THE SPAB RESEARCH REPORT 3.

The SPAB Hygrothermal Modelling:

Interim Report

OCTOBER 2012.

Dan Browne

www.spab.org.uk

Foreword

This report forms part of the SPAB's Building Performance Survey, a research project that looks at the performance of a number of traditional buildings both before and after refurbishment designed to improve energy efficiency. This report concentrates on one of the case study houses from that survey, located in Shrewsbury. Following a review of the British Standards the report presents findings from a study using BS 15026 advanced condensation risk analysis software. The advanced hygrothermal simulation of the case study house, both pre-refurbishment and post-refurbishment raises various issues and has serious consequences, especially for the Green Deal. Methods for improving accuracy in modelling thermal upgrades are presented along with further research needed and other recommendations for the building industry.

Acknowledgements

I would like to thank, Ian Brocklebank from Plymouth University, Jason Hawkes from J3 Building Futures, Valentina Marincioni from University College London, Christian Bludau from the Fraunhofer Institute for Building Physics, Joseph Little from Building Life Consultancy, James Ayres of Lime Green, Stephen Bull from SPAB Technical Panel, and Oliver Barrow for their assistance in preparing this report. On behalf of the SPAB I would also like to thank English Heritage for their kind support with the analysis and publication of this report, through their National Heritage Protection Commissions Programme.

Supported by

ENGLISH HERITAGE

TABLE OF CONTENTS

1. INTRODUCTION 1

2. U-VALUE AND CONDENSATION RISK ANALYSIS TOOLS IN THE BUILDING INDUSTRY 2

3. ENERGY EFFICIENCY AND TRADITIONAL BUILDINGS 4

4. CONDENSATION RISK ANALYSIS WITHIN THE BRITISH, EUROPEAN AND INTERNATIONAL STANDARDS 7

BS 5250:2011 *Code of practice for control of condensation in buildings.*

BS EN ISO 13788:2002 *Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods.*

BS EN 15026:2007 *Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation.*

5. WUFI Pro 5.1 ONE-DIMENSIONAL HYGROTHERMAL SIMULATION SOFTWARE 20

Hygrothermal Material Properties

Measurement of Material Properties

Climate Data

Thermal Transmittance (U-Value) and Calculation Standards

6. CASE STUDY - ABBEYFOREGATE, SHREWSBURY 32

Energy Efficiency Measures

Overview of the Study

One-dimensional Representation of the Walls with and without IWI

Establishing Material Inputs

- *Brick*
- *Mortar Sensitivity Analysis*
- *Brick Sensitivity Analysis*
- *U-values*

Climatic Variables

Results of climate sensitivity analyses

Water Content

Relative Humidity

7. DISCUSSION **59**

General overview

Application to the Wider Context

Material Testing

Climatic Variables

Comparison with in situ Results

8. CONCLUSIONS **69**

General

Case Study Conclusions

9. RECOMMENDATIONS AND FURTHER RESEARCH **74**

Immediate Recommendations

WUFI

Standardised Approaches to Simulating Traditional Buildings

Communication

Material Testing and Public Material Database

Liability

In Situ Monitoring

APPENDIX A **77**

Water content of IWI study, calculation summary

APPENDIX B **84**

Climatic variables, calculation summary

APPENDIX C **87**

BS 8104:1992 wind-driven rain calculation

REFERENCES **88**

1. INTRODUCTION

As part of the on-going Building Performance Survey by the Society for the Protection of Ancient Buildings (SPAB), this interim report presents findings from the hygrothermal study using computer simulation software conforming to BS EN 15026:2007. A general review of the British Standards that relate to condensation risk analysis and U-value calculation, including BS EN ISO 13788:2002, is also undertaken.

The experiments using WUFI 5.1 computer software focus on a case study property in Shrewsbury, which is to date the most completed energy efficiency refurbishment in the aforementioned SPAB research project. Inaccuracies in results are put down to poor knowledge of the building's hygrothermal properties and representation of climatic variables. The cost of measuring a material's full range of hygrothermal properties in a specialist laboratory is prohibitively expensive. Recommendations are made on how to improve accuracy of input data with affordable and accessible test methods.

It is important to clarify that this research is not questioning the validity of the software, more the practical application of it to traditional buildings in the UK where a limited set of hygrothermal material properties and climatic inputs are known. Validation of the software has already taken place over many years of field-testing by the Fraunhofer Institute for Building Physics (Straube & Burnett 1998) and complies with BS EN 15026:2007 (Fraunhofer IBP 2007).

Analysis of these results aims to identify how appropriate it is with the current access to information for BS EN 15026:2007 to replace BS EN ISO 13788:2002 as an industry standard methodology for assessing condensation risk in thermal upgrades of traditional walls. All references to BS EN ISO 13788 and BS EN 15026 are to the 2002 and 2007 editions respectively.

2. U-VALUE AND CONDENSATION RISK ANALYSIS TOOLS IN THE BUILDING INDUSTRY

The ability to predict the behaviour of building elements and components under realistic service conditions plays an important part in evaluating non-standard solutions to building design. Traditional buildings have proved their suitability to local climate and lifestyle needs just by demonstrating a lengthy existence devoid of significant defects and therefore rebuilding in the local vernacular has been a tried and tested way of reducing errors in construction. With new methods and theories in refurbishment changing all the time, and with the diverse range of building types, climates and lifestyles, simulation tools play an important part in helping designers to meet criteria such as a building's estimated energy consumption and assessing risk of new designs failing. If this process was left to time alone, progress in areas such as energy efficiency refurbishments would be slow and government targets would be missed. This does not however suggest that the widespread deployment of thermal refurbishments should be carried out with only simulation results to guide us. New *in situ* measured information must be fed back into models to increase accuracy and improve energy saving designs.

At present, almost the whole building/insulation industry uses U-value software based on BS EN ISO 6946:2007 and BR443 and Condensation Risk Analysis software based on methodologies presented in BS EN ISO 13788, also known as the Glaser method. BS EN ISO 13788 assesses interstitial and surface condensation and is not just used in the UK, it is also a European Standard (EN) and an International Standard (ISO). Assessments made with software based on the BS 13788 methodology are used to develop and specify new products, and are needed to gain a BBA product approval certificate. Architects normally require the certificates to satisfy their professional indemnity insurance. Without BBA certification products are usually (but not exclusively) deemed unacceptable for use in buildings and can cause complications when being signed off by Local Authority Building Control. This guarantee of conformity is issued to the homeowner and, when purchasing a house, mortgage lenders require a Building Control Completion Certificate as a condition of the lending agreement. In summary, it is clear that the reverberations of BS 13788 are far reaching and the implications of changing the methodology are significant for many industries.

For many years, as recounted by Hens (2007), the limitations of industry standard tools conforming to BS 13788 (Glaser) have been known. This does not suggest that all calculations with BS 13788 based software will over or underestimate moisture accumulation within structures. However, it has become clear that condensation risk analysis of capillary active solid walls in contact with driven-rain requires additional factors to be evaluated, factors that are covered in another standard: BS EN 15026:2007. Establishing exactly when BS 13788 fails to predict high-risk designs is complex due to the vast set of variables at play in and around every building at each location.

3. ENERGY EFFICIENCY AND TRADITIONAL BUILDINGS

With new energy design criteria and modern lifestyle standards, traditional buildings are being subjected to conditions that may have rarely or never occurred in the environments that they were designed for and where they have historically proved their suitability. Misguided changes to the building fabric can result in a number of moisture related complications, some of which are unhealthy for the buildings and residents. BS 5250, BS 13788 and BS 15026 are all in place to ensure that the structure and health of buildings are not compromised through poor design. There are many cases of failed attempts to ‘improve’ traditional buildings, and, due to their cultural importance, it would be wise to gather as much information as possible prior to the widespread introduction of energy efficiency measures. Aside from issues regarding aesthetics, controversy over inappropriate measures in the traditional buildings community usually revolves around materials or practices that inhibit the movement of water or water vapour, which can ultimately lead to the accumulation of moisture in the wrong place, where deterioration can start to take place.

The complexity of delivering good design lies in understanding the ever-changing conditions that buildings are subjected to by climate and occupants. Unfortunately these conditions are inherently complex and design strategies that succeed are therefore likely to be adaptable, resilient and easily repairable. Condensation risk analysis tools only provide assessment of one aspect of overall appropriate design.

The step changes in the name of saving energy over the last 50 years have been logical and a simplified description of this is expressed in the flow chart (Fig. 1) below.

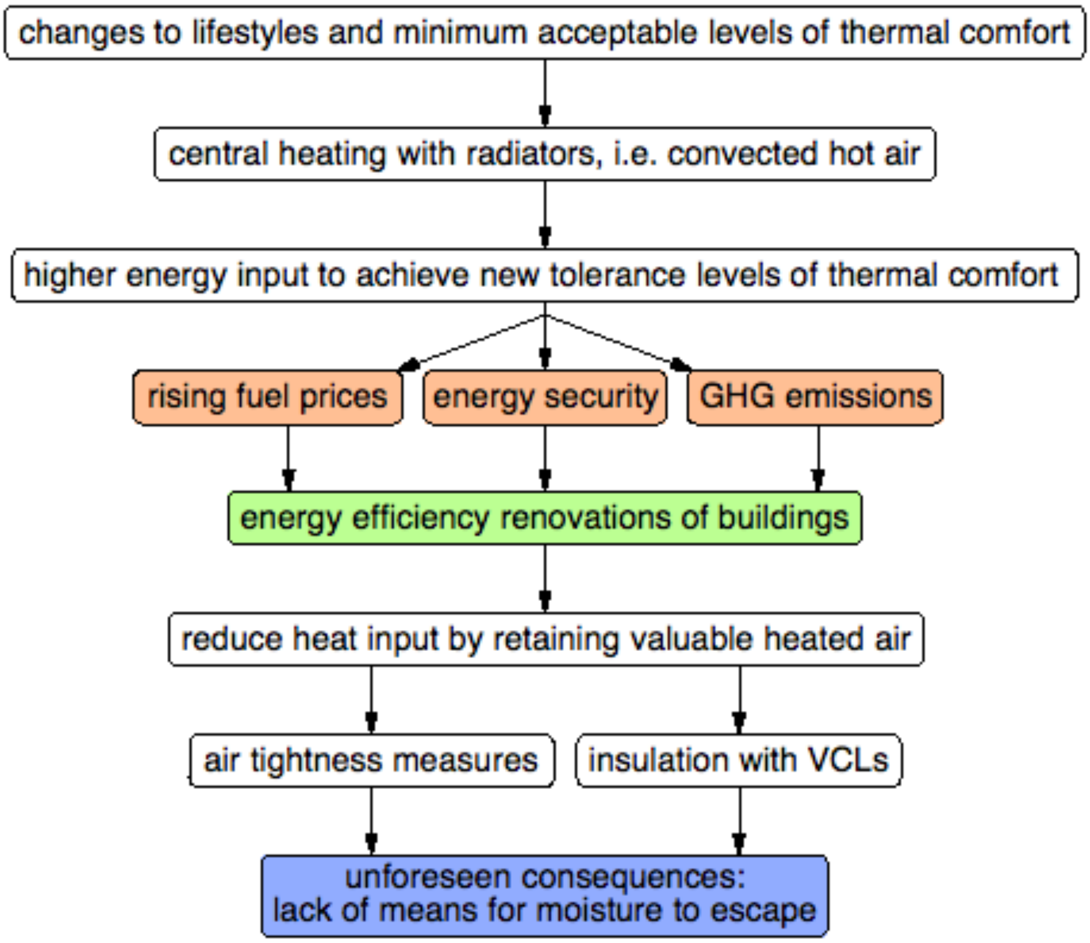


Figure 1. Logical step changes of energy saving in buildings and the resulting unforeseen consequences. Green house gas (GHG) and Vapour control layer (VCL).

In order to evaluate the risk of these more complicated unforeseen consequences, including surface and interstitial condensation, certain progressive areas of the building industry have moved towards methods conforming to BS 15026. Whilst the adoption of such simulation programmes is arguably the correct approach, there currently exists no standard methodology within BS 15026 for investigating additional internal or external insulation to the solid walls of existing buildings. There is concern within the building physics community over urgently resolving the issues of standardising materials testing and simulation procedures (ASTM 2007). If resolved, the resulting norms should help to provide researchers with greater confidence in modelling. Academic studies using BS 15026 compliant software frequently make claims over results, but the precise methodologies and programmes' inputs, including material properties, are not always available to examine. Consequently, different researchers studying the same building can end up with a wide variety of results, each of which could go towards informing different retrofit strategies. In order to minimise risk of moisture related damage to our built heritage and avoid having to repeat any nationwide thermal retrofits, significantly more confidence is needed in the practical application of simulation software.

The aim of this research is to:

1. assess condensation risk of the energy efficiency measures applied to the case study house.
2. evaluate the limitations and accuracy in the practical application of BS 15026 software.
3. inform the building industry of the complexity of condensation risk analysis.
4. highlight areas lacking in research and clarify some of the issues with modelling that may lead to retrofit failures.

4. CONDENSATION RISK ANALYSIS WITHIN THE BRITISH, EUROPEAN AND INTERNATIONAL STANDARDS

Over 60 British Standards are directly relevant to this research paper, either in the specification of materials, test methods for material properties or in other areas of building design. It is obviously way beyond the scope of this research to review them all, but a selection of those relating to material testing is presented in Chapter 5, *Measurement of Material Properties*. The standards relating directly to condensation control in buildings are reviewed below. These are:

- **BS 5250:2011** *Code of practice for control of condensation in buildings.* This is the governing document addressing numerous issues surrounding moisture control and building design.

- **BS EN ISO 13788:2002** *Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods.* Software using this methodology is most commonly used and is often referred to as the Glaser method. Pertinently, this standard is current but its revision is in hand, the opportunity to comment closed on 30th September 2011.

- **BS EN 15026:2007** *Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation.* This standard describes methodologies and benchmark tests to which the software used in this research conforms.

Note: For a full set of terms and definitions relating to hygrothermal processes please refer to:

- BS 5250:2011 *Code of practice for control of condensation in buildings.*

- BS EN ISO 9346:2007 *Hygrothermal performance of buildings and building materials - Physical quantities for mass transfer - Vocabulary (ISO 9346:2007).*

- BS EN ISO 13788:2002 *Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods.*

- BS EN 15026:2007 *Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation.*

BS 5250:2002 and 2011 *Code of practice for control of condensation in buildings.*

As previously mentioned this standard is the governing document for moisture control in relation to buildings. The document is exhaustive, lists many useful terms and definitions, and has recently been updated to include reference to BS 15026:2007, which had not been published at the time of the now superseded 2002 edition.

The standard covers:

Moisture in buildings
Diagnosis of dampness problems
The temperature and moisture content of air
Calculating condensation risk
Properties of materials
Application of design principles – Floors
Application of design principles – Walls
Application of design principles – Roofs
Application of design principles at junctions
Application of design principles – Occupied space Ventilation
Application of design principles – Heating
Guidance for builders
Guidance for occupiers on how to avoid damaging condensation

BS 13788 is introduced in Chapter 4 - *Design to avoid moisture related problems,* where BS 5250:2011 states that:

> *Designers should assess the risk of surface condensation, mould growth and interstitial condensation using the methods described in BS EN ISO 13788, which determines three criteria for assessment.*
>
> *1) The design of the structure and the heating system should ensure that, over the coldest month, the average relative humidity at internal surfaces does not exceed 80%, the limit for mould growth (but see also 4.5.2).*
>
> *2) Any interstitial condensation which might occur in winter should evaporate during the following summer, preventing an accumulation of moisture year on year.*
>
> *3) The risk of degradation of materials should be assessed in terms of the maximum level of condensate which might occur.*
>
> *NOTE 1 Software programs are available to perform the calculations.*

Apart from one reference to BS 15026, all references to the assessment of condensation direct the reader to BS 13788, even though the standard highlights some of the limitations of the methodology. It states importantly that:

> *[BS EN 13788] makes no allowance for the moisture in the materials or rainwater absorbed during construction. Consequently, while it is useful for comparing the performance of different structures, it does not provide an accurate prediction of moisture conditions within the structure under service conditions. More advanced methods, which are standardized in BS EN 15026, are available and are described more fully in [5] (BSI 2011).*

This is the only mention of BS 15026 in the whole document and reference 5 leads off-topic to BRE IP 5/06. *Modelling condensation and airflow in pitched roofs*. Garston: BRE. April 2006. Regrettably, IP 5/06 makes no mention of BS 15026, as it was not published at the time of the BRE report, or to the importance of considering capillary conduction in walls. The whole document focuses on the need to include airflow in the assessment of flat roofs for which it establishes that BS 13788 is not an appropriate methodology (Sanders 2006).

Further limitations of BS 13788 are outlined in Annex D chapter 3.5 *Limitations of the Glaser Method [BS 13788]:*

> *This method assumes moisture transfer is affected solely by diffusion; thermal conductivity and thermal resistance of materials are assumed constant; the effects of phase changes and the specific heat capacity of materials are ignored. These simplifications ignore the following, and give rise to several errors.*
>
> *a) Air movements within or through the construction will redistribute moisture by convection.*
>
> *b) The use of constant material properties is an approximation: precipitation and water used in construction increase the moisture content of materials; the thermal conductivity of a material depends on its moisture content.*
>
> *c) Changes in the distribution of moisture within a construction will be caused by capillary action within absorbent materials: most materials are hygroscopic to some degree.*
>
> *d) Heat released by condensation or absorbed during evaporation changes temperature and vapour pressure within the structure.*
>
> *e) Environmental conditions are not constant over a month.*
>
> *f) The effects of radiation are ignored.*
>
> *g) If an element experiences large diurnal temperature changes and is likely to contain significant amounts of moisture the results of analysis using this method have to be treated with caution, they are likely to overestimate the risk of interstitial condensation.*
>
> *h) If there is significant air movement within or through an element the results of analysis will be unreliable and have to be applied with caution (BSI 2011).*

Chapter 6 of the now superseded BS 5250:2002 highlights some of the more general issues relating to condensation, interstitial condensation and high humidity in buildings. This standard states:

> *"Interstitial condensation can increase the moisture content of components in a structure, but this can be inconsequential, e.g. condensate occurring on the outer leaf of a masonry cavity wall, where the amount of condensate can be small compared to the effect of wetting by rain (BSI 2005).*

BS 5250:2011 also acknowledges the significance of rainwater, affirming that it is the main source of moisture affecting a building and that driving-rain can be absorbed into masonry. This fact along with its implications is recognised by many other sources including Kunzel (1998); Blocken & Carmeliet (2004) and Straube et al. (2011). In the context of porous masonry walls BS 5250:2011 highlights the importance of cavities in helping to inhibit the tracking of water to the interior and states that insulation within a cavity may compromise the role of the cavity in preventing rainwater penetration (BSI 2011).

In summary, both BS 5250:2002 and the revised 2011 edition point at BS 13788 for the assessment of condensation risks in walls. A brief mention is made of BS 10526 but within the context of condensation in roofs. BS 5250:2011 also clearly highlights the significance of driving-rain to porous walls whilst at the same time outlining the limitations of BS 13788 in not accounting for it.

Incidentally, an additional point to note is that BS 5250:2011 is also responsible for suggesting comfortable internal conditions to be between 18°C and 24°C. This band as a target, particularly the upper limit is often difficult to achieve in traditional buildings, and is especially high at a time when the UK is required to be reducing energy use in buildings.

BS EN ISO 13788:2002 ***Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods.***

By far the most popular method of assessing the hygrothermal behaviour of walls is the Glaser methodology which is presented in BS EN ISO 13788:2002. This is a British, European and International Standard. These Glaser based computer programmes go some way to predicting condensation risk within structures but exclude some important factors that are particularly relevant when evaluating solid masonry walls with and without additional insulation. The standard outlines its scope and limitations:

> *6.1*
> *This standard gives calculation methods for:*
>
> *a) The internal surface temperature of a building component or building element below which mould growth is likely, given the internal temperature and relative humidity – the method can also be used to assess the risk of other surface condensation problems.*
>
> *b) The assessment of the risk of interstitial condensation due to water vapour diffusion. The method used assumes built-in water has dried out and does not take account of a number of important physical phenomena including:*
>
> *- the dependence of thermal conductivity on moisture content;*
> *- the release and absorption of latent heat;*
> *- the variation of material properties with moisture content;*
> *- capillary suction and liquid moisture transfer within materials;*
> *- air movement through cracks or within air spaces;*
> *- the hygroscopic moisture capacity of materials.*
>
> *Consequently the method is applicable only to structures where these effects are negligible (BSI 2002).*

According to Hens (2007) who quotes Glaser's original German publications from 1958 -1959, the method was developed to control condensation in cold store walls. Since the temperature and vapour conditions were near to steady-state, the constructions airtight and materials were mostly non-porous the method provided good results. The only process left for moisture transport is vapour diffusion and this straightforward method estimates the total amount of condensation and evaporation occurring in the wall to establish and annual moisture balance. For this only two basic values are needed; the materials' dry thermal conductivity and the water vapour diffusion resistance. As conditions are assumed to be steady-state climate can be approximated from monthly averages for internal and external relative humidity and temperature.

