Assessment of ICF energy saving potential in whole building performance simulation tools

ASSESSMENT OF ICF ENERGY SAVING POTENTIAL IN WHOLE BUILDING PERFORMANCE SIMULATION TOOLS

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ABSTRACT

Insulating Concrete Formwork (ICF) is classified among the site-based Modern Methods of Construction (MMC) and consists of hollow insulation blocks and cast in-situ concrete. ICF construction elements can achieve very low U-values and high levels of air-tightness. The aim of the study was to examine the inconsistency in the simulation results provided by five widely used Building Performance Simulation (BPS) tools when calculating the energy consumption and the thermal performance of ICF. Moreover, the paper aims to analyse the energy consumption of ICF when compared to low and high thermal mass construction methods. The results indicate that there is a divergence in the BPS predictions, which is more noticeable in the annual and peak heating demand. Moreover, simulation predictions indicate that the ICF building has the potential to reduce the annual and peak energy use significantly, when compared to a lightweight structure, but consumes slightly increased energy compared to a high mass building.

INTRODUCTION

The UK housing construction industry has been characterised as conservative with very little changes noticed in the building design and layout over the past 100 years (Pan et al, 2007; Rodriques, 2009). However, the last English Housing Survey indicated that there is a noticeable turn toward lightweight and other off-site Modern Methods of Construction (MMC) (DCLG, 2008), due to their advantages in reducing cost, time, defects, health and safety risks and their environmental impact (Pan et al, 2007). Research has shown that there is currently a housing shortage in the UK, (Pan et al, 2007). Between 1990-2010 population growth accelerated, while the corresponding number of completed dwellings per year decreased (Swann et al, 2012). The UK government has to deal with the challenges imposed by the housing crisis and it is committed in the National Planning Policy Framework (NPPF) to facilitate the supply of housing, since further increase of population by 10.2 million people is expected by 2033 (Swann et al, 2012; Troop, 2013). According to Gibb (Pan et al, 2007), MMC are defined as a number of mostly off-site innovative technologies in house building, moving work away from the construction site to the factory. Based on a BRE research project conducted in 2005 (Kempton and Syms, 2009) MMC can be classified in five categories summarised in Table 1.

Table 1
Modern Methods of Construction (MMC)
(Adapted from Kempton and Syms, 2009)

MMC TYPE	DESCRIPTION
Volumetric	Factory produced 3D units, produced off-site and transported in modules to site
Panelised	Flat panel units produced in the factory and transported to site for assembly
Hybrid	A combination of both volumetric and panelised construction
Sub-assemblies and components	Building approaches that are not classified as off-site MMC, but include factory-produced elements
Site-based MMC	Modern and innovative site-based process of construction

The drivers of and barriers to MMC have been analysed in previous work (Pan et al., 2007; Kempton and Syms, 2009) and are outside of the scope of this research. The analysis presented in this paper focuses on one of the site-based MMC, called Insulated Concrete Formwork (ICF).

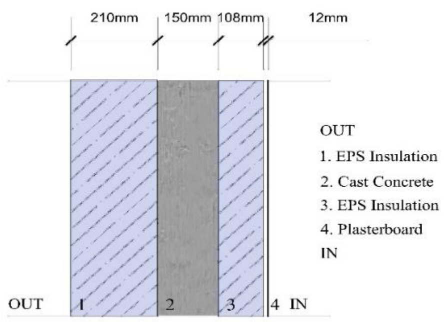

Figure 1: Example of a cross section of an ICF wall assembly

Even though ICF is not a lightweight, factory-made construction method, it is classified as a site-based MMC mainly due to the innovative approach of house building (Rodriques, 2009). ICF consists of cast in situ concrete between two layers of insulation. Once the concrete has cured, the (insulating) formwork stays in place, providing complete thermal insulation and high levels of airtightness in the building (Rajagopalan et al, 2009). ICF is a fairly new building technology in the UK; hence the amount of research associated to ICF is limited compared to other construction methods. Previous studies conducted in the US (NAHB, 1997; Lewis, 2000) highlighted several advantages associated with ICF's material properties:

- Thermal resistance
- Fire resistance
- Sound reduction
- Air-tightness
- Consistency of insulation
- Strength and durability

