PAPER

Housing Affordability Under the Microscope: Measuring Heat Transfer to Quantify Cost Versus Performance

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Residential energy consumption comprises the largest market sector in the US, totaling almost 40% of US energy sales[1]. Increasingly-advanced design tools for modeling assemblies, energy consumption, and embodied carbon have vastly changed the design and construction of high-performance housing and present a rich opportunity to reduce energy consumption through incorporation of energy efficiency measures in residential buildings. However, in the market sector of affordable, single-family housing, the value of implementing high-performance measures can be more difficult to assess. Frequently, housing "affordability" is addressed by simply reducing up-front construction costs. Consequently, one of the primary barriers to delivering high-performance homes in the affordable market is the additional up-front cost that these performance "upgrades" necessitate. This research theorizes that targeted increases in construction costs can enhance affordability when they are considered as a variable in the total cost of homeownership.

As part of an in-depth study and cost-benefit analysis of constructing homes to multiple beyond-code standards, this line of research studies heat transfer across key assemblies in a pair of houses built to two different beyond-code energy standards. The research team evaluated the cost to construct key envelope elements directly related to beyond-code performance improvements and considered the correlation between the cost to construct key details and impact on energy consumption. The team identified areas where significant heat loss could occur within the building envelope and selected locations where investments in beyond-code performance was greatest. Using remote sensors to monitor wall and floor surface temperatures and ambient interior and exterior temperatures, the team measured heat transfer through the assemblies relative to the energy required to condition the space.

Implementation of energy efficiency measures in affordable housing requires consideration of multiple factors beyond initial construction cost. This study analyzes key details and assemblies to gain a clearer understanding of thermal transfer through these assemblies to determine if reductions in construction cost and simplifying constructability can yield similar performance results.

INTRODUCTION

The residential sector is widely accepted as having the greatest potential for reduction in energy consumption, as it consumes 21.7% of US electrical use, the largest of any major end-use sector, and comprises almost 40% of US electricity retail sales[1]. In particular, single-family detached housing has the highest energy use of any housing type, primarily due to long service life and size of home[2]. Within the residential sector, space heating and space cooling consume the largest electrical loads, totaling 32% of residential energy consumption[1]. As a result, numerous studies point to efficiency upgrades to equipment producing thermal energy as priorities for decarbonization efforts.

In the affordable housing sector, the initial cost of construction is frequently minimized to maximize the number of units constructed, and, therefore, individuals housed. Decisions that reduce the initial construction cost can negatively impact long-term housing affordability through increased energy consumption and, consequently, utility costs. Conversely, improvements in building performance can lower operational costs and reduce energy cost burden as well as improve health outcomes and increase resilience in the face of uncertain energy and climate futures. The Institute for Market Transformation (IMT) has concluded that default rates on mortgages for ENERGY STAR-certified homes average 32% lower than for non-ENERGY STAR homes[3], suggesting that improved energy performance can contribute to a homeowner's economic stability. Furthermore, savings realized through improved energy performance can be shifted from an operational expense to investment in the asset of the home.

Previous research[4] investigated the cost to construct a pair of homes built in Opelika, Alabama,to two different beyond-code energy standards, Passive House Institute US (PHIUS) and the Department of Energy's Zero Energy Ready Home (ZERH), and then compared the cost of energy consumed to heat, cool, and ventilate each home. After three years of circuit-level energy monitoring, the research team concluded that increases in the initial cost to construct the home to the more stringent standard (PHIUS) could not be recovered by energy savings over the life of the mortgage.

Research detailed in this paper furthers the analysis of this pair of houses by investigating heat transfer through areas of the building envelope with the greatest difference in construction cost between the two houses. Comparing interior ambient temperature, exterior ambient temperature, and interior surface temperatures, the team evaluated the effectiveness of each insulation strategy and its applicability to future builds.

METHODOLOGY

This study was developed and executed by faculty in Auburn University's College of Architecture, Design and Construction (CADC) in partnership with Auburn Opelika Habitat for Humanity (AOHFH). A not-for-profit housing provider, AOHFH serves households at or below 80% of the area median income (AMI). Working in suburban and small-town settings in the mixed-humid climate of Alabama, AOHFH focuses on providing detached single-family housing. The partnership combined the resources of Auburn Opelika Habitat for Humanity with faculty and students from CADC's Architecture and Building Science programs.