> *6.2*
> *Starting with the first month in which any condensation is predicted, the monthly mean external conditions are used to calculate the amount of condensation or evaporation in each of the twelve months of a year. The accumulated mass of condensed water at the end of those months when condensation has occurred is compared with the total evaporation during the rest of the year. One-dimensional, steady-state conditions are assumed. Air movements through or within the building elements are not considered (BSI 2002).*

Further limitations and their implications are presented in Chapter 6.3:

> *6.3*
> *There are several sources of error caused by the simplifications described in 6.2.*
>
> *a) The thermal conductivity depends on the moisture content, and heat is released/absorbed by condensation/evaporation. This will change the temperature distribution and saturation values and affect the amount of condensation/drying.*
> *b) The use of constant material properties is an approximation.*
> *c) Capillary suction and liquid moisture transfer occur in many materials and this may change the moisture distribution.*
> *d) Air movements through cracks or within air spaces may change the moisture distribution by moisture convection. Rain or melting snow may also affect the moisture conditions.*
> *e) The real boundary conditions are not constant over a month.*
> *f) Most materials are at least to some extent hygroscopic and can absorb water vapour.*
> *g) One-dimensional moisture transfer is assumed.*
> *h) The effects of solar and long-wave radiation are neglected.*
>
> *NOTE Due to the many sources of error, this calculation method is less suitable for certain building components and climates. Neglecting moisture transfer in the liquid phase normally results in an overestimate of the risk of interstitial condensation (BSI 2002).*

Whilst being a simple and clever tool for the assessment of certain structures, it is highlighted above in BS 13788:2002 and established in BS 5250:2011 that Glaser assessment is not appropriate where rain and capillary open, hygroscopic materials are present. As the model only uses values for dry thermal conductivity and water vapour diffusion, any accumulation of moisture in the structure can only be interstitial condensation. The disregard for liquid movement in the model is assumed to *overestimate* the risk of interstitial condensation, as capillaries will not move any accumulation of condensate away from the exact point of its occurrence. In neglecting liquid movement the model will therefore also *underestimate* the accumulation of rainwater at vulnerable points in the structure that has arrived there solely by capillarity in pores.

When walls fail in the Glaser model and show an accumulation of interstitial condensation, the logical solution is to prevent vapour movement from the inside with a vapour control layer (VCL). Unfortunately as liquid movement is not considered in the model it cannot predict whether there is now an accumulation of moisture on the outside of the VCL. Where walls are insulated internally, heat flow to the outside is reduced; this impedes the ability of the masonry to dry-out after wetting from driven rain, and in-turn, the higher water content increases the thermal conductivity of the masonry (Hendry 2001). The vapour resistance of insulation and a VCL also reduces moisture movement and therefore drying potential to the inside of the wall. As the wall establishes its new higher dynamic equilibrium moisture content there is increased risk of decay to any organic materials in contact with it.

Finally, Annex F of BS 13788:2002 makes reference to the use of more advanced models when greater accuracy is needed. It also highlights the problems in defining accurate material properties and climate conditions (BSI 2002).

BS EN 15026:2007 *- Hygrothermal performance of building components and building elements — Assessment of moisture transfer by numerical simulation.*

The introduction of BS EN 15026:2007 outlines how the standard differs from BS 13788:

> *This standard defines the practical application of hygrothermal simulation software used to predict one- dimensional transient heat and moisture transfer in multi-layer building envelope components subjected to non steady climate conditions on either side. In contrast to the steady-state assessment of interstitial condensation by the Glaser method (as described in EN ISO 13788), transient hygrothermal simulation provides more detailed and accurate information on the risk of moisture problems within building components and on the design of remedial treatment. While the Glaser method considers only steady-state conduction of heat and vapour diffusion, the transient models covered in this standard take account of heat and moisture storage, latent heat effects, and liquid and convective transport under realistic boundary and initial conditions. The application of such models has become widely used in building practice in recent years, resulting in a significant improvement in the accuracy and reproducibility of hygrothermal simulation (BSI 2007).*

Inputs needed for a simulation are as follows:

- *Assembly, orientation and inclination of building components*
- *Hygrothermal material parameters and functions*
- *Boundary conditions, surface transfer for internal and external climate*
- *Initial condition, calculation period, numerical control parameters (BSI 2007)*

Results can be outputted as:

- *Temperature and heat flux distributions and temporal variations*
- *Water content, relative humidity and moisture flux distributions and temporal variations (BSI 2007)*

BS EN 15026:2007 defines the equations required for calculations and outlines a benchmark example and tolerances that computer programmes have to match in order to state their conformity to the standard.

The equations for heat and moisture transport and storage are coupled, meaning that one affects the other. The following phenomena are covered:

- *Heat storage in dry building materials and absorbed water*
- *Heat transport by moisture-dependent thermal conduction*
- *Latent heat transfer by vapour diffusion; moisture storage by vapour sorption and capillary forces*
- *Moisture transport by vapour diffusion*
- *Moisture transport by liquid transport (surface diffusion and capillary flow) (BSI 2007)*

Each simulation is assigned an external climate file and the internal conditions are normally defined by the certain parameters derived from external conditions. Internal climate should represent the highest humidity loads that the building is likely to experience (BSI 2007). The inputs needed are:

- *Internal and external dry bulb temperature*
- *Internal and external humidity*
- *Solar and longwave radiation*
- *Sky temperature*
- *Precipitation (normal and driving rain)*
- *Wind speed and direction*
- *Vapour pressure, or any other humidity parameter that can be used to calculate vapour pressure*
- *Total atmospheric pressure (BSI 2007)*

These complex climatic parameters need defining with a good degree of accuracy and should be specific to the location of the building. These can be obtained as Test Reference Years (TRY), which contain averaged data but do not necessarily contain the correct weather extremes for specific studies investigating moisture movement (BSI 2007). Ideally measured data is used, but it is not normally available. As this data is unavailable Reference Years should be used that contain the most severe conditions likely to occur once in ten years. If the climatic data does not account for this then a temperature shift can be applied to the data of ± 2 K to represent one-in-ten year severe conditions (BSI 2007). Even though hourly values for rain and wind are needed, the standard makes no suggestion for how to adjust relative humidity, precipitation or wind speed to represent extreme moisture events. When studying moisture movement in most situations, the standard deems a moisture failure rate of one-in-ten years to be generally acceptable. It also points out the need for Moisture Reference Years (MRY) that include extreme events, that creating them is complex, and that data is generally not available. It goes on to say that normally the results using these extreme MRY files do not differ significantly to those with extreme TRY files where only temperature is considered (BSI 2007).

Even though the processes and factors in these calculations are highly complex they are still only one-dimensional. Two-dimensional versions of software programmes are available but require significant computer processing powers and are normally reserved for specific studies on interfaces such as joist ends embedded in walls and the exact role of mortar in a construction. The standard clearly deems one-dimensional simulation of walls to be acceptable but does state that it should not be used in circumstances where:

- *Convection takes place through holes and cracks*
- *Two-dimensional effects play an important part (e.g. rising dampness, conditions around thermal bridges, effect of gravitational forces)*
- *Hydraulic, osmotic, electrophoretic forces are present*
- *Daily mean temperatures in the component exceed 50 °C (BSI 2007)*

In order to establish the moisture content of the construction over the calculation period the sum of water vapour and liquid water entering the structure is calculated against the evaporation or shedding of water under the given climatic conditions. As moisture enters the construction it changes the thermal performance of the materials, which in turn affects their moisture behaviour. Materials with a higher specific heat capacity will react more slowly to temperature changes and the latent heat of evaporation and condensation are also included. The moisture storage properties of a material are the result of how it interacts with, and holds humidity and liquid water. The driving forces for most processes are ultimately temperature, relative humidity, vapour pressure or capillary suction (Kunzel 1995).

Given all the processes that are considered in a calculation, the amount of data needed on the material's properties is significantly more than those needed in the Glaser method. BS 15026:2007 highlights these properties and sets out standards for measuring them in specialist laboratories. The properties include:

- Density
- Specific heat capacity
- Thermal conductivity
- Moisture storage function (sorption curve) for vapour
- Moisture storage function (suction curve) for liquid
- Water vapour diffusion resistance factor
- Moisture movement in the liquid phase

Due to the vast number of variables involved in performing a calculation to BS EN 15026:2007, the standard also requires the inputs and the outputs to be documented in a summary report. This is to ensure that the exact calculation can be repeated again to provide identical results (BSI 2007).

Evaluation of the results is obviously more complicated that with BS 13788 and depending on the nature of the study, a variety of factors will need to be investigated. The calculation method itself just predicts the conditions in the construction and the therefore additional 'post-processing' computer software is needed to investigate specific areas of concern such as surface mould growth. However, as a rule, the year on year accumulation of any moisture in the structure should be assessed and compared to the tolerances of individual materials or any specified limits (BSI 2007).

In summary, software conforming to this standard is not easy to use and good results can only be obtained by using accurate input data for climate and all material properties. Clearly, a good understanding of physics in relation to buildings and the implications of making one input choice over another is required. These factors make it clear why BS 15026 has not been widely adopted by the building industry.

5. WUFI Pro 5.1 ONE-DIMENSIONAL HYGROTHERMAL SIMULATION SOFTWARE

The computer software programme used for this study is **W**ärme **u**nd **F**euchte **i**nstationär (transient heat and moisture) WUFI Pro 5.1 that complies with the requirements of BS 15026 and was developed by the Fraunhofer Institute for Building Physics (IBP). The use of this software should not be considered as being biased. Any criticisms are ultimately directed at BS 15026 and not at the programme manufacturers or their theories.

WUFI is a one-dimensional tool, and therefore does not take account of more than one material occupying the same cross-sectional space. This is not necessarily a problem when modelling walls in this study. If modelling sensitive areas such as timber joist-ends embedded in external masonry walls, a two-dimensional version is available, although its use is even less widespread than that of the 1D version.

The complex theories in WUFI are based on the reasonably well-understood processes of heat and moisture movement. Their conformity within the tolerances set out in BS 15026 show that they are capable of good accuracy and WUFI is considered to be one of the most advanced of the commercially available programmes, having been validated against full scale field tests over many years (Straube & Schumacher 2006). Other validated programmes like Delphin also exist and a variety of more advanced non-commercial programmes are available for research purposes only. However, within even the most complex model there is still room for inaccuracies due to the vast number of variables involved and the fact that any model has to make mathematical assumptions and approximations about reality (Straube & Burnett 1998). Human error when inputting the data is always a concern, especially with users unfamiliar with the consequences of leaving tick boxes unchecked or inputting seemingly slightly incorrect values without first conducting a sensitivity analysis. Figure 2 below displays WUFI's page for defining surface transfer coefficients.

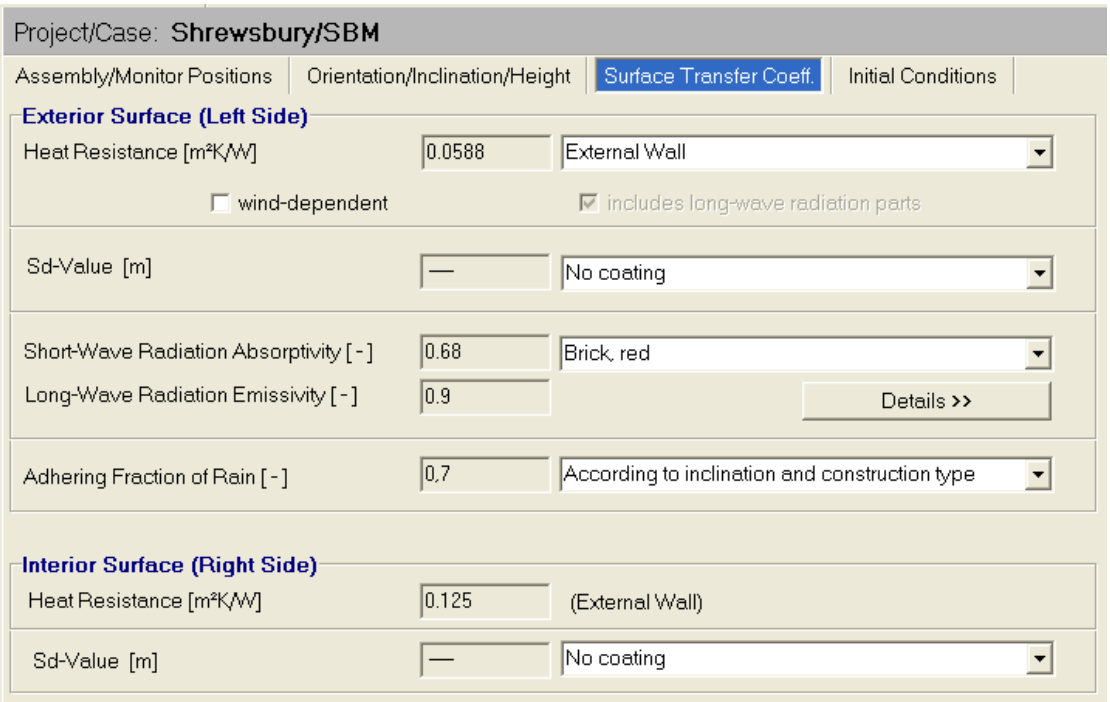


Figure 2. Example page from WUFI simulation program, defining surface transfer coefficients.

When starting a new calculation many preset and default values are assumed and relatively few inputs are actually required to run a calculation. Climate files must to be assigned to the construction, as must all the materials within it. The accuracy of simulations using certain default or simplified values may be poor and the variances in some results derived from different assumptions are explored in this report.

Hygrothermal Material Properties

For calculation results to be acceptable, the values for material properties should be as close as possible to those of the real material. The number of material properties required by BS 15026, and therefore by WUFI, are notably more than for BS 13788. As the building industry has adopted the latter standard, the widespread testing of many materials for the complete set of values listed below has never taken place. The references below to Schmidt are from the extensive help menu within WUFI and can also be found online at: www.wufi-wiki.com/mediawiki/index.php5/1D:Wufi_1D

Property	Symbol	Unit
Bulk density	ρ_{bulk}	kg/m^3
Porosity	w_{max}	m^3/m^3
Specific heat capacity	c_p	J/kgK
Thermal conductivity, Dry 10°C	λ	W/mK
Water vapour diffusion resistance factor	μ	-
Reference water content	w80	kg/m^3
Free water saturation	w_f	kg/m^3
Water absorption coefficient	A	$kg/m^2\sqrt{s}$

Table 1. The basic values that WUFI requires in order for it to run accurate calculations.

The above properties may differ in name to those listed in BS 15026 but are ultimately all required by the software to run a conforming calculation.

Bulk density [kg/m³] - This property is easy to measure and is the mass of the sample over its volume. This is different to the true density, which would involve calculating the volume of the material after it had been crushed and therefore just the volume of the matrix material is being measured. Schmidt (2009) states that density does not need to be exactly defined as it only affects the specific heat capacity, which does not depend on very precise values. However, an accurate density may be helpful in defining values of other material properties where strong correlations exist and, in the case of organic materials, it will affect the critical limits of water content as measured by mass percent.

Porosity [m^3/m^3] - This is the maximum water content of a material and is normally only achieved under high pressure or through water vapour diffusion in a temperature gradient (Kunzel 1995). The standard method for measuring this in the brick industry is to boil a sample in water for five hours and calculate the ratio of increase of mass between the saturated sample and the dry sample (BSI 2011).

Specific heat capacity [J/kgK] - This can be estimated at 850 J/kgK for mineral materials and 1500 J/kgK for organic materials as it is not accurately required for simulations. When the moisture content of a material rises, WUFI automatically increases the heat capacity accordingly Schmidt (2009a).

Thermal conductivity (dry 10°C) [W/mK] - The measurement of heat flow being conducted across a sample. According to Schmidt (2009a), when studying the moisture contents and distributions, hygrothermal simulations do not normally depend very sensitively on a precise value for thermal conductivity. It is therefore mostly relevant for just studying heat flow, which includes U-values. The thickness of a material multiplied by its thermal conductivity gives the thermal resistance (R-value) [m^2 K/W].

Water vapour diffusion resistance factor (dry) [-] - This describes how a material impedes the diffusion of water vapour compared to diffusion through stagnant air (Schmidt 2009a). Vapour open materials like mineral wool have a value of around 1 and bricks and mortar commonly area round 10-20. The actual resistance of a material is the vapour diffusion thickness (s_d-value) [m], where μ is multiplied by thickness.

Reference moisture content [kg/m³] - The moisture content of the material at 80% RH.

Free water saturation [kg/m³] - The amount of liquid held in the pores under normal saturation pressures.

Moisture storage function [-] - The reference moisture content and free water saturation are needed for WUFI to approximate the moisture storage function if it has not been completely defined in a laboratory. This material property indicates the moisture content of a material at a given relative humidity. A curve from 0% RH through the reference water content, the free water saturation and up to total porosity is then generated (Schmidt 2009b)

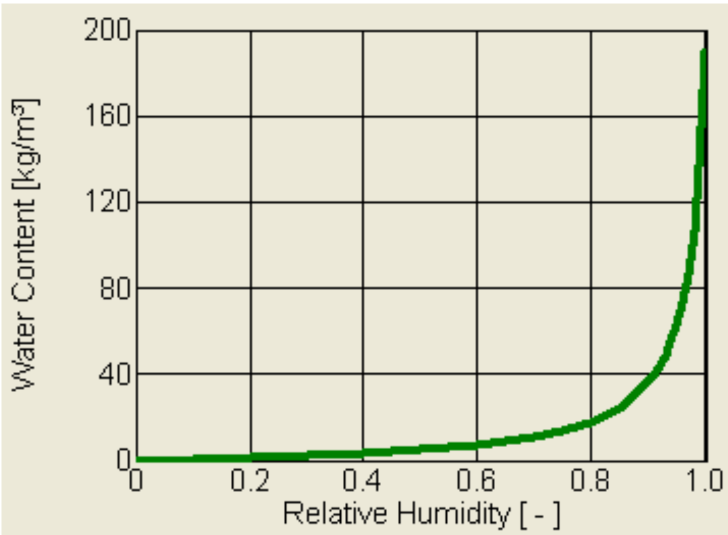


Figure 3. The moisture storage function of 'solid brick masonry'.

In the context of brick, free water saturation is measured by a cold-water submersion test where the pores fill up under their own suction pressure. Total porosity is established by boiling a brick, thereby forcing water into all of its open pores. Both are measured in kg/m³.

Water absorption coefficient [kg/m²√s] - This measurement is used to approximate how liquid water moves around the capillaries in the material. After wetting by driving rain, water is quickly drawn into the wall predominantly by the larger diameter capillaries. Once in the wall, and even after rain has stopped, the liquid is slowly redistributed from the larger capillaries that have a lower capillary tension to the smaller capillaries which have a higher tension. WUFI uses the water absorption coefficient to approximate rates for both initial suction and redistribution (Schmidt 2009c).

Diffusion Resistance Factor, Moisture-dependent - For mineral materials like brick, a constant diffusion resistance factor is advised and will be adjusted accordingly if free water saturation is reached (Schmidt 2009d).

Heat Conductivity, Moisture-dependent - This can be generated by WUFI with a moisture-induced heat conductivity supplement, which for brick is estimated at being between 8-15 %/M.-%.

Enthalpy, Temperature-dependent - This is not normally relevant unless a phase change materials is being investigated.

Measurement of Material Properties

The importance of establishing accurate material properties is highlighted in BS EN 15026:2007. For many materials, generic information on their hygrothermal properties may suffice and individual testing may not be necessary. WUFI offers a large database of predefined materials that cover nearly all mainstream materials used in modern construction. This database is a reliable source for many 'standardised' materials that are needed to run calculations. However, due to the sensitivity of the programme certain materials should be selected with caution. Depending on the nature of the study the variations within some groups of materials may be insignificant, for example mineral wool, but within other groups like natural stones the variations may have implications for the hygrothermal design. The knowledge base needed to conduct accurate hygrothermal simulations is broad and multidisciplinary. Whilst geologists or brick specialists may understand the technical make up and derivation of stones or clays, they may not currently fully understand the implications of the materials' physical characteristics within the context of hygrothermal studies on thermal retrofits and their vast experience and knowledge needs to be added to.

Laboratory testing of each material's hygrothermal properties is available through select institutions and the Fraunhofer Institute for Building Physics but is currently prohibitively expensive for the vast majority of studies. It is for this reason that WUFI and similar programmes offer its users internal material databases. In many cases, values will need to be defined for the specific material in question and the variance between materials found in apparently similar materials in the database may be unacceptable.

As an alternative to full hygrothermal testing a select number of values can be measured to improve the accuracy of simulations. If BS 15026 is to be accessible to all researchers these tests need to be quick, easy to perform, cost effective and have an appropriate degree of accuracy. Table 2 below lists test methods that can be performed with simple apparatus to improve simulation inputs.

Property	Unit	Basic method	Apparatus
Density	kg/m^3	Weigh and establish volume	Balance accurate to 0.1% of the mass of the sample. Sample should be at least 100g
Total Porosity	m^3/m^3	Boil sample for 5hrs in water then weigh: BS EN 772-7:1998	If sample is a whole brick a balance accurate to 1g, or accurate to 0.05% of the mass of the sample
Specific heat capacity	J/kgK	Estimate from similar materials	-
Thermal conductivity	W/mK	Estimate from density or from similar materials	-
Water vapour diffusion resistance factor	-	Estimate from similar materials	-
Reference water content	kg/m^3	Expose sample to saturated salt solution and weigh BS EN ISO 12571:2000	Water and salt solution (sodium chloride) and sealed container. Balance accurate to 0.01% of the mass of the sample
Free-water saturation	m^3/m^3	24hr soak in cold water then weigh: BS EN 772-21:2011	Balance accurate to 0.1% of the mass of the specimen
A-value (water absorption coefficient)	$kg/m^2\sqrt{s}$	Capillary rise test. Sample with a face of at least 50-100 cm^2, sides sealed with a water and vapour tight sealant. Sample should be a thickness representative of its thickness in service. The open face of the sample is suspended in a water bath to a depth of 5mm from the underside of the sample. The sample is removed and periodically weighed over 24hrs. BS EN ISO 15148:2002	Water tank capable of maintaining a constant level of 10mm ± 2 mm. A grid or points to support the sample 5mm from the bottom of the tank A balance accurate to 0.1% of the mass of the specimen
Liquid transport coefficient for suction/ redistribution	m^2/s	Generate in WUFI	-

Table 2. Simple methods for establishing key material properties.

