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The Design of a Modelling, Monitoring and Validation Method for a Solid Wall Structure.

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Abstract

Hygrothermal assessment is the combined analysis of heat, air and moisture transfer through the building fabric. The two approaches are covered by conventions known as the IS EN 5250:2011 (Glaser method) and IS EN 15026:2007 which differs from Glaser by solving the equations numerically using computer software. Results for hygrothermal analysis provide valuable information for surface and interstitial condensation risk assessment and the impact of energy upgrades. For traditional solid walled structures, conditions such as wind driven rain (WDR) and rising ground water can have a significant impact on the environmental behaviour and in particular the moisture behaviour of the building envelope. The convention IS EN 5250:2011 is still widely used to assess the moisture performance of buildings and their components, even though it is not a comprehensive assessment methodology as it fails to include the movement of liquid water and for solid wall structures in particular, it is imperative that all forms of moisture movement are assessed. This research sets out a design methodology, to establish the hygrothermal performance of rendered solid brick wall constructions to ultimately establish the optimum and most appropriate retrofit intervention. The methodology chosen establishes all material properties of a monitored wall. A weather station is used to establish all weather data for the site. The building, will be monitored initially for a 12 month period to determine its hygrothermal condition. The data logged monitoring will establish the temperature and RH profile through the wall. The data from this monitoring will be inputted to software which meets the IS EN15026:2007 convention-a dynamic model which assesses the movement of water both as a vapour and as a liquid.

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Keywords: Hygrothermal; solid brick wall; monitoring; condensation risk assessment.

1. Introduction

The European Directive on the Energy Performance of Buildings (2002/91/EC) was adopted into Irish law in 2006 with a subsequent recast in 2010 specifically targeting energy requirements of buildings whether residential or non-residential, new or existing build. The energy performance and the standard of energy conservation measures required of new buildings has risen significantly in recent years and is expected to continue as we head closer to the nZeb target by 2020. This has also focused attention on the retrofitting of our existing buildings including a substantial number with solid-wall constructions.

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The percentage of homes in the republic of Ireland built pre 1919 were shown to be 10.6% in the 2006 national census representing approximately 150,000 homes. The figure is greater in Northern Ireland at 16.1% in 2006 [1] (NIHE, 2008) England's dwelling stock shows the number of pre 1919 houses at 4,731,000 or 22% of the total stock [2] CLG (2008a). The numbers in Scotland and Wales are 20% and 34% respectively [3] (Edwards. 2011), representing a vast number of properties, however, upgrading the thermal efficiency of the existing building stock presents a challenge, particularly where the building was built using traditional materials and construction methods and is of architectural or historical significance. The challenge for designers of thermal interventions is to ensure that they fully understand the particular building system and in particular the movement of heat, air and moisture. There is limited robust hygrothermal analysis of heritage structures particularly in temperate climates using accurate local microclimatic data and actual properties of the in-situ materials. Data monitoring of the movement of temperature and humidity through the wall over a substantial time period and dynamic modeling simulation of the different retrofit interventions is rare, often due to the time and costs involved. Material damage, corrosion, loss of insulating capacity, organic growth (mold) and poor air quality can result in uncontrolled condensation, particularly where moisture management is not adequate. One approach to dealing with this problem is design-stage hygrothermal modelling assessment however material properties from historic buildings were often manufactured locally and made from different raw materials. Coupled to this is the fact that a buildings location and geometry can also influence its local climate and subsequent weather data input. It is therefore necessary in establishing accurate results, to carry out material testing of the in-situ materials and produce weather data that is accurate for this micro-climate for the building being tested. This is necessary as the inconsistency of traditional materials unfortunately presents an additional problem in generalising over a material's properties [4], which can be often done in 'more simulated' approaches. The aim of this paper therefore is to develop an experiment design to gather the data necessary to validate a numerical hygrothermal model of a solid-wall construction in a temperate climate. This can be used to simulate the effects of energy retrofit options on the hygrothermal performance of these structures, to assist in the development of suitable policies and standards. The approach taken is to monitor a rendered solid brick wall construction to better inform the retrofit interventions, (based on the structures hygrothermal performance} which will enhance both comfort levels and structural integrity.