Gajda and VanGeem (2000) using thermal simulation modelling compared the energy consumption of an identical building for two different exterior wall construction types: timber frame and ICF. The analysis was conducted in five representative US climates. They concluded that for every location ICF showed an inherent capacity of higher insulation, which resulted in reduced energy consumption compared to the timber-framed wall. Rajagopalan et al (2009) performed a comparative Life Cycle Assessment (LCA) of ICF with traditional timber-framed wall sections from cradle to grave. They found that even though ICF exhibits higher environmental impact compared to traditional building materials during manufacturing, its thermal properties resulted in significantly reduced energy consumption during the use phase of the LCA. Hart et al (2014) performed a wider study, analysing the impact of wall type selection on residential buildings by simulating various wall assemblies, including exterior and interior insulated masonry walls, ICF and timber-framed walls. Regarding ICF, they concluded that its total energy use falls between the energy use of exterior and interior insulated masonry walls and is always better than the energy use of timber-framed walls with equal amounts of insulation.

An onsite monitoring study was conducted on a seven-storey residential building in Canada investigating the thermal resistance of ICF wall assemblies (CMHC, 2007). Evidence from the monitoring study indicated that ICF wall system provides a significant thermal buffer between indoor and outdoor conditions, and that the indoor air temperature was relatively steady during the three months of monitoring. Moreover, the temperatures on either side of the ICF concrete core were also stable. The inner surface of the concrete core was found to be isolated effectively from outdoor temperature variations by the insulation levels on the exterior of the wall, but also by the capacitance of the concrete itself. Finally, air leakage testing demonstrated high levels of air-tightness, associated to significant energy savings.

The aim of this paper is to analyse the energy performance of ICF when compared to low mass and high mass construction methods. Moreover, the study aims to investigate the ability of five widely used BPS tools to calculate the energy consumption and thermal performance of ICF in whole BPS. The analysis will contrast the simulation results provided by each of the five BPS tools for annual energy consumption, peak thermal loads and indoor air temperatures produced for a single zone test building and for three different construction methods, low mass (timber-framed), high mass (concrete) and ICF wall assemblies. The research objectives are:

- To question the consistency, or otherwise, among the simulation results provided by the BPS tools for the ICF building.
- To analyse the energy performance of the ICF building when compared to high and low thermal mass construction.
- To analyse the indoor air temperature variations in free floating building operation (no space conditioning).
- To investigate the energy saving potential of ICF wall assembly when compared to timber-framed wall.

METHODOLOGY

The building model used in the analysis was a simple single-zone test building. Three different construction methods were simulated, an ICF, a high mass and a low mass building case. The ICF fabric description is based on actual building construction details and is used as a reference to specify the U-Values for each construction element, which were kept consistent among all three models. Hence, the only difference between the three construction methods was the level of thermal mass in the fabric. Table 5 includes a detailed description of the fabric construction details for all three building cases. The structure of the building is the same in all three scenarios; each model has the same building footprint, windows, HVAC system, internal gains and infiltration rates, as summarised in Table 2.

Table 2
Input data used for the building model

BUILDING MODEL DETAILS	
Floor Area	6m x 8m = 48m^2
Orientation	Long axis on East-West direction
Windows	Two double glazed windows, 2m x 3m each, on south façade
HVAC system	Ideal loads
HVAC Set points	20º Heating/ 27º Cooling
Internal Gains	200W (other equipment)
Infiltration	0.5ach

Energy is used for space conditioning and other equipment. No domestic hot water usage was assumed. The DRYCOLD weather file, downloaded from NREL[1], was used as a Typical Meteorological Year (TMY) representing a climate with cold clear winters and hot dry summers. The weather data description is included in Table 3.

Table 3
Indicative values of the weather file used for the simulations

WEATHER DATA	
Dry Bulb Temperature (C°)	
Minimum	-24.4
Maximum	35
Mean	9.7
Direct Horizontal Solar Radiation (kWh/m^2.y)	1339.48
Diffuse Horizontal Solar Radiation (kWh/m^2.y)	492.34

The analysis was carried out in three parts. The first part consisted of an inter-model comparative analysis on the annual thermal energy consumption and the system peak loads provided by the five BPS tools for the ICF building construction. Two of the tools included in the analysis were open source, free software, the others were proprietary, commercial tools. For reasons of sensitivity and fairness, we have chosen not to name the BPS tools used. We do not feel that this distracts from the scientific merits of the paper. Error bars were used in the bar chart to demonstrate the deviation in energy use when comparing the ICF construction to the low and the high thermal mass building cases.

