Detailed Modelling of the Masonry Unit-Mortar Interface Using Hygrothermal Simulation

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Abstract. *Hygrothermal models are important tool for assessing the risk of moisture-related decay mechanisms in historic masonry structures. However, there are significant uncertainties in the process related to material properties, boundary conditions and quality of construction that effect confidence in the model's predictions compared to measured values. This paper examines one potential source of uncertainty; the imperfect nature of mortar joints in masonry walls, exemplified by such things as open joints, hairline cracks and imperfect bonds at the interface between mortar and unit. These are rarely considered in hygrothermal modelling in detail, where perfect interfaces are typically inferred. The premise is that at this interface, liquid transport behaviour is more similar to that of a fracture than that of a bundle of capillaries. These fractures of varying heights (or aperture) can affect transport into and out of the plane of the wall (perpendicular plane) and impede the liquid transport between mortar and the masonry unit (in-plane). This could lead to the "effective" moisture transport being different than what would be predicted using measured bulk material properties. A more detailed method for modelling this interface, borrowing techniques from the field of geohydrology is presented which demonstrates the effect that detailed modelling of the mortar joint has on moisture transport in masonry. A brick wall with cement mortar is studied. A two-dimensional hygrothermal model was created to demonstrate the effect of increased liquid conductivity into the wall cause by fractures.*

Keywords: *Masonry, Hygrothermal Simulation, Moisture Transport, Calibration, Mortar.*

1 Introduction

Hygrothermal models are an important tool for assessing the risk of moisture-related decay such as biological growth (mould and wood rot fungi), corrosion and freeze-thaw action in building envelopes. There are several gaps in our understanding and application of hygrothermal modelling involving uncertainty of material properties, boundary conditions, two-dimensional interactions and quality of construction. This can make it difficult to calibrate hygrothermal models to in-situ measurements and without calibration, our confidence in a hygrothermal model's predictions is lessened.

This paper examines one potential source of uncertainty; namely, the imperfect interface between mortar and the masonry unit. Imperfections may take the form of open joints (mm range), hairline cracks (μm range), or an imperfect bond between the mortar and the unit (**Figure 1**). These can be caused by structural displacements, shrinkage, decay/maintenance or inherent from its construction. It is intuitive to assume that a large presence of these openings will increase moisture transfer into the wall caused by wind-driven rain. The question is how much

and how do we properly account for this in hygrothermal simulations?
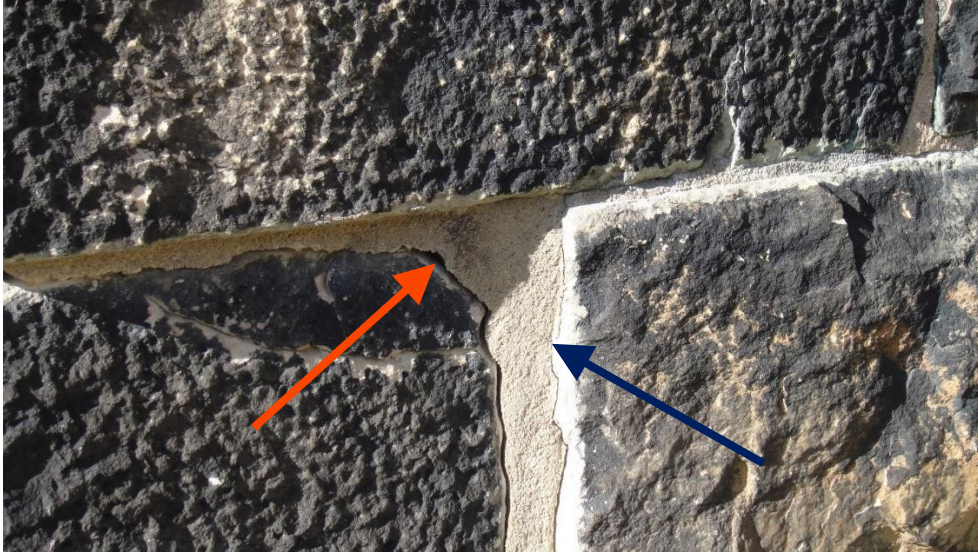
Figure 1. Sandstone masonry wall with open joint (Orange arrow) and hairline crack (dark blue arrow) between stone and mortar.