2. Literature review

Hygrothermal assessment or evaluation is the combined analysis of heat, vapour and moisture transfer through the building fabric and are performed to predict and prevent detrimental accumulation of condensation within enclosure systems. There are two approaches or conventions used, namely [5] IS EN 13788:2002, Dew Point Assessment, known as the Glaser method and [6] IS EN 15026:2007 Hygrothermal performance of building components and elements which uses hygrothermal numerical simulation. It is imperative particularly for solid wall constructions that all forms of moisture movement are assessed as high indoor humidity is one of the most important means of causing the harmful accumulation of moisture in a structures envelope [7]. Results for hygrothermal analysis provide valuable information for surface and interstitial condensation risk assessment and the impact of subsequent energy upgrades. In the three-dimensional and highly dynamic real-world environment, moisture is hard to find and materials are constantly wetting, drying, heating and cooling, therefore field moisture measurement and location techniques, and prudent threshold values to avoid microbial growth in actual buildings are quite different from the steady-state circumstances of laboratory studies [8] and also a greater range of hygrothermal properties can be expected in historic building materials [4]. Research in the field of assessment of hygrothermal response has focused on either laboratory experimentation or modelling, but less work has been reported in which both are combined and such studies can potentially offer useful information regarding the benchmarking of models and related methods to assess hygrothermal performance of wall assemblies [9]. Simulation methods are flexible in that they can be used to represent a variety of changing boundary conditions and result in much more timely analysis. There are now increased numbers of numerical hygrothermal models. Simple to complex problems can be solved by models ranging from the simpler one dimensional (1D)steady state to the complex 2D and 3D transient models.

2.1. Hygrothermal theory

The difference in psychrometric properties between inside and outside (brought about by the vapor pressure differential between the two), sets up the driving force for water vapor diffusion. The direction of water vapor flow will be from the side with high vapour pressure (high humidity) to the side with low vapour pressure (low humidity) levels. In warmer climates the inside air will usually have lower levels of humidity due to air conditioning and hence low vapour pressure with the resultant vapour pressure or driving force coming from the outside with its higher humidity. If water vapor condenses in a wall (interstitial condensation) and is restricted from drying out, then conditions necessary for mold growth, mildew and/or wet and dry rot can develop. As this is a dynamic situation condensation may occur during one part and evaporation during another part of the day.

There are four mechanisms by which water vapour can travel through building structures; Diffusion caused by vapour pressure differentials, Air flow created by temperature differentials, Air flow created by mechanical systems and Rain penetration. Relative humidity (RH) describes the amount of moisture the air holds relative to the maximum it can hold at that temperature. If for example, the air temperature is 21^0C and the relative humidity is, say 50 percent, the air at that temperature contains only 50 percent of the moisture it is capable of holding. If the temperature then drops to 11^0C, the relative humidity increases to 92.3 percent even though the amount of moisture in the air remained unchanged. The reason is that cold air cannot hold as much moisture as warm air. In both cases, however, the absolute humidity, W(g/m^3), is the same.. When the moisture content in a wall increases, the surface temperature of that wall can be affected by five different mechanisms.

- Thermal Conductivity differences. Moisture increases the density and therefore increases the heat flow through porous materials.
- Conduction. Water cools or warms a surface by direct contact when it is flowing, dripping or moving by capillary suction away from a warm or cold source.
- Radiation. If warm or cold water is present inside a wall, the outer surface of that wall can be changed as it absorbs heat from or releases heat to the internal water by radiation
- Evaporation. Moisture cools the surface as it evaporates, so that moist areas appear cooler than dry areas. As water evaporates, it pulls heat from the wall, creating a darker (slightly cooler) pattern in the moist areas.
- Thermal lag. Water is dense, so it slows the thermal change of a porous material when ambient temperatures change. Moist areas appear cooler when the rest of the surface is warming up, [10].

2.2. Modelling methods

Hygrothermal assessment methods determine the enclosure's ability to control or manage water transport through the system under varying conditions. These can be classified as follows and further categorisation can be explored in Table 1.