In order to conduct most tests small samples of the material are required which may prove controversial depending on the heritage status of the building. In fact, depending on the retrofit measures proposed and the severity of the consequences the argument for taking samples from high status buildings may be most strong.

Climate Data

Climate data within WUFI needs to be assigned to both sides of the wall in order to run a simulation. WUFI 5.1 contains a selection European climate files but currently offers no standard files for the UK and therefore synthetic data has to be created in an external programme.

There are various sources for international climate data, the most appropriate and most easily accessible are files created in Meteotest's Meteonorm software. These synthetic files are generated with data interpolated between the closest weather stations to the location of interest. Files consist of one year of hourly weather data that repeats for each year the simulation is run.

Other options include files from the Meteorological Office, ASHRAE and Energy Plus. The ASHRAE International Weather for Energy Calculations (IWEC) CD ROM contains files for 10 locations in Great Britain with three settings available for driving rain load. Energy Plus EPW files are available for free but contain no driving rain data.

Internal climate files can be created using one of four methods:

- **BS 13788** - The internal temperature is set by the user and remains constant throughout the year. The humidity class can also be changed.

- **BS 15026** - The internal temperature during the heating season is fixed at 20°C and moisture load can be defined as normal or high. Summer conditions are derived from external climate using the algorithm defined in BS 15026 and during winter, internal humidity is determined by external temperature and therefore fluctuates. In the context of traditional buildings, internal conditions of 20°C are often unrealistic and unachievable.

- **ASHRAE 160P** - The summertime internal climate is derived from the external file using the algorithm defined in ASHRAE 160P. The option exists to set the wintertime internal temperature and a floating temperature shift. Moisture load can be estimated by defining occupancy numbers, building volume and the number of air changes per hour at normal pressure. The vapour pressure from the continuous moisture production rate determines RH during winter. Moisture load can be entered precisely, if known. Document 160P has now been published as ASHRAE Standard 160-2009.

- **Sine curves** - A simplified option that uses predefined curves or alternatively the user can define the mean internal temperature and relative humidity. Within the user defined option the amplitude can be set to represent the deviation from the mean values during summer or winter conditions.

Thermal Transmittance (U-Value) and Calculation Standards

The thermal transmittance (U-value) of a wall represents the heat conducted through one square metre of wall [W/m^2K]. It includes the heat transfer properties of the surfaces and is commonly used for calculating heat loss. A lower number denotes greater thermal resistance. The main documents relating to the calculation of U-values are:

- **BS EN ISO 6946:2007** - *Building components and building elements — Thermal resistance and thermal transmittance — Calculation method (ISO 6946:2007).*

- **BR443** *Conventions for U-value calculations.*

- **CIBSE Guide A***: Environmental design.*

In order to calculate U-values the thermal conductivity and the thickness of each material needs to be known. A distinction should be made between the *dry* thermal value and the *design* thermal value; the latter accounts for moisture within the material and more closely represents its thermal properties under normal service conditions. This is relevant for masonry materials where exposed facing bricks have a higher moisture content than the sheltered inner units.

In accordance with BR443 (Anderson 2006), CIBSE Guide A (2007) and BS EN ISO 6946:2007 (BSI 2007) U-values must be calculated with appropriate design thermal conductivities. BR443 lists two values for outer and inner leaves of brick: 0.77 W/mK and 0.56 W/mK respectively. BR443 also refers to CIBSE Guide A for appropriate correction factors to convert dry masonry thermal values to design thermal values. The Build Desk U-value calculator uses these two masonry thermal values, which appear to consider the water content of outer leaf. However, in general, manufacturers only supply the dry thermal conductivities of their materials.

In order to convert *dry* masonry thermal values to *design* masonry thermal values, CIBSE Guide A (2007) states that ‘exposed’ and ‘protected’ masonry should have its moisture content adjusted to 5% (by volume) and 1% (by volume) respectively. A correction factor is then applied to the dry thermal conductivity of 10% per 1% increase in moisture content (by volume). Therefore an exposed clay brick with a dry thermal conductivity of 0.6 W/mK should have a design thermal conductivity of 0.9 W/mK. The resulting U-value of a 215mm solid brick wall, the outer leaf exposed (5%) and inner protected (1%), would change from a dry U-value of 1.85 W/m^{2}K to design U-value 2.15 W/m^{2}K. Internal and external surface heat resistances are 0.125 m^{2}K/W and 0.0588 m^{2}K/W respectively.

Transient Thermal Transmittance (Transient U-value)

When building a wall in WUFI, the U-value is automatically calculated using design thermal conductivities at 80% RH. It is also possible to use WUFI's built in post-processing tool to calculate the monthly transient thermal transmittance. These values are normally shown for each month during the heating season and take into account the moisture dependent thermal conductivity of the materials at that time. Transient U-value results over summer months can end up being negative due to the summertime interior heat flux often changing twice a day (WUFI 2009). The values lower than the dry U-value in Figure 4 are an example of negative results and should be discounted. They are presented here as a point of interest.

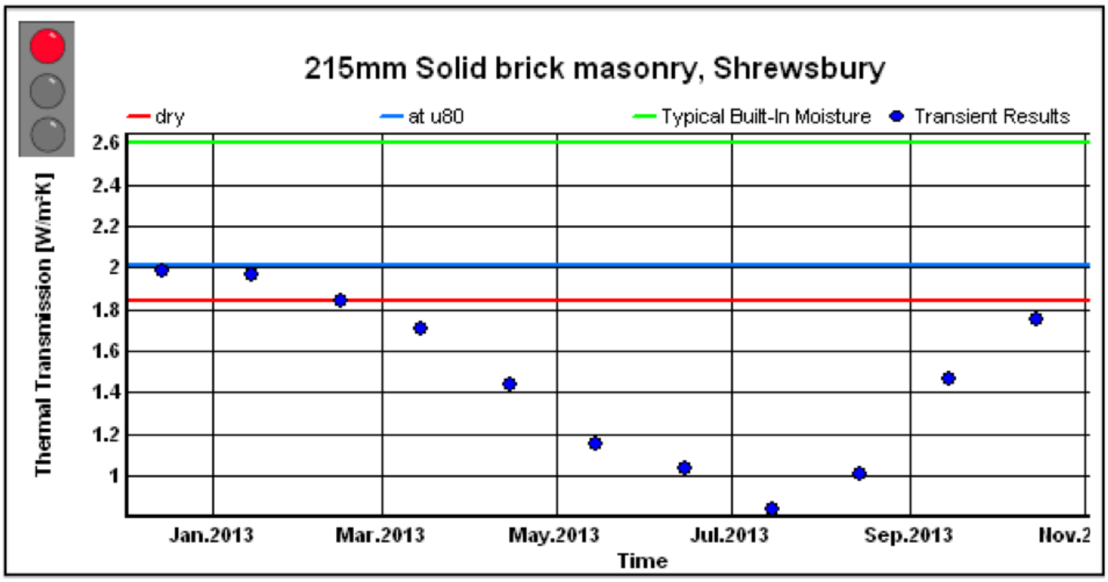


Figure 4. WUFI post-processor results for transient thermal transmission.

From Figure 4 it is clear that the dry U-value of 1.85 W/m^2K matches the worked example above and the U-value at 80% RH is reasonably close to the 'exposed' U-value of 2.15 W/m^2K calculated with the CIBSE Guide A conversion factors.

6. CASE STUDY - ABBEYFOREGATE, SHREWSBURY

The property on Abbeyforegate has undergone a period of pre and post refurbishment monitoring as part of the SPAB's Building Performance Survey (please see The SPAB Research Report 2 for more information). The building is brick built from around 1820, it was originally mid-terrace but has had one adjoining building demolished. The building is two storeys high plus an attic dormer with a usable floor area of approximately 60m^2. The 'brick and a half thick' walls at Shrewsbury are 400mm thick and laid in a Flemish bond. The lime based mortar joints are approximately 10mm wide and in many places the pointing is weathered. In its current condition, driven rain will sit in the open mortar joints and for the wall to shed water more effectively it should be repointed in an appropriate material. From initial investigations there is a marked difference between external 'facing' bricks and internal 'common' bricks. The internal 'common' bricks of traditional buildings are often a poorer quality with a less uniform shape and lower frost resistance. However, because these variables were not measured, one type of brick will be used throughout the wall for the purposes of this study.

Figure 5. Bricks at Shrewsbury laid in a 'brick and a half thick' Flemish bond.

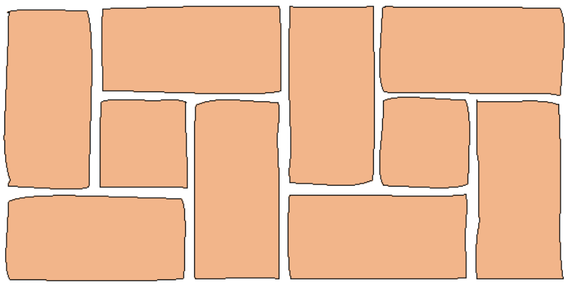


Figure 6. Plan view showing 'half batts' in the centre of the wall.

From a visual identification by Dr Gerard Lynch (2011), the bricks appear to be imperial and hand-made. Unfortunately these characteristics do not help in identifying any of their hygrothermal properties. The dimensions of the bricks vary but are approximately 225mm x 110mm x 70mm (length, width, height) and with 10mm joints the wall thickness would add up to around 345mm. Curiously, the thickness of the brick wall is actually between 362mm and 377mm indicating either more mortar in the centre of the wall or mortar with some air voids. The theory that outer the leaf of the wall is made with snapped headers and a small 27mm to 42mm cavity has been ruled out. The densities of four brick samples taken from the building are markedly varied as seen in Table 3.

Measured by	**Sample**	**Density [kg/m^3]**
Ayres	1	1593
Rye	2	1768
Rye	3	1800
Rye	4	1859
Average		1755

Table 3. Variation in density of brick samples

The sample taken by James Ayres is of a whole ‘common’ brick from the inner face and the measurements by Dr Caroline Rye are from cores samples taken during the installation of monitoring equipment. There is a significant difference in the density of the samples.

Energy Efficiency Measures

Over the summer of 2011 a number of energy efficiency measures were installed at the property in Shrewsbury. The most significant for this study are additional internal wall insulation (IWI) and air tightness measures. The IWI used is a woodfibre board from Steico with a thermal conductivity of 0.039 W/mK. It is vapour open, hygroscopic and capillary active. The internal plaster is a one-coat lime based system from Lime Green Products Ltd. The woodfibre board and lime plaster have *μ*-values of 5 and 5-20 respectively. The air change rate at the property has also been improved, the results at normal pressure are approximated and presented below (Table 4). The values have been calculated using Sherman's rudimentary but standard divisor of 20, which does not take into consideration the exposure of the building. Estimating additional flow rates through open flues is also complex and the figure used here is an approximation based on the additional airflow measured of $44m^3$/hr at ambient pressure. This relates to an additional 0.33 air changes per hour.

	Excluding flue	**Including flue**
Pre renovation	0.8 ach @ normal pressure	1.13 ach at normal pressure
Post renovation	0.59 ach @ normal pressure	0.92 ach @ normal pressure

Table 4. Pre and post renovation air change rates at normal pressure.

Overview of the Study

This study uses WUFI Pro 5.1 software to investigate interstitial moisture and the design U-value of the south-facing ground floor wall at the property on Abbeyforegate, Shrewsbury. Pre and post renovation scenarios are modelled for thermal transmittance and to assess whether critical limits of moisture are reached at the IWI and masonry wall interface. Microbial growth on the internal surface of the wall is not investigated

One-dimensional Representation of the Walls with and without IWI

In order to represent solid masonry walls in WUFI 1D the presence of brick and mortar occupying the same cross-sectional space needs to be slightly simplified. The percentage of mortar is one of the variables known to affect the thermal transmittance of a wall (Baker 2011) and therefore its proportion within the wall should be estimated as closely as possible. The bricks at the property have no indentions (otherwise known as frogs) and as the exact core of the wall is unknown, the percentage of mortar has been estimated at 23%, which includes the 10mm bedding and perpendicular joints. This proportion of brick to mortar will be represented as two bands in the centre of the wall even though in reality it would be normal to find unfilled internal joints and small air pockets. The presence of these pockets would decrease the wall's U-value and provide a capillary moisture break. As the voids will not be consistent enough to provide a continuous cavity the wall is modelled as a solid wall where there is a full bond between all materials (Fig. 6). This is likely to provide worst-case scenarios for both high U-values and moisture contents.

Pre-refurbishment assignment of materials**:**

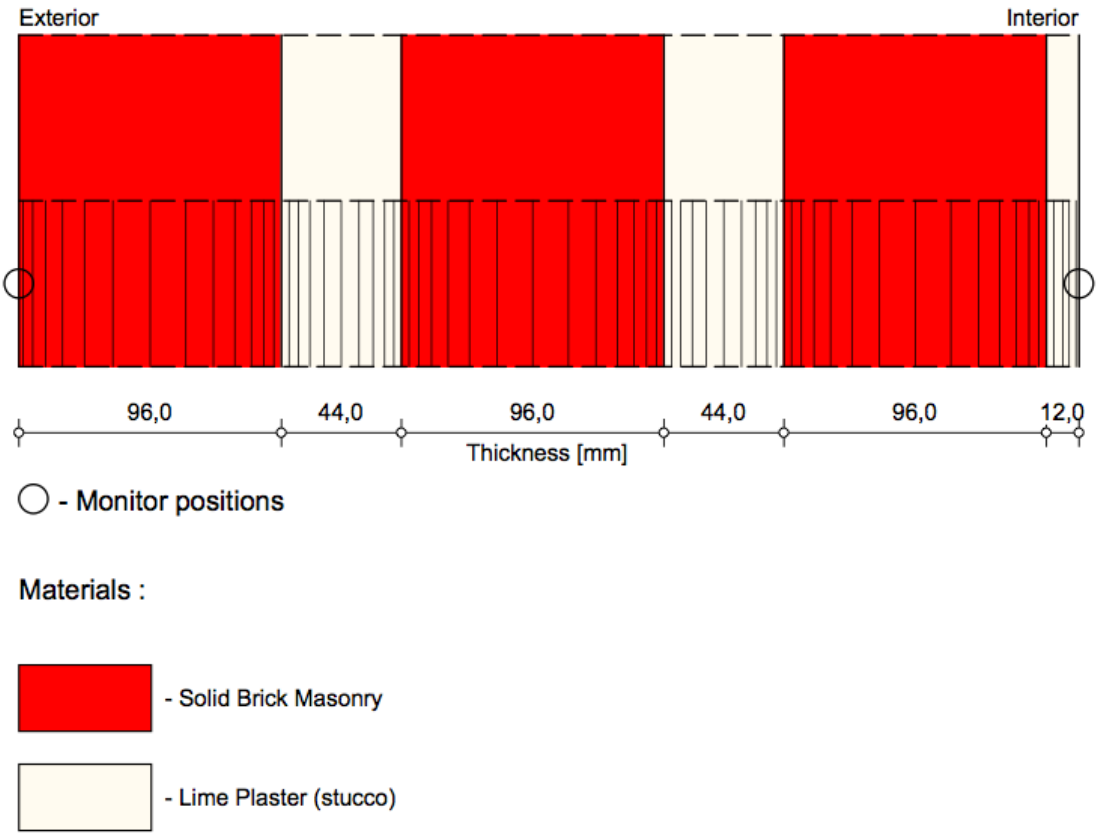


Figure 6. 23% mortar in a brick and a half thick wall represented in a one-dimensional simulation.

After the refurbishment has taken place the wall has an additional 40mm of woodfibre insulation on the inside (Fig. 7). This is split into two layers, one of 5mm and another of 35mm enabling the total water content of the vulnerable inner 5mm layer to be monitored.

Post-refurbishment assignment of materials**:**

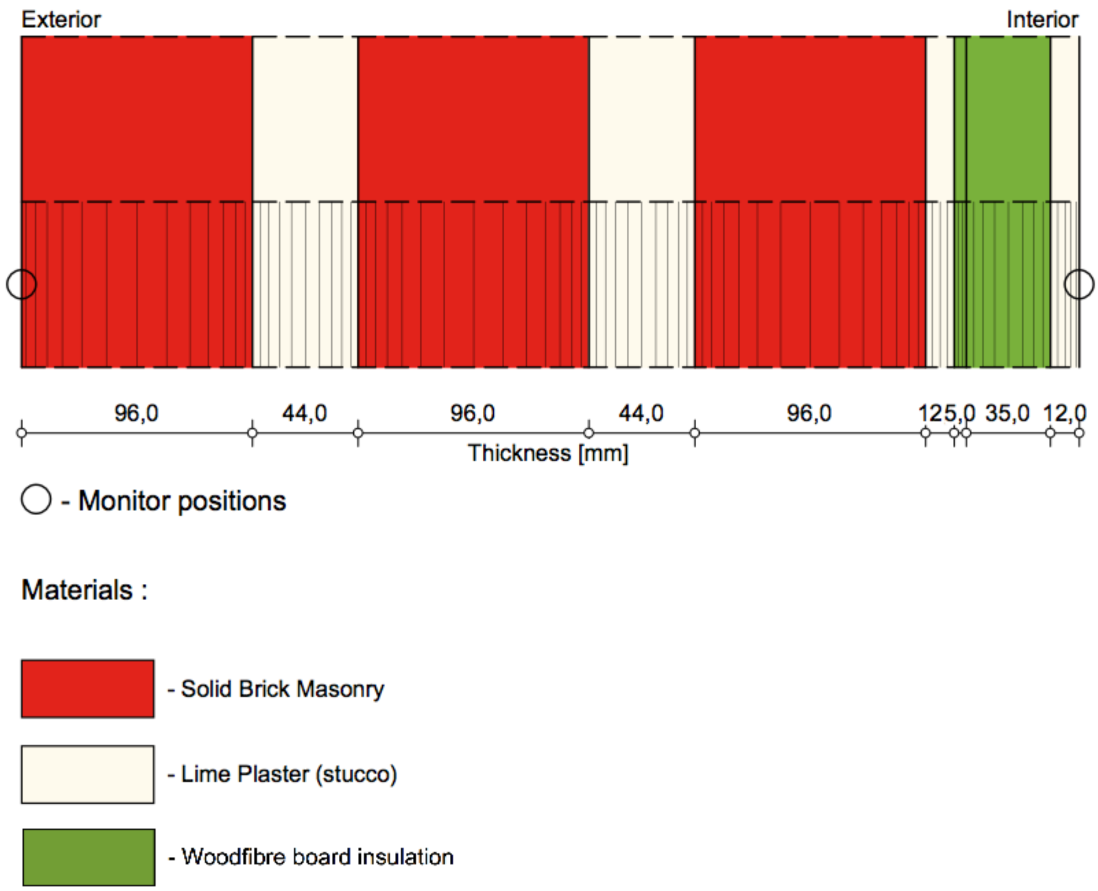


Figure 7. Representation of how woodfibre insulation is modelled in the simulation.

Once the wall without IWI has established dynamic equilibrium, the profile for water content from the end of the calculation is outputted and amended to include the typical built-in moisture content of the new layers. This new profile is used to start the new calculation with IWI.

Establishing Material Inputs

Brick

With the building at Shrewsbury, as in most cases, the actual materials' properties are unknown and therefore have to be selected from a library of predefined materials within WUFI.

When selecting a brick from the WUFI material database, catalogues from eight different institutions are available. The Fraunhofer IBP material catalogue is possibly the most obvious to refer to as it is compiled by the software manufacturers and the range of materials in it are extensive. Within the 'masonry bricks' folder there are four available bricks; solid brick masonry, historical, hand-formed and extruded. After inspecting the notes in each bricks file the use of solid brick masonry is perhaps the most obvious choice as it has had its values altered to include a percentage of mortar. With further examination of the other catalogues the user will find a total of 30 different bricks, each of which have had their values measured by different institutions over Europe and North America.

Some files contain pictures of the brick samples, which offer limited help in choosing a brick. Unfortunately there are no details of firing techniques or clay types that may assist selection. Some catalogues contain bricks with names like, 'historical' or 'hand formed', but the majority are found in the MASEA catalogue, 24 in total, where most have names like ZA or ZQ. Ultimately the process of selecting a brick is completely arbitrary and for this reason all the bricks in the WUFI database will need to be simulated in order to assess the range possible in the results and to establish whether specific bricks are more appropriate for certain studies. Bricks that give worst-case scenarios for U-values and moisture levels in the IWI are perhaps the most logical to use for further assessments.

Where values are not known for a calculation BS EN 15026:2007 refers the reader to BS EN ISO 10456:2007 - *Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values*. This standard lists some of the values needed for many common materials, including 17 generic building stones, but none for brick (BSI 2010). Where no thermal conductivity values exist BS EN ISO 10456:2007 suggests they should be derived from correlations between a related property, such as density, or measured according to a number of listed test methods. Tabulated values for the thermal conductivity of bricks are presented in BS EN 1745:2012 - *Masonry and masonry products — Methods for determining thermal properties.* As shown below (Fig. 8) the relationship between density and thermal conductivity is not strictly linear as presented in BS 1745:2012.

