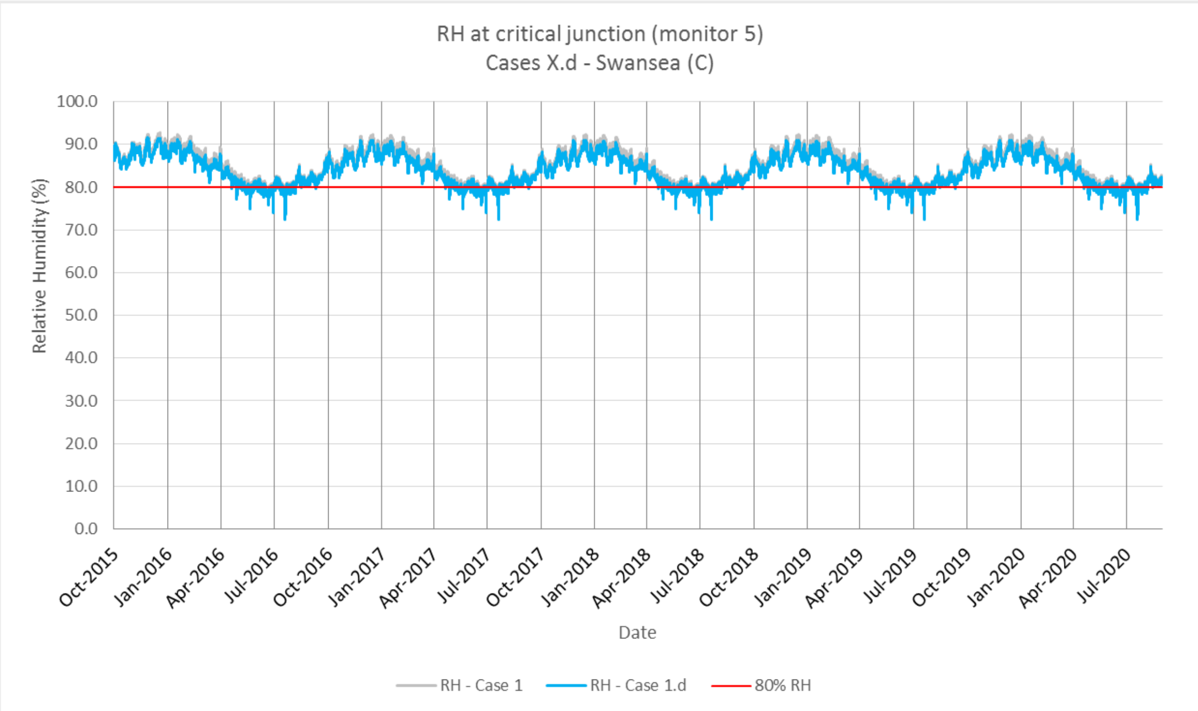


Figure 143: RH levels at critical junction for Cases 1 and 1.d

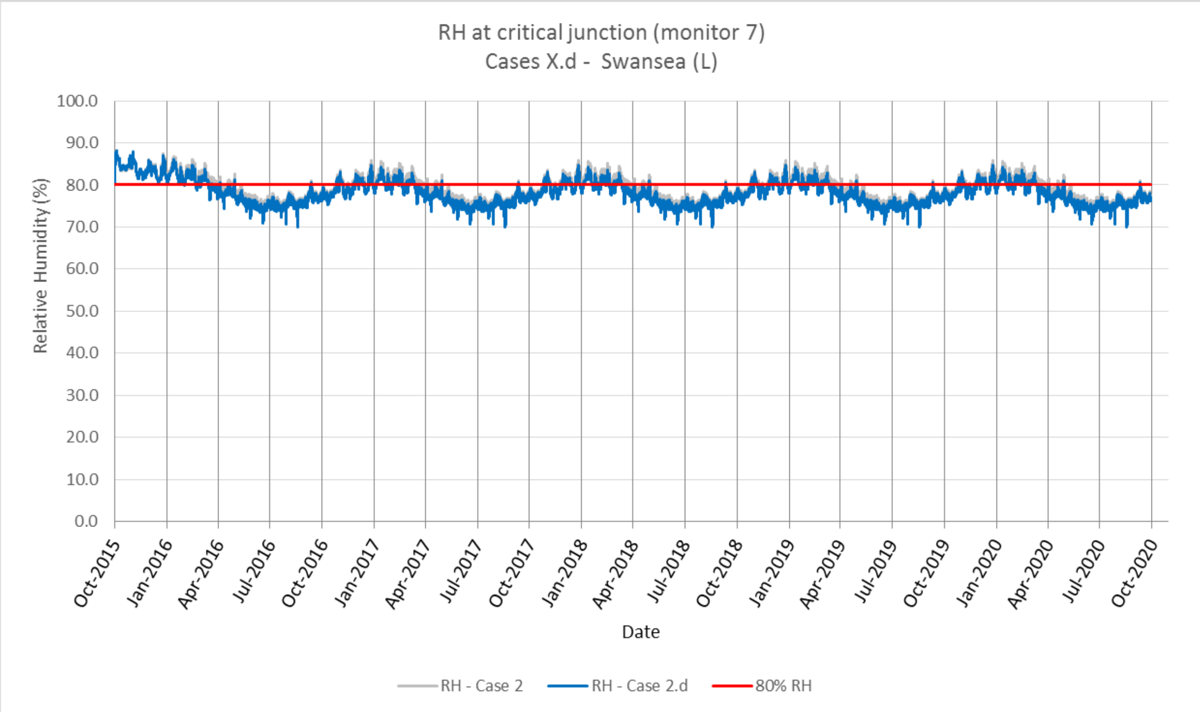


Figure 144: RH levels at critical junction for Cases 2 and 2.d

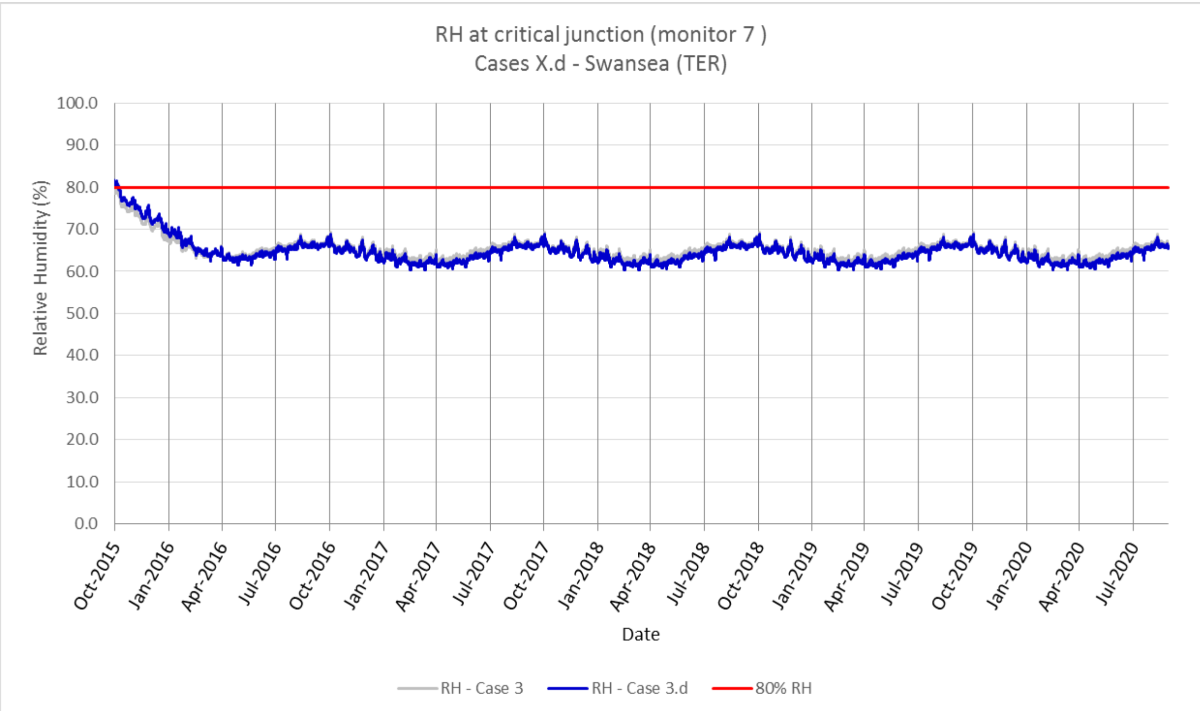


Figure 145: RH levels at critical junction for Cases 3 and 3.d

18.4.4. Conclusions – Sensitivity Analysis Cases X.d

All the modelled sensitivity cases show almost no improvement on the baseline cases, and therefore continue to fail following the moisture risk assessment criteria listed in section 2.3.

The impacts of the change in AVCL characteristics on the hygrothermal performance of the build-up are not clearly visible on the graphs above. Therefore, additional sensitivity analysis cases were modelled to understand more clearly the effects of increasing the vapour resistance of the AVCL layer on the hygrothermal performance of the build-up.

The baseline AVCL has an sd-value of 2m. The first sensitivity analysis is done with an AVCL with an sd-value increased to 3.15m to match the BS 5250 (2011) recommendation. However, an AVCL with an sd-value around 2 to 3m is considered to be a semi-permeable material (according to the ASHRAE classification). Therefore, the sd-value of the AVCL for the following sensitivity analysis is further increased to reflect the use of a less permeable material.

The following sd-values are used:

- AVCL with sd = 20m (semi-impermeable material)
- AVCL with sd = 50m (impermeable material)

18.4.5. Graphs at Critical Junction (sd = 20m)

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL with sd = 20m) are displayed as a coloured line, while their respective baseline cases (with ACVL with sd = 2m) are displayed with a grey line.

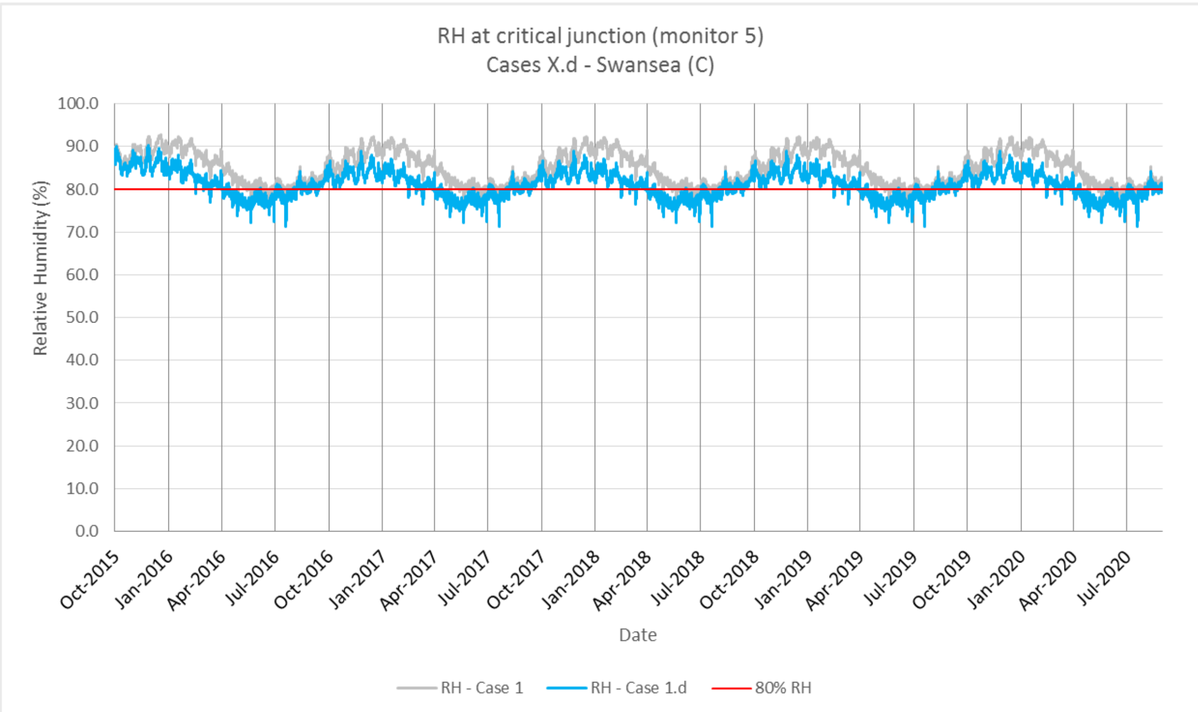


Figure 146: RH levels at critical junction for Cases 1 and 1.d

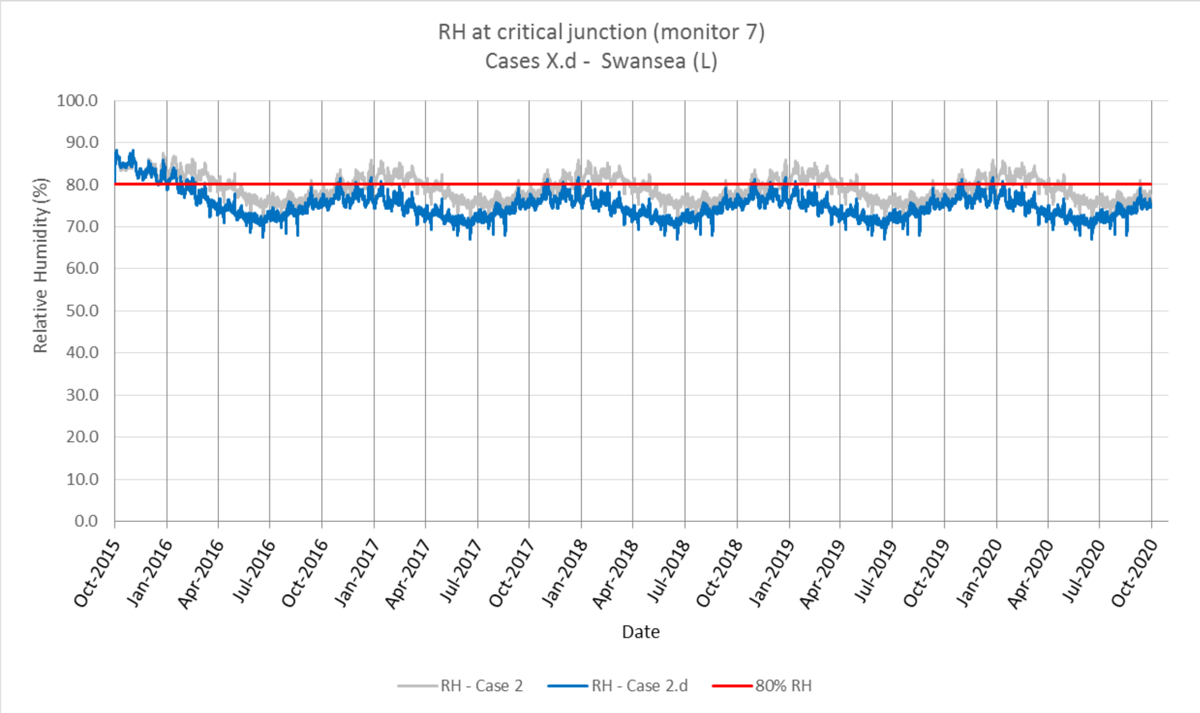


Figure 147: RH levels at critical junction for Cases 2 and 2.d

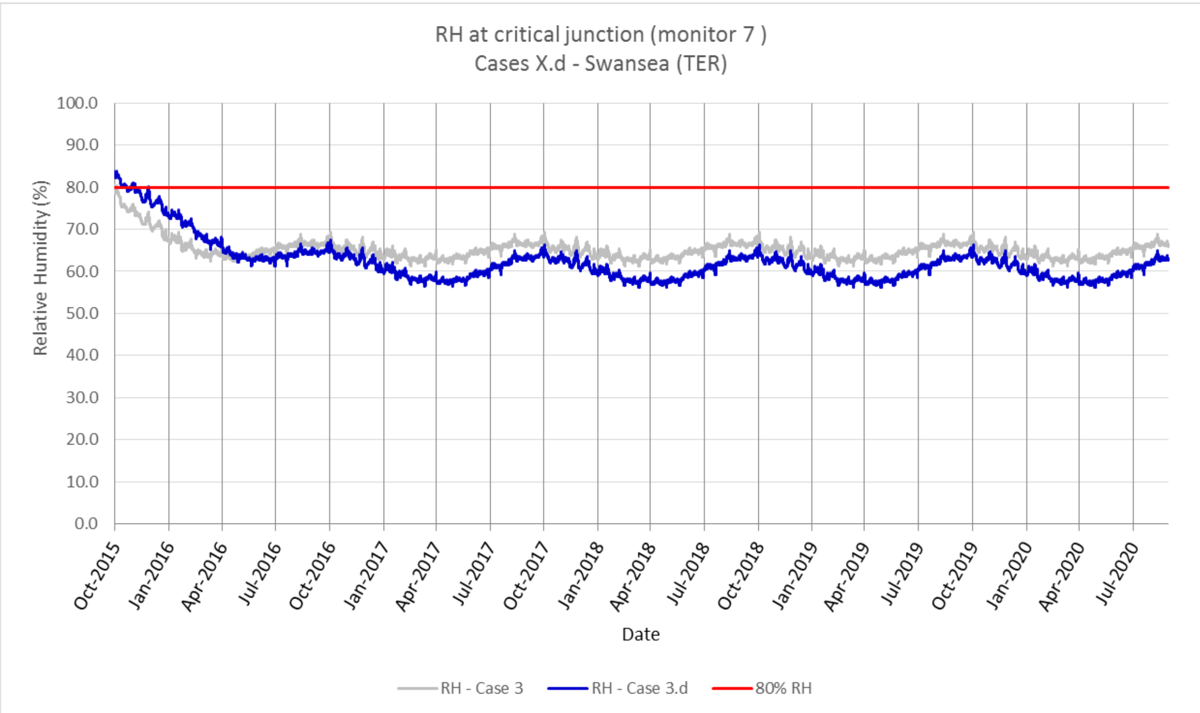


Figure 148: RH levels at critical junction for Cases 3 and 3.d

18.4.6. Graphs at Critical Junction (sd = 50m)

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL with sd = 50m) are displayed as a coloured line, while their respective baseline cases (with ACVL with sd = 2m) are displayed with a grey line.

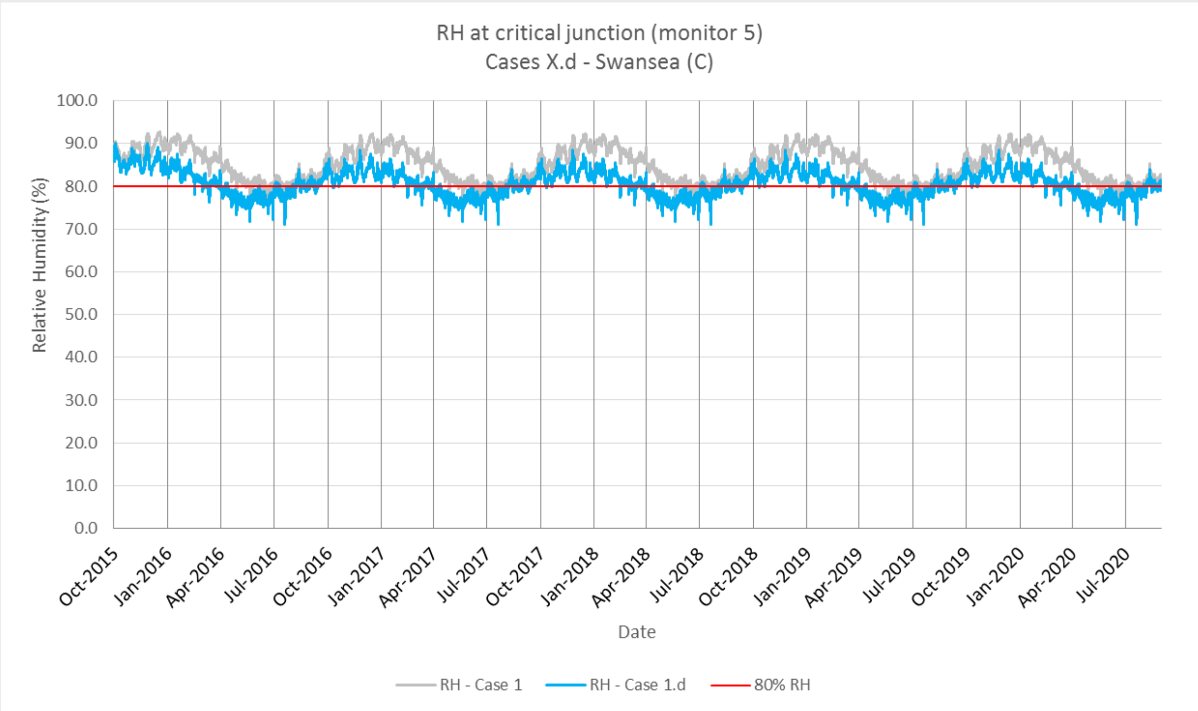


Figure 149: RH levels at critical junction for Cases 1 and 1.d

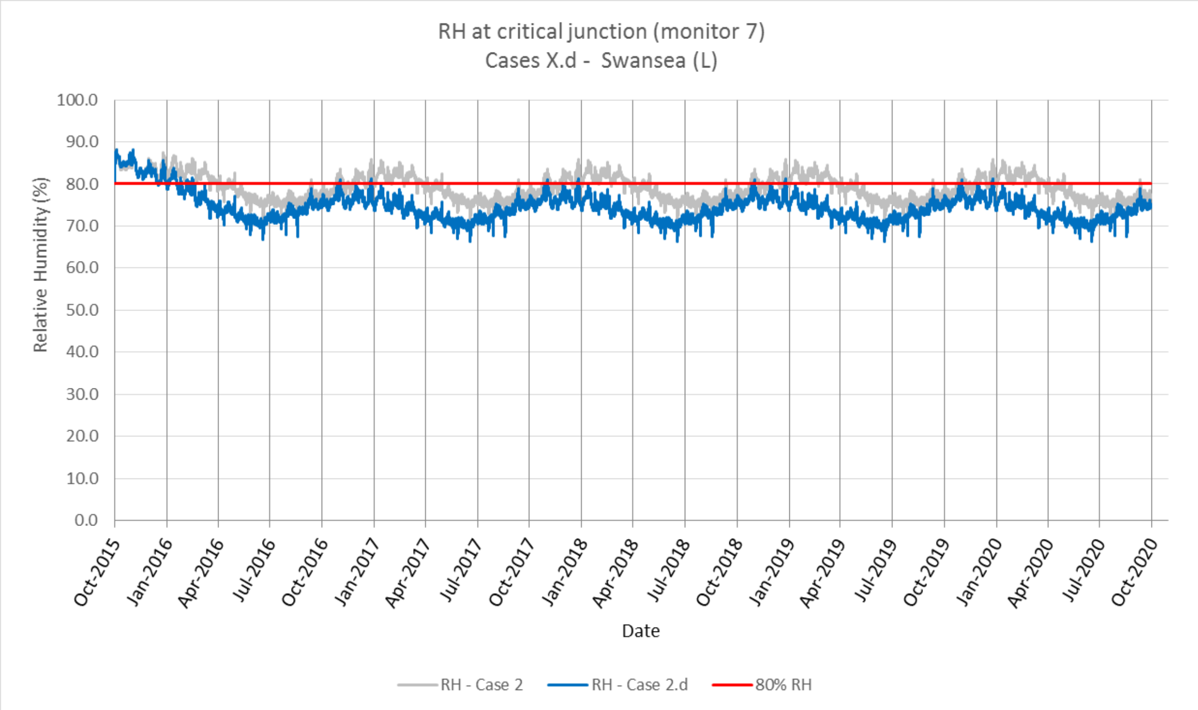


Figure 150: RH levels at critical junction for Cases 2 and 2.d

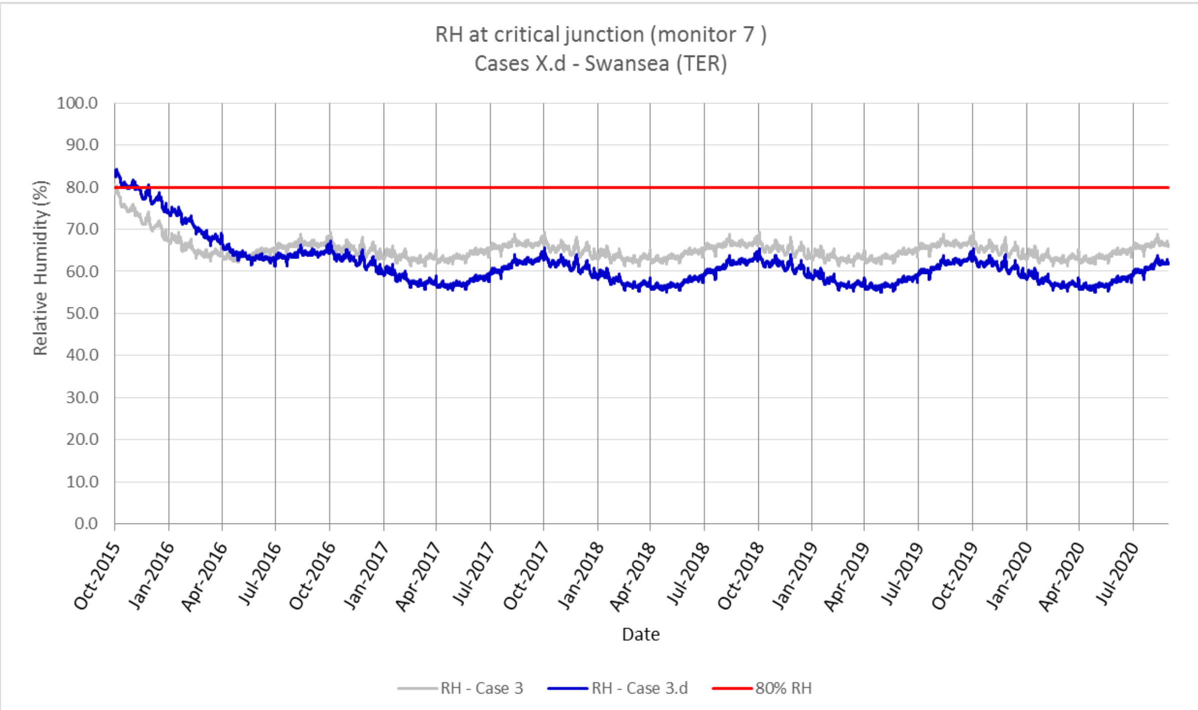


Figure 151: RH levels at critical junction for Cases 3 and 3.d

18.4.7. Conclusions – Sensitivity Analysis Cases X.d

The results show that that all the modelled sensitivity cases perform slightly better than their baseline cases. However, increasing levels of insulation diminishes the extent of the improvement of the hygrothermal performance of the build-up, where this improvement is almost not visible for the TER cases.

The small improvement seen in the sensitivity analysis is not enough to bring the RH levels at the critical junction below the recommended 80% RH threshold. Therefore, the build-up status remains as a ‘fail’ following the moisture risk assessment criteria listed in section 2.3.

Results (including sd = 3.15m, sd = 20m and sd = 50m)

Table 61: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Fail	-	-	-
Part L	Case 2.d Fail	-	-	-
TER	Case 3.d Fail	-	-	-

It is worth noting that the sensitivity analysis is done for the most exposed zone, where all baseline cases are considered a ‘fail’. Due to the change in exposure zone, the results for the baseline cases in the least exposed zone (Zone 1 – London) are only considered ‘risky’ rather than a ‘fail’. This could mean that the increase in vapour resistance of the AVCL could lead to ‘safe’ RH levels for medium to high U-values cases (Part L and Part C) and the build-up declared a ‘pass’.

Prescriptive guidance BS 5250 (2011)

The inclusion of a high vapour resistivity layer on the warm side of the insulation is insufficient to declare that this wall structure to be considered a ‘safe’ build-up, as the results are similar to the baseline results (which are declared as ‘fail’).

Consequently, the recommendation provided by BS 5250 (2011) for the AVCL, located on the warm side of the insulation, to have a vapour resistance to be at least twice the vapour resistance of the sheathing does not seem to be a robust recommendation regarding the build-up’s resistance to moisture. A more precise recommendation on the AVCL vapour resistance characteristics would be useful, in addition to details on which conditions the presence of the AVCL is more necessary / useful.

18.5. Sensitivity Analysis – Change in Material [Cases X.d]: Absence of AVCL

18.5.1. Role of AVCL

As shown in the previous section, the vapour resistance characteristics of the AVCL play a role in the hygrothermal performance of the build-up. The guidance as to what the best vapour resistance / sd-value in each case should be is not very clear yet in the BS 5250 (2011) prescriptive guidance, but the need for an AVCL seems to be agreed in the industry.

To understand more clearly the role of the AVCL, a final sensitivity analysis is done with the omission of the AVCL in the build-up.

18.5.2. Sensitivity Analysis Cases

The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 62:

Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

18.5.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (without an AVCL) are displayed as a coloured line, while their respective baseline cases (with an ACVL with sd = 2m) are displayed with a grey line.

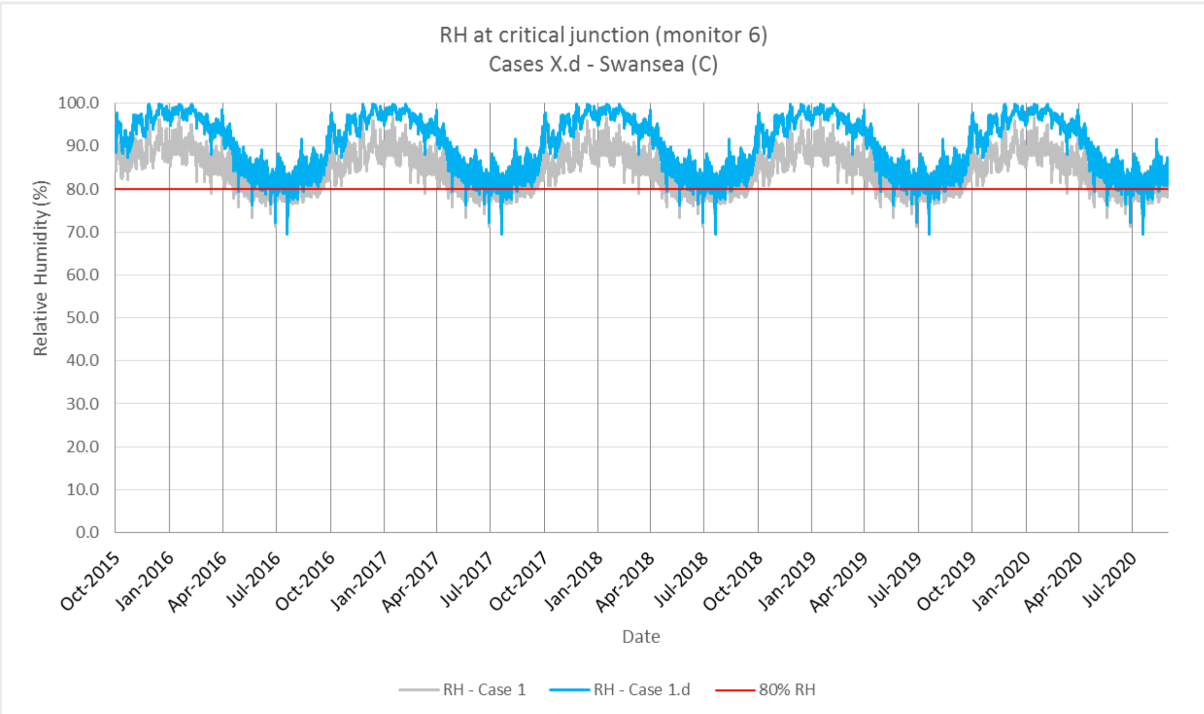


Figure 152: RH levels at critical junction for Cases 1 and 1.d

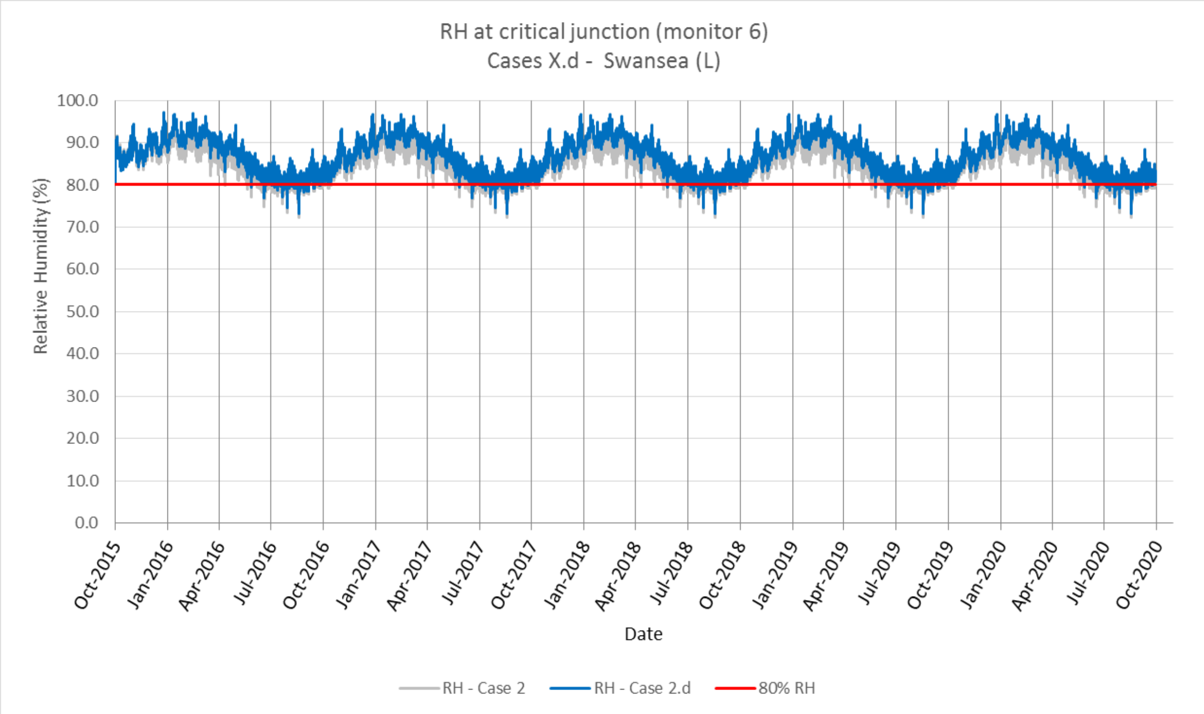


Figure 153: RH levels at critical junction for Cases 2 and 2.d

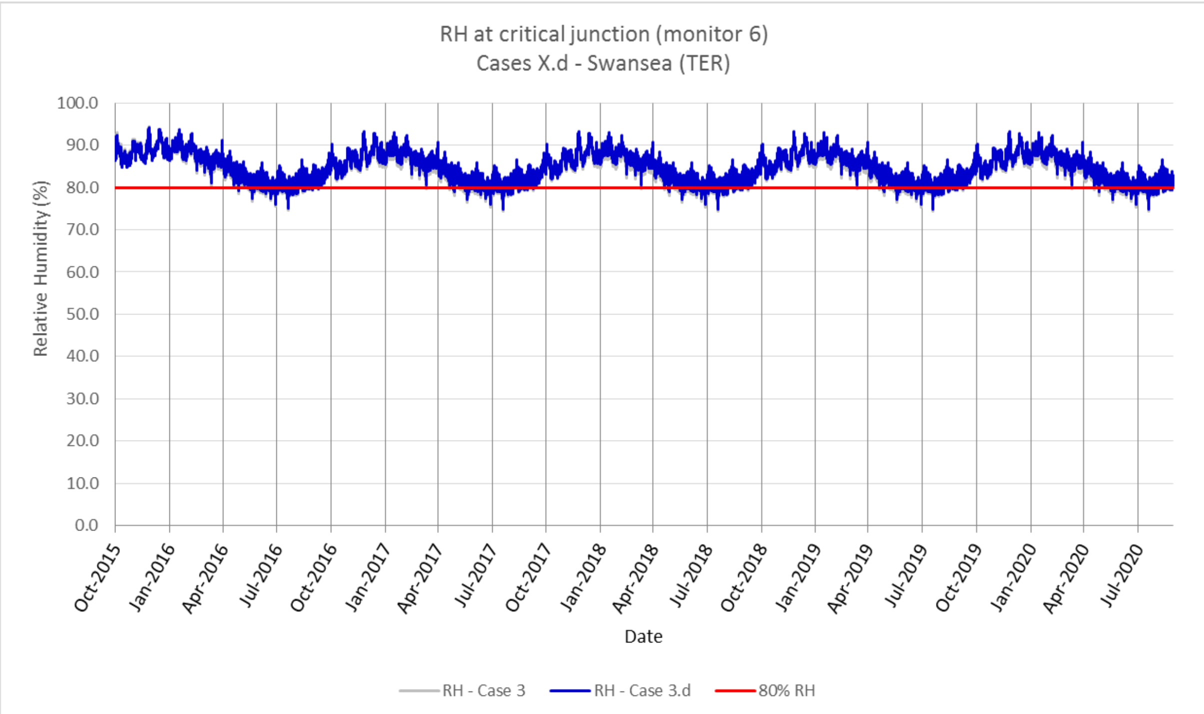


Figure 154: RH levels at critical junction for Cases 3 and 3.d

18.5.4. Conclusions – Sensitivity Analysis Cases X.d

The results show that that all the modelled sensitivity cases perform slightly worse than their baseline cases, demonstrating the useful role of an AVCL in the build-up. However, increasing levels of insulation diminishes the extent of the deterioration of the hygrothermal performance of the build-up, where this deterioration is almost not visible for the TER cases.

Results

The RH levels at the critical junction remain above the recommended 80% RH threshold, similarly to the baseline cases. Therefore, the build-up status remains as a 'fail' following the moisture risk assessment criteria listed in section 2.3.

Table 63: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Fail	-	-	-
Part L	Case 2.d Fail	-	-	-
TER	Case 3.d Fail	-	-	-

The results seem to show that the presence of the AVCL is more useful in cases with medium / high U-values (Part C and Part L). However, the WUFI modelling uses 'perfect' materials, e.g. a fully performing AVCL in this situation. If the AVCL was to have damages (gaps or cracks) and allow the passage of moisture-laden air present in the indoor environment through the build-up, this could lead to serious interstitial condensation risks.

Therefore, the results of all the sensitivity cases without and with AVCLs of different vapour resistance show that the presence of an AVCL in this build-up always has a beneficial impact on the hygrothermal performance of the build-up. However, the presence of an AVCL does not ensure that the RH levels at the critical junction will be kept below the recommended levels.

19. Typology N14: Timber frame wall – with air gap and a non-porous finish (e.g. render)

The N14 typology is a new-build timber frame wall with an air gap and a non-porous finish (e.g. render). The thermal performance of the build-up is improved with the use of EWI (external wall insulation) on the external side of the timber frame.

The N14 typology was originally modelled as a timber frame build-up with no air gap and a non-porous finish. However, the vast majority of timber frame systems are built with a ventilated cladding (such as timber cladding or brick veneer). Therefore, the build-up of this typology has been changed from the *Using calculation methods to assess surface and interstitial condensation* report, to reflect typical build-ups currently used in the industry.

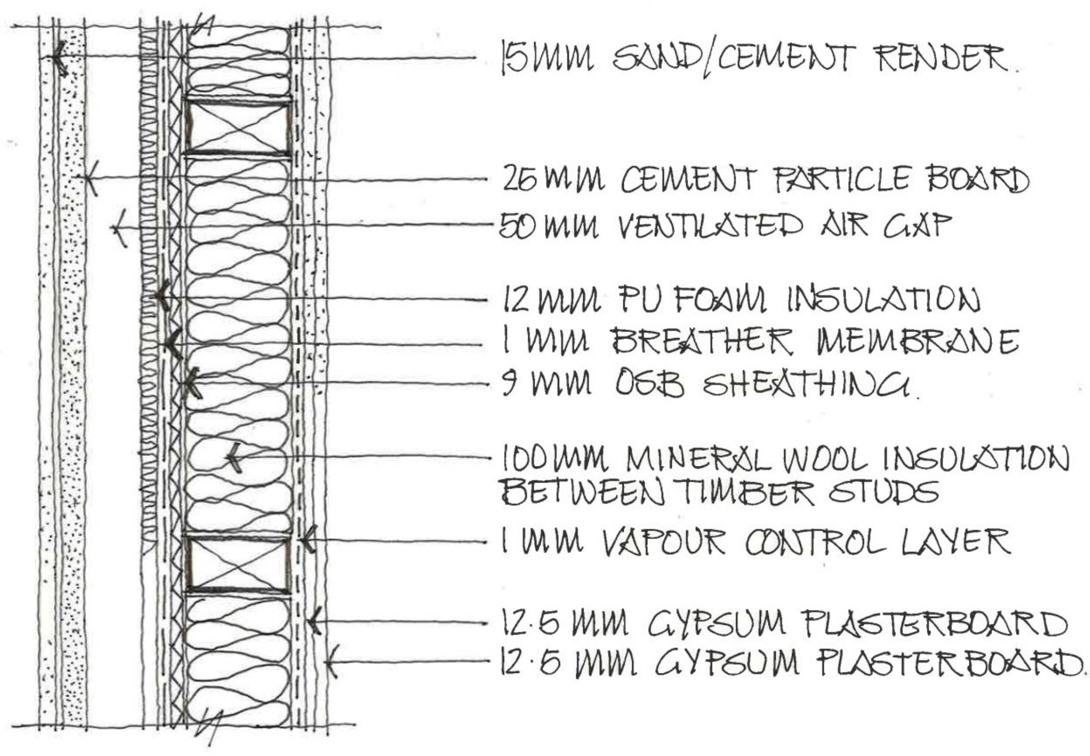


Figure 155: Illustration of the build-up of the typology (Part L case)

19.1. Assessment Method

As BS 5250 (2011) states in the general framed wall section (G.4.1), *'there is a risk of interstitial condensation occurring behind impermeable external finishes or cladding: to avoid that, a vented space should be provided immediately behind the finish or cladding'.*

To follow prescriptive guidance, the cavity behind the wall finish (cement particle board with sand & cement render) is ventilated to the outside, to allow any moisture present in the cavity to be removed. This means that the external finishing layers are considered as a 'protective cladding' and are not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the external insulation layer (on the cold side of the frame) to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to the elements (rain, wind and solar radiations). Consequently, this build-up should be properly assessed with the BS EN ISO 13788 (2012) method.

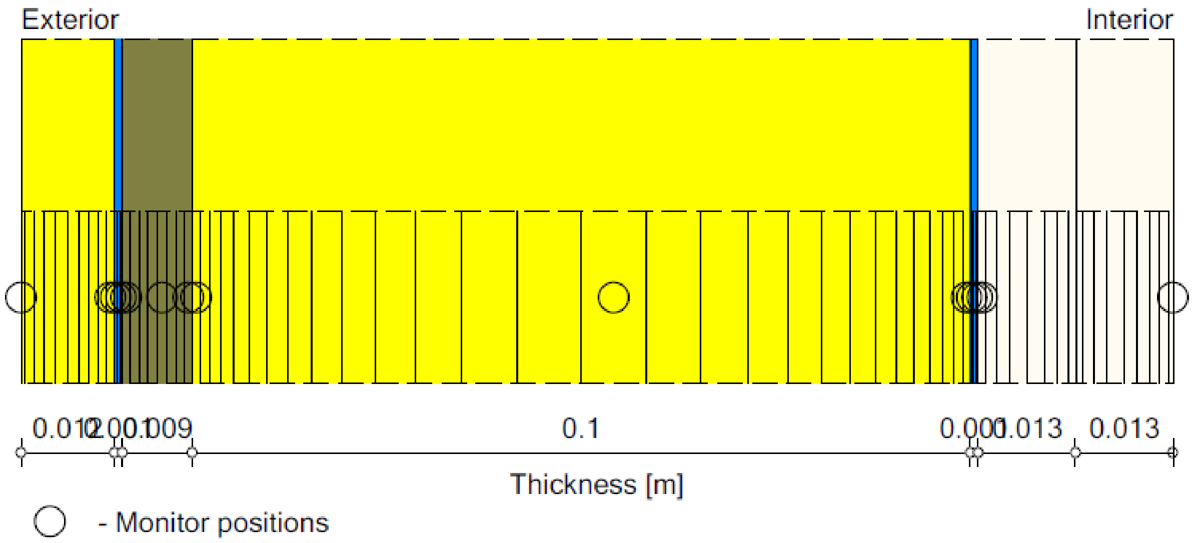
The results by the Glaser method show that this build-up is considered a 'safe' build-up, with no risk of interstitial condensation. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

19.2. Build-up

Please find below the build-up of the typology.

Build-Up:

- 15mm sand and cement render *(considered outside of the WUFI build-up)*
- 25mm cement particle board *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 0mm // 12mm // 80mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 100mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard



Materials:

- PU (heat cond.: 0,025 W/mK)	0.012 m
- *Breather Membrane (sd=0,04m) (unlocked)	0.001 m
- Oriented Strand Board (density 615 kg/m³)	0.009 m
- Mineral Wool (heat cond.: 0,04 W/mK)	0.1 m
- vapour retarder (sd=2m)	0.001 m
- Gypsum Board	0.013 m

<u>WUFI Input Parameters</u>

As the cavity is considered ventilated, the cement particle board, the external render layer and the air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the PU foam insulation layer) is exposed to different external conditions due to the external finishing layers acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the outer brick layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the 'sheltered' condition in the cavity
-

19.3. Baseline Results

19.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 64: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

19.3.2. Critical Junction

Prescriptive guidance BS 5250 (2011) states that *'there is a risk of interstitial condensation occurring on the inner surface of any sheathing applied directly to the outside of the framing'.* Therefore, all graphs will display RH levels at the interface between the OSB (sheathing) and the cold side of the insulation layer within the frame (mineral wool).

This critical junction is not identified by the BS EN ISO 13788 (2012), as this calculation shows no presence of interstitial condensation in the build-up throughout the year.

19.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the monitored junction, at the interface between the OSB (sheathing) and the cold side of the insulation layer within the frame (mineral wool).

As per previous typologies, each zone is associated with a colour (blue for Zone 4). Within each colour, the darker the colour, the higher / better the U-value is.