- Overall balance point method such as the Passive House Planning Package (PHPP)
- Component assessment such as Psi Therm thermal bridge assessment
- Dynamic calculations such as Delphin, and Wufi

Avoiding the risk of condensation can be complex as high levels of humidity can still pose problems even when hygroscopic insulation is used. The movement of water vapour through parts of the construction is a key issue when considering thermal interventions but other factors need to be considered to arrive at an optimum solution such as heating/cooling, orientation and exposure of the particular building. Theoretical calculations are frequently used to understand and assess the movement of energy and moisture through solid walls, however there is an inherent danger in theoretically assessing the movement of moisture through solid wall constructions in so far as accurate data giving the hygrothermal properties of many traditional materials is not available and calculations are often based upon 'idealised homogenous walls'. Calculations can be misleading due to inadequate understanding of the wall composition and the often, presence of salts. If 'theoretical modelling' only, is used as a basis for the design of thermal interventions then monitoring of the performance post retrofit is essential [11]. In order to represent solid masonry walls for example 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 [12] and therefore its proportion within the wall should be estimated as closely as possible however, often a wall is modelled as a solid wall where there is a full bond between all materials. This is likely to provide worst-case scenarios for both high U-values and moisture contents. Often the hygrothermal properties of historic bricks are not measured and the program's internal material database is then used. The aim of advanced hygrothermal simulations therefore [6] is to provide a greater degree of accuracy than the previously mentioned Glaser method but due to the users inability to refine inputs the results still present uncertainties for the industry. IS EN 15026:2007 compliant software such as WuFi was developed to provide more accurate outputs through the use of better inputs and it has been shown that WUFI has passed benchmark tests (Fraunhofer IBP 2007) and proved its accuracy in field trials over many years [13].

In summary, there is a distinct requirement for a 'national specific' database for the hygrothermal properties of historic building elements. This has also been highlighted by the Sustainable Traditional Building Alliance's (STBA) report 'Responsible Retrofit of Traditional Buildings' [14].

2.3. Commercial models

All simulation tools are based on numerical methods for space and time discretization but Straube and Burnett (1991) have indicated how these can vary significantly depending on their mathematical sophistication used and the granularity of the envelope models, from the simplest transfer functions, through 1D, over 2D to 3D modelling A non-exhaustive but comprehensive list of whole building HAM analysis tools were assessed under Annex 41[15]. Table 1 gives a summary of the different approaches taken with numerical modelling and is assessed under different headings, however there are still many differences even within each of the categories in Table 1, for example DELPHIN 5 additionally deals with salt transportation. The software is used for a range of different applications including the evaluation of internal insulation systems, thermal bridge calculations, mould growth risks and construction moisture drying. WUFI (Wärme und Feuchte Instationär) allows calculation of the transient coupled one-dimensional heat and moisture transport in multi-layer building components and can be used to demonstrate and analyse the changing dew point within a construction. The introduction to individual layers, of water and/or air leakage can be modeled and it also considers the hygroscopic nature (wetting/drying) of materials through absorption/desorption. Real-time animation that simulates the change in a system materials' moisture content, RH and temperature, as it runs through a given hourly weather tape is provided [16]. WUFI is considered to be one of the most advanced of the commercially available programs, having been validated against full scale field tests over many years [17].

Table 1. Categorisation of assessment methods

Approach	Numerical methods	Sample software	Objectives	Standard	Information required	Type of Flow	Comments	Limitations
Energy Balance Point Method		PHPP	Used for design of buildings with low energy.	Design Tool to certify	Detailed component worksheets.	Steady state except (for WUFI Passive).	No great comfort or damage analysis.	Static calculation Thermal mass?
Component assessment		Psi Therm	Analyses 3-d heat flow for point thermal bridge values,, surface and Interstitial condensation & temperature.	ISO 10211	-Enclosure geometry -Boundary conditions -Material properties.	Steady state heat transport	Identifies reduced thermal performance and potential for moisture accumulation and biological growth.	Fast analysis of the temperature conditions in an existing or proposed enclosure.
Dew Point Assessment		Glaser and extended methods e.g COND, GLASTA.	Tool to determine the risk of condensation only.	IS EN 13788 (2002)		Steady state. 1D heat-moisture	Simplified Heat and Moisture transport process.	Considers vapour but not liquid water.
Mass Balance/ Numerical simulation	1.Finite Difference Method and Finite Control Volume 2.Finite Element Method 3.Response Factor and Transfer function.	WUFI DELPHIN TRANSYSIS-ITT, HAM FitPlus hygIRC. LATENITE MATCH BSim2000.	Computation of the coupled heat and moisture transfer in building components with predefined boundary conditions.	(CEN, 2003) IS EN 15026 (2007)	-Enclosure geometry -Boundary conditions -Material properties -Physics modelling -Performance thresholds.	Transient heat and moisture transport or Heat Air and Moisture transport.	Condensation risk analysis, dew point calculation and moisture accumulation risk assessment.	Some use less advanced mathematical equations.

