# Numerical Assessment of the Thermal Performance of Structural Precast Panels

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#### Abstract

With the increasing cost of energy the need to provide energy efficient buildings continues to grow. In 2003 the EU introduced the Energy Performance of Buildings Directive and this was enforced by all member states by 2006. The need to continually improve thermal performance has lead to member states implementing their own national initiatives, and from next year the National Standards Authority of Ireland will specify that all certified sandwich panel products comply with the incoming building regulations. The incoming building regulations stipulate that all sandwich panels achieve a U-value of 0.15 W/m<sup>2</sup>K, a reduction from the current value of 0.25 W/m<sup>2</sup>K. This is a significant challenge and requires that there be no significant heat loss through the panel.

This paper presents the results of a collaborative project with a sandwich panel manufacturer whereby the thermal performance of a number of concrete panels was assessed. Each sandwich panel contained an inner concrete wythe of 150mm thickness, a 120mm layer of phenolic foam insulation and a 90mm thick outer layer of concrete. For structural reasons it is necessary to use connectors between the inner and outer concrete wythes, but these connectors have the potential to allow heat loss. In this study 2 connector types were used: 1 manufactured using FRP, the other with stainless steel. A control (non-structural) panel was manufactured containing no connectors. The thermal performance of each panel was assessed through experimental hot-box testing to determine U-values. This was complemented by a series of images taken using a thermal camera to show areas of heat loss. In addition the U-values were also determined using a theoretical numerical approach and a thermal finite element analysis (using MSC Patran) was conducted to determine the heat flux through the panel.

The results showed that the connector type has a significant influence on the thermal performance of the sandwich panels, and that those containing steel connectors were not capable of providing the required U-value. The relative performance of the various panel types was consistent between analysis methods, as the finite element, the numerical and experimental approaches were in agreement. In addition, the heat losses observed through the thermal imaging camera were consistent with the heat losses predicted by the finite element analysis. It is proposed then that the use of numerical and finite element approaches has a valuable role in the design of thermally efficient sandwich panels. The experimental testing required is time consuming and requires significant effort. The analysis approach described above will make the design process more efficient and facilitate the construction of energy efficient buildings.

### 1. Introduction

The pressure to reduce energy losses in buildings represents a significant challenge and this has been recognised internationally. The Europe 2020 strategy sets a series of targets that must be achieved by the year 2020; a key component of the Climate Change/Energy target is a 20% increase in energy efficiency. In Ireland, the steps being taken to meet these efficiencies may be charted in the changing U-value targets of the building regulations. The current building regulations [1] specify that the maximum U-value for a wall is 0.27 W/m<sup>2</sup>K. The current draft building regulations 2010 [2] are proposing to reduce this figure to 0.2 W/m<sup>2</sup>K, with a further reduction to a U-value of 0.15 W/m<sup>2</sup>K scheduled for 2013.

The thermal resistance of sandwich panels is compromised by the presence of thermal bridges across the insulation layer [3]. A thermal bridge is defined as any penetration through the insulation by a material that is more conductive of heat than the insulation itself. It is now widely established that this decreases the overall thermal performance of the panel [4, 5]. To minimise the effect of this thermal bridge, the use of fibre reinforced polymer (FRP) connectors with low thermal conductivity in place of traditional metallic connectors was proposed [6]. This purpose of this paper then is to investigate the effects of thermal bridges caused by wythe connectors used to structurally tie the wall together. The aim of the research was to investigate the potential for these precast insulated panels to achieve a target U-value of 0.15 W/m<sup>2</sup>K as will be required by future building regulations.

### 2. Experimental Programme

For this study three sandwich panel designs were assessed; a panel containing stainless steel connectors, a panel containing FRP connectors and a control non-structural panel containing no connectors. Each of these panels would be evaluated using an experimental approach, a numerical study and a finite element analysis.

### 2.1. Physical Testing

This involves establishing and maintaining a temperature difference over the test specimen for a period of time. It is widely acknowledged in the literature that the most general test method used is the hot-box method [7-9]. The method for the set up and operation of a hot box system is outlined in the relevant EN and ASTM standards, whereby the test panel is placed between the metering box and cold box. It is exposed to warm air at the metering side and cold air at the cold side. Testing is performed by establishing and maintaining a desired steady temperature difference across a test panel for a period of time so that constant heat flow and steady temperatures are ensured.