Interdisciplinary design-build studios[5] constructed two versions of the same house, the prototype of which was originally designed by students at Auburn University Rural Studio[6]. The pair of houses was constructed on the same street, with similar solar orientations, to two different energy standards. House 66, completed in 2018, was built to the highest single-family residential energy standard at the time, Passive House Institute US (PHIUS). In 2019, a second studio analyzed the assemblies and detailing of the PHIUS home to evaluate where construction costs could be reduced while maintaining performance. The resulting project, House 68, was adapted the home to meet DOE's Zero Energy Ready Homes (ZERH) standard. To eliminate any financial risk to AOHFH, extra costs to construct the homes to elevated energy performance levels were covered through grants and contracts secured by Auburn University.

The desired performance outcomes of ZERH are similar to PHIUS requirements, but the ZERH standard is more descriptive in nature, providing more flexibility in detailing and material selection. While each house utilized the same floor plan, the assemblies varied as required to meet each performance standard. Below is a brief summary of the key envelope and systems utilized in each of the homes, as well as the air tightness and Home Energy Rating System (HERS) Index Score achieved:

ASSEMBLIES AND SYSTEMS

House 66 (PHIUS) has an elevated slab foundation with R-24 underslab insulation and an R-15 thermal break between the stem wall and slab, R-33 walls with both cavity and continuous insulation, and a vented attic with R-62 insulation at the ceiling plane. The HVAC system consists of a ductless mini split system, balanced ventilation provided by an energy recovery ventilator (ERV), and an in-wall dehumidifier. Hot water is produced in a heat pump water heater. Final air tightness was measured as 0.37 ACH50, and the home received a HERS Index Score of 38.

House 68 (ZERH) has an elevated slab foundation with no underslab insulation, an R-5 thermal break between the stem wall and slab, R-29 walls with both cavity and continuous insulation, and a vented attic with R-46 insulation at the ceiling plane. The HVAC system consists of a ductless mini split system, balanced

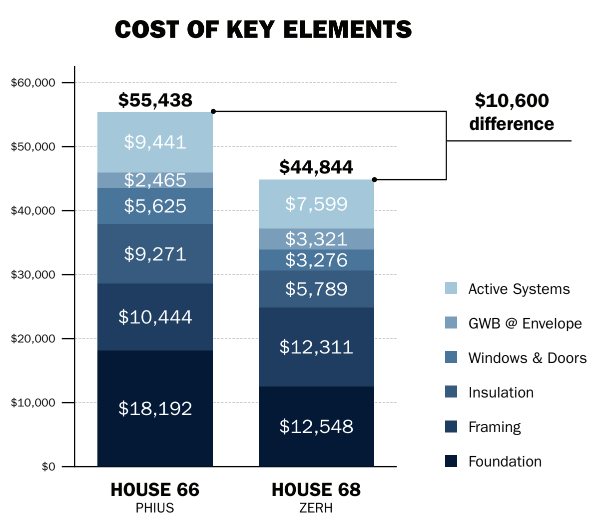

Figure 1. Comparative costs of key assemblies. Image credit CADC.

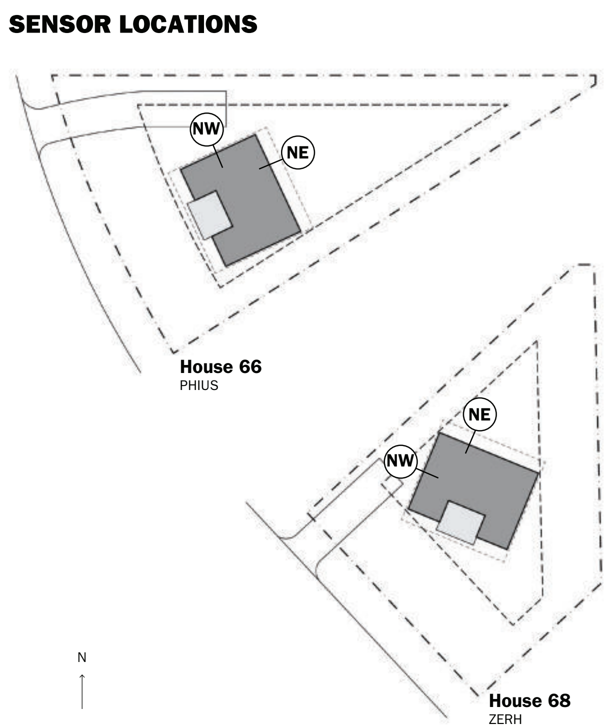

Figure 2. Key plan of sensor locations. Image credit CADC.