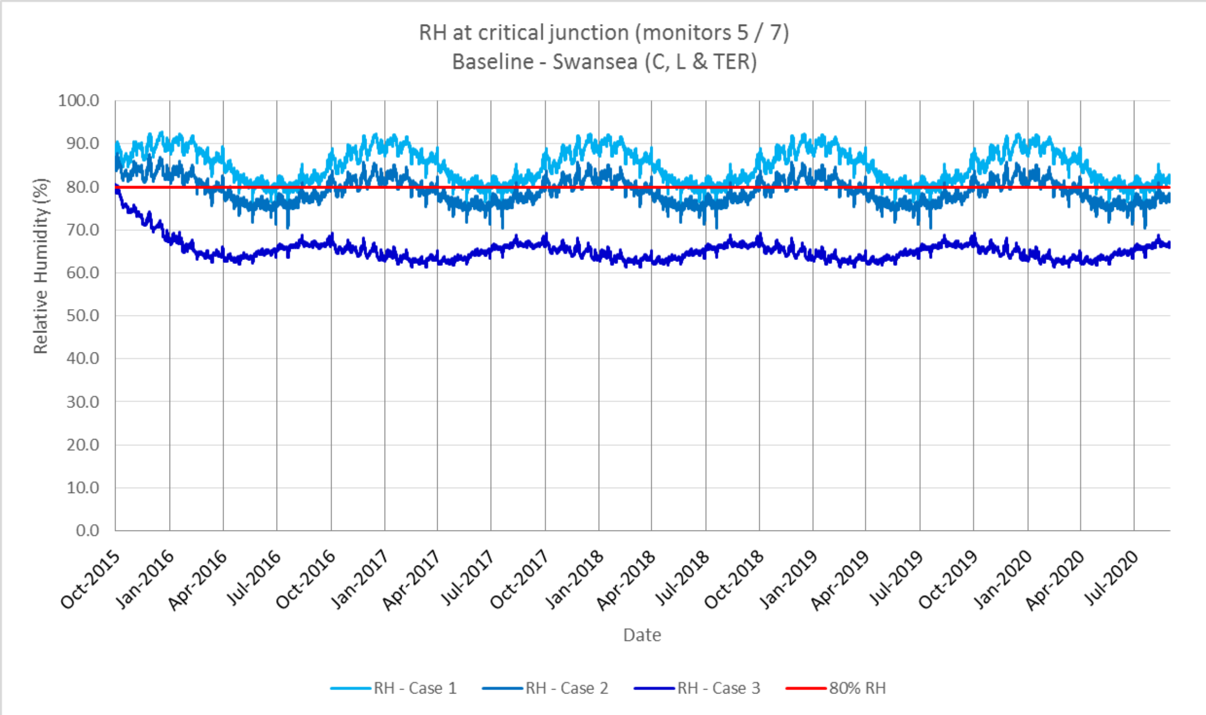


Figure 156: RH levels at critical junction for Cases 1, 2 and 3

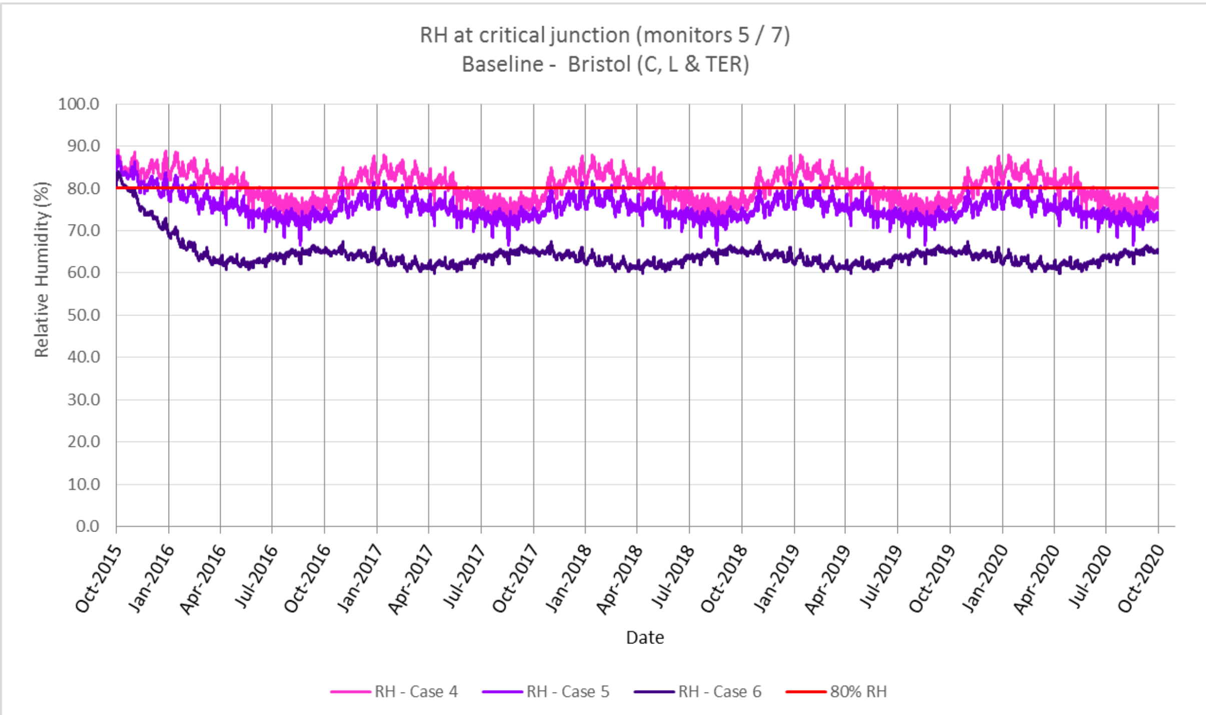


Figure 157: RH levels at critical junction for Cases 4, 5 and 6

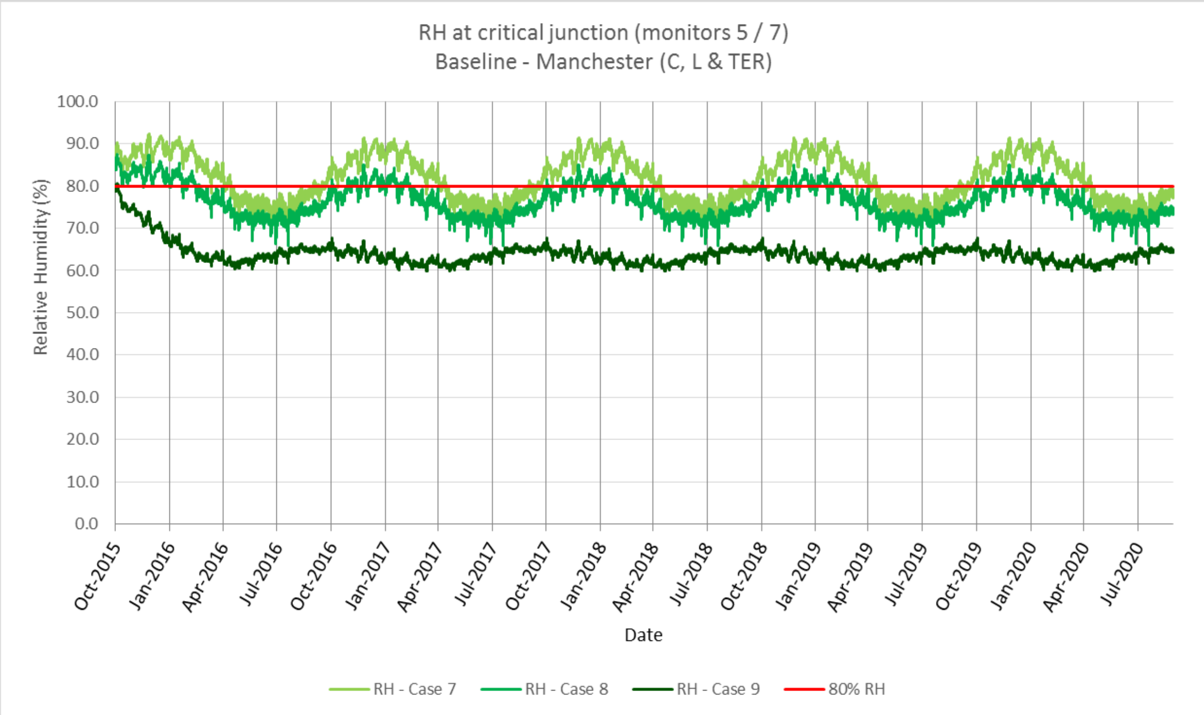


Figure 158: RH levels at critical junction for Cases 7, 8 and 9

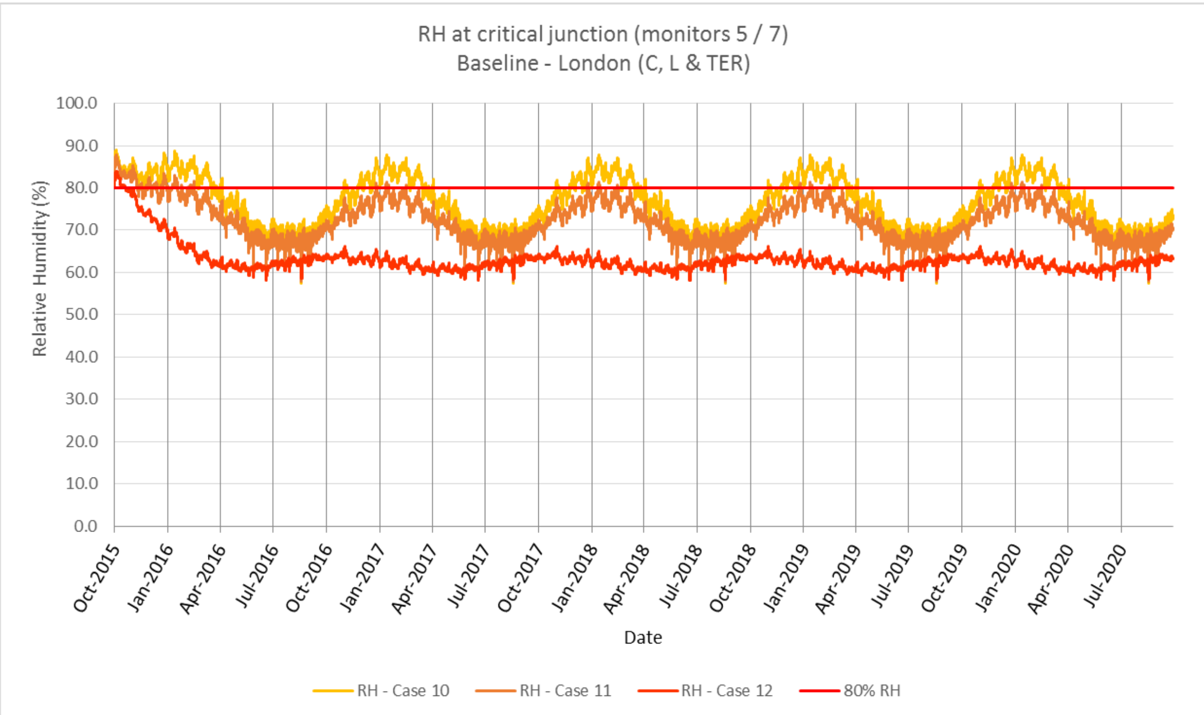


Figure 159: RH levels at critical junction for Cases 10, 11 and 12

19.3.4. Results Analysis

Moisture risk assessment criteria

None of the cases display risks of interstitial condensation, as in all cases, the RH peaks do not go above 90% RH throughout the year. This is in line with the BS EN ISO 13788 (2012) calculations.

All cases achieve equilibrium. However, some cases display intermittent RH levels above the 80% RH threshold. As the critical junction is the interface between the mineral wool insulation and the OSB, considered a 'fragile' material, the RH threshold cannot be relaxed from 80% to 95%. However, the risk of mould growth is not as significant as it could be as, with a well-built construction, no air should be present at this interface and the RH peaks only happen during the winter period, which does not promote mould growth.

All Part C cases, independently to their exposure zone, display RH levels kept above the 80% RH threshold for significant periods of the year (several consecutive months) during the winter period. This means that they do not meet all the set moisture risk criteria listed in section 2.3 and therefore are considered a 'fail'.

All Part L cases display a similar RH profiles to the Part C cases, with lower overall RH profiles. All RH profiles peak around 80% RH, but depending on the exposure zone, these peaks are just above or below 80%. Consequently, the status of the Part L cases varies between 'pass', 'risky' and 'fail'.

All TER cases, independently to their exposure zone, display RH levels below 70% RH, which is well below the 80% threshold, as soon as the build-up reaches equilibrium (reached after the first year). These cases are therefore considered as 'pass'.

Table 65: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Fail	Case 4 Fail	Case 7 Fail	Case 10 Fail
Part L	Case 2 Fail	Case 5 Pass	Case 8 Risky	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

Risk from Mould Growth

Despite the risk of mould growth being present, this risk might not be as significant as it could be. The build-up is considered easily buildable, due to the ease of installing adequately flexible insulation in between timber studs. This should lead to the absence of air at this critical junction, due to the additional installation of the breather membrane externally to the OSB / sheathing.

Effects of exposure zones and U-values

The effects of exposure zones are only slightly visible on the graphs, with build-ups in less exposed zones displaying on average slightly lower RH levels.

The impact of the U-values is very visible on the graphs. Indeed, the lower / better the U-value is, the warmer the critical junction is kept, which has a beneficial impact of the RH levels. The Part L U-value, with a build-up using a 12mm PU foam insulation layer on the outside of the frame, appears to be the tilting point around which the build-up displays RH levels around the 80% threshold, and can be declared either a ‘pass’, ‘risky’ or ‘fail’ case depending on the exposure zone it is. However, a 12mm additional layer outside the frame is not a realistic construction, as such thin insulation layers are not available in practice. Therefore, a sensitivity analysis will be done for a more realistic build-up, using a 30mm external insulation layer.

These findings are in line with best industry practice (primarily done for thermal performance), as the use of external insulation installed on the cold side of a framed wall is known to be particularly effective to reduce (and even avoid) thermal bridging due to the frame structure when insulation is only installed between the framing members, which leads to increased heat losses as well as risk of mould growth (as highlighted in paragraph G.4.1 of BS 5250 (2011)).

AVCL and Vapour Resistance

Prescriptive guidance BS 5250 (2011) also mentions that *‘to avoid [the risk of interstitial condensation on the inner surface of any sheathing applied directly to the outside of the framing], an AVCL with a vapour resistance of at least double that of the sheathing should be provided on the warm side of the insulation, behind the internal surface finish’*.

In the baseline cases, an AVCL is present on the warm side of the insulation, while the sheathing is done with OSB. With the characteristics of each material, the vapour resistance of the AVCL and the OSB are as follow:

- Vapour resistance of AVCL = 10 MNs/g (with sd = 2m)
- Vapour resistance of OSB = 7.875 MNs/g (with μ = 175 and 9mm thickness)

These results show that the recommendation from BS 5250 (2011) is not met in the baseline build-up. In order to respect it, the AVCL characteristics should be increased to reach sd = 3.15m. It is also quite common for the sheathing to be ply, which has a much higher vapour resistance diffusion factor (μ = 700), compared to OSB. If ply was used as sheathing, the AVCL characteristics should be further increased to reach sd = 12.6m (as 9mm ply has a vapour resistance of 31.5 MNs/g) to respect the recommendation in BS 5250 (2011).

19.3.5. Conclusions – Baseline

- The build-up is sheltered from the elements and moisture driven by vapour diffusion, with AVCL on the warm side of the insulation, so safe in theory

19.4. Sensitivity Analysis – Change in Material [Cases X.d]: Change in AVCL characteristics

19.4.1. Baseline model versus BS 5250 (2011)

The baseline build-up does not fully follow the recommended build-up present in BS 5250 (2011), as the AVCL included between the insulation layer and the plasterboard in the baseline model should have a higher vapour resistance (more precisely, a vapour resistance of at least double that of the sheathing), as stated in the previous section.

<u>Improvement in AVCL</u>

Therefore, the first sensitivity analysis undertaken is to include an AVCL of an sd-value of 3.15m (instead of an sd-value of 2m) in the build-up, located on the warm side of the insulation, and installed between the insulation layer and the plasterboard in order to match the requirements of BS 5250 (2011).

19.4.2. Sensitivity Analysis Cases

As the impact of the different exposure zones has already been assessed in the baseline cases, the three sensitivity cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 66: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

19.4.3. Graphs at Critical Junction (sd = 3.15m)

All graphs displayed below show the RH levels at the critical junction (similar to the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL with sd = 3.15m) are displayed as a coloured line, while their respective baseline cases (with ACVL with sd = 2m) are displayed with a grey line.

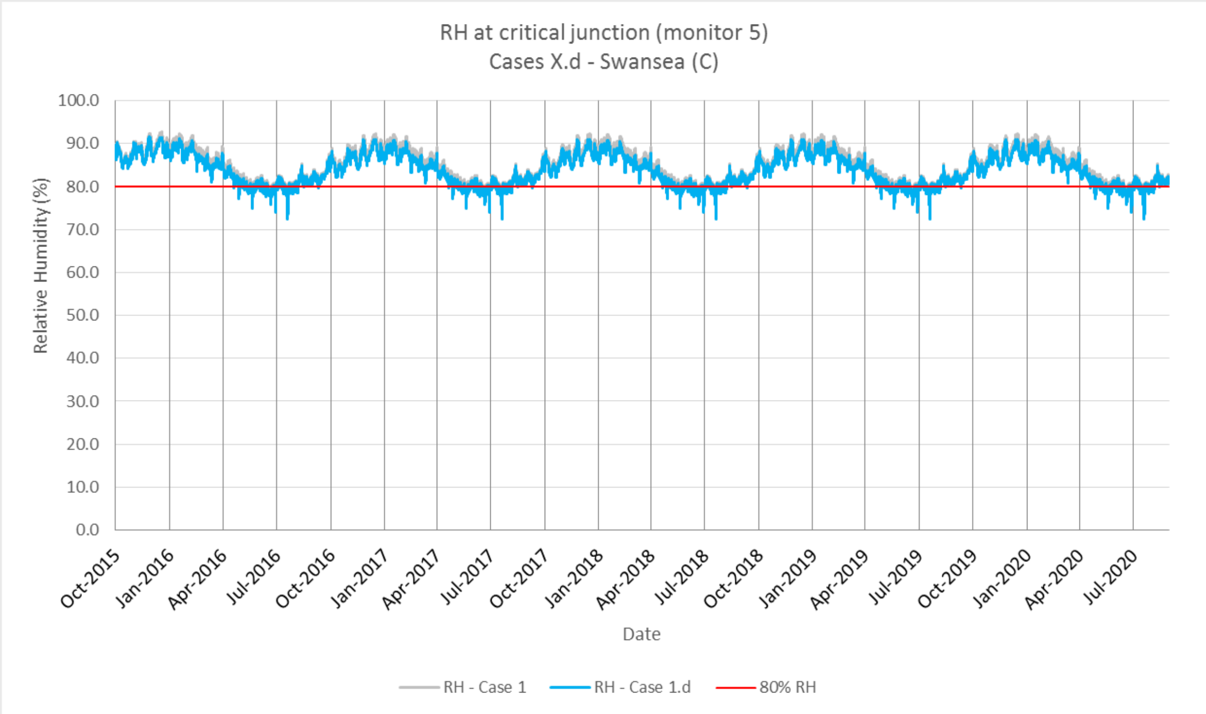


Figure 160: RH levels at critical junction for Cases 1 and 1.d

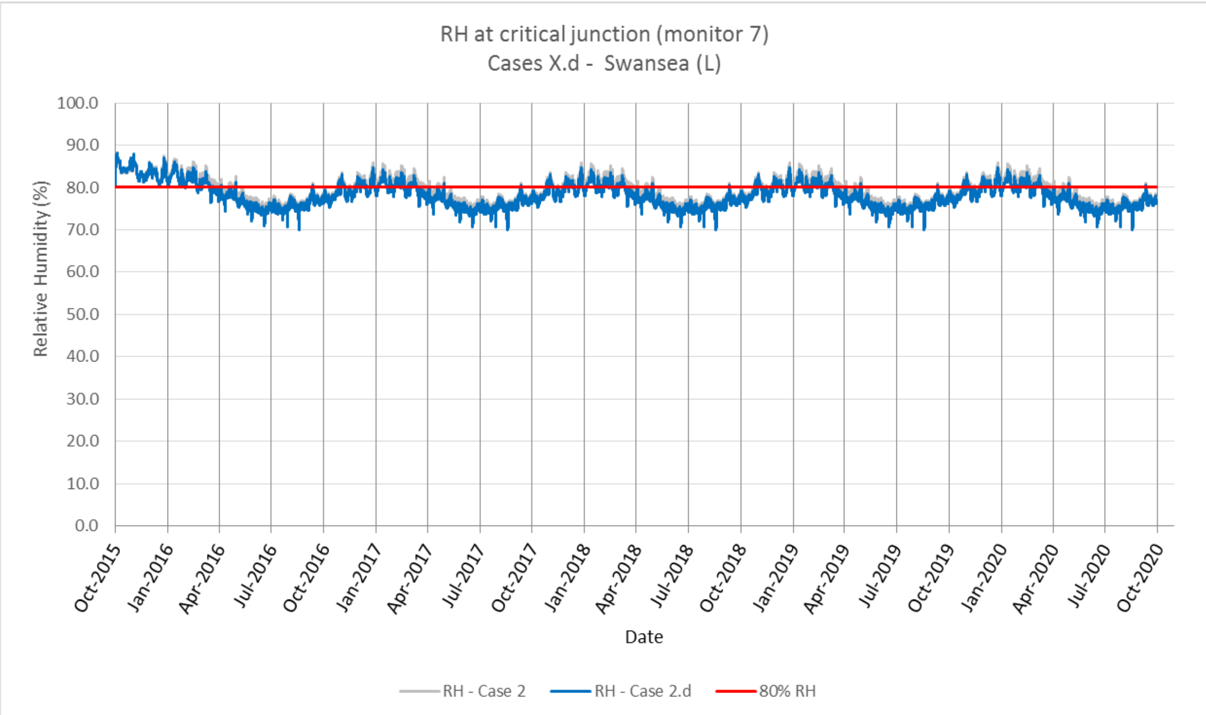


Figure 161: RH levels at critical junction for Cases 2 and 2.d

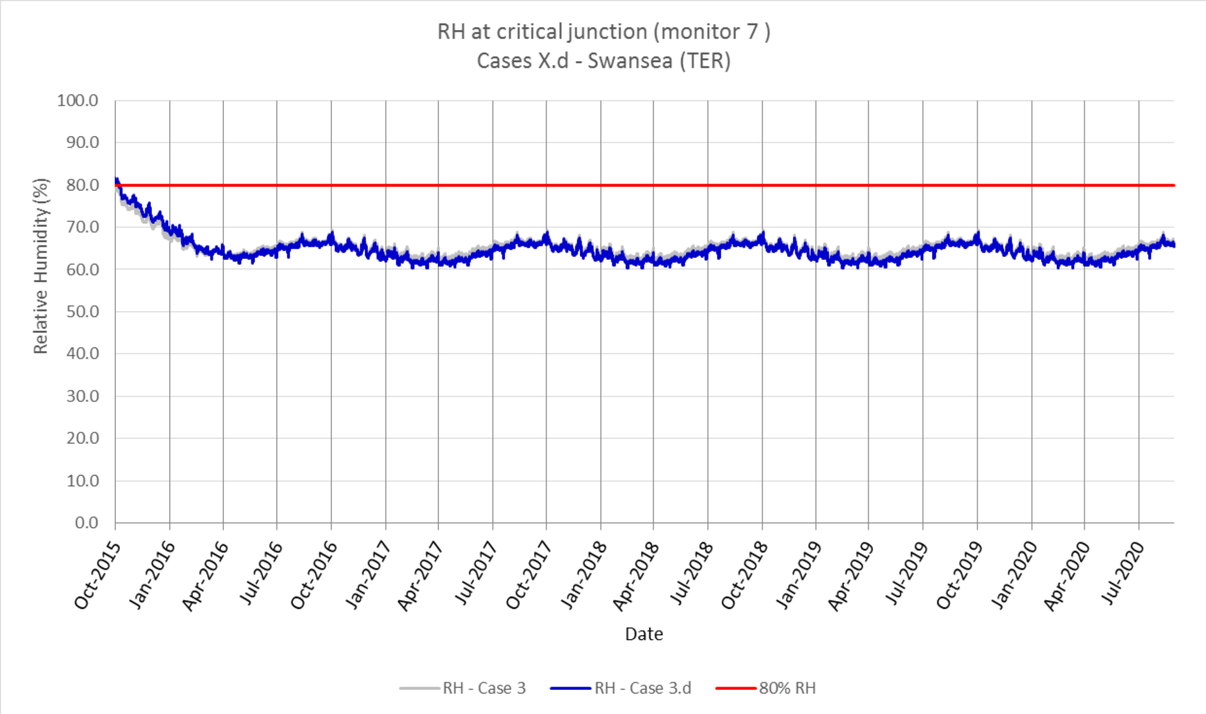


Figure 162: RH levels at critical junction for Cases 3 and 3.d

19.4.4. Conclusions – Sensitivity Analysis Cases X.d

All the modelled sensitivity cases show almost no improvement to the baseline cases, and therefore, the status of all sensitivity analysis cases remains unchanged from the baseline cases status (Part C and Part L declared as 'fail' and TER as 'pass').

The impacts of the change in AVCL characteristics on the hygrothermal performance of the build-up are not clearly visible on the graphs above. Similarly to typology N13 (timber frame with an air gap with a semi-porous finish), additional sensitivity analysis cases are modelled to understand more clearly the effects of increasing the vapour resistance of the AVCL layer on the hygrothermal performance of the build-up.

The baseline AVCL has an sd-value of 2m. The first sensitivity analysis is done with an AVCL with an sd-value increased to 3.15m to match the BS 5250 (2011) recommendation. However, an AVCL with an sd-value around 2m to 3.15m is considered to be a semi-permeable material (according to the ASHRAE classification). Therefore, the sd-value of the AVCL for the following sensitivity analysis is further increased to reflect the use of a less permeable material.

The following sd-values are used:

- AVCL with sd = 20m (semi-impermeable material)
- AVCL with sd = 50m (impermeable material)

19.4.5. Graphs at Critical Junction (sd = 20m)

All graphs displayed below show the RH levels at the critical junction (similar to the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL with sd = 20m) are displayed as a coloured line, while their respective baseline cases (with AVCL with sd = 2m) are displayed with a grey line.

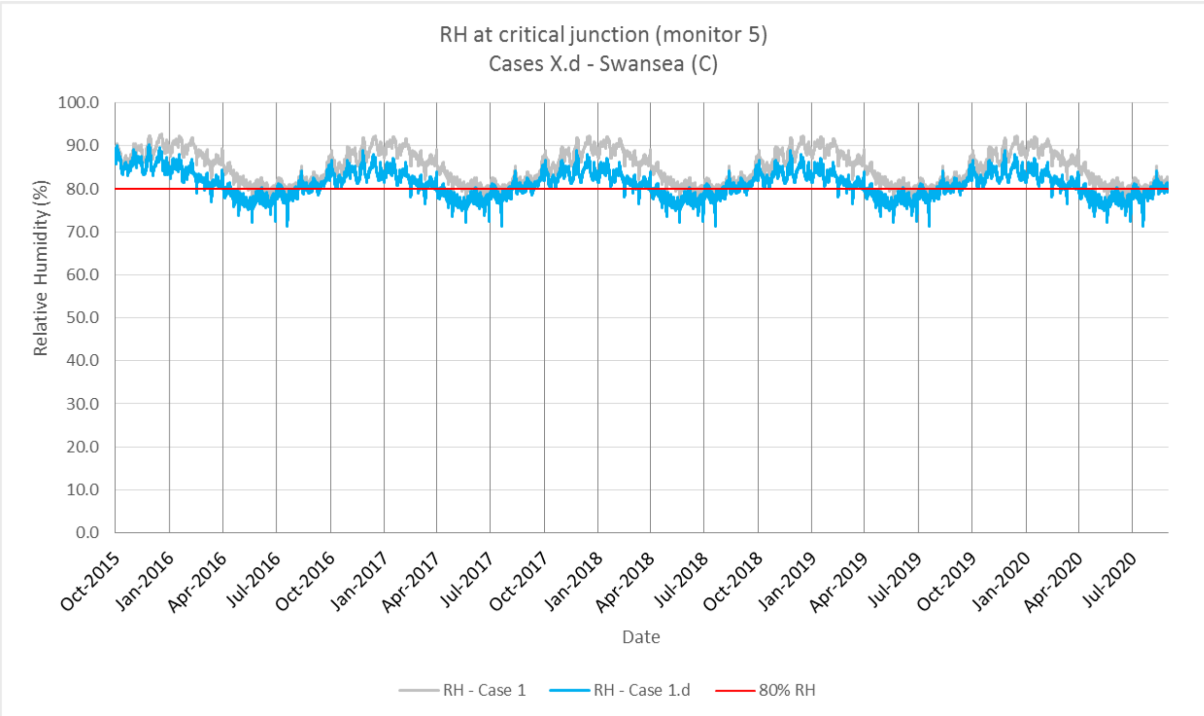


Figure 163: RH levels at critical junction for Cases 1 and 1.d

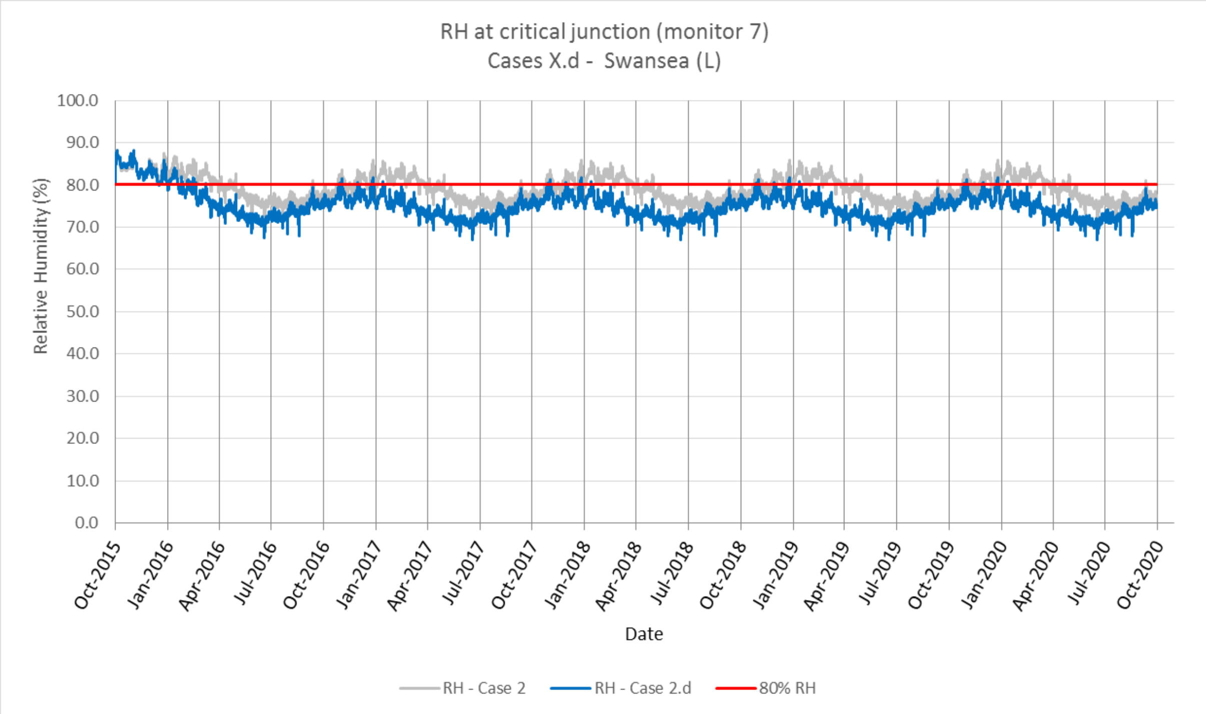


Figure 164: RH levels at critical junction for Cases 2 and 2.d

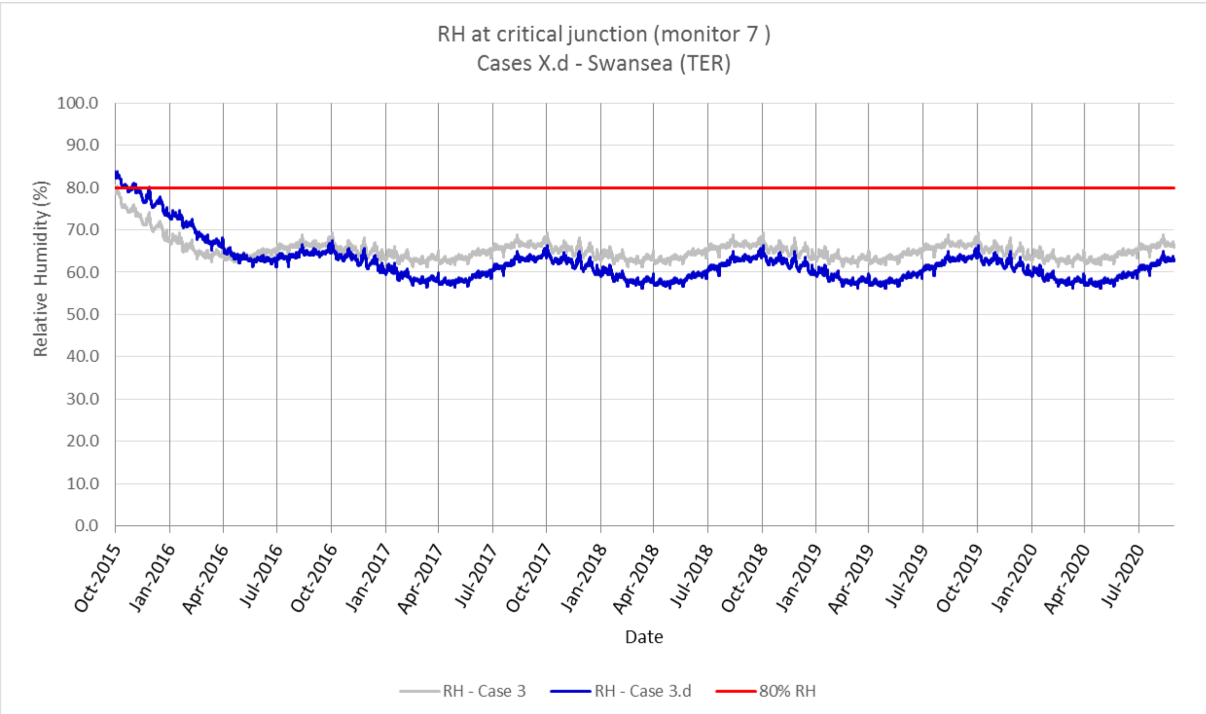


Figure 165: RH levels at critical junction for Cases 3 and 3.d

19.4.6. Graphs at Critical Junction (sd = 50m)

All graphs displayed below show the RH levels at the critical junction (similar to the baseline cases), at the interface between the sheathing layer (OSB) and the cold side of the insulation, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL with sd = 50m) are displayed as a coloured line, while their respective baseline cases (with AVCL with sd = 2m) are displayed with a grey line.

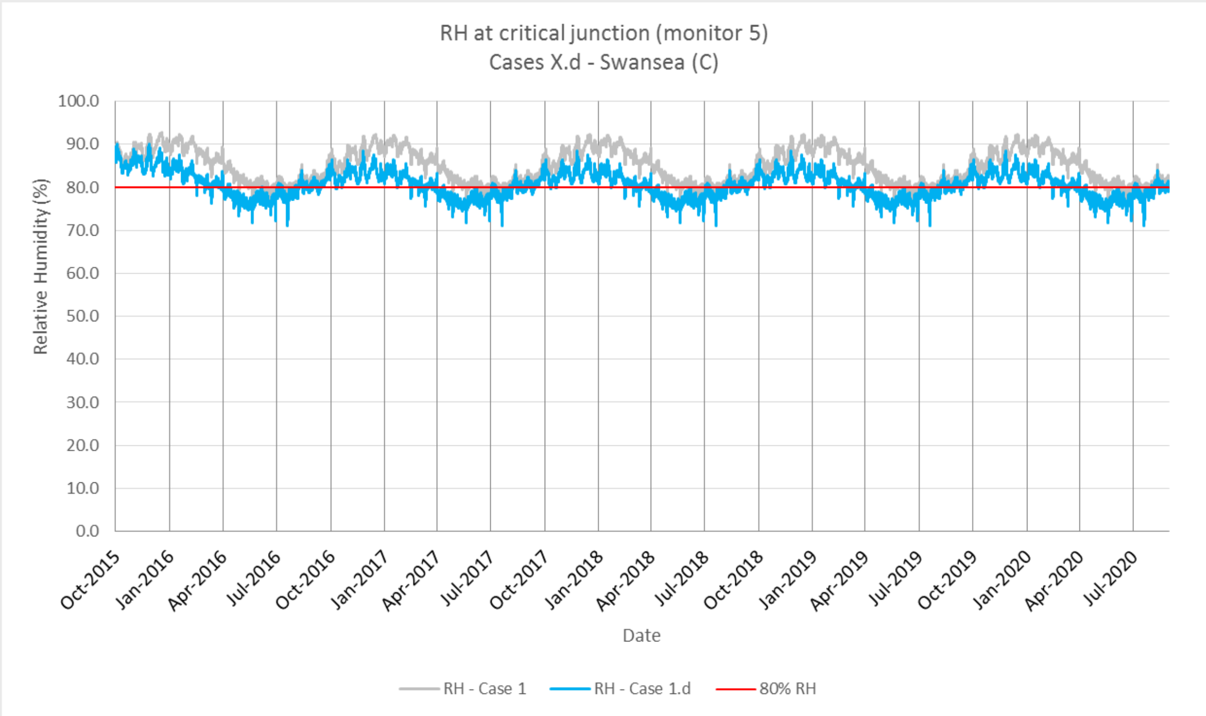


Figure 166: RH levels at critical junction for Cases 1 and 1.d

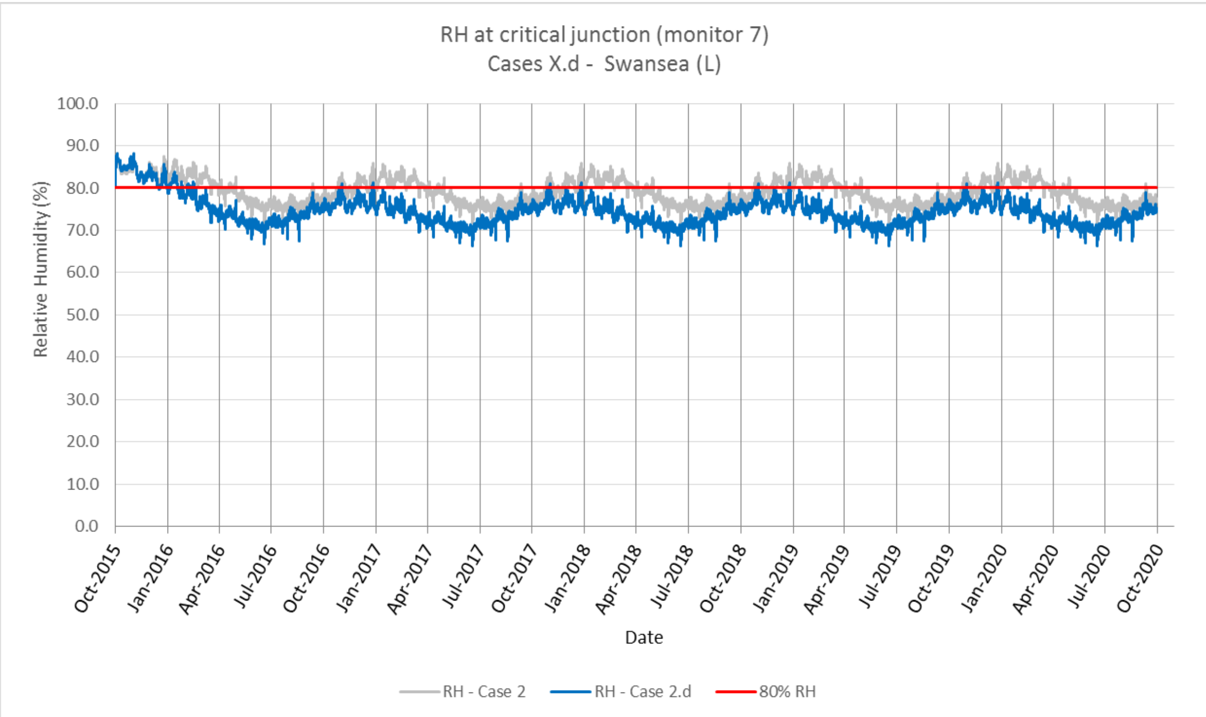


Figure 167: RH levels at critical junction for Cases 2 and 2.d

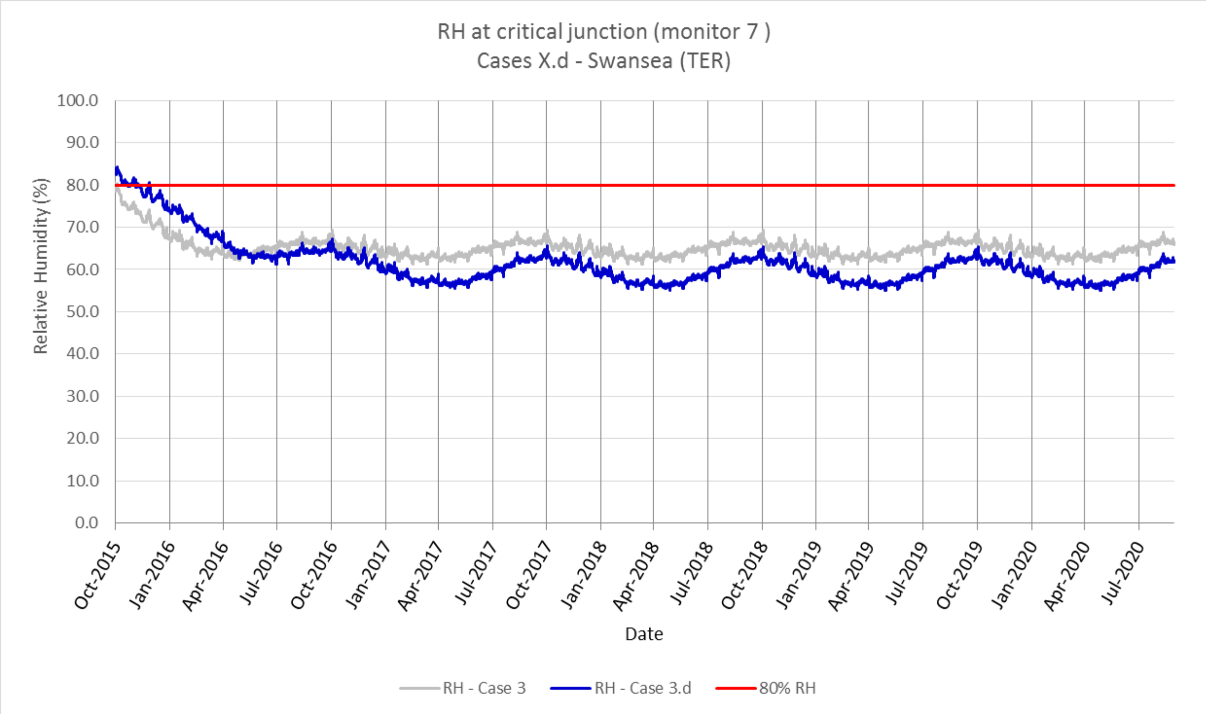


Figure 168: RH levels at critical junction for Cases 3 and 3.d

19.4.7. Conclusions – Sensitivity Analysis Cases X.d

The results show that that all the modelled sensitivity cases perform better than their baseline cases, though it is worth noting that increasing levels of insulation diminishes the extent of the improvement of the hygrothermal performance of the build-up. The improvement is more important and visible in Part C cases than in TER cases.

The improvement seen in the sensitivity analysis is not enough to bring the RH levels at the critical junction below the recommended 80% RH threshold for the Part C case. Therefore, the build-up status remains as a ‘fail’ following the moisture risk assessment criteria listed in section 2.3. However, the RH levels in the sensitivity analysis case Part L are now fully below the 80% RH threshold for the entire modelling period, except following initial conditions for a short period. Therefore, the Part L case status is upgraded from a ‘fail’ to a ‘pass’, due to the presence of the AVCL (sd = 20 or 50m) on the warm side of the insulation.

Results (including sd = 20m and sd = 50m)

Table 67: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Fail	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

It is worth noting that the sensitivity analysis is done for the most exposed zone, where both Part C and Part L baseline cases are considered as 'fail' because of the presence of the AVCL (sd = 20 or 50m), the Part L case status is upgraded from a 'fail' to a 'pass'. As Swansea was the most extreme zone, with the worst RH levels, this sensitivity analysis shows that, by deduction, all Part L cases can be declared a 'pass' in these conditions.

Prescriptive guidance BS 5250 (2011)

The modelled Part L case has a continuous insulation layer installed externally to the frame being 12mm thick, which has a 'pass' status in the worst exposure zone. Although this thickness is not a realistic insulation thickness as it is not available on the market (the minimum insulation thickness currently available in the industry is typically 25mm). By deduction, the inclusion of an AVCL with a high sd-value (in this case, sd ≥ 20m) on the warm side of the insulation is sufficient to declare this wall structure a 'safe' build-up, as long as the build-up has a continuous insulation layer installed externally to the frame (which will be 25mm or thicker).

Consequently, the recommendation provided by BS 5250 (2011) for the AVCL, located on the warm side of the insulation, to have a vapour resistance to be at least twice the vapour resistance of the sheathing, does not seem to be a robust enough recommendation to ensure the build-up's resistance to moisture. A more precise recommendation on the AVCL vapour resistance characteristics would be recommended, in addition to details on which conditions the presence of the AVCL is more necessary / useful.

19.5. Sensitivity Analysis – Change in Material [Cases X.d]: 30mm external insulation

19.5.1. Use of 30mm external insulation

As mentioned in the previous section, The Part L U-value is the tilting point at which a build-up displays RH levels around 80% and can be declared 'pass', 'risky' or 'fail' depending on its associated exposure zone. However, this build-up uses a 12mm PU foam insulation layer, which is unrealistic as the minimum thickness for this type of material use would be approximately 30mm.

The baseline graphs show that the build-up in the most extreme exposure zone, Swansea, displays the most risky RH levels, out of all Part L cases in the different exposure zones.

Therefore, the first sensitivity analysis done here is to increase the external insulation layer from 12mm to 30mm in the Part C cases located in Swansea. If this build-up is declared 'pass', then by deduction, the rest of the Part L cases can then be declared 'safe' too.

19.5.2. Sensitivity Analysis Cases

The sensitivity case is set across the Zone 4 wind-driven rain exposure zone, exceeding the Part L target U-value.

Table 68: Case chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L	Case 2.d	-	-	-
TER	-	-	-	-

19.5.3. Graphs at Monitored Junction

The graph displayed below shows the RH levels at the monitored junction (which is the same as the baseline cases), i.e. at the interface between the OSB (sheathing) and the cold side of the insulation layer within the frame (mineral wool).

The sensitivity analysis cases (with 30mm external insulation) is displayed as a coloured line, while the respective baseline case is displayed with a grey line.

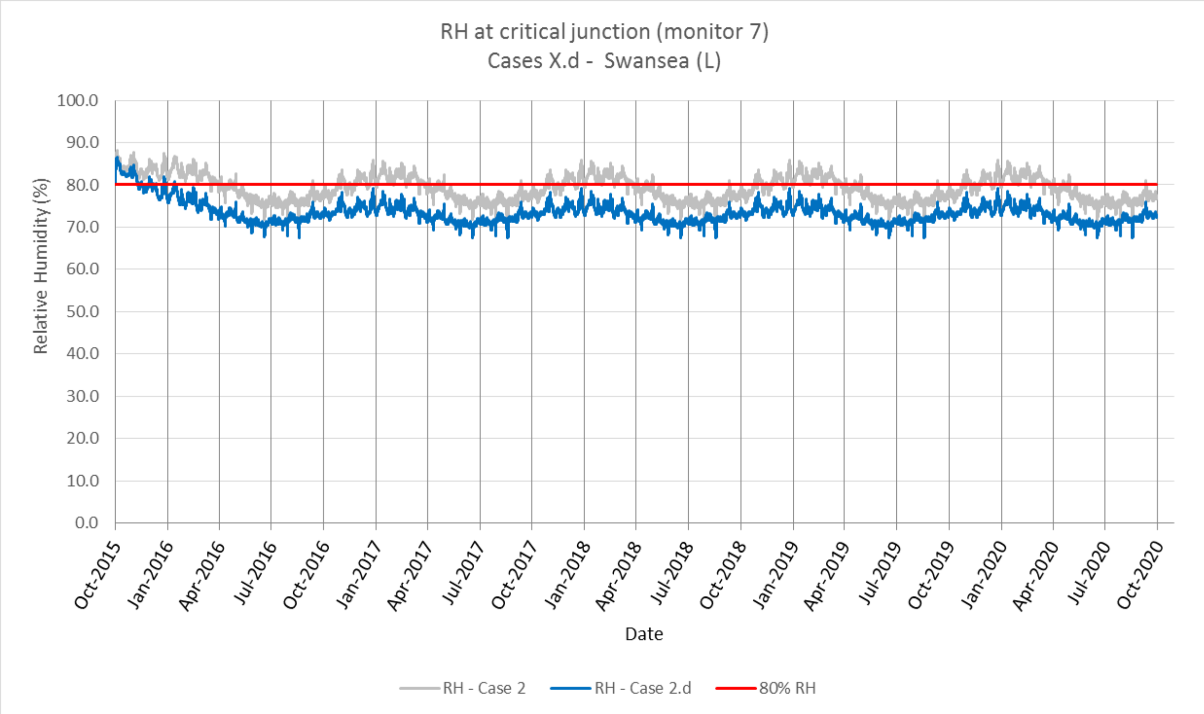


Figure 169: RH levels at critical junction for Cases 2 and 2.d

19.5.4. Conclusions – Sensitivity Analysis Cases X.d

The results show that that the modelled sensitivity case performs better than its baseline case. This improvement is enough to ensure the RH levels at the critical junction are always kept below the 80% RH threshold, after reaching equilibrium (achieved after six months). Therefore, this build-up is now considered as 'pass'.

Results

Table 69: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	-	-	-	-

As the worst performing Part L case (Part L in Swansea) is now a 'safe' build-up, all other Part L cases can be declared 'safe' by deduction.

The baseline cases and this sensitivity analysis show that this build-up cannot be considered safe if insulation is only installed between the framing members. However, with the minimum thickness that is realistic to be installed externally to the wall frame (30mm), the build-up is made 'safe'. In addition, the thicker the external insulation layer thickness gets, the ‘safer’ the build-up is (meaning the RH levels at the critical junction are getting lower).

19.6. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of foil layers on both sides of the external insulation layer

19.6.1. Addition of foil layers on both side of the external insulation layer

As rigid foam insulation used in this construction commonly has foil layers, additional sensitivity cases are done to assess the impact of adding foil layers to both sides of the insulation onto the hygrothermal performance of the build-up.

A foil layer is added on both sides of the external layer present in the baseline build-up. Please note that this sensitivity analysis does not apply to the Part C case, as no external insulation is present in this case (the insulation is only installed in between the framing members).

19.6.2. Sensitivity Analysis Cases

As the impact of the different exposure zones has already been assessed in the baseline cases, this sensitivity analysis is done in the most extreme exposure zone, Swansea. As the Part L case was made ‘safe’ with an increased external insulation layer from 12mm to 30mm, this upgraded build-up is used for this sensitivity analysis.

The two cases are set across the Zone 4 wind-driven rain exposure zone, meeting the two target U-values (as per baseline cases).

Table 70: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L (30mm)	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

19.6.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), at the interface between the OSB (sheathing) and the cold side of the insulation layer within the frame (mineral wool) for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with foil layers) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

The Part C case is not displayed below, as there is no distinction between the sensitivity analysis and the baseline cases, as no external insulation is installed on the outside of the frame.

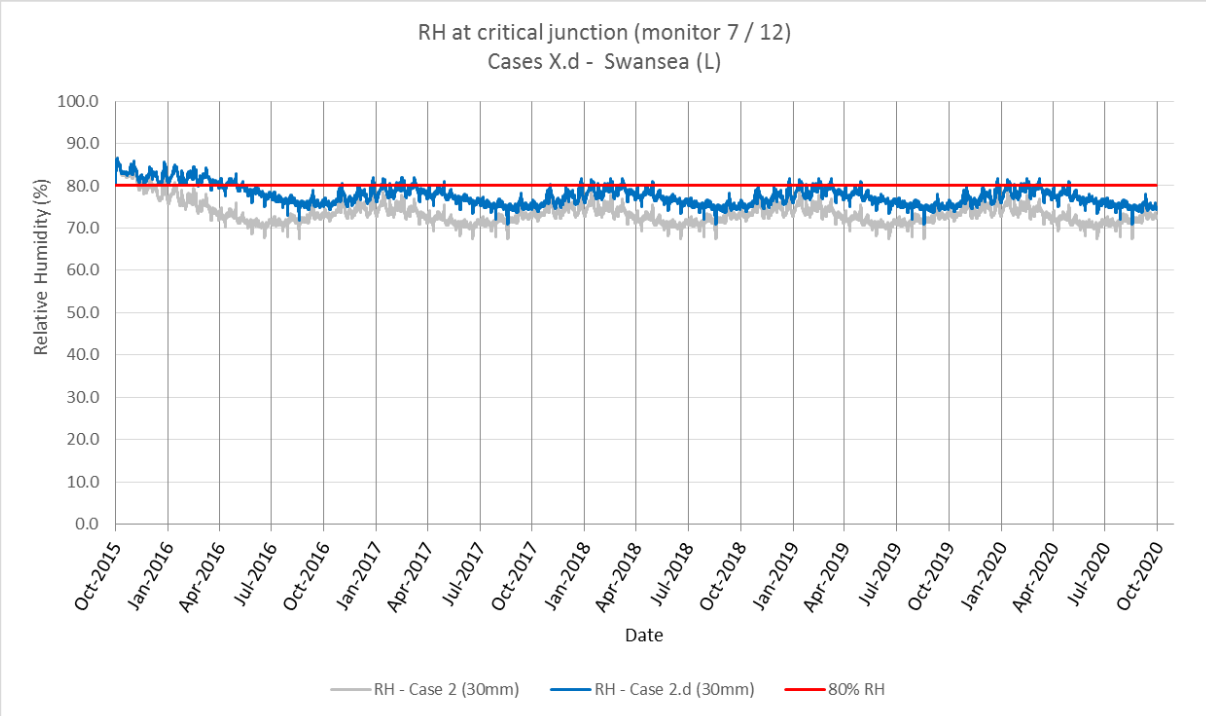


Figure 170: Cases chosen for sensitivity analysis 2 and 2.d

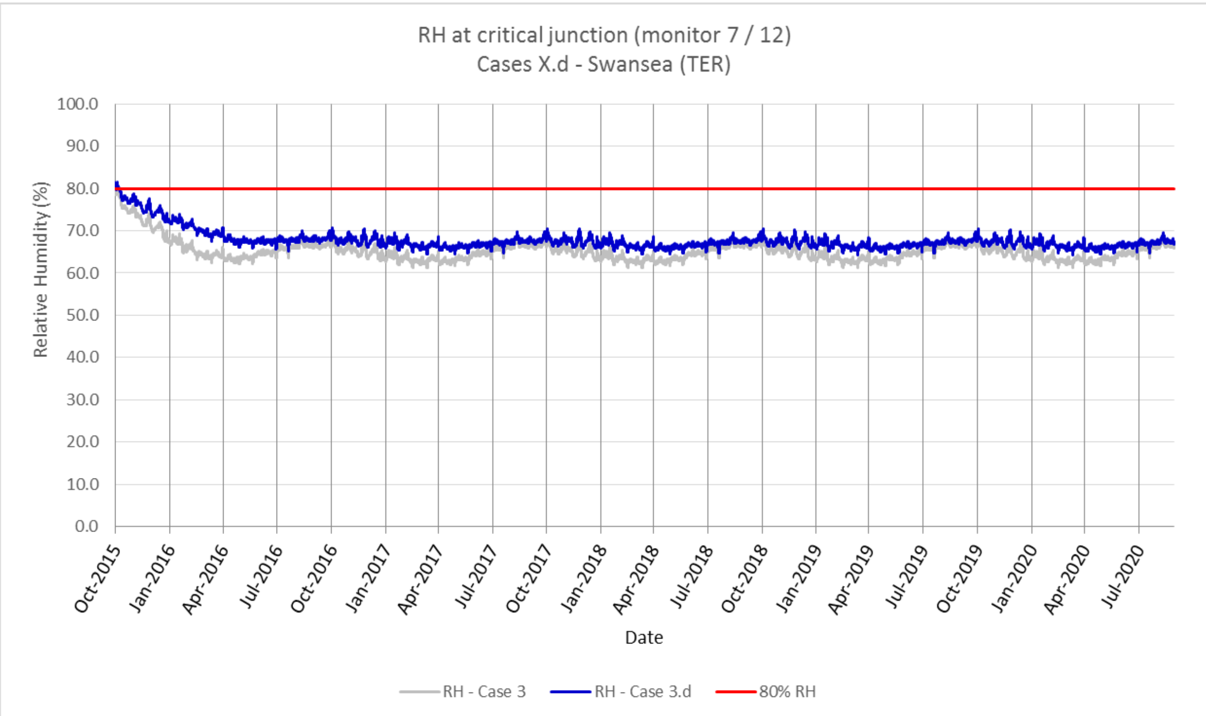


Figure 171: Cases chosen for sensitivity analysis 3 and 3.d

19.6.4. Conclusions – Sensitivity Analysis Cases X.d

The results show that that all the modelled sensitivity cases perform worse than their respective baseline cases. The presence of the foil layers on both sides of the external insulation increases the total vapour resistance of the build-up notably. This added resistance is located directly on the outside of the sheathing layer (OSB), meaning that moisture travelling from inside to outside will accumulate more at the sheathing layer, than in the baseline conditions. This leads to increased RH levels at the critical junction.