The standard procedure in assessing the outputs from a hot-box test is to determine the U-value by dividing the heat flux by the temperature gradient, as expressed in Eqn 1. This is widely accepted as the most reliable way to determine U-values [8, 10-16].

$$U = \frac{Q}{\Delta T} \tag{1}$$

#### 2.1.1. Hot-box testing

The hot box was constructed in accordance with the standard ISO EN 8990:1996. It consisted of a ceiling, floor and three of the four walls of a box. The sandwich panel to be tested formed the fourth wall of the hot box. The dimensions of the hot box were such that the opening of the box was  $1.2m \times 1.2m$ , producing an area of  $1.44 \text{ m}^2$ . The area of the panel in which measurements were taken was less than the gross area of the panel. Both the edge insulation and the edge boundary losses were neglected by taking an inner test area of  $1 \text{ m}^2$ . The panels were of a non-composite type and consisted of: a structural wythe (150mm thick), an insulation layer (120mm thick) and a non-structural wythe (90mm thick). Each of the panels was cast on flat beds using formwork. All panels were poured from the same batch of concrete and cast with the same type of insulation used throughout; this ensured consistency across the three test panels.

#### 2.1.2. Panel designs

In total, 3 panel designs were tested: one with steel connectors, one with FRP connectors and one control panel with no connectors (non-structural). When constructing the panels the steel mesh and concrete cover spacers were placed into the formwork; the non-structural wythe of concrete was then poured. The insulation was then placed down on top of the first pour of concrete and the structural wythe of concrete then poured down on top of the insulation. The panels were placed in a curing chamber to cure for 48 hours at 32°C. After the curing process, to minimise heat loss through the edges of the panel, white polystyrene insulation was then glued (using bostik) to each of the four sides of the panel. This meant that the overall dimension of the panel was the same as that of the dimensions of the hot box opening.

When casting the panel with Halfen steel connectors, the manufacturer's recommendations were followed. This involved tying 3 sets of connectors into the mesh, which also necessitated cutting holes through the insulation for the connectors to penetrate through. The insulation was then placed down on top of the first pour of concrete, with the steel connectors penetrating through the insulation. Foam was sprayed into the holes of the insulation, as per the Halfen recommendation. The connectors are quite bulky, as can be seen from Figure 1a.

When casting the panel with Thermomass FRP connectors, an array of 9 connectors were simply pushed through the insulation. The insulation was placed down on top of the first pour of concrete, with one side of the Thermomass connectors protruding down into the first pour of concrete and the other sticking up through the insulation. The structural wythe of concrete was then poured down on top of the insulation. The small size of the FRP connectors relative to those made from steel can be seen in Figure 1b.



Figure 1a: Steel connectors tied into steel mesh; 1b: FRP connectors protruding from insulation

### 2.1.3. Panel testing

When the hot box was completed an initial check of performance was made to ensure that design requirements were fulfilled, as recommended by the relevant British Standard [17]. This consisted of taking thermal images at the start of the first test to ensure no air leakage out of the hot box. The only apparent leakage of air was at the front top of the box where the cables for the sensors exited the box, but this was considered to be negligible. The thermal equipment was set up in accordance with [17] and included temperature sensors to measure both air temperature and surface temperature. These were evenly spaced over the panel test area and located on opposite sides (i.e. hot and cold sides) of the panel. The number of sensors for air and surface temperature measurement were at least two per square meter. The sensors were held in place with duct tape and did not influence the temperature being measured. In addition PT100 sensors were placed at different heights inside the box to measure internal temperature. The thermocouples, heat flux sensors and the PT100 sensors were connected to a datalogger, which recorded the data at one-minute intervals.

Test conditions were chosen considering the end-use application. In this testing, a temperature difference of 30°C was required [17]. Ambient temperature at the time of this research was 10°C, and as such an internal temperature of 40°C was chosen. For testing, some heaters enabled with thermostats were placed inside the hot-box. A baffle was also used so as to allow the effects of radiation heat transfer be neglected. In these circumstances, the air temperature may then be used to determine the temperature gradient across the medium. The sandwich panel, surrounded in insulation, was then placed in firm contact with the hot box and secured using tie-straps. The tests were allowed to run for 48 hours so as to achieve steady state conditions.