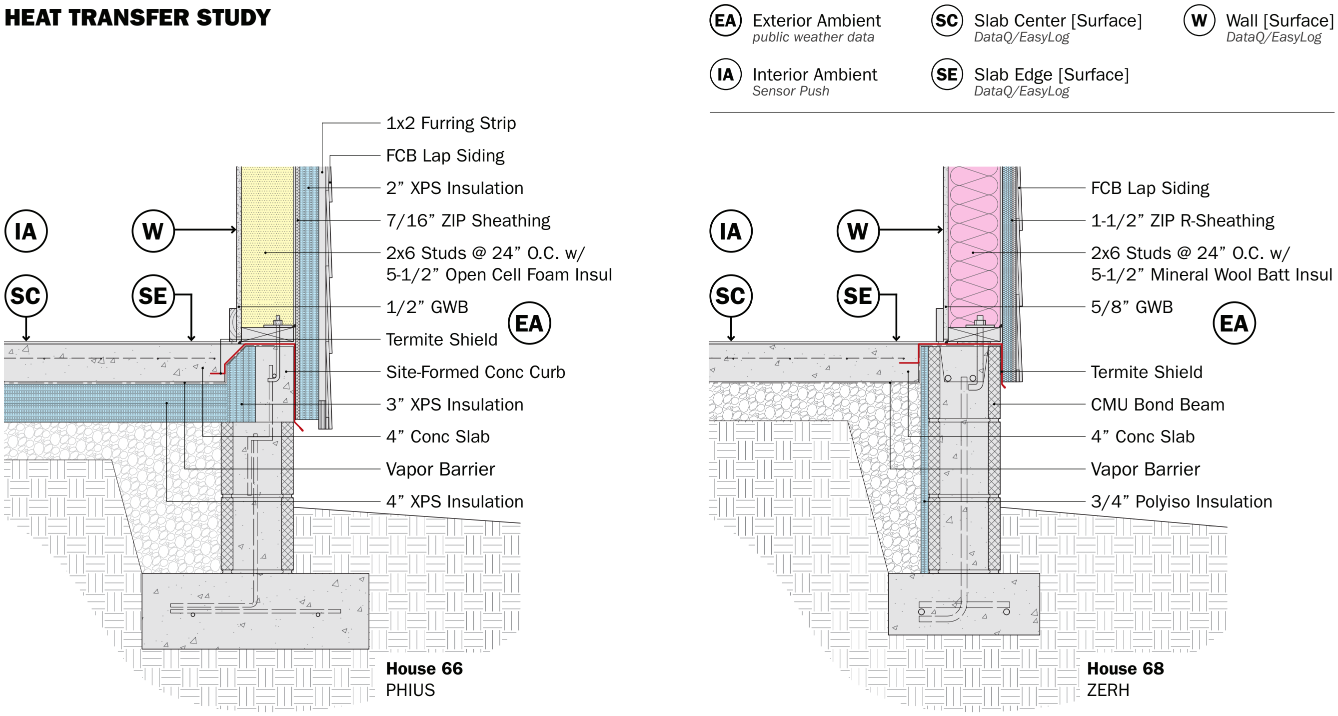

Figure 3. Key of sensor locations. Image credit AU CADC.

ventilation provided by an ERV, and an in-wall dehumidifier. Hot water is produced in a heat pump water heater. Final air tightness was measured as 1.76 ACH50, and the home received a HERS Index of 40.