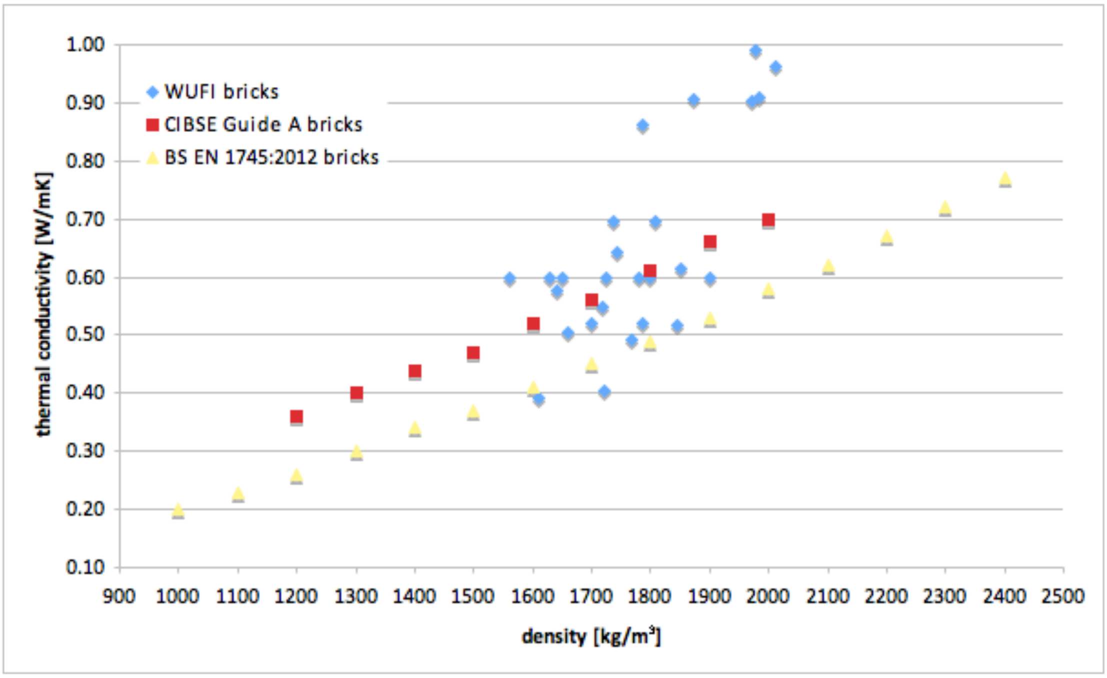


Figure 8. The relationship between the density and thermal conductivity of bricks from various sources.

It is clear from the chart above that all 30 bricks in the WUFI database have had their thermal conductivity measured and that the CIBSE Guide A and BS EN 1745:2012 bricks have had their values extrapolated from the linear relationship to density. Figure 9 shows just the bricks from the WUFI database and although there is a correlation it is not strong. Whilst building stones are not relevant to this particular case study the subsequent chart (Fig.10) shows that the correlation between density and thermal conductivity in WUFI's selection of stones is even weaker.

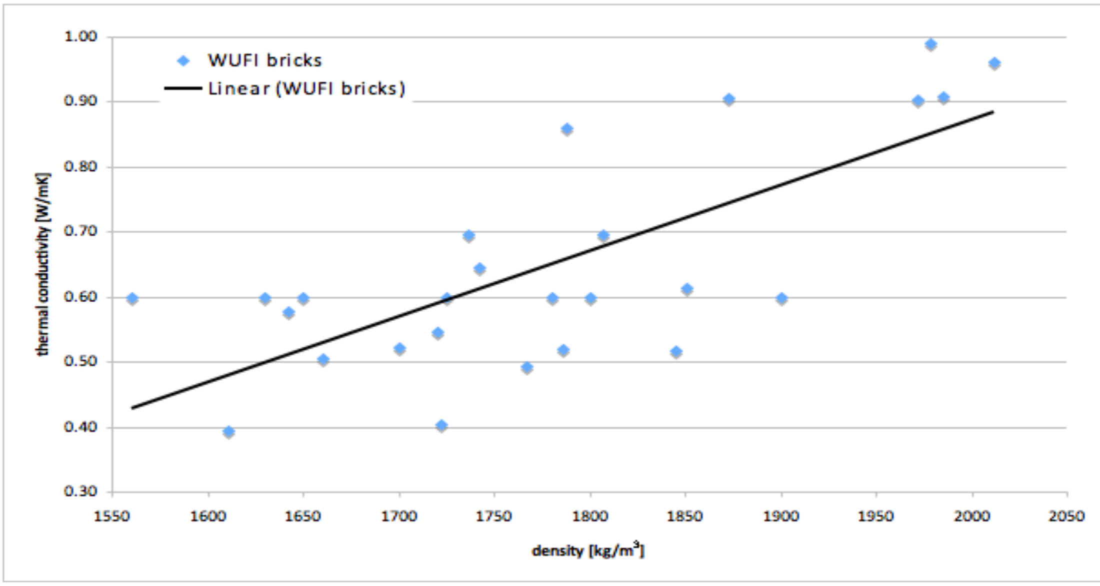


Figure 9. The relationship between the density and thermal conductivity of bricks from the WUFI database.

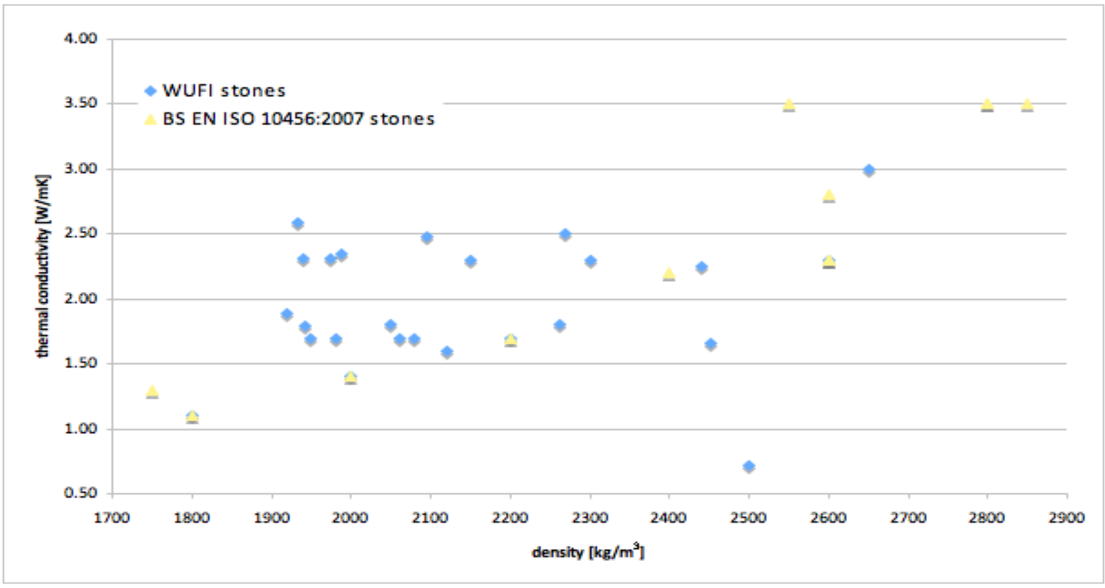


Figure 10. The relationship between the density and thermal conductivity of building stones from the WUFI database and BS EN 10456:2007.

The density of the brick samples taken from the building range from between 1593 kg/m^3 and 1859 kg/m^3 which, when using the chart (Fig. 9) as a guide, relates to thermal conductivities of between approximately 0.4 W/mK and 0.6 W/mK. If encompassing the brick in the chart with a density of 1873 kg/m^3 then the upper limit is 0.9 W/mK. The trend line suggests approximate values of between 0.45 W/mK and 0.75 W/mK.

As a means of comparison the Fletton brick will be included in the study. Flettons are a widely used and well-known British brick and the values used here are taken from a brick specifically from the Stewartby site in Bedfordshire where production started in the 1880s. Flettons may not necessarily be classed as a 'historical' brick but they did make up a large proportion of the total UK brick output up to 1930 when many traditional solid walled homes were built (Brick Development Association 1974). The values for all bricks in the WUFI database, including Flettons, are listed in order of density in the table below. Three bricks have been excluded due to lack of confidence in their data set. The values for Stewartby Flettons are provided by Sharp (2009) and following a sensitivity analysis the μ-value is given as 16.

Brick	Density [kg/m³]	Porosity [m³/m³]	Spec. Heat Cap. [J/kgK]	Therm. Cond. [W/mK]	Water Vapour Dif. Res [-]	Ref Water [kg/m³]	Free Water Sat [kg/m³]	A-value [kg/m²√s]
ZF – MASEA	2012	0.24	815	0.962	41	9.9	127	0.016
ZC – MASEA	1985	0.28	836	0.908	23	3.1	188	0.183
ZP – MASEA	1979	0.25	834	0.990	45	2.5	82	0.050
ZQ – MASEA	1972	0.26	800	0.904	30	1.5	108	0.014
Solid brick masonry - IBP	1900	0.24	850	0.600	10	18.0	190	0.110
ZO – MASEA	1873	0.29	823	0.907	45	3.4	126	0.068
ZH – MASEA	1851	0.30	816	0.614	12	2.1	209	0.260
ZA – MASEA	1845	0.30	794	0.518	16	5.2	216	0.183
ARB – MASEA	1807	0.32	861	0.695	10	1.2	161	0.250
Solid brick, historical - IBP	1800	0.31	850	0.600	15	4.5	230	0.360
Solid Brick Jöns - MASEA	1788	0.35	868	0.861	13	2.4	257	0.230
Solid brick, Wienerberger – MASEA	1786	0.35	889	0.519	19	13.0	262	0.200
Solid brick, handmade – VIENNA	1780	0.32	850	0.600	10	1.8	236	0.283
ZJ – MASEA	1767	0.33	868	0.492	17	3.4	192	0.183
ZS – MASEA	1742	0.34	914	0.644	23	8.9	222	0.110
Stewartby Fletton	1740	0.33	1000	0.470	16	3.3	278	0.260
ZK – MASEA	1737	0.34	916	0.695	25	14.0	250	0.106
Solid brick, hand-formed – IBP	1725	0.38	850	0.600	17	2.7	200	0.300
ZI – MASEA	1722	0.35	881	0.404	21	30.0	246	0.030
ZM – MASEA	1720	0.35	937	0.547	19	5.0	264	0.116
ZG – MASEA	1700	0.36	920	0.521	22	7.7	231	0.136
ZL – MASEA	1660	0.37	934	0.506	13	5.5	216	0.183
Solid brick extruded - IBP	1650	0.41	850	0.600	10	9.2	370	0.400
ZE - MASEA	1642	0.38	899	0.577	13	4.7	254	0.216
Solid brick extruded - VIENNA	1630	0.35	850	0.600	10	8.7	333	0.267
ZD - MASEA	1611	0.39	953	0.393	10	3.6	216	0.183
Solid brick, historical - VIENNA	1560	0.38	850	0.600	15	11.8	369	0.583

Table 5. Values of all bricks in the WUFI database. The brick name is followed by the name of the institution that measured the values: IBP - Fraunhofer IBP; VIENNA - University of Technology Vienna; MASEA - free, online material database and research program run by the Fraunhofer IBP, Dresden University of Technology and the Centre for Environmentally Conscious Building in Kassel.

Mortar Sensitivity Analysis

Before running calculations the mortar content also needs to be defined. Within the database there exists 16 different types of mortar/plaster; none of which are highlighted as being historic mortars from lime putty and therefore none are obvious choices for this study. A sensitivity analysis has been performed to establish to what extent the choice of mortar affects the results. Figure 11 shows how the mortar choice changes the water content [M%] of the 5mm insulation interface with each different mortar. In this instance the wall is simulated at 210 mm thick with a core of 23% mortar.

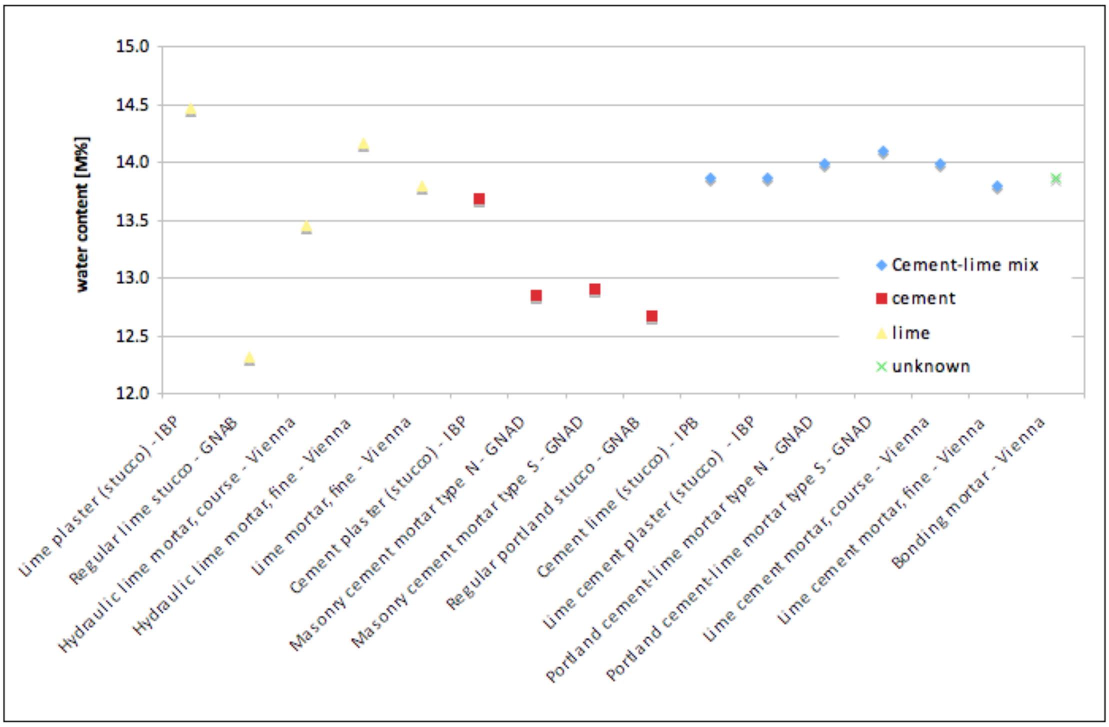


Figure 11. Water content in mass % of the 5 mm insulation layer in contact with the masonry.

For the purpose of this study Lime Plaster (stucco) from the Fraunhofer IBP database has been chosen as it represents a worst-case scenario. Interestingly, lime based products return both the highest and lowest results.

Brick Sensitivity Analysis

Each brick is modelled at three different thicknesses (100 mm, 210 mm and 377 mm) as a solid wall without mortar and with 23% lime plaster (stucco). This represents walls that are 'half, 'one' and 'one and a half' bricks thick. Where possible default settings are used for inputs, including the default BS EN 15026 setting for internal climate with a 'normal' moisture load. Simulations are run until the dynamic equilibrium of each material is established. The resulting peak water contents by mass percent of the 5 mm IWI/masonry interface layer are shown below (Fig. 12). The critical limit stated in the WUFI training literature for wood-based materials like the wood fibre insulation is around 18% moisture content, although there is not full agreement on this limit between other sources. If the water content is consistently above this limit then decay can occur. The bricks are sorted left to right in order of increasing peak water content in the IWI interface to the 100 mm wall.

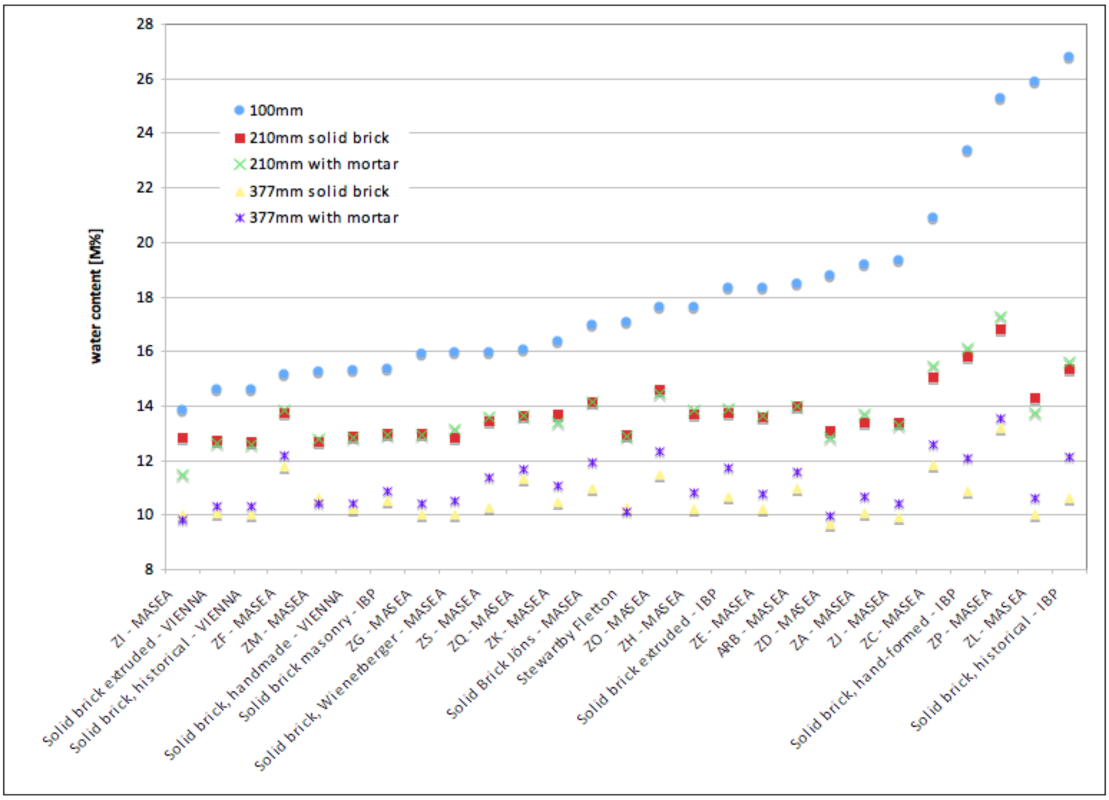
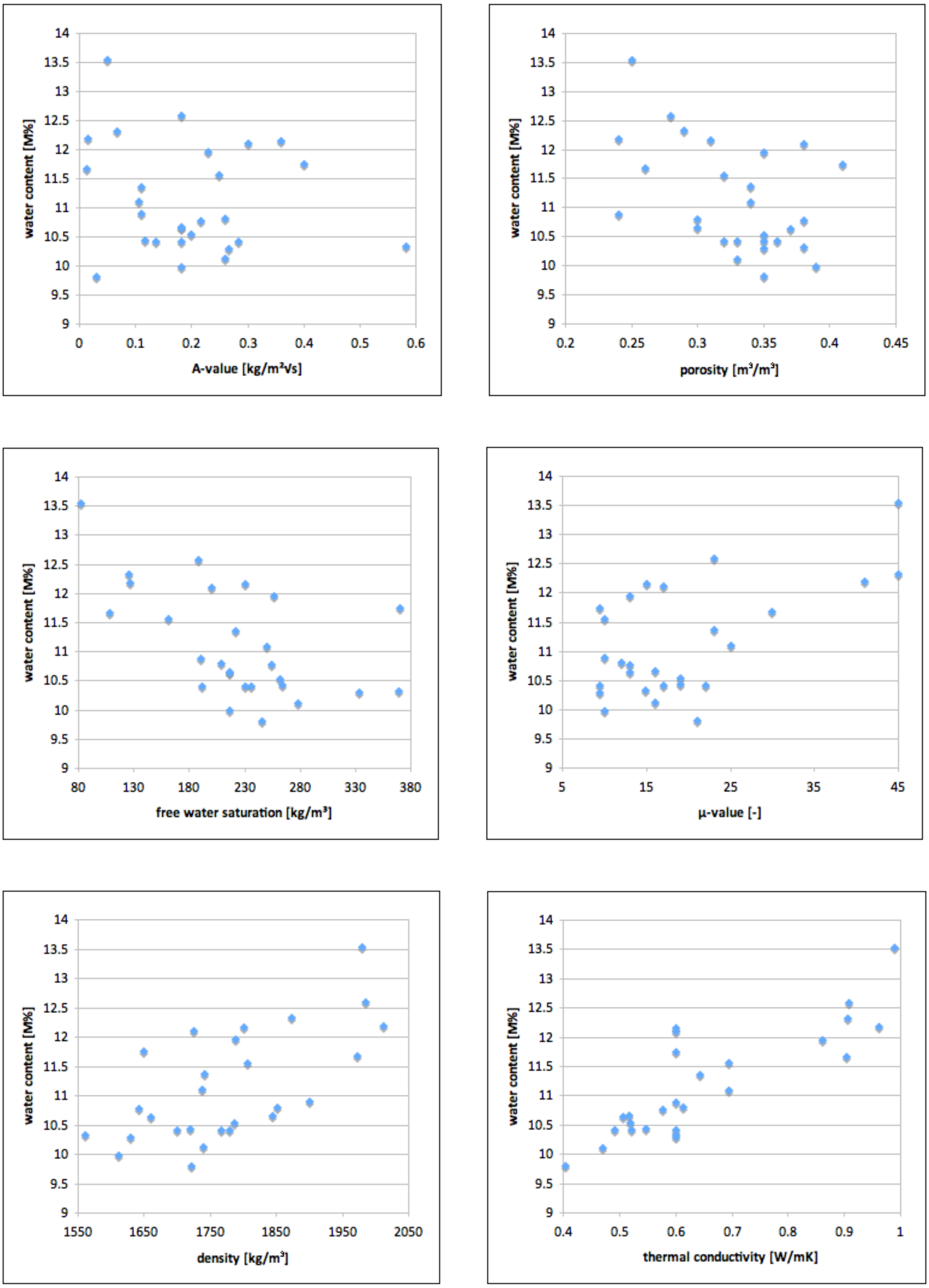


Figure 12. Peak water content [M%] of the IWI at the masonry interface shown for each brick at three wall thicknesses.