This added resistance, making the travelling of moisture more difficult through the entire build-up, can also be seen with the offset (delay) of a few months in the peaks in the RH profiles.

Despite all sensitivity cases performing worse than their baseline cases, they all display RH levels below the 80% recommended threshold for most of the year. Therefore, these cases remain as 'pass'. However, the Part L (30mm) case shows RH levels just reaching 80% for a small period of time (less than a month). Therefore the Part L case is considered as a 'pass' / 'risky' build-up.

<u>Results</u>

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L (30 mm)	Case 2.d Pass (Risky)	-	-	-
TER	Case 3.d Pass	-	-	-

<u>Effects of U-values</u>

The graphs show that the small detrimental effect of the addition of the foil layers on both sides of the insulation is decreasing the thicker the external insulation layer is. This is linked to the fact that the more insulation is installed externally to the frame, the warmer the temperature at which the critical junction is kept.

The graphs show that the use of insulation including foil layers (considered vapour retarders) commonly used in the building industry only has a small detrimental to the hygrothermal performance of the build-up.

It seems that the detrimental effect of the addition of the foil layers on both sides of the insulation can be disregarded as soon as the external insulation layer reaches a certain percentage of the total insulation thermal resistance.

In this case, the limit is reached with the Part L case using a 30mm PU foam external insulation layer, which represents about 1/3 of the total insulation's thermal resistance.

19.7. Sensitivity Analysis – Change in Build-up [Cases X.e]: Change from ventilated cladding to render layer

19.7.1. Change from ventilated layer to render layer

As render is also a commonly used external finish, additional sensitivity cases are done to assess the impact of removing the ventilated cladding and using a render finish applied directly onto the continuous rigid insulation layer installed on the outside of the frame. It is worth noting that no recommendation is given in BS 5250 (2011) for this type of build-up, as this is currently considered a 'hybrid' build-up.

Please note that this sensitivity analysis does not apply to the Part C case, as no external insulation is present in this case (the insulation is only installed in between the framing members).

<u>Build-Up</u>

- 15mm silicone render
- 0mm // 12mm // 80mm PU foam insulation (λ = 0.025 W/m. K)
- 9mm OSB
- 100mm mineral wool insulation (λ = 0.040 W/m.K) between timber studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard

EPS is the insulation material typically used in the industry in this sensitivity analysis build-up, which makes this build-up slightly unrealistic. However, as EPS and PU foam have fairly similar characteristics in terms of resistance to moisture and to ensure only one variable is changed between the baseline and any sensitivity analysis, PU foam has been kept in this sensitivity analysis.

19.7.2. Sensitivity Analysis Cases

As the impact of the different exposure zones has already been assessed in the baseline cases, this sensitivity analysis is done in the most extreme exposure zone, Swansea. As the Part L case was considered as 'safe' with an increased external insulation layer from 12mm to 30mm, this upgraded build-up is used for this sensitivity analysis.

The two cases are set across the Zone 4 wind-driven rain exposure zone, meeting the two target U-values (as per baseline cases).

Table 71: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L (30mm)	Case 2.e	-	-	-
TER	Case 3.e	-	-	-

19.7.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), at the interface between the OSB (sheathing) and the cold side of the insulation layer within the frame (mineral wool) for the sensitivity analysis cases based in Swansea (excluding Part C case).

The sensitivity analysis cases (with render) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

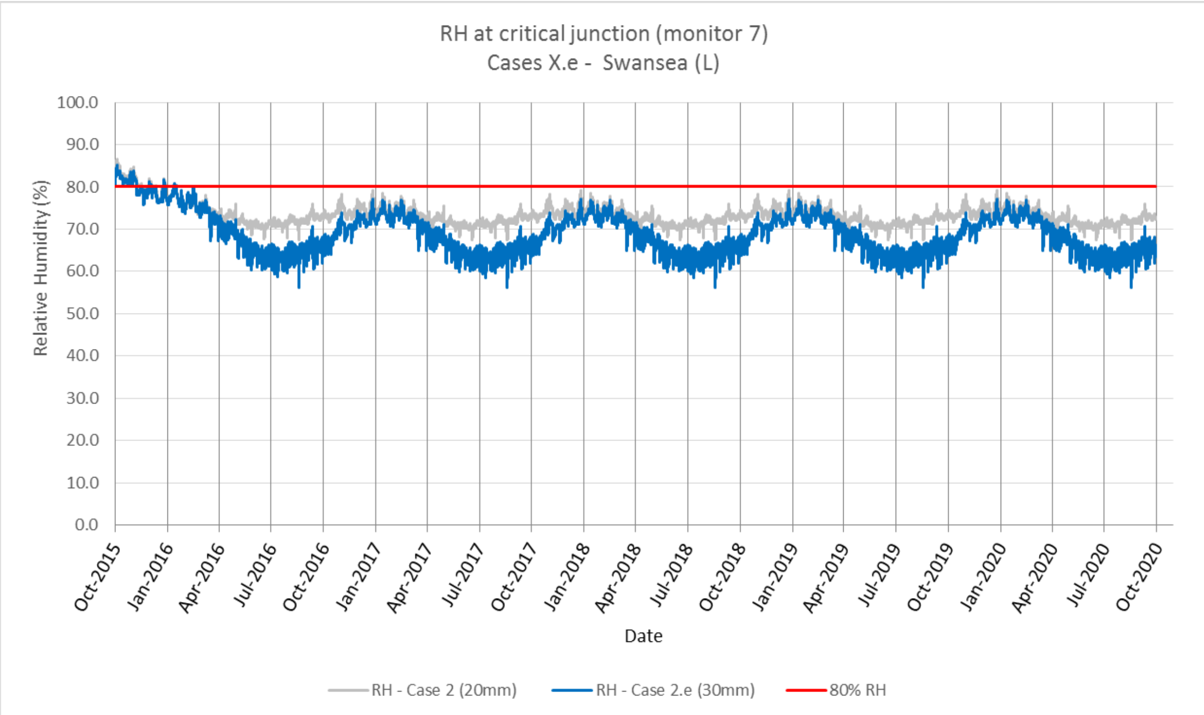


Figure 172: RH levels at critical junction for Cases 2 and 2.e

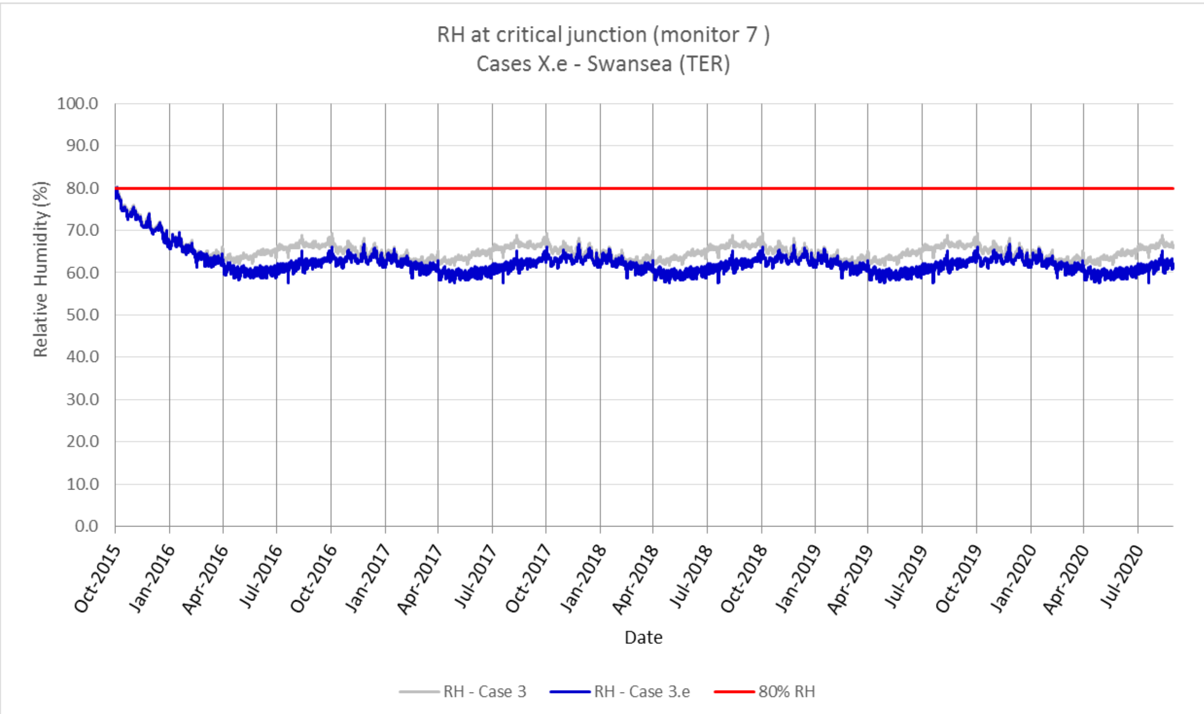


Figure 173: RH levels at critical junction for Cases 3 and 3.e

19.7.4. Conclusions – Sensitivity Analysis Cases X.e

The results show that that all the modelled sensitivity cases perform slightly better than their baseline cases. As the status of both baseline cases is a ‘pass’, the status of these sensitivity analysis cases remains unchanged.

The presence of the silicone render on the outside of the insulation adds an additional protection layer, which significantly increase the vapour resistance on the external side of the continuous insulation. This means that the amount a water vapour entering the build-up / continuous insulation layer is significantly reduced, despite the fact that these sensitivity analysis cases are directly exposed to wind-driven rain (compared to the baseline cases, which are not).

This added resistance, making the travelling of moisture more difficult through the entire build-up, can also be seen with the slight offset (delay) in time in the peaks in the RH profiles.

Results

Table 72: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	-	-	-	-
Part L (30 mm)	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

Sheathing Board: Cement Particle Board versus OSB

This build-up is commonly done with a cement particle board instead of an OSB layer, for the sheathing layer installed on the outside of the frame. As cement particle board is a less vapour-resistant material than OSB, the change of materials from OSB to cement particle board will not have a detrimental effect on the hygrothermal performance of the build-up.

Presence of an Air Gap

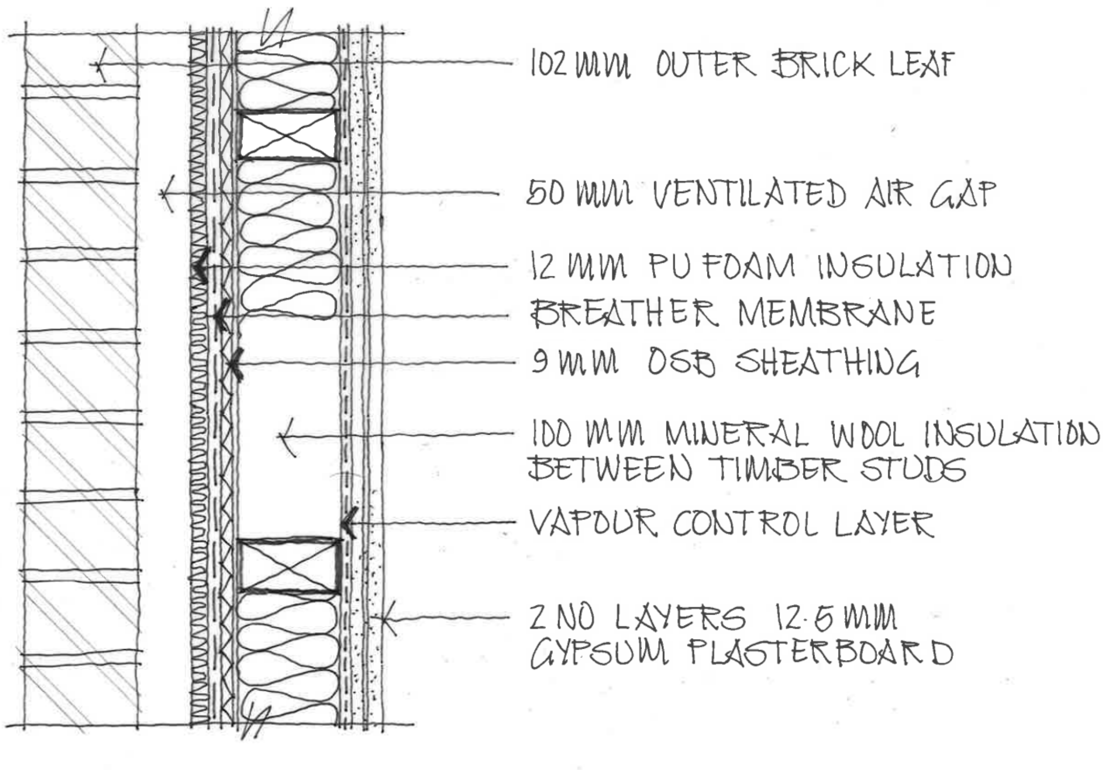
The graphs show that the use of EWI onto a timber frame structure has a similar hygrothermal performance to a timber frame structure with ventilated cladding. Both build-ups appear to be 'safe' build-ups, as long as a continuous insulation layer is installed on the outside of the frame (to protect the critical junction).

19.8. Conclusions

- This baseline is safe provided the guidance in BS5250:2011 (in particular in regards to ventilation loft space) is followed.
- AVCL with high vapour resistance (sd ≥ 20m in this case) has a beneficial impact on the hygrothermal performance of the build-up. So AVCL and presence of continuous EWI on the outside of the frame creates a 'robust' build-up
- AVCL resistance to be double of the sheathing (BS 5250 (2011) recommendation) is not detailed / precise enough

20. Typology N15: Light Gauge Steel Frame (LGSF) – with air gap and a semi-porous finish (e.g. facing brickwork)

The N15 typology is a new-build light gauge steel frame (LGSF) with an air gap and a semi-porous finish (e.g. facing brickwork). The thermal performance of the build-up is improved with the use of EWI (external wall insulation) on the external side of the timber frame.



20.1. Build-up

As WUFI is a one-dimensional model, it cannot model bridged elements. In this typology, the WUFI model is cut through the insulation layer, instead of through the steel frame system.

Similarly to the N14 typology, BS 5250 (2011) states in the general framed wall section (G.4.1), *'there is a risk of interstitial condensation occurring behind impermeable external finishes or cladding: to avoid that, a vented space should be provided immediately behind the finish or cladding'.*

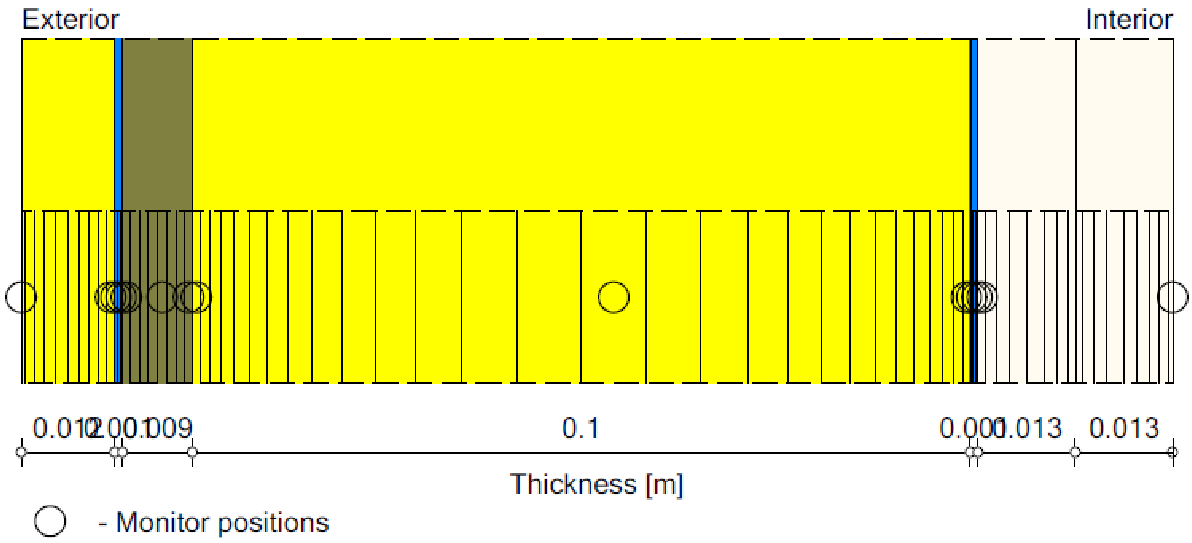
To follow prescriptive guidance, the cavity behind the wall finish (outer brick layer) is ventilated to the outside, to allow any moisture present in the cavity to be removed. This means that the external finishing layer is considered as a ‘protective cladding’ and is not technically part of the ‘thermal’ build-up. As shown in the following section, the modelled build-up therefore only extends from the external insulation layer (on the cold side of the frame) to the internal finish.

As the outer brick layer plays this protective role, the build-up is now considered not to be exposed to rain, wind and solar radiations.

Please find below the build-up of the typology:

Build-Up:

- 102mm outer brick layer *(considered outside of the WUFI build-up)*
- 50mm ventilated air gap *(considered outside of the WUFI build-up)*
- 0mm // 12mm // 80mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm breather membrane (sd = 0.04m)
- 9mm OSB
- 100mm mineral wool insulation (λ = 0.040 W/m.K) between steel studs
- 1mm AVCL layer (sd = 2m)
- 12.5mm gypsum plasterboard
- 12.5mm gypsum plasterboard



Materials:

	- PU (heat cond.: 0,025 W/mK)	0.012 m
	- *Breather Membrane (sd=0,04m) (unlocked)	0.001 m
	- Oriented Strand Board (density 615 kg/m³)	0.009 m
	- Mineral Wool (heat cond.: 0,04 W/mK)	0.1 m
	- vapour retarder (sd=2m)	0.001 m
	- Gypsum Board	0.013 m

Due to WUFI one-dimensional limitations and the need for the cavity to be ventilated, the exact build-up modelled in WUFI for this typology (N15) is exactly identical to the WUFI model for the N14 typology (timber frame with an air gap and a non-porous finish). For these reasons, no baseline or sensitivity modelling is performed on this typology (please refer to section 17).

It is worth noting that the Part C case will have surface condensation as the steel frame is bridging the entire insulation layer (no continuous external insulation layer is present in this case). This is similar in principle to the N14 typology (timber frame with an air gap and a non-porous finish) but the surface condensation risk is significantly increased due to the extremely high thermal conductivity of steel compared to timber.

21. Typology N17: Cold pitched roof (slates/concrete/clay tiles)

The N17 typology is a new-build cold pitched roof, i.e. with the insulation layer installed between (and in some cases above) timber joists at ceiling level.

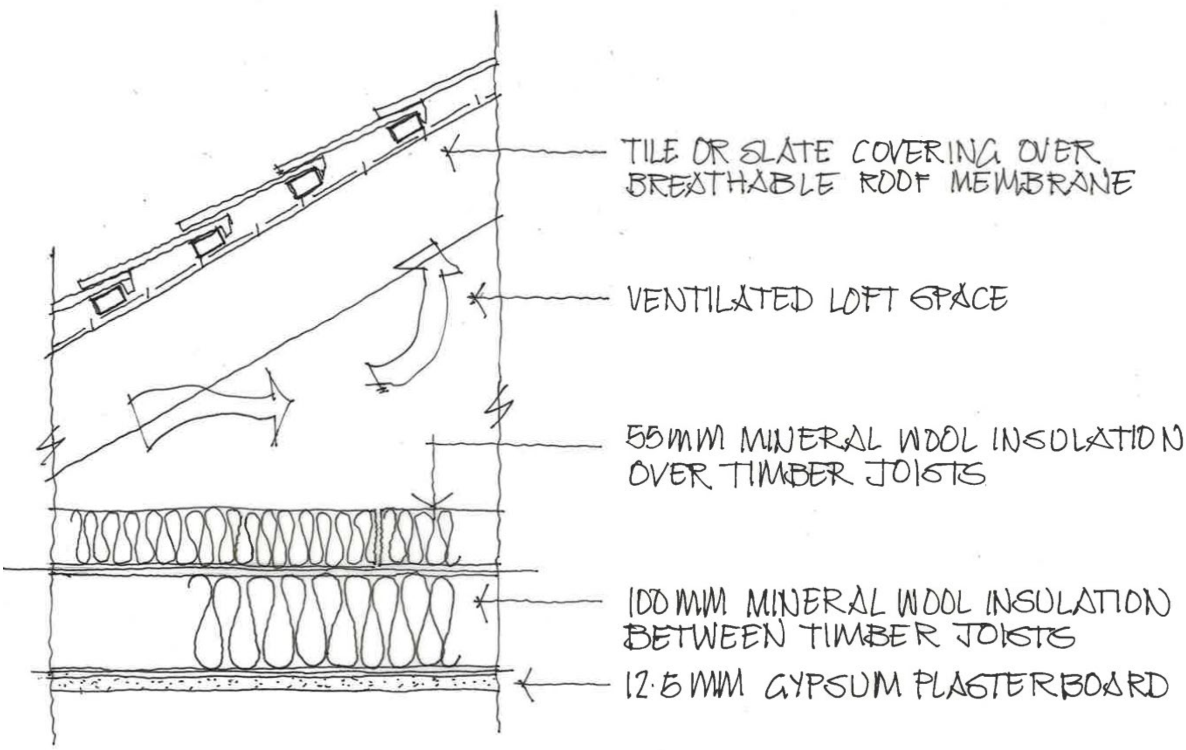


Figure 174: Illustration of the build-up of the typology (Part L case)

21.1. Assessment Method

Current prescriptive guidance in BS 5250 (2011) (paragraph H.4.1) states that *'there is a significant risk of interstitial condensation forming on the roof structure and on the underside of the underlay, from where it might run and drip onto the insulation and some risk of interstitial condensation in the batten space. Persistently high levels of humidity cause hygroscopic materials (such as timber and timber-based products) to absorb sufficient moisture to encourage the growth of moulds and the decay of structural members.'*

Paragraph 4.2.2 of BS 5250 (2011) also states that *'condensation on the coldest plane, usually on the underlay, should be removed by ventilation to outside air, assisted by wind action. The rate of ventilation is based on empirical experience.'*

To follow this prescriptive guidance, the loft space above the insulation is ventilated to the outside, to allow any moisture present in the loft space to be removed. This means that the roof covering is considered as a 'protective cladding' and is not

technically part of the ‘thermal’ build-up. As shown in the following section, the modelled build-up therefore only extends from the upper surface of the insulation to the internal finish.
BS 5250 (2011) paragraph 4.2.2 also adds that *’the methods of assessing condensation risk described in BS EN 13788 do not apply to cold roofs.'.*

As the BS EN ISO 13788 (2012) method is described as unreliable for pitched roof calculations, its results are taken with caution. The calculation shows a risk of surface condensation occurring on the cold side of the insulation. However, BS 5250 (2011) explains that this should not be a risk, if the loft space is well ventilated.

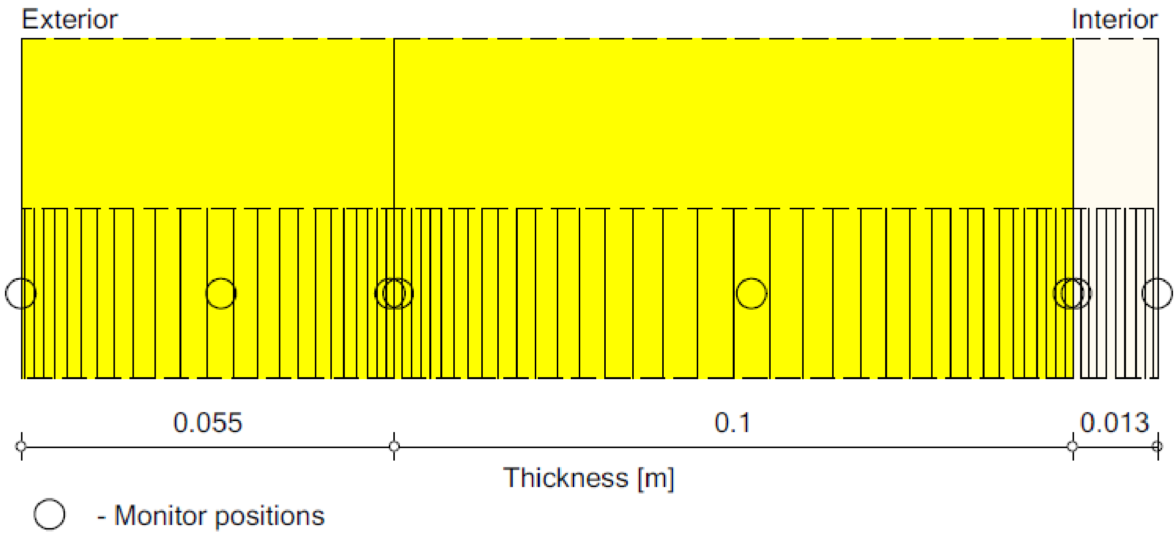
Additional WUFI modelling to BS EN 15026 (2007) is used to obtain additional information on the hygrothermal performance of the build-up. However, it is known that WUFI has limitations, especially around modelling air layers. Therefore, the use of WUFI modelling on this typology might not provide a deep insight onto its hygrothermal performance, compared to other typologies.

21.2. Build-up

Please find below the build-up of the typology, as modelled in the BS EN ISO 13788 (2012) (the Glaser method) assessed model and in the BS EN 15026 (2007) (WUFI) model.

Build-Up:

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated loft space *(considered outside of the WUFI build-up)*
- 10mm // 55mm // 220mm mineral wool insulation (λ = 0.040 W/m.K)
- 100mm mineral wool insulation (λ = 0.040 W/m.K) in between timber joists
- 12.5mm gypsum plasterboard



Materials:

	- Mineral Wool (heat cond.: 0,04 W/mK)	0.055 m
	- Mineral Wool (heat cond.: 0,04 W/mK)	0.1 m
	- Gypsum Board	0.013 m

<u>WUFI Input Parameters</u>

As the structure is considered as externally ventilated, both the roof material layer and the loft space are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the outer surface of the insulation) is exposed to different external conditions due to the outer roof covering acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the roof covering layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)

<u>Baseline Build-Up</u>

Please note that this build-up does not reflect the technical recommendations as set out in BS 5250 (2011), as the baseline build-ups were chosen to reflect typical UK new-build constructions and they were agreed prior to the modelling phase.

In the build-up, we have omitted the AVCL layer as this is a more realistic reflection of the industry practice. Assessment on the addition of the recommended AVCL to follow prescriptive guidance BS 5250 (2011) is included in the sensitivity analysis section.

21.3. Baseline Results

21.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 73: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

21.3.2. Monitored Junction

External surface of the insulation

The build-up is protected from the elements, and should not present any moisture risks when built correctly, meaning there is not a 'critical' junction per se. A critical junction is identified by BS 5250 (2011), stating that *'there is a significant risk of interstitial condensation forming on the roof structure and on the underside of the underlay […] and some risk of interstitial condensation in the batten space'.* However, the interfaces mentioned are technically not included in the WUFI model (due to WUFI's limitations on the modelling of ventilated voids) and cannot be monitored.

The first monitored junction to be analysed is the interface the closest to the identified 'critical' junctions. This 'monitored' junction corresponds to the 'external' monitor on the build-up and will display exactly the 'external' conditions applied to the model.

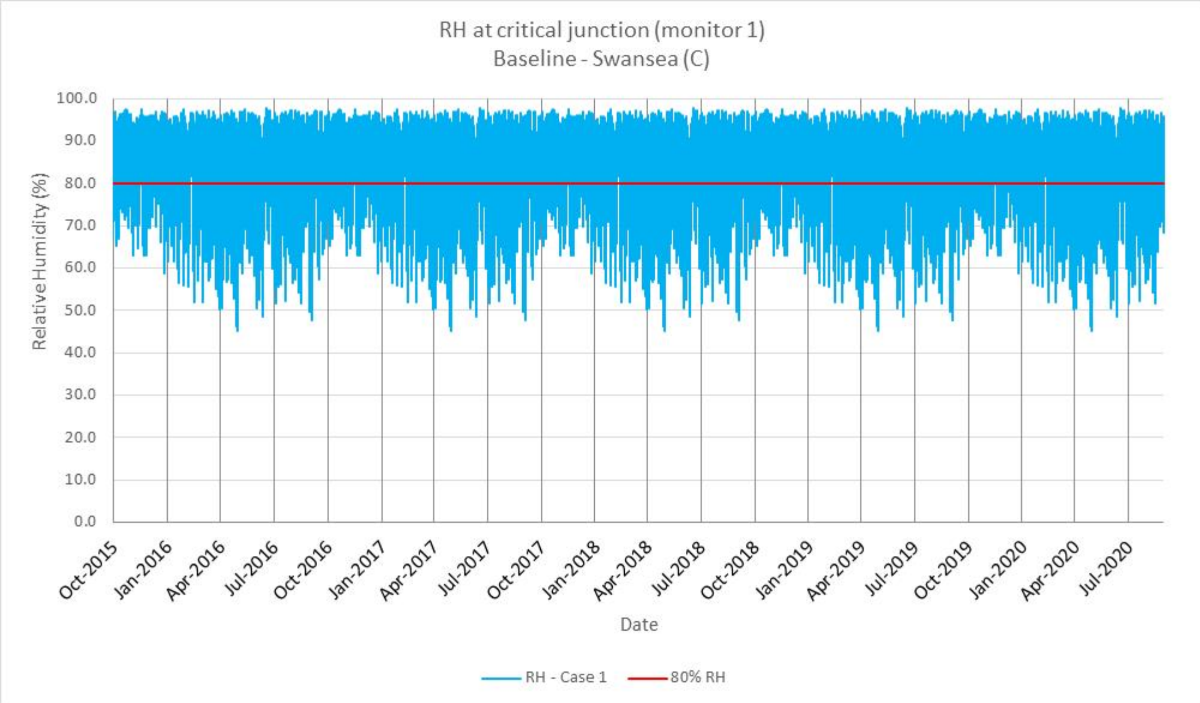


Figure 175: RH levels at monitored junction for Case 1

However, these graphs (only represented for Case 1 – Part C in Swansea) have been excluded from the analysis, as the RH levels displayed represent exactly the external conditions applied to the build-up which means that the analysis is not necessary.

The only comment linked to this first monitored junction is that the outer surface of the insulation is kept at high RH levels (similarly to case N11, partial-fill cavity wall). This is not a significant problem in terms of mould growth (due to the lack of food for mould growth present at that location and the isolation from the indoor environment) but may have a detrimental effect on the overall thermal performance on the insulation. It is also worth noting that the research done on the N11 typology showed the majority of the insulation is kept at 'safe' RH levels (except the last few millimetres of the insulation on the cold side), and is therefore mainly performing.

Top of the joists

As the first monitored junction will not be able to provide useful data to be analysed, a second monitored junction is chosen to analyse the RH levels at the top of the joists. In the WUFI model, this interface is the interface located between the insulation layer bridged by the timber rafters and the continuous insulation layer, installed above the joists.

21.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction, i.e. at the top of the joists.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

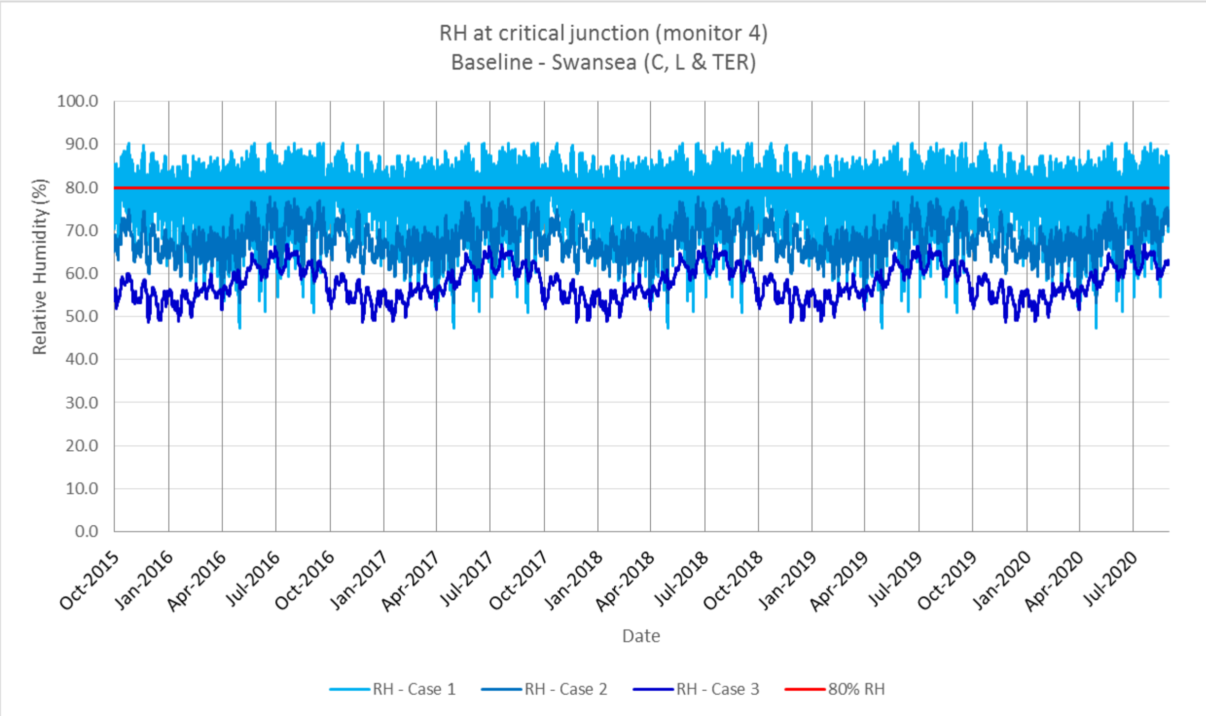


Figure 176: RH levels at monitored junction for Cases 1, 2 and 3

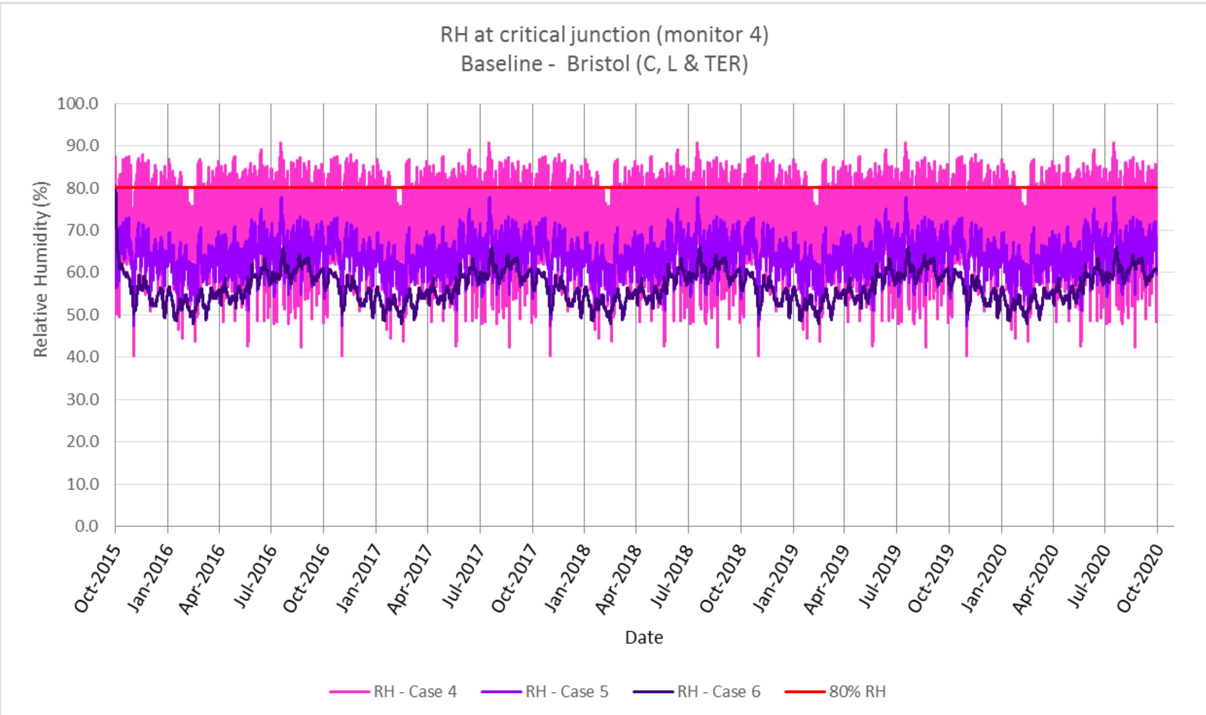


Figure 177: RH levels at monitored junction for Cases 4, 5 and 6

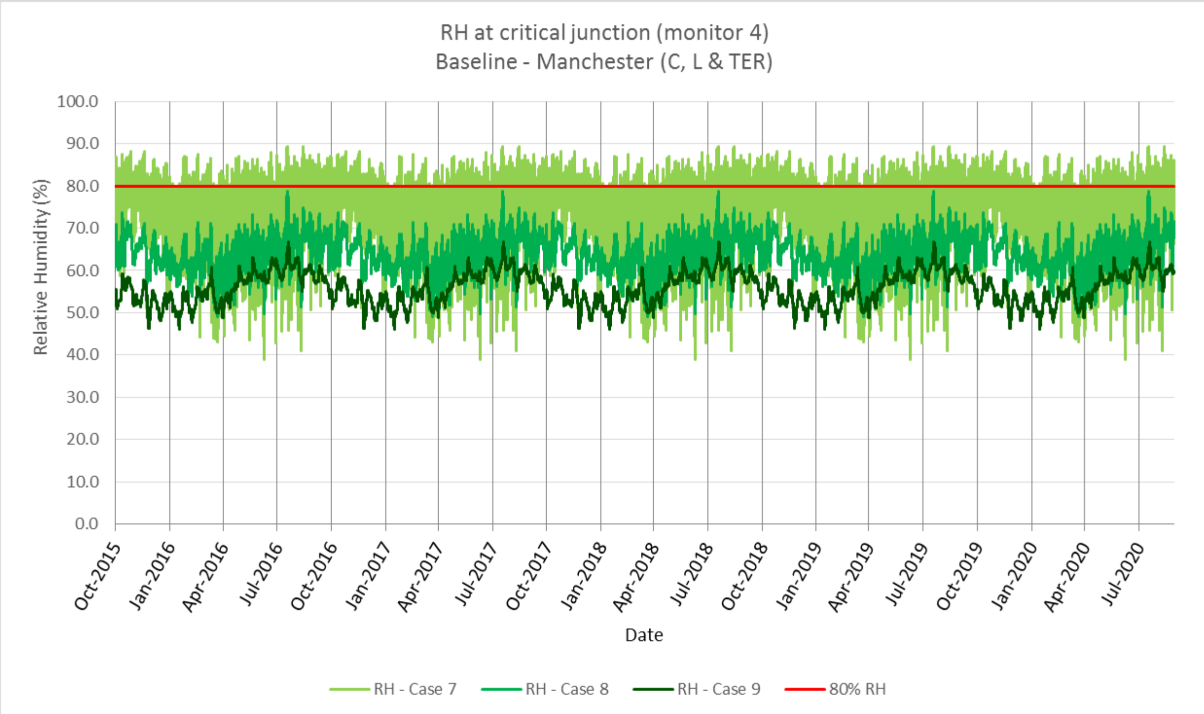


Figure 178: RH levels at monitored junction for Cases 7, 8 and 9

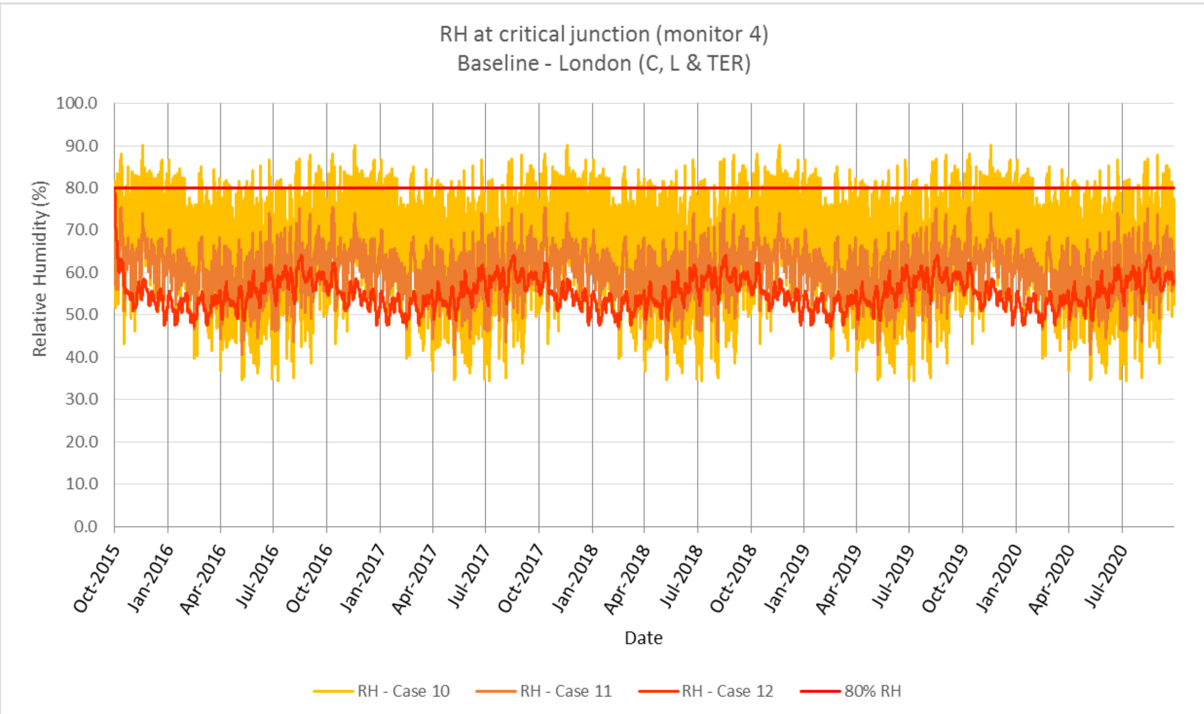


Figure 179: RH levels at monitored junction for Cases 10, 11 and 12

21.3.4. Conclusions - Baseline

<u>Results</u>

The fact that these graphs are displaying mainly 'safe' RH levels (safe for Part L and TER cases, though higher levels displayed for Part C) it is not sufficient to declare the build-up as safe. However, as no critical junction is available to be monitored through the limitations of the software used, the results for the twelve baseline cases are based on experience shown in the prescriptive guidance BS 5250 (2011). The results are summarised in the table below.

Table 74: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

Moisture risk assessment criteria

All cases reach equilibrium and do not keep on accumulating moisture. However, different RH levels are shown, depending on the case displayed (Part C, Part L or TER).

The graphs show that the thicker the continuous insulation installed above the joists, the lower the RH levels experienced on the top of the joists. This is due to the monitored junction (at the top of the joists) being kept warmer with thicker insulation installed above the joists.

Safe RH levels are reached very quickly, in terms of additional continuous insulation layer installed above the joists. Part C cases are the only cases displaying RH levels above the 80% RH threshold. To meet Part C target U-values, Part C cases have a 10mm additional continuous insulation layer to be installed above the joists, which is unrealistic. Part L cases have an additional continuous insulation layer of 55mm, which is also unrealistic (as the minimum thickness for loft insulation is typically 100mm). While the Part L additional insulation thickness is still considered unrealistic, the graphs show that the RH levels are kept below the 80% RH threshold, which display 'safe' conditions for the timber joists to be in.

Effects of exposure zones

The effect of wind-driven rain exposure zones is only slightly visible on the graphs (only due to differences in external RH and temperature weather data), as all RH levels at the monitored junction are very similar for all cases. Similarly to the N19 typology, the effect of wind-driven rain exposure zones is really minimal, as any deterioration in the roof finish leads to complete system failure.

21.4. Sensitivity Analysis – Change in Material [Cases X.d]

21.4.1. Baseline model versus BS 5250 (2011)

The baseline build-up differs from the build-up present in BS 5250 (2011), as no AVCL is included below the insulation layer (at the interface with the ceiling internal layer) in the baseline model, as the baseline model is based on current typical construction practice.

Presence / Absence of AVCL

The current guidance of BS 5250 (2011) states the following: *'Air leakage through gaps in a ceiling or lining allows substantial amounts of heat and moisture to be transferred into the roof by convection. Restricting air leakage by sealing the ceiling or lining using an AVCL or air leakage barrier reduces the transfer of both heat and moisture, improving the energy efficiency of the building and minimizing the risk of interstitial condensation'.*

Therefore, the first sensitivity analysis done here is to include an AVCL in the build-up, located on the warm side of the insulation (installed between the insulation layer and the ceiling) to follow BS 5250 (2011) prescriptive guidance.

21.4.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones make little difference in the hygrothermal performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis. The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 75: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

21.4.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction (which is the same as the baseline cases), i.e. at the top of the joists for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with AVCL) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

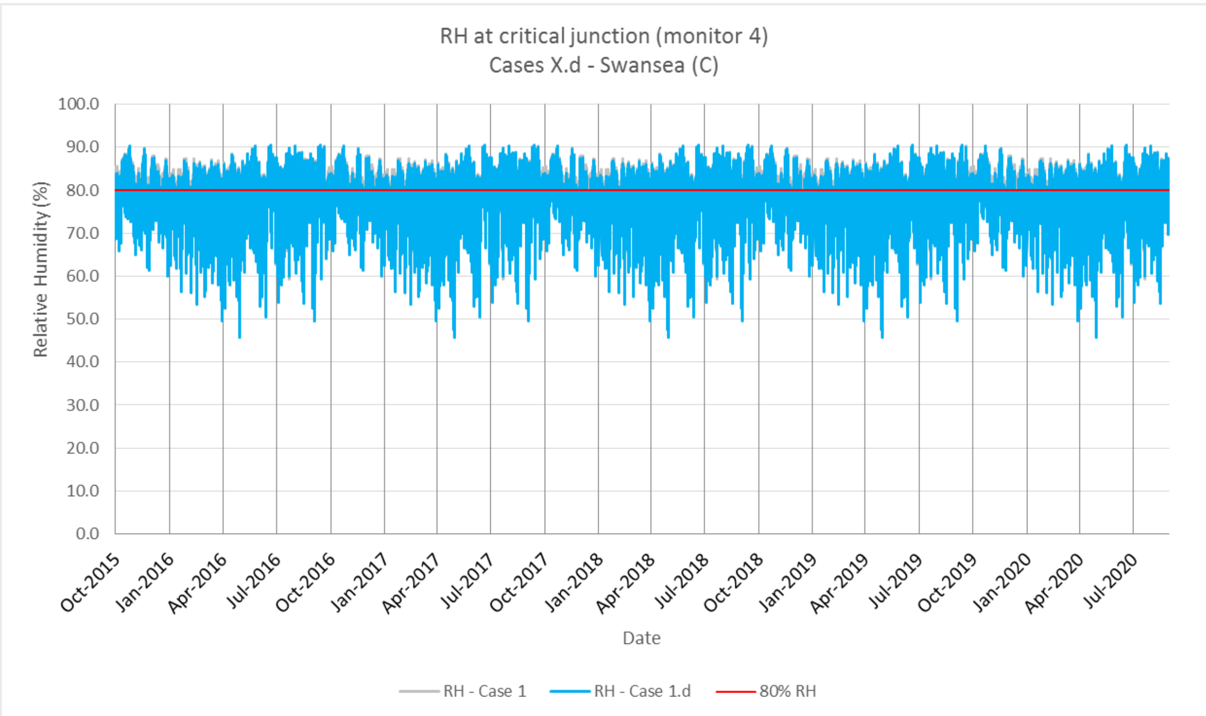


Figure 180: RH levels at monitored junction for Cases 1 and 1.d

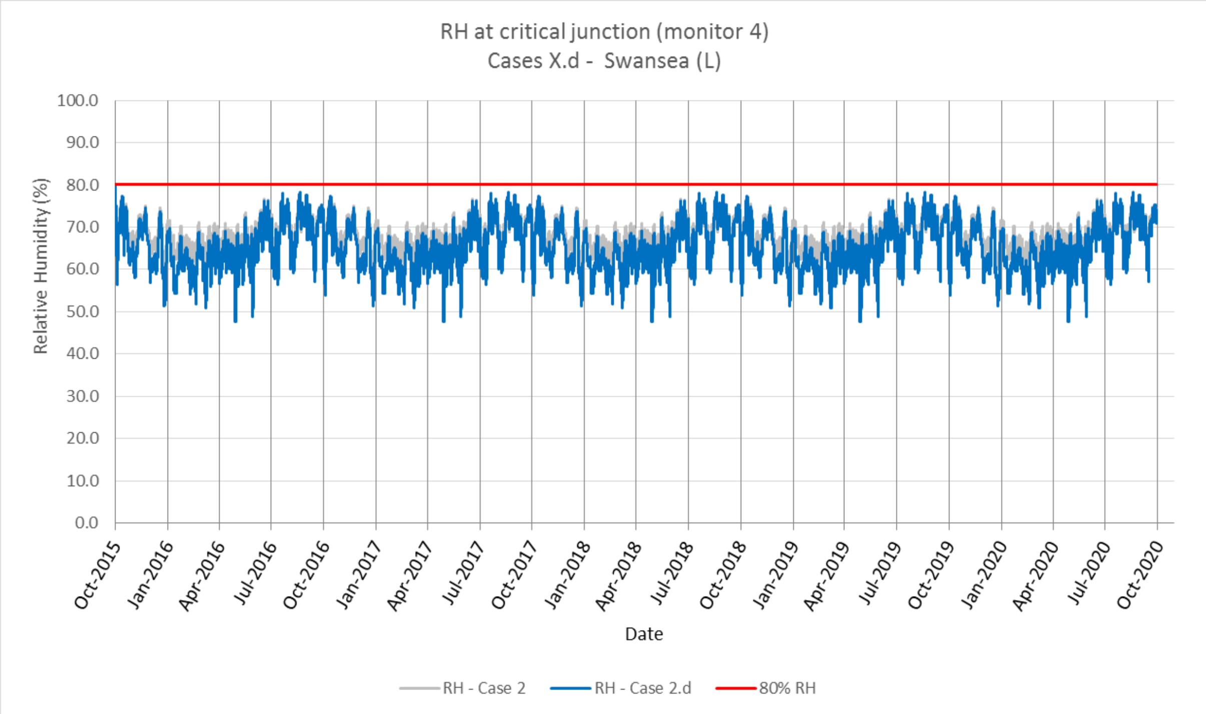


Figure 181: RH levels at monitored junction for Cases 2 and 2.d

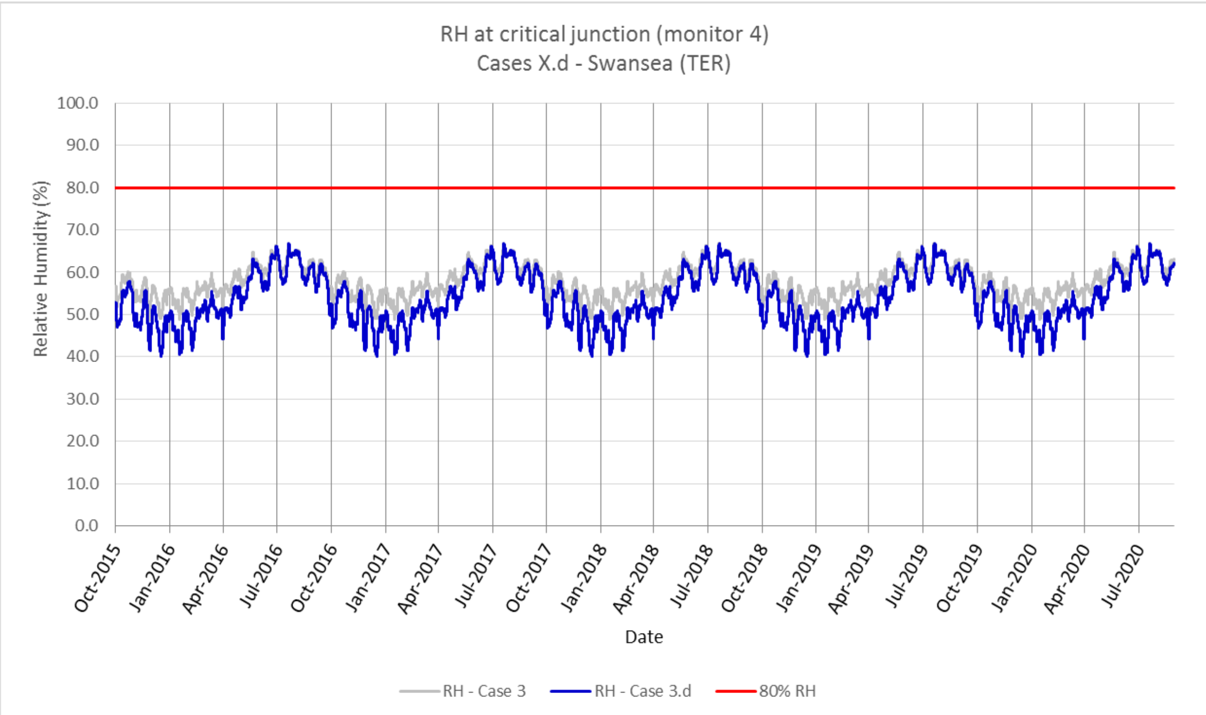


Figure 182: RH levels at monitored junction for Cases 3 and 3.d

21.4.4. Conclusions – Sensitivity Analysis Cases X.d

The results show that that all the modelled sensitivity cases perform only slightly better than their baseline cases. However, all baseline cases were already displaying RH levels below the 80% RH threshold. As no critical junction is available to be monitored through the limitations of the software used, the results for the sensitivity cases are also based on experience shown in the prescriptive guidance BS 5250 (2011).