This paper proposes a methodology for explicitly modelling imperfections at the masonry interface by modelling this region as a fracture. The models assume a varying crack width (also called aperture). Material properties of the fracture are derived from fundamental principles for moisture retention and liquid conductivity.

2 Literature Review

Hygrothermal modelling software simulates the coupled heat and moisture flow (vapour and liquid) through building envelopes and assemblies using finite-element methods. The coupled heat and moisture equations are given in Equations 1 and 2:

$$\frac{\partial H}{\partial t} = -\nabla[\lambda \nabla T + h_v(k_v \nabla P_v) + h_l(k_l \nabla P_c)] \tag{1}$$

$$\frac{\partial w}{\partial t} = -\nabla(k_v \nabla P_v + k_l \nabla P_c) \tag{2}$$

Of particular interest to this paper is the term for liquid conductivity k_l. This controls the rate of liquid water ingress into a material by a capillary pressure gradient. Liquid conductivity is a function of moisture content and can be estimated from water absorption tests or pressure plate apparatus.

2.1 Masonry Interface

Previous studies have looked at moisture transfer at the interface and have shown that there is an interface resistance (R_{IF}) which inhibits transfer from one material to the other. This is analogous to contact resistances in the heat transfer of electronics. The presence of an interface resistance is caused by one of two reasons. The first is an imperfect contact between the two materials which forces water to travel across the interface through vapour diffusion instead of

the faster capillary method. The second reason is migration of fine particles toward the mortar joint during the curing stages (Brocken, 1998). The fine particles form smaller pores near the interface, and this reduces liquid flow.

Laboratory testing has measured the interface resistance between 1.0E08 and 1.0E12 m/s (Calle, De Kock, Cnudde, and Van den Bossche, 2019; Derluyn, Janssen, and Carmeliet, 2011; Qiu, Haghighat, and Kumaran, 2003). Simulations have demonstrated the effect that the interface resistance have on moisture uptake (Vereecken and Roels, 2013; Zhou, Desmarais, Vontobel, Carmeliet, and Derome, 2018). These methods only consider moisture transfer across the interface and not parallel to it.

2.2 Fractures in Masonry

There have been previous studies exploring water uptake in fractured building materials. Roels (2003) examined water uptake in a fractured brick sample and Rouchier (2012) modelled a detailed 2D crack network in a sample of concrete. Both studies required a detailed geometry of the fracture to be defined and meshed into a finite – element model. This is time and computationally expensive. It is also highly unfeasible to do on anything greater than a small sample. Modelling with an assumed fracture width will remove this need.

These simulations were also done on homogenous materials, meaning that the material was the same either side of the fracture. In a masonry interface that is not true as the material properties of the two adjacent materials may be quite different. These studies also looked primarily at water uptake and did not consider the drying phase.

2.3 Capillary Mechanics

Hygroscopic materials are often idealized as a bundle of round capillaries or pores of varying sizes. With knowledge of the pore size distribution though porosimetry or other means, it is possible to infer many of the important hygroscopic material properties required to model moisture transport. This includes the moisture retention, liquid conductivity and vapour diffusion curves. The Young-Laplace equation relates capillary pressure to pore radius:

$$\Delta P = \frac{2\gamma cos\theta}{r} \tag{3}$$

If the capillary suction pressure is greater than this, a capillary with this radius will not be filled. The Kelvin Equation describes the relationship between vapour pressure and condensation inside the capillary:

$$\text{LN} \left(\frac{p}{p_{sat}}\right) = \frac{2\Gamma V_M}{RRT} \tag{4}$$

These equations combined with the pore size distribution allow for construction of the moisture retention curve, describing the relationship between saturation and capillary suction pressure. Narrower pores retain moisture longer and larger pores catch and release moisture more easily.