2.4. Verification and validation

U-Values: Recently there have been a number of attempts to measure in-situ U-values of solid walls, in order to assess the impact of energy upgrade interventions. Included are the Energy Saving Trust (EST) Solid Wall Insulation Field Trials [18] and studies by Glasgow Caledonian University (GCU) for Historic Scotland [12] and also the Society for the Protection of Ancient Buildings (SPAB) [19] The significance of these studies is that the in-situ measured U values were better by between 33%-38% as compared to the accepted theoretical values and this difference can be significant for Government energy policies when upscaled to large numbers of properties requiring intervention.

Hygrothermal: IEA Annex 24 identified three possible validation methods for the provision of HAM simulation tools namely; 1) analytical, 2) empirical and 3) intermodel methods [20]. Verifications were limited to aggregating large quantities such as heat flux values, total energy flow, total moisture content and amounts of condensed moisture, and this was due to the difficulties in obtaining robust experiment data. It was suggested that more rigorous validation through well-controlled experimentation should form the basis for future work in this area as no straightforward validation through experimentation was completed.

Actual measurements and computer simulations of lightweight roofs from which a comparison was made between experimental results and simulations was undertaken on a number of different models in Norway [21]. Comparison was made between the moisture content at a specific location in a wood element and of that generated by the simulation model. In none of the cases was there complete agreement between results for moisture content of the components. Field testing and simulation of the hygrothermal performance of wood frame walls in which temperature and moisture content were measured at various locations in the wall assembly were carried out by Geving and Karagiozis (1996), with the overall trend being that there was good agreement between both, except for the early winter simulated values, which were much higher. It was noted, however, that there existed many difficulties related to simulating field experiments in particular, modelling an adequate representation of the imperfections inherent in the real structure as well as uncertainties in the input data.

Various wall assemblies subjected to different climatic conditions were hygrothermally simulated using the hygIRC software [22] as it was used as an analytical tool to conduct parametric studies on the assemblies. Results obtained from small-scale tests and those derived from the use of hygIRC are in close agreement [23] A comparison of results between hygIRC model simulations and those of controlled laboratory measurements can be found in technical reports under the MEWS (Moisture Management in Exterior Wall Systems) project [22].

In the SPAB (Society for the Protection Ancient Buildings) 2012 report WUFI Pro 5.1 software was used to investigate interstitial moisture and the design U-value of the south-facing ground floor wall at a case study property in Abbeyforegate, Shrewsbury, UK. Two scenarios one Pre-retrofit and one post-retrofit were modelled for thermal transmittance and to ascertain whether critical limits of moisture are reached at the interface between the internal insulation with the masonry wall surface. Investigation of the risk of microbial growth on the internal surface was not modeled as the project aims were to:

- Assess condensation risk of the energy efficiency measures applied;
- evaluate the limitations and accuracy in the practical application of BS EN 15026 software;
- inform the building industry of the complexity of condensation risk analysis and
- highlight areas lacking in research and clarify some of the issues with modelling that may lead to retrofit failures.

Common Exercise (CE) 1A as part of Annex 41 used Delphin to verify the model from the hygric prediction capacity point of view [24]. The Delphin model was able to simulate well coupled HAM transport through the building envelope which is especially important for historic buildings [25].

3. Experimental design for hygrothermal validation model

Location, aspect, and the differing exposure of individual elevations to direct sunlight and wind driven rains have important influences on a building's condition and performance, which need to be taken into account when proposing energy interventions. The main aim is to carry out experiments that will gather data on the hygrothermal properties and behaviour of a rendered solid brick wall assembly when subjected to transient state climatic conditions, enabling the results to be used to evaluate the expected performance and predictive capabilities within WuFi.

