Resilience to climate change in buildings: Rethink the role of building enclosure to alleviate cold stress in warmer climate

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Abstract

Climate change with extreme weather conditions impacts on the building sector significantly. Especially, building occupants are vulnerable since our buildings lack of resiliency for such changes. In this paper, we simulate a typical single family house under possible power outage scenarios during the Winter Storm Uri in Texas. Local building codes are investigated to various residential building types in the North Texas area. By calculating heating energy consumption and indoor air temperature in a building, we evaluate building resiliency to balance between energy efficiency and occupant comfort with our new metric (energy to comfort ratio). Our study envisions what is necessary to change in residential buildings to prepare against the forthcoming challenges of climate change.

Introduction

In recent years, we have experienced climate change in the built environment (e.g., global warming, extreme weather events). Especially, weather and climate disasters have caused a situation where people rarely or never experienced before (e.g., cold stress in warmer climate regions). The building industry takes a significant responsibility to correspond the change as people spend the majority of time indoors and consume energy to maintain our comfortable indoor environment.

In February 2021, the Winter Storm Uri affected to Texas significantly. Due to the high demand, approximately 10 million Texans were forced to stay without electricity. Subsequently, they were not able to operate their mechanical heating systems while some of them relied on unusual heating methods (e.g., using ovens to heat, burning furniture), resulting in house fire and carbon monoxide poisoning. In February 2022, the Texas Department of State Health Services reported a total of 246 people who died by the winter storm.

Fundamentally, there are two approaches to maintain our thermal comfort against cold stress in buildings: 1) providing heating energy to the indoor environment using mechanical systems, and/or 2) minimizing heat loss through building enclosure. Although the two are equally important in buildings, the role of building enclosure (e.g., insulation, fenestration) should be even more emphasized during the situation where the mechanical systems are unavailable (e.g., the extreme scenario of power outage).

In this paper, we model a typical residential home in the North Texas area. Acquiring the actual meteorological year data of 2021, we simulate the building performance with the realistic power outage scenarios during the winter storm. We test four different building enclosure sets to evaluate how different constructions would perform to maintain occupant comfort in a building without the full power supply during the winter storm.

Methodology

We developed a prototype model from a compact single family house for 3 occupants in the North Texas area (Figure 1). The size of the model is $12m \times 8m$, and it includes two small windows on each side. We select our building location at Dallas (Texas), which is categorized as hot-humid climate. According to the U.S. energy administration residential energy Consumption survey, 70% of households used electricity for space heating, so we used power based fan-coil unit in our simulation. Air-change was simulated by exhaust ventilation (only ideal version has heat recovery ventilation, and this did not affect indoor temperature simulation as power outage for ventilation was also off). Building internal loads and usage profiles followed the U.S. Department of Energy (DOE) reference building and ASHRAE 90.2 standards. It is important to mention that during power outage time the lighting and all appliances were off and

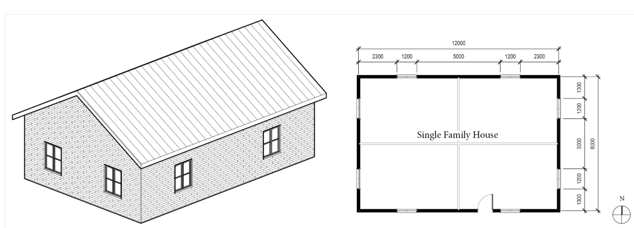

Figure 1: A typical compact single family house in the North Texas area

did not contribute any internal loads.

We used IDA Indoor Climate and Energy dynamic simulation calculation tool (IDA ICE) for our simulation study. This tool allows detailed and dynamic building simulations of indoor climate, energy consumption and building performance. The software has been validated according to European Standard CEN 13791, Thermal Performance of Buildings – Calculation of Internal Temperatures of a Room in summer without Mechanical Cooling – General Criteria and Validation Procedures (Kropf and Zweifel, 2001).