Similarly to the baseline cases, the Part C case is the only case displaying RH levels above the 80% RH threshold. However, this case is disregarded, as this case only requires a 10mm additional continuous insulation layer to be installed above the joists to meet Part C target U-value, which is an unrealistic construction in practice.

Results

Table 76: Summary of results

	Exposure Zones			
Target U-values	Swansea (Zone 4)	Bristol (Zone 3)	Manchester (Zone 2)	London (Zone 1)
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

The graphs seem to show that the presence of the AVCL in the build-up does not lead to a significant improvement in its hygrothermal performance. However, the WUFI modelling uses 'perfect' materials, e.g. a fully performing AVCL and finishing plasterboard layer in this situation. If the AVCL was to have damage (gaps or cracks) and allow the passage of moisture-laden air present in the indoor environment through the build-up, this could lead to serious interstitial condensation risks.

Therefore, the results of the sensitivity cases, as well as understanding of ABIS (As-Built In-Service) conditions, show that the presence of an AVCL in this build-up always has a beneficial impact on the hygrothermal performance of the build-up.

21.5. Sensitivity Analysis

21.5.1. Airtightness and ABIS Conditions

It is important to note that the build-up modelled in WUFI is done in theoretical conditions, which means that the gypsum plasterboard layer is continuous and plays the role of the airtightness layer. As highlighted in BS 5250 (2011) (paragraph H.3.2), *'Air leakage through gaps in a ceiling or lining allows substantial amounts of heat and moisture to be transferred into the roof by convection. Restricting air leakage by sealing the ceiling or lining using an AVCL or air leakage barrier reduces the transfer of both heat and moisture, improving the energy efficiency of the building and minimizing the risk of interstitial condensation'.*

No sensitivity analysis modelling is done in this report, in which air leakage is modelled through the gypsum plasterboard layer to create a leaking airtightness layer. However, despite the absence of modelling, the impact of such conditions is known: this could lead to moisture-laden air making its way through the build-up and condensing within the build-up when it reaches its dew point. Therefore, particular care should be given around ensuring good airtightness to the ceiling.

21.6. Conclusions

- Baseline safe provided the guidance in BS5250:2011 (in particular in regards to ventilation loft space) is followed

22. Typology N18: Warm roof – slates / concrete / clay tiles

The N18 typology is a new-build warm flat roof, i.e. a timber frame structure with closed-cell insulation installed between (and in some cases below) the timber rafters.

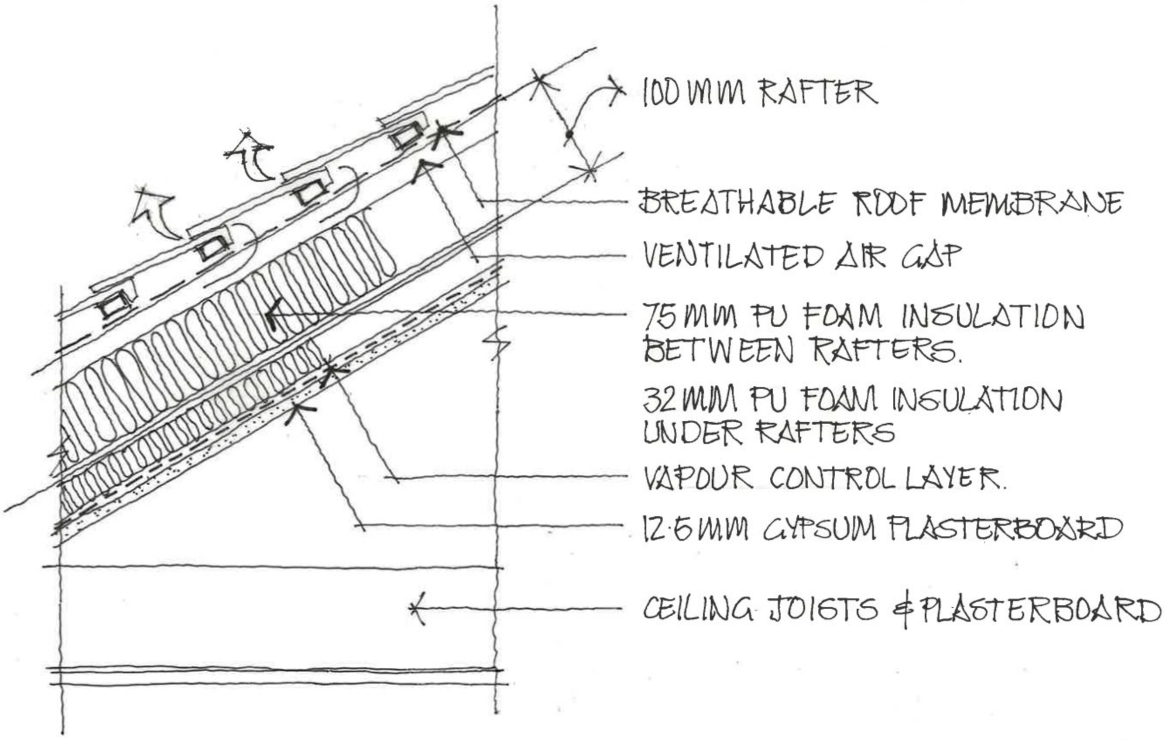


Figure 183: Illustration of the build-up of the typology (Part L case)

22.1. Assessment Method

Current prescriptive guidance in BS 5250 (2011) paragraph H.5.3 states that *'in warm pitched roofs with a low resistance underlay, an AVCL should be provided at ceiling line. Where the external covering (such as fibre cement slates) is relatively airtight, there is a risk of interstitial condensation forming on the underside of the underlay and the external covering. To avoid that risk, the batten space should be vented'.*

To follow this prescriptive guidance, the void above the insulation is ventilated to the outside, to allow any moisture present in the void to be removed. This means that the roof covering is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the breather membrane to the internal finish.

The build-up does not contain very porous materials. In addition, the modelled build-up is not directly exposed to the elements (rain, wind and solar radiations), as the roof covering is acting as a protection layer. Therefore, the BS EN ISO 13788 (2012) assessment method should provide valid results for this typology.

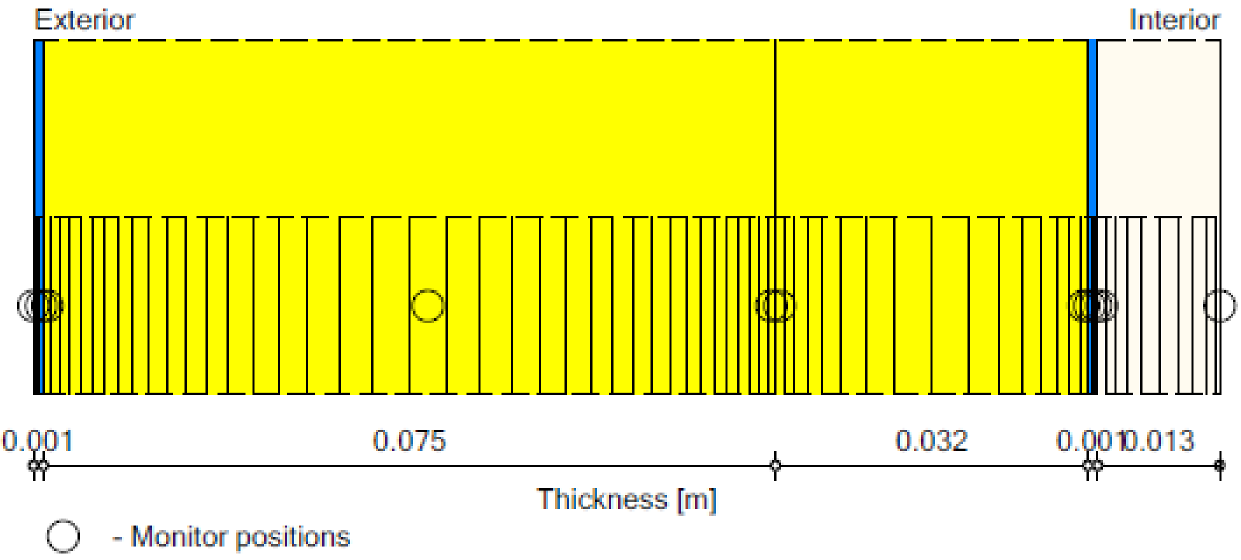
The results by the Glaser method show that this build-up is considered a ‘safe’ build-up, with no risk of interstitial condensation, if the cavity at battens level is well ventilated. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

22.2. Build-up

Please find below the build-up of the typology, as modelled in the BS EN ISO 13788 (2012) (the Glaser method) assessed model and in the BS EN 15026 (2007) (WUFI) model.

Build-Up:

- Tile or slate roof *(considered outside of the WUFI build-up)*
- Ventilated air layer *(considered outside of the WUFI build-up)*
- Breather membrane (sd = 0.04m)
- 75mm PU foam insulation (λ = 0.025 W/m.K)
- 0mm // 32mm // 130mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL (sd = 2m)
- 12.5mm gypsum plasterboard



Materials:

(blue)	- *Breather Membrane (sd=0,04m) (unlocked)	0.001 m
(yellow)	- PU (heat cond.: 0,025 W/mK)	0.075 m
(yellow)	- PU (heat cond.: 0,025 W/mK)	0.032 m
(blue)	- *vapour retarder (sd=2m) (unlocked)	0.001 m
(off-white)	- Gypsum Board	0.013 m

WUFI Input Parameters

As the structure is considered as externally ventilated, both the roof material layer and the air gap are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the cold side of the insulation) is exposed to different external conditions due to the outer roof covering acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the roof covering layer is protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)

22.3. Baseline Results

22.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out below.

Table 77: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

22.3.2. Monitored Junction

In ‘perfect’ conditions (i.e. ‘normal’ internal moisture load, roof covering layer in good condition, without additional water ingress due to leaks, poor drainage, etc.), the build-up is protected from the elements, and should not present any moisture risks (as shown with the BS EN ISO 13788 (2012) calculations), meaning there is not a ‘critical’ junction per se.

The only useful interface which could be monitored is the interface located at the inner edge of the joists. In the WUFI model, this interface is located between the insulation and the continuous inner ceiling layers (including additional insulation used to achieve lower U-values) - i.e. at the inner face of the joists.

However, RH levels at the interface can already be predicted: this interface is in general kept on the warm side of the insulation (except for the TER case where a thick additional insulation layer is installed under the joists), with the remaining layers internally being the AVCL and the gypsum plasterboard. The RH levels should be kept at relatively ‘safe’ RH levels, with this interface being additionally protected from moisture-laden air penetrating the build-up (which could increase the risk of interstitial condensation).

22.3.3. Graphs at monitored Junction

All graphs displayed below show the RH levels at the monitored junction, i.e. at the inner edge of the joists (between the insulation between and below the joists).

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

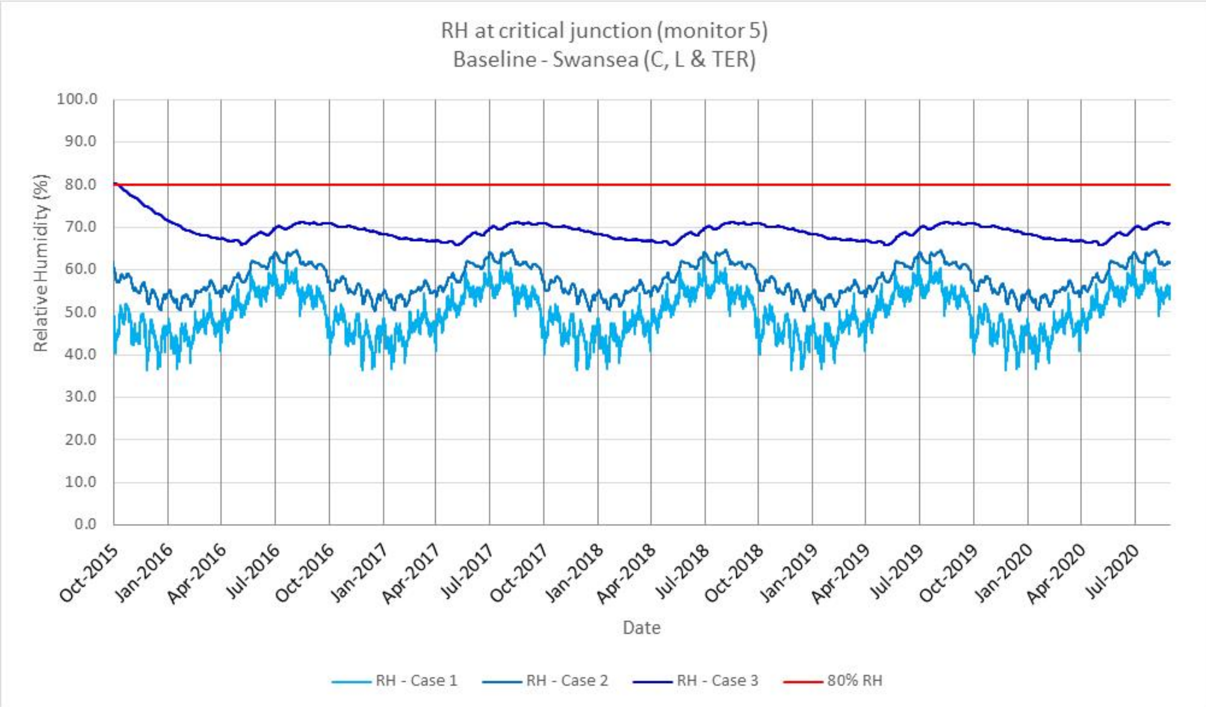


Figure 184: RH levels at monitored junction for Cases 1, 2 and 3

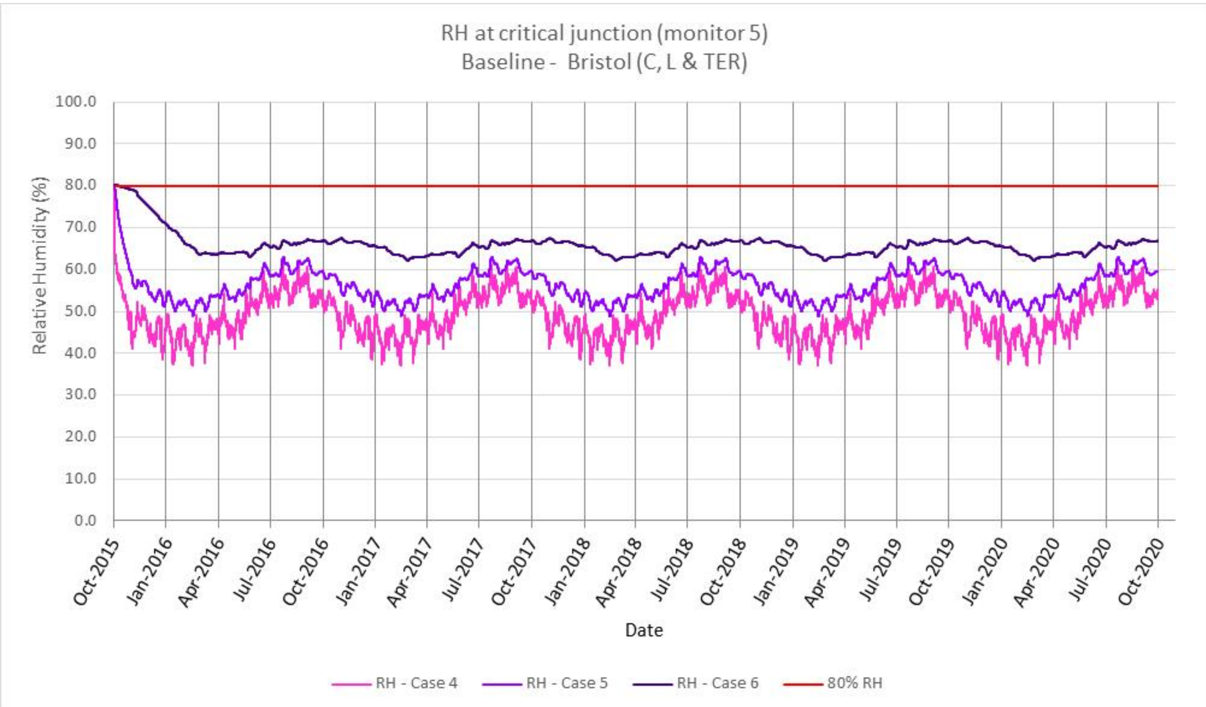


Figure 185: RH levels at monitored junction for Cases 4, 5 and 6

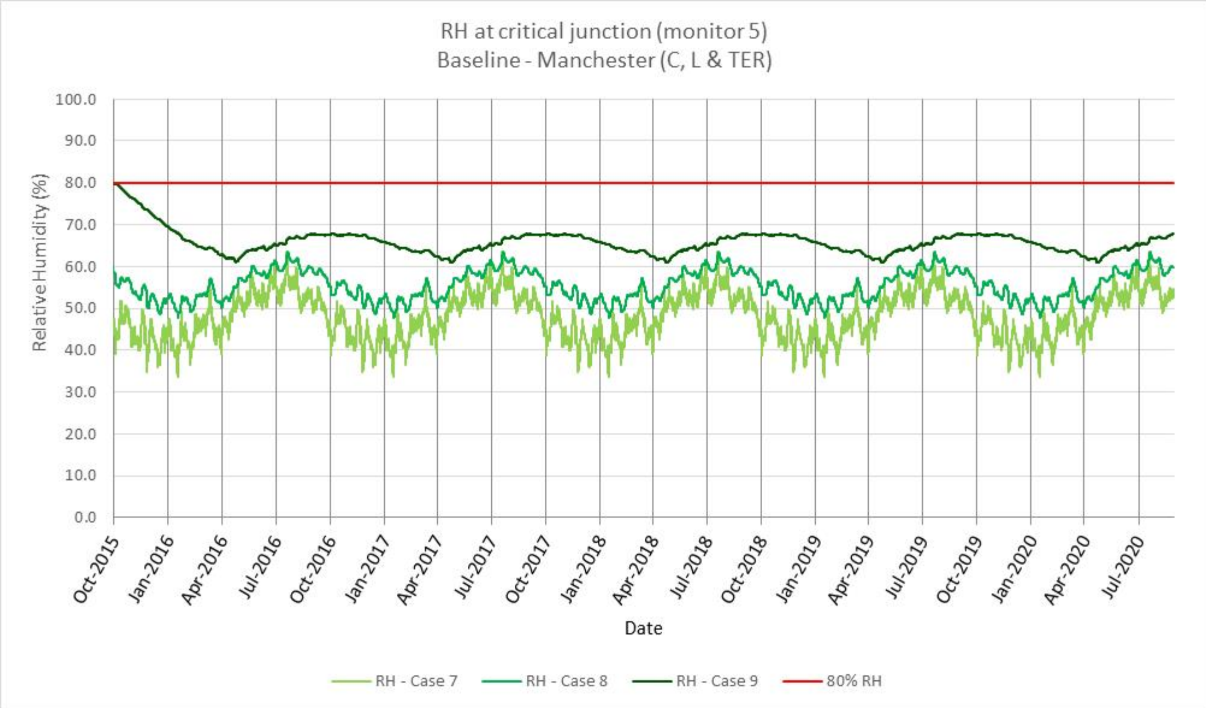


Figure 186: RH levels at monitored junction for Cases 7, 8 and 9

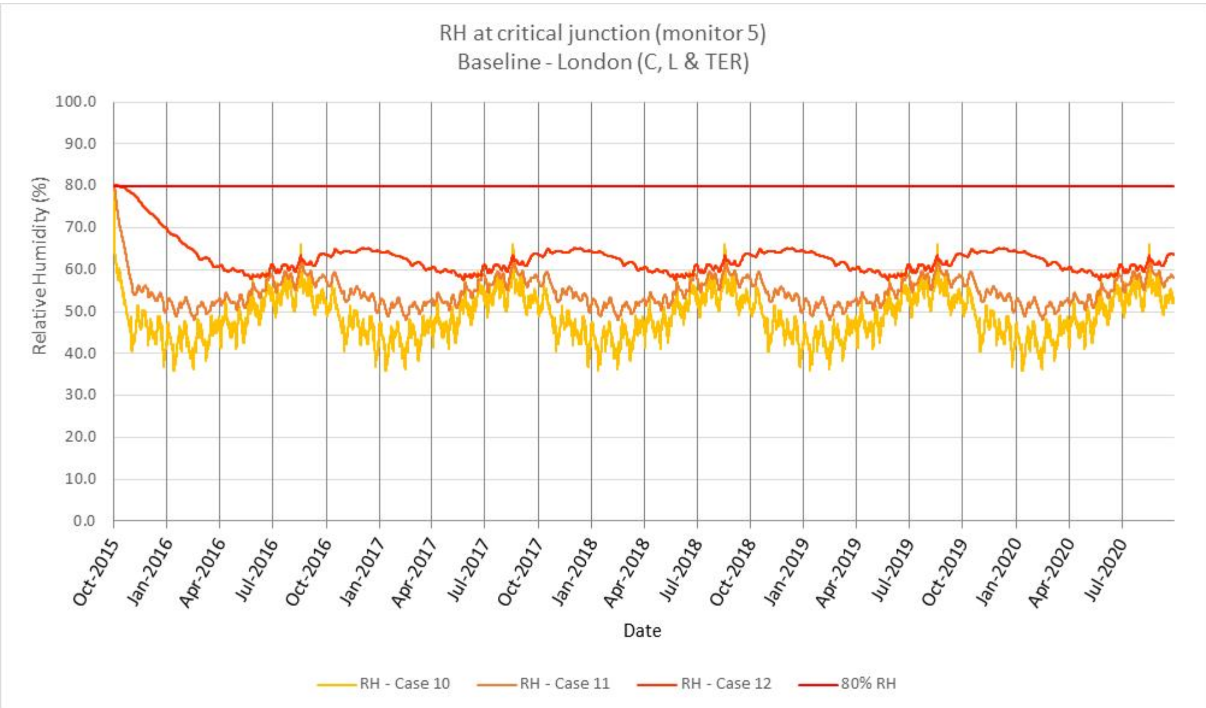


Figure 187: RH levels at monitored junction for Cases 10, 11 and 12

22.3.4. Results Analysis

<u>Moisture risk assessment criteria</u>

As predicted, all cases display RH levels well below 80% (after initial conditions), and the monitored junction does not accumulate moisture overtime.

The fact that these graphs are displaying 'safe' RH levels is not sufficient to declare the build-up safe. However, as no critical junction is available to be monitored through the limitations of this modelling, the results for the twelve baseline cases are based on BS EN ISO 13788 (2012) calculations, as well as experience shown in the prescriptive guidance BS 5250 (2011). The results are summarised in the table below.

Table 78: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in line with current practice in the industry, as this is one of the typologies considered highly resistant to moisture (when constructed correctly).

Effects of exposure zones and U-values

The effect of wind-driven rain exposure zones is slightly visible on the graphs (graphs not displayed in this report) – with lower average RH levels in less exposed zones. However, this is directly due to different external (and consequently internal) conditions. This difference in exposure zones will not have an impact on the hygrothermal performance of the build-up, as the modelled build-up is sheltered from direct wind-driven rain.

The graphs show that the RH levels at the monitored junction are higher when the U-value gets better. This is due to the fact that the monitored junction is kept at cooler temperatures when more insulation is installed continuously underneath the joists. As the junction is kept cooler, the RH levels then increase accordingly, as to the ability of colder air to handle less moisture.

Fragile Materials

With 'fragile' materials (timber) present at this interface, the RH levels are considered as 'safe' RH levels. However, as the RH levels are rising with the thickness of the insulation layer installed underneath the joists, the 80% RH threshold might be reached once the insulation installed continuously under the joists reaches a certain percentage of the whole insulation installed. Therefore, specific hygrothermal analysis might be required once the build-up starts differing significantly from the original build-up, due to the large amount of insulation placed continuously underneath the joists.

22.3.5. *Conclusions – Baseline*

- Build-up is sheltered from the elements and externally ventilated, with warm side AVCL, so it is theoretically safe
- Therefore no critical junction and limitations of WUFI modelling (for ventilated void)
- Safe results at monitored junction, similar to BS EN ISO 13788 calculations – but limitations of WUFI modelling (ventilated void)
- High impact of ventilation in void (refer to other typologies)
- Low impact of exposure / orientation

22.4. Sensitivity Analysis – Change in Material [Cases X.d]: Addition of foil layers on both sides of the rigid insulation

22.4.1. *Added foil layers on insulation*

As rigid foam insulation used in this construction commonly has foil layers, additional sensitivity cases are done to assess the impact of adding foil layers to both sides of the insulation onto the hygrothermal performance of the build-up.
A foil layer is added on both sides of each insulation layer present in the baseline build-up (i.e. one insulation layer for the Part C case, and two layers for the Part L and TER cases).

22.4.2. *Sensitivity Analysis Cases*

As the baseline cases showed that the exposure zones make relatively little difference in the hygrothermal performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis.

The three cases are set across the Zone 4 wind-driven rain exposure zone, meeting the three target U-values (as per baseline cases).

Table 79: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	-	-	-
Part L	Case 2.d	-	-	-
TER	Case 3.d	-	-	-

22.4.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction (which is the same as the baseline cases), at the inner edge of the joists (between the insulation between and below the joists) for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases (with foil layers) are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

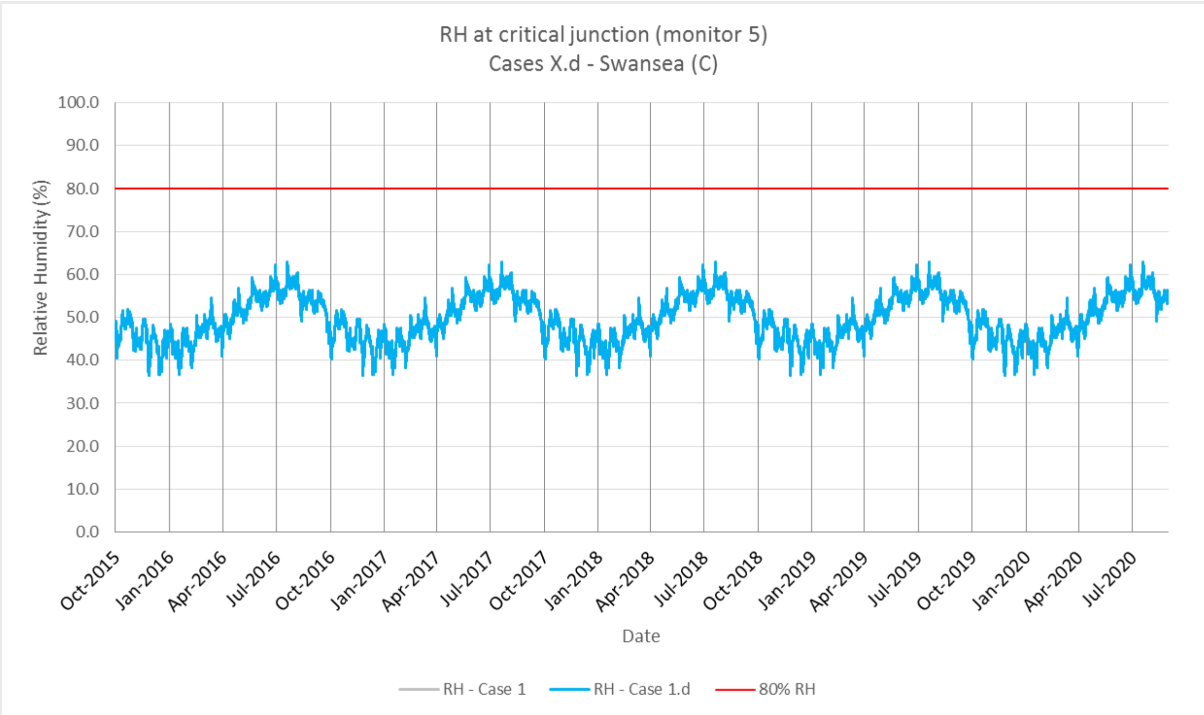


Figure 188: RH levels at monitored junction for Cases 1 and 1.d

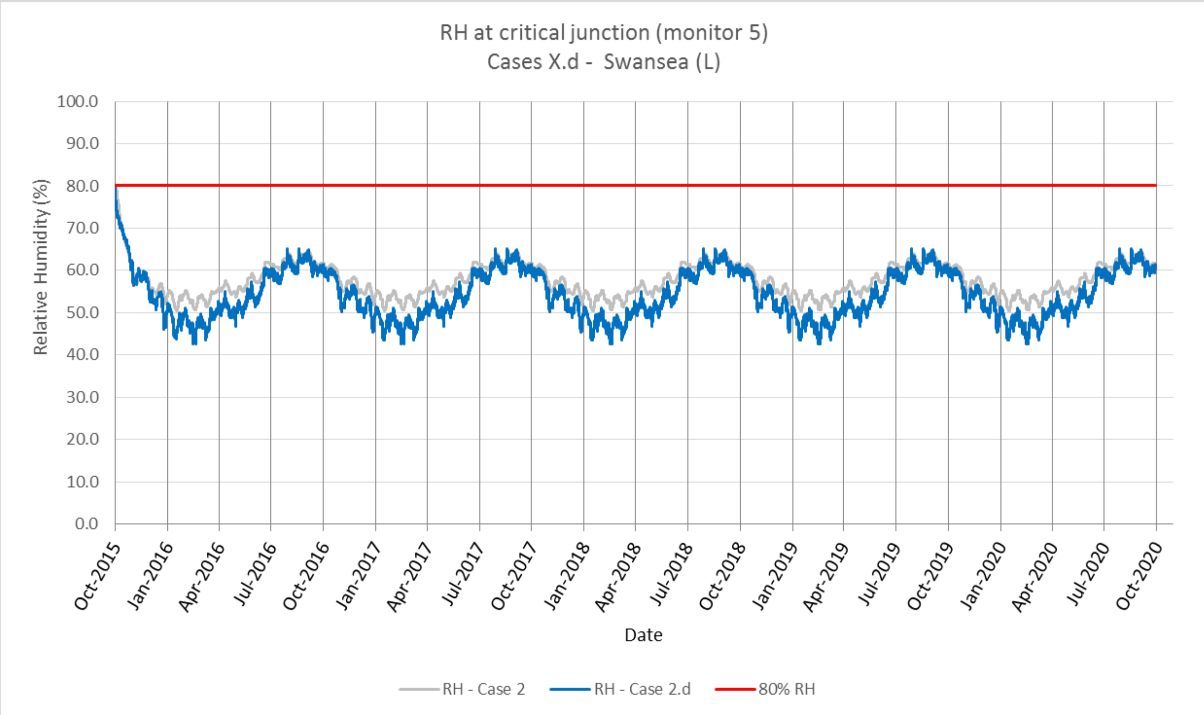


Figure 189: RH levels at monitored junction for Cases 2 and 2.d

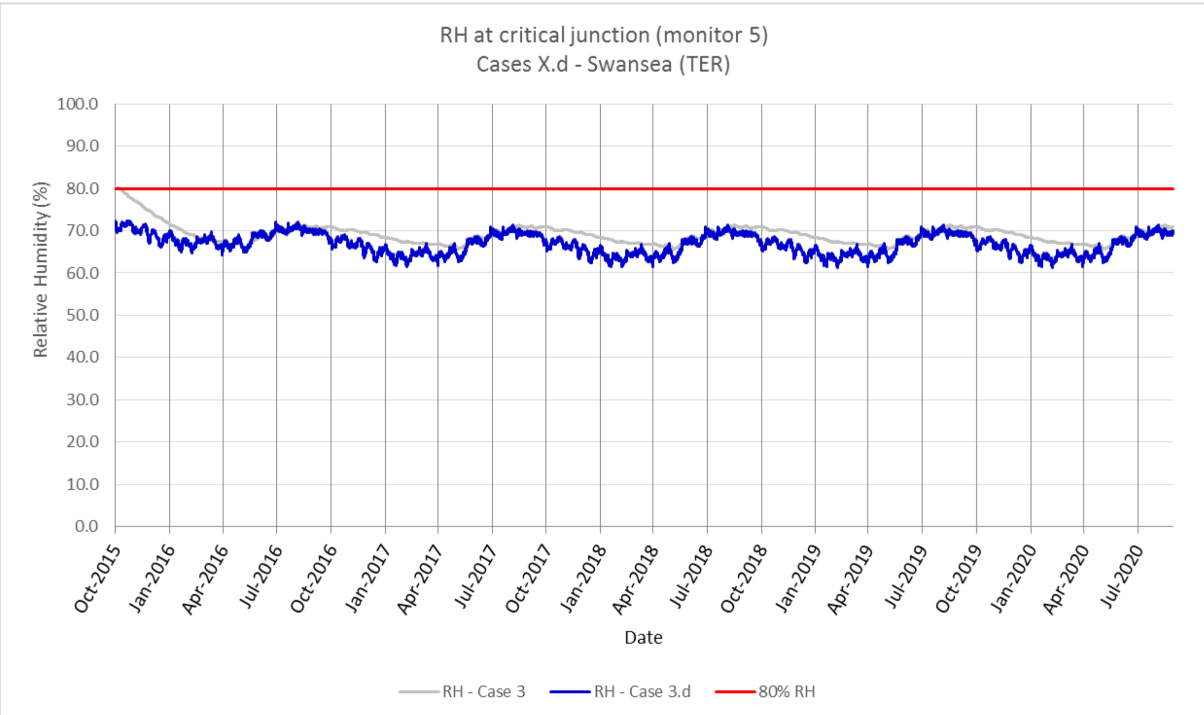


Figure 190: RH levels at monitored junction for Cases 3 and 3.d

22.4.4. Conclusions – Sensitivity Analysis Cases X.d

The results show that that all the modelled sensitivity cases perform only slightly better than their baseline cases. Similarly to the baseline cases, the results for the sensitivity analysis cases are based on BS EN ISO 13788 (2012) calculations, as well as experience shown in the prescriptive guidance BS 5250 (2011) as no critical junction is available to be monitored through the limitations of this modelling. The results are summarised in the table below.

Results

Table 80: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	-	-	-
Part L	Case 2.d Pass	-	-	-
TER	Case 3.d Pass	-	-	-

The graphs show that the use of foil layers (considered vapour retarders) commonly found in foil backed insulation are not detrimental to the hygrothermal performance of the build-up.

22.5. Sensitivity Analysis

22.5.1. Further Sensitivity – BS 5250 (2011) Recommendations

The baseline build-up differs from the build-up present in BS 5250 (2011), as no AVCL is included below the insulation layer (at the interface with the ceiling internal layer) in the baseline model (as the baseline model is based on current typical construction practice).

Presence / Absence of AVCL

Paragraph H.5.3 of prescriptive guidance BS 5250 (2011) states that: *'in warm pitched roofs with low resistance underlay, an AVCL should be provided at ceiling line'.*

The second sensitivity analysis could have been to include an AVCL on the warm side of the insulation in the baseline build-up. However, this sensitivity analysis was omitted, as the AVCL used in a modelling has a sd-value of 2m, while the foil facing has an sd-value of 14m, This means that the foil facing layer is 7 times more resistant compared to the AVCL layer. Therefore, the previous sensitivity analysis already shows (to a bigger extent) what the impact of including an AVCL on the warm side of the insulation is.

22.5.2. Airtightness and ABIS Conditions

It is important to note that the build-up modelled in WUFI is done in theoretical conditions, which means that the gypsum plasterboard layer is continuous and plays the role of the airtightness layer. As highlighted in BS 5250 (2011) (paragraph H.3.2), *'Air leakage through gaps in a ceiling or lining allows substantial amounts of heat and* *moisture to be transferred into the roof by convection. Restricting air leakage by sealing the ceiling or lining using an AVCL or air leakage barrier reduces the transfer of both heat and moisture, improving the energy efficiency of the building and minimizing the risk of interstitial condensation'.*

No sensitivity analysis modelling is done in this report, in which air leakage is modelled through the gypsum plasterboard layer to create a leaking airtightness layer. However, despite the absence of modelling, the impact of such conditions is known: this could lead to moisture-laden air making its way through the build-up and condensing within the build-up when it reaches its dew point. Therefore, particular care should be given around ensuring good airtightness in this build-up.

22.6. Conclusions

- Build-up sheltered from the elements and external ventilated, with warm side AVCL so theoretically safe
- Therefore no critical junction and limitations of WUFI modelling (for ventilated void)
- Safe results at monitored junction, similar to BS EN ISO 13788 calculations – but limitations of WUFI modelling (ventilated void)
- High impact of ventilation in void (refer to other typologies)
- Low impact of exposure / orientation
- Low impact of use of foil-backed insulations underneath the rafters

23. Typology N19: Warm flat roof - timber

The N19 typology is a new-build warm flat roof (framed structure), i.e. with the closed-cell insulation layer installed continuously above the framed structure.

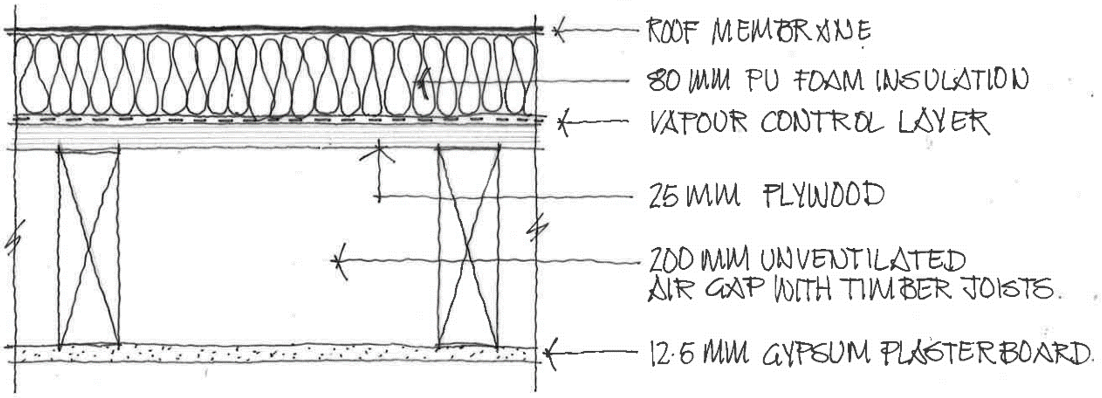


Figure 191: Illustration of the build-up of the typology

23.1. Assessment Method

Current prescriptive guidance in BS 5250 (2011) (paragraph H.8) states that *'there is no risk of surface condensation on warm flat roofs with framed structure'*. It also states that *'with all warm flat roofs, there is a risk of interstitial condensation forming between the thermal insulation and the waterproof covering. To avoid that risk, an AVCL with a vapour resistance at least equal to that of the waterproof covering, should be provided immediately above the supporting structure.'*

This typology falls into the conditions in which the BS EN ISO 13788 (2012) method can be used effectively, as the build-up does not use any materials with significant moisture storage and the build-up should not be significantly impacted by external rain conditions (as any deterioration in the roof finish leads to complete system failure).

Therefore, this build-up is assessed in the first instance with the BS EN ISO 13788 (2012) method. This calculation shows that interstitial condensation occurs at the critical junction (correctly identified by BS 5250 (2011)), and does not fully evaporate throughout the year. Therefore, this shows that this build-up presents moisture risks. BS 5250 (2011) explains these results through the use of an AVCL layer which has a lower vapour resistance compared to the waterproof covering vapour resistance.

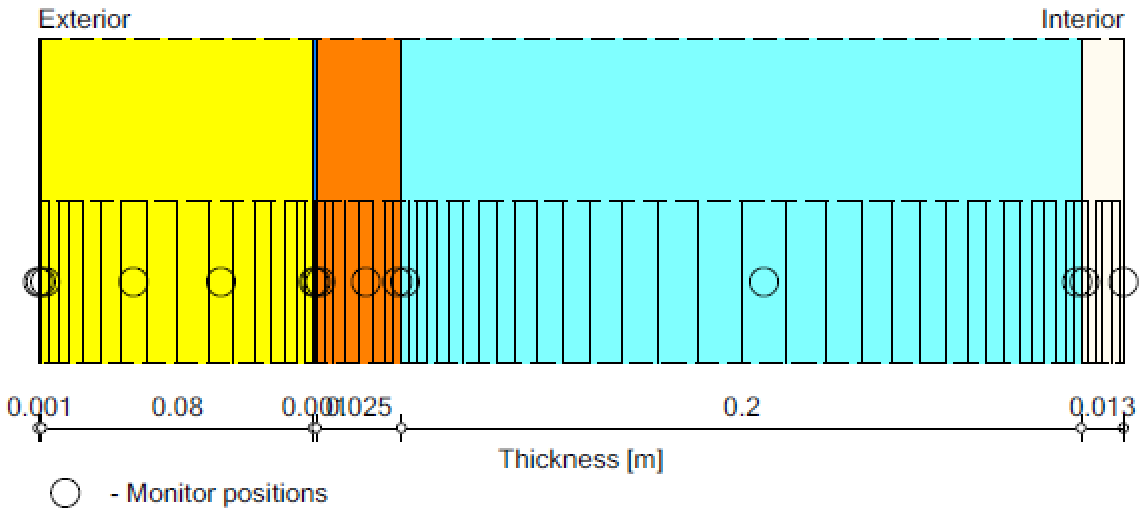
WUFI modelling to BS EN 15026 (2007) is then used to confirm the adequacy and accuracy of the BS EN ISO 13788 (2012) method to assess this type of build-up.

23.2. Build-up

Please find below the build-up of the typology, as modelled in the BS EN ISO 13788 (2012) (the Glaser method) assessed model and in the BS EN 15026 (2007) (WUFI) model.

Build-Up:

- 1mm roof membrane (bituminous felt sd = 100m)
- 50mm // 80mm // 180mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL (sd = 2m)
- 25mm plywood board
- 200mm unventilated air gap with timber joists
- 12.5mm gypsum plasterboard



Materials:

- Roof Membrane V13	0.001 m
- PU (heat cond.: 0,025 W/mK)	0.08 m
- vapour retarder (sd=2m)	0.001 m
- Plywood Board	0.025 m
- *Air Layer 200 mm; without additional moisture capacity (unlocked)	0.2 m
- Gypsum Board	0.013 m

This build-up does not reflect the technical recommendations laid down in BS 5250 (2011), as the baseline build-ups were chosen to reflect typical UK new-build constructions and they were agreed prior to the modelling phase. The build-up depicted in the prescriptive guidance is analysed later on in the sensitivity analysis of this modelling work.

In this build-up, we have used an AVCL which has the characteristics of what is considered a typical AVCL product in the industry - our AVCL has an sd-value of 2m. However, our AVCL with an sd-value of 2m is by far less vapour resistant than the waterproof roof covering (bitumen) which has an sd-value of 100m.

23.3. Baseline Results

23.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set out in paragraph 5.1.

Table 81: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

23.3.2. Critical Junction

For this typology, the focus is given on RH levels and moisture content at the interface between the waterproof roof covering and the insulation. This critical junction is correctly identified by the BS EN ISO 13788 (2012) assessment, as any moisture travelling through the build-up will be trapped at this interface, as the waterproof roof covering is the layer with the highest vapour diffusion resistance factor in this build-up.

23.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the insulation layer for all baseline cases.

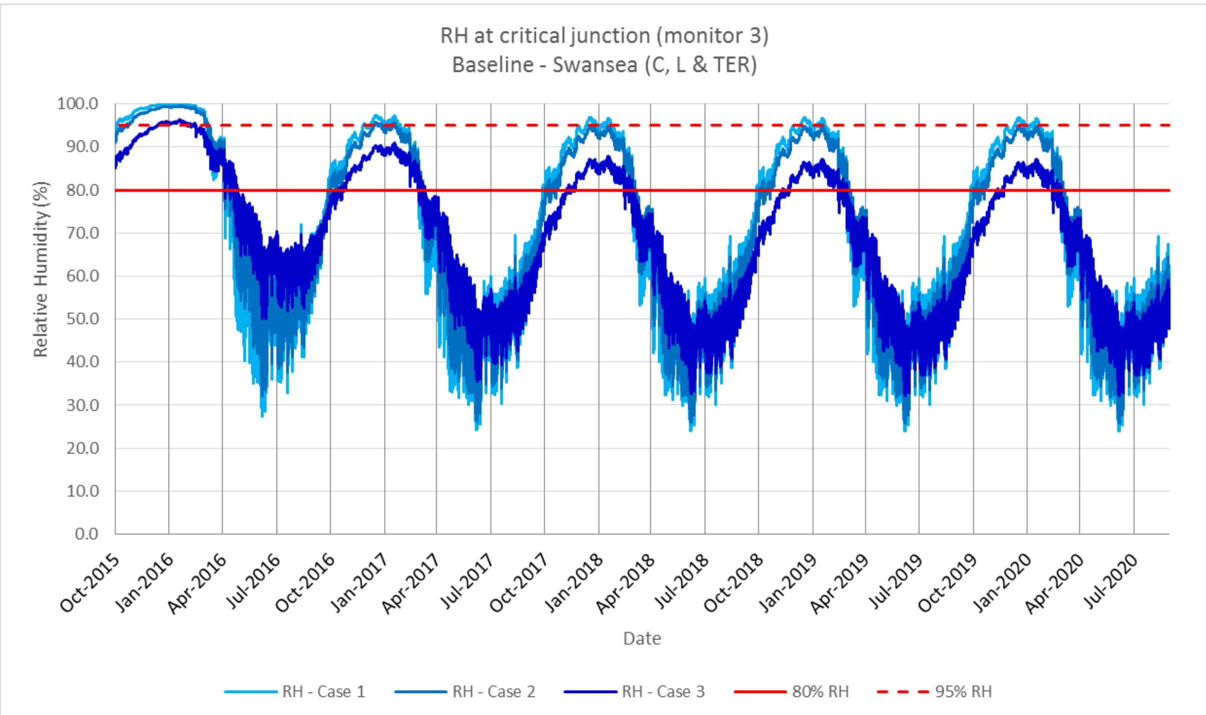


Figure 192: RH levels at critical junction for Cases 1, 2, and 3

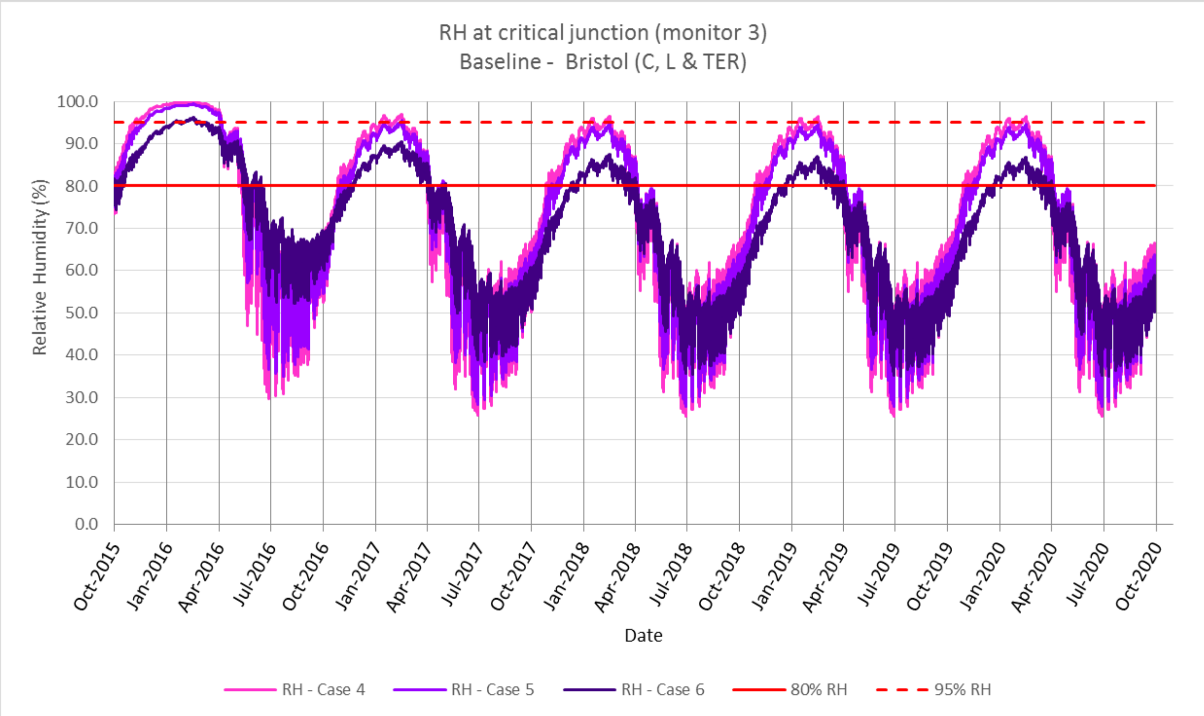


Figure 193: RH levels at critical junction for Cases 4, 5 and 6

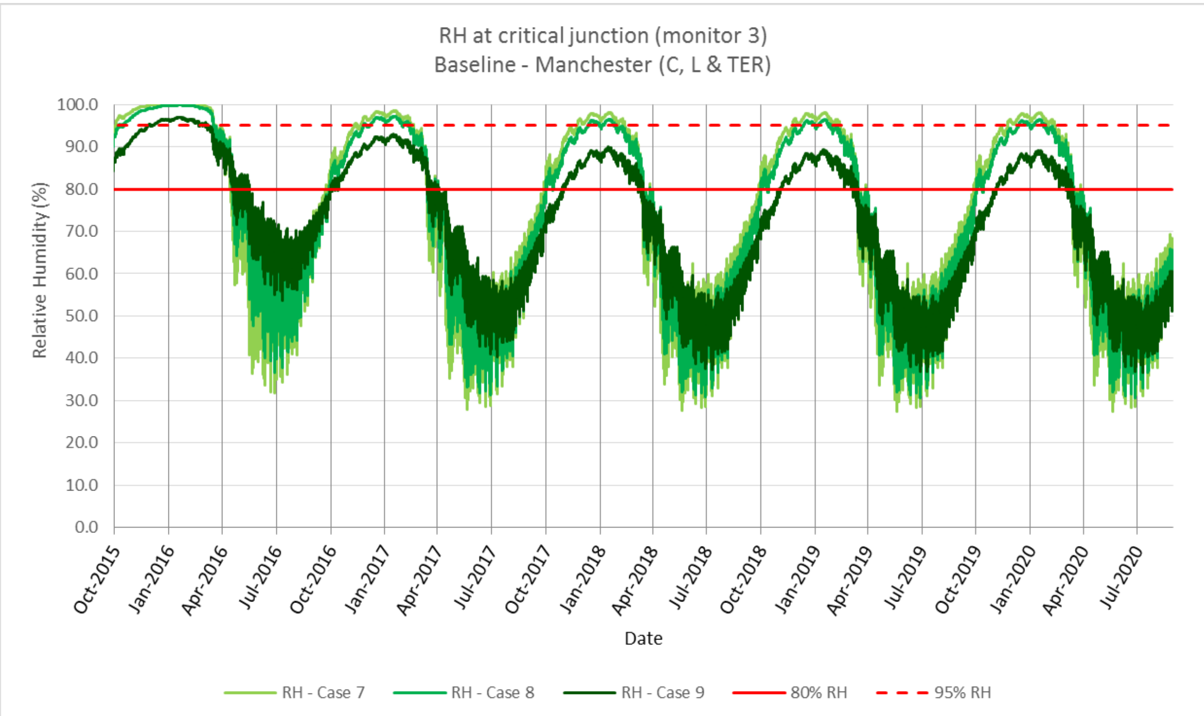


Figure 194: RH levels at critical junction for Cases 7, 8 and 9

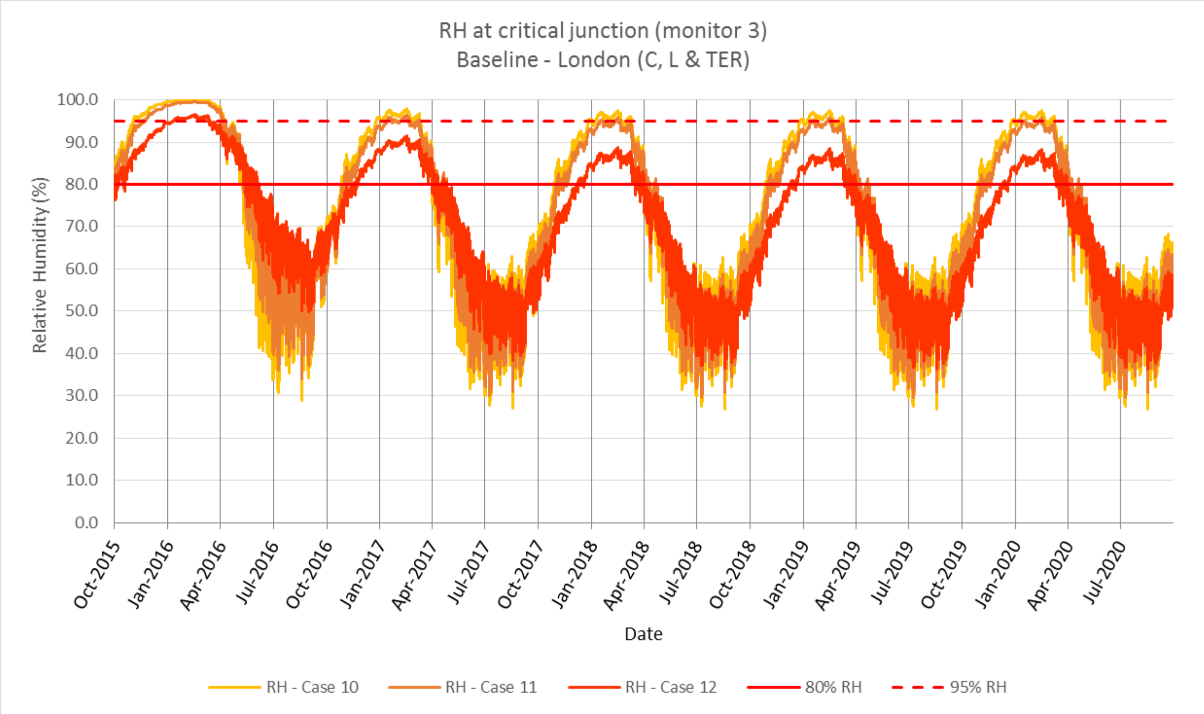


Figure 195: RH levels at critical junction for Cases 10, 11 and 12

23.3.4. Conclusions - Baseline

<u>Moisture risk assessment criteria</u>

All scenarios achieve equilibrium after a reduction in overall water content in the element; therefore moisture does not keep on accumulating over time.