While House 68 meets the ZERH standard, it is not representative of other ZERH-certified houses. Because the faculty-student team elected to design House 66 to the most stringent standard of PHIUS, the subsequent design of House 68 to ZERH aimed to reduce cost and complexity while maintaining a similar level of energy performance. The team identified the House 66 details and assemblies required to meet PHIUS that would prove costly and challenging to a volunteer-based non-profit housing developer, for example, 4” of underslab insulation with a 2” upturn at the edge of slab providing a thermal break and compressing the stem wall width. This detail necessitated a site-formed concrete curb to support the wood stud wall. In House 68, this detail was reduced to a simple ¾” thermal break between the slab and an 8” CMU stem wall. Constructability and sequencing in House 68 were aligned with a more typical AOHFH build.

For Houses 66 and 68, the research team ensured each house met the respective energy standard through a four-step process: 1) computational modeling to work through various assemblies, 2) testing the air tightness of the envelope at critical points during construction, 3) verification of final performance through independent third-party raters, and 4) monitoring energy consumption at the circuit level to track energy consumption. With the permission of the homeowners, the research team installed monitoring equipment in each home that provides hourly circuit-level information on energy use. The research team monitored energy consumption remotely using SiteSage, a web-based interface. This process yielded three data sets for analysis: cost to construct, model-predicted energy consumption, and measured energy consumption.

Construction costs were tracked and documented for the key assemblies most related to conditioning and ventilating the homes, excluding costs of scope unrelated to performance. Building elements relevant to thermal energy consumption include:

- Foundation
- Framing
- Insulation
- Fenestration
- Gypsum board at envelope
- Active systems, including HVAC equipment

The previously published initial study[7] included the cost breakdown for these building elements shown in Figure 1. The largest differences between the two homes occurred in the Foundation and Insulation categories. For underslab and slab edge insulation alone, the material cost for House 66 totaled $3,175 compared to $220 for House 68.

As part of this study, the research team conducted focused investigations into the performance of specific elements of those two assemblies to correlate the energy savings associated with those elements. Because previous research identified foundations and insulation as having the largest construction cost difference, the team collected temperature data at key points