Under test conditions, heat enters the panel from the hot box. The heat flux entering the panel is the value to be used in calculating the U-value as it represents the heat leaving the hot box. In addition, U-values were also calculated using theoretical heat flux values. This neglected the experimental readings of heat flux but still utilised the recorded temperature values. The relevant British Standard [17] provides a formula for calculating theoretical heat flux (Eqn. 2). The internal surface resistance of concrete is typically taken to be 0.13 m<sup>2</sup>K/W.

$$\dot{Q} = \frac{T_{Air} - T_{Surface}}{R_{InternaSurface}}$$
(2)

Heat flux and temperatures were measured at three locations on the panel and point U-values were calculated at these locations. The mean of these values was taken to be the composite U-value for the entire panel.

### 2.2. ASHRAE Numerical Analysis

The ASHRAE Handbook [18] describes a U-value as the inverse of the resistances of a material. The thermal resistances of the materials can be treated as electric resistances, which are arranged in parallel, series, or a combination of both, to estimate the thermal resistance of the assembly. This is considered a theoretical U-value based only on the material properties. Figure 2a and 2b show the various resistances in series and parallel for the panels containing steel connectors and FRP connectors respectively.



Figure 2a: Resistance model of panel containing steel connectors; 2b: Resistance model of panel containing FRP connectors

### 2.3. Finite Element Analysis

According to Chen et al. [11] the use of a FEA is a valid tool for the comparative study of building components. The use of FEA for assessing thermal performance of sandwich panels is not widespread but has been used by some researchers [8, 15, 19]. Lee and Pessiki [8]

assessed the thermal performance of a three-wythe concrete sandwich panel by using a 2dimensional model of a panel in a guarded hot-box. In this case only convection and conduction heat transfer were considered and the FE results were found to be within 10% of the experimental value.

For this research a 3-dimensional FE model was built of each of the sandwich panels using the package MSC Patran; the models were designed to replicate the experimental hot box testing. As such, each panel had a surface area of 1.44 m<sup>2</sup>, with a 150mm structural wythe, a 90mm non-structural wythe and 120mm of insulation. The geometry of the panel and connectors were modelled as 3-D solids and the mesh was created using hex shaped elements (nodes only on corners, not on edges). Material properties of thermal conductivity, specific heat capacity and mass density for the concrete, steel, FRP and insulation were defined and associated to the relevant elements as can be seen in Table 1 below.

Material	Thermal Conductivity (W/mK)	Density (kg/m³)	Specific Heat Capacity (J/kgK)
Concrete	2.50	2500	880
Foam	0.02	6	1.47
Insulation	0.02	4.2	1880
Steel	17.00	7830	500
FRP	0.99	2.1	1500

Table 1: Material Properties

For the each of the models, two convection loads were applied to the element surfaces. This involved specifying the convection coefficient and the ambient air temperature around the surface. The first convection load simulated the inside of the hot box, using a convection coefficient of 8.29 W/m<sup>2</sup>K and an ambient temperature of 40°C. The second convection load simulated the outside surface of the panel in the hot box test and used a convection coefficient of 34 W/m<sup>2</sup>K and an ambient temperature of 10°C. There were two degrees of freedom per node (temperature and heat flux). The contact between the connectors and the concrete was modelled using the Patran *Connector* function which links two nodes together with different material properties. For these models, a transient analysis was selected, as heat flow by its nature changes with time. Results from the FE modelling are in the form of temperature and heat flux, which were then used to determine the U-value.

## 3. Results

## 3.1. Physical Testing

From hot box testing, a U-value may be determined by dividing the heat flux through the sandwich panel by the environmental temperature gradient across it. The British Standards [17] suggests that where a baffle is used, radiation heat transfer may be neglected. The air temperature may then be used to determine the temperature gradient across the medium. Heat enters the panel from the hot box. The heat flux entering the panel is the value to be used in calculating the U-value as it represents the heat leaving the hot box. In addition to calculating U-values using the experimental heat flux reading, U-values were also calculated using theoretical heat flux values. This neglected the experimental readings of heat flux but still utilised the recorded temperature values.