However, all scenarios display RH levels well above 80%. In addition, both the Part C and Part L models show some RH levels close to / reaching 100%, meaning condensation will also happen at that interface during the first year due to the initial conditions the build-up is subjected to. These conditions do not recur after the first year, with the build-up slowly moving towards equilibrium.

It is worth questioning if the 80% RH level criteria is suited in these conditions or if it can be relaxed due to the conditions around the build-up:

- At the critical interface between the waterproofing roof covering and the insulation, no air layer should be present (in a 'perfect' build-up as being model in WUFI)
- In addition, both the bituminous layer and the PU foam insulation layer are not materials considered to encourage mould growth by providing food for mould spores
- Finally, higher RH levels are occurring during colder months. This means that high RH levels are not linked to higher temperatures, which is favourable to mould growth

Therefore, it appears that the 80% RH level criteria could be relaxed from 80 to 95% in this situation, as we do not meet all the conditions favourable to mould growth.

However, despite the critical junction being less prone to mould growth risk, it is still essential for the RH levels to be reduced to acceptable levels, as the thermal characteristics of the PU foam insulation material vary with moisture content. Indeed, the WUFI Fraunhofer database shows that the thermal conductivity λ degrades from 0.025 W/m.K in typical conditions to 0.060 W/m.K when the RH levels reach 100%.

Results

The table below summarises the performance of each case, following the more relaxed 95% RH recommended levels explained above.

Both Part C and Part L cases (thin and medium insulation) fail with the presence of interstitial condensation during the first year. TER cases are considered a 'pass', thanks to the RH levels reducing below recommended levels after the first six months.

Table 82: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Fail	Case 4 Fail	Case 7 Fail	Case 10 Fail
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Fail
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

These findings are in accordance with current recommendations and prescriptive guidance. As the waterproof roof covering excludes external moisture, then the main moisture source leading to moisture problems is internal moisture travelling through the build-up, driven by vapour diffusion, and getting trapped in front of the layer with the highest vapour diffusion resistance factor, the waterproof roof covering.

Effects of exposure zones and U-values

The effect of wind-driven rain exposure zones can be very slightly seen on the graphs but has a relatively small impact, as any deterioration in the roof finish leads to complete system failure.

The difference in U-values between cases leads to a difference in RH levels, with thicker insulation reducing the RH peaks in winter. This is due to the fact that more moisture can get 'stored' in the insulation layer the thicker it is. Therefore, for the same moisture conditions internally, a smaller amount of moisture will accumulate at the critical junction for a thicker insulation layer, compared to a thinner one.

Comments on BS 5250 (2011)

Analysing this build-up also highlights the need for more detailed guidance regarding the characteristics of the materials listed and used in build-ups in BS 5250 (2011).

Indeed, this build-up uses an AVCL and there is no precise technical details as to what vapour diffusion characteristics an AVCL should have in BS 5250 (2011). The range given by BS 5250 (2011) in the table E.2: 'Vapour resistance of thin membranes and foils', only shows that high vapour resistance membranes have sd-values typically range between 0.2 and infinity.

Therefore, respecting the build-up drawn in BS 5250 (2011) without the text accompanying it (asking for the vapour resistance of the AVCL to be at least equal to the vapour resistance of the waterproof covering) or without being able to check vapour diffusion resistance characteristics of these materials (AVCL and waterproof roof coverings) could lead to a failing build-up, as shown in the results paragraph above. Materials used in build-ups, and their respective characteristics, need to be more clearly defined to ensure the correct materials are installed, following precisely the BS 5250 (2011) prescriptive guidance and leading to the installation of build-ups actually resistant to moisture in reality.

23.4. Sensitivity Analysis – Change in Material [Cases X.d]

23.4.1. Sensitivity Analysis Cases

As guidance given in BS 5250 (2011) is available on this type of construction, the first sensitivity analysis performed on this modelling is a change in materials, to match the build-up recommended in BS 5250 (2011).

BS 5250 (2011) recommends to install '*an AVCL with a vapour resistance at least equal to that of the waterproof covering, immediately above the supporting structure'* to avoid the risk of interstitial condensation. As the waterproof covering has a vapour diffusion resistance much more important (sd = 100m) than the AVCL (sd = 2m), we will change the AVCL to a material with closer characteristics to the waterproof covering layer – chosen here as a material already available in the WUFI Fraunhofer database 'vapour retarder (sd = 100m)'.

The 12 cases for this sensitivity analysis are set across the four wind-driven rain exposure zones, meeting the three targets U-values (as per the baseline cases), as set below.

Table 83: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	Case 4.d	Case 7.d	Case 10.d
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
TER	Case 3.d	Case 6.d	Case 9.d	Case 12.d

23.4.2. Graphs at Critical Junction

It was observed in the baseline cases that the external weather conditions play a much minor role compared to the U-value (i.e. insulation thickness) on the hygrothermal performance of the build-up. Therefore, the results for Zone 4 – Swansea only are displayed below, as the rest of the graphs in other zones look similar to the graphs in Zone 4.

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

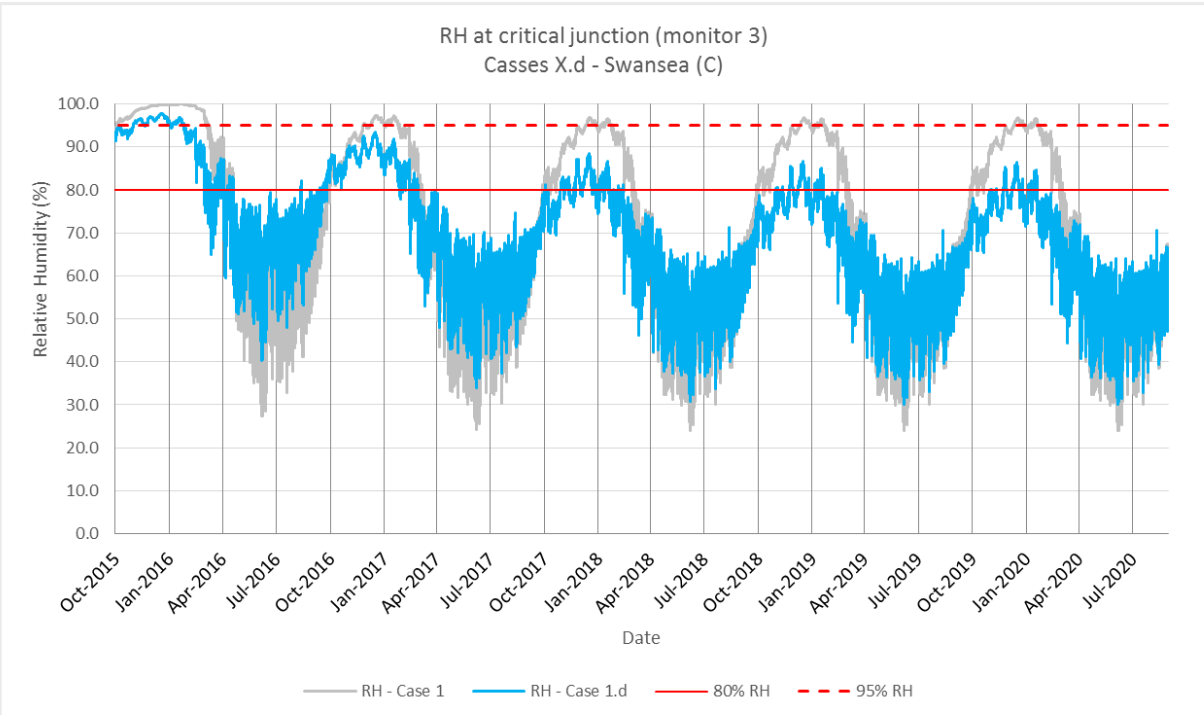


Figure 196: RH levels at critical junction for Cases 1 and 1.d

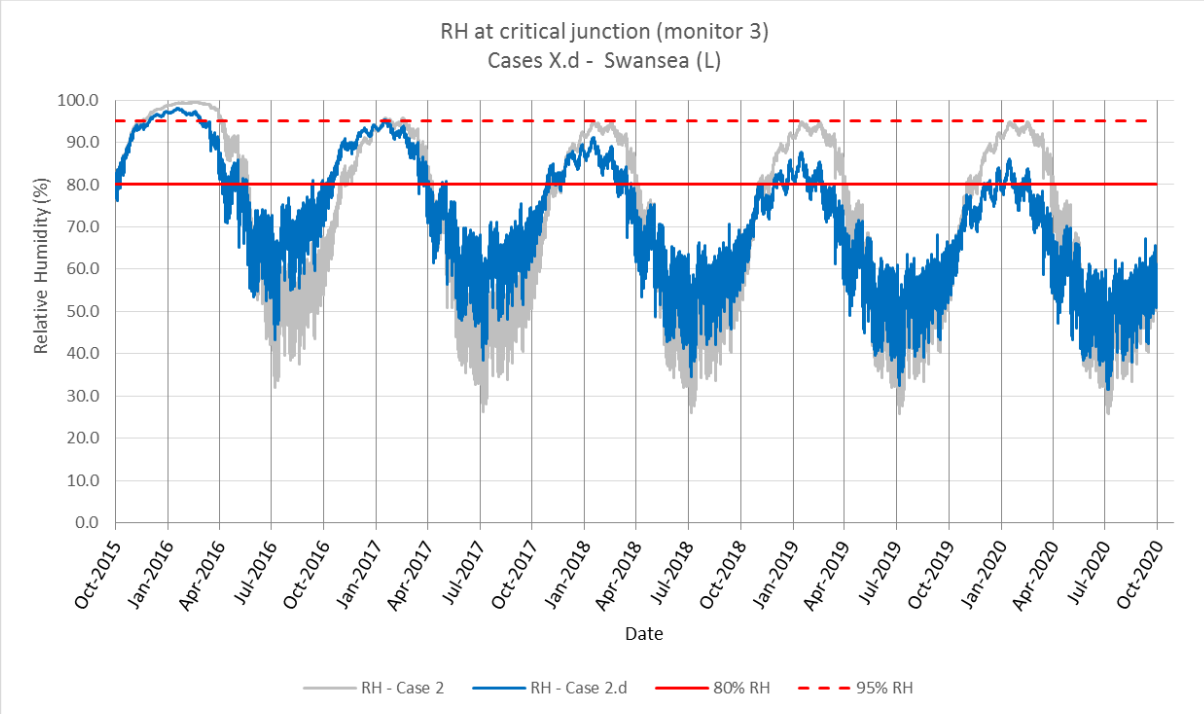


Figure 197: RH levels at critical junction for Cases 2 and 2.d

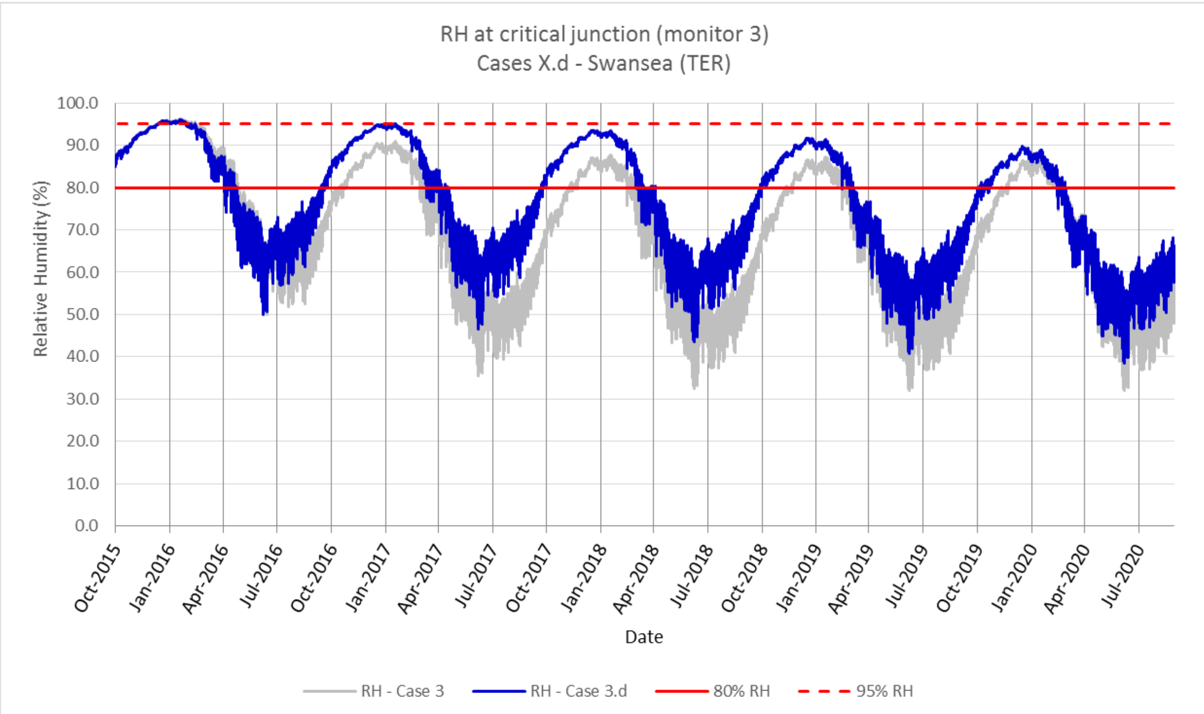


Figure 198: RH levels at critical junction for Cases 3 and 3.d

23.4.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show on average that the cases modelled in this sensitivity analysis perform better than their respective baseline cases.

All cases show the build-up slowly drying out towards equilibrium, which confirms there is not accumulation of moisture in the build-up. The graphs also show that both Part C and Part L cases display RH peaks at the critical junction reducing quickly from 95% (during 3 months in the first year, following the initial conditions) to RH peaks around 80% from the 4th year onwards. These high RH levels during the first year, similarly to the baseline cases, are due to the initials conditions, being worse than the equilibrium reached by the build-up after a few years.

Therefore, the build-up does not accumulate moisture over time, RH levels do not go above recommended levels (in this case 95%) during typical years and only reach above recommended RH levels for a few months during the first year. These results show that the upgraded build-up in the sensitivity analysis is made safer in terms of hygrothermal performance, compared to the baseline build-up.

Results

The table below summarises the performance of each case, following the more relaxed 95% RH recommended levels explained in the baseline results analysis.

All cases are considered a 'pass', as they do not accumulate moisture and the build-up slowly dry towards an equilibrium, which is within recommended RH levels.

Table 84: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	Case 4.d Pass	Case 7.d Pass	Case 10.d Pass
Part L	Case 2.d Pass	Case 5.d Pass	Case 8.d Pass	Case 11.d Pass
TER	Case 3.d Pass	Case 6.d Pass	Case 9.d Pass	Case 12.d Pass

These findings are in accordance with current recommendations and prescriptive guidance in BS 5250 (2011). With the AVCL now having at least the same diffusion resistance characteristics as the waterproof roof covering, the build-up is now safer, without any moisture accumulating over time just below the waterproof roof covering.

Effects of exposure zones and U-values

The difference in U-values between cases shows that the thicker the insulation is, the slower the build-up reaches equilibrium. Indeed, Part C and Part L cases reach equilibrium within about four years. However, TER cases do not reach equilibrium within the 5 years modelled.

The graph below displays the TER case for Swansea run for a period of 10 years, instead of 5 years. The graph shows that it takes eight to nine years for the build-up to fully reach equilibrium, and like the other sensitivity analysis cases, the equilibrium is within acceptable RH levels, proving this build-up is 'safe'.

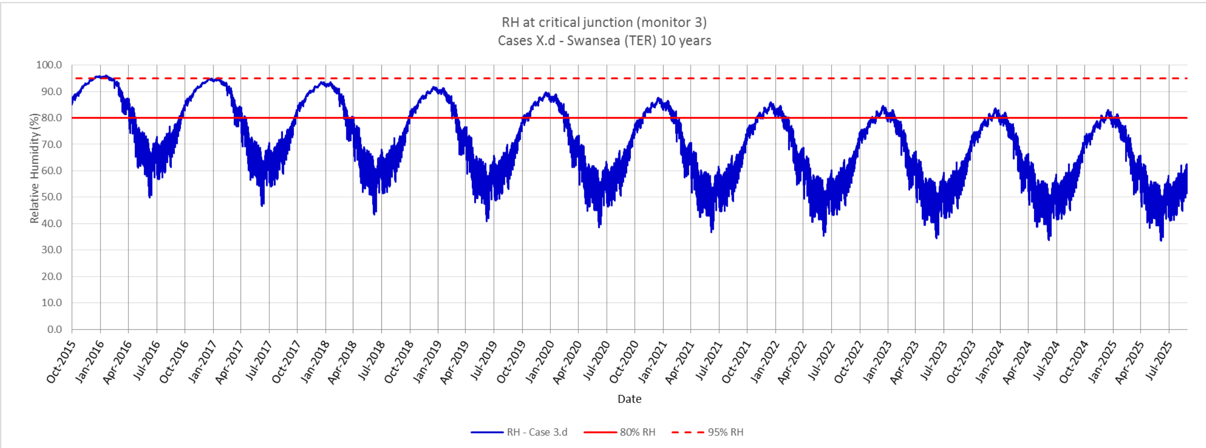


Figure 199: RH levels at critical junction for Case 3.d for a period of 10 years

However, this graph highlights the need for 'good' initial conditions, especially with thicker levels of insulation. Indeed, if the materials used in this build-up (especially the insulation layer) are not kept in optimal conditions (e.g. stored in a humid location or subject to direct rain), then this would have a direct impact on the hygrothermal performance of the build-up, keeping the RH levels in winter higher than considered acceptable. So it is important to highlight the need to keep materials dry to ensure this build-up is safe, independently to the level of insulation installed.

23.5. Sensitivity Analysis – Change in Internal Moisture Load [Cases X.a]

23.5.1. Sensitivity Analysis Cases

The second sensitivity analysis is to change the internal moisture load, from typical to poorer conditions (called 'high' moisture load) following the BS EN 15026 (2007) procedure (described in Annex C of BS EN 15026 (2007)).

This sensitivity analysis was performed on the 'upgraded' build-up tested in cases X.d, as this build-up is the recommended build-up (rather than the build-up used in the baseline, which is not robust enough against moisture).

The 12 cases for this sensitivity analysis are set across the four wind-driven rain exposure zones, meeting the three targets U-values (as per the baseline cases), as set below.

Table 85: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.a	Case 4.a	Case 7.a	Case 10.a
Part L	Case 2.a	Case 5.a	Case 8.a	Case 11.a
TER	Case 3.a	Case 6.a	Case 9.a	Case 12.a

23.5.2. Graphs at Critical Junction

Similarly to the previous sensitivity analysis on this build-up, the results for Zone 4 – Swansea only are displayed below, as it was observed that the graphs in the other zones look similar to the graphs for Zone 4.

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

For these results, the sensitivity analysis cases X.a tested here (i.e. high moisture load) are displayed as a coloured line, while their respective original cases X.d (i.e. recommended build-up from BS 5250 (2011) - instead of typical build-up in the industry) are displayed with a grey line.

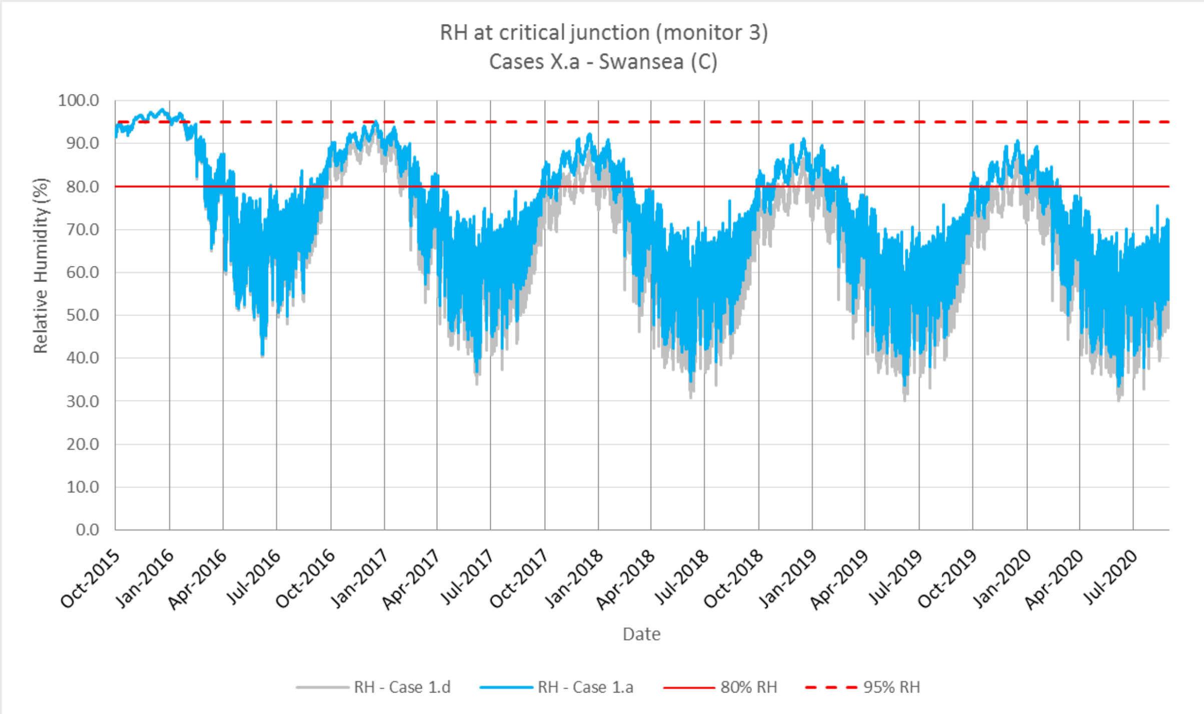


Figure 200: RH levels at critical junction for Cases 1.d and 1.a

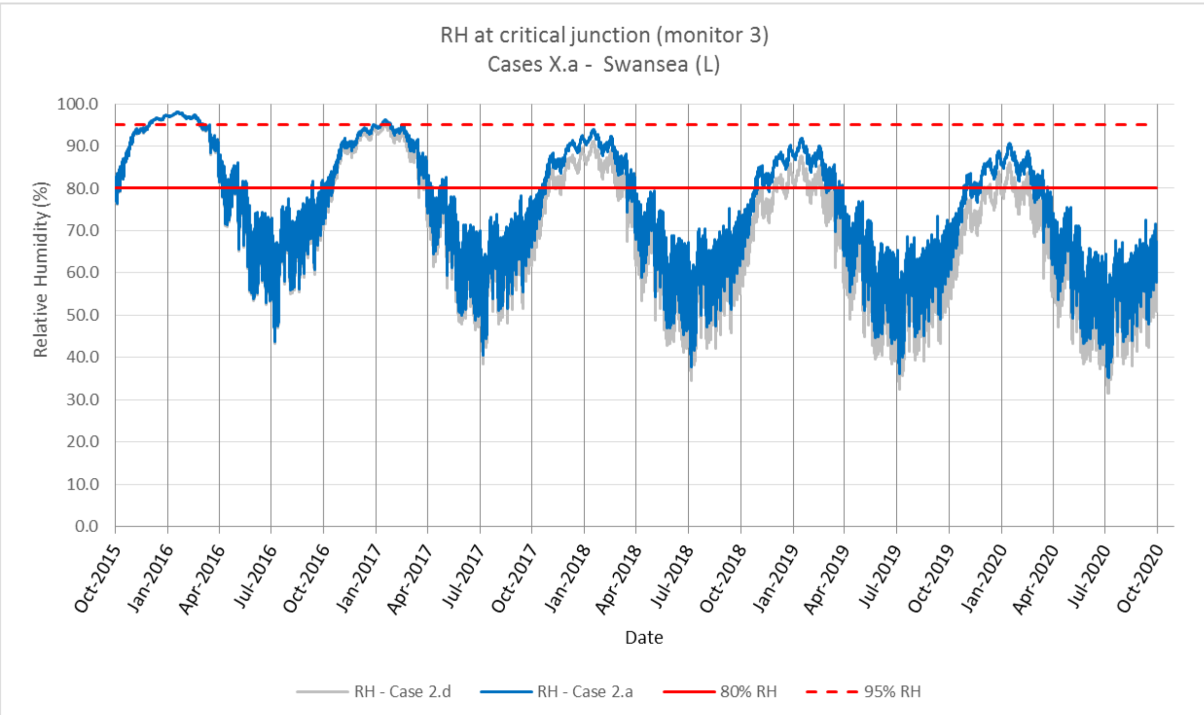


Figure 201: RH levels at critical junction for Cases 2.d and 2.a

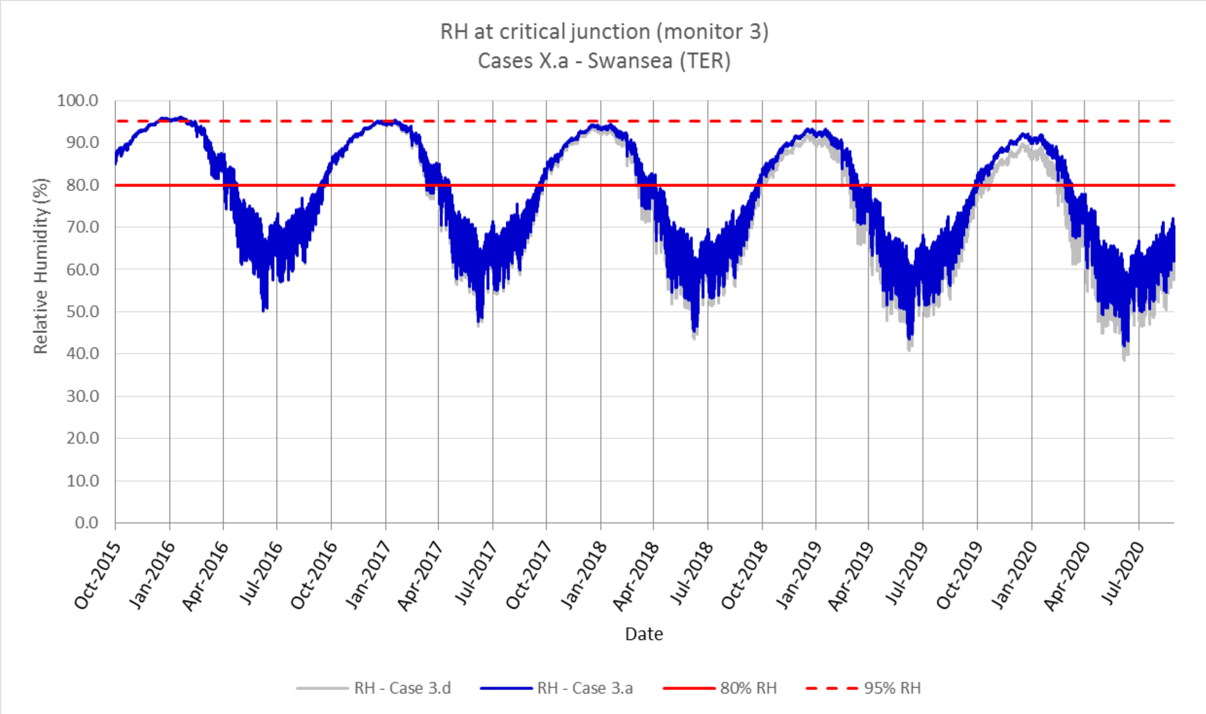


Figure 202: RH levels at critical junction for Cases 3.d and 3.a

23.5.3. Conclusions – Sensitivity Analysis Cases X.a

<u>Moisture risk assessment criteria</u>

The graphs show on average that the cases modelled in this sensitivity analysis X.a perform slightly worse compared to the cases X.d.
All cases simulated here still pass, though the effect of higher internal moisture load is directly visible at the critical junction, where an increase of internal RH levels by 10% leads to an increase of RH levels at the critical junction by up to 5%.

<u>Results</u>

The table below summarises the performance of each case, following the more relaxed 95% RH recommended levels explained in the baseline results analysis.

All cases are considered a ‘pass’, as they do not accumulate moisture and the build-up slowly dry towards an equilibrium (equilibrium now slightly higher than in the cases X.d, due to poorer internal moisture conditions), which is within recommended RH levels.

Table 86: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.a Pass	Case 4.a Pass	Case 7.a Pass	Case 10.a Pass
Part L	Case 2.a Pass	Case 5.a Pass	Case 8.a Pass	Case 11.a Pass
TER	Case 3.a Pass	Case 6.a Pass	Case 9.a Pass	Case 12.a Pass

Effects of ‘high’ moisture load (internal conditions)

In this sensitivity analysis, the increase of RH levels at the critical junction is not significant enough to change the status of the simulations from ‘pass’ to ‘risky’ / ‘fail’ but it is important to remember that the conditions described as ‘high’ moisture load following BS EN 15026 (2007) are not considered the most extreme internal conditions a building could be in – likely due to very poor ventilation, higher occupancy, etc.

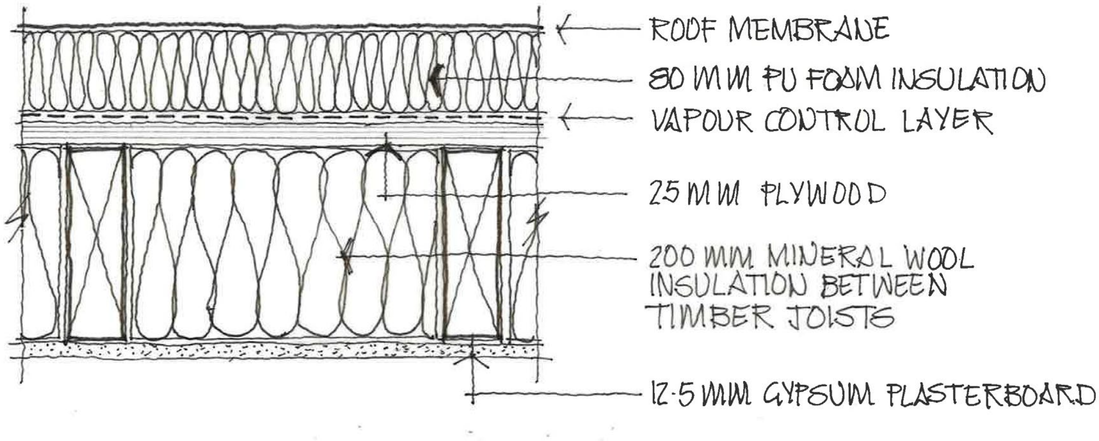
Therefore, it is likely that the worsening of internal moisture conditions will, starting at a certain level, lead to the failure of the build-up (as the internal moisture conditions are directly reflected in the RH levels at the critical junction). This reiterates the importance of ‘adequate’ internal conditions for build-ups to display a good hygrothermal performance where neither the occupant nor the building envelope is a risk.

23.6. Sensitivity Analysis – Change in Build-up [Cases X.e]: Addition of mineral wool in between timber joists

23.6.1. Hybrid Roof Type

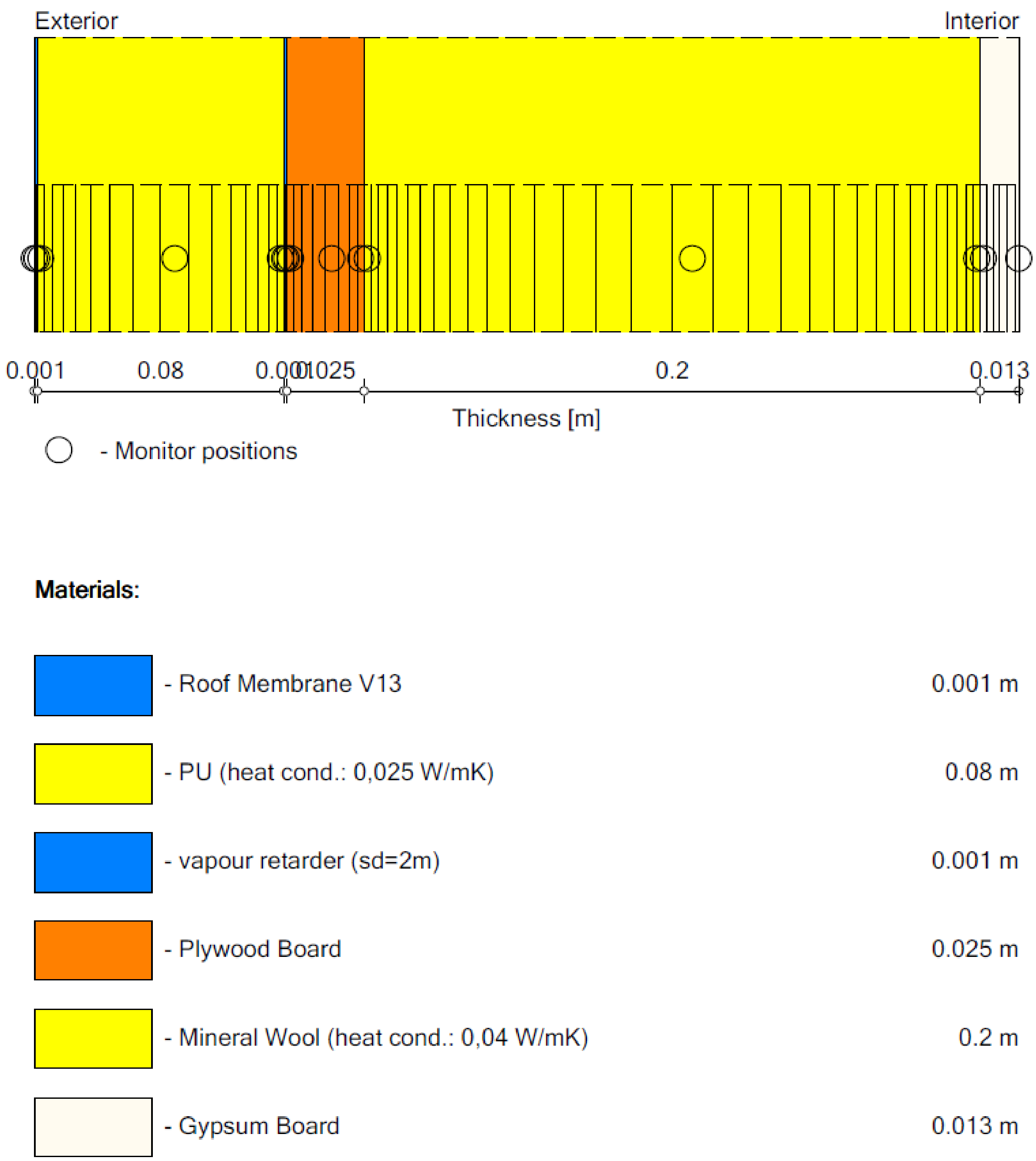
The low U-values required in new buildings have driven up the thickness of flat roof constructions. Recently, designers have sought to reduce these thicknesses by proposing the use of “hybrid” warm roof construction where, as well as the insulation included above the roof deck, the joists beneath the roof deck are fully filled with mineral wool insulation also (instead of being left empty) to achieve the desired U-value.

The new build-up for this sensitivity analysis is shown in the diagram below.



Build-Up:

- 1mm roof membrane (bituminous felt sd = 100m)
- 50mm // 80mm // 180mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL (sd = 2m)
- 25mm plywood board
- 200mm mineral wool (λ = 0.040 W/m.K) in between timber joists
- 12.5mm gypsum plasterboard



This type of build-up is not covered directly in BS 5250 (2011).

23.6.2. Sensitivity Analysis Cases

As the baseline cases showed that the exposure zones make little difference in the hygrothermal performance of the build-up, the cases in the worst exposure zones (i.e. Zone 4 – Swansea) are the only cases modelled in this sensitivity analysis.

The three cases are set across the Zone 4 wind-driven rain exposure zone, exceeding the three target U-values (as per baseline cases).

Table 87: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.e			
Part L	Case 2.e			
TER	Case 3.e			

23.6.3. Critical Junction

As for the baseline cases, the focus is given on RH levels at the interface between the waterproof roof covering and the insulation, considered the 'critical' junction.

However, as this is a 'hybrid' design, we have also looked at the RH levels at the interface between the plywood roof deck and the mineral wool insulation below (as per a cold roof construction) in case the moisture build-up on the warm side of the AVCL is too high.

23.6.4. Graphs at Critical Junctions

<u>First Critical Junction</u>

The results for Zone 4 – Swansea are displayed below. All graphs displayed below show the RH levels at the first critical junction (as per the baseline cases), i.e. at the interface between the waterproof covering and the cold side of the main insulation layer, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

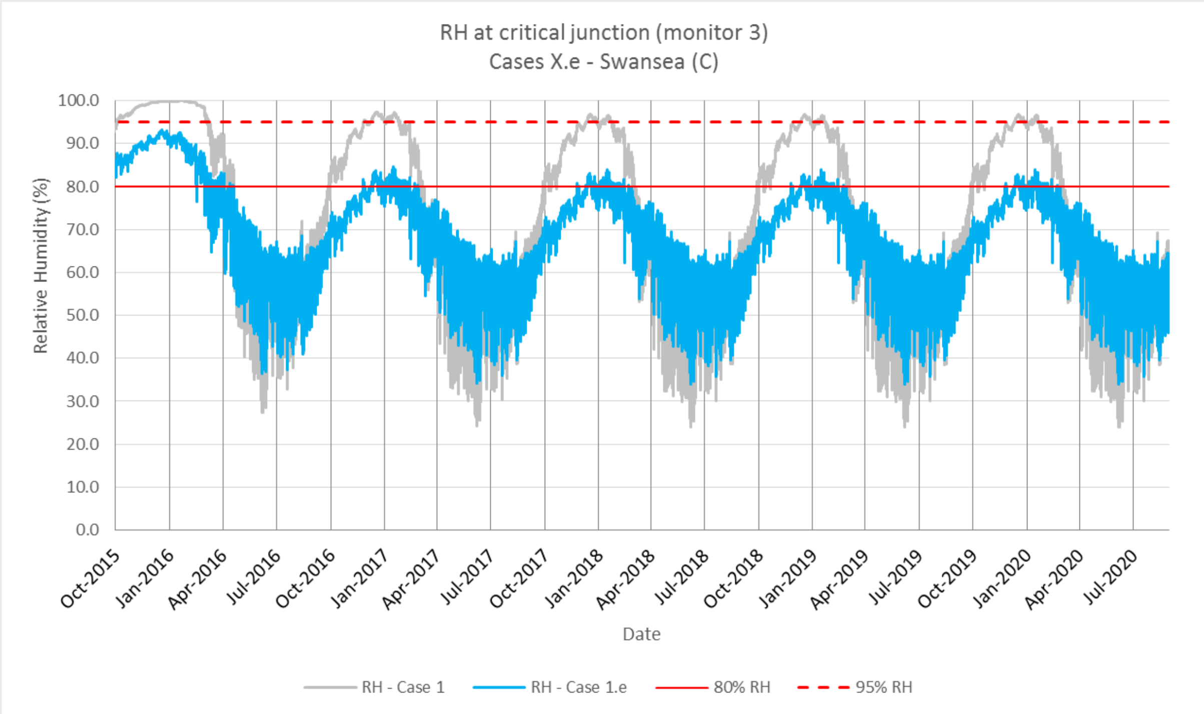


Figure 203: RH levels at critical junction for Cases 1 and 1.e

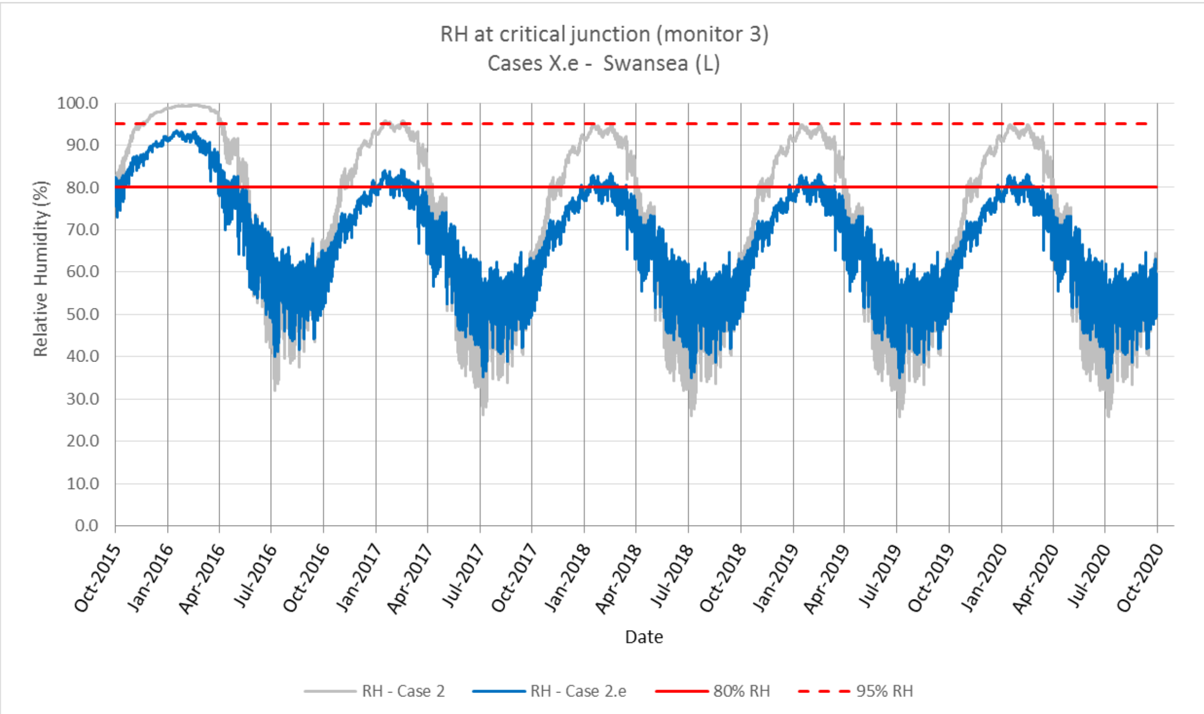


Figure 204: RH levels at critical junction for Cases 2 and 2.e

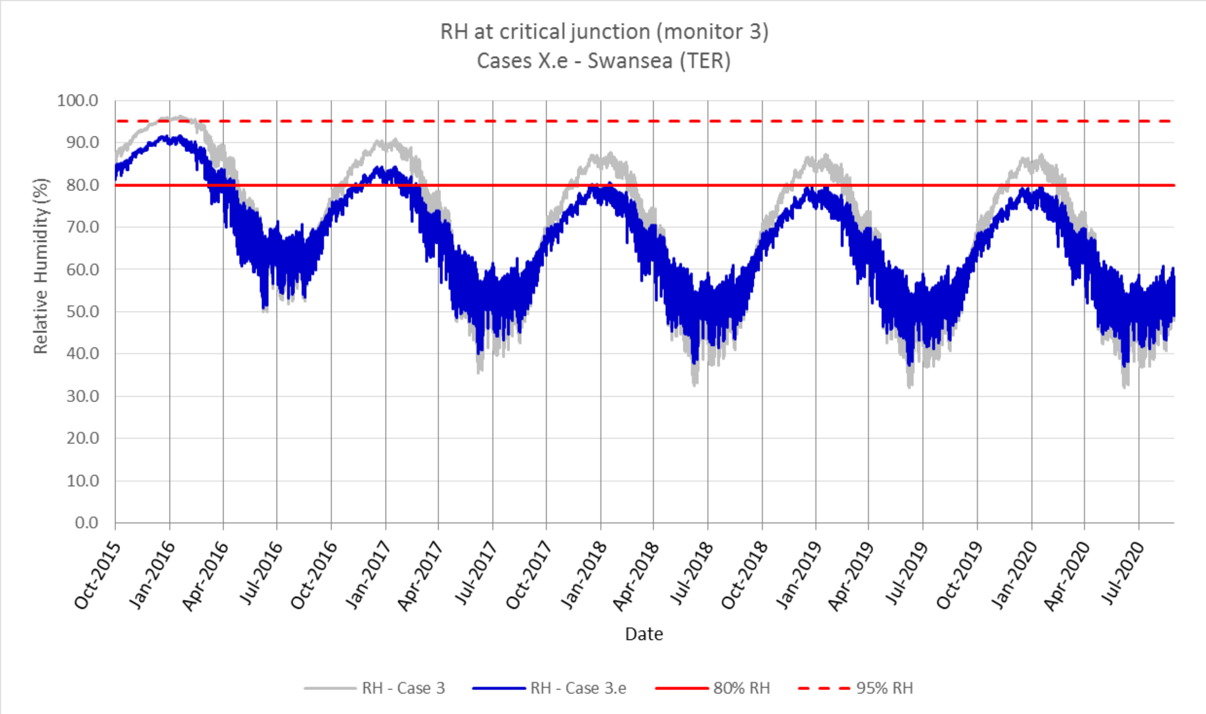


Figure 205: RH levels at critical junction for Cases 3 and 3.e

Second Critical Junction

All graphs displayed below show the RH levels at the second critical junction, between the plywood deck and the mineral wool insulation below the joists, for the sensitivity analysis cases based in Swansea.

The sensitivity analysis cases are displayed as a coloured line; the baseline cases are not shown.