The second part analysed the free-floating internal temperature fluctuations when no space conditioning is provided in the buildings. The differences in the simulation results provided by the BPS tools were explored for both a three-day winter and a summer period to interrogate the ability of the tools in estimating the thermal performance of ICF. As a next step, the free-floating temperatures of ICF were compared to those of the low and high mass construction, to examine the ability or otherwise of ICF in stabilising the internal temperatures.

The third part of the research was focused solely on the energy saving potential of the ICF wall assembly, when compared to a lightweight, timber-framed wall. A fourth hybrid building model was created based on the ICF building, keeping all construction details consistent and changing only the exterior walls to timber-framed construction. The simulation results for the system loads of the two buildings were compared to quantify the energy saving potential of the ICF wall due to its inherent thermal mass.

[1] Available at http://www.nrel.gov/publications/
(Last visited on 05/05/15)

RESULTS

System Loads Comparison

The analysis shows that the inconsistency in the simulation results for the annual energy consumption (Figures 2 and 4) and the peak thermal loads (Figures 3 and 5) is more significant for heating than for cooling. The absolute differences between the maximum and the minimum values are relatively insignificant, around 0.25MWh for the annual heating and cooling demand and 0.25kW for the peak thermal loads. Nevertheless, when questioning the relative differences in the results, it can be seen that the impact of these inconsistencies is more substantial for the annual heating energy consumption (15% difference between the maximum and minimum value) and the peak heating loads (12% difference).

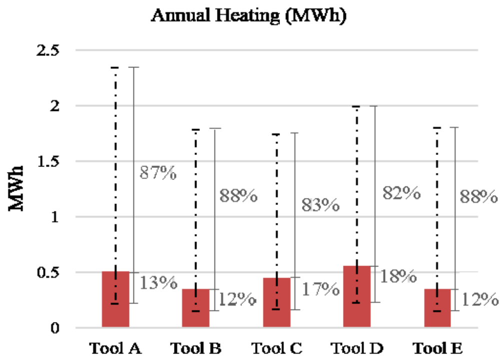

Figure 2: The graph demonstrates the results for annual heating energy consumption (MWh). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the annual heating energy consumption of the low mass construction and the lower limit showing the results of the high mass construction.

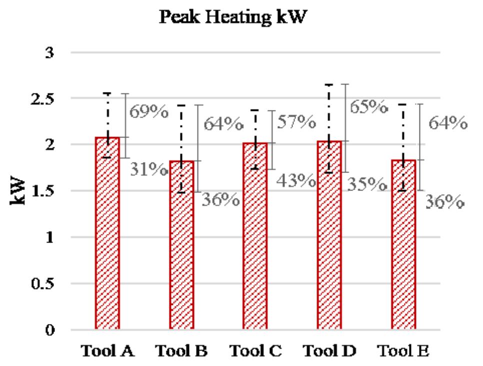

Figure 3: The graph demonstrates the results for peak hourly integrated heating loads (kW). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the peak heating loads of the low mass construction and the lower limit showing the results of the high mass construction.

In the annual heating energy consumption (Figure 2) Tool D estimates the highest value for the annual heating energy consumption, while Tools B and E estimate the lowest. In the peak heating loads (Figure 3) Tools A, C and D calculate similar peak energy use increased by 12% compared to Tools B and E. There is general consistency in the simulation results provided by the five BPS tools for the annual cooling energy consumption (Figure 4) and the peak cooling loads (Figure 5). In both cases, Tool C estimates the highest value, around 6% increase, compared to the minimum values given by Tool D for the annual cooling demand and Tools B and E for the peak cooling loads.

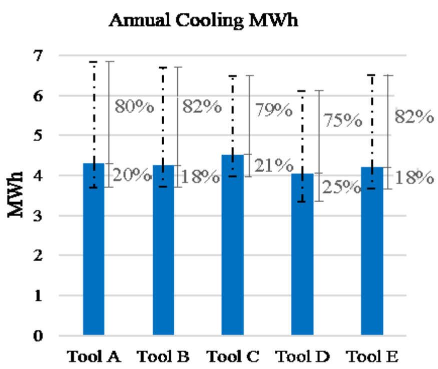

Figure 4: The graph demonstrates the results for annual cooling energy consumption (MWh). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the annual cooling consumption of the low mass construction and the lower limit showing the results of the high mass construction.