Building enclosure selections

For the best estimation of existing building enclosure types for Texas homes, we investigated the required code for single family house construction. In Texas, there was no mandatory statewide building energy code prior to 1999. On September 1, 2001, State Energy Conservation Office (SECO) adopted 2000 International Energy Conservation Code (IECC) with 2001 supplement until 2011. In the beginning of 2012, SECO finally used 2009 International Residential Code (IRC) and updated 2015 version in 2016 (International-Code-Council, 2009).

To cover both newly built and older existing homes (e.g., 10 years old), we assigned 2009 and 2015 IRC code on our model home to evaluate their performance against the winter storm. Although the two codes describe the minimum requirements for single family house construction in Texas, it is important to note that they are not the ideal ones under current extreme weather conditions. Therefore, we adopted practical building construction requirements for enclosure selection in colder climate regions (e.g., Nordic countries) (Simson et al., 2021). Last, we also considered the worst building enclosure selection in our study. In fact, the most affected occupants with cold stress are from low-income housings which are constructed by insufficient or even no insulation for buildings (e.g., no renovation more than 20 years). All four building enclosure selections (simulation inputs) are summarized in Table 1.

Table 1: Simulation input

	Worst	2009	2015	Ideal
Wall (W/m^2K)	1.6	0.44	0.28	0.15
Attic floor ($W/^2K$)	1.6	0.41	0.15	0.1
Ground floor (W/m^2)	2.2	0.3	0.3	0.3
Window (W/m^2)	3.7	2.84	1.7	0.8
SHGC	0.4	0.25	0.25	0.25
Infiltration ($50Pa$)	10	5	3	1
Ventilation rate (l/s^2)	0.48	0.48	0.48	0.48

Weather data and power outage scenarios

We used the climate file (AMY 2021), which is constructed by the OikoLab climate database measurements[1]. The weather on February, 2021 was extremely cold due to the winter storm. Figure 2 compares outdoor dry-bulb temperature of AMY 2021 and TMY3 in February, which confirms a significant difference during the winter storm period. Regarding heating-degree days (HDD), the comparison indicates 44% more HDD in AMY2021 (355) than TMY3 (245) by the balance temperature of 18°C.

Therefore, we focused on the coldest period during the winter storm (02/13 — 2/19) for our simulation. During this period, the households in Texas experienced intermittent power outages because of rolling blackout, which was intentionally conducted to shutdown electricity supply to manage the extreme demand. Depending upon the grid conditions, some households lost their power for 3 days continuously and others were supplied without any power lost. Based on the reference report (King et al., 2021), we developed 8 power outage scenarios (Figure 3). Scenario 1 is the worst case with total power outage of 3 days and Scenario 8 is the best without power outage. In addition, we varied scenarios

[1]https://oikolab.com/

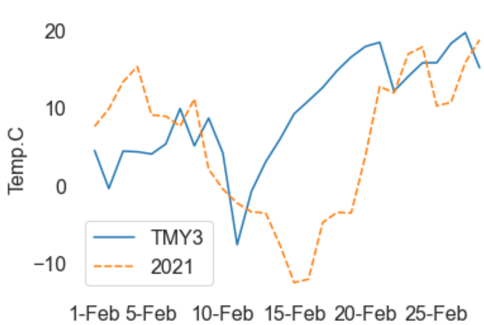

Figure 2: External dry-bulb temperature by TMY3 and 2021 in February in Dallas, Texas