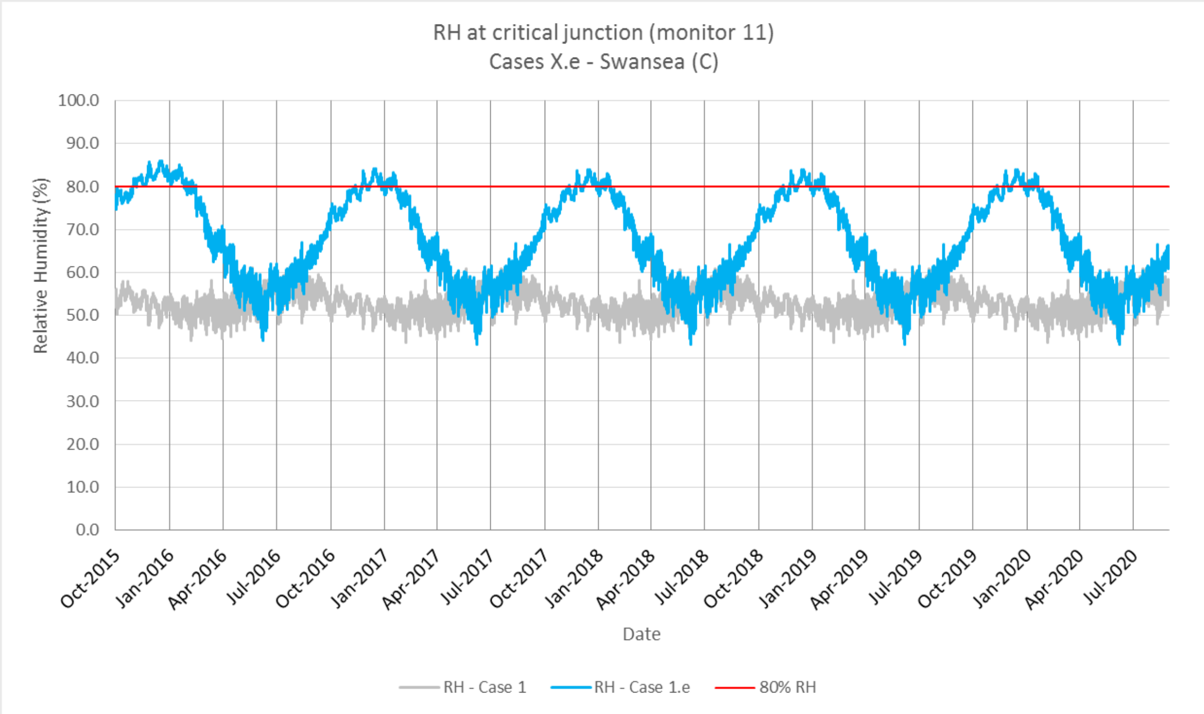


Figure 206: RH levels at critical junction for Cases 1 and 1.e

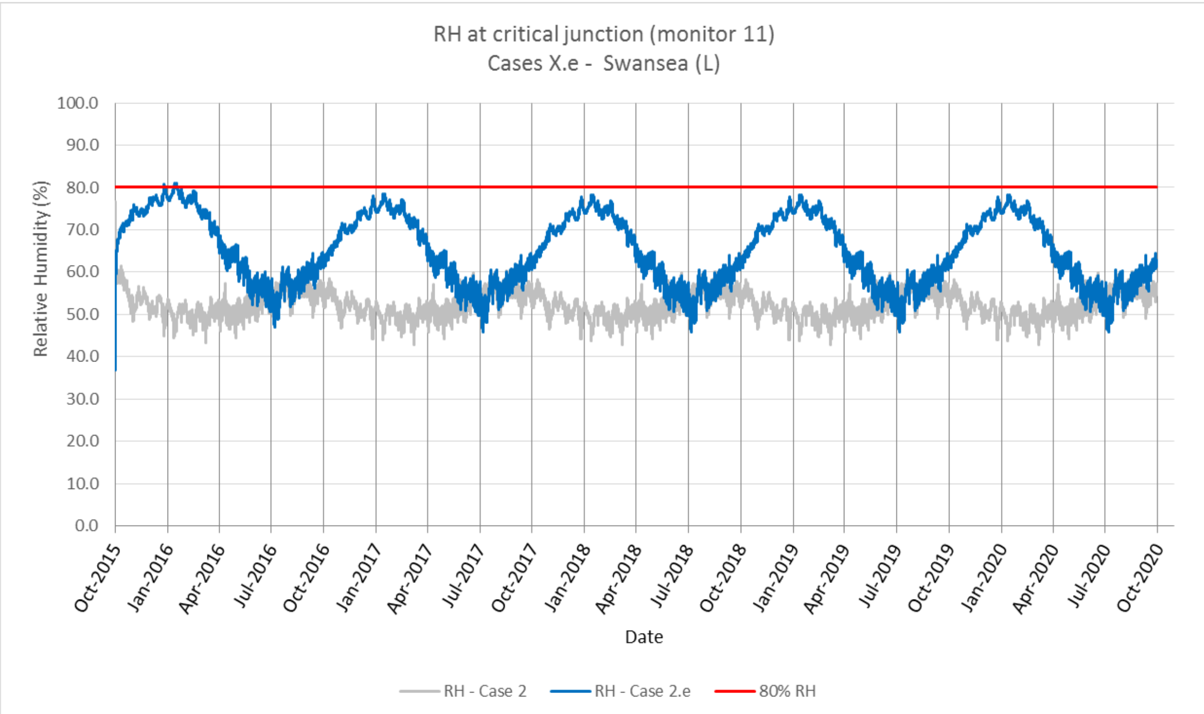


Figure 207: RH levels at critical junction for Cases 2 and 2.e

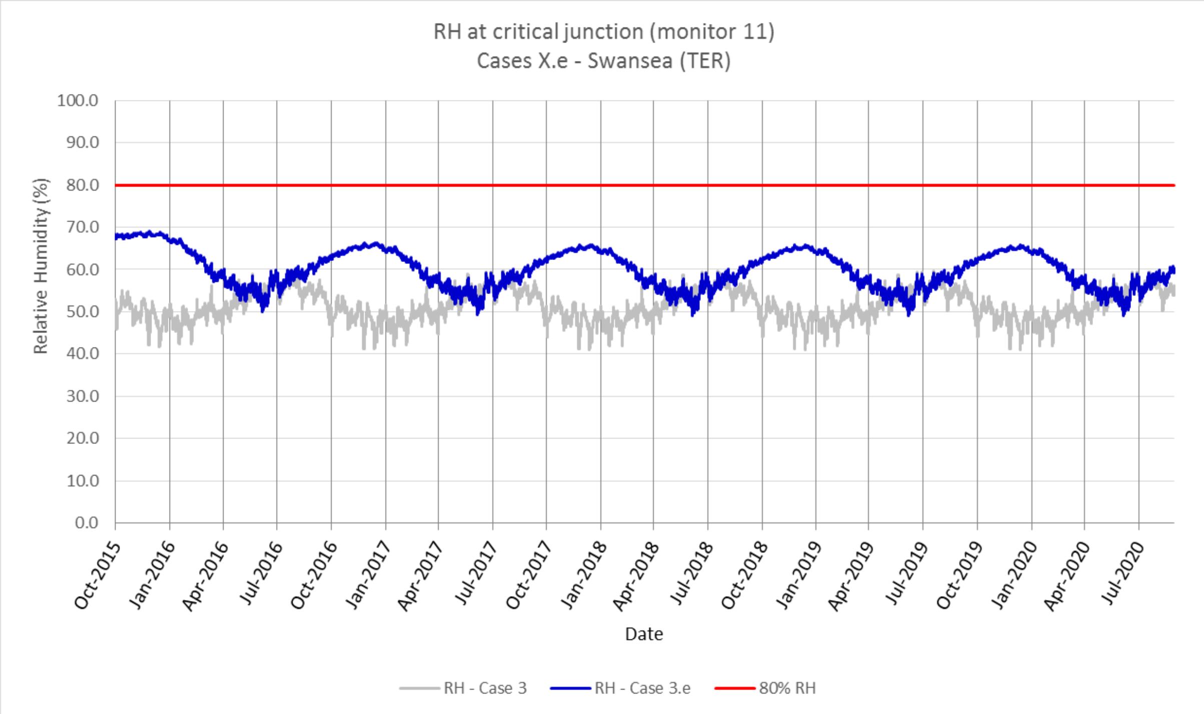


Figure 208: RH levels at critical junction for Cases 3 and 3.e

23.6.5. Conclusions – Sensitivity Analysis Cases X.e

<u>Moisture risk assessment criteria</u>

The first set of graphs shows that the sensitivity analysis cases perform better than their respective baseline case, However, this cannot be considered a like for like comparison, due to the added insulation between the joists which leads to higher U-values..

All cases show the build-up reaching equilibrium after the first one or two years, which confirms there is not accumulation of moisture in the build-up. The graphs also show that all cases display RH peaks at the first critical junction reducing quickly from just over 90% to RH peaks around 80% from the 2nd year onwards. These high RH levels during the first year, similarly to the baseline cases, are due to the initial conditions, being worse than the equilibrium reached by the build-up after a few years.

The second set of graphs shows that, for the Part C build up (with little insulation above the plywood deck) the moisture levels continue to peak slightly above 80% for some short periods during the winter season. As this junction is on the ‘interior’ of the building and that ‘fragile’ material is present at this interface, the 80% criteria is considered valid. The Part L & TER build-ups, with more insulation above the deck, display RH profiles only below the recommended 80% RH threshold.

<u>Results</u>

The table below summarises the performance of each case, following both the 95% RH (first critical junction) and 80% RH (second critical junction) recommended levels.

Only the Part L and TER cases are considered a ‘pass’, as they keep RH levels well below the recommended RH levels in both monitored interfaces. As the Part C case display RH levels around the 80% threshold, the build-up status is considered ‘risky’. However, the risk of mould growth is not considered an issue as, with a well-built construction, no air should be present at this interface and the RH peaks only happen during the winter period, which does not promote mould growth.

Table 88: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.e Risky			
Part L	Case 2.e Pass			
TER	Case 3.e Pass			

Recommendations for safe hybrid build-up

There is clearly a minimum level of insulation required above the plywood decking to make this hybrid design safe. This is likely to be close to the Part L minimum used in the cases here (in this case, 80mm PU foam insulation with λ = 0.025 W/m.K). Again ‘good’ initial conditions are also important. Materials should be kept dry to ensure this build-up is safe and avoid trapping moisture between less-breathable layers, independently to the level of insulation installed.

23.7. Conclusions

- Baseline not safe
- Sensitivity X.d = BS 5250 (2011) recommendation is safe
- Need for clearer guidance (and clearer / narrower material characteristics) in BS 5250 (2011) as still possible to follow BS 5250 (2011) ‘drawing’ without respecting the real guidance and installing a failing build-up
- Importance of initial conditions (especially in recommended cases – with thick insulation) i.e. keeping materials dry on site
- Importance of adequate indoor conditions
- Deterioration of indoor conditions directly reflected at critical junction – pushing the build-up closer to ‘risky’ / ‘fail’ → MEDIUM effect / link

24. Typology N20: Cold roof – timber deck

The N20 typology is a new-build 'cold roof' with timber deck and insulation between the timber joists, beneath a well ventilated gap between the deck and the insulation layer.

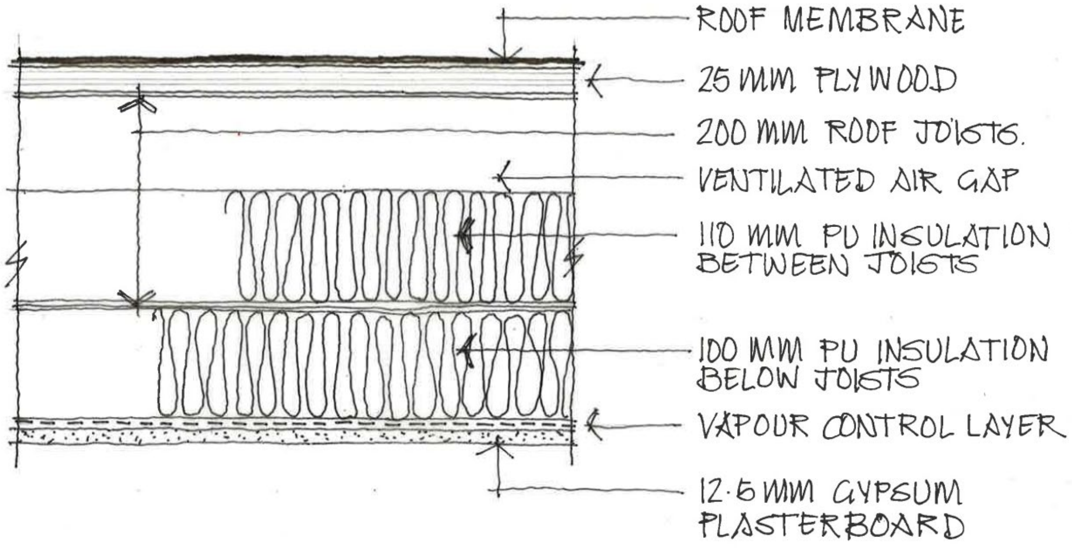


Figure 209: Illustration of the build-up of the typology (Part L case)

24.1. Assessment Method

The prescriptive guidance in BS 5250 (2011) states that, *'Designers should be aware that it is difficult to avoid interstitial condensation in cold flat roofs. To avoid the risk of interstitial condensation, an AVCL should be provided on the warm side of the insulation and there should be a cross-ventilated void, not less than 50mm deep, between the deck and the insulation'.*

This is further supported with the STBA/DECC's Moisture Risk Assessment and Guidance (2014) stating that *'cold deck roofs require considerable care in the design and construction, as the ventilation to the underside of the decking is critical'.*

To follow this prescriptive guidance, the void above the insulation is ventilated to the outside, to allow any moisture present in the void to be removed. This means that the roof covering is considered as a 'protective cladding' and is not technically part of the 'thermal' build-up. As shown in the following section, the modelled build-up therefore only extends from the insulation layer to the internal finish.

The build-up does not contain very porous materials having the capacity to store moisture. In addition, the modelled build-up is not directly exposed to the elements (rain, wind and radiations), as the roof covering is acting as a protection layer.

Therefore, the BS EN ISO 13788 (2012) assessment method should provide valid results for this typology. This will be confirmed with some modelling done following the BS EN 15026 (2007) assessment method.

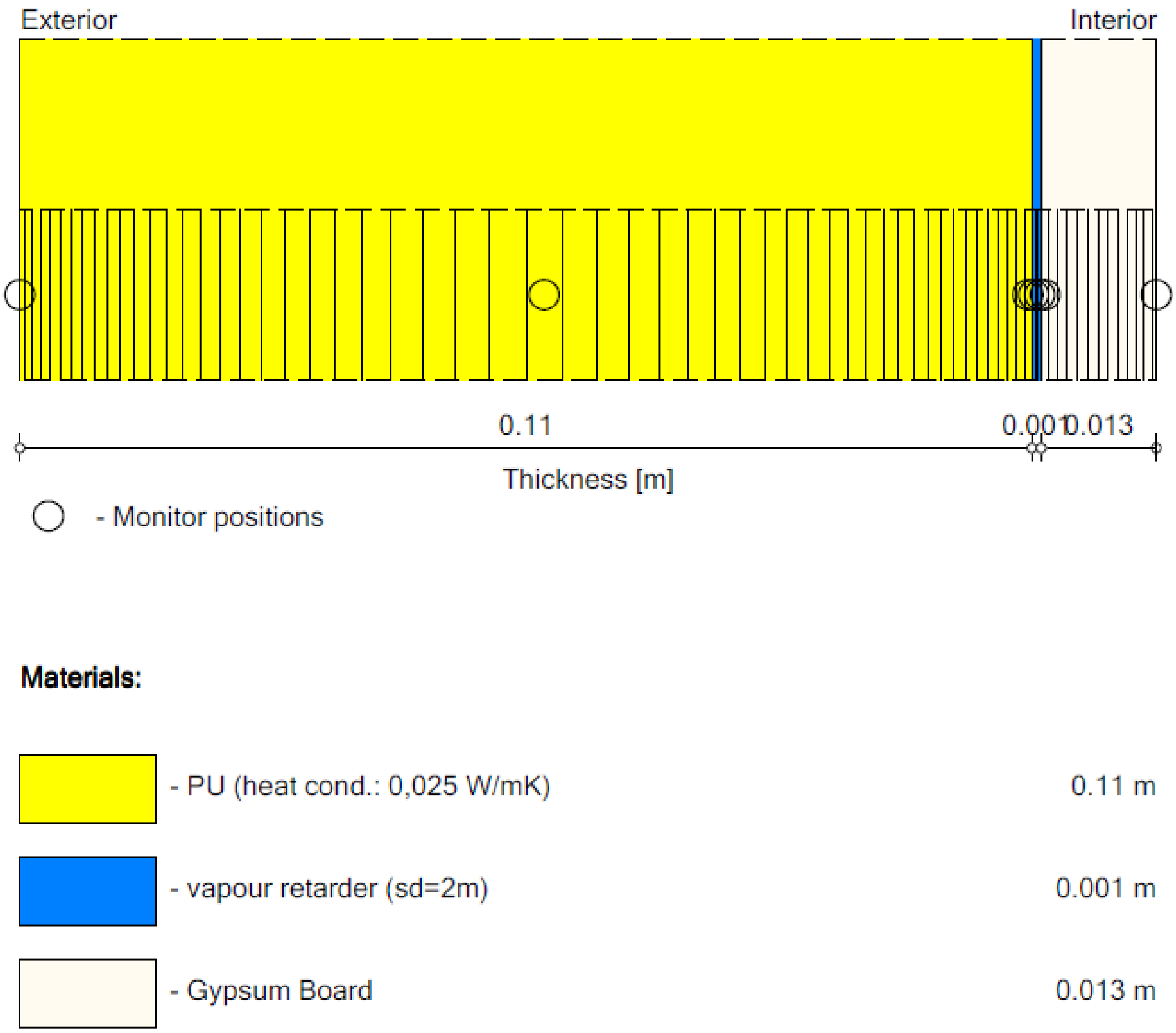
The results by the Glaser method show that this build-up is considered a ‘safe’ build-up, with no risk of interstitial condensation, when the void above the insulation is well ventilated. These results will be verified through the use of transient modelling following BS EN 15026 (2007) using WUFI.

24.2. Build-up

Below is the build-up of the typology, as modelled in WUFI.

Build-Up:

- Bitumen felt roof membrane *(considered outside of the WUFI build-up)*
- 25mm Plywood deck *(considered outside of the WUFI build-up)*
- 50mm Ventilated Air layer *(considered outside of the WUFI build-up)*
- 200mm softwood joists bridging air/insulation layers *(considered outside of the WUFI build-up)*
- 75mm // 110mm // 200mm polyurethane insulation between joists (λ = 0.025 W/m.K)
- 100mm polyurethane insulation below joists (λ = 0.025 W/m.K) (TER only)
- 1mm AVCL layer
- 12.5mm gypsum plasterboard



<u>WUFI Input Parameters</u>

As the void is considered ventilated, all the elements located on the outside of the insulation layer are omitted from the WUFI model. It is important to note that the external surface of the WUFI build-up (i.e. the insulation layer) is exposed to different external conditions due to the roof covering acting as a protective layer.

The climate files used in the WUFI modelling remain unchanged (including external temperatures and RH levels). However, the following changes in the WUFI input parameters are made:

- The solar gains are not taken into account (as the roof covering layers are protecting the external surface of the insulation)
- Similarly, the rainfall is not taken into account (i.e. the adhering fraction of rain is reduced to 0%)
- The external surface resistance is adjusted to allow for the ‘sheltered’ condition in the air gap.

24.3. Baseline Results

24.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values, as set below.

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

24.3.2. Monitored Junction

As mentioned previously, the build-up is protected from the elements, and should not present any moisture risks (as shown with the BS EN ISO 13788 (2012) calculations, when the void is well ventilated), meaning there is not a ‘critical’ junction per se.

The interface between the insulation and the ventilated air layer will mirror the external conditions, so has not been shown here. This is similar to several previous typologies, such as the N11 partial-fill cavity wall.

The only other interface in this build-up is located on the warm side of the insulation. As a vapour barrier (AVCL) is present between the insulation layer and the internal plasterboard surface, the RH levels on the outer face of the AVCL will be protected from any potentially ‘detrimental’ internal conditions (not modelled in the baseline). In addition, as the monitored junction is located on the warm side of the insulation, the temperature at which the monitored junction is kept will be quite warm and therefore, RH levels should be kept well within the recommended RH range.

24.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the monitored junction – interface between the insulation and the AVCL layer, interface being on the warm side of the insulation layer.

To make the reading of graphs as clear as possible, each zone has been associated with a colour (blue for Zone 4, purple for Zone 3, green for Zone 2 and orange for Zone 1). Within each colour, the darker the colour, the higher / better the U-value is.

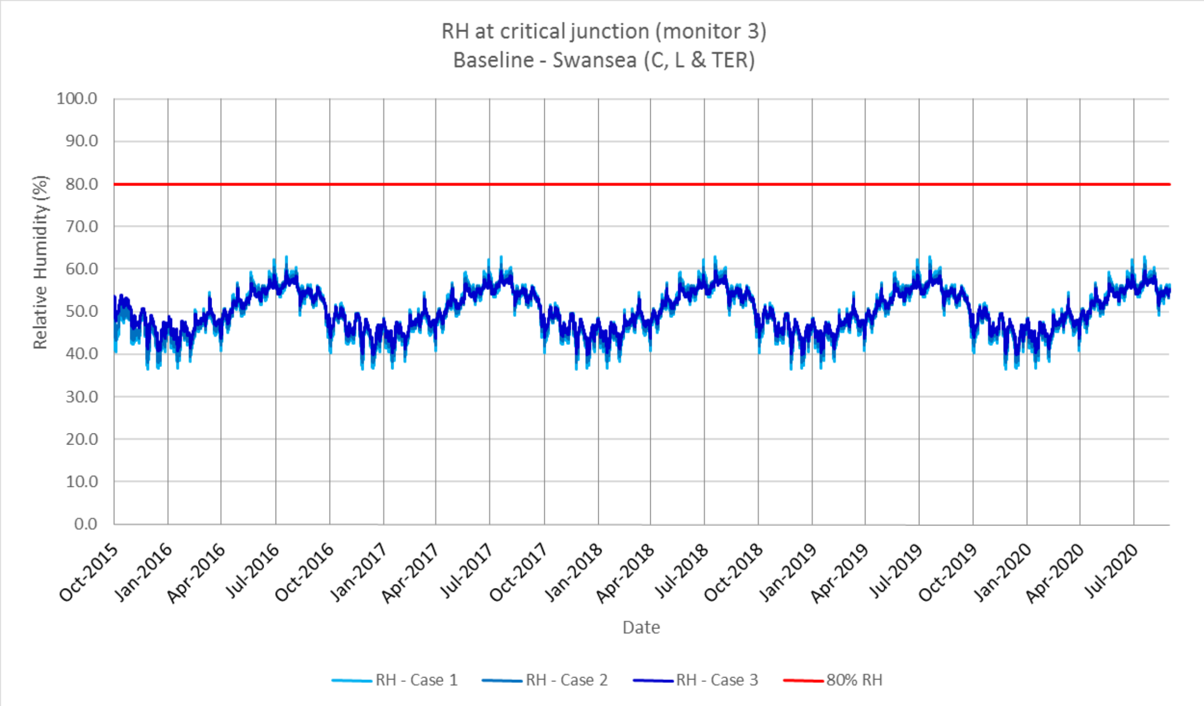


Figure 210: RH levels at monitored junction for Cases 1, 2 and 3

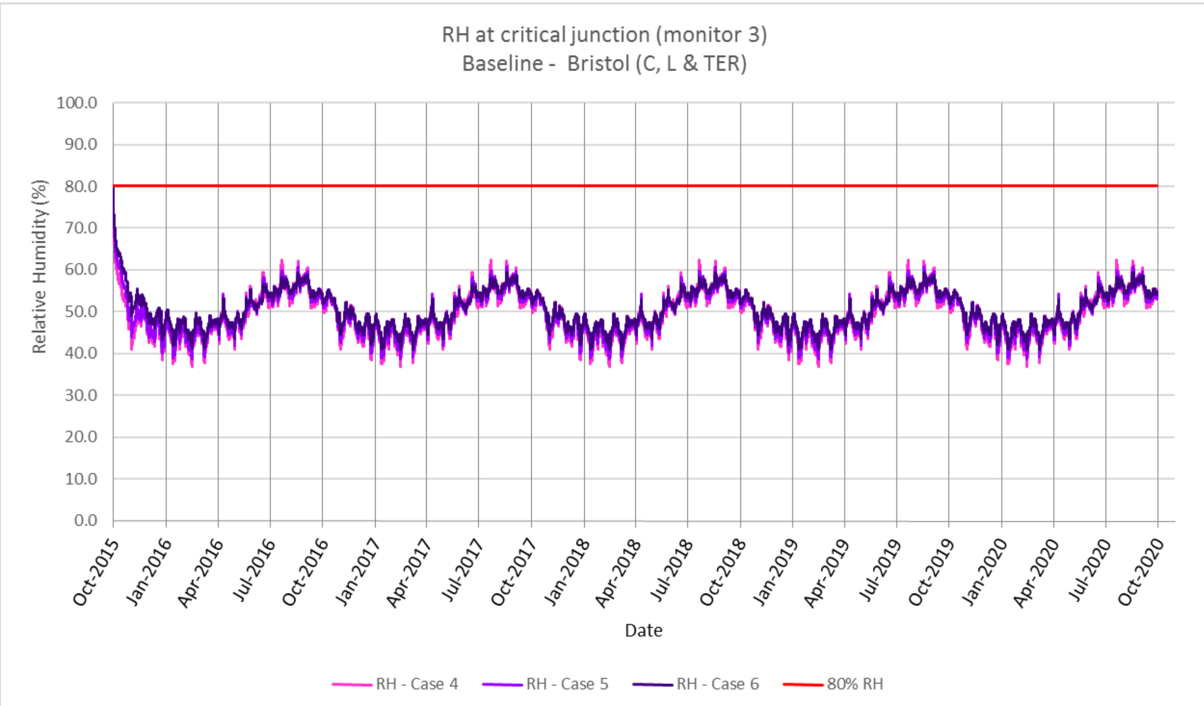


Figure 211: RH levels at monitored junction for Cases 4, 5 and 6

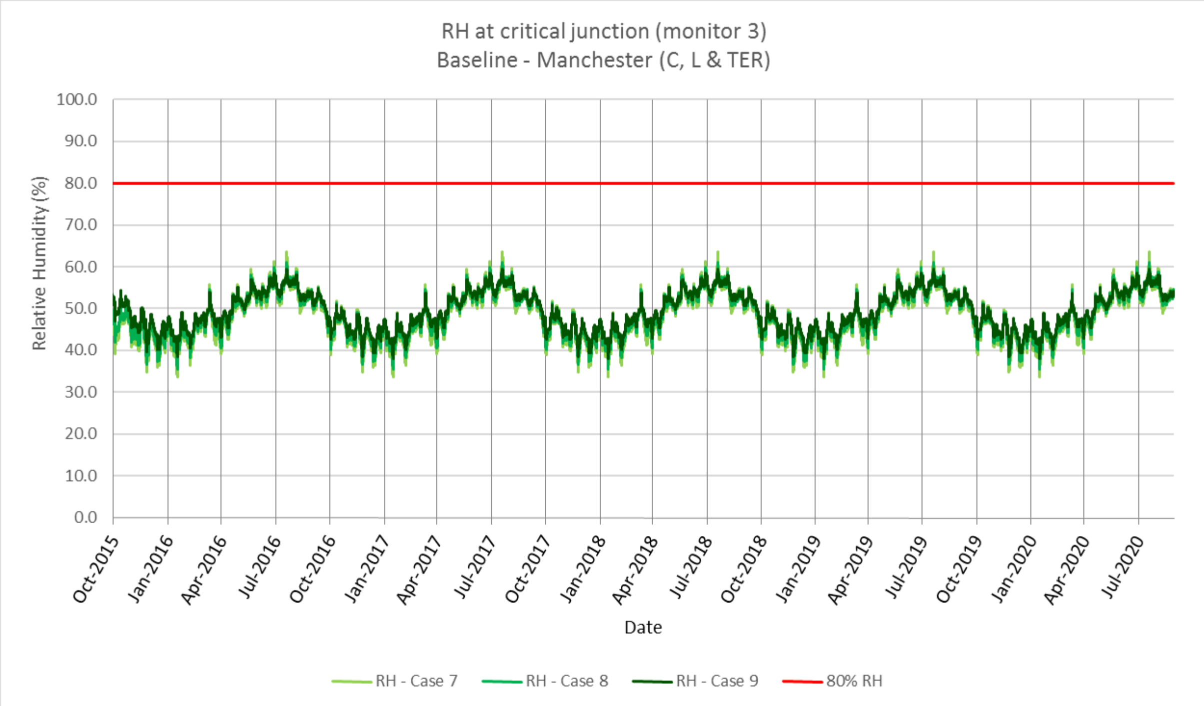


Figure 212: RH levels at monitored junction for Cases 7, 8 and 9

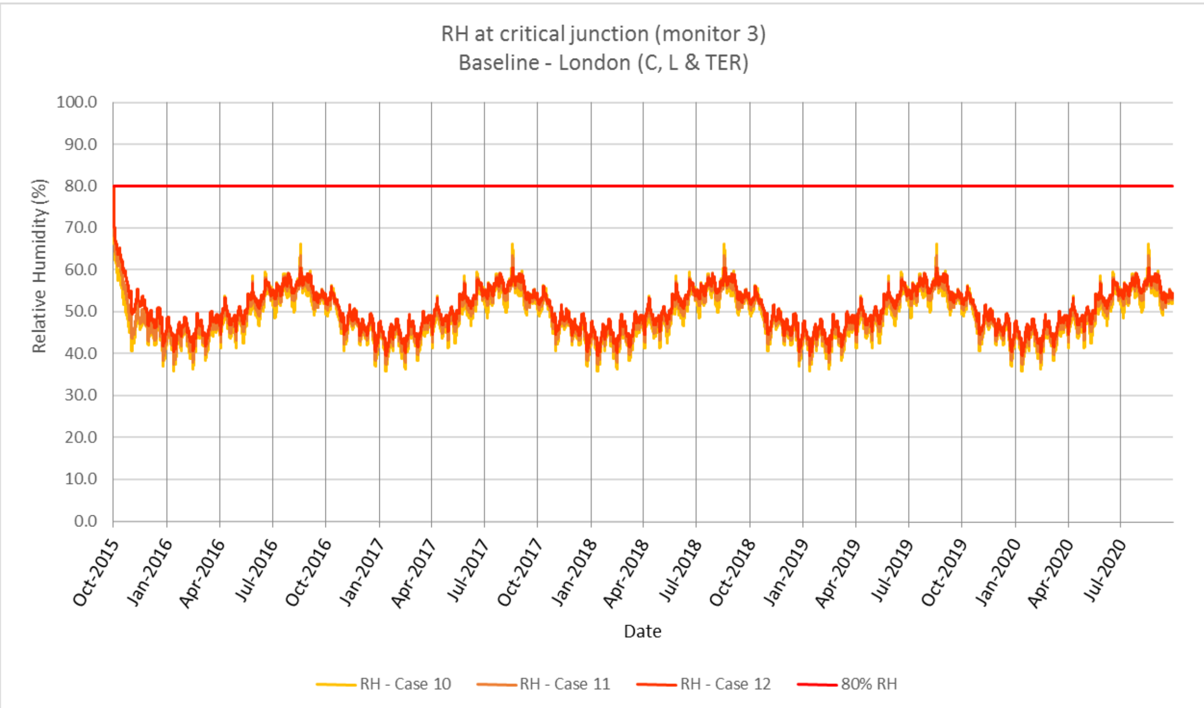


Figure 213: RH levels at monitored junction for Cases 10, 11 and 12

24.3.4. Results Analysis

Moisture risk assessment criteria

As predicted, all cases display RH levels well below 80% (after initial conditions), and the monitored junction does not accumulate moisture overtime.

The fact that these graphs are displaying ‘safe’ RH levels is not sufficient to declare the build-up safe. However, as no critical junction is available to be monitored through this modelling, the results for the twelve baseline cases are based on experience and knowledge from prescriptive guidance. The results are summarised in the table below.

Table 89: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

Effects of exposure zones and U-values

The effect of wind-driven rain exposure zones is almost undistinguishable on the graphs, as all RH levels at the monitored junction look similar for all cases. Similarly to the N19 typology, the effect of wind-driven rain exposure zones is really minimal, as any deterioration in the roof finish leads to complete system failure.

As the monitored junction is located on the warm side of the insulation, the difference in temperature at this junction will be absolutely minimal, meaning that the effect of the difference in U-values should not be visible on these graphs, as demonstrated on them.

24.3.5. Conclusions - Baseline

In accordance with current best practice in the industry, this typology is believed to be resistant to moisture. As several other roof typologies modelled here, the exposure zones do not have an impact on the hygrothermal performance of the build-up, as any deterioration of the waterproof roof covering would lead to a complete system failure, showing that the amount of wind-driven rain the build-up is exposed to does not have an effect.

- Timber (cold side) protected by adequate ventilation against rot
- Amount of insulation not having a significant impact on hygrothermal performance of build-up

The results are also in accordance with calculations done following the BS EN ISO 13788 (2012) method, which demonstrates no interstitial condensation risk in this build-up when the void above the insulation is well ventilated.

24.4. Sensitivity Analysis

24.4.1. Airtightness and ABIS Conditions

It is important to note that the build-up modelled in WUFI is done in theoretical conditions, which means that the gypsum plasterboard and AVCL layers are continuous. As highlighted in BS 5250 (2011) (paragraph H.3.2), *'Air leakage through gaps in a ceiling or lining allows substantial amounts of heat and moisture to be transferred into the roof by convection. Restricting air leakage by sealing the ceiling or lining using an AVCL or air leakage barrier reduces the transfer of both heat and moisture, improving the energy efficiency of the building and minimizing the risk of interstitial condensation'.*

No sensitivity analysis modelling is done in this report, in which air leakage is modelled through the AVCL to create a leaking airtightness layer. However, despite the absence of modelling, the impact of such conditions is known: this could lead to moisture-laden air making its way through the build-up and condensing within the build-up when it reaches its dew point. Therefore, particular care should be given around ensuring good airtightness in this build-up.

24.4.2. Dense Structure

BS 5250 (2011) lists two types of cold flat roofs:

- cold flat roof with a framed structure (as per the baseline model) and,
- cold flat roof with dense structure

No sensitivity analysis is done in this report, in which the timber frame structure is changed into a concrete deck (dense) structure. However, as the structure (dense or timber frame) is considered outside of the WUFI model (not included in the model as WUFI cannot model ventilated cavities), the results listed in this report are applicable to both types of structure.

24.5. Conclusions

- Build-up very safe in ‘theoretical’ conditions
- Deterioration of workmanship, not tested here, but well known in BS 5250, for example a lack of ventilation or cracks / gaps in the AVCL (or poorly installed). There is a need to follow ‘best practice’ installation guidance
- BS EN ISO 13788 has potential for being a sufficient method to assess the performance of build-up (impossibility / limitations of WUFI / BS EN 15026 (2007) to model actual build-up) and (no need for WUFI / BS EN 15026 (2007) if proper ‘best practice’ guidance for design and installation followed)

25. Typology N21: Warm roof - concrete

The N21 typology is a new-build warm flat roof (dense structure), i.e. with the closed-cell insulation layer installed continuously above the dense structure (concrete).

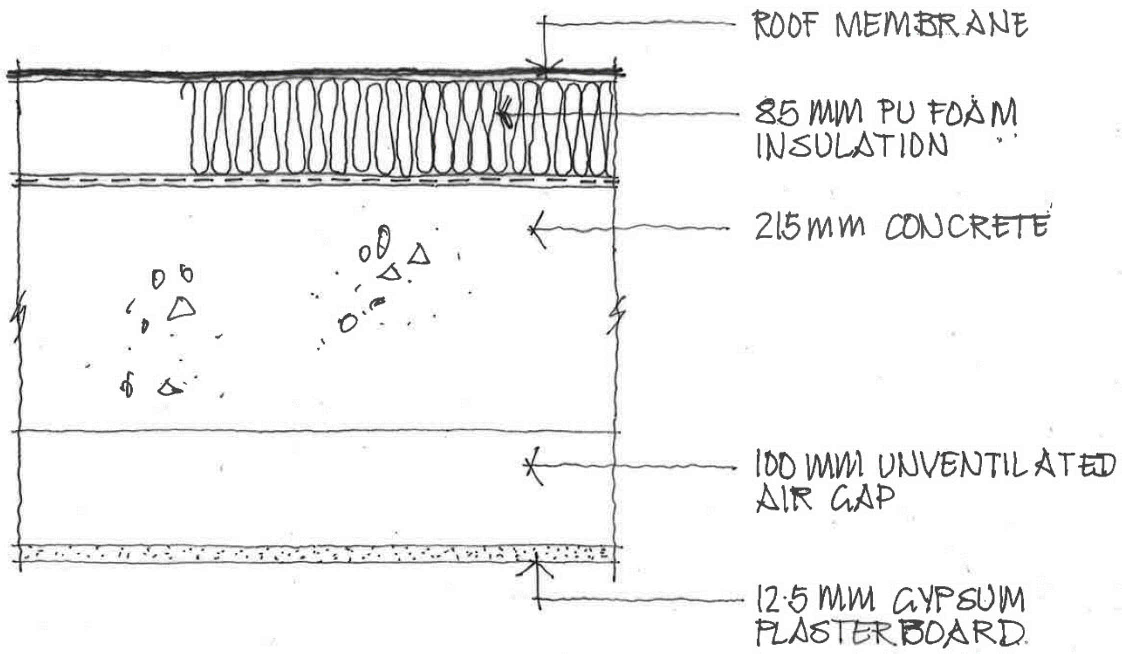


Figure 214: Illustration of the build-up of the typology (Part L case)

25.1. Assessment Method

Current prescriptive guidance in BS 5250 (2011) (paragraph H.8) states that *'there is a risk of surface condensation on warm flat roofs if the supporting structure is a concrete slab and if the building is heated only intermittently'*. However, the modelling work done for this project is focused on occupied buildings and the modelling is done to reflect a continuous occupancy (i.e. continuous heating through winter). Therefore, this assumption will not be verified through modelling to BS EN 15026 (2007).

It also states that *'with all warm flat roofs, there is a risk of interstitial condensation forming between the thermal insulation and the waterproof covering. To avoid that risk, an AVCL with a vapour resistance at least equal to that of the waterproof covering, should be provided immediately above the supporting structure.'*

Similarly to the previous typology (N19: warm roof – timber), this build-up is assessed in the first instance with the BS EN ISO 13788 (2012) method. This calculation shows that interstitial condensation occurs at the critical junction (correctly identified by BS 5250 (2011), and does not fully evaporate throughout the year. Therefore, this shows that this build-up presents moisture risks. BS 5250 (2011) explains these results through the use of an AVCL layer which has a lower vapour resistance compared to the waterproof covering vapour resistance.

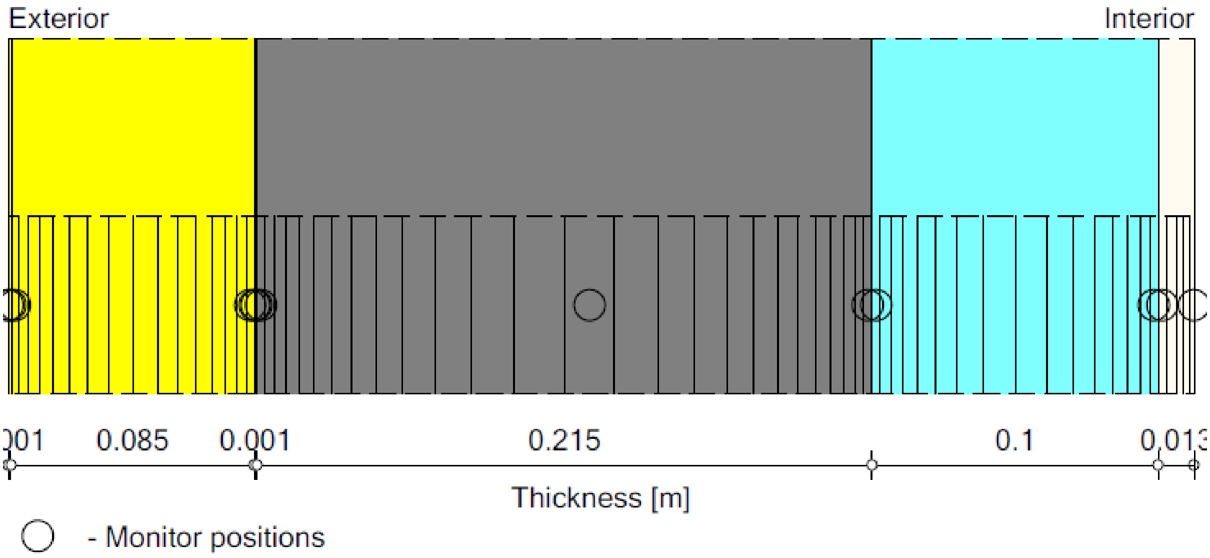
WUFI modelling to BS EN 15026 (2007) is then used to confirm the adequacy and accuracy of the BS EN ISO 13788 (2012) method to assess this type of build-up.

25.2. Build-up

Please find below the build-up of the typology, as modelled in the BS EN ISO 13788 (2012) (the Glaser method) assessed model and in the BS EN 15026 (2007) (WUFI) model.

Build-Up:

- 1mm roof membrane (bituminous felt sd = 100m)
- 55mm // 85mm // 190mm PU foam insulation (λ = 0.025 W/m.K)
- 1mm AVCL (sd = 2m)
- 215mm concrete structure
- 100mm unventilated air gap with metal ceiling rails
- 12.5mm gypsum plasterboard



Materials:

- Roof Membrane V13 — 0.001 m
- PU (heat cond.: 0,025 W/mK) — 0.085 m
- vapour retarder (sd=2m) — 0.001 m
- Concrete, C35/45 — 0.215 m
- Air Layer 100 mm; without additional moisture capacity — 0.1 m
- Gypsum Board — 0.013 m

Similarly to the N19 typology, please note that this build-up does not reflect the technical recommendations laid down in BS 5250 (2011), as the baseline build-ups were chosen to reflect typical UK new-build constructions. The build-up depicted in the prescriptive guidance in BS 5250 (2011) is analysed later on in the sensitivity analysis of this modelling work.

The AVCL has an sd-value of 2m and is representative of typical AVCL used nowadays in the building industry. This is significantly less vapour resistant than the waterproof roof covering (bitumen) which has an sd-value of 100m.

25.3. Baseline Results

25.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values (as set in paragraph 5.1).

Table 90: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

25.3.2. Critical Junction

Similarly to typology N19, the focus is given on RH levels and moisture content at the interface between the waterproof roof covering and the insulation. This critical junction is correctly identified by the BS EN ISO 13788 (2012) assessment, as any moisture travelling through the build-up will be trapped at this interface due to the waterproof roof covering.

25.3.3. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction, on the cold side of the insulation layer for all baseline cases.

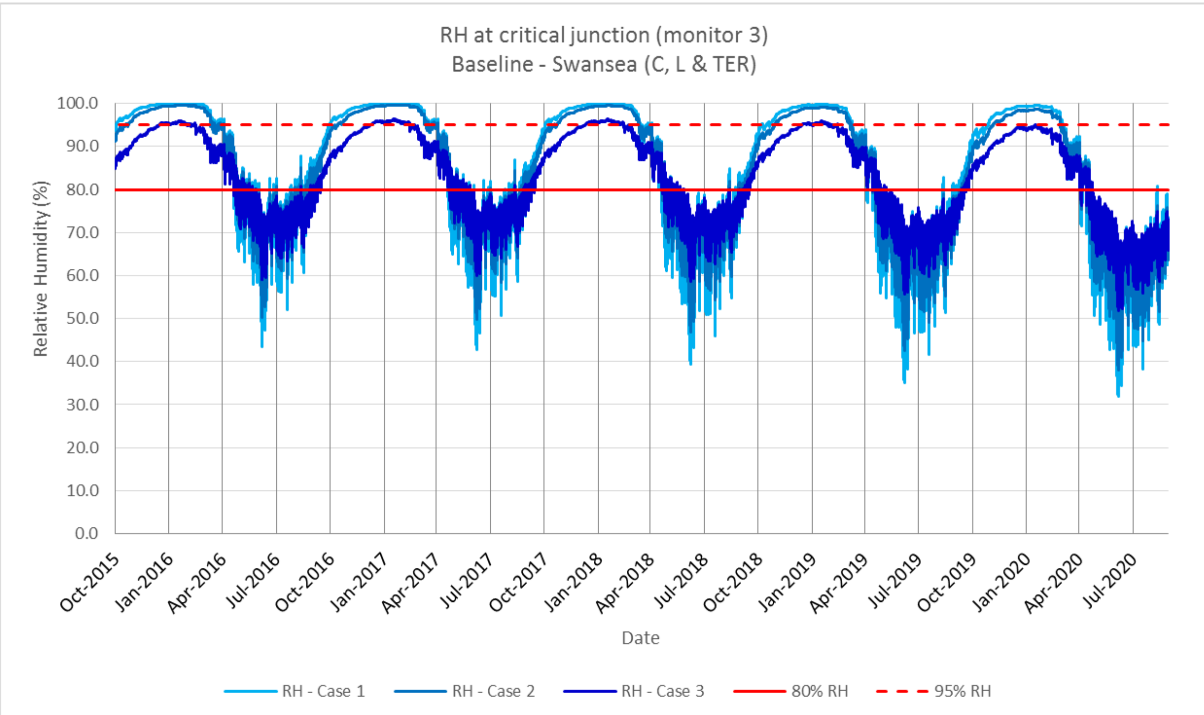


Figure 215: RH levels at critical junction for Cases 1, 2 and 3

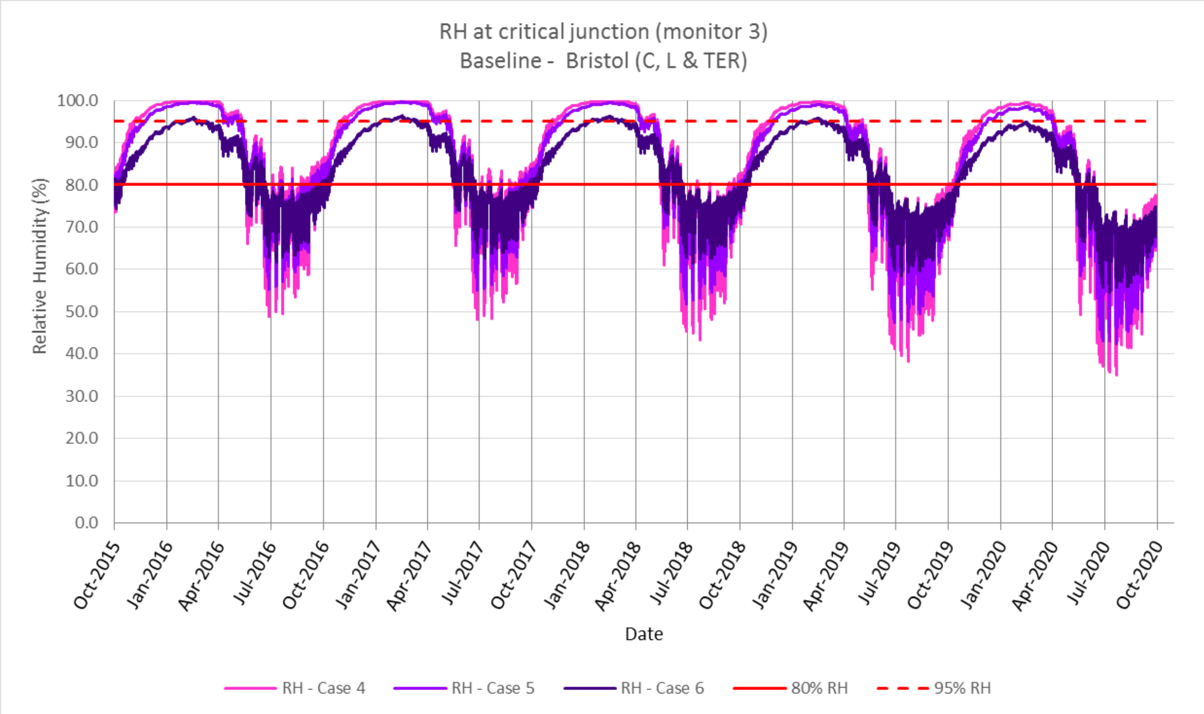


Figure 216: RH levels at critical junction for Cases 4, 5 and 6

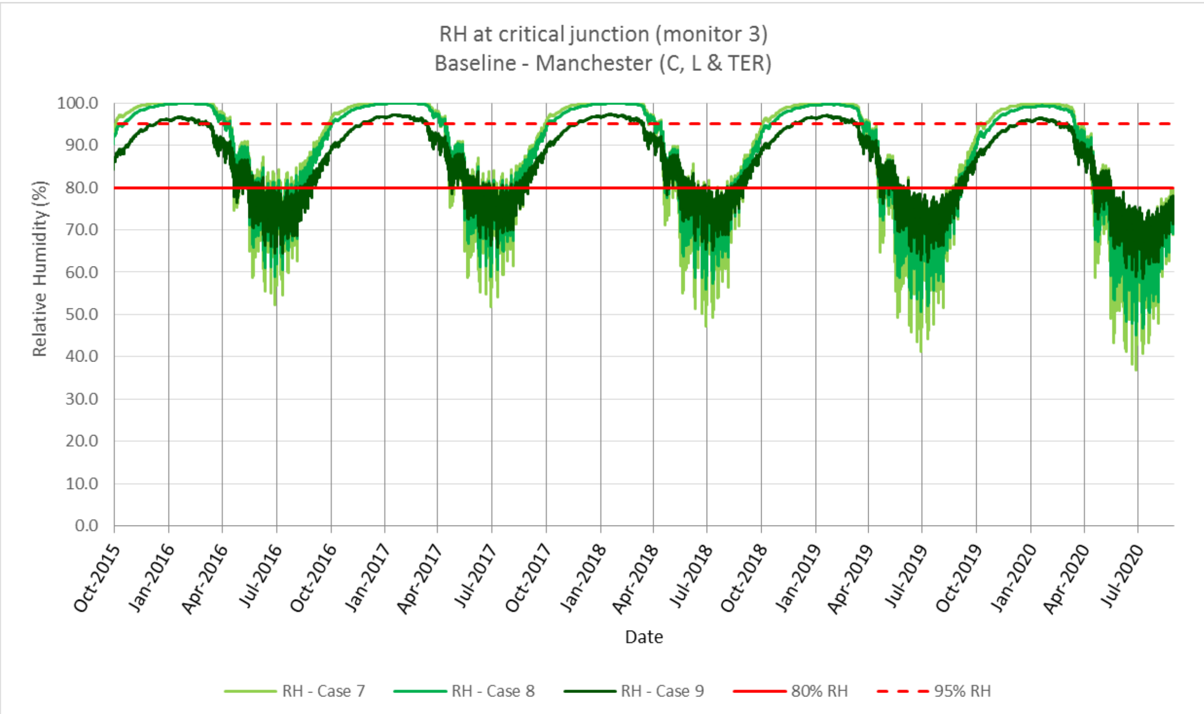


Figure 217: RH levels at critical junction for Cases 7, 8 and 9

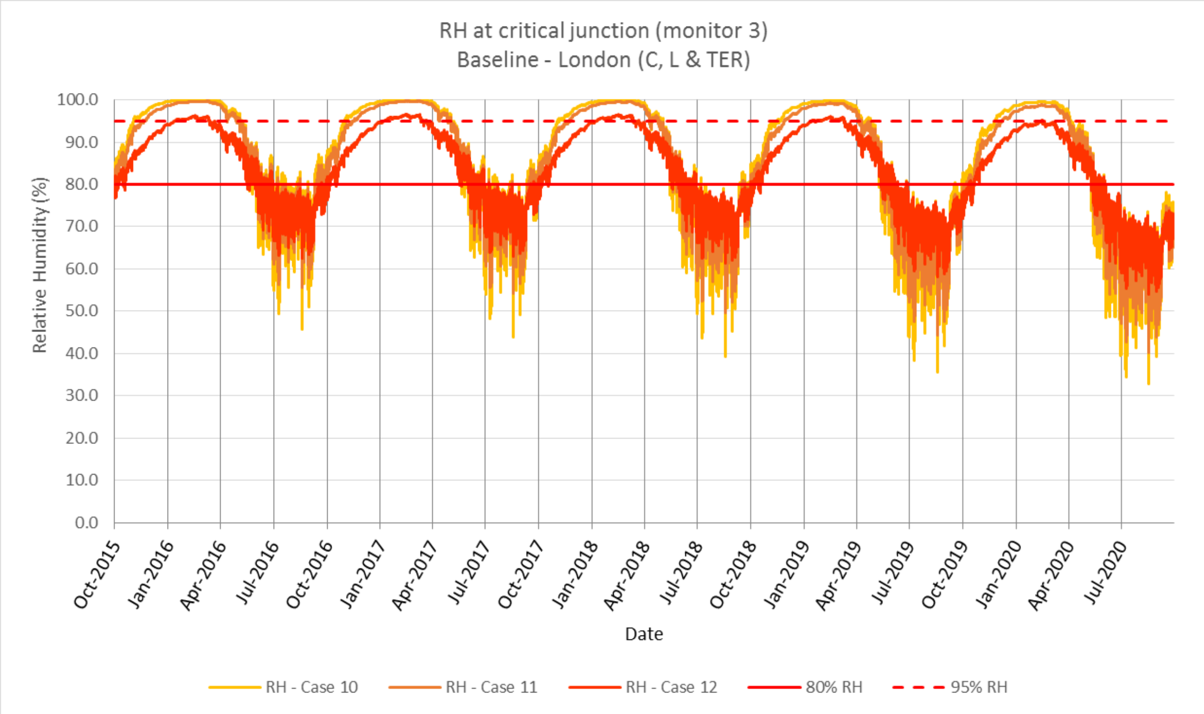


Figure 218: RH levels at critical junction for Cases 10, 11 and 12

25.3.4. Conclusions - Baseline

Moisture risk assessment criteria

All scenarios display RH levels well above 80% for most of the year. In addition, both the Part C and Part L models show some RH levels close to / reaching 100%, meaning condensation will also happen at that interface.