3.1. Monitoring setup collection and analysis

A Davis Vantage Pro2 weatherstation has been set up on the property to determine all the localised weather data. The weatherstation will gather information on precipitation, wind speed, wind direction, external temperature, external relative humidity, internal temperature and internal relative humidity. A National Instruments (NI) datalogger was connected internally to a number of thermocouples to monitor the temperature at different points throughout the thickness of the walls, floor and beam ends. The 'wall positions' monitored for temperature are;

- External air
- External wall surface
- 20mm from external face inside the render and at the external brick face position
- Mid thickness of the wall
- At the embedded wooden beam end (110 mm from internal wall surface)
- At the internal brick surface 18mm behind internal plaster
- Internal surface plaster
- Internal air temperature

Monitoring of both the north and south facing walls are currently being undertaken with the north face monitoring sending data via Wifi to the datalogger positioned close to the south facing wall (which has its thermocouples directly wired to it).

Samples from the building including bricks, mortar, render and lime plaster has been obtained for testing. The laboratory testing to determine all properties necessary for inputting to WuFI will involve the construction of a small scale test chamber

Datalogging for a 12 month period over the four seasons will be undertaken. The data will also include the relative humidity values at the end of the wooden beam end which is embedded in the loadbearing wall. This humidity and temperature monitoring is also been carried out over a 12 month period but is being monitored independently with a Lascar EL-USB-2 data logger.

3.2. Case study choice and description

Different parts of a building are affected by different micro-climates, for example north facing elevations can be subject to prolonged damp, as they do not benefit from a drying sun and are usually sheltered from drying winds however, they receive little driving rain from the prevailing south-westerly winds, so conditions are more stable. The approach taken for this research is to provide monitoring of both north and south walls. Predominantly south facing walls tend to suffer more from accelerated rates of decay due to the alternating wetting and drying cycles and temperature fluctuations as a result of more solar incidence [26].

The building chosen for this research is a mid-terraced building, which is located approximately 2km from the sea with a front elevation facing SSW. The monitoring positions are on the third floor of a four storey building. Local weather data is been gathered for the building because a building's exposure to the elements is as much influenced by the proximity and position of surrounding buildings and its own projections and extensions as by the exposure of the site and English Heritage argue that such complex variations in microclimate would ideally need to be taken into account.

In identifying the inputs and outputs it is important to note that a coupled heat, air, and moisture simulation relies on the proper input data. Besides climatic conditions, boundary conditions and contact conditions between different construction layers, high quality material data is crucial to obtaining reliable results. Material data are composed of two aspects: basic data and functionalised data. Basic data include some single parameters, e.g., density and thermal conductivity and resistances. Functionalised data provides values derived from material models, for example the moisture retention or absorption curve. Building materials testing will be carried out in the laboratory based on International Standards such as Bulk density, matrix density and porosity: ISO 11272 (2001), Thermal conductivity: EN 12664 (2001), Water vapor transmission: EN ISO 12572 (2001) and Water absorption coefficient: EN ISO 15148 (2003) Hygric sorption isotherm: EN ISO 12571 (2000),

4. Conclusions

The establishment of accurate hygrothermal properties of materials is critical in achieving a robust set of results. This paper outlines a method for the dynamic modelling and validating of the hygrothermal conditions in a solid wall historic structure for a temperate climate. A review of existing theories and models identified the importance of a) getting accurate local live weather data, b) accurate data logging monitoring of the structure over a sustained period, c) the requirement to obtain accurate material properties for all elements of the construction and d) a suitable numerical model to be used to calculate the hygrothermal conditions. WUFI was chosen for this study as it is a commercially available product and has been the subject of numerous validation and verification studies including that for historic structures. Based on these findings, the experimental approach chosen involved wall monitoring, weather data and material properties collection and other requirements based on WUFI inputs/outputs and intermediate states. The monitoring will be in place for at least twelve months, the material properties are currently being established and validation and verification using WUFI will be inputted and examined to establish the risks involved. Finally, for historic structures the variation in material properties can be widely varied and making theoretical assumptions only, without the advent of accurate material testing can be dangerously inaccurate. This case study building being monitored, along with the material properties being tested will provide the accurate data input to achieve accurate results and set out to establish best practice in establishing an appropriate and robust experimental design suitable for a solid walled structure.

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