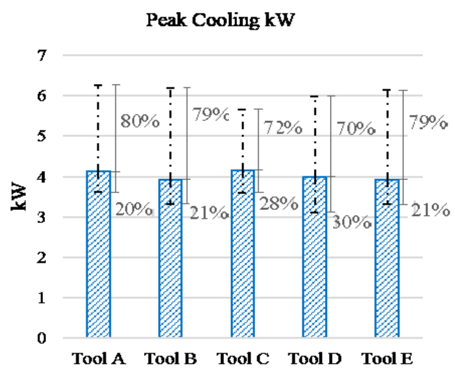

Figure 5: The graph demonstrates the results for peak hourly integrated cooling loads (kW). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the peak cooling loads of the low mass construction and the lower limit showing the results of the high mass construction.

There are also inconsistencies in the simulation results provided by the BPS tools for the other two building cases, the low and the high thermal mass constructions. Previous studies on the accuracy of simulation predictions have shown that the key factors contributing to the divergence in the simulation results when modelling an identical building using different BPS tools are associated to the modelling uncertainties in the calculation methods and the solution algorithms employed in the tools' source code (Hopfe el al, 2007; Zhu et al, 2012; Mantesi et al, 2015). The results for the two other building cases indicate that the maximum divergence is also in the annual heating energy consumption. Table 4 summarises the relative differences between the maximum and minimum values in the simulation results for all three building cases.

Table 4
Relative differences between the maximum and minimum estimated energy consumption in [%]

ENERGY USE	ICF	LOW MASS	HIGH MASS
Annual Heating	38%	26%	36%
Peak Heating	12%	7%	20%
Annual Cooling	6%	11%	16%
Peak Cooling	6%	10%	14%

With the exception of peak cooling loads, in every other case, the tools which estimate the maximum and minimum annual and peak energy use for the ICF building are the same tools that estimate the maximum and minimum annual and peak energy use for the high mass building. In the low mass case, the divergence in the results follows a different pattern.

When analysing the energy and thermal performance of the ICF construction in comparison to the low and high mass buildings, the general observation is that ICF falls between the aforementioned construction methods and behaves closer to the high thermal mass building. In the annual thermal energy consumption, the ICF building requires approximately 85% less energy than the low mass building for annual heating and 80% less energy for annual cooling. In the peak heating and cooling loads, the average reduction in energy use when comparing the results of the ICF and the low mass structure is around 64% for heating and 76% for cooling.

From the inter-model comparison, it can be seen that in most of the cases (except of the peak heating loads), Tools B and E estimate the highest reduction in the energy use between the ICF and low mass construction, while Tool D estimates the lowest reduction.

Zone Temperature Comparison

The inter-model comparison for the free-floating temperature fluctuation was performed for a three-day cold winter period (Figure 6). The results show that Tools C and D estimate lower temperatures during the night hours than all the other BPS tools. Moreover, the spikes in the line chart indicate that Tool D gives significantly increased peak internal temperatures during daytime compared to all the other tools. All other BPS tools show relatively consistent results.

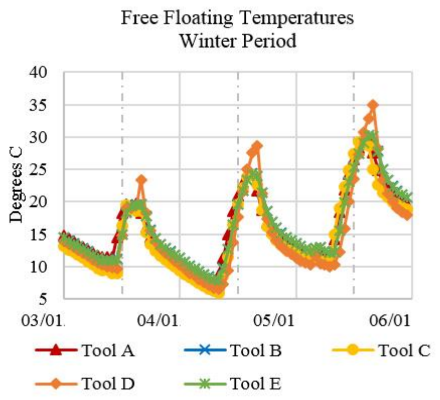

Figure 6: Free-floating internal temperature variations of the ICF construction for a three-day heating period

When investigating the free-floating temperature fluctuations in a three-day hot summer period (Figure 7) Tool D estimates significantly increased internal air temperatures during the whole of the period and for both day and night time. Tool A shows slightly decreased temperatures, especially during night hours. The remaining BPS tools show an overall consistency in the simulation results for the internal air temperature variation.