Moisture retention curves can be measured in the laboratory or estimated with the Van Genuchten equation, where α and n are material- specific parameters (van Genuchten, 1980).

$$P_c = \frac{1}{\alpha} \left[S_{eff}^{-\left(\frac{n}{n-1}\right)} - 1 \right]^{\frac{1}{n}} \tag{5}$$

Liquid Conductivity is also a function of the capillary radius and can be calculated through the Hagen-Poiseuille equation:

$$k_l = \frac{\rho r^2}{8\eta_l} \qquad (6)$$

Liquid transport only occurs when capillaries are filled. Therefore, liquid conductivity is a function of saturation and exponentially increases with saturation. The moisture-dependent conductivity $k_l(\theta_l)$ can be estimated by integrating the Hagen-Poiseuille over the range of active capillaries or by using the Burdine relative permeability approach (Burdine, 1953).

$$k_l(\theta_l) = \frac{\rho}{\tau} \int_{R_{min}}^{\tilde{R}} \frac{\pi r^4}{8\mu_l} \frac{dn}{dr} dr \qquad (7)$$

The theoretical curve will not match the measured liquid conductivity curves (Scheffler, Grunewald, and Häupl, 2004). Tortuosity (τ) is included in this equation to account for the reduction in flow due to tortuosity, pore shape and the degree of interconnectivity of pores. Likewise, vapour diffusion can be estimated from fundamentals, but is not discussed here.

Determining the hygroscopic properties of a fracture is similar to the process for determining those of capillary materials. To begin, we need to determine the size of the aperture with which liquid is flowing, similar to what is learned from the pore size distribution. Aperture (h) is the distance between the boundary surfaces of the fracture. Apertures are not constant in real-world applications because it widens and contracts along its path and generally follows a tortuous path. There are two methods for determining an "effective" aperture. The first is to use the average aperture ($\bar{h}$), and the other is to use the hydraulic aperture (h_H) which is the value which would make the cubic law true (Zimmerman and Bodvarsson, 1994).

Typical apertures in subterranean rock are reported to be in the 0.001-0.1 mm range (Pyrack-Nolte, Myer, Cook, and Witherspoon, 1987). Fractures in building materials range are in a similar range ((Roels *et al.*, 2003; Rouchier, 2012). Anything much smaller than this and liquid transport is greatly reduced.

The hygroscopic material properties of the fracture can be calculated with a few distinctions to that of capillary materials. The liquid conductivity is calculated with the cubic-law or Reynold's Equation, the difference being a change in the denominator.

$$k_l = \frac{\rho h^2}{12\eta_l} \qquad (8)$$

Fractures can also have a much higher porosity with few obstructions. A smooth moisture retention curve can be created if an aperture distribution is assumed. The larger the aperture the further to the left the curve will be.

3   Methodology

DELPHIN 6.0 was used for hygrothermal simulations (Bauklimatik Dresden, 2018). DELPHIN allows input of custom material properties including direction-dependent properties, detailed moisture retention curves, and moisture-dependent liquid and vapour transfer coefficients.

3.1 Material Properties

The first step was to define material properties of the masonry. Typical bulk material properties for brick and cement mortar were determined by the taking median values for all materials of its class in the DELPHIN library. The moisture retention curve for each material was estimated using a unimodal Van Genuchten with parameters n and α where calculated using least-squares regression.

Table 1. Bulk material properties used in hygrothermal simulations.

Position	Clay Brick	Cement Mortar
θ [--]	0.294	0.2296
λ [W/m-K]	0.682	0.723
μ [--]	20.2	25.6
$k_{l, eff}$ [s]	2.21E-09	9.053E-12
n [--]	1.55	1.48
α [1/Pa]	1.00	2.172

The approach for creating the liquid conductivity curve was to use the theoretical curve (Equation 7) below the capillary water content (θ) scaled by the tortuosity (τ).

$$\tau = \frac{k_l(\theta_{cap})}{k_{l,eff}} \tag{9}$$

The liquid conductivity above the capillary suction curve was held fixed at $k_{l,eff}$. For simplicity, sorption hysteresis, temperature or moisture-dependent thermal properties and air permeability were neglected for the purposes of this experiment.

The fracture material properties were calculated based on apertures in a range from 0.25μm to 10μm. The fractures were modelled as a normally distributed curve with standard deviation of (h/2). This was done to smooth the moisture retention curve and help the numerical calculations. At high degrees of saturation, the liquid conductivity of the fracture is several orders of magnitude greater than the brick and mortar. It is less pronounced at lower degrees of saturation. Even though the exposed area of the fracture is small it can contribute to an increase in overall moisture transport.