Figure 12 shows the peak water content of the insulation interface decreases as the wall becomes thicker. The effect of the mortar is shown to be negligible in the 215 mm wall and causes a slight increase in the peak water contents of the 377 mm wall IWI. The choice of brick is the most important factor in determining the peak water content of the IWI interface. Just less than half of the 100 mm simulations exceed 18%. Brick ZP reached 17.5% in the 210 mm wall and none of the bricks modelled at 377 mm go above 13.5%.

Figures 13 to 18 also show that there are no strong correlations between peak water content of the IWI interface and any other moisture properties of the bricks. Figures 17 and 18 do however show a weak correlation with density and dry thermal conductivity.



Figures 13 to 18. Relationships between the water content of the IWI masonry interface in mass percent and the A-value (Fig. 13 top left), porosity (Fig. 14 top right), free water saturation (Fig. 15 middle left), µ-value (Fig. 16 middle right), density (Fig. 17 bottom left), thermal conductivity (Fig. 18 bottom right).

U-values

Using the same selection of 27 bricks with and without mortar, U-values have been calculated in order to understand the range possible within the bricks. These design U-values use the thermal conductivity of materials at the reference water content and 80%RH (w80). Figure 19 relates to the Shrewsbury building before the renovation and shows all bricks from the WUFI database.

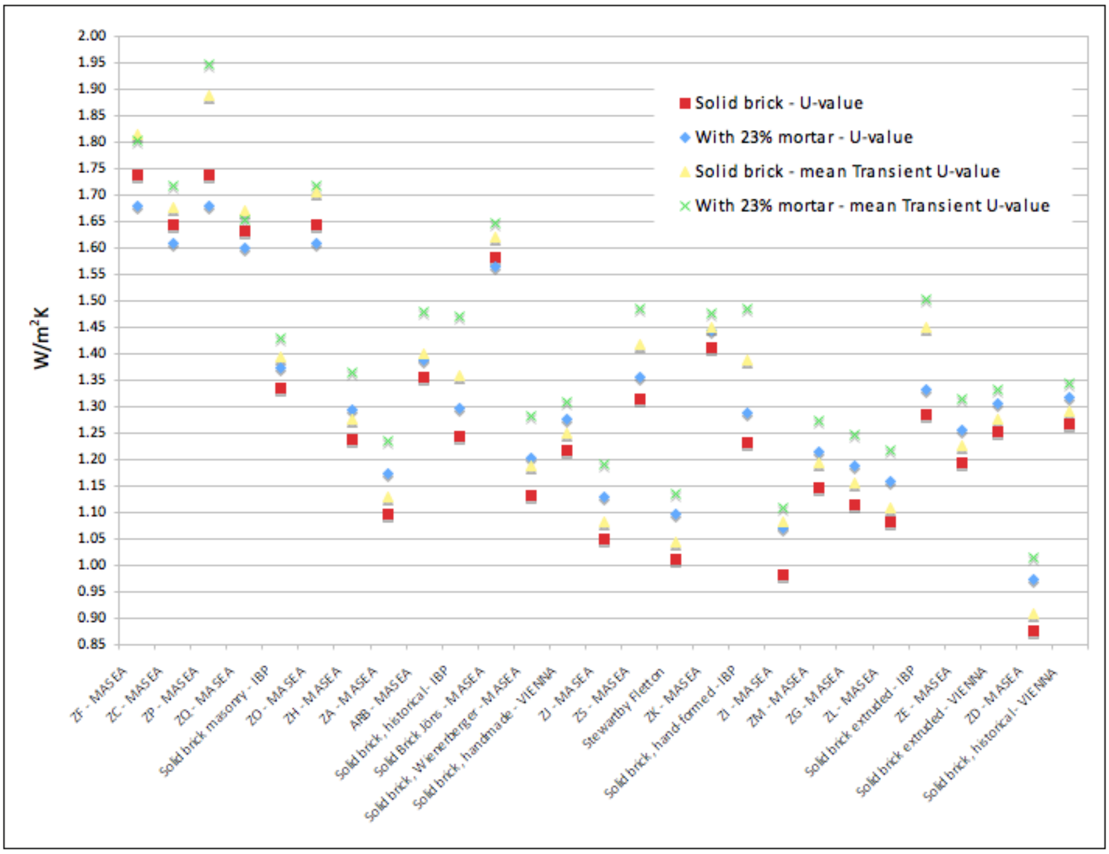


Figure 19. The U-values and mean transient U-values for Shrewsbury pre-renovation using all bricks in WUFI with and without mortar.

Whilst the range in U-values for an individual brick may not be vast, on average 0.1 to 0.2 W/m^{2}K, the total range in U-values from all bricks is over 1 W/m^{2}K. The bricks in the table are sorted in order of density with the highest density on the right. A general, but not strong trend can be seen with lower density bricks showing lower U-values. Figure 20 shows the same dataset post-renovation with the inclusion of 40mm of internal insulation.

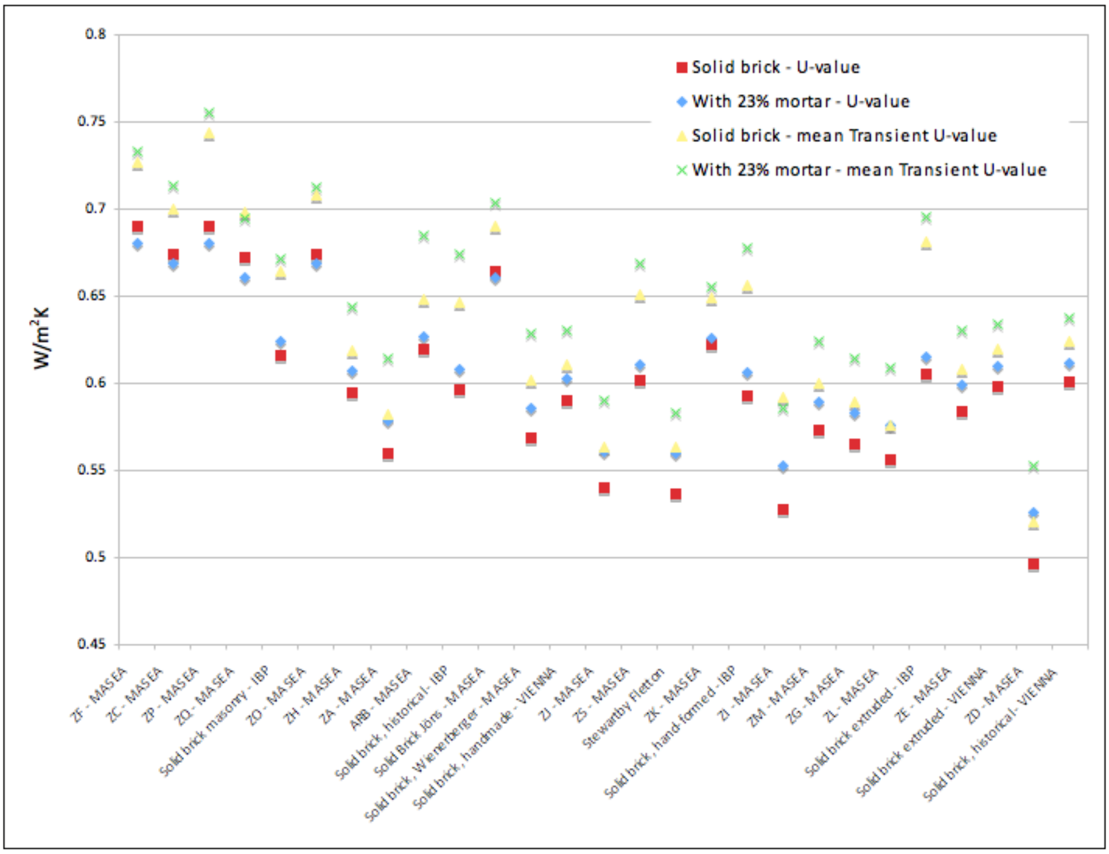


Figure 20. The U-values and mean transient U-values for Shrewsbury post-renovation using all bricks in WUFI with and without mortar.

With the introduction of 40mm of insulation the total range in the results has reduced to just over $0.25W/m^2K$, a similar amount to the range found just within solid brick, hand-formed - IBP in the pre renovation chart.

Figure 21 shows the deviation within each transient U-value over the heating season compared to the solid state U-value at w80. The deviation is due to the changing moisture content of the wall from month to month.

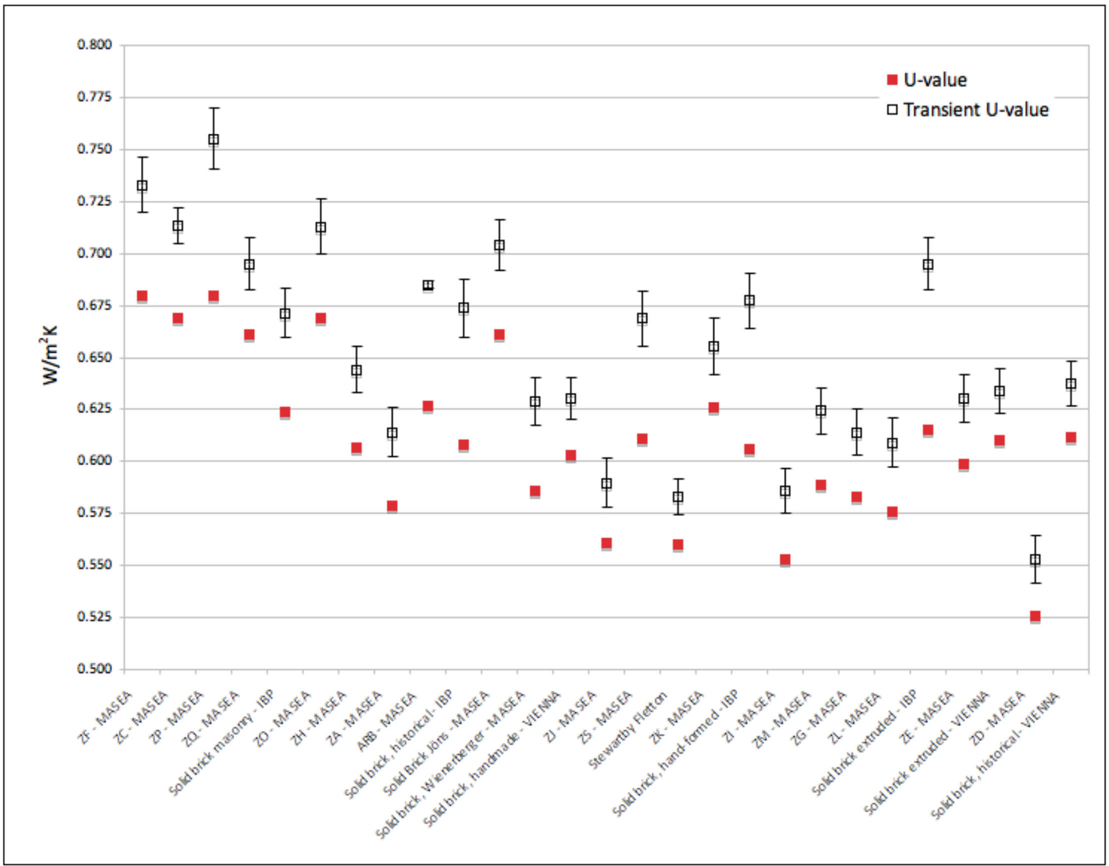
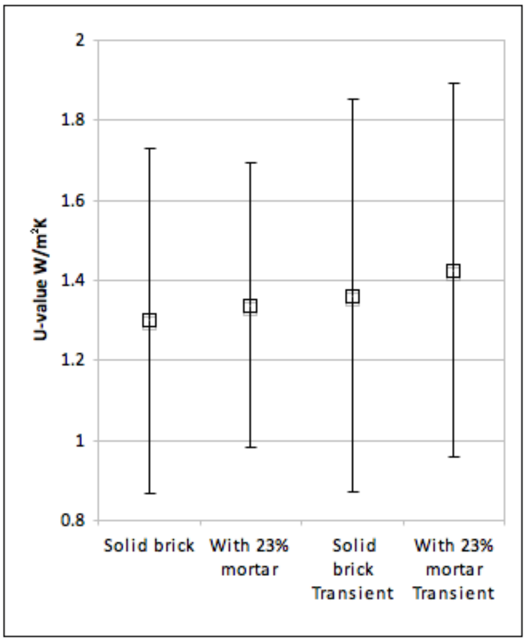
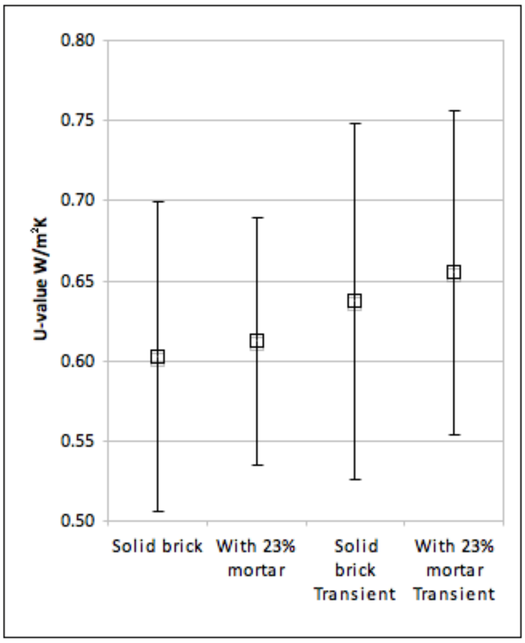


Figure 21. The difference between U-values and transient U-values of all bricks in WUFI post renovation.

Figure 21 highlights the difference between methods of calculating U-values and shows their transient nature over the heating season. For means of comparison Figures 22 and 23 present the total deviation in U-value results from WUFI over all bricks with and without mortar. Bricks ZP, ZC and ZO, which produced the highest moisture contents at the IWI interface also have some of the worst U-values. These bricks have some of the highest densities, thermal conductivities and lowest porosities in the data set but unfortunately no single value correlates well with a high moisture content in the IWI interface.





Figures 22 and 23. Total range in pre-refurbishment (left) and post-refurbishment (right) U-values and transient U-values from all bricks in WUFI.

Figure 22 illustrates the importance of defining the thermal conductivity of bricks in order to accurately calculate U-values in buildings without insulation. The transient U-value range in post-renovation results is much narrower but still notable.

In summary the use of the programme in an unprofessional way where material properties cannot be defined produces very broad results for U-values. Even though the results for peak water content at the IWI interface are imprecise, none of the bricks in the 377 mm wall actually caused failure conditions. This can only be stated for this particular location (Shrewsbury) with the selected wall orientation, ventilation rates and other variables in the synthetic climate files.

Climatic Variables

As material properties for the brick at Shrewsbury are unknown, local climatic variables are explored using brick ZP as it represents the worst case for high water content of the IWI. The following simulations all use the same assignment of materials, unless otherwise stated, and explore the sensitivity of a number of variables. The external climate file from Meteonorm stays the same throughout all the simulations.

The way WUFI uses the Meteonorm weather data depends on a number of factors that also need to be defined. For the external climate these mostly revolve around response to long and short wave radiation, exposure to wind-driven rain, the adhering fraction of driven-rain on the external surface, and whether a temperature shift is applied to the file to represent one-in-ten year severe conditions. The internal climate is defined by a combination of variables that primarily include the external climate, internal temperature, ventilation rates and internal moisture loads.

As discussed previously in Chapter 5 there are a number of initial options for assigning an internal climate file. In summary these are:

BS EN ISO 13788:2002 - The internal temperature is set by the user and remains constant throughout the year. The humidity class can also be changed.

BS EN 15026:2007 - The internal temperature during the heating season is fixed at 20°C and moisture load can be defined as normal or high.

ASHRAE 160P - Internal wintertime temperature and a floating temperature shift can be user defied. Moisture load can be estimated by defining occupancy numbers, building volume and the number of air changes per hour at normal pressure.

Sine curves - A simplified option that uses predefined curves or alternatively the user can define the mean internal temperature and relative humidity.

Users own data - Measured data can also be used to create an internal climate file.

Given that internal wintertime temperatures in many traditional buildings are often below the 20°C limit in the BS EN 10526 internal climate file, lower temperatures are explored using the ASHRAE 160P methodology. The ASHRAE methodology requires further information on occupancy levels, ventilation rates and building volume, which have been taken from a site survey. Table 6 below summarises details used to create the external climate file and Table 7 shows factors measured on site considered in the calculation.

External climate is defined as follows:

Location	Shrewsbury 2.71°W, 52.71°N. 51 metres above sea level
Climate file	Synthetic data for Shrewsbury created in Meteonorm 6
Format	.WAC
Extreme temperature events as part of file	No

Table 6. Summary of the external climate file

Derived from:	External climate
Air conditioning system	Heating only
Approximate internal temperature	16°C
Estimated number of air changes per hour at normal pressure (including chimney)	0.92
Building volume	134m^3
Number of occupants	1

Table 7. Reference internal climate characteristics

Case	Method	Int. temp. [°C]	Int. temp. shift [°C]	Ext. temp shift [°C]	Ad. fac. of rain [-]	Ach [1/h]	Moisture load/gen. rate [kg/s]	Misc
1	ASHRAE 160P	16	2.8	2	0.7	0.92	9.00E-05	-
2	**BS EN 15026**	**20**	-	2	0.7	-	**normal**	-
3	ASHRAE 160P	**20**	-	2	0.7	0.92	9.00E-05	-
4	ASHRAE 160P	16	2.8	2	**0.8**	0.92	9.00E-05	-
5	ASHRAE 160P	16	2.8	2	**0**	0.92	9.00E-05	-
6	ASHRAE 160P	16	2.8	2	0.7	**1.13**	9.00E-05	-
7	ASHRAE 160P	16	2.8	2	0.7	**2.5**	9.00E-05	-
8	ASHRAE 160P	16	2.8	2	0.7	0.92	**1.60E-04**	-
9	ASHRAE 160P	16	2.8	2	0.7	0.92	9.00E-05	**VCL s_d 20**
10	ASHRAE 160P	16	2.8	2	0.7	0.92	9.00E-05	**Brick: Fletton**
11	ASHRAE 160P	16	2.8	2	0.7	0.92	9.00E-05	**ASHRAE RDF 0.5**
12	ASHRAE 160P	16	2.8	2	0.7	0.92	9.00E-05	**ASHRAE RDF 1.0**

Table 8. Summary of all the internal and external climatic variables explored. Case 1 is used as a reference case with variations to it shown in bold.

In order to highlight the sensitivity of specific variables in the case study a selection of different climatic scenarios are simulated. Initially the reference Case 1 that uses the ASHRAE 160P internal climate methodology at 16°C is compared with Case 2 that uses the programme's default internal climate methodology from BS EN 15026. Further default settings are used in Case 2 for the adhering fraction of rain (0.7), internal temp, (20°C) and internal moisture load (normal). Case 3 increases the internal temperature to 20°C in order to see how ASHRAE and BS 15026 methods differ at the same temperature. Case 3 uses site data for the ventilation rate and estimated moisture production.

As changing the amount of rain in the climate file is beyond the scope of this research, instead its increased presence is investigated in Case 4 and 12 by increasing exposure to the rain in the climate file. Case 4 increases the fraction of rain that adheres to the surface of the wall from 0.7 to 0.8. Case 5 isolates the driven rain by completely removing any rain absorption from the calculation. This will highlight to what extent driven rain is responsible for the moisture content of the wall. Case 6 increases ventilation rates to the same level as before the renovation and Case 7 double rates to 2.5 ach at normal pressure. The three ventilation rates can then be compared to establish what difference the variable makes in the model. Case 8 returns to post-renovation ventilation levels and keeps the building volume the same but increases the internal moisture production rates. Moisture levels are changed from the minimum setting of a one-bedroom house (two occupants) to that of a three-bedroom house, indicating four occupants. This aims to indicate what difference there is in assuming worst-case internal moisture levels of a fully occupied house.

Case 9 introduces a vapour control layer (VCL) with an s_d value of 20 (μ 20,000) to the warm side of the IWI and represents a similar degree vapour resistance to a foil vapour retarder. This scenario relates to the industry standard solution of the inclusion of a vapour layer to reduce interstitial condensation. Case 10 replaces Brick ZP with approximated values for a Stewartby Fletton brick in order to highlight any significant differences with this widely used British brick.

Finally, Cases 11 and 12 use calculated rain loads according to ASHRAE 160P and assumes medium exposure to rain. Case 11 uses the default rain deposition factor (RDF) of 0.5 for walls on a building with a pitched roof, as is the case in Shrewsbury. As adapting the amount of wind-driven rain in the climate file is beyond the scope of the research Case 12 increases the RDF to 1.0 representing the driven rain on walls on a flat roof building and should highlight to what degree moisture levels in the wall are sensitive to rain exposure. The ASHRAE methodology for driven rain is versatile and can also be used to select the exposure; open, medium, or sheltered, building height and walls specifically subject to rain runoff. The ASHRAE 160P rain exposure variables will be the subject of a further investigation.

Results of Climate Sensitivity Analyses

In order to show incidents of failure from liquid transport and from vapour diffusion, all cases are assessed for both water content (WC) by mass percent [M%] and relative humidity (RH) at the IWI/masonry interface.

The results are presented for WC and RH in Figures 24-27. The reference Case 1 is shown in each graph. The water content of Case 9 is especially high and is read from the right hand Y-axis and is identified accordingly.