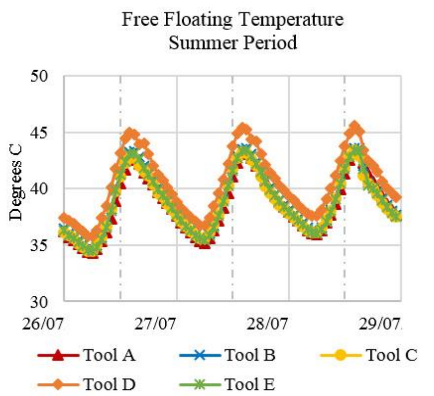

Figure 7: Free-floating internal temperature variations of the ICF construction for a three-day summer period

The free-floating temperature fluctuations of the ICF building were plotted against those of low and high thermal mass building cases. Tool E was selected for this analysis, based on the results from the previous two figures (Figures 6 and 7). Tool E shows an overall consistency with the simulation results provided by most of the BPS tools included in the inter-model comparison. When comparing the free-floating temperatures of the ICF building to those of low and high thermal mass cases, the general observation is that in both winter and summer periods, ICF behaves closer to the high thermal mass building. The results for the winter period (Figure 8) show that ICF follows similar internal temperature fluctuations as the high mass case. The internal air temperatures of ICF are slightly lower than the high mass building for most of the period. The diurnal internal temperature variations are slightly higher in the ICF building (around 15K) compared to the high mass case (10K). Nevertheless, the ICF building shows a significantly more stable internal environment, compared to the low mass building (40K diurnal internal temperature variations).

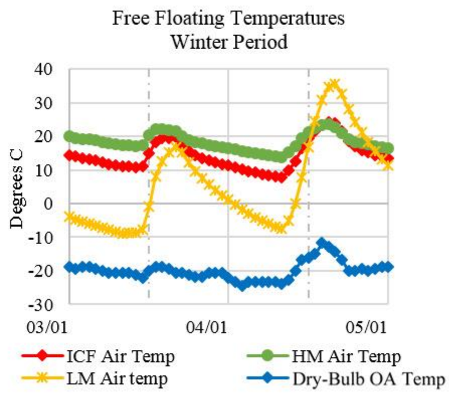

Figure 8: Free-floating internal temperature variations. Comparison between low mass, high mass and ICF constructions for a three-day heating period

In the summer period (Figure 9), the ICF building again shows similar internal air temperature variations to the high mass case. The peak internal temperatures of ICF are around 2K higher than those of the high thermal mass building during daytime, and slightly lower during night hours. Likewise, the ICF building shows significantly more steady internal temperatures (around 7K diurnal internal temperature difference) compared to the low mass building case (20K diurnal internal temperature difference).

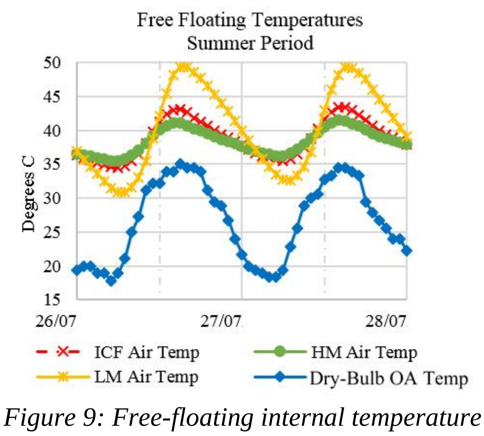

Figure 9: Free-floating internal temperature variations. Comparison between low mass, high mass and ICF constructions for a three-day cooling period

ICF Wall Energy Saving Potential

The energy saving potential of ICF wall due to its thermal mass (compared to an identical building with timber-framed walls) is mainly found in the annual heating energy consumption and the peak heating demand. The ICF building shows a 15% reduced annual heating energy consumption compared to the hybrid building with timber-framed walls and around 10% lower peak heating loads (Figure 10). The contribution of the ICF thermal mass is insignificant for the annual and peak cooling demand, where there is around 1.5% lower energy use in the ICF building (Figure 11).