3.2 Finite-Element Model

There are three materials in the finite element model shown in Figure 2: unit, interface and mortar. The dimensions of the model (taking advantage of symmetry) are 5mm thick mortar, *x* mm aperture and 28mm brick. The width of the assembly is 92mm.
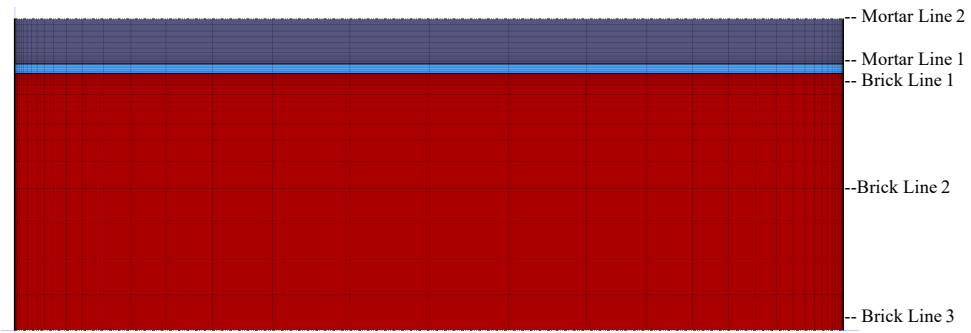
**Figure 2.** Finite Element Model (interface is not drawn to scale).

3.3   Boundary and Initial Conditions

The simulation was performed under the following boundary conditions:

1.   Water Uptake – All materials set to 50%RH and exposed to a capillary pressure of -0.025m on one side only. This was done to mimic a water absorption experiment.

2.   Drying – All materials are set to 99.99%RH and exposed to an RH of 30% on one side.

All other sides are adiabatic and there is no temperature gradient, sources/sinks in the model.

4 Results

A sample of the results are shown in **Figure 3** and **Figure 4** for the moisture content of the brick
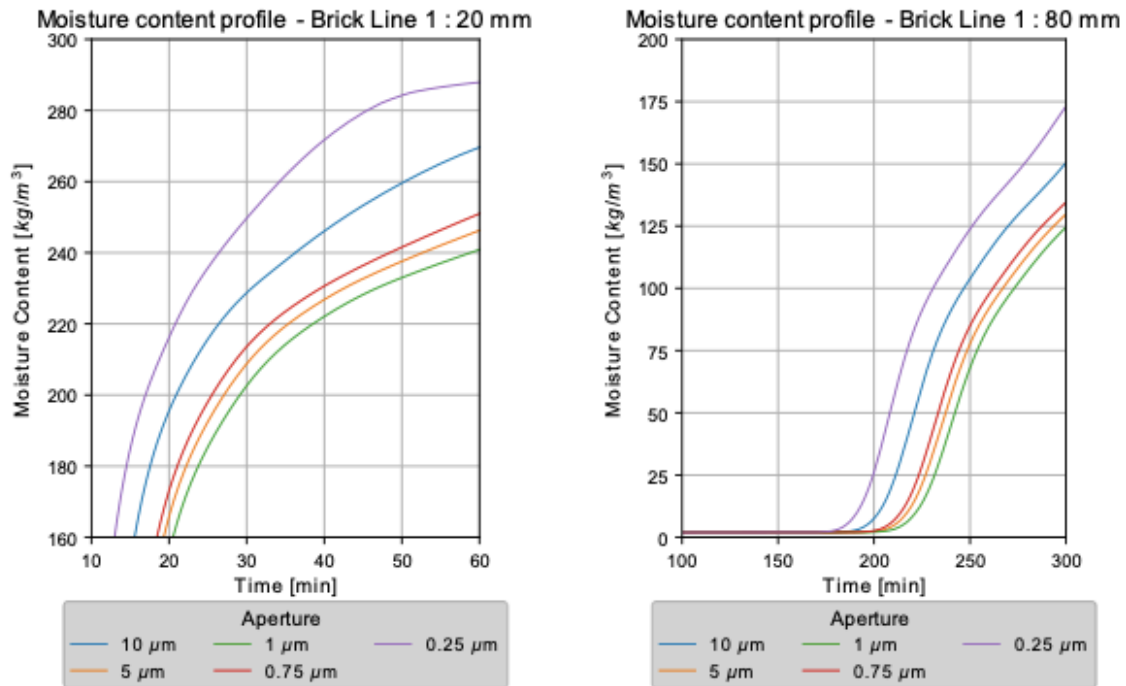
Figure 3. Moisture content of the brick adjacent to the fracture at 20mm depth (left) and 80 mm depth (right).
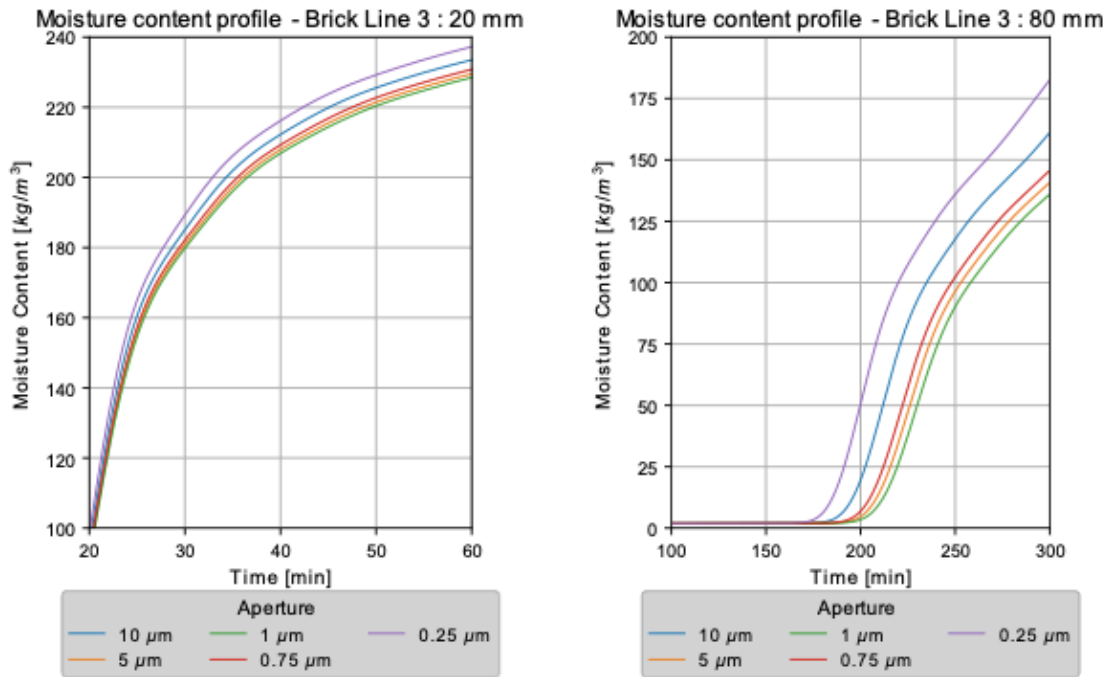
Figure 4. Moisture content of the brick at centreline of brick at 20mm depth (left) and 80 mm depth (right).