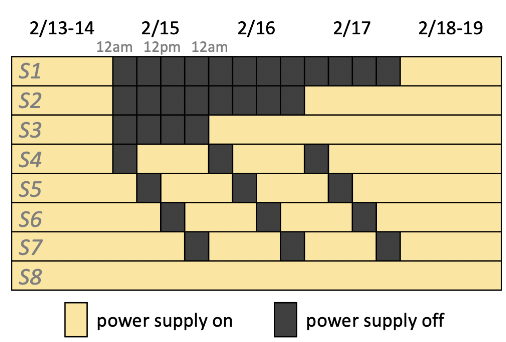

Figure 3: Power outage scenarios during the Winter Storm Uri

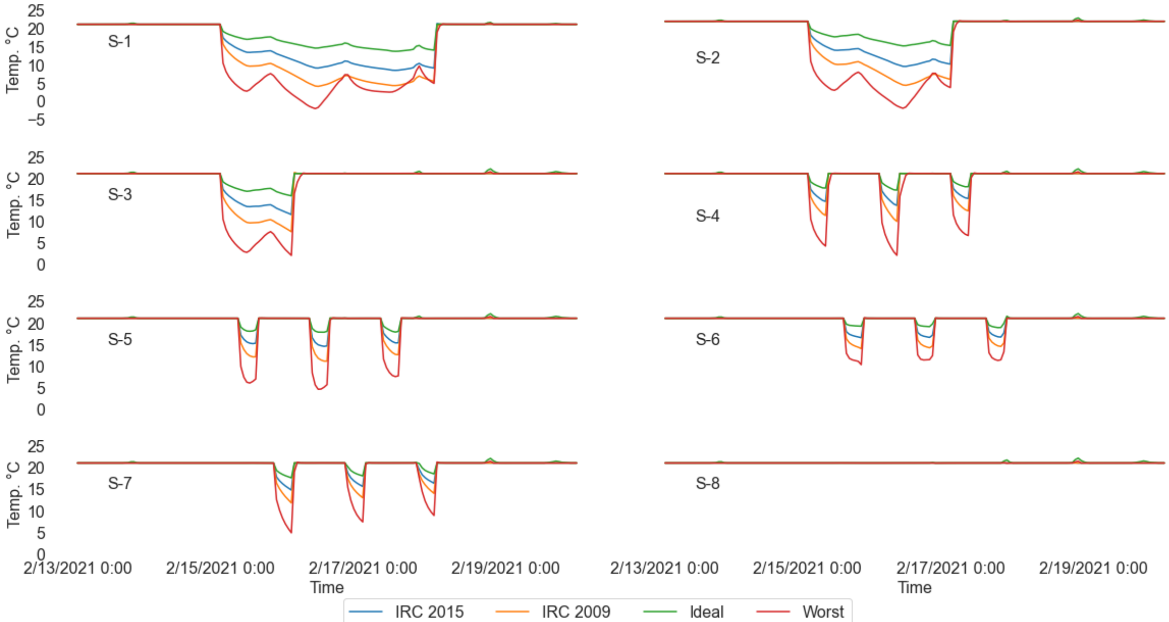

Figure 4: Indoor air temperature by different outage scenarios and building enclosures

to describe random power outages in the North Texas area. Scenarios 2 and 3 indicate 2 days and 1 day continuous power outages, respectively. Scenario 4, 5, 6, and 7 show different short power outage times during the winter storm period.

Evaluation metrics

To evaluate each enclosure type under 8 scenarios, we used three metrics to interpret our simulation results. Following the concept of Energy Use Intensity (EUI), we calculate heating energy consumption per its floor area (kWh/m^2) during the coldest period (1 week). Next, we evaluate occupant comfort by calculating unmet degree hours (°C·h) with the base temperature of 18°C.

Although the two metrics can evaluate energy and comfort, we added another metric to compare the ratio between energy and comfort (O'Brien et al., 2017) to capture both energy and comfort perspectives. To calculate the energy to comfort ratio (ECR), we first calculated heating energy consumption with the worst enclosure selection (Table 1) under Scenario 8 (Figure 3) and put this result as the maximum heating energy consumption (i.e., 14.2 kWh/m^2). Similarly, we calculate the total hours during the coldest period, which is 168 hours in our case. Then, we can calculate ECR as,

$$ECR = \frac{\frac{H_{met}}{168h}}{\frac{E_{heating}}{14.2kWh/m^2}} \quad (1)$$

where H_{met} and $E_{heating}$ are the total hours of comfortable range (i.e., indoor air temperature > 18°C) and the unit area heating energy consumption (kWh/m^2) during the coldest period, respectively. ECR is a dimensionless metric and higher ECR indicates consuming energy efficiently to maximize occupant comfort with respect to its worst case.