As detailed in the N19 typology, this typology can benefit from a 'relaxed' moisture risk assessment criteria, with limit RH levels increased from 80 to 95%. This is suggested, as no air should be present at the critical junction, materials present at that junction are not materials favouring mould growth (as food for mould spores) and the high RH levels are happening during the winter season (again not favourable for mould growth).

However, despite the critical junction being less prone to mould growth risk, it is still essential for the RH levels to be reduced to acceptable levels, as the thermal characteristics of the PU foam insulation material degrades with higher moisture content.

Results

The table below summarises the performance of each case, following the more relaxed 95% RH recommended levels explained above.

Both Part C and Part L cases (thin and medium insulation) fail with presence of interstitial condensation (or with RH levels being very close to 100%) each winter. TER cases are considered a 'risky', due to RH levels reaching around 95% during each winter.

Table 91: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Fail	Case 4 Fail	Case 7 Fail	Case 10 Fail
Part L	Case 2 Fail	Case 5 Fail	Case 8 Fail	Case 11 Fail
TER	Case 3 Risky	Case 6 Risky	Case 9 Risky	Case 12 Risky

Similarly to the N19 typology, these findings are in accordance with current recommendations and prescriptive guidance. Indeed, the main moisture source leading to moisture problems is internal moisture travelling through the build-up, driven by vapour diffusion, and getting trapped in front of the layer with the highest vapour diffusion resistance factor, the waterproof roof covering.

Effects of exposure zones and U-values

Similarly to the N19 typology, the effect of wind-driven rain exposure zones is really minimal, as any deterioration in the roof finish leads to complete system failure.

The difference in U-values between cases is also shown through the difference in RH levels, with thicker insulation reducing the RH peaks in winter. This is due to the fact that more moisture can get 'stored' in the insulation layer the thicker it is. Therefore, for the same moisture conditions internally, a smaller amount of moisture will accumulate at the critical junction for a thicker insulation layer, compared to a thinner one.

25.4. Sensitivity Analysis – Change in Material [Cases X.d]

25.4.1. Sensitivity Analysis Cases

As guidance given in BS 5250 (2011) is available on construction where there is good evidence of success, the first sensitivity analysis performed on this modelling is a change in materials, to match the build-up recommended in BS 5250 (2011) – similarly to the N19 typology.

BS 5250 (2011) recommends to install '*an AVCL with a vapour resistance at least equal to that of the waterproof covering, immediately above the supporting structure'* to avoid the risk of interstitial condensation. As the waterproof covering has a vapour diffusion resistance much more important (sd = 100m) than the AVCL (sd = 2m), we will change the AVCL to a material with closer characteristics to the waterproof covering layer – chosen here as a material already available in the WUFI Fraunhofer database 'vapour retarder (sd = 100m)'.

The 12 cases for this sensitivity analysis are set across the four wind-driven rain exposure zones, meeting the three targets U-values (as per the baseline cases), as set below.

Table 92: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d	Case 4.d	Case 7.d	Case 10.d
Part L	Case 2.d	Case 5.d	Case 8.d	Case 11.d
TER	Case 3.d	Case 6.d	Case 9.d	Case 12.d

25.4.2. Graphs at Critical Junction

All graphs displayed below show the RH levels at the critical junction (which is the same as the baseline cases), on the cold side of the insulation layer for the sensitivity analysis cases based in Swansea.

It was observed in the baseline cases that the external weather conditions play a much minor role compared to the U-value (i.e. insulation thickness) on the hygrothermal performance of the build-up. Therefore, the results for Zone 4 – Swansea only are displayed below, as the rest of the graphs in other zones look similar to the graphs in Zone 4.

The sensitivity analysis cases are displayed as a coloured line, while their respective baseline cases are displayed with a grey line.

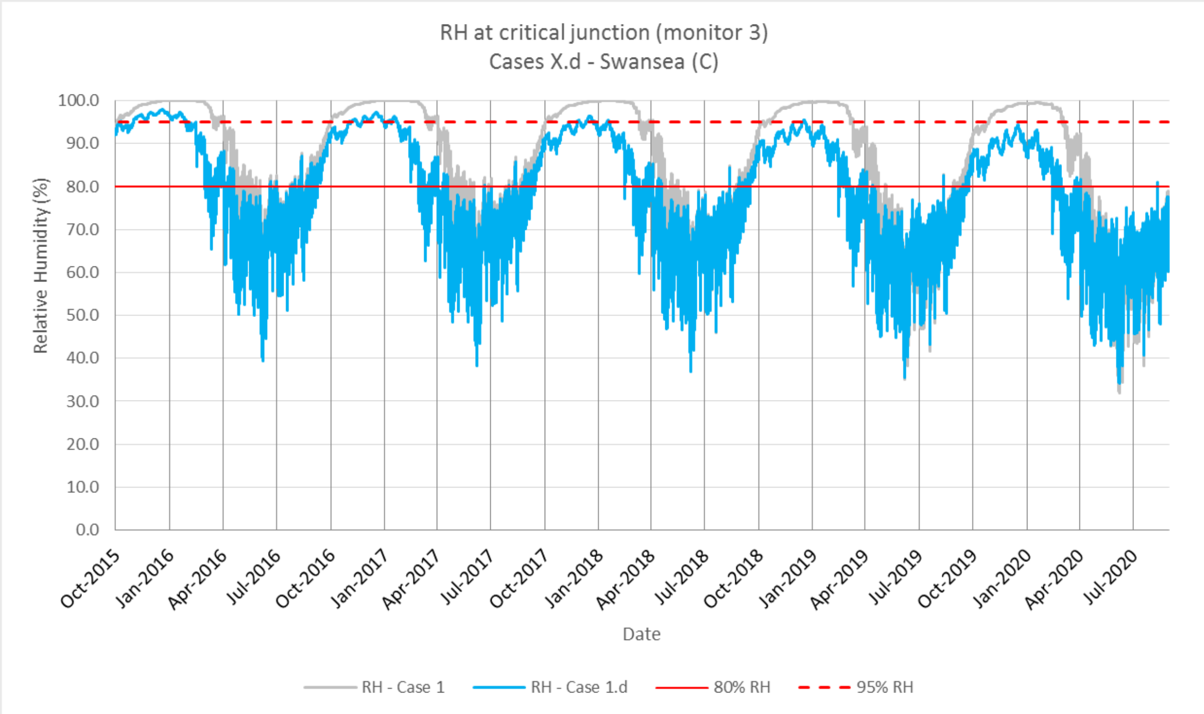


Figure 219: RH levels at critical junction for Cases 1 and 1.d

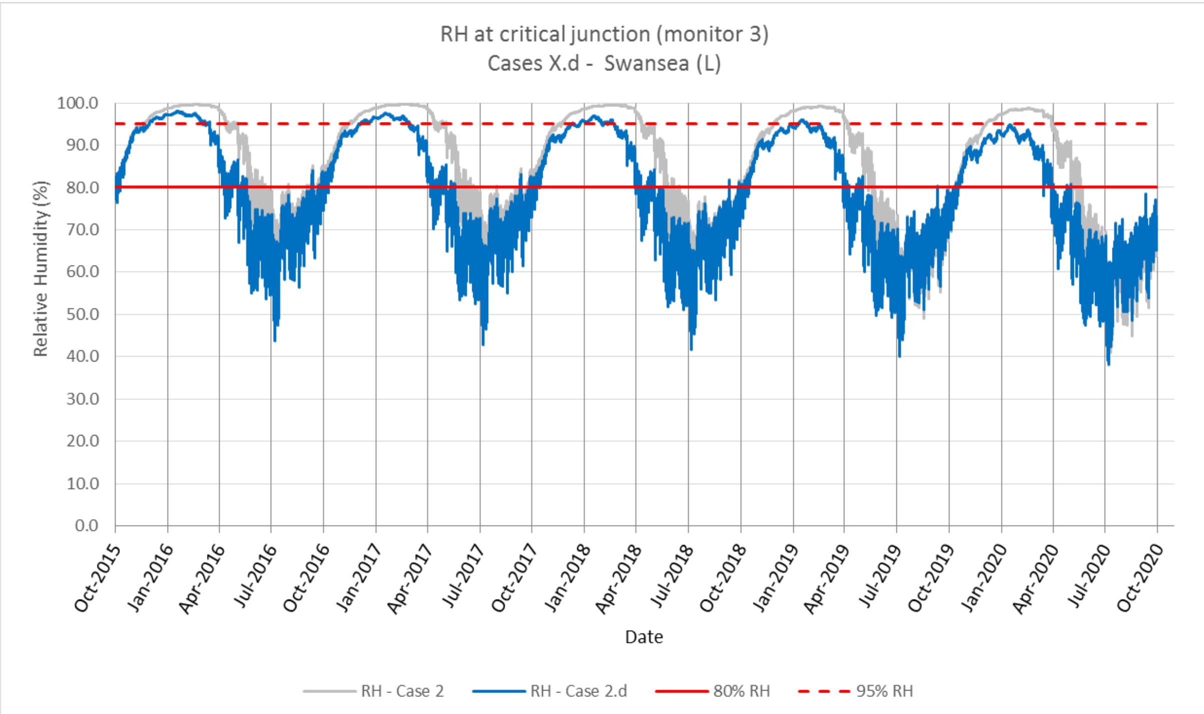


Figure 220: RH levels at critical junction for Cases 2 and 2.d

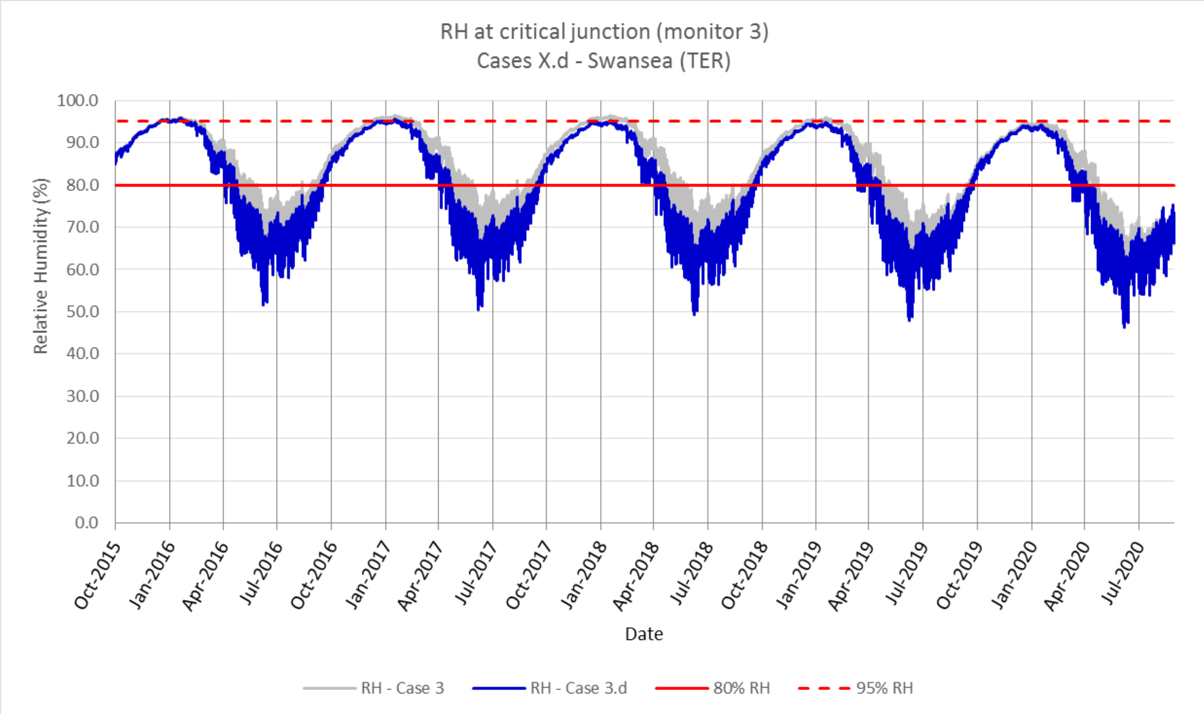


Figure 221: RH levels at critical junction for Cases 3 and 3.d

25.4.3. Conclusions – Sensitivity Analysis Cases X.d

Moisture risk assessment criteria

The graphs show on average that the cases modelled in this sensitivity analysis perform better than their respective baseline cases.

All cases show the build-up slowly drying out towards equilibrium, which confirms there is not accumulation of moisture in the build-up. The graphs also show that both Part C and Part L cases display RH peaks at the critical junction reduced to 95%, compared to close to 100% in their baseline scenarios.

Therefore, the build-up does not accumulate moisture over time, RH levels do not go above recommended levels (in this case 95%) during typical years and only reaches above recommended RH levels for a few months only during the first year. These results show that the upgraded build-up in the sensitivity analysis is made safer in terms of hygrothermal performance, compared to the baseline build-up.

Results

The table below summarises the performance of each case, following the more relaxed 95% RH recommended levels explained in the baseline results analysis.

All cases are considered a ‘pass’ (though the Part L cases are described as ‘risky/pass’ as they tend to take 2 to 3 years before keeping RH levels consistently below 95% and becoming fully safe), as they do not accumulate moisture and the build-up slowly dry towards an equilibrium, which is within recommended RH levels.

Table 93: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.d Pass	Case 4.d Pass	Case 7.d Pass	Case 10.d Pass
Part L	Case 2.d (Risky) Pass	Case 5.d (Risky) Pass	Case 8.d (Risky) Pass	Case 11.d (Risky) Pass
TER	Case 3.d Pass	Case 6.d Pass	Case 9.d Pass	Case 12.d Pass

These findings are in accordance with current recommendations and prescriptive guidance in BS 5250 (2011). With the AVCL now having at least the same diffusion resistance characteristics as the waterproof roof covering, the build-up is now safer, without any moisture accumulating over time just below the waterproof roof covering.

Effects of moisture storage in concrete

Due to high capacity for moisture storage of the concrete layer, all build-ups appear almost stable but equilibrium is never fully reached within the five years of simulations. Therefore, the Swansea cases for all cases (Part C, Part L and TER) were run for an extended simulation period of 10 years.

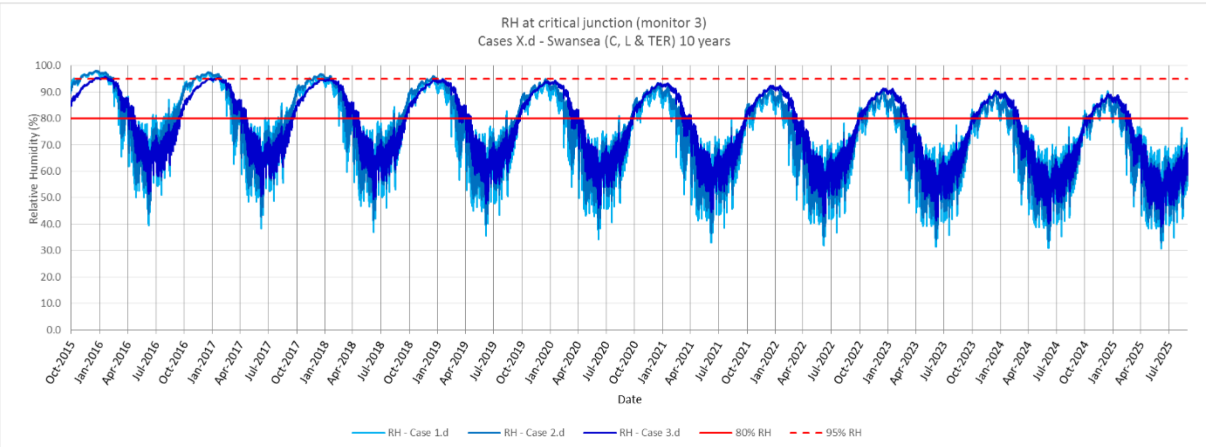


Figure 222: RH levels at critical junction for Cases 1.d, 2.d and 3.d for a period of 10 years

The difference in U-values between cases is very slightly visible and shows that the thicker the insulation is, the slower the build-up reaches equilibrium. Even after 10 years of modelling simulation, all build-ups are still slowly drying towards equilibrium.

However, similarly to the N19 typology, this graph highlights the need for ‘good’ initial conditions. Indeed, if the materials used in this build-up (e.g. the insulation layer the concrete slab) are not kept in optimal conditions (e.g. stored in a humid location or subject to direct rain for the insulation, concrete not dry enough for the slab), then this would have a direct impact on the hygrothermal performance of the build-up, keeping the RH levels in winter higher than considered acceptable. So it is important to highlight the need to keep materials dry to ensure this build-up is safe, independently to the level of insulation installed.

26. Typology N22: Inverted roof - concrete

The N22 typology is a new-build inverted flat roof (dense structure), i.e. with the closed-cell insulation layer installed continuously above the dense structure (concrete) as well as above the roof waterproof covering layer.

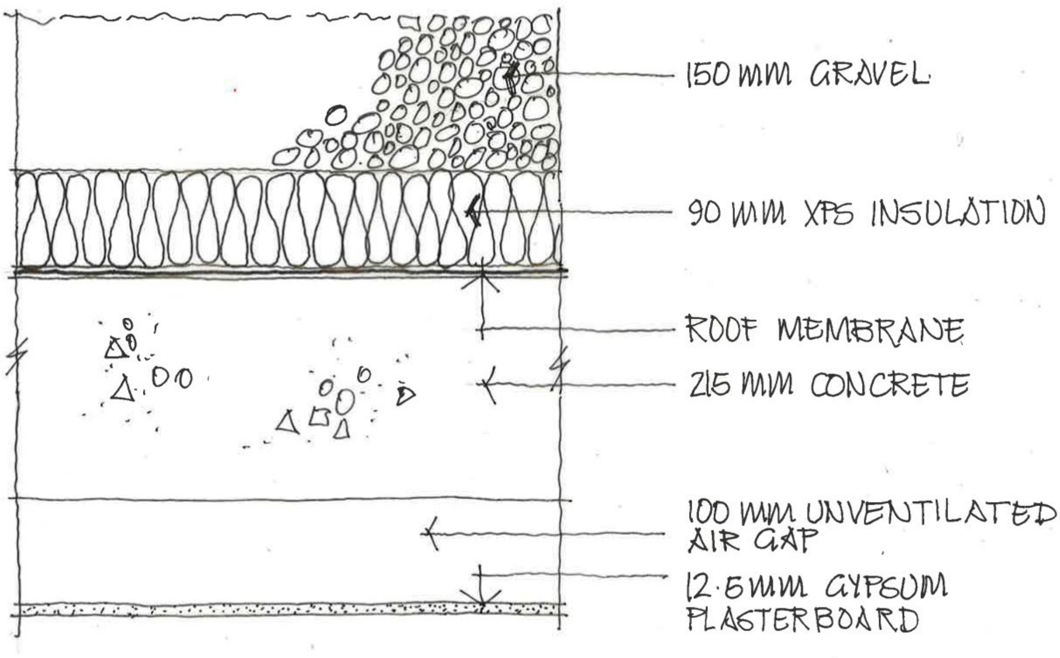


Figure 223: Illustration of the build-up of the typology (Part L case)

26.1. Assessment Method

Current prescriptive guidance in BS 5250 (2011) (paragraph H.9) states that *'there is a risk of surface condensation on inverted flat roofs if the supporting structure is a concrete slab and if the building is heated only intermittently'*. However, the modelling work done for this project is focused on occupied buildings and the modelling is done to reflect a continuous occupancy (i.e. continuous heating through winter). Therefore, this assumption will not be verified through modelling to BS EN 15026 (2007).

It also states that *'there is no risk of surface condensation in inverted flat roofs, irrespective of the form of the supporting structure, as the insulation maintains the impermeable waterproof covering above dew point.'*

This build-up is assessed in the first instance with the BS EN ISO 13788 (2012) method, as the build-up should not be significantly impacted by external rain conditions (as any deterioration in the roof finish leads to complete system failure). The results by the Glaser method show that this build-up is considered a 'safe' build-up, with no risk of interstitial condensation.

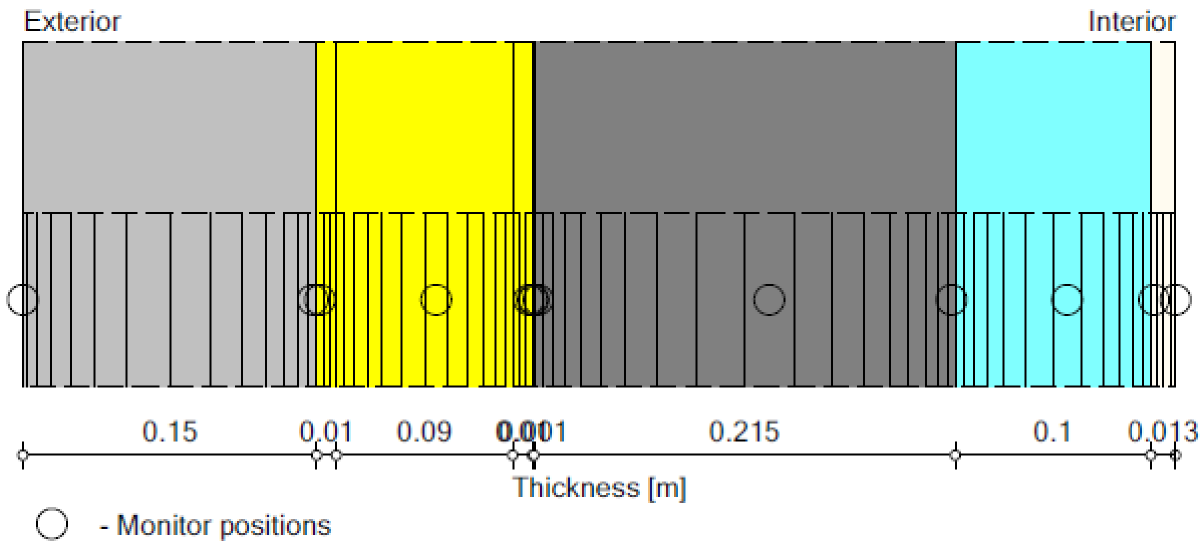
WUFI modelling to BS EN 15026 (2007) is then used to confirm the adequacy and accuracy of the BS EN ISO 13788 (2012) method to assess this type of build-up.

26.2. Build-up

Please find below the build-up of the typology, as modelled in the BS EN ISO 13788 (2012) (the Glaser method) assessed model and in the BS EN 15026 (2007) (WUFI) model.

Build-Up:

- 150mm gravel
- 50mm // 90mm // 210mm XPS insulation (λ = 0.030 W/m.K) modelled in three layers as suggested by the WUFI software (XPS surface skin around XPS core)
- 1mm DPM roof covering (vapour retarder sd = 136m)
- 215mm concrete structure
- 100mm unventilated air gap with metal ceiling rails
- 12.5mm gypsum plasterboard



Materials:

(grey)	- generic gravel	0.15 m
(yellow)	- XPS Surface Skin (heat cond.: 0,03 W/mK)	0.01 m
(yellow)	- XPS Core (heat cond.: 0,03 W/mK)	0.09 m
(yellow)	- XPS Surface Skin (heat cond.: 0,03 W/mK)	0.01 m
(blue)	- *DPM vapour retarder (sd=136m) (unlocked)	0.001 m
(dark grey)	- Concrete, C35/45	0.215 m
(cyan)	- Air Layer 100 mm; without additional moisture capacity	0.1 m
(off-white)	- Gypsum Board	0.013 m

It is worth noting that in the drawing shown in BS 5250 (2011) (figure H.13), the build-up would include an AVCL, if the drawing is analysed following the key / legend to the figures. However, this build-up includes in reality an impermeable waterproof covering, as mentioned in the H.9 paragraph accompanying the figure. As these two materials (ACVL and impermeable waterproof roof covering) have vapour resistance characteristics significantly different, it is important to label them accurately and differentiate between them to ensure correct and robust build-ups are installed on site.

26.3. Baseline Results

26.3.1. Baseline Cases

The 12 baseline cases are set across the four wind-driven rain exposure zones, meeting the three targets U-values (as set in paragraph 5.1).

Table 94: 12 baseline cases

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1	Case 4	Case 7	Case 10
Part L	Case 2	Case 5	Case 8	Case 11
TER	Case 3	Case 6	Case 9	Case 12

26.3.2. Critical / Monitored Junction

Any layers located above / externally to the impermeable waterproof covering are not at risk, as these layers are exposed to the external climate, are resistant to water absorption and are not enclosed in any AVCL, which could trap moisture in certain locations and create damages.

Therefore, the focus is given on RH levels and moisture content at the interface between the waterproof roof covering and the concrete slab. This is not identified as a 'critical' junction as the insulation is keeping this interface above the dew point, but the results are checked at this junction, as this is the only junction at which moisture could potentially be trapped if the build-up was to fail (in a build-up installed in 'good' conditions).

26.3.3. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the junction where potential problems could be seen, at the interface between the impermeable roof covering and the concrete slab.

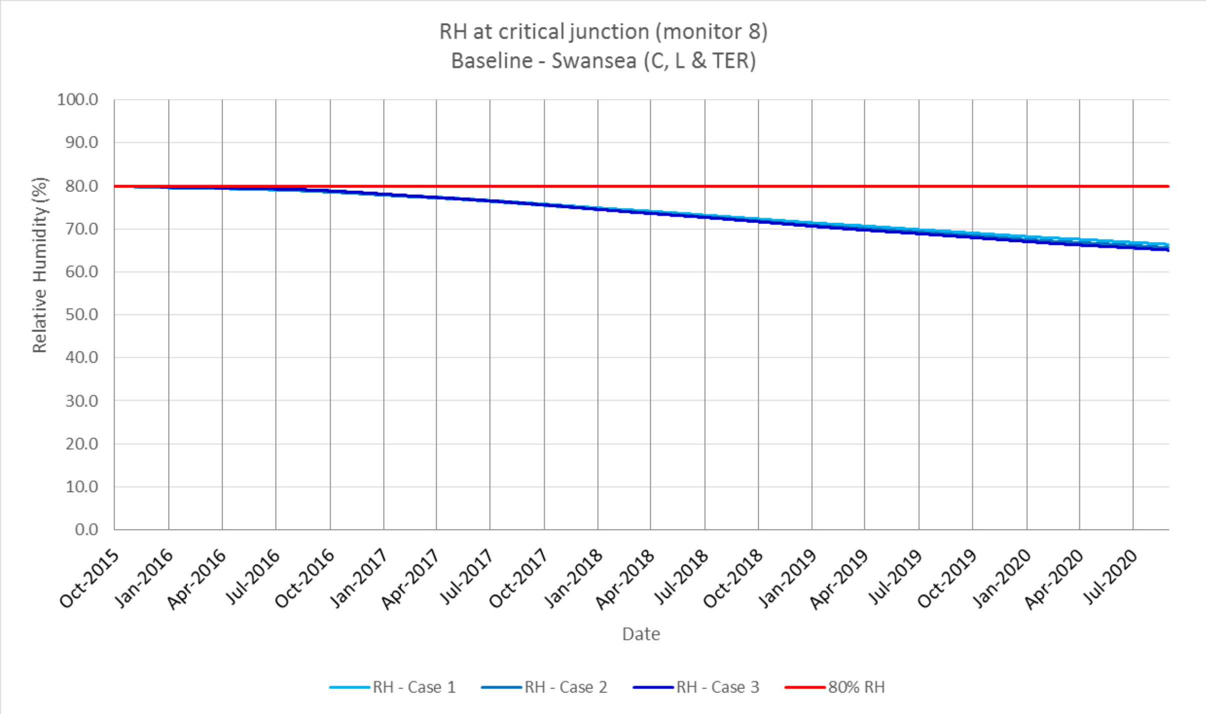


Figure 224: RH levels at critical junction for Cases 1, 2 and 3

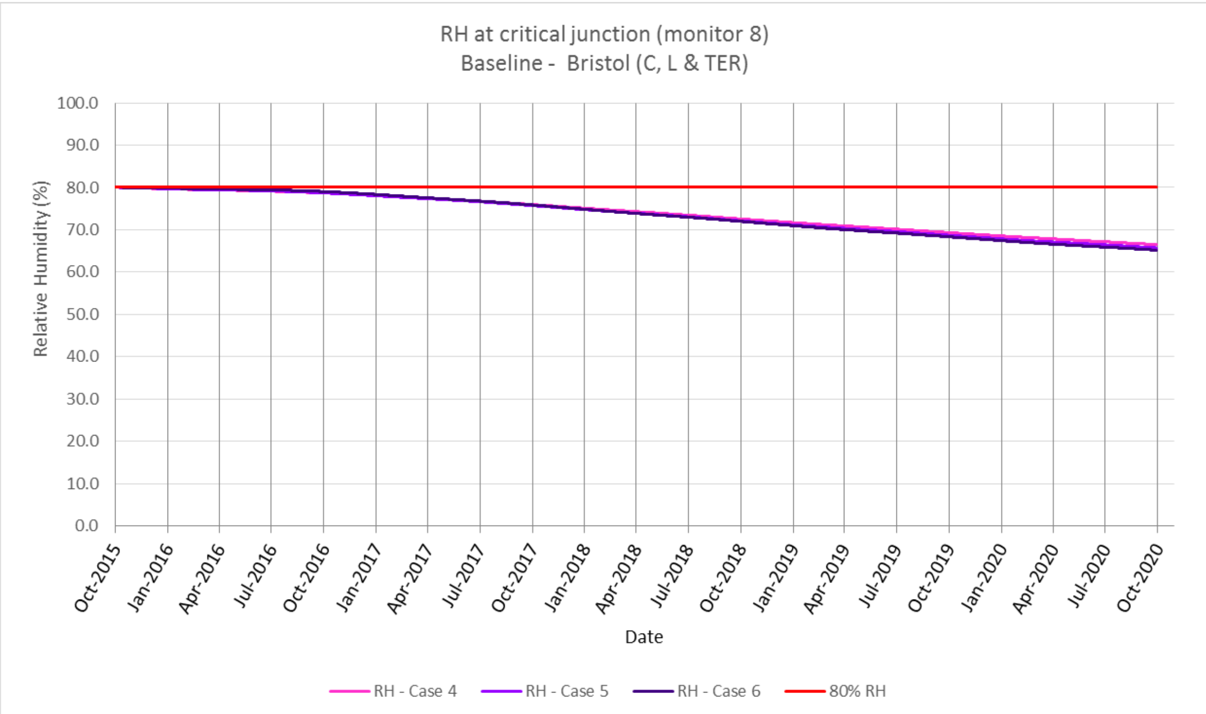


Figure 225: RH levels at critical junction for Cases 4, 5 and 6

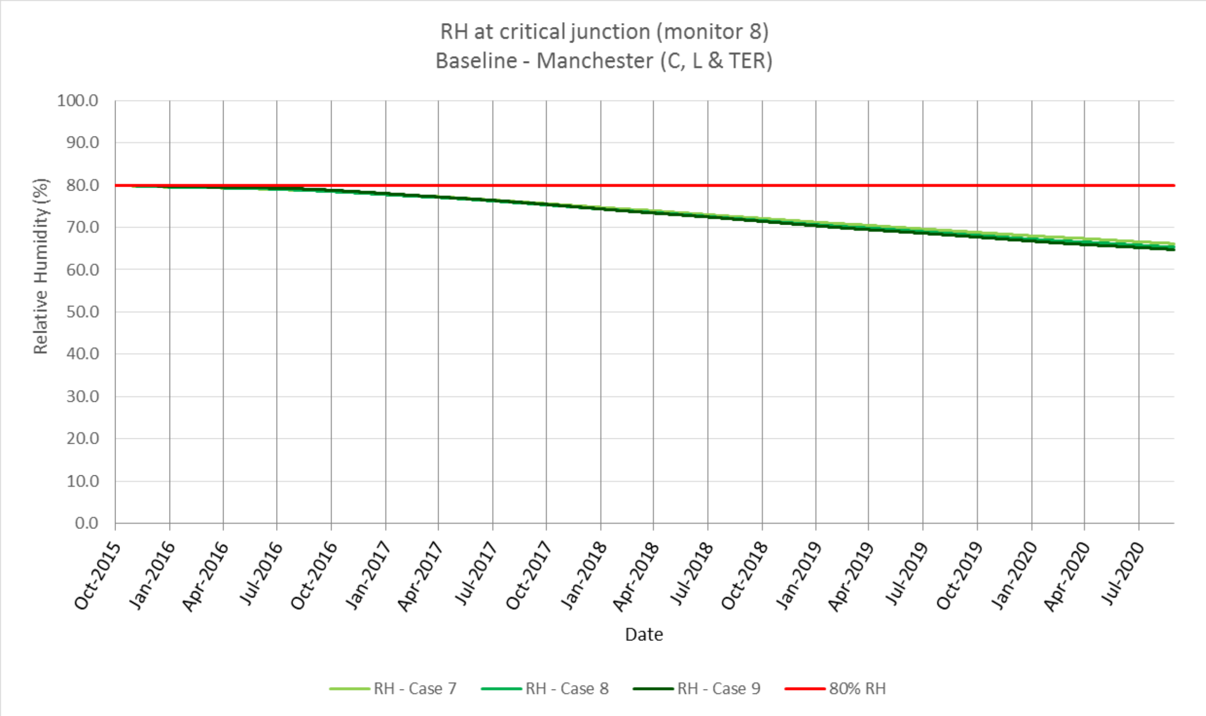


Figure 226: RH levels at critical junction for Cases 7, 8 and 9

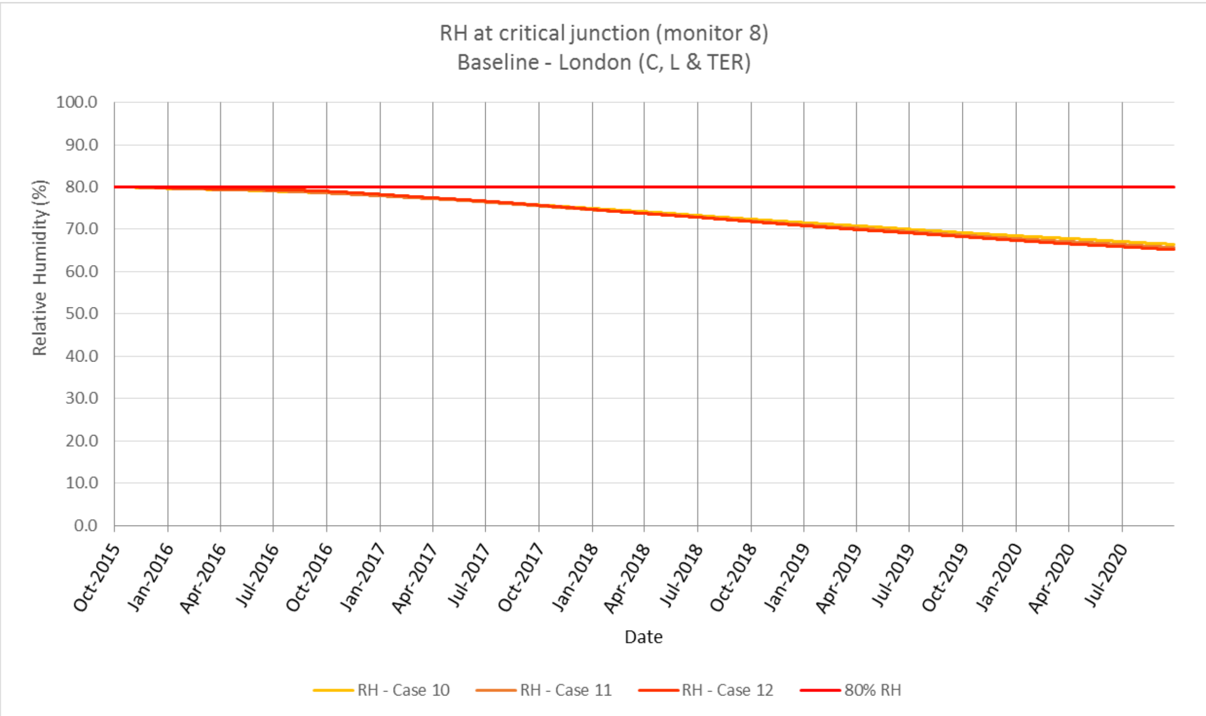


Figure 227: RH levels at critical junction for Cases 10, 11 and 12

26.3.4. Conclusions - Baseline

Moisture risk assessment criteria

All scenarios display RH levels well below 80% for the entire simulation period, slowly drying towards equilibrium.

Results

The table below summarises the performance of each case, following the moisture risk assessment criteria listed in section 2.3:

Table 95: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1 Pass	Case 4 Pass	Case 7 Pass	Case 10 Pass
Part L	Case 2 Pass	Case 5 Pass	Case 8 Pass	Case 11 Pass
TER	Case 3 Pass	Case 6 Pass	Case 9 Pass	Case 12 Pass

All cases are a 'pass', due to RH levels continuously maintained below 80% throughout the entire period of simulation, starting from initial conditions around 80% RH levels and slowly drying towards equilibrium located within the recommended RH levels.

These findings are in accordance with current recommendations and prescriptive guidance. Indeed, the junction considered the most at risk is continuously kept within recommended level, which shows the absence of mould growth or interstitial condensation.

Effects of moisture storage in concrete

Due to high capacity for moisture storage of the concrete layer, no seasonal variations can be seen on the RH levels of the build-ups at the chosen junction.

Effects of exposure zones and U-values

The difference in exposure zones is not visible on the hygrothermal performance of the build-up, which is expected, as any deterioration in the roof finish leads to complete system failure. Similarly, the difference in U-value performance is also not visible, as each level of insulation modelled is enough to ensure this interface is kept at a temperature above the dew point, to avoid mould growth and interstitial condensation risks.

26.4. Sensitivity Analysis – Change in Internal Moisture Load [Cases X.a]

26.4.1. Sensitivity Analysis Cases

This sensitivity analysis reflects a change in internal moisture load, from typical to poorer conditions (called 'high' moisture load) following the BS EN 15026 (2007) procedure (described in Annex C of BS EN 15026 (2007)).

As the baseline cases showed that the difference in exposure zones does not have an impact on the hygrothermal performance of the build-up, only cases for Zone 4 – Swansea are modelled in this sensitivity analysis, as set below.

Table 96: Cases chosen for sensitivity analysis

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.a	-	-	-
Part L	Case 2.a	-	-	-
TER	Case 3.a	-	-	-

26.4.2. Graphs at Monitored Junction

All graphs displayed below show the RH levels at the junction where potential problems could be seen, at the interface between the impermeable roof covering and the concrete slab, for the three cases located in Zone 4. The simulation period is also extended from five to ten years to better observe the build-up reaching equilibrium.

For these results, the sensitivity analysis cases X.a tested here (i.e. high moisture load) are displayed as a coloured line against their respective baseline cases, displayed with a grey line.

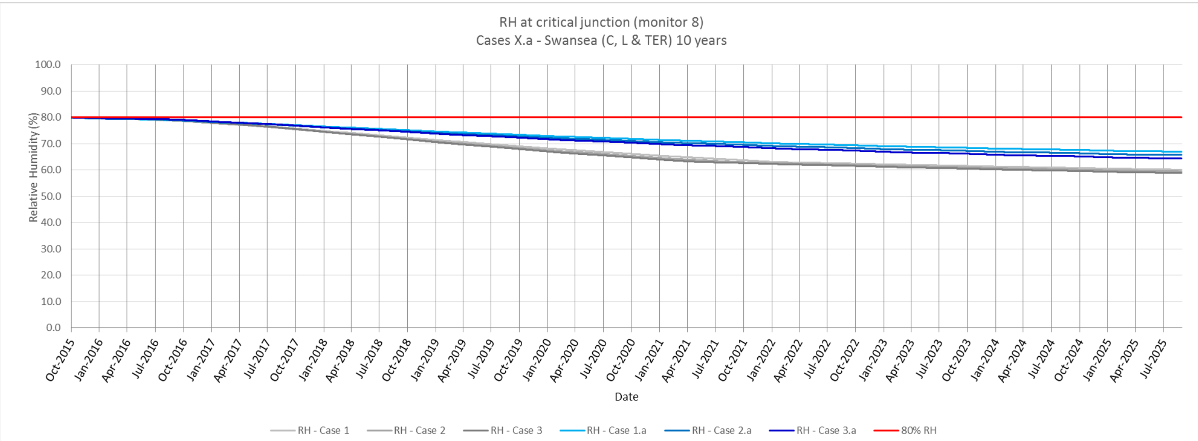


Figure 228: RH levels at critical junction for Cases 1, 1.a, 2, 2.a, 3, and 3.a for a period of 10 years

26.4.3. Conclusions – Sensitivity Analysis Cases X.a

Moisture risk assessment criteria

As predicted – due to the deterioration of indoor conditions, the graphs show that the cases modelled in this sensitivity analysis X.a perform worse compared to the baseline cases. All cases simulated here still pass, though the effect of higher internal moisture load is directly visible at the monitored junction, where an increase of internal RH levels by 10% leads to an increase of RH levels at the monitored junction between 5% to 8% (while remaining below 70%, i.e. in safe levels).

Results

The table below summarises the performance of each case modelled (as well as non-simulated cases, where results are listed by deduction), following the moisture risk assessment criteria listed in section 2.3.

All cases are considered a 'pass', as they do not accumulate moisture and the build-up slowly dry towards an equilibrium (equilibrium now slightly higher than in the baseline cases, due to poorer internal moisture conditions), which is still within recommended RH levels.

Table 97: Summary of results

	Exposure Zones			
Target U-values	**Swansea (Zone 4)**	**Bristol (Zone 3)**	**Manchester (Zone 2)**	**London (Zone 1)**
Part C	Case 1.a Pass	Case 4.a Pass	Case 7.a Pass	Case 10.a Pass
Part L	Case 2.a Pass	Case 5.a Pass	Case 8.a Pass	Case 11.a Pass
TER	Case 3.a Pass	Case 6.a Pass	Case 9.a Pass	Case 12.a Pass

Effects of 'high' moisture load (internal conditions)

Similarly to other sensitivity analyses regarding the deterioration of indoor conditions, the increase of RH levels at the monitored junction is not significant enough in this sensitivity analysis to change the status of the simulations from 'pass' to 'risky' / 'fail' but it is important to remember that the conditions described as 'high' moisture load following BS EN 15026 (2007) are not considered the most extreme internal conditions a building could be in – likely due to very poor ventilation, higher occupancy, etc.

This typology is a one of the safer typologies regarding resistance to moisture, with this build-up reaching RH levels at equilibrium much lower than RH levels setting the 'pass'/'risky' limit. In addition, any intermittent peaks in RH levels are also attenuated by the ability of the concrete layer to store high levels of moisture, which makes this build-up even safer.

Therefore, the deterioration of internal conditions has a detrimental effect on the hygrothermal performance of the build-up, which can is directly visible at the monitored junction. So it is likely that the deterioration of internal moisture conditions will, starting a certain level (likely to be extremely high for this typology), lead to the failure of the build-up.

26.5. Sensitivity Analysis – Change in External Conditions [Cases X.b]

26.5.1. Sensitivity Analysis Cases

The graphs on the hygrothermal performance of this typology (inverted roof) show that it is a very robust construction. This is due to the insulation layer, protecting the junction potentially most at risk by raising its temperature above the dew point.

However, for this to function, *'it is essential that the thermal insulation used in an inverted roof resists water absorption'* as highlighted by BS 5250 (2011). It adds that *'rainwater movement into and under the insulation will have a significant detrimental effect on the thermal performance'*.

Indeed, the performance of this build-up is linked to the quality of installation (especially around the insulation layer). If there is any rainwater or air movement into or under the insulation layer, this means the insulation cannot play its role and part of this monitored junction (interface insulation / roof covering / concrete) is then experiencing lower temperatures. These lower temperatures (with similar levels of absolute moisture) mean that RH levels increase, proving the detrimental effect of water or air penetration into and under the insulation layer.

Sensitivity analysis to try to model water / air penetration into and under insulation.:

- WUFI additional moisture source = Percentage of rain fraction (1%) in one element = last 'element' / part of insulation layer
- WUFI additional moisture source = air infiltration (class C with q50 = 5) in entire XPS insulation layer
- WUFI additional moisture source = air infiltration (class C with q50 = 5) in entire XPS and gravel layers

WUFI modelling done (as listed above) does not appear to show anticipated poor moisture and thermal performance – despite additional moisture and/or air leakage source (and additional moisture added above waterproof roof covering – so technically not a problem).

26.6. Conclusions

- Build-up safe as in BS 5250 (2011)
- Deterioration of indoor conditions has a direct consequence at monitored junction. Though build-up very safe to start with so low effect / link

- Build-up (likely to be) very impacted by bad workmanship, for example gaps in the insulation layer leading to water / air penetration into and under the insulation layer

27. Connective Effects in New Buildings using THERM junction modelling

A working set of the most common new build junctions currently not covered by ACDs was proposed in the *Identification of common types of construction* report and these are shown in the table below. These junctions have been chosen on the basis of a high default internal Ψ-value, greater than or equal to 0.1 W/m.K.

The models built in THERM will analyse the connective effects of elements that are built according the requirements of AD L and will assess the impact of the omission of junction insulation as per standard practice in absence of an accredited construction detail (ACD).

With the modelled conditions using a 20°C internal temperature (T_i) and 0°C external temperature (T_e), all surface temperatures (T_{si}) should have a minimum temperature of 15°C to avoid mould risk and meet the f_{RSi} minimum value required.

Table 98: New Build Junctions analysed

	SAP Ref	Thermal Bridge Description	Default internal ψ-value (W/m·K)
1	E20	Exposed floor (normal)	0.32
2	E21	Exposed floor (inverted)	0.32
3	E23	Balcony within or between dwellings, balcony support penetrates wall insulation	1.00
4	E24	Eaves (insulation at ceiling level - inverted)	0.24
5	E25	Staggered party wall between dwellings	0.12
6	P1	Ground floor	0.16
7	P7	Exposed floor (normal)	0.16
8	P8	Exposed floor (inverted)	0.24

The internal surface temperature factor f_{Rsi} is used as a risk indicator for mould growth, and is effectively a ratio of the internal surface temperature to the external air temperature (see equation below):

$f_{Rsi} = (T_{si} – T_e) / (T_i – T_e)$
where:

- T_{si} = internal surface temperature (°C)
- T_i = internal temperature (°C)
- T_e = external temperature (°C)

See also paragraph 3.4.1 for further detail on the internal surface temperature factor.

27.1. Risk categorisation

In order to aid interpretation, the following categorisation is given to the level of risk of mould growth depending on fRsi.

Table 99: Risk categorisation

f_{Rsi}	Risk
below 0.6	very high risk
≤0.6 - 0.7	high risk
≤0.7 - 0.75	risk
≤0.75 - 0.85	low risk
above 0.85	very low risk

27.2. Thermal performance of junctions

This study is concerned only with moisture risk and is therefore not primarily concerned with thermal performance at junctions. Junctions are modelled as typically constructed and may exhibit high heat loss characteristics. Any new junction design will need to consider both of these aspects.

28. Junction E20: Exposed floor (normal)

28.1. Build-up

Junction E20 is a new-build junction, and comprises an exposed timber floor (typology N5) and a typical partially filled cavity (typology N11). Typical construction of this junction includes support provided by a steel lintel.

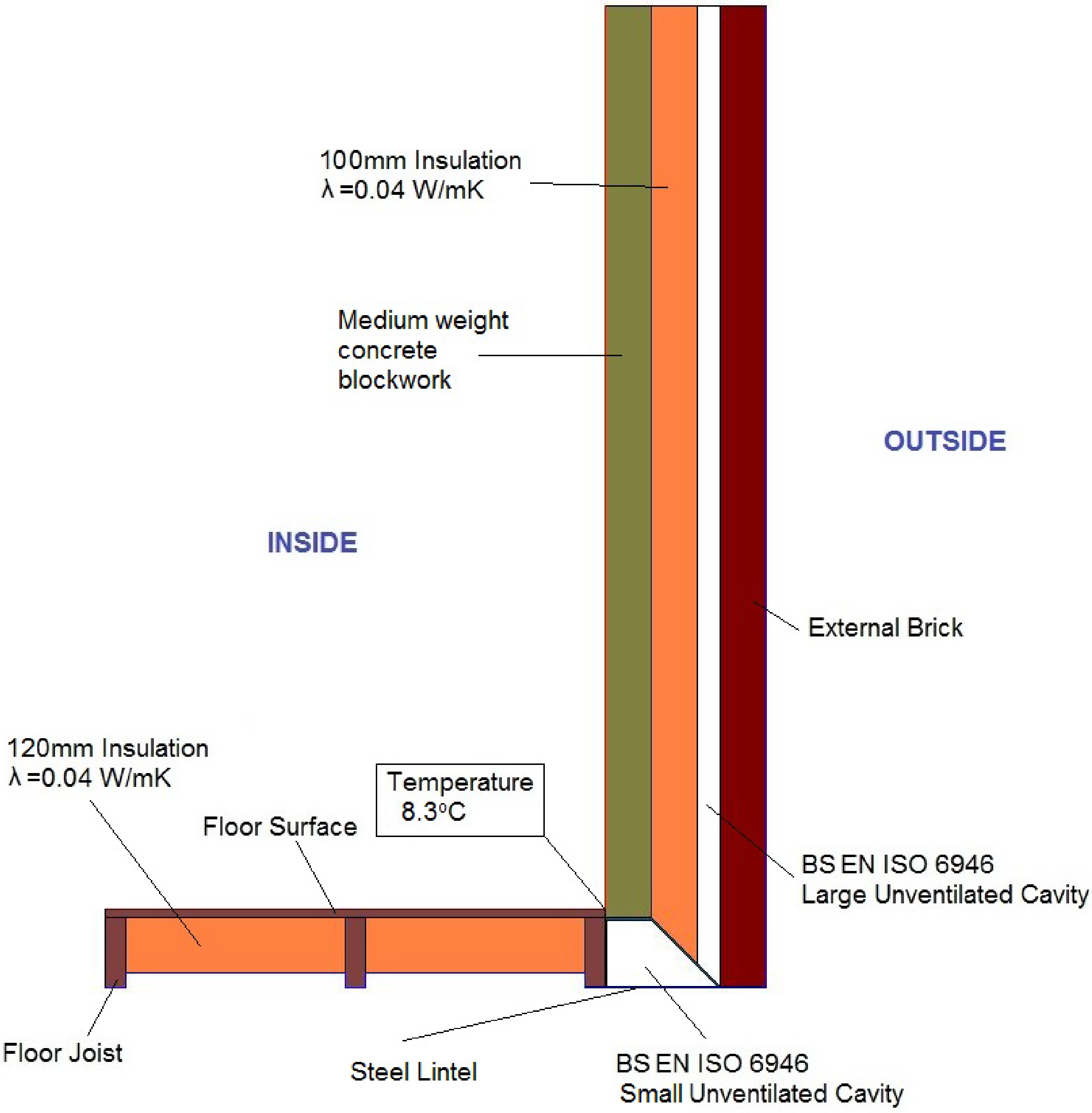


Figure 229: Modelling of the junction

28.2. Results Analysis

Lowest internal surface temperature and moisture risk assessment

The lowest internal surface temperature (T_{si}) is 8.3°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.42, which indicates a very high risk of mould growth at this junction.