adjacent to the fracture and at the centreline of the brick. The results show that there is a significant change in moisture content depending on the aperture height. What is interesting to note is that there does not appear to be a linear relationship between moisture absorption and aperture, in fact it appears to be parabolic. Both sets of graphs show that a 1 μm aperture (green) has the minimum uptake while both smaller apertures (purple and red) and larger apertures (blue and orange) have increased absorption. The smaller apertures, while having a lower maximum flow rate are easier to fully wet and become active at higher capillary pressures. The larger apertures need extremely low (and in the reality of building walls, extremely rare) capillary pressures to become active and allow liquid to flow. The effect was noticeable adjacent to the fracture and the centre of the unit.

The simulation was performed on a sandstone/lime mortar combination with roughly twice the material dimensions. The results were not as pronounced as the case of brick/cement mortar combination. The impact of the fracture appears to be dependent on bulk material properties and the relative area density of the interfaces.

The drying simulation was performed over the course of one calendar year. The effect of the fracture was found to be minimal with a reduction in RH of less than 1% at the centre of the brick. It was determined that any enhancement to vapour diffusion out through the fracture was minimal.

5 Conclusion

The results of the DELPHIN simulations show that modelling imperfections at the masonry interface explicitly as fractures can affect simulation results compared to using only bulk material properties. The presence of fractures greatly increases the liquid conductivity locally

in a fashion similar to a thermal bridge. Future work will look at incorporating an anisotropic model into the fracture interface to account for interface resistances across the fractures as well as under more realistic boundary conditions such as typical meteorological years. Further research needs to be done to determine what the range of apertures are common in masonry walls and correlate the models to experimental data. The goal is to determine "effective" moisture transport coefficients which take into consideration imperfections and two-dimensional interactions which can be used by practitioners.

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