Water Content

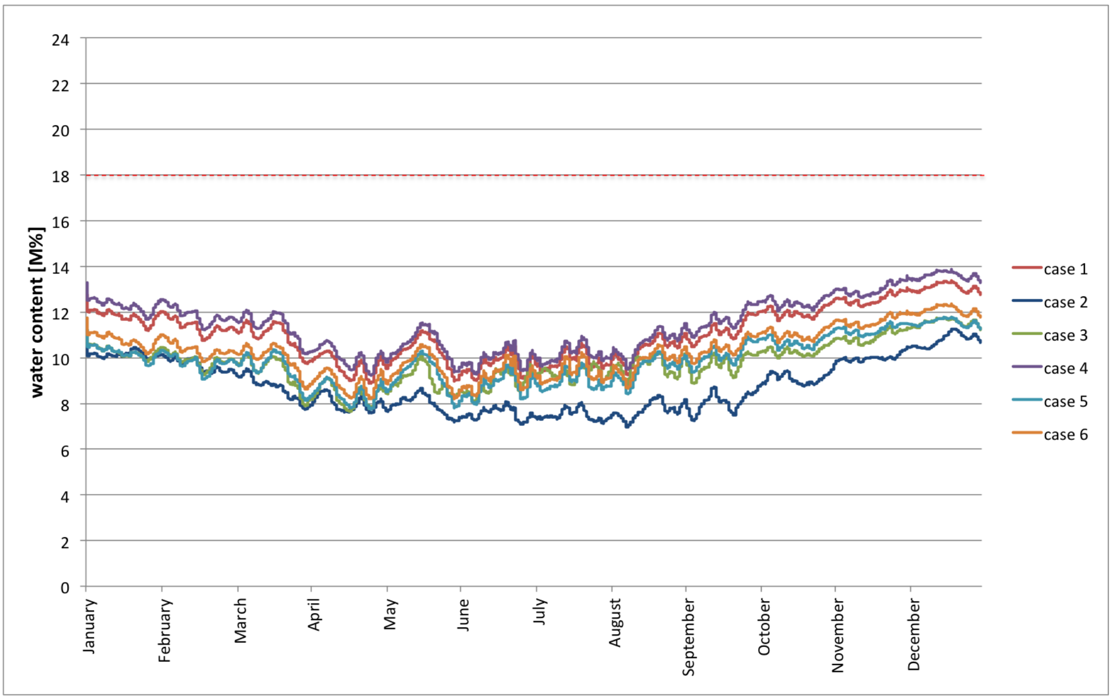


Figure 24. Cases 1-6. The water content (M%) of the 5mm woodfibre IWI layer at the masonry interface with a variety of climatic variables. Position of months needs to tally with previous graph format such as Figure 4.

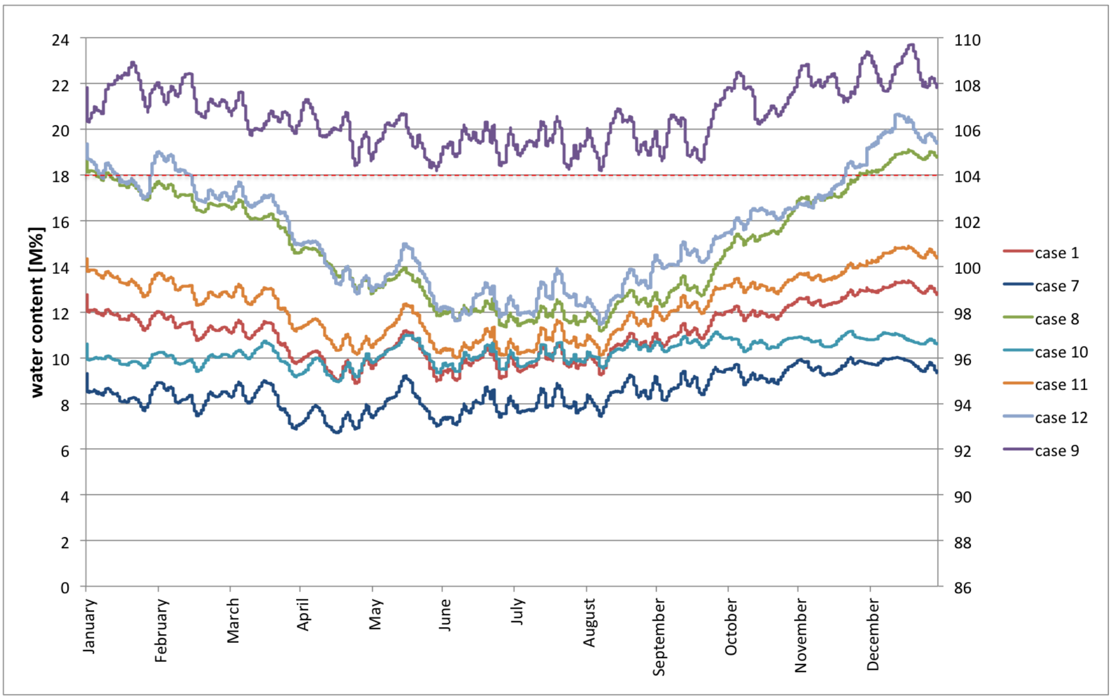


Figure 25. Cases 7-12. The water content (M%) of the 5mm woodfibre IWI layer at the masonry interface with a variety of climatic variables. Case 9 is read from the right hand Y-axis.

The critical limit for water content is defined by the red dotted line at 18% (IBP 2012). Most Cases sit fairly comfortably under 15% with the exception of 8, 9 and 12. Increasing the internal temperature in Cases 2 and 3 has the effect of slightly lowering the WC at the interface. Increasing ventilation levels (Cases 6 and 7) shows to have a similar effect. Failure from levels of water exceeding 18% by mass occurs in Cases 8, 9 and 12. Case 8 causes failure with the moisture generation rates of a family of four and Case 12 with a rain deposition factor (RDF) of 1, which is normally used for buildings with flat roofs. Alarmingly Case 9 uses the industry standard and BS 13788 based solution of a vapour retarder, which causes complete failure with levels constantly above 100%. The increased adhering fraction of rain in Case 4 had little effect and turning the rain off in Case 5 is also shown to make only a small reduction in water content when compared to Case 1.

Relative Humidity

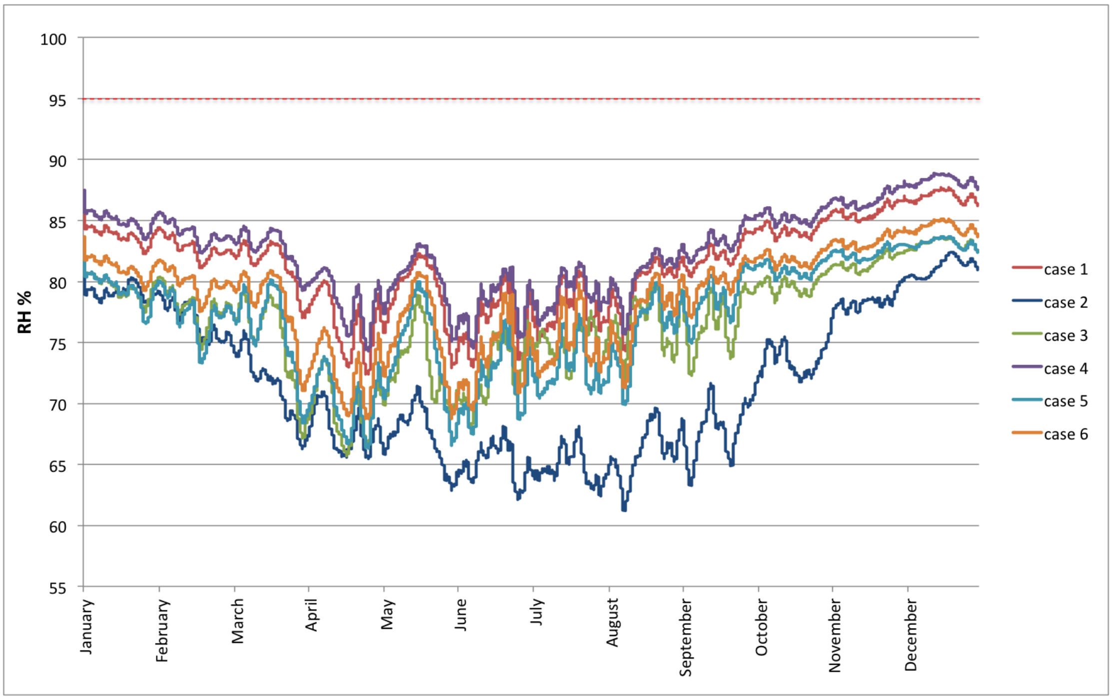


Figure 26. Cases 1-6. The RH of the 5mm woodfibre IWI layer at the masonry interface with a variety of climatic variables.

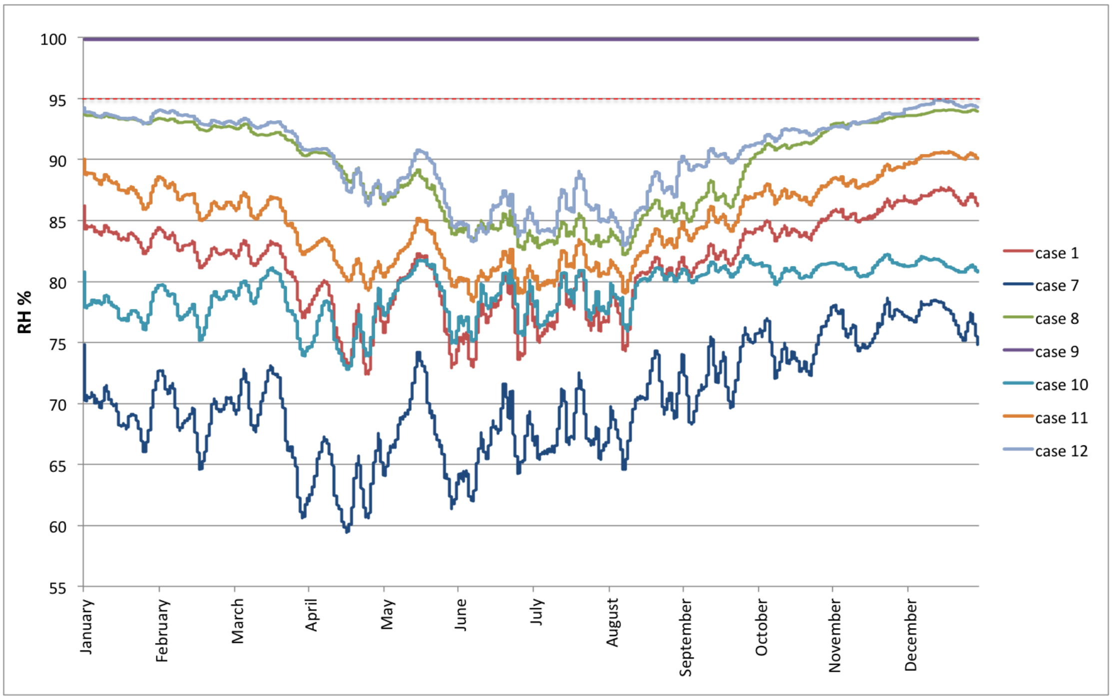


Figure 27. Cases 7-12. The RH of the 5mm woodfibre IWI layer at the masonry interface with a variety of climatic variables.

The critical limit for RH is defined by the red dotted line at 95%. There is disagreement over this limit as the absence of air in a perfect construction technically means that mould growth is not possible. This limit is from Zirkelbach (2012), Group Manager of Development of hygrothermal models at the Fraunhofer IBP, quoting the German WTA guidelines for interior insulations for which he is part of the standard's workgroup.

Case 1 rises to 87% in winter and is over 80% for more than half the year. If oxygen were present in voids behind the insulation then, depending on the temperature, mould growth would be likely to occur. Case 2, the BS 15026 20°C internal climate file shows the second lowest wintertime RH and the lowest summertime RH. Cases 2 and 3 differ during the summer, autumn and early winter but roughly converge from December to May. Increasing the adhering fraction of rain in Case 4 to 0.8 causes very slightly higher results. On average, having 'no rain' in Case 5 reduces the results compared to the reference Case 1 by just under 5% at all times. Increasing ventilation rates in Case 6 to pre-renovation levels decreases RH again by just over 5% at all times.

Doubling the ventilation rate causes the lowest wintertime RH levels at the interface by nearly 10% to 70-75% indicating that high indoor ventilation rates reduce the RH at the interface, when compared to the reference case, more than having no driven rain at all. Case 8 changes the internal moisture load to a family of four with the ASHRAE file, which causes the joint second highest RH, similar levels to increasing the RDF to 1. Again Case 9, which includes a vapour control layer of s_d 20 (μ 20,000) on the warm side of the insulation, causes the IWI wall interface to reach 100% for all of the year, and is the most common solution to avoiding interstitial condensation and moisture related problems in building design.

7. DISCUSSION

General overview

WUFI Pro 5.1 hygrothermal simulations software has been used to undertake condensation risk analysis and U-value calculations of a case study house in Shrewsbury. Due to the hygrothermal values for the bricks not being measured the programme's internal material database is referred to. This database contains 30 bricks, none from the UK, and no specific bricks are an obvious choice for the study.

The Shrewsbury house has been internally insulated with a woodfibre insulation board and finished with a lime based render. The organic nature of the board, whilst offering the benefits of being vapour open, hygroscopic and capillary active, also makes it vulnerable to moisture damage. Simulations have been conducted to establish the risk of harmful humidity levels and water contents at the IWI/masonry interface.

The U-value and transient thermal transmittance results show a significant range in values. Pre-renovation U-values, transient and solid state, vary from approximately 0.90 to 1.90 W/m^2K depending on the choice of brick. This range is significantly reduced post-renovation to between 0.50 and 0.75 W/m^2K. In the post-renovation scenario the insulation is providing the majority of the thermal resistance and therefore establishing accurate measurements for the brick's thermal conductivity in this context is of a lesser importance. It should however be noted that the thermal conductivity of the brick showed the strongest correlation to the water content at the IWI interface and should therefore be established with some degree of accuracy for moisture investigations.

In the numerical simulations the presence of mortar plays a less significant part in determining thermal performance than the brick type. This is due to the thermal conductivity of mortar and brick being roughly similar. Simulations run with stone will be more sensitive to a mortar fraction as many building stones have significantly higher thermal conductivities, this will be especially true of rubble stone buildings that have a higher proportion of mortar.

The range of results has implications for energy design and building control bodies that both ask for compliance with very specific numbers. Some material properties for hygrothermal simulations are relatively easy to measure with basic equipment. Unfortunately thermal conductivity requires a specialist laboratory and therefore accurately assessing it will only be available to studies with higher budgets. Even though density is not a precise way of estimating the thermal conductivity of brick it should be used on the understanding that the resulting thermal values are only indicative. Exactly how Local Authority Building Control (LABC) recognises this in relation to U-value and SAP compliance is uncertain.

In the UK there are an also extremely diverse range of clays and firing techniques used in the manufacture of traditional bricks. It cannot be guaranteed that data taken from the sources investigated here; WUFI, BS EN 1745:2012 and CIBSE Guide A, relate well to any British bricks. Nationwide material testing will establish the degree of variability in thermal conductivity within British units and how well this correlates to density.

Water contents exceeding recommended guidelines have not been reached in any of the brick simulations in the case study house using the default BS 15026 internal climate file. The thickness of the wall at 377 mm has a large part to play in this with near failure conditions (to 17%) occurring when the wall is modelled at the more common thickness of 215 mm. The inclusion of mortar is shown to have little effect in simulation results of brick.

Internal and external climate uncertainties, namely lower internal temperatures, changes in ventilation rates, exposure to driven-rain and higher rates of internal moisture production, add further uncertainties to numerical modelling and question which limits and methodologies should be applied to simulations where exact climate inputs are unknown.

The most concerning variable explored here is that of the inclusion of a vapour control layer (VCL) on the warm side of the insulation. This industry standard solution arrived at through BS 13788 software has had a devastating effect on the water content and RH of the IWI and would, according to the WUFI simulation, cause complete IWI failure. It is unlikely that the woodfibre insulation itself contributes to these conditions and similar conditions are likely to be found at the interface regardless of the type of insulation used. Any organic materials in this region, joist ends or battens, would also be exposed to decay conditions. Moisture levels in this environment exceed mould growth conditions and create good conditions for wet rot. The moisture accumulation at this interface is clearly not interstitial condensation derived from internally produced vapour and suggests that a significant amount of drying to the inside of this type of buildings is required.

In the context of the case study, which, due to its location is relatively sheltered to driven rain, doubling the ventilation rate causes lower wintertime RH levels at the interface compared with having no driven rain at all.

Application to the wider context

Whilst the water content and U-value results of the study may not be directly applicable to other properties, the range presented in the results is. The aim of advanced hygrothermal simulations (BS 15026) is to provide a greater degree of accuracy than BS 13788 but due to the users inability to refine inputs the results still present uncertainties for the industry. BS 15026 software was designed to arrive at precise outputs through the use of good inputs and it should be reiterated that WUFI has passed benchmark tests (Fraunhofer IBP 2007) and proved its accuracy in field trials over many years (Straube & Burnett 1998).

The scenario of running calculations with ill-defined material and climate data is common for the majority of hygrothermal studies undertaken outside academia where budgets prohibit the testing of individual materials. The careful and intelligent application of IWI is already costly enough and results in long financial payback periods. The additional cost of materials testing can only act as a disincentive to thermal retrofits for all but the most dedicated homeowners.

The basic test methods presented here are a compromise between costly full hygrothermal testing and the assignment of arbitrary assumptions over a material's properties. Further studies using these basic test methods alongside full *in situ* monitoring including driven rain will help to establish what degree of accuracy can be expected from this sort of modelling within the constraints of normal budgets.

The results presented here also have implications for the Government's Green Deal scheme that aims to help homeowners with finance for energy efficiency measures and includes internal wall insulation.

Unfortunately the solid wall insulation field trials run by the Energy Saving Trust (EST) in preparation for Green Deal failed to include interstitial moisture monitoring which could have been an opportunity to highlight potential shortfalls in the industry-standard BS 13788 calculation methods. This missed opportunity to investigate arguably the most important unintended consequence of additional solid wall insulation is greatly regrettable as there is a distinct lack of UK specific research in this area as highlighted recently by the Sustainable Traditional Building Alliance's (STBA) report *Responsible Retrofit of Traditional Buildings* (May & Rye 2012).

Material testing

In order to establish greater accuracy in material inputs basic inexpensive tests should be performed. Unfortunately these require samples to be taken from the building, which may prove controversial, especially for buildings of historical importance. A variety of non-destructive tests are available to establish factors such as the water absorption coefficient through the use of the Karsten tube or contact sponge method (Vandevoorde et al. 2009). However, when considering the implications of large-scale moisture damage to historical, listed fabric the careful removal of key materials like bricks for assessment seems less contentious. With this logic, higher status buildings undergoing thermal upgrades should demand greater accuracy in the measurement of their materials' hygrothermal characteristics and the argument for removing them is strongest.

The inconsistency of traditional materials unfortunately presents an additional problem in generalising over a material's properties. Modern methods of manufacture have reduced variables in production and whilst a good degree of consistency may be found in the appearance of traditional facing bricks, 'commons' used for internal brickwork would have often consisted of miss-shapen, over/under fired bricks. Along with different clay types, the firing of bricks affects their physical performance (Cook & Hinks 1992) and therefore a greater range of hygrothermal properties can be expected within internally used 'commons' (Straube et al. 2011).

The extent to which these variables affect density has been shown by the range in the samples taken from the case study building which varies from 1593 kg/m^3 to 1859 kg/m^3 and presents some problems in making assumptions over the general material properties of the construction without the costly testing of many samples. As thermal conductivity was shown to have, along with density, the strongest correlations to water contents at the IWI interface, the variation in the density of samples combined with the often poor correlation between density and thermal conductivity is especially inconvenient when it comes to estimating the general hygrothermal performance of a wall. Studies that are able to perform basic tests on material properties should consider measuring the density of a selection of units from both the inner and outer face. Until further recommendations are made researchers will have to decide whether continuing with the remainder of tests on mid density samples or high density samples is most appropriate.

Sensitivity analyses with Monte Carlo simulations that can recognise trends in complicated datasets should be undertaken to investigate the more complex relationships between a brick's material properties and high water contents at the IWI/masonry interface. This should be undertaken with UK bricks, not just the bricks in the database, and results may help to reduce the number of variables that need to be accurately measured in the future.

The study also included the use of one British Fletton brick that has had its values approximated from data from the manufacturer. In all cases the results for this brick sit within the mid range of the results of all bricks. It is useful to know that results for the well-used British brick don't sit outside the general dataset. Even though the other bricks in the database are not from the UK some results are not dissimilar to the Fletton's. If additional information for accurately identifying bricks was included in WUFI's database the predetermined material files could be utilised for studies on UK bricks.

Climatic variables

Variables in the climates surrounding both the inside and outside of a wall are also subject to a degree of uncertainty that can present complexities for modelling. One problem is that of driven rain, which whilst having a significant effect on the hygrothermal behaviour of walls is also subject to a great degree of uncertainty (Straube et al. 2011) both in its measurement (Blocken & Carmeliet 2006) and its numerical representation (Abuku et al. 2009).

The guidelines in the UK for calculating amounts of driven rain are BS EN ISO 15927-3:2009 and BS 8104:1992. BS 8104:1992 (confirmed in 2008) - *Code of practice for assessing exposure of walls to wind-driven rain* utilises grid references and wind roses combined with a number of exposure factors to estimate the litres per m^2 incident on a wall arising from a single spell and the sum over one year. The resulting estimation is representative of a one-in-three year extreme. The standard also states that driven rain spells are most relevant to studies investigating rain penetration through brickwork (BSI 1992). Research across three cities in the UK by Rydock & Gustavsen (2007) has shown the links between the annual sum of driven rain and the intensity of a driven rain spell, and suggests that the more widely available annual sum may prove useful in assessing moisture risk in solid masonry walls. Unfortunately, the way wind and therefore driven-rain from Meteonorm files is approximated means that it is averaged over all four orientations, north, south, east and west, and therefore depending on the location and orientation of the simulation, it is suggested that rain loads could be incorrect (IBP 2012). A quick method for assessing this potential inaccuracy would be to determine whether there is good agreement between the amount of annual driven-rain from BS 8104:1992 for the location and orientation with the annual amount shown by the WUFI analysis of the Meteonorm file for the same location.