28.3. Conclusions

- A common construction solution (as tested above) for this junction type has a very high mould growth risk

29. Junction E21: Exposed floor (inverted)

29.1. Build-up

Junction E21 is a new-build junction, and comprises an exposed concrete floor (typology N6 or N7) and a typical partially filled cavity (typology N11). This junction is commonly found where an overhang occurs and is at the inner edge of the overhang.

29.2. Cases

29.2.1. Case 1 (N6 floor type - insulation above)

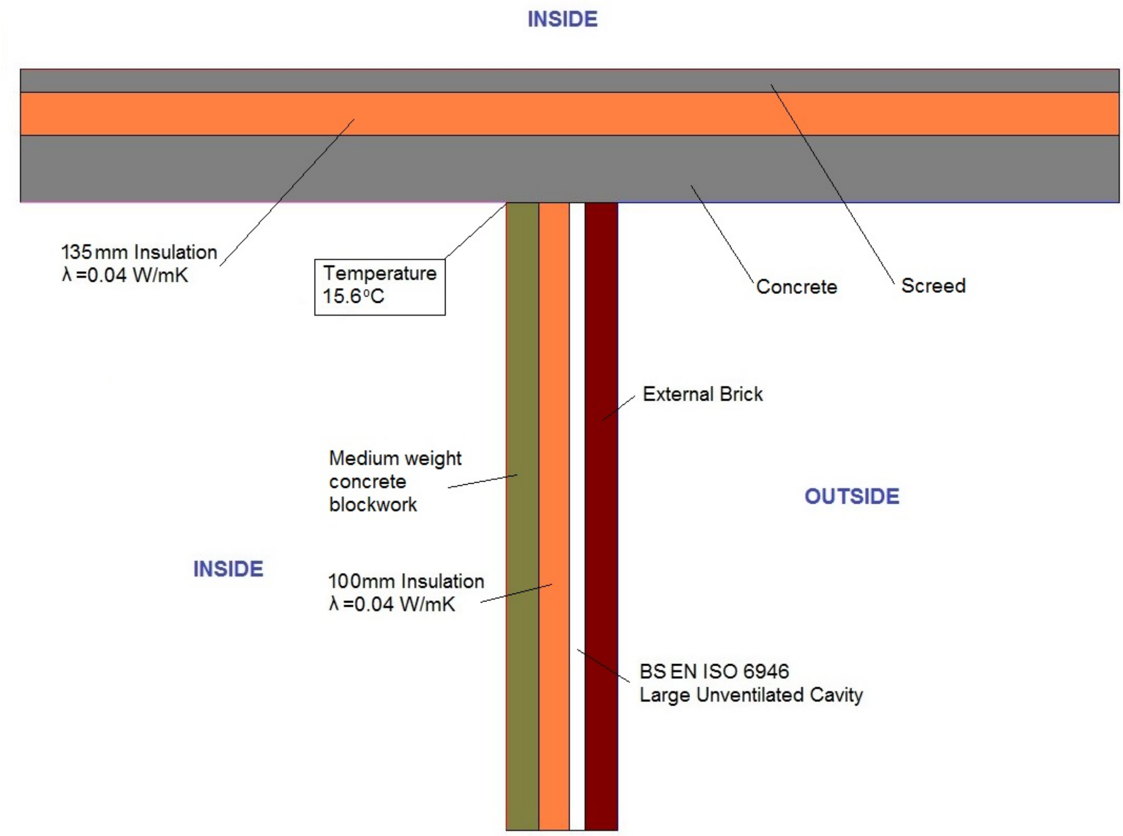


Figure 230: Modelling of the junction

29.2.2. Case 2 (N7 floor type - insulation below)

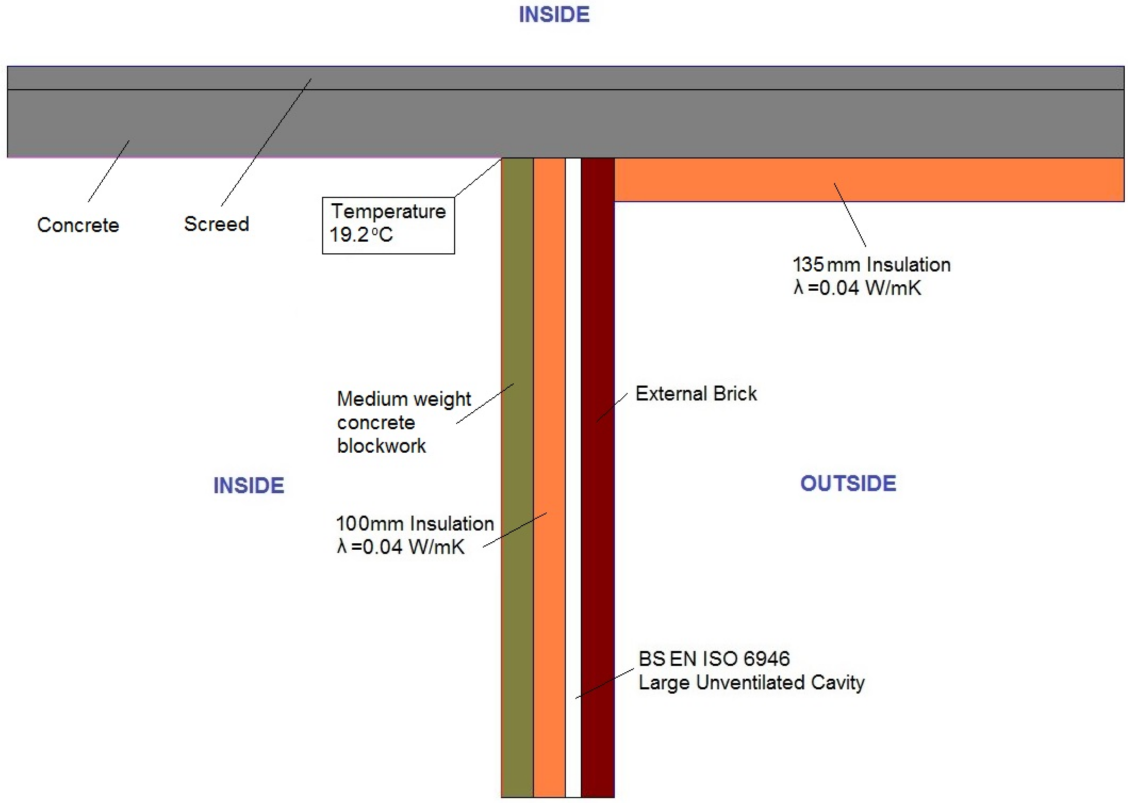


Figure 231: Modelling of the junction

29.3. Results Analysis

<u>Case 1 Lowest internal surface temperature and moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 15.6°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.78, which although indicates a low risk of mould growth at this junction, can be considered as a 'risky' junction.

<u>Case 2 Lowest internal surface temperature and moisture risk assessment</u>

The lowest internal surface temperature (T_{si}) is 19.2°C. With an external temperature of 0°C, the resultant f_{Rsi} is 0.96, which indicates a very low risk of mould growth at this junction.

29.4. Conclusions

- Case 1 is risky since the f_{RSi} is not much greater than 0.75 and mould growth could occur in colder / wetter conditions or with greater discontinuity of insulation at the junction. Where this junction is used, a bespoke calculation should be used to show that the risk of mould growth is minimised.
- Case 2 can be considered to be a robust junction against the risk of mould growth.
- Case 2 still contains a considerable thermal bridge.

30. Junction E23: Balcony within or between dwellings, balcony support penetrates wall insulation

30.1. Build-up

Junction E23 comprises of a cantilevered reinforced concrete floor slab passing through a typical partially filled cavity (typology N11).

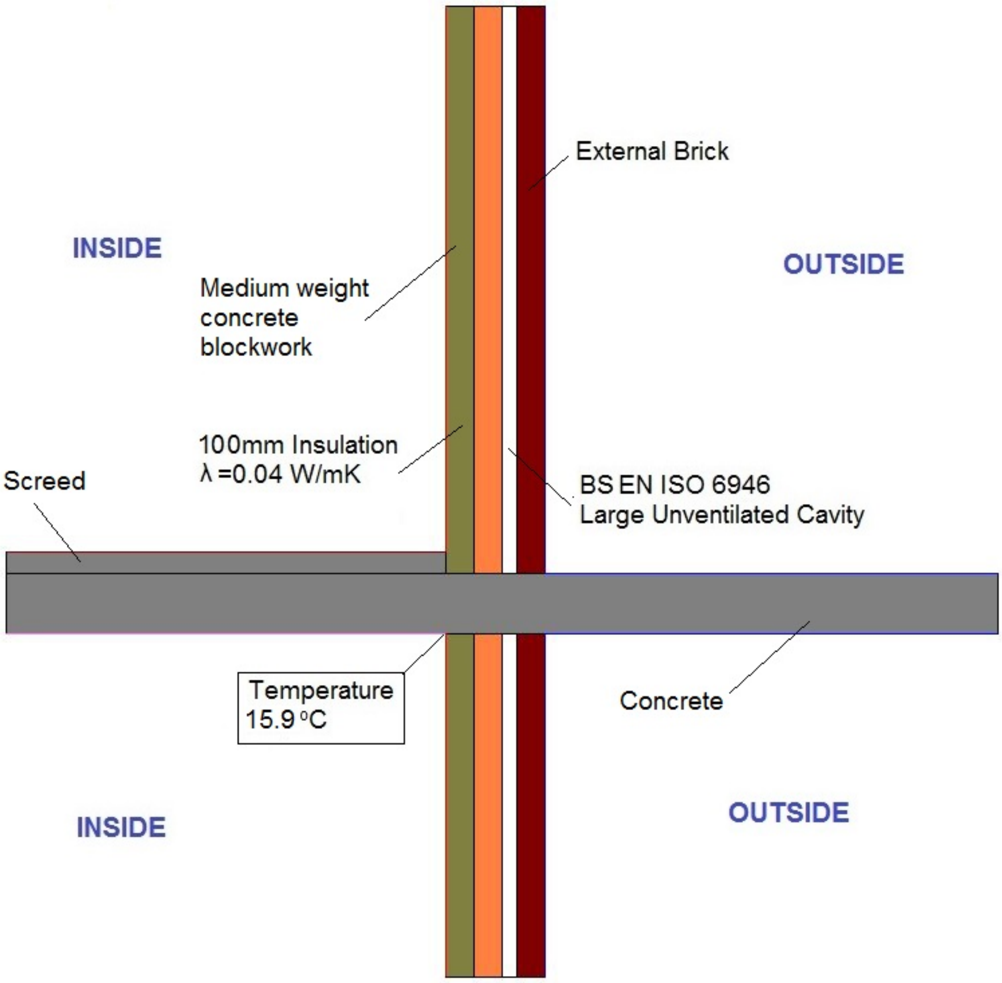


Figure 232: Modelling of the junction

30.2. Results Analysis

<u>Lowest internal surface temperature and moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 15.9°C. With an external temperature of 0°C, the resultant f_{RSi} is 0.80, which although indicates a low risk of mould growth at this junction, can be considered as a 'risky' junction.

30.3. Conclusions

- This junction is risky since the f_{RSi} is not much greater than 0.75 and mould growth could occur in colder / wetter conditions or with greater discontinuity of insulation at the junction. Where this junction is used, a bespoke calculation should be used to show that the risk of mould growth is minimised.
- Cantilevered balconies with no thermal break are becoming rarer as a construction technique since the thermal bridging values associated with the construction are very high and detrimental to compliance with AD L.

31. Junction E24: Eaves (insulation at ceiling level - inverted)

31.1. Build-up

Junction E24 is a junction between a partially filled cavity (typology N11) and an exposed concrete floor insulated above the floor slab (typology N6).

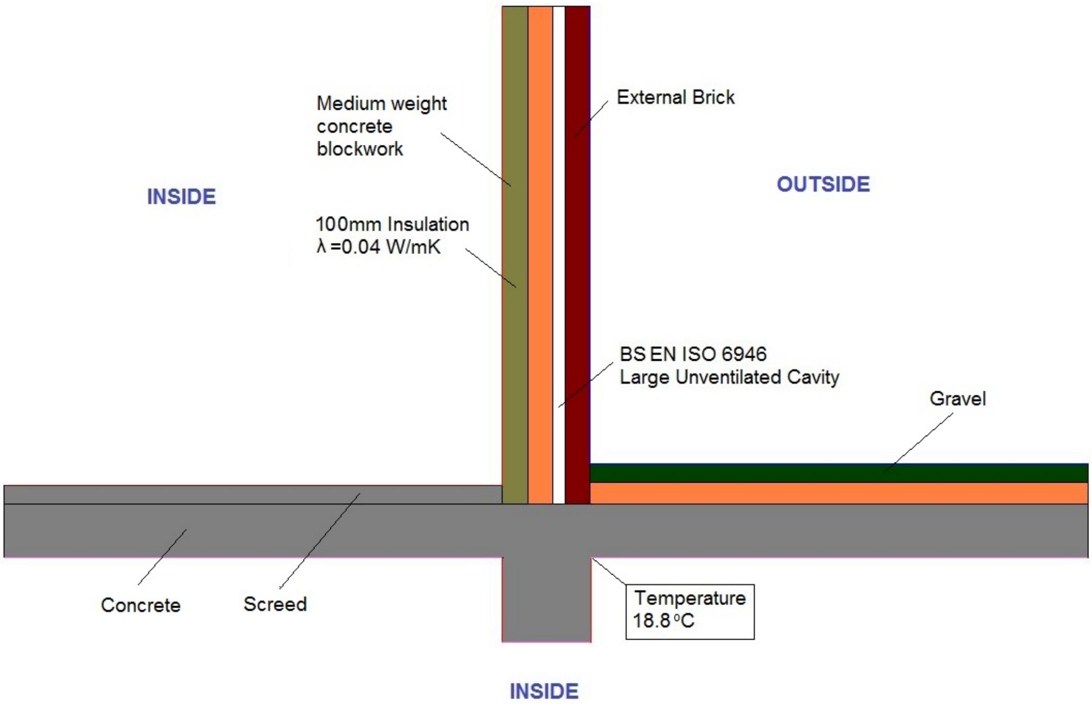


Figure 233: Modelling of the junction

31.2. Results Analysis

<u>Lowest internal surface temperature and moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 18.8°C. With an external temperature of 0°C, the resultant fRsi is 0.94, which indicates a very low risk of mould growth at this junction.

31.3. Conclusions

- This junction can be considered to be a robust junction against the risk of mould growth.

32. Junction E25: Staggered party wall between dwellings

32.1. Build-up

Junction E25 occurs where 2 dwellings are 'staggered' from each other and is located where 2 external walls and a party wall meet. A sketch of Junction E25 to clarify the location is shown below.

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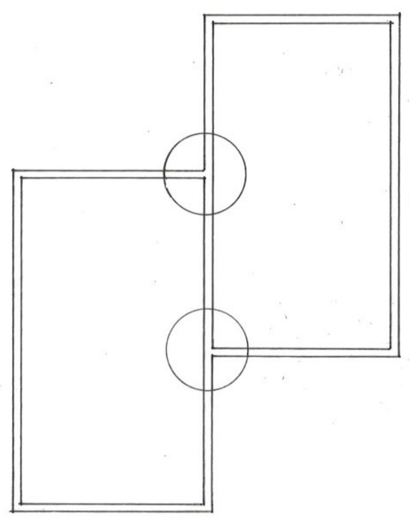

Figure 234: A Sketch of Junction E25

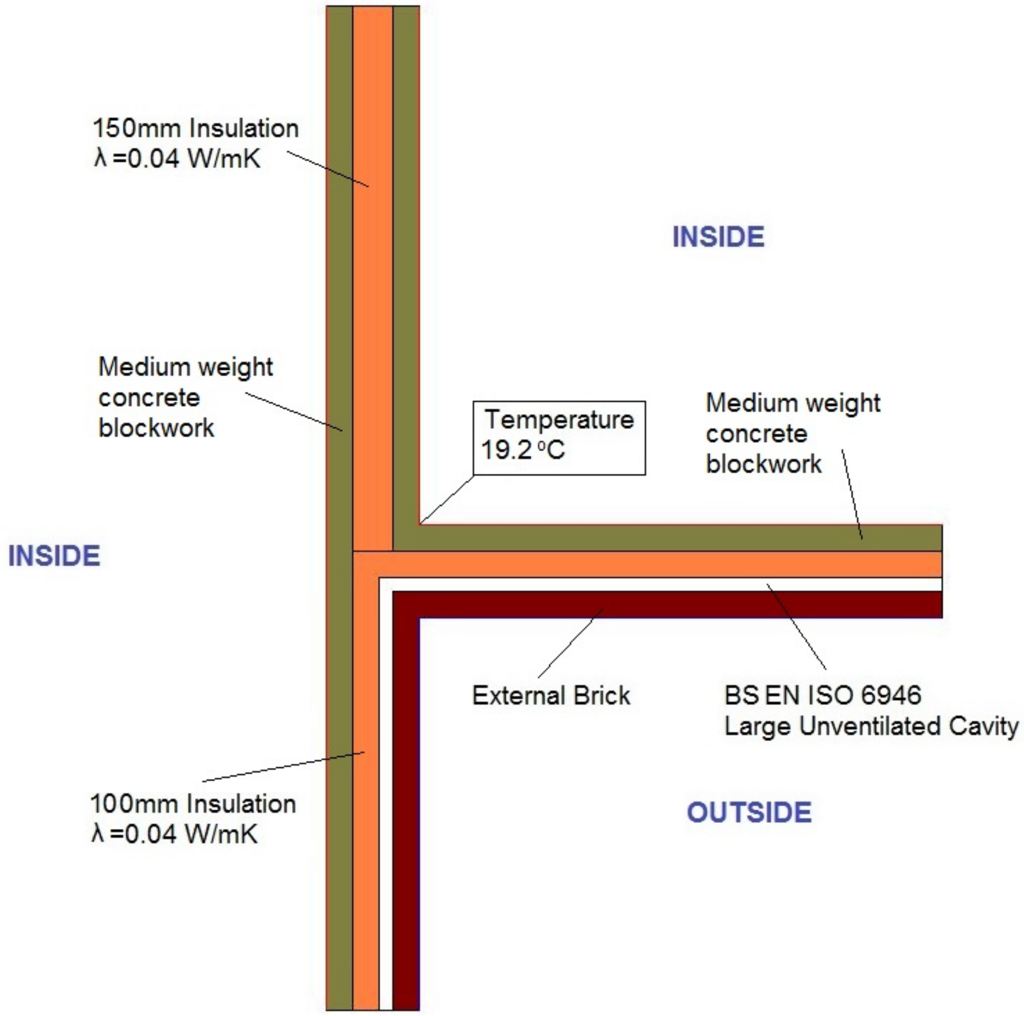

Figure 235: Modelling of the junction

32.2. Results Analysis

<u>Lowest internal surface temperature and moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 19.2°C. With an external temperature of 0°C, the resultant f_{RSi} is 0.96, which indicates a very low risk of mould growth at this junction.

32.3. Conclusions

- This junction can be considered to be a robust junction against moisture risk.

33. Junction P1: Suspended ground floor (block and beam)

33.1. Build-up

Junction P1 junction occurs where a typical block and beam floor (typology N4) meets a typical fully filled cavity (consisting of medium weight block walls separated by a fully filled cavity).

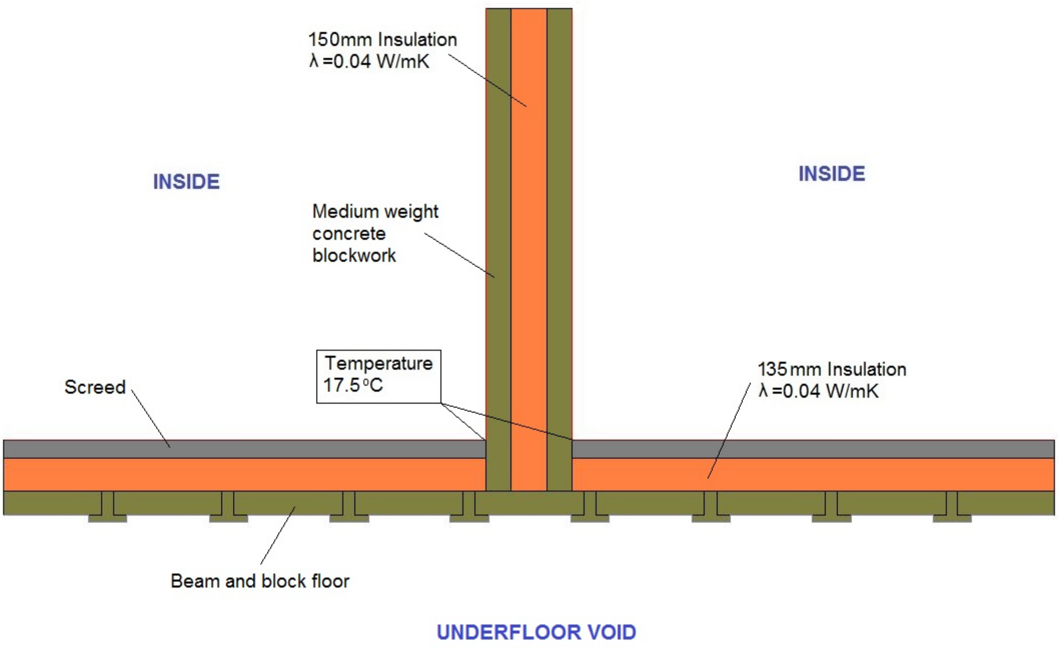

Figure 236: Modelling of the junction

33.2. Results Analysis

Lowest internal surface temperature and moisture risk assessment

The lowest internal surface temperature (Tsi) is 17.5°C. With an external temperature of 3.2°C, the resultant f_{RSi} is 0.85, which indicates a low risk of mould growth at this junction.

33.3. Conclusions

- This junction can be considered to be a robust junction against moisture risk.

34. Junction P7: Sheltered exposed floor (normal)

34.1. Build-up

Junction P7 occurs where an upper floor meets a typical fully filled cavity (consisting of medium weight block walls separated by a fully filled cavity). The boundary condition used for this section is equal to an unheated space assumed to be at 6°C.

Two different cases are analysed, where the floor is insulated above and below the concrete floor slab, respectively typology N6 or N7.

34.2. Cases

34.2.1. Case 1 (N6 floor type)

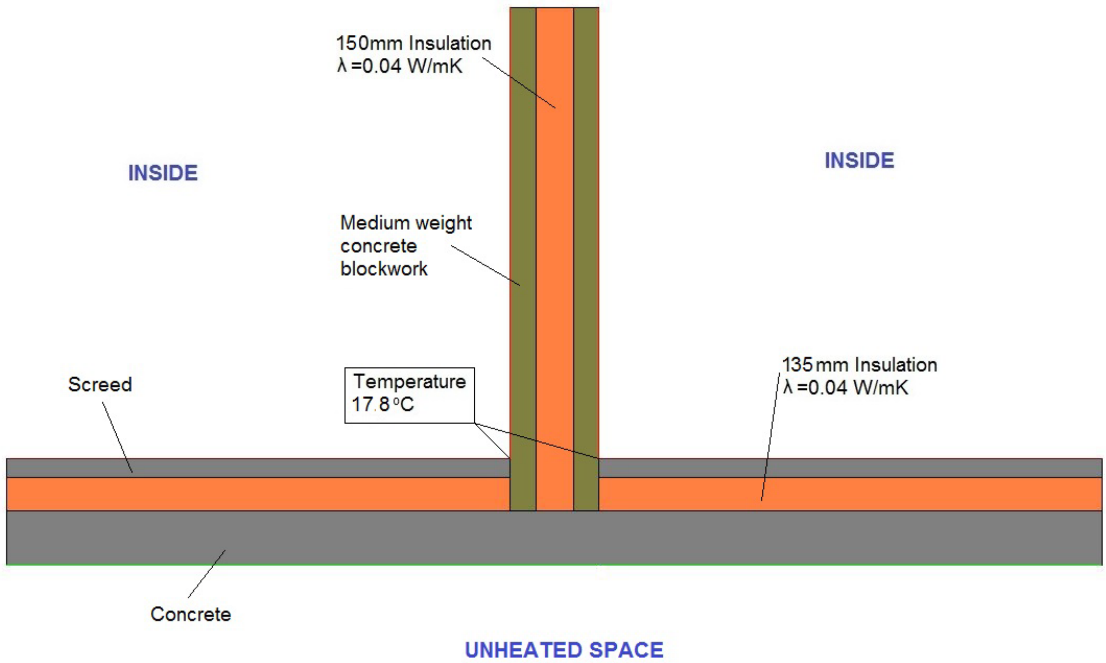

Figure 237: Modelling of the junction

34.2.2. Case 2 (N7 floor type)

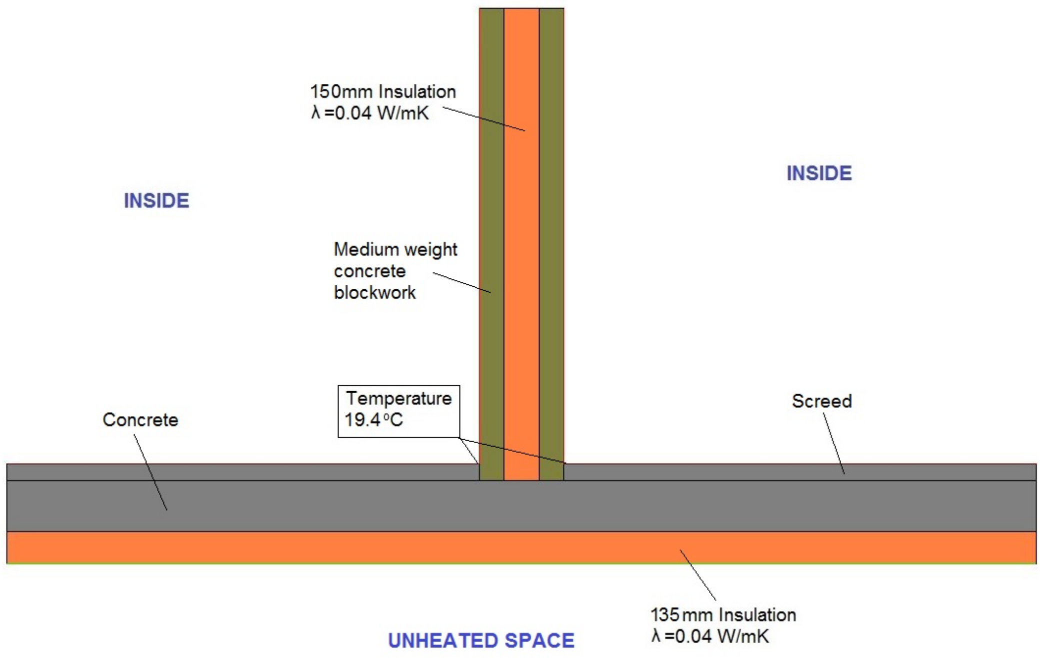

Figure 238: Modelling of the junction

34.3. Results Analysis

Case 1 Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 17.8°C. With an external temperature of 6°C, the resultant f_{Rsi} is 0.84, which indicates a low risk of mould growth at this junction.

Case 2 Lowest internal surface temperature and Moisture risk assessment

The lowest internal surface temperature (T_{si}) is 19.4°C. With an external temperature of 6°C, the resultant f_{Rsi} is 0.96, which indicates a very low risk of mould growth at this junction.

34.4. Conclusions

- Case 1 can be considered to be a robust junction against moisture risk.
- Case 2 can be considered to be a robust junction against moisture risk.

35. Junction P8: Exposed floor (inverted)

35.1. Build-up

Junction P8 is a new-build junction, and comprises an exposed floor (typology N7) and a typical partially filled cavity (typology N11).

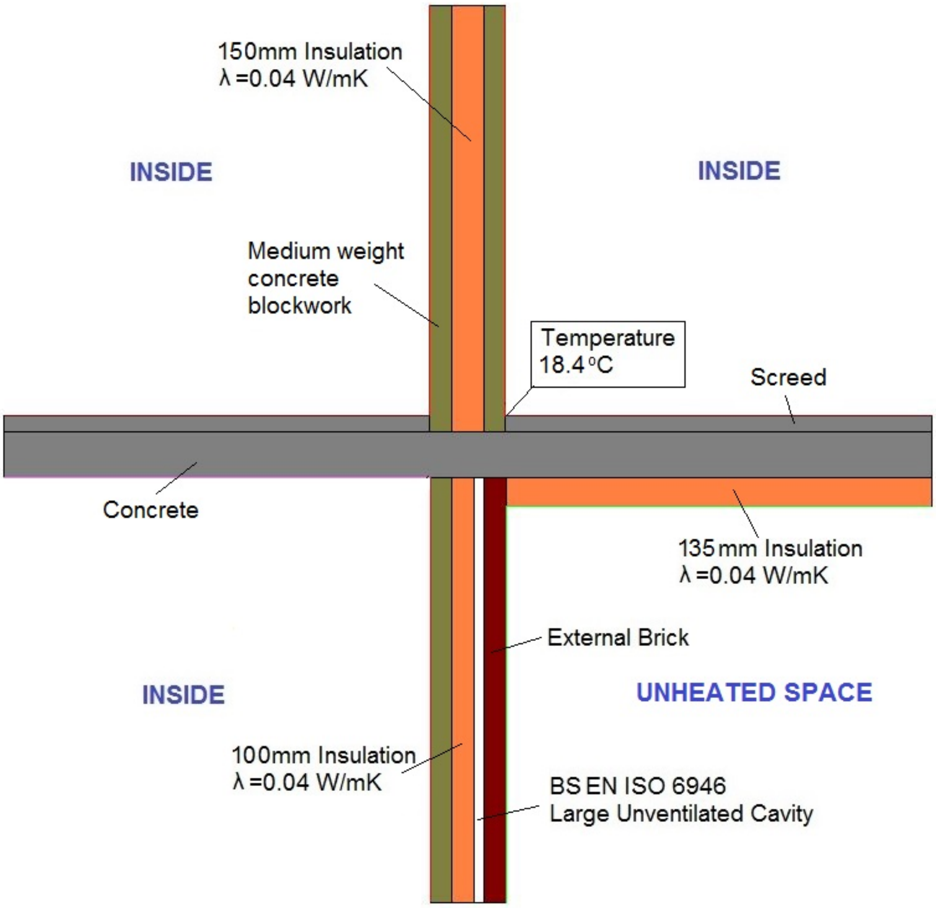

Figure 239: Modelling of the Junction

35.2. Results Analysis

<u>Lowest internal surface temperature and Moisture risk assessment</u>

The lowest internal surface temperature (Tsi) is 18.4°C. With an external temperature of 6°C, the resultant f_{RSi} is 0.89, which indicates a very low risk of mould growth at this junction.

35.3. Conclusions

- This junction can be considered to be a robust junction against moisture risk.

36. Appendix A – Exhaustive material list and their respective parameters used in the WUFI modelling

Material	Data Source	Material in standard U-value / WUFI database	WUFI database baseline material for new material	Thickness	Bulk Density	Porosity	Specific Heat Capacity, Dry	Thermal Conductivity, Dry 10°C	Water Vapour Diffusion Resistance Factor	Equiv. Air Thickness	Reference Water Content	Free Water Saturation	Water Absorption Coefficient	Water Absorption Coefficient
				t	ρ_{bulk}	w_{max}	cp	λ	μ	s_d	w80	w_f	A	A
				(mm)	(kg/m3)	(m3/m3)	(J/kg.K)	(W/m.K)	(-)	(m)	(kg/m³)	(kg/m³)	(kg/m²√s)	(kg/m²√h)
1 Timber Joists	3	Timber (softwood)	-	150	500	Ø	Ø	0.13	20	~	Ø	Ø	Ø	Ø
	1	**Softwood**	-	**150**	**400**	**0.73**	**1500**	**0.09**	**200**	~	**60**	**575**	-	-
2 Chip board	3	Chipboard	-	18	600	Ø	Ø	0.14	15	~	Ø	Ø	Ø	Ø
	1	**Chipboard**	-	**18**	**600**	**0.5**	**1500**	**0.11**	**70**	~	**90.0**	**400**	-	-
3 Plywood	3	Plywood	-	9	500	Ø	Ø	0.13	70	~	Ø	Ø	Ø	Ø
	1	**Plywood board**	-	**9**	**500**	**0.5**	**1500**	**0.10**	**700**	~	**75**	**350**	-	-
4 OSB	3	OSB	-	9	650	Ø	Ø	0.13	30	~	Ø	Ø	Ø	Ø
	1	**OSB (density 615 kg/m3)**	-	**9**	**615**	**0.9**	**1500**	**0.13**	**175**	~	**92**	**636**	**0.001**	**0.06**
5 Concrete screed	3	Concrete screed	-	75	1200	Ø	Ø	1.15	60	~	Ø	Ø	Ø	Ø
	1	**Concrete screed (mid layer)**	-	**75**	**1970**	**0.177**	**850**	**1.60**	**69**	~	**8**	**152**	**0.016**	**0.96**
6 Concrete slab	3	Concrete slab	-	150	2000	Ø	Ø	1.35	60	~	Ø	Ø	Ø	Ø
	1	**Concrete (C35/45)**	-	**150**	**2220**	**0.18**	**850**	**1.60**	**248**	~	**8**	**147**	**0.009**	**0.54**
7 Concrete	3	Insitu Concrete	-	102	1800	Ø	Ø	1.15	60	~	Ø	Ø	Ø	Ø
	1	**Concrete (C35/45)**	-	**150**	**2220**	**0.18**	**850**	**1.60**	**248**	~	**8**	**147**	**0.009**	**0.54**
8 Floor Blocks	3	Concrete floor blocks	-	100	660	Ø	Ø	0.16	6	~	Ø	Ø	Ø	Ø
	1	**Concrete blocks (pumice aggregate)**	-	**100**	**664**	**0.67**	**850**	**0.14**	**4**	~	**28**	**291**	**0.047**	**2.82**
9 Blockwork	3	Blockwork - medium aggregate	-	100	1400	Ø	Ø	0.57	10	~	Ø	Ø	Ø	Ø
	5	**Blockwork - medium density**	**Concrete blocks (pumice aggregate)**	**100**	**1450**	**0.43**	**850**	**0.47**	**10**	~	**18**	**219**	**0.028**	**1.68**
10 Gravel	3	Gravel	-	150	1700	Ø	Ø	2	50	~	Ø	Ø	Ø	Ø
	1	**Generic Gravel**	-	**150**	**1400**	**0.3**	**1000**	**0.70**	**1**	~	**5**	**50**	-	-
11 Brick wall	3	Solid brick wall	-	215	1700	Ø	Ø	0.77	45	~	Ø	Ø	Ø	Ø
	1	**Solid brick (hand-formed)***	-	**215**	**1725**	**0.38**	**850**	**0.60**	**17**	~	**2.7**	**200**	**0.300**	**18**
		*In solid brick wall with IWI, we know that the brick characteristics play a major role on the hygrothermal performance of the build-up. A sensitivity analysis will be done and we suggest some of the following bricks from WUFI database:												
	1	Solid brick masonry	-	215	1900	0.24	850	0.6	10	~	18	190	0.110	6.600
	1	Aerated clay brick (650 kg/m3)	-	215	650	0.74	850	0.13	15	~	15	178	0.097	5.820
12 EPS Insulation	3	EPS	-	87.5	15	Ø	Ø	0.04	60	~	Ø	Ø	Ø	Ø
	1	**EPS (density: 15 kg/m3)**	-	**87.5**	**15**	**0.95**	**1500**	**0.04**	**30**	~	-	-	-	-
13 XPS	3	XPS	-	30	30	Ø	Ø	0.03	50	~	Ø	Ø	Ø	Ø
	1	**XPS Surface Skin (heat. cond.: 0.03 W/m.K)**	-	**30**	**40**	**0.95**	**1500**	**0.03**	**450**	~	-	-	-	-
	1	**XPS Core (heat. cond.: 0.03 W/m.K)**	-	**30**	**40**	**0.95**	**1500**	**0.03**	**100**	~				
14 Polyurethane	3	PU Foam	-	30	30	Ø	Ø	0.025	50	~	Ø	Ø	Ø	Ø
	1	**PU (heat cond.: 0.025 W/m.K)**	-	**30**	**40**	**0.95**	**1500**	**0.025**	**50**	~	-	-	-	-
15 Mineral wool	3	Mineral wool	-	100	12	Ø	Ø	0.04	1	~	Ø	Ø	Ø	Ø
	1	**Mineral wool (heat cond.@ 0.04W/m.K)**	-	**100**	**60**	**0.95**	**850**	**0.04**	**1.3**	~	-	-	-	-
16 DPM	3	DPM	-	0.3	920	Ø	Ø	0.17	400000	Ø	Ø	Ø	Ø	Ø
	1	**DPM (sd = 136m)**	**vapour retarder (sd = 100m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**136400**	**136**	-	-	-	-
17 Foil paper facing	3	Foil paper facing	-	0.05	1100	Ø	Ø	200	999999	Ø	Ø	Ø	Ø	Ø
	1	**Foil paper facing (sd = 14m)**	**vapour retarder (sd = 10m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**14000**	**14.0**	-	-	-	-
18 VCL	3	VLC / Polyethylene	-	0.05	920	Ø	Ø	0.17	300000	Ø	Ø	Ø	Ø	Ø
	1	**VLC (sd = 2m)**	**vapour retarder (sd = 2m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**2000**	**2**	-	-	-	-
19 Breather Membrane	3	Breather membrane	-	0.1	350	Ø	Ø	0.17	2000	Ø	Ø	Ø	Ø	Ø
	1	**Breather membrane (sd = 0.04m)**	**weather resistive barrier (sd = 0.1m)**	**1**	**130**	**0.001**	**2300**	**2.30**	**40**	**0.04**	-	-	-	-
20 Gypsum Plasterboard	3	Gypsum plasterboard	-	12.5	700	Ø	Ø	0.21	4	~	Ø	Ø	Ø	Ø

Material	Data Source	Material in standard U-value / WUFI database	WUFI database baseline material for new material	Thickness	Bulk Density	Porosity	Specific Heat Capacity, Dry	Thermal Conductivity, Dry 10°C	Water Vapour Diffusion Resistance Factor	Equiv. Air Thickness	Reference Water Content	Free Water Saturation	Water Absorption Coefficient	Water Absorption Coefficient
				t	ρ_{bulk}	w_{max}	cp	λ	μ	s_d	w80	w_f	A	A
				(mm)	(kg/m3)	(m3/m3)	(J/kg.K)	(W/m.K)	(-)	(m)	(kg/m^3)	(kg/m^3)	(kg/m^2√s)	(kg/m^2√h)
	1	**Gypsum board**	-	**12.5**	**850**	**0.65**	**850**	**0.20**	**8.3**	~	**6.3**	**400**	**0.287**	**17.22**
21 Gypsum Plaster	3	Wet plaster	-	12.5	700	∅	∅	0.21	4	~	∅	∅	∅	∅
	1	**Interior Plaster (Gypsum plaster)**	-	**12.5**	**850**	**0.65**	**850**	**0.20**	**8.3**	~	**6.3**	**400**	**0.287**	**17.22**
22 Silicone render	3	Silicone render	-	15	1250	∅	∅	0.3	9.8	~	∅	∅	∅	∅
	2	**Silicone resin finishing coat (Masea database)**	-	**15**	**1475**	**0.44**	**1000**	**0.69**	**74**	~	**2.9**	**303**	**0.000**	**0.01**
23 Render	3	Render (sand and cement)	-	15	1600	∅	∅	0.8	6	~	∅	∅	∅	∅
	1	**Cement plaster (stucco, A = 0.51 kg/m2√h)**	-	**12.5**	**2000**	**0.3**	**850**	**1.20**	**25**	~	**35**	**280**	**0.009**	**0.51**
24 Cement particle board	3	Cement particle board	-	25	1200	∅	∅	0.23	30	~	∅	∅	∅	∅
	2	**Cement board (North American database)**	-	**25**	**1130**	**0.48**	**840**	**0.26**	**28**	~	-	-	-	-
25 Bitumen	3	Bitumen	-	25	110	∅	∅	0.23	50000	∅	∅	∅	∅	∅
	2	**Bitumous felt (Generic database)**	**Roof membrane V13 (sd = 100m)**	**1**	**2400**	**0.001**	**1000**	**0.5**	**100000**	**100.0**	-	-	-	-
26 Unventilated air gap	3	Unventilated air gap - 15mm	-	15	1.2	∅	∅	0.088	1	~	∅	∅	∅	∅
	2	**Air Layer 15mm w/o add. moist. cap. (Generic database)**	**Air layer average (10mm + 20mm)**	**15**	**1.3**	**0.999**	**1000**	**0.10**	**0.65**	~	-	-	-	-
27 Unventilated air gap	3	Unventilated air gap - 50mm	-	50	1.2	∅	∅	0.278	1	~	∅	∅	∅	∅
	2	**Air Layer 50mm w/o add. moist. cap. (Generic database)**	-	**50**	**1.3**	**0.999**	**1000**	**0.28**	**0.32**	~	-	-	-	-
28 Unventilated air gap	3	Unventilated air gap - 100mm	-	100	1.2	∅	∅	0.9	1	~	∅	∅	∅	∅
	2	**Air Layer 100mm w/o add. moist. cap. (Generic database)**	-	**100**	**1.3**	**0.999**	**1000**	**0.59**	**0.15**	~	-	-	-	-
29 Unventilated air gap	3	Unventilated air gap - 200mm	-	100	1.2	∅	∅	0.9	1	~	∅	∅	∅	∅
	2	**Air Layer 200mm w/o add. moist. cap. (Generic database)**	**Air layer assumption (150mm)**	**100**	**1.3**	**0.999**	**1000**	**1.08**	**0.05**	~	-	-	-	-
30 Stone wool Rockwool	-	-	-	-	-	-	-	-	-	~	-	-	-	-
	1	**Stone wool Rockwool RedART**	**Mineral wool**	**100**	**107**	**0.96**	**1030**	**0.036**	**1.1**	~	**0.09**	**150**	**0.00083**	**0.050**
31 Silicone Render Rockwool	-	-	-	-	-	-	-	-	-	~	-	-	-	-
	2	**Silicone render Rockwool RedART**	**Silicone resin finishing coat**	**15**	**1800**	**0.41**	**1500**	**0.70**	**80**	~	**3.1**	**350**	**0.00019**	**0.011**
RETROFIT														
32 Lime Plaster	1	-	-	-	-	-	-	-	-	~	-	-	-	-
	1	**Lime Plaster (stucco, A-value: 3.0 kg/m2h0.5)**	-	**15**	**1600**	**0.3**	**850**	**0.70**	**7**	~	**30**	**250**	**0.05**	**3**

\# **Data sources**
- 1 - Fraunhofer IBP database in WUFI
- 2 - Other Database in WUFI
- 3 - Estimated based on standard materials (i.e. Builddesk)
- 4 - Manufacturer information
- 5 - Adapted from manufacturer literature
- 6 - Estimate based on industry literature

37. Appendix B – Glossary

Accredited construction detail	Junction details developed to assist the construction industry achieve the performance standards required to demonstrate compliance with the energy efficiency requirements (Part L) of the Building Regulations. They focus on thermal bridging (i.e. avoiding extra heat loss at the junctions of insulted elements) and the consequential risk of surface condensation / mould growth. They are not designed to address interstitial condensation.
Adhering fraction of rain	Ratio of available rain fall penetrating the external surface of an element over the total amount of rain fall. It takes into account that some of the rain water hitting the component surface splashes off on impact and might not be available for capillary absorption (it varies from zero if the facade is protected from rain, 0.7 for an exposed wall and 1 if all rain water shall be available for absorption, flat roof)
As-Built / In-Service (ABIS) conditions	ABIS conditions describe conditions to which a build-up is submitted, which occur in the real world and take into account the existing or likely-to-exist conditions in buildings, as opposed to a partial risk assessment “as designed” or “theoretical”(ADT), which excludes these ABIS conditions
Building fabric	Elements of the external building envelope (consisting of the building’s roofs, floors, walls, windows and doors), being the separation between the internal environment and the external conditions. It is a critical component of any building, since it both protects the building occupants and plays a major role in regulating the indoor environment.
Condensation	Process whereby water is deposited from air containing water vapour when its temperature drops to or below the dew point (or the vapour pressure rises above the saturated vapour pressure at a given temperature).
Connective effects	Moisture or thermal related effects that occur at interfaces/junctions between elements or materials
Convective transport	Collective motion of water molecules in a fluid (encompassing both diffusion and advection). Convective heat transfer is one of the major types of heat transfer, with convection being a major mode of mass transfer in fluids.
Critical junction	The intersection within a build-up that is the most at risk of interstitial condensation and/or mould growth

Diffusion	The net movement of water molecules from high concentration to low concentration
Equilibrium	An object reaches ***moisture equilibrium*** with the environment when it neither gains nor loses moisture over a set period of time (typically a year) from the constant, dynamic exchange of moisture with the environment
Fragile material	Material that is susceptible to damage (e.g. rot, dimensional instability, surface mould) due to high moisture levels
Glaser method	A simplified one-dimensional steady-state assessment method, described in BS EN ISO 13788, to calculate the amount of interstitial condensate formed during a cold winter period and the theoretical amount of evaporable water in a cold summer. If the amount of condensate does not exceed specified limits and, if it is lower than the evaporable amount of water, the building assembly is considered to be safe.
Ground moisture	Moisture contained in a ground material (e.g. soil), as opposed atmospheric moisture or rain.
Hygroscopic material	A material attracts and hold water molecules from the surrounding environment
Hygrothermal	Relating to the movement of both heat and moisture
Internal Surface Temperature Factor (f_{Rsi})	The ratio of the total thermal resistance of the building envelope to the thermal resistance of the building envelope without the internal surface resistance as defined in EN ISO 10211. Depends on the indoor and outdoor air temperatures and on the temperature at the internal surface of the building envelope. Also referred to as the temperature ratio, temperature index, or condensation resistance factor. In this report, f_{Rsi} is used to indicate the risk of mould growth in indoor environments
Interstitial condensation	Condensation occurring within or between layers of construction elements that are part of a building's thermal envelope.
Masonry walls	Wall made of concrete blocks, stone or brick and mortar
Membranes	A thin pliable sheet of material which forms a barrier, covering or lining
Micro-climates	The climate of a very small or restricted area, especially when this differs from the climate of the surrounding area
Moisture-open	A description for a building material or element that allows water vapour to pass through it without significant barriers.

Moisture Risk Assessment Criteria	Criteria used for assessing the risk of moisture in a building element
Moisture storage function	A curve (approximated in WUFI) for porous hygroscopic materials that defines the way a material absorbs, stores and redistributes water relative to the moisture conditions in the material (relative humidity and total water content)
Porosity	The measure of the void (i.e. "empty") spaces in a material, and is a fraction of the volume of voids over the total volume. Value expressed as a ratio (between 0 and 1), or as a percentage (between 0 and 100%)
Precipitation	Any product of the condensation of atmospheric water vapour that falls under gravity (e.g. rain)
Relative humidity	The ratio of the vapour pressure in air at a given temperature to the saturation vapour pressure at the same temperature; commonly expressed as a percentage (between 0 and 100%).
s_d-value (equivalent air layer thickness)	A measure of the vapour resistance of a material expressed as the thickness which a stagnant air layer would need in order to have the same diffusion resistance. As its name suggests, it is measured in metres. Like vapour resistance, it can only be quoted for a particular thickness of a material.
Solar radiation	Radiant energy emitted by the sun that provides heat energy to exposed objects including building elements.
Specific heat capacity	The property of a material, which measures the energy required to raise the temperature of 1kg of that material by 1°C measured in joule per kelvin J/K.
Surface condensation	Condensation occurring on interior surfaces of a building.
Surface heat transfer coefficients	Thermal resistance of a surface (internal or external) expressed in m2.K/W. Values that are used in conjunction with building material properties (material thermal conductivity and thickness) to calculate the U-value of building elements.
Synthetic weather files	Hourly weather files used for WUFI simulation created from monthly climatic averages using Meteonorm software. Although Meteonorm provides precipitation data, the synthetically derived rain data may have limitations for hygrothermal (WUFI) modelling.
Thermal	Where heat is transferred via convection in a building

bypass	element due to air gaps within or between materials/components (including cavities). This air movement bypasses the normally expected heat transfer mechanisms (used to calculate U-values) and reduces the effective thermal performance of that building element.
Thermal conductivity	The property of a material that describes its ability to conduct heat. Measured in watts per meter kelvin (W/(m·K)). Used, along with a material's thickness, to calculate U-values
U-value	A measure of thermal transmittance, which describes how effective an element of building fabric is as a heat insulator. The lower the U-value, the better the construction is as an insulator. U-values are measured in watts per square metre of surface element per degree Kelvin (W/m^2K).
Vapour Control Layer (VCL)	A material with high vapour resistance (there are varying definitions of this) that reduces/prevents vapour diffusion through a building element.
Vapour diffusion	The physical process of water vapour (not liquid water) passing through porous building materials due to the difference in vapour pressures (water content of the air) on either side on that material.
Vapour resistance	A measure of a material's resistance to letting water vapour pass through. The vapour resistance takes into account the material's thickness, so can only be quoted for a particular thickness of material. It is usually measured in MNs/g ("MegaNewton seconds per gram"). See also s_d Value
Water absorption coefficient A-value	Defined in DIN 52617: "Determination of the water absorption coefficient of building materials". Measured in $kg/m^2s^{1/2}$. For hygroscopic, capillary active materials (such as masonry) the A value provides a reasonable means of estimating how the material absorbs and stores liquid water over time.
Water content	The quantity (mass) of water contained in a material
Wind-driven rain	Rain that is given a horizontal velocity component by the wind otherwise known as "driving rain". Exposure to wind driven rain in the UK is assessed using BS 8104: 1992 – 'Assessing exposure of walls to wind-driven rain'. This standard provides a driving rain index measured in litres per m^2 façade area per spell and also has an exposure map with four zones as follows: • Zone 1 – sheltered – less than 33 l/m2 per spell

	• Zone 2 – moderate – 33 to less than 56.5 l/m2 per spell • Zone 3 – severe – 56.5 to 100 l/m2 per spell • Zone 4 – very severe – 100 l/m2 per spell, or more.
WUFI (Wärme und Feuchte instationär - Transient Heat and Moisture)	Software developed by the Fraunhofer Institute of Building Physics (IBP) in Germany and implements the approach set out in BS EN 15026. It allows realistic calculation of the transient hygrothermal behaviour of multi-layer building components exposed to natural climate conditions and has been validated using data derived from outdoor and laboratory tests. WUFI is based on the newest findings regarding vapour diffusion and liquid transport in building materials. The modelling in this report was carried out with WUFI Pro 5.3, one-dimensional hygrothermal simulation software.

38. Appendix C – References

BS 5250 (2011): Code of practice for control of condensation in buildings. BSI Standards Publication.

BS EN 15026 (2007): 'Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation'. BSI Standards Publication.

BS EN ISO 10211 (2007): Thermal bridges in building construction - heat flows and surface temperatures - detailed calculations. BSI Standards Publication.

BS EN ISO 13788 (2012): 'Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods'. BSI Standards Publication.

May, N. & Sanders, C. (2014). Moisture Risk Assessment and Guidance. Sustainable Traditional Building Alliance and Department of Energy & Climate Change.

Rirsch, E., Zhang, Z. (2012). Energy Saving from Water Repellents. Retrofit 2012. University of Salford.

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