Investigation of thermal resistance and bridging in examples of contemporary and vernacular solid wall architecture

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ABSTRACT

Contemporary architecture has tended to increase envelope insulation levels in an unceasing effort to reduce U-values. Traditional masonry architecture in contrast was devoid of insulation, except for the inherent insulative nature of vernacular materials. Also the consistency of the outer membrane of the building skin diminished any impact due to bridging. In contemporary highly insulated walls bridges are numerous due to the necessity to bind inner and outer structural skins through insulation layers. This paper examines thermal bridging in an example of contemporary façade design and compares it with an example of traditional vernacular architecture currently being researched which is characterized by a lack of bridging elements. Focus is given to heavy weight materials of high thermal mass, which appropriately for passive architecture help moderate fluctuations in internal temperature. In an extensive experimental study samples of highly insulated precast concrete sandwich panels and lime rendered masonry walls are tested in a guarded hot-box. The building construction methods are compared for static and dynamic thermal transmittance, via heat flux and surface temperature differential measurements. Focus is given to the differential heat loss due to the thermal bridging in the sandwich panels and its associated impact on overall heat loss relative to traditional masonry construction.

INTRODUCTION

Building envelopes are becoming increasingly capable at retaining heat. European and national regulations are emphasizing ever-lower U-values, increasing pressure on building designers to augment the insulation content of walls so as to meet these targets.

Standard domestic construction is generally either of solid masonry wall, timber or steel frame construction. Focusing on solid wall construction, Stazi et al. (Stazi, Vegliò, Di Perna, & Munafò, 2013) define the 3 different wall construction categories common to temperate climates as (i) capacity, (ii) stratification and (iii) resistance. In Western Europe since mid 1900s cavity wall (stratification) construction has prevailed (Hens, Janssens, Depraetere, Carmeliet, & Lecompte, 2007). Prior to the postwar emphasis on cavity wall stratified construction, solid or capacity walls were common. Monolithic or rubble stone walls were common in vernacular construction, and still constitute the envelope of many farmhouse and cottage architecture in the European and Irish context. Today many of

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this building stock is in need of thermal upgrade. Contemporary insulation materials trap moisture and prevent these traditional structures from ‘breathing’. Novel alternatives based on natural, sustainable materials are required.

Today cavity walls are often in the 3rd category described by Stazi, resistance, given that many have been either retrofit with pumped interstitial insulation or augmented with a layer of internal or external insulation. Another type of resistance wall is the precast wall, or sandwich panel type. This construction type, which is becoming increasingly popular in Europe and is already well established in the tilt up construction market of the US, is endowed with the benefits of prefabrication which ensure time, cost and quality efficiencies of factory floor construction. In multi-story construction precast sandwich panels (PCSP) must be designed to ensure composite action between the interior and exterior concrete wythes. Lower U-values imply thicker insulation layer, which in turn implies larger tie elements, often metallic and hence highly conductive of heat. So even though specified U-values might be achievable using high levels of insulation, the thermal bridging impact of the ties becomes relatively more significant as the insulation gets thicker, a phenomenon now well established (Mao, 1997).

There are a number of reasons why PCSPs are specified (robust nature, finished surface etc.) but primary amongst these is their superior thermal mass properties over lightweight construction alternatives. They might be viewed as closer in thermal mass terms to traditional solid wall structures than to contemporary frame structures. They have a capacity likely to impact on the internal thermal environment however, the heat transmission to the outside is minimized due to the interstitial insulation layer. However, thermal bridges are numerous in PCSPs (Lee & Pessiki, 2006). Thermal bridging in contemporary facades has long been recognized as a significant failing in the resistance model of façade design with some authors claiming up to 30% of building heating requirements are given to façade thermal bridges (Theodosiou & Papadopoulos, 2008).