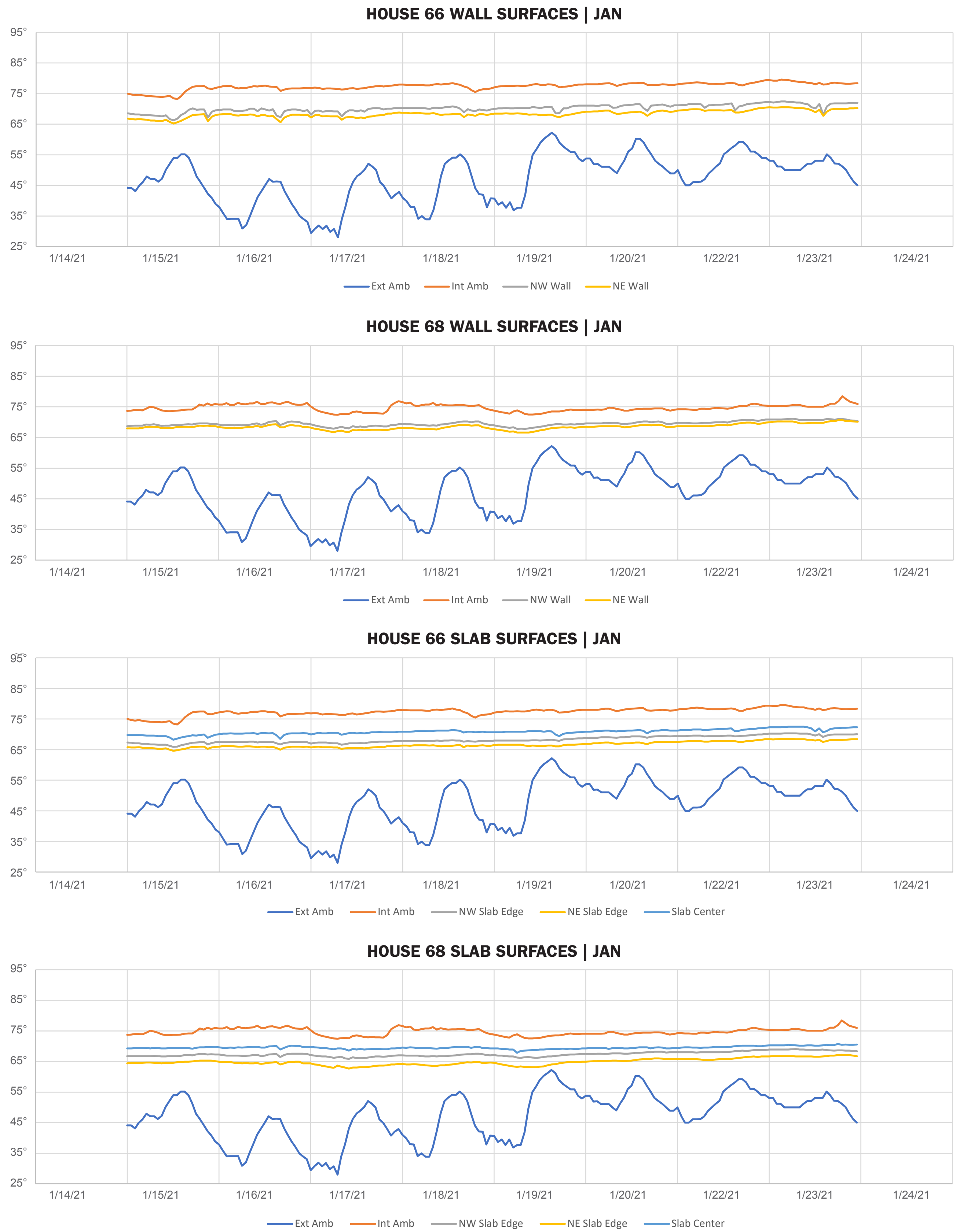

Figure 4. Interior ambient, interior surface, and exterior ambient temperatures measured in January 2021. Image credit CADC.