Using the BS 8104:1992 methodology for the orientation of the case study wall in Shrewsbury the wall's annual driven-rain index is calculated, the worked example is shown in Appendix 3. WUFI's analysis of the driven-rain from the Shrewsbury Meteonorm file is shown below (Figure 28).

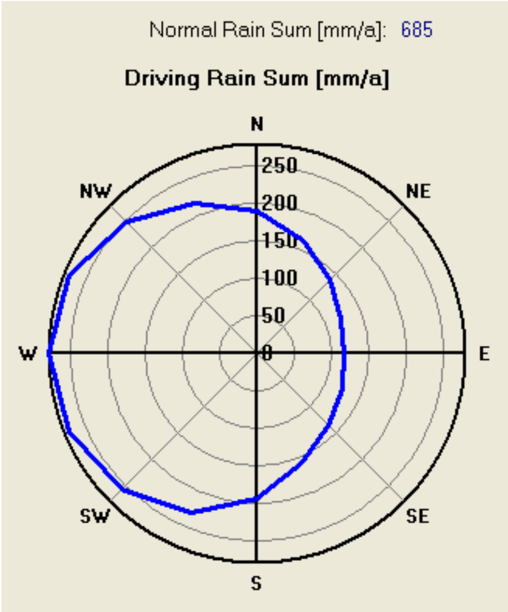


Figure 28. Driving rain rose for Shrewsbury from Meteonorm data.

With litres/ m^2 being equivalent to mm, the annual driving rain sum for a south-facing wall in Shrewsbury is 355 litres/m^2 from BS 8104:1992 and 200 mm from WUFI/Meteonorm. It has been beyond the scope of this study to change the quantity of rainfall and driven-rain in the climate files so to investigate the sensitivity of this variable the exposure factor of the wall to the same data was explored. The amount of exposure to driven-rain over an undefined limit has been shown to affect simulation results of the moisture content of the IWI. When the exposure factor of the wall was increased the moisture content of the IWI rose significantly. Conversely, when the adhering fraction of rain was set to zero the change in moisture content was relatively small when compared to the reference case. It is unknown how this increased exposure to driven rain relates to the difference in sums from BS 8104:1992 and WUFI/Meteonorm and whether the critical moisture limit for the IWI sits between the two figures. Given that the majority of researchers rely on the combination of synthetic weather files from Meteonorm and WUFI's numerical interpretation of that data, the question of critical limits of driven rain should be the subject of a further investigation. The ASHRAE 160P method for calculating wind driven rain within WUFI is similar in its approach to the methodology in BS 8104:1992 and the two should be more closely compared.

Comparison with *in situ* results

The averaging of weather extremes into a single or combination of one-year reference years for hygrothermal simulations also presents complications particularly when comparing simulated results to *in situ* results. It is unknown where data taken from site sits between the extremities experienced in severe events over for example a ten-year period that encompasses high and low extremes in temperature, humidity and driven-rain. The direct comparison between *in situ* data and simulated data is therefore complex and requires longer periods of site conditions to be measured. These longer periods with additional data taken for RH and temperature inside the wall would aid comparison of *in situ* data with the resulting dynamic equilibrium moisture contents of the walls components. As illustrated in Figure 29 below, all results presented here are of peak conditions in the construction after a significant number of years.

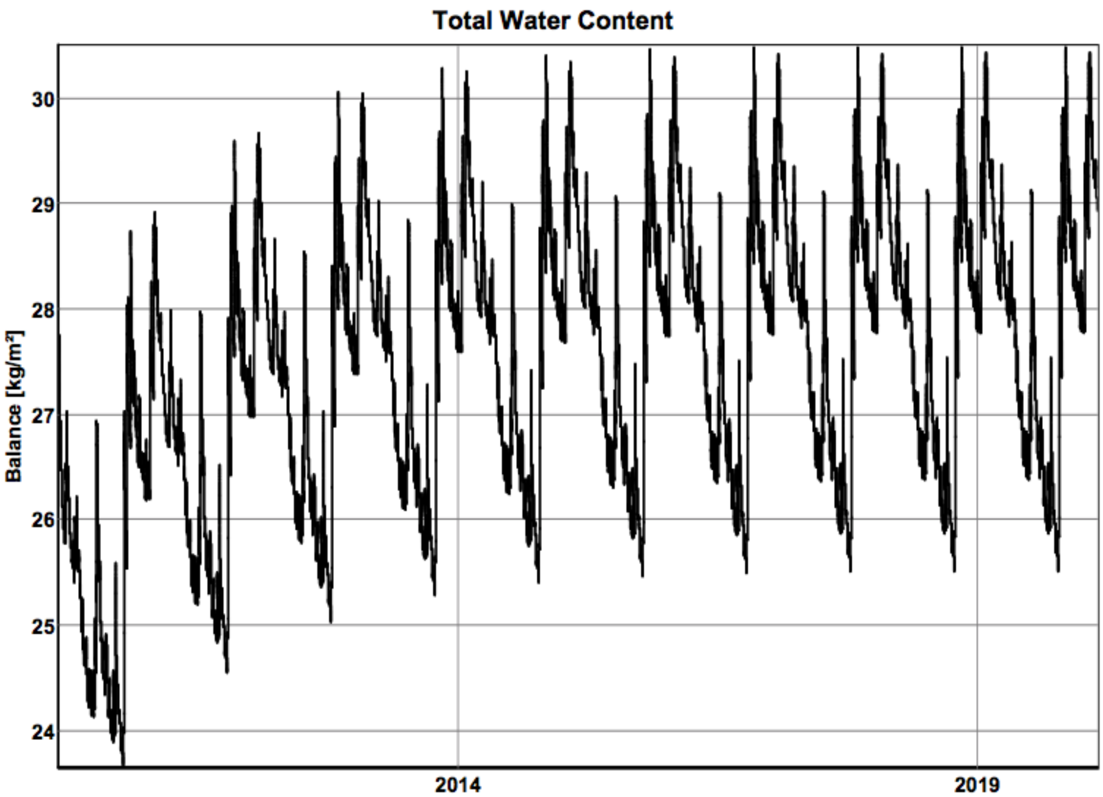


Figure 29. Estimated time taken to for the case study wall to establish a new dynamic equilibrium moisture content. A repeating cycle is seen from 2017.

Modelling undertaken as part of this case study suggests that walls can take up to 20 years to establish a new moisture balance, although most cases investigated in this study took between 5 and 10 years. *In situ* data for 2012 is showing the immediate conditions following the refurbishment where moisture used in the construction process is still present and before the wall has adjusted to its new imposed conditions. Therefore a direct comparison between the two datasets at the present moment is open to interpretation. Additionally, whilst demonstration of the moving *in situ* dewpoint in a wall at a specific point in time is interesting its comparison to *simulated* moving dewpoints is impractical for many of the reasons outline above. For a more accurate comparison between *in situ* and simulated results annual fluctuations in temp, RH and water content of the wall should be compared taking into consideration that the moisture levels in the wall are still seeking homeostasis.

8. CONCLUSIONS

General

Following the review of the British standards relating to condensation risk analysis in Chapter 4, it is clear that in their current state, the standards are confusing which needs to be rectified as soon as possible. BS 5250:2011 clearly states the significance of driving rain to porous walls and the importance of cavities in stopping rain water tracking to the inside. This is highlighted at the same time as directing the reader to BS 13788 calculation methods, which it states does not account for rain, and other factors, and therefore *“does not provide an accurate prediction of moisture conditions within the structure under service conditions”*

Due to the failings of BS 13788 (Glaser), condensation risk analysis has been conducted here using more advanced BS EN 15026:2007 compliant software. Some of the uncertainties in the practical application of this advanced software and associated U-value tools have been investigated. The variables in the study have been chosen to represent the uncertainties that are normally present in simulations currently undertaken to BS 13788. Whilst the advanced software used here has proved its accuracy in field trials over many years, the problems with accessing quality input data for ordinary non-academic studies on the implications of energy efficiency refurbishments to traditional buildings has lead to a significant degree of uncertainty in the results.

Whilst it is clear that the simplified methodology of BS 13788 is not always appropriate for condensation risk analysis, the normal constraints of time, money and available information make establishing greater accuracy with BS 15026 software difficult, especially to calculations run outside academia.

This research set out to cover the following issues, which are discussed in greater detail in the sections below:

1. assess condensation risk of the energy efficiency measures applied to the case study house.
2. evaluate the limitations and accuracy in the practical application of BS 15026 software.
3. inform the building industry of the complexity of condensation risk analysis.
4. highlight areas lacking in research and clarify some of the issues with modelling that may lead to retrofit failures.

One of the main intentions of this research has been to inform the mainstream building industry of the complexity of condensation risk analysis. It is therefore important to consider that this research has been prepared for building professionals and not building physicists. Whilst the latter may recognise the inappropriate use of certain inputs, they may not necessarily be obvious to the vast majority of researchers who currently use BS 13788 tools on a daily basis. The Fraunhofer Institute for Building Physics, developers of the WUFI software used in this study, are attempting to resolve this issue by running regular training events and seminars to ensure software users are knowledgeable and are kept up-to-date with relevant developments in building physics.

The consequences of poor moisture design can not only result in degradation of the building fabric through rot and mould but also contribute to poor human health from mould spores and dust mites. It is therefore imperative that a very clear methodology for the study of traditional buildings accompanies BS 15026 to ensure that simulation errors do not result in building defects.

The variables explored here that have had the most significant bearing on results broadly fall into two categories; unmeasured hygrothermal material properties; and complications in accurately representing interior and exterior climates. For numerical simulations to improve confidence in internal wall insulation (IWI) investigations, basic materials testing must be undertaken alongside research into critical limits of driven rain and standards in expressing highest likely levels of internally produced moisture.

Most urgently the issue of including vapour barriers in IWI installations needs further investigation. Results from the case study showed the vapour control layer to cause moisture failure conditions of 100% all year round on the outside of the vapour layer. This is alarming due to it being a commonly used solution to preventing interstitial condensation in IWI installations.

Follow up research to this interim report will continue to investigate the case study buildings and aim to improve accuracy in the climatic variables. The hygrothermal properties of the materials in the case study buildings can be determined with the basic methods presented here. The results can then be discussed within the context of the measured *in situ* data.

Case Study Conclusions

This research set out to investigate condensation risk in the thermal retrofit of the case study building using BS 15026 compliant software. The investigation has used a brick-built building as a case study and has evaluated the accuracy in the practical application of the software. The house has undergone a thermal refurbishment with a woodfibre based IWI that has been fixed directly to the lime plastered brick wall. The research concludes that the lack of measured hygrothermal properties for UK bricks and building stones makes the assignment of brick from a predefined material database ultimately arbitrary. When combined with the lack of clear information on how to represent interior and exterior climatic conditions the total range in results is wide and crosses damaging limits for water contents at the IWI/masonry interface.

The range in results for estimated transient thermal transmittance (transient U-values) is between approximately 0.9 and 1.9 W/m^{2}K pre-renovation and 0.52 and 0.75 W/m^{2}K post-renovation. The inclusion of mortar at 23% is shown to be less important than the brick choice. This is due to the thermal conductivities of brick and mortar being similar. The inclusion of mortar for materials with higher thermal conductivities than brick, such as stone, will reduce the U-value of the wall and narrow the range in results.

Moisture conditions for all 27 brick types modelled with the 377mm wall and with the default internal climate do not cause problematic conditions at the IWI/masonry interface. Across all brick types the peak water content of the IWI was shown to reduce as the wall thickness increases. The wall at Shrewsbury is half a brick thicker than the majority of 215mm brick walls in the UK. Water content results for all bricks modelled at 215mm show higher water contents at the IWI interface, with one brick, named ZP, coming within 1% of critical conditions. Due to lack of material testing in the UK it is unknown how the bricks in the database relate to the diverse range of bricks in the UK but the inclusion of approximated values for the widely used Fletton brick show it to sit comfortably within the mid section of results.

Further climatic investigations with brick ZP caused failure conditions in the brick and a half thick wall. The variables that lead to failure were increasing internal moisture production levels from a 2 person household to a 4 person house and increasing the wall's exposure to driving rain. The most alarming failure conditions were experienced with the inclusion of a vapour control layer on the warm side of the insulation with a similar s_d value to a foil vapour retarder. Conditions at the IWI interface were saturated showing 100% RH all year round.

This implies that even in a location where driven rain is relatively low, the traditional wall still requires a significant amount of drying to the inside for moisture levels to stay within acceptable limits. Any organic materials present at that interface such as joist ends or battens will be subjected to the same degrading conditions. This result is especially concerning as the inclusion of a vapour control layer is a standard solution proposed by BS 13788 software for preventing interstitial condensation behind IWI and is therefore common practice in IWI installations undertaken today.

Although the UK is under great pressure to deliver energy saving measures within the housing sector it is vital that these issues are recognised prior to the full deployment of a nationwide retrofit scheme such as the Green Deal.

9. RECOMMENDATIONS AND FURTHER RESEARCH

Immediate Recommendations

Until implicit guidance exists, simulation errors should be minimised by undertaking the basic material tests presented here in Chapter 5. Where Meteonorm climate files are utilised, the sum of driven-rain should be compared to an estimation using BS 8104:1992 and a judgement made over their suitability. The ASHRAE 160P method for calculating wind-driven rain within WUFI is similar in its approach to the methodology in BS 8104:1992 and sensitivity analyses may prove it to be a more accurate approach. Internal climate should also be modelled using the ASHRAE method with ventilation rates deriving from a door blower test and moisture production rates determined by the number of bedrooms, not the number of present occupants, unless it exceeds the number of bedrooms plus one.

WUFI

Additional information needs to be included in the predetermined material files of bricks and stones identifying the physical characteristic, geological derivation and common regions of usage. The additional information will assist in the appropriate selection of materials.

Standardised Approaches to Simulating Traditional Buildings

This study has focused on IWI but there is an urgent need to standardise methodologies for both internal and external wall insulation to traditional buildings. This should occur before the widespread industry transition from BS EN ISO 13788:2002 to BS EN 15026:2007.

Communication

Hygrothermal modelling encompasses such a wide range of disciplines and industries that far greater dialogue is needed between specialists in a variety of areas. In relation to some of the uncertainties of modelling, communication is desperately needed between hygrothermal researchers, the Meteorological Office, Building Research Establishment (BRE), British Ceramic Research Ltd (CERAM), British Geological Survey (BGS) and conservation specialists to enable the records to be updated.

Material Testing and Public Material Database

Future widespread testing of UK materials should be undertaken and a public database compiled to aid and improve research. A subsidised research body/laboratory that can provide low-cost and standardised hygrothermal material testing linked to a public database would be extremely useful. Once material testing of a range of UK bricks and building stones has been completed a sensitivity analysis of variables using Monte Carlo simulation should be undertaken. This may help to identify a set of key variables that need to be tested for each material group and reduce the need for full hygrothermal testing of all materials.

In the calculations performed here thermal conductivity and density were shown to have the strongest correlations to water content at the IWI interface. Due to the significance of this relationship further investigations are needed to see whether this correlation is specific only to the case study or more widely applicable. Additionally the issue of how to approximate widely ranging brick densities from the same building need to be resolved.

Ultimately an English version of the MASEA hygrothermal material properties database that combines knowledge from many industries with identification guides and mapping would be especially useful. Information should be based on the years of data already recorded by the Meteorological Office, BRE/Stone list, BGS, CERAM etc. The Strategic Stone Study, a collaborative project between English Heritage, the British Geological Survey and local geologists has already started identifying and mapping building stones in the south-west of the UK. This work will enable researchers and conservation officers to accurately identify building stones for numerical simulations.

Liability

Currently all the risks of failed retrofits are taken by homeowners. A requirement of BS EN 15026:2007 is that simulation inputs and results are recorded. This should be legal obligation for any thermal refurbishment and will help reduce the misuse of the software and enable homeowners to demonstrate where manufacturers miscalculations are responsible for retrofit failures.

***In Situ* Monitoring**

As part of all solid wall insulation projects, simple monitoring for high levels of RH at the IWI/masonry interface should be incorporated into every retrofit. Basic loggers are easy to install and cheaper and than running sensitivity analyses of all variables in BS 15026 software. Perturbing results can be subject to further investigations.

Appendix A

Water content of IWI study, calculation summary.

WUFI® Pro 5.1

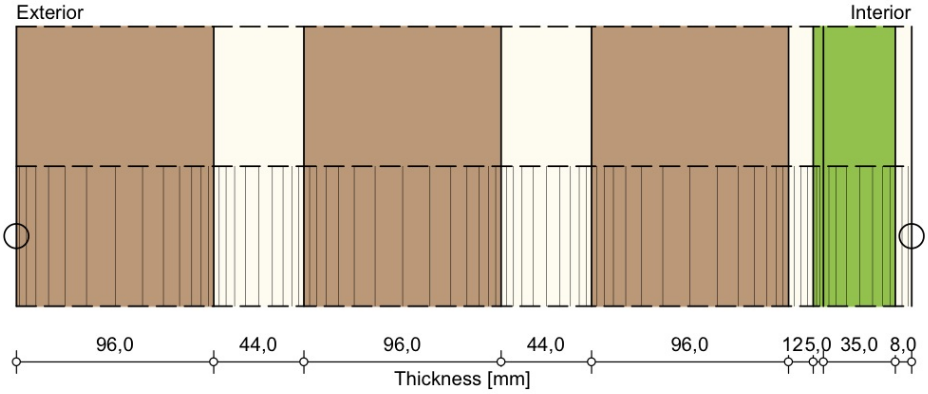
Project Data

Project Name	Shrewsbury, Abbeyforegate
Project Number	WC study
Client	SPAB Research Report 3
Contact Person	Dan Browne
City/Zip	
Street	
Phone	
Fax	
e-mail	
Responsible	Calculations performed by Dan Browne
Date	18/05/2012 08:20:27

WUFI® Pro 5.1

Component Assembly

Case: ZP



◯ - Monitor positions

Materials :

- Solid Brick ZP
- Lime Plaster (stucco)
- Solid Brick ZP
- Lime Plaster (stucco)
- Solid Brick ZP
- Lime Plaster (stucco)
- *Woodfibre board insulation (unlocked)
- *Woodfibre board insulation (unlocked)
- Lime Plaster (stucco)

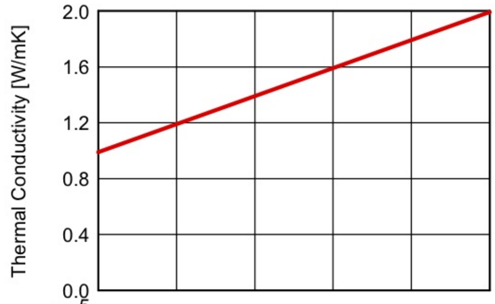
Total Thickness: 0,44 m
R-Value: 1,29 m²K/W
U-Value: 0,68 W/m²K

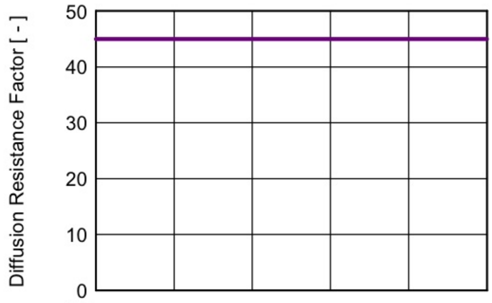
WUFI® Pro 5.1

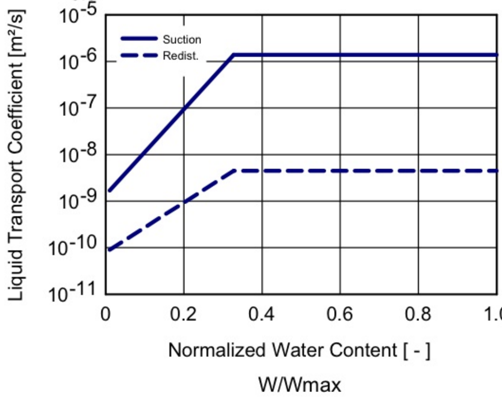
Material : Solid Brick ZP

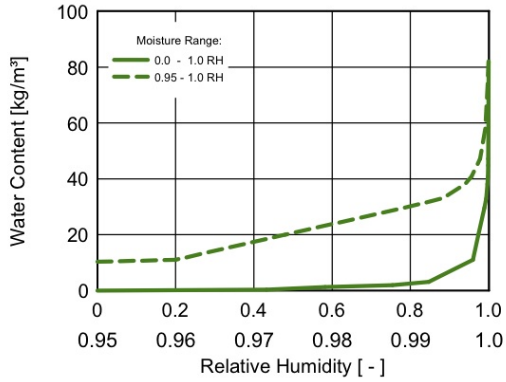
Checking Input Data

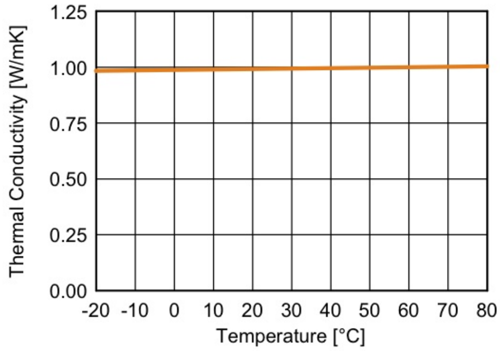
Property	Unit	Value
Bulk density	[kg/m³]	1979,0
Porosity	[m³/m³]	0,25
Specific Heat Capacity, Dry	[J/kgK]	834,0
Thermal Conductivity, Dry ,10°C	[W/mK]	0,99
Water Vapour Diffusion Resistance Factor	[-]	45,0
Reference Water Content	[kg/m³]	2,5
Free Water Saturation	[kg/m³]	82,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,05
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	8,0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002