Given that the heat flux and temperatures were measured at three locations on the panel, the point U-values were calculated at these locations. From this, a composite U-value for the entire panel was calculated. Two different sets of U-values were calculated, one by dividing the empirical heat flux values by the air temperature gradient and the second by dividing the theoretical heat flux values by the air temperature gradient. The temperature gradients across the panels were then calculated by subtracting the outside temperature from the

inside temperature for each of the three points of measurement. This was done for each of the three panels.

It was also decided to take a rolling average of the data. Each point was averaged with fifty data points before it and fifty data points after it. The aim was to minimise the influence of any non-steady state conditions. The rolling average approach was applied to empirical and theoretical heat flux measurements and temperature gradients at three different locations on the panel, making it possible to calculate the U-value at these points. Therefore 6 different U-values have been calculated for each panel (three measurement points using both empirical and theoretical heat flux). It was decided that the theoretical heat flux values were most appropriate to use due to uncertainty regarding the reliability of some heat flux data.

A composite analysis of the steel panel was also undertaken and point U-values were calculated. Given that the U-values were different at the steel connector compared with the rest of the panel, it was necessary to calculate a composite U-value for the whole panel as can be seem in figure 3. This was unnecessary for the FRP panel as the point U-values were the same on the connector as elsewhere on the panel.



Figure 3: Panel with steel connectors composite U-value

From the steady state portions of the graphs of U-values, an average U-value was calculated for each of the three panels as can be seen in Table 2. In the case of the panel with steel connectors, this was taken from the graph of composite U-values for the entire panel. In the case of the panels containing FRP connectors and no connectors, an average of the three point U-value readings were taken.

Table 2: U-values Obtained from the Experimental Hot Box Method

Panel	U-value (W/m <sup>2</sup> K)
Control	0.139
FRP connectors	0.150
Steel connectors	0.260

#### 3.1.1. Thermal Images

Thermal images were taken at the start and the end of each of the three tests. These images were taken as a qualitative addition to the quantitative data collected in the hot box testing. Figure 4a is a thermal image taken at the start of the test of the panel with steel connectors. The steel connectors cannot be identified this early in the test. Figure 4b is a thermal image

taken at the end of the test of the panel with steel connectors. The steel connectors can be clearly seen as the reds spots in the image.

Figure 4c is a thermal image taken at the start of the test of the panel with FRP connectors. The sensors can be identified in the image but the FRP connectors cannot. Figure 4d is a thermal image taken at the end of the test of the panel with FRP connectors. The sensors may be seen in the image but the FRP connectors cannot be identified. The image suggests that the temperature of the panel was almost uniform at approximately 6°C.



Figure 4a & 4b: Thermal image at the start and end of testing of the panel with steel connectors

4c & 4d: Thermal image at the start and end of testing of the panel with FRP connectors

## 3.2. ASHRAE Numerical Analysis

The flow of heat through the panel is examined from the heated inside to the outside. For the panels using steel or FRP connectors, the flow encounters two paths. The first is a path along the connector; the second path is through concrete, then insulation and then more concrete. The resistor circuit is solved to find the total resistance, which is then inverted to yield a U-value as listed in Table 3.

Table 3: U-values calculated using ASHRAE approach

Panel	U-value (W/m <sup>2</sup> K)	
Control	0.168	
FRP connectors	0.169	
Steel connectors	0.288	

As expected, the panel with no thermal bridges through the insulation achieved the best U-value. The panel with the FRP connectors achieved a similar U-value to the control, but the panel with the steel connectors had a significantly higher U-value. Using this method, none of the panels would achieve the required U-value of 0.15  $W/m^2K$ .

## 3.3. Finite Element Analysis

The results from the FE modelling were expressed in terms of heat flux and temperature. As per the hot-box method, the U-values from the FE modelling were determined by dividing the heat flux through the panel by the temperature gradient across the panel. Point U-values were determined for each element on the panel surface and these were then averaged to produce a single composite U-value for the entire panel. The results of this analysis are presented in Table 4.