This paper investigates $R$ and $U$-values in two wall construction methods. The construction types are disparate but enable exploration of the impact of thermal resistance and bridging in contemporary (insulation heavy) solid wall construction in contrast to a sustainable, vernacular-appropriate, alternative (with inherent insulation properties). These are compared and contrasted with past research in the literature that documents thermal bridging in other common construction methods, including frame construction. The theoretical $U$-values are compared with the real $U$-value calculated experimentally via hot-box testing procedure. The traditional envelope consists of an insulating lime-hemp render applied to the external of a solid brick masonry wall. Lime-hemp is under general research investigation by these researchers as an appropriate ‘breathable’ insulation method for historic building renovation. An example contemporary envelope is investigated via PCSP samples. These sandwich panels include significant insulation layers. Although the $U$-value when analysed both with and without the impact of thermal bridging is relatively low the relative impact of thermal bridging is significant and needs to be accounted for.

METHODOLOGY

Experimental and simulation studies were undertaken. The experimental program was based on five wall samples; (i) a solid clay-brick masonry wall bound with hemp-lime mortar, (ii) a lime-hemp (2:1 by mass ratio) render applied to (i), (iii) a lime-hemp (1:1.25 by mass ratio) render applied to (i), (iv) PCSP with 240mm insulation and 240mm deep, 3mm thick bridging plate, (v) PCSP with 160mm insulation and 80mm deep, 2mm thick bridging plate. The impact of the bridging plate was then investigated using a simplified Finite Element Model (FEM) that was developed.

Experimentation

A one-sided hot box is used to measure the total amount of heat transferred from one side of the specimen to the other for a given temperature difference, irrespective of the individual modes of heat
transfer. The internal environment is tightly controlled (at 35°C) however the external environment vary with ambient indoor conditions. EN ISO 8990 and ASTM C1363-05 specify similar hot-box testing procedures and methods of heat exchange calculation. Neither consider the sample configuration but instead calculate the total heat transfer that passes through the sample under test based on recorded heat flux and temperature values (Asdrubali & Baldinelli, 2011). According to BS ISO 9869-1 data is taken for a minimum of 3 days for each heat flux recording and care is taken to choose days of minimal temperature variation. Samples taken every 10 minutes are averaged according to the average method described by equation (1).

The steady state thermal resistance of the wall \( R_t \) can be calculated by,

\[
R_t = \frac{\sum_{i=1}^{n} (T_{si} - T_{so})}{\sum_{j=1}^{m} (q_j)} = \frac{T_{si} - T_{so}}{\phi/T_A} = \frac{\Delta T}{T_A} \text{ (m}^2\text{K/W)}
\]  

(1)

where, \( T_{si} \) and \( T_{so} \) are inside and outside surface temperatures, \( \phi \) is the heat flux over area \( A \).

The whole building heat loss might then be characterized (CIBSE Guide A, 2006) using the equation,

\[
H_t = \sum A U + \sum L \Psi
\]  

(3)

where, \( H_t \) is the whole building heat loss, \( A \) is the area of all surfaces, \( \Psi \) is the thermal bridge and \( L \) is its length of thermal bridges.

A number of methods of calculating thermal bridging in PCSPs with varying levels of accuracy have been proposed in the literature, as previously reviewed (O’Hegarty & Kinnane, 2012). For a 2D analysis Griffith et al (Griffith, Finlayson, Yazdanian, & Arasteh, 1997) present a THERM based parallel path method of \( U \)-value approximation that is adopted here. Given their depth to thickness ratio the bridging plates in this study might be approximated to propagate heat in the 2D plane. The parallel path \( U \)-value \( (U_p) \) is given by,

\[
U_p = F_B U_B + F_N U_N \]  

(4)

where \( F_B \) is the fraction of bridged section and \( F_N \) is the fraction of non-bridged section.

To further evaluate the effect of thermal bridging in the precast panels in this study a FEM was developed. The model was a simplified representation including concrete, insulation and plate geometry and properties, but without reinforcement detail.

**Masonry Walls.** Figure 1 shows the 1m x 1m brick masonry wall (Figure 1 a)) and lime-hemp render subsequently applied to one half of the wall (Figure 1 b)). A second and different mix is applied to the other half of the wall and both are monitored for heat loss (Figure 1 c)). No thermal bridging is evident in the 1m\(^2\) section of masonry wall, and the lime-hemp render is homogenous over the complete surface of the wall. Two lime-hemp renders were investigated with different proportions. Mix 1 was based on the standard mix commonly used in industry – proportions 2:1, lime:hemp. Mix 2 reduced the
lime content and increased the hemp content with the aim of achieving greater thermal insulation – proportions 1:1.25, lime:hemp. The brick is a filled-clay, machine-pressed brick, presoaked and bound with a Natural Hydraulic Lime 3.5 mortar. Approximate density and thermal conductivities are 1200 kg/m$^3$ and 0.36 W/mK respectively (CIBSE Guide A, 2006).