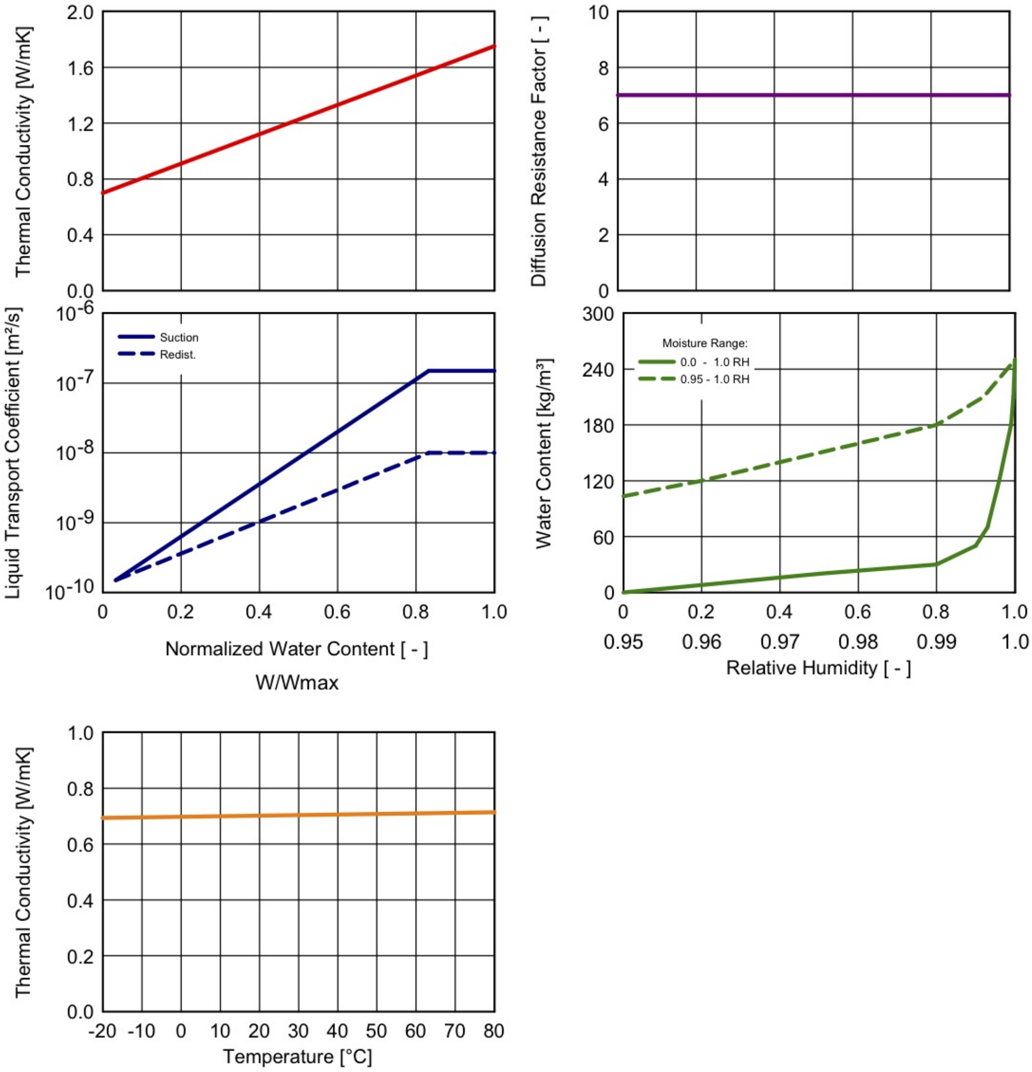


WUFI® Pro 5.1

Material : Lime Plaster (stucco)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1600,0
Porosity	[m³/m³]	0,3
Specific Heat Capacity, Dry	[J/kgK]	850,0
Thermal Conductivity, Dry ,10°C	[W/mK]	0,7
Water Vapour Diffusion Resistance Factor	[-]	7,0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	8,0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002

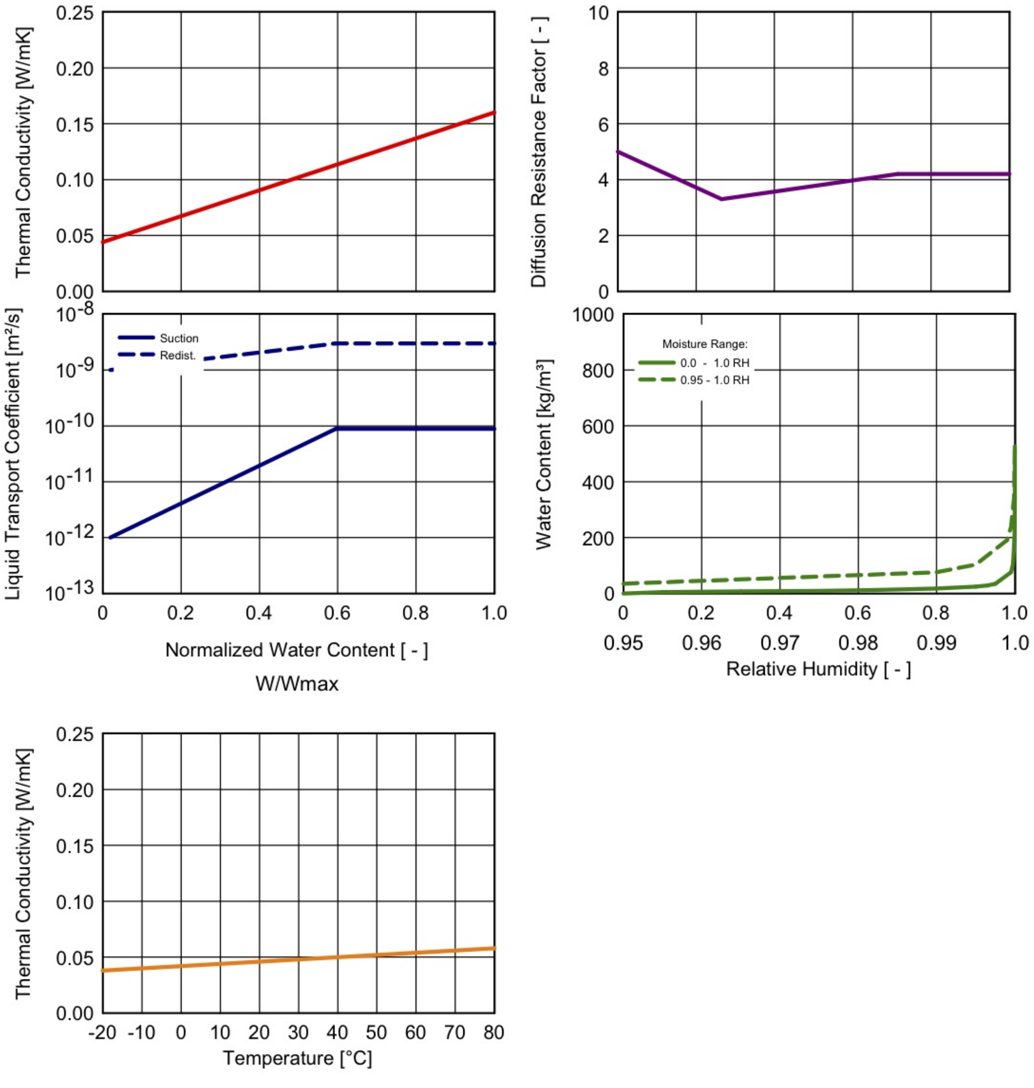


WUFI® Pro 5.1

Material : *Woodfibre board insulation (unlocked)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	168,0
Porosity	[m³/m³]	0,883
Specific Heat Capacity, Dry	[J/kgK]	2100,0
Thermal Conductivity, Dry ,10°C	[W/mK]	0,044
Water Vapour Diffusion Resistance Factor	[-]	5,0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	0,5
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002



WUFI® Pro 5.1

Boundary Conditions

Exterior (Left Side)
Location: Shrewsbury_hour_wac.wac
Orientation / Inclination: South / 90 °

Interior (Right Side)
Indoor Climate: EN 15026
Normal Moisture Load

Surface Transfer Coefficients

Exterior (Left Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.0588	External Wall
Sd-Value	[m]	----	No coating
Short-Wave Radiation Absorptivity	[-]	----	No absorption/emission
Long-Wave Radiation Emissivity	[-]	----	No absorption/emission
Adhering Fraction of Rain	[-]	0,7	According to inclination and constru

Interior (Right Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.125	External Wall
Sd-Value	[m]	----	No coating

Explicit Radiation Balance

Exterior (Left Side)

Name	Value
Enabled	no

WUFI® Pro 5.1

Results from Last Calculation

Status of Calculation

Calculation: Time and Date	21/05/2012 14:46:03
Computing Time	0 min,29 sec.
No. of Convergence Failures	0
No. of Rain Absorption Failures	0

Check for numerical quality

Integral of fluxes, left side (kl,dl) [kg/m²]	10,0 -7,12
Integral of fluxes, right side (kr,dr) [kg/m²]	0,32 2,56
Balance 1 [kg/m²]	-0,01
Balance 2 [kg/m²]	-0,0

Water Content [kg/m³]

Layer/Material	Start of Calc.	End of Calc.	Min.	Max.
Solid Brick ZP	43,29	43,29	31,72	69,25
Lime Plaster (stucco)	240,02	240,01	225,33	244,22
Solid Brick ZP	43,03	43,02	37,16	44,62
Lime Plaster (stucco)	207,33	207,28	199,17	208,23
Solid Brick ZP	23,54	23,52	20,40	24,08
Lime Plaster (stucco)	49,97	49,95	32,69	50,84
STEICO therm	22,31	22,30	17,07	22,63
STEICO therm	14,11	14,11	12,45	14,86
Lime Plaster (stucco)	20,24	20,22	16,42	24,26
Total Water Content [kg/m²]	31,6	31,59	28,69	33,52

Time Integral of fluxes

Heat Flux, left side [MJ/m²]	-276,15
Heat Flux, right side [MJ/m²]	-267,06
Heat Sources [MJ/m²]	0,0
Moisture Fluxes, left side [kg/m²]	2,94
Moisture Fluxes, right side [kg/m²]	2,89
Moisture Sources [kg/m²]	0,0
Clipped Moisture Sources [kg/m²]	0,0

Appendix B

Climatic variables, calculation summary.

Material properties and component assembly are the shown in Appendix A

WUFI® Pro 5.1

Project Data

Project Name	Shrewsbury, Abbeyforegate
Project Number	post-retrofit
Client	SPAB Research Report 3
Contact Person	Dan Browne
City/Zip	
Street	
Phone	
Fax	
e-mail	
Responsible	Calculations performed by Dan Browne
Date	21/05/2012 08:20:27

WUFI® Pro 5.1

Boundary Conditions

Exterior (Left Side)
Location: Shrewsbury_hour_wac.wac
Orientation / Inclination: South / 90 °

Interior (Right Side)
Indoor Climate: ASHRAE 160P
Heating only; 2.8 °C; 16 °C
M.Rate 9.00E-05 kg/s; A.Ch.Rate 0.92 1/h; Vol. 134 m³
Humidity Ratio Wo 0.0098 kg/kg

Surface Transfer Coefficients

Exterior (Left Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.0588	External Wall
Sd-Value	[m]	----	No coating
Short-Wave Radiation Absorptivity	[-]	0.68	Brick, red
Long-Wave Radiation Emissivity	[-]	0.9	Brick, red
Adhering Fraction of Rain	[-]	0,7	According to inclination and constru

Interior (Right Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.125	External Wall
Sd-Value	[m]	----	No coating

Explicit Radiation Balance

Exterior (Left Side)

Name	Value
Enabled	no

WUFI® Pro 5.1

Results from Last Calculation

Status of Calculation

Calculation: Time and Date	21/05/2012 14:28:03
Computing Time	0 min,28 sec.
No. of Convergence Failures	0
No. of Rain Absorption Failures	0

Check for numerical quality

Integral of fluxes, left side (kl,dl) [kg/m²]	16,24 -13,97
Integral of fluxes, right side (kr,dr) [kg/m²]	-0,31 2,58
Balance 1 [kg/m²]	-0,0
Balance 2 [kg/m²]	-0,0

Water Content [kg/m³]

Layer/Material	Start of Calc.	End of Calc.	Min.	Max.
Solid Brick ZP	37,70	37,70	23,23	59,29
Lime Plaster (stucco)	232,08	232,07	202,67	232,95
Solid Brick ZP	36,25	36,24	31,08	36,25
Lime Plaster (stucco)	172,74	172,70	169,55	175,13
Solid Brick ZP	17,61	17,60	14,99	17,61
Lime Plaster (stucco)	45,99	45,99	27,66	48,63
Woodfibre board insulation	21,44	21,43	14,91	22,50
Woodfibre board insulation	16,61	16,61	13,91	20,35
Lime Plaster (stucco)	25,19	25,16	19,76	44,37
Total Water Content [kg/m²]	28,14	28,14	24,64	29,66

Time Integral of fluxes

Heat Flux, left side [MJ/m²]	-43,53
Heat Flux, right side [MJ/m²]	-38,77
Heat Sources [MJ/m²]	0,0
Moisture Fluxes, left side [kg/m²]	2,26
Moisture Fluxes, right side [kg/m²]	2,27
Moisture Sources [kg/m²]	0,0
Clipped Moisture Sources [kg/m²]	0,0

Appendix C

BS 8104:1992 wind-driven rain calculation

Worked example of a wind-driven rain calculation using BS 8104:1992 methodology for the orientation of the case study wall in Shrewsbury.

Location: Shrewsbury, Shropshire
Grid reference: 2.71°W, 52.71°N
Orientation: 180°
Map subregion: MA6

		Spell index	Annual index
Geographical increment	i	-2	-2
Rose value	r	22	13
Map value $(i+r)$	m	20	11
Airfield indices (table 1 or 2)		D_S = 63.5 l/m^2 per spell	D_A = 355 l/m^2 per year
Terrain roughness factor (table 3)	R	0.75	
Topography factor (table 4)	T	1	
Obstruction factor (table 5)	O	0.3	
Wall factor (table 6)	W	0.6	
Wall indices for the appropriate direction of wall		D_{WS} = 8.6 l/m^2 per spell	D_{WA} = 47.9 l/m^2 per year

Figure 1. Typical worksheet for wind-driven rain calculations

Figure 30. Wind-driven rain calculation for Shrewsbury from BS 8104:1992.

References:

Abuku, M., Blocken, B. & Roels, S., 2009. Moisture response of building facades to wind-driven rain: Field measurements compared with numerical simulations. *Journal of Wind Engineering and Industrial Aerodynamics*, 97, 197-207.

Anderson, B., 2006. *Conventions for U-value calculations*, Garston: BRE.

ASTM, 2007. Heat Air Moisture Transport Measurements on Building Materials - Overview. Available at: http://www.scribd.com/doc/80400500/Heat-Air-Moisture-Transport-Measurements-on-Building-Materials-ASTM-Special-Technical-Publication-1495#page=1 [Accessed August 16, 2012].

Baker, P., 2011. *Historic Scotland Technical Paper 10*, Edinburgh: Historic Scotland. Available at: http://www.historic-scotland.gov.uk/hstp102011-u-values-and-traditional-buildings.pdf [Accessed September 20, 2011].

Blocken, B. & Carmeliet, J., 2004. A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Aerodynamics*, 92(13), 1079-1130. Available at: http://www.sciencedirect.com/science/article/B6V3M-4D5JX6P-1/2/a22dbd63a4c07b1da77ed9ec672f32e9 [Accessed March 25, 2009].

Blocken, B. & Carmeliet, J., 2006. On the accuracy of wind-driven rain measurements on buildings. *Building and Environment*, 41, 1798–1810.

Brick Development Association, 1974. *Bricks: Their Properties and Use*, Construction Press LTD.

BSI, 2005. BS 5250:2002 - Code of practice for control of condensation in buildings.

BSI, 2011. BS 5250:2011 - Code of practice for control of condensation in buildings.

BSI, 1992. BS 8104:1992 - Assessing exposure of walls to wind-driven rain (confirmed 2008).

BSI, 2007. BS EN 15026:2007 - Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation.

BSI, 2011. BS EN 771-1:2011 - Specification for masonry units. Part 1: Clay masonry units.

BSI, 2010. BS EN ISO 10456:2007 Building materials and products — Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values.

BSI, 2002. BS EN ISO 13788:2002 - Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods.

BSI, 2007. BS EN ISO 6946:2007 - Building components and building elements — Thermal resistance and thermal transmittance — Calculation method (ISO 6946:2007).

CIBSE, 2007. *Environmental Design Guide A* 7th ed., London: The Chartered Institution of Building Services Engineers.

Cook, G.K. & Hinks, A.J., 1992. *Appraising Building Defects: Perspectives on Stability and Hygrothermal Performance*, Harlow: Longman Scientific & Technical.

Fraunhofer IBP, 2007. *WUFI Passes Benchmark Test of EN 15026*, Fraunhofer Institute for Building Physics. Available at: http://www.hoki.ibp.fhg.de/download/EN15026_en.pdf [Accessed October 10, 2011].

Hendry, E.A., 2001. Masonry walls: materials and construction. *Construction and Building Materials*, 15(8), 323-330. Available at: http://www.sciencedirect.com/science/article/B6V2G-4459TY4-1/2/019a92558fd104987864d47d1a210ec9 [Accessed March 24, 2009].

Hens, H., 2007. Modeling the Heat, Air, and Moisture Response of Building Envelopes: What Material Properties are Needed, How Trustful Are the Predictions? In West Conshohocken: ASTM International. Available at: http://www.scribd.com/doc/80400500/Heat-Air-Moisture-Transport-Measurements-on-Building-Materials-ASTM-Special-Technical-Publication-1495#page=1 [Accessed August 16, 2012].

IBP, 2012. WUFI Pro Seminar Material.

Kunzel, H., 1998. Effect of Interior and Exterior Insulation on the Hygrothermal Behaviour of Exposed Walls. *Materials and Structures*, 31, 99-103. Available at: http://www.wufi.de/index_e.html [Accessed March 29, 2009].

Kunzel, H., 1995. *Simultaneous Heat and Moisture Transfer in Building Components*, Suttgart: Fraunhofer Institute for Building Physics. Available at: http://www.building-physics.com/ [Accessed March 11, 2009].

Lynch, G., 2011. Shrewsbury Brick Identification. Email communication with Dr. Gerard Lynch.

May, N. & Rye, C., 2012. *Responsible Retrofit of Traditional Buildings*, London: Sustainable Traditional Buildings Alliance. Available at: http://www.building.co.uk/Journals/2012/09/27/x/u/l/RESPONSIBLE-RETROFIt.pdf [Accessed October 15, 2012].

Rydock, J.P. & Gustavsen, A., 2007. A look at driving rain spells at three cities in Great Britain. *Building and Environment*, 42(3), 1386-1390. Available at: http://www.sciencedirect.com/science/article/B6V23-4J4HK7T-1/2/fd940898c75c2cf37119fcc9de0251a8 [Accessed May 5, 2009].

Sanders, C., 2006. *Modelling condensation and airflow in pitched roofs*, Garston: BRE. Available at: http://www.ihsti.com/tempimg/55ea396-CIS888614800278428.pdf [Accessed August 16, 2012].

Schmidt, T., 2009a. On-line help for WUFI Pro 5.0. Topic 13.

Schmidt, T., 2009b. On-line help for WUFI Pro 5.0. Topic 14.

Schmidt, T., 2009c. On-line help for WUFI Pro 5.0. Topic 15.

Schmidt, T., 2009d. On-line help for WUFI Pro 5.0. Topic 16.

Sharp, R., 2009. Fletton brick data - Email communication with Roger Sharp. Laboratory Manager, Hanson Brick Company UK.

Straube, J. & Burnett, E., 1998. Chapter 5-Overview of Hygrothermal (HAM) Analysis Methods. *ASTM MANUAL SERIES MNL*, 40, 81-89. Available at: http://www.astm.org/BOOKSTORE/MNL40PDF/Ch5.pdf [Accessed March 27, 2009].

Straube, J. & Schumacher, C., 2006. Assessing the durability impacts of energy efficient enclosure upgrades using hygrothermal modeling. *WTA Journal*, 2. Available at: http://www.hoki.ibp.fhg.de/download/WTA-Journal_2-06_Straube%20u%20Schumacher.pdf [Accessed May 29, 2009].

Straube, J., Ueno, K. & Schuhmacher, C., 2011. *Internal Insulation of Masonry Walls: Final Measure Guideline*, Somerville: Building Science Corporation.

Vandevoorde, D. et al., 2009. Contact sponge method: Performance of a promising tool for measuring the initial water absorption. *Journal of Cultural Heritage*, 10(1), 41-47. Available at: http://www.sciencedirect.com/science/article/pii/S1296207408001659 [Accessed October 15, 2012].

WUFI, 2009. Thermal Transmission Postprocessor Online Help. Topic 1.

Zirkelbach, D., 2012. WUFI :: View topic - Critical RH limit for woodfibre IWI at masonry interface. *WUFI Forum*. Available at: http://www.wufi-forum.com/viewtopic.php?t=718 [Accessed October 15, 2012].