Table 4: U-values calculated using FE modelling

Panel	U-value (W/m <sup>2</sup> K)	
Control	0.145	
FRP connectors	0.149	
Steel connectors	0.286	

The results produced are quite similar to those obtained using the ASHRAE testing, and again show the relatively poor performance of the panel manufactured using steel connectors. Again the performance of the FRP panel is only slightly inferior to that associated with the control panel manufactured without connectors.

An additional benefit of the FE modelling is that it does allow the designer to see potential area of weakness within the panels. For this particular study the area of interest are potential thermal losses around the connectors. When conducting a transient FE analysis it is possible to observe the changes in temperature over time, and these are very useful in highlighting the relative performance of the materials. This can be seen below when the results of the transient analysis of the panels with FRP and steel connectors are inspected.



Figure 5a: Localised temperature losses around the FRP connectors.

5b: Increased losses around the larger steel connectors

### 4. Discussion

Table 5 below shows the U-value results from the three methods of testing. Using the ASHRAE method, none of the panels are expected to meet the new energy requirements. However the U-values calculated using this approach are higher than the other two methods. Possible explanations are that the ASHRAE method fails to take into account the lateral heat flow [9, 15] and that the thermal conductivity values used are conservative.

With the experimental hot box method, the panel with no connectors meets the requirements, while the others do not. However, the FRP panel is marginally over the requirement with a U-value of 0.154 (W/m<sup>2</sup>K). This would indicate that the FRP connector is most suited to meeting the incoming requirements. Using the finite element method, both the panel with FRP connectors and no connectors meet the required U-value of 0.15 (W/m<sup>2</sup>K). From the three methods, it can be concluded that the FRP connectors are the most suitable for the incoming energy requirements with respect to thermal efficiency.

Table 5: U-value results from three methods

Panel	Calculated U-value (W/m <sup>2</sup> K)			
	ASHRAE	Experimental Hot Box	Finite Element	
Steel Connectors	0.288	0.297	0.286	
FRP Connectors	0.169	0.154	0.149	
No Connectors	0.168	0.139	0.145	

Thermal images were taken at the start and the end of each of the three experimental tests. Comparisons of the thermal camera images with the finite element modelling images illustrate where the heat loss occurred in the panels. The red spots indicate regions of high temperature and thus large heat losses. From inspection of Figure 6a & b, it can be seen that there is good agreement between the theoretical results of the finite element modelling and the experimental hot box results. These areas correspond to the location where the steel connectors are located and gives confidence that the modelling process is accurately modelling the thermal movement in the panel.

From inspecting the results from the thermal images of the panel with FRP connectors, there is no obvious heat loss associated with the connectors. This is in contrast with that obtained from the finite element modelling where some minor heat loss can be seen in the areas around the FRP connectors (Figure 6 c & d). It is considered likely that these minor heat losses could be seen by the thermal imaging camera by fine tuning the resolution and temperature scale.



-13.1 C -10.4 C - 7.7 C - 5.0 C



6 49+0

Figure 6a & b: Thermal image and finite element image at the end of testing for the panel with steel connectors ;

Figure 6c & d: Thermal image and finite element image at the end of testing for the panel with FRP connectors

### 5. Conclusions

The use of finite element modelling for designing sandwich panels with respect to thermal resistance is not widely used. More common is the use of the numerical ASHRAE method in conjunction with experimental studies. This study has shown that FE modelling has the potential to replace the ASHRAE method as a tool for designing panels. The FE method resulted in U-values that were considerably closer to the experimental hot-box tests than those obtained using the ASHRAE approach. It is considered likely that this is due to the simplifying assumptions that make the ASHRAE approach relatively easy to use.

Both the FE and experimental approach offer the opportunity to visually assess the performance of the panels, so as to identify areas of weakness within the structure. The use of thermal imaging cameras is also beneficial in this regard. These approaches have very obvious benefits when used for product development.

Finally, the significant influence of the connector type on thermal performance has been illustrated. The insulation used in this research was the thickest commercially available and suggests that if sandwich panels are to meet the ambitious targeted U-values, then the selection and installation of structural connectors is a critical step. If this can be resolved then it should be possible to construct environmentally sustainable concrete sandwich panels.

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