![Masonry brick wall, one half of wall rendered with lime-hemp render, heat flux probes and surface temperature sensors installed for hot-box testing, and infra-red image during testing.](image)

**Figure 1** a) Masonry brick wall, b) one half of wall rendered with lime-hemp render, c) heat flux probes and surface temperature sensors installed for hot-box testing, and d) infra-red image during testing.

**Precast walls.** Two precast concrete sandwich panels (1m x 1m) were tested in the guarded hot-box. An example panel configuration is shown in Figure 2. The exact plate and panel configuration is given in Table 2. The plates that are responsible for ensure composite action are also shown in Figure 2. These are threaded with reinforcement bar prior to casting. The exterior wythe of both panels is 100mm, the internal wythe which is structurally salient is 120mm. The wythe of insulation layer varies from 240mm in panel 1 to 160mm in panel 2. The insulation is Expanded Polystyrene (EPS) with thermal conductivity of 0.035 W/mK. Approximate density and thermal conductivity for concrete are 2200 kg/m$^3$ and 1.7 W/mK respectively (CIBSE Guide A, 2006).

![Precast sandwich panel configuration, example of plate tie used and method of attachment to rebar prior to casting of concrete.](image)

**Figure 2** a) precast sandwich panel configuration, and b) example of plate tie used and method of attachment to rebar prior to casting of concrete.

**RESULTS**
Key results for the hot-box analysis of the brick masonry and PCSPs are documented in subsequent tables.

**Masonry walls.** The results of the hot-box and thermal resistance tests are presented in Table 1. The thermal benefit of adding the lime-hemp insulative render to different wall types is evident. The thermal resistance increases by approximately 50% with the addition of 21mm lime-hemp render layer.

<table>
<thead>
<tr>
<th>Wall construction</th>
<th>Heat Flux W/m²</th>
<th>R-value m²K/W</th>
<th>U-value W/m²K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick and lime mortar</td>
<td>48.35</td>
<td>0.175</td>
<td>2.89</td>
</tr>
<tr>
<td>Brick and lime mortar with lime-hemp render (Mix 1)</td>
<td>36.5</td>
<td>0.259</td>
<td>2.33</td>
</tr>
<tr>
<td>Brick and lime mortar with hemp lime render (Mix 2)</td>
<td>37.74</td>
<td>0.274</td>
<td>2.25</td>
</tr>
</tbody>
</table>

The lime-hemp render can be seen to add an additional 0.084 m²K/W and 0.1 m²K/W to the bare brick masonry wall R-value.

**Precast walls.** Precast concrete sandwich panels were investigated for overall thermal resistance and for the effect of bridging. Aggregated results of hot-box tests for the two panels are described in Table 1.

<table>
<thead>
<tr>
<th>Panel and Plate dimensions</th>
<th>Heat Flux W/m²</th>
<th>R-value m²K/W</th>
<th>U-value W/m²K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1. Insulation width -240mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate thickness - 3mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel 2. Insulation width -160mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate thickness - 2mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate depth - 240mm</td>
<td>4.24</td>
<td>4.54</td>
<td>0.22</td>
</tr>
<tr>
<td>Plate depth - 80mm</td>
<td>4.69</td>
<td>3.13</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Heat flux values are low in both PCSPs as might be expected given the considerable quantity of insulation within the panels. Panel 1 with 240mm insulation has a 45% greater thermal resistance than Panel 2 with 80mm extra insulation.

<table>
<thead>
<tr>
<th>Panel and Plate bridge dimensions</th>
<th>U non-bridged location</th>
<th>U bridged location</th>
<th>U % locational difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1.</td>
<td>0.22</td>
<td>0.45</td>
<td>104%</td>
</tr>
<tr>
<td></td>
<td>0.33</td>
<td>0.49</td>
<td>48%</td>
</tr>
</tbody>
</table>
The heat loss through the concrete surface is considerably greater at the location of the plates than over the centre. The plates are 55mm below the surface yet the heat flux increases from 4.24 to 10.46 W/m² in Panel 1 and 4.69 to 9.9 in Panel 2. The effect of bridging is relatively considerably more evident in Panel 1 than in Panel 2. This is due to the greater depth (240mm vs 80mm) and thickness (3mm vs 2mm) parameters of the plate.