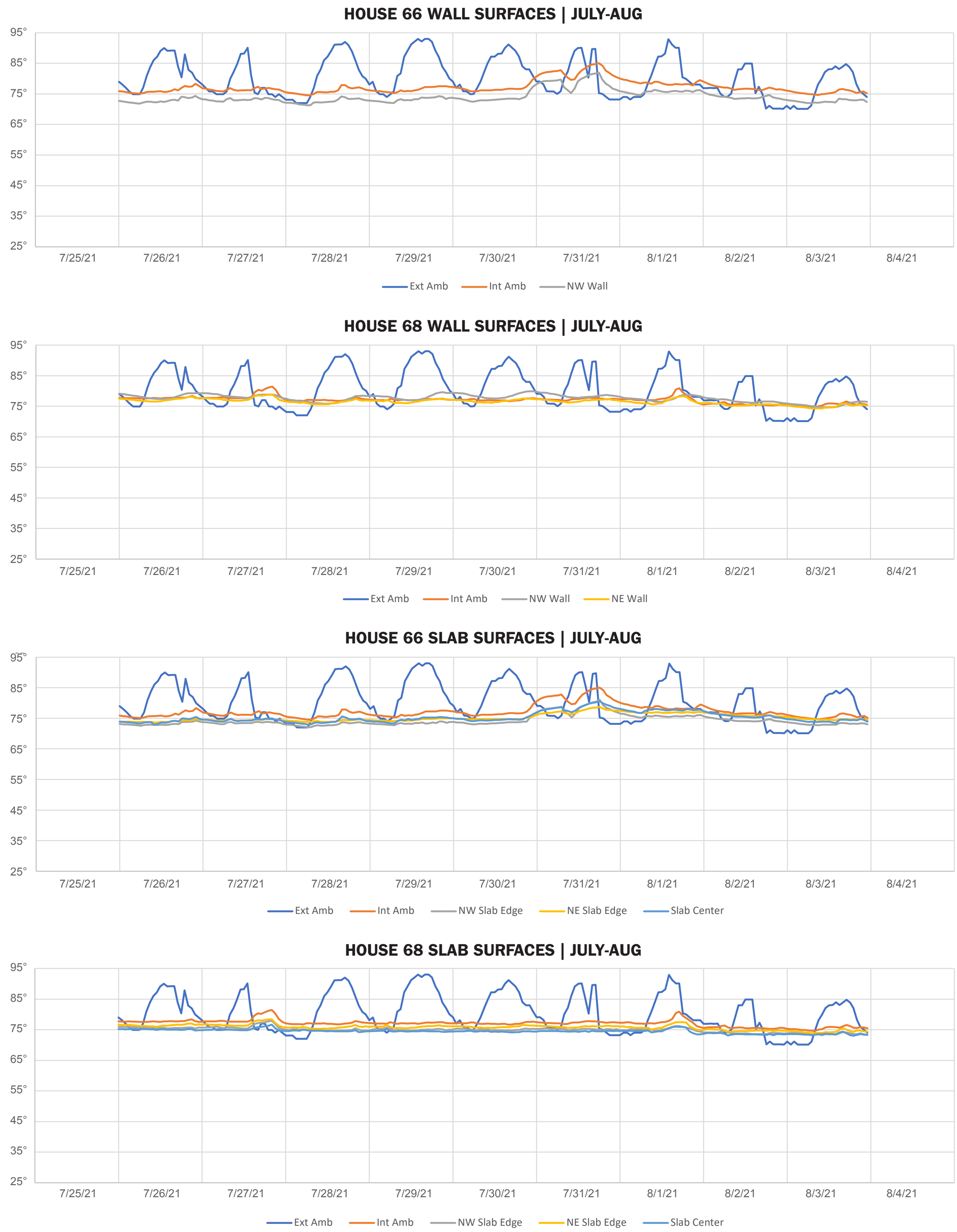

Figure 5. Interior ambient, interior surface, and exterior ambient temperatures measured in July-August 2021. Image credit CADC.

in the wall and slab edges with the goal of understanding heat flows across the wall and floor assemblies. DATAQ surface temperature sensors mounted at the base of the wall, on the floor nearest the exterior wall, and on the floor nearest the center of the house registered indoor surface temperatures. Figures 2 and 3 illustrate sensor locations in plan and on each wall section. A SensorPush ambient temperature sensor logged interior temperature to track thermostat setpoints, and hourly exterior ambient temperature data was downloaded from weather.gov.

Two time periods were selected for study: one week with the coldest exterior ambient temperatures of the winter of 2021 and one week with the warmest exterior ambient temperatures in the summer of 2021. The study duration of a week was selected to discern overall trends, track daily variations in temperature, and account for thermal lag.

The study did not account for variables such as the number of occupants and the variability of occupant behavior, of which the influence on results is recognized. Additionally, the research team acknowledges the limitations inherent in a small sample set.

RESULTS

The research team hypothesized that differences between interior and exterior surface temperatures at key points in the floor and wall assemblies of each home could be analyzed to infer each assembly's resistance to heat transfer. Additionally, the research team aimed to gain a more nuanced understanding of the efficacy of a fully insulated slab in comparison to a thermally broken slab, as energy modeling provided limited insight on this topic.

Figure 4 illustrates the measured temperatures for each house during the week of January 15-22, 2021 (cold weather). Figure 5 displays the same locations for the week of July 25-August 4, 2021 (warm weather).

In the cold weather graphs (Fig. 4), neither slab nor wall surfaces are registering broad temperature fluctuations, suggesting that insulation strategies in both houses are successful. However, the gap between interior ambient and interior surface temperatures is greater in House 66 (PHIUS) than in House 68 (ZERH). This could be attributed to the slightly higher interior ambient temperature in House 66, which create a larger temperature difference (ΔT) between interior and exterior ambient temperatures. Considering interior surface temperatures only, the houses return similar results even though the interior setpoint is higher in House 66. This suggests the wall and slab assemblies are performing comparably relative to heat transfer.

In the warm weather graphs (Fig. 5), interior wall surfaces in House 66 were consistently colder than the indoor ambient temperature while, in House 68, interior wall surface temperatures tracked closely with indoor ambient temperature. Distribution of interior ambient and interior surface temperatures was similar for slabs in both houses. The research team attributed the cooler wall surface temperatures in House 66 to the occupants' tendency to leave the insulated front and rear doors open and instead utilize uninsulated storm doors for enclosure, adding more thermal load and causing the HVAC system to cool the walls more while maintaining a consistent interior setpoint. The slightly higher temperature of the northwest wall in House 68 can be attributed to late afternoon solar gain.