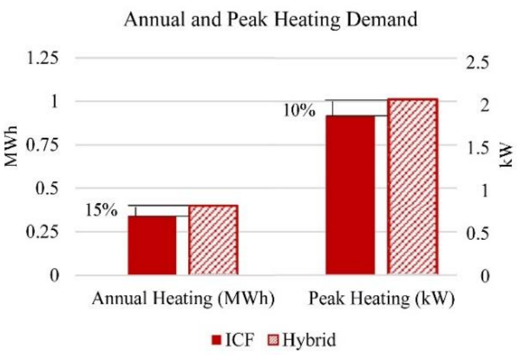

Figure 10: Annual and peak heating demand. Comparison of the ICF and hybrid construction

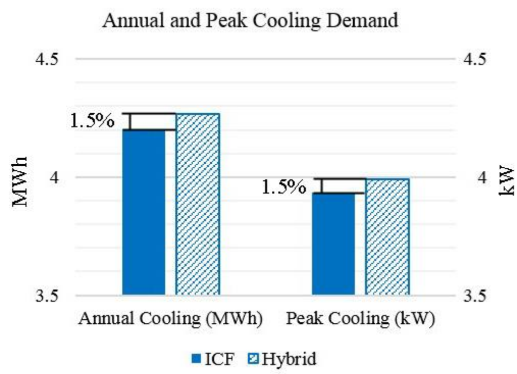

Figure 11: Annual and peak cooling demand. Comparison of the ICF and hybrid construction

DISCUSSION

The analysis presented here shows that there are inconsistencies in the simulation results provided by all five BPS tools when calculating the energy consumption and the thermal performance of an ICF building. The divergence in the results was more substantial in the annual and peak heating demand, and relatively insignificant for the annual and peak cooling demand. Tools B and E predict the lowest energy consumption of ICF, showing decreased energy use almost in every case compared to the other BPS tools. On the contrary, Tool D estimates the highest energy consumption of ICF; it was also disadvantageous in estimating the free-floating internal temperature variations of ICF, compared to the other BPS tools. In the comparative analysis between ICF, the low mass and the high mass buildings, the findings are consistent with those from previous studies (i.e. Gajda and VanGeem, 2000; Rajagopalan et al, 2009; Hart et al, 2014). The simulation results showed that the ICF building uses significantly reduced energy for space conditioning compared to the low mass building, and slightly increased compared to the high mass case. Moreover, the ICF building provides a relatively stable internal environment compared to the low mass case, damping the internal air temperatures swings for both winter and summer periods. Finally, the analysis of the energy saving potential of the ICF wall solely showed that the inherent thermal mass in the concrete core of the element had a significant impact on the annual and peak heating demand when compared to the equivalent timber-framed wall construction. The contribution of the ICF thermal mass was insignificant for the annual and peak cooling demand.

RESEARCH LIMITATIONS

The analysis presented in this paper was based on a simple, single zone test building, where constant values were provided for the dynamic loads (i.e. internal gains, infiltration rates and so on) and consistent U-Values were used in the fabric of all three construction methods. This is an assumption to facilitate direct comparison between the three different building methods. The impacts of variable airflows (ventilation and infiltration) and realistic internal heat gains were excluded from the analysis. Moreover, the simulations were performed based on the DRYCOLD weather file, representing a TMY with cold winter and hot summer temperatures. In order to draw conclusions on the suitability of ICF construction method for the UK climate, it is essential to repeat the simulations for weather data provided for an Actual Meteorological Year (AMY) for the UK climate.

CONCLUSIONS

ICF is classified among the site based MMC due to its innovative approach of house building. Previous studies have shown that ICF has several advantages associated to its structural strength, its durability, its fire resistance and so on. The analysis presented in this paper was focussed on the thermal performance of ICF and its energy saving potential. An inter-model comparative analysis was conducted on the simulation results provided by five widely known BPS tools, aiming to interrogate the tools' ability in estimating the system loads and the internal temperatures of an ICF building. The input data were rigorously specified for all five BPS tools. In order to eliminate the user uncertainty, all simulations were conducted by the same person. The inconsistencies in the simulation results were found to be higher in the annual and peak heating demand, while they were insignificant for the annual and peak cooling demand. In the comparison between ICF, the low mass and the high mass building cases, ICF showed significantly reduced energy consumption for space conditioning compared to low mass construction and slightly increased energy use compared to high mass construction. The results of the free-floating analysis (no space conditioning) showed that ICF is able to provide a stable internal environment, with reduced internal temperature fluctuations compared to a lightweight building. Finally, the ICF wall assembly, when compared to a timber-framed wall construction with equal levels of insulation (same U-Value) shows a 15% reduction on the annual heating demand and a 10% reduction on the peak heating loads due to its inherent thermal mass in the concrete core.