A 240mm deep plate is 24% of the cross section of the panel, and an 80mm plate, 8%. Using the parallel method equation (4) the U-value for Panel 1 and Panel 2 can be corrected to 0.277 W/m²K and 0.34 W/m²K respectively, to account for the thermal bridging along the line of the panel.

Finite Element Model. Results of the FEM model of the precast concrete sandwich panel are shown in Figure 3. The steady state heat profile is shown in Figure 3(a) when the interior wythe of concrete is heated in a hot-box to 35°C. The temperature at the internal face of the exterior wythe, on the other side of the insulation later, of the precast sandwich panel is as low as 23.7°C. The model shows minimal temperature impact of thermal bridging on the panel with the outer face of the exterior wythe only fractionally higher (0.3°C) than standard room temperature 22°C.

![Figure 3](image)

**Figure 3** a) FEM thermal analysis (simulation of concrete wythe heated to 35°C in a hot-box), (hot-box and insulation hidden in model). b) Isolated solution showing temperatures at interior face of external concrete wythe and, c) Heat flux through front surface of panel

CONCLUSIONS

This paper presents an experimental study of two solid walls, an example sustainable vernacular construction and an alternative highly insulated contemporary, solid wall constructions. Both constructions have their individual strengths. In the vernacular construction, sustainable materials with less well recognized insulative ability are investigated. Brick and stone solid walls are characterized by low U-values, however introduction of the lime-hemp render layer enhances the thermal resistance of solid architecture construction by up to 16% in some cases, and 50% on the single leaf brick wall. Even with the addition of the lime-hemp render the thick vernacular masonry walls listed in Error! Reference source not found. retain high $U$-values. However, given their lack of spot bridging, thermal capacity capability and recognized beneficial impact on the internal environmental conditions in appropriate
climates (Martín, Mazarrón, & Cañas, 2010), traditional solid solid wall constructions retain advantages over contemporary façade systems. These walls are generally also devoid of thermal bridging.

In the example of solid but panelised contemporary wall construction, although the U-value of the wall is low due to a significant insulation layer, thermal bridging exists and effects the overall thermal performance. However, given the relatively small area over which it acts its impact is not seen as a considerable deficiency. Next stages in this research study involve analysis of the thermal mass effects of both wall types. The walls will behave differently in dynamic environments. The position of the insulation layer within the build up of the contemporary wall reduces the fluctuations in temperature that the sandwich panel wall will experience relative to a solid alternative.

The study is not without its limitations, and these are subsequently outlined. The hot-box used is somewhat more primitive than that used in past studies – given that its made of four walls created by layering insulation panels - however it can offer approximate thermal resistance values. A limitation of the study is the impact of dynamic environmental conditions on the ambient air on the cold side of the hot-box. Although the surface temperatures vary in a very narrow range (~2-3°) relative to the ambient air temperature fluctuations (~5-6°). Another matter that should be noted is that the steady state modeling study returns lower heat flux values, of up to 33%, than the experimental study. The model does not capture the reinforcement bar and hence the conductive route of bars to plate is not modeled. The bars lie perpendicular to the plates, but contact them at a number of locations.

Further research aims to develop accurate models of thermal bridge in solid wall construction and to investigate alternative sustainable insulation materials. The transient effects of thermal bridging and its impact on thermal storage and diffusivity will be investigated through experimental and numerical simulation. This paper outlines some of the basis for this research by investigating examples of traditional, capacity, wall types, and contemporary, resistance wall types through an experimental steady state evaluation.

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NOMENCLATURE

\[ R_t = \text{thermal resistance} \]
\[ R_{Si}, R_{So} = \text{thermal resistance of inside surface and outside surface} \]
\[ U = \text{thermal transmittance} \]
\[ \Psi = \text{thermal bridging} \]

REFERENCES