From an energy use standpoint, the measured data reveals that the additional construction cost invested in House 66 does not result in corresponding energy savings related to heating and cooling the interior. In fact, the significant investment in slab edge insulation and underslab insulation at House 66 yields very little difference in measured temperatures as compared to House 68 and suggests minimal difference in the heat transferred through the wall and slab. Moreover, data from this limited sample size suggests that the performance of the slab edge insulation in House 68 is as effective at limiting thermal transfer as the fully isolated slab in House 66. For reference, 2015 IECC, code baseline at the time of construction, did not mandate edge of slab insulation for Climate Zone 3; 2021 IECC has since incorporated a minimum requirement of R-10.

When evaluating the energy used by the mini-split systems to maintain steady interior ambient temperatures, House 66 does consume less energy overall than House 68 and exhibits fewer spikes in consumption. However, the energy cost savings are not commensurate to the cost premium needed to achieve the more robust assembles at House 66.

CONCLUSIONS

Heat can be transferred through the slab, walls, ceiling plane, windows and doors, and through infiltration. The research team tracked energy transfer across the slab and wall assemblies and learned that the two houses in this comparative study—though constructed in significantly different methods—are performing relatively analogously. The edge of slab does not appear to be the primary path for heat transfer and does not justify the added material cost and complexity of construction of the foundation detail in House 66.

This narrowly scoped study focused on improvements to building assemblies due to their length of service compared to that of equipment and systems. The research study provides tangible data for understanding the impact of performance improvements to the building envelope and will serve to inform the team's work with other housing provider partners. . The team will continue to rely on energy modeling to inform material selections and plans to expand the monitoring of energy consumption and interior temperatures into other climate zones. While the methods of the study are transferable and the knowledge is expandable beyond this pair of houses, the findings are climate dependent.

ENDNOTES

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5. The student team for House 66 included: Spring Studio- Lauren Ballard, Meghan Bernhardt, Fox Carlson, Emma Clark, Katherine Ferguson, Jed Grant, Haley Hendrick, Jeff Jeong, Mary Ma, Kate Mazade, Ashley Mims, Walker Reeves, Rowland Sauls, Jordan Staples, and Matthew Wigard. Summer Seminar- Heath Barton, Emma Clark, Noah Dobosh, Melissa Ensley, John Going, Mason Handey, Dee Katoch, Mack Mahoney, Ashley Wiley, Joshua Williams, and Valencia Wilson. The student team for House 68 included: Spring Studio – Clare Bruce, Justin David, Ozzy Delatorre, Adam Fehr, Jonathan Grace, Emily Hiester, Dongting Huan, Reeed Klimoski, Mingtao Liu, and Emma Porter. Summer Seminar – Erik Aguilar, Carol Allison, Craig Baker, Elizabeth Bowman, Caty Bowman, Zack Burrogh, McClean Gonzalez, Davis Johnson, Emme Mora, Karmon Sullivan, and Nieman Ugbesia.The faculty team for House 66 & 68 included Professors David Hinson and Mackenzie Stagg (Architecture) and Professor Mike Hosey (Building Science). The consultant team included David Bitter, CPHC; Bruce Kitchell, PHIUS+ Rater; and Alexander Bell, energy modeler. The team also received generous assistance from Mark Grantham, Executive Director of Auburn Opelika Habitat for Humanity; Jaqueline Dixon, Contractor of Record; Rob Howard of Mitsubishi Electric Heating & Cooling; Alex Cary and Warner Chang from the Institute of Business and Home Safety (IBHS); and Eric Oas of Oasis Heating and Air.
6. Buster's Home was designed and built by a team of 5th-year architecture students at Auburn University Rural Studio in 2017. The student design team for Buster's Home included Olivia Backer, Carley Chastain, Ben Malaier, and Janine Mwenja. The Buster's House prototypes in this study are based on this design.
7. The initial study also presented two years of the modeled and actual energy consumption for each home and summarized the average monthly energy use for each home. Because it is most directly affected by modifications to the building envelope and less dependent on occupant behavior, analysis focused on the cost of energy required to heat, cool, and ventilate each home. The research team's findings showed that the added cost to construct key assemblies, calculated as a cost premium on the monthly mortgage payment equaling $44, vastly exceeded the monthly energy savings of $6.52 returned by the PHIUS house compared to the ZERH.