FUTURE WORK

This work is the first part of a doctoral research project seeking to investigate the thermal behaviour of heavyweight construction methods, including ICF and to quantify the effects of thermal mass in low carbon building design (Mantesi et al, 2015). A monitoring study of an actual ICF building case is planned, and is expected to provide valuable information on both the energy consumption and the thermal performance of the ICF. Moreover, it should provide useful feedback on the accuracy of the BPS predictions.

ACKNOWLEDGEMENTS

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Table 5
Building fabric construction details

CONSTRUCTION DETAILS							
Element (Outside – Inside)		K (W/mK)	Thickness (mm)	Density (kg/m^3)	Cp (J/kgK)	U-Value (W/m^{2}K)	Thermal Capacitance (kJ/m^{2}K)
INSULATED ROOF PANEL SYSTEM	Roof Decking	0.14	25	530	900		
	EPS Insulation	0.035	300	25	1400		
	Plasterboard	0.16	13	950	840		
	Total					0.1115	10.37
ICF & HIGH MASS FLOOR	Stone Bed	1.8020	300	2243	837		
	Wet Lean	1.73	50	2243	837		
	Membrane	0.19	5	1121	1674		
	EPS Insulation	0.035	350	25	1400		
	Concrete Slab	1.13	150	1400	1000		
	Total					0.0948	140.00
LOW MASS FLOOR	Stone Bed	1.8020	300	2243	837		
	Wet Lean	1.73	50	2243	837		
	Membrane	0.19	5	1121	1674		
	EPS Insulation	0.035	350	25	1400		
	Timber Flooring	0.14	25	650	1200		
	Total					0.0944	19.50
ICF WALL ASSEMBLY	EPS Insulation	0.035	210	25	1400		
	Cast Concrete	1.13	147	1400	1000		
	EPS Insulation	0.035	108	25	1400		
	Plasterboard	0.16	12	950	840		
	Total					0.1059	9.58
LOW MASS WALL	Wood Siding	0.14	9	530	900		
	EPS Insulation	0.035	210	25	1400		
	EPS Insulation	0.035	108	25	1400		
	Plasterboard	0.16	12	950	840		
	Total					0.1067	9.58
HIGH MASS WALL	EPS Insulation	0.035	210	25	1400		
	EPS Insulation	0.035	108	25	1400		
	Cast Concrete	1.13	147	1400	1000		
	Plasterboards	0.16	12	950	840		
	Total					0.1059	132.78

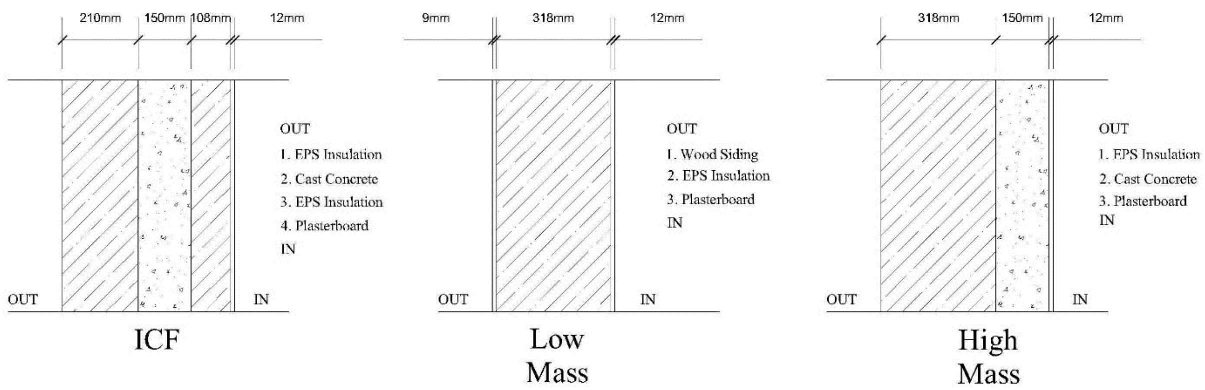

Figure 12: Cross-section of the three wall construction methods used in the analysis