Results

Figure 4 shows the indoor air temperatures by different enclosure types and power outage scenarios during the coldest period. In all power outage scenarios (S1 — 7), the average temperature decreased rapidly, which could have serious consequences of cold stress in warmer climate. S1 with the worst enclosure selection (i.e., more than 20 years old low-income houses) reached as low as -2°C. With the same outage scenario (S1), the ideal enclosure selection keeps the indoor temperature almost $+14$°C. Our results also indicate that IRC 2015 raise the lowest temperature $+4$°C compared to IRC 2009. For the intermittent power outages scenarios (S4 — 7), the temperature drops were very rapid especially in nighttime or early in the morning (S4, 5, 7) while we could take some advantages of solar heat gain in S6.

We found similar outcomes in Figure 5 (right), where enclosure selection highly determines occupant unmet degree hours under every power outage scenario. Note that occupants theoretically did not experienced discomfort under S8. However, this also implies occupants have to consume a significant amount of energy (Figure 5 (left)). Especially for the worst building enclosure case, the heating energy consumption is relatively high even though they have some unmet degree hours

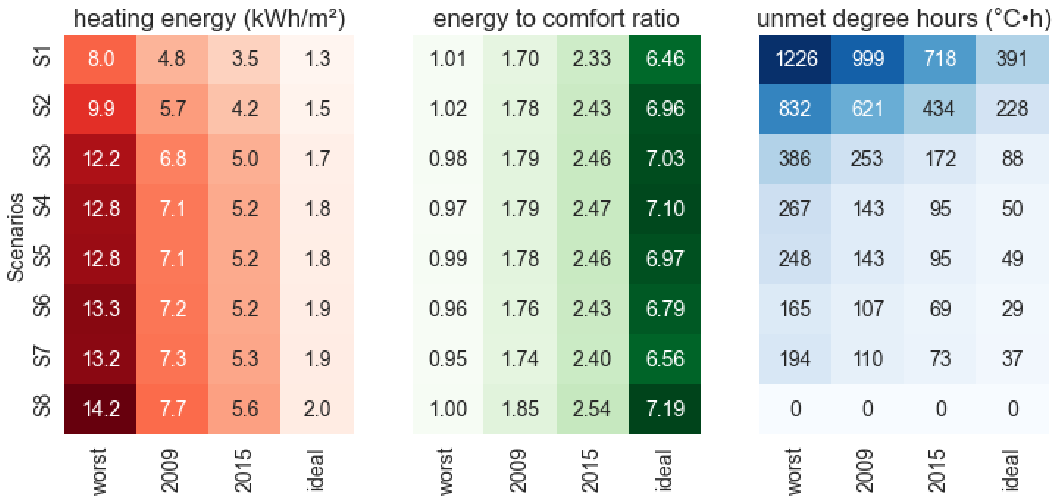

Figure 5: Simulation results for energy consumption (left), energy to comfort ration (middle), and comfort (right)

(S3 — 7). This clearly suggests that the critical energy consumption by mechanical heating system is not well protected against heat loss through building enclosures. For the ECR calculation (Figure 5 (middle)), we found the highest ratio numbers in the ideal building enclosure selection regardless of power outage scenarios. Again, this means building enclosure selection takes an important role for building resiliency under extreme weather conditions and associated power outages.

Discussion

In chapter 4 of IECC, provisions have kept being updated through the qualitative analysis for actual building code developments (Mendon et al., 2015). This change may have an impact on energy efficiency of the specific building types. As the proposals are based on several prototype building simulations with an average weather data, researchers and policy makers need to consider climate change and extreme weather scenarios for the code change determination. Furthermore, our results may suggest for local architects to consider serious weather conditions as they have critical roles to choose building envelope assemblies to maintian occupant comfort.

Although our paper clearly presents the implication of building enclosure under the winter storm in Texas, it is important to highlight that extreme weather conditions (e.g., heat wave, winter storm) exist everywhere on the earth. Therefore, our future study will investigate the performances of various existing enclosure composites from the building industry to identify their resiliency to extreme weather conditions. Furthermore, our developed metric (ECR) should be evaluated under various building types and locations toward the nationwide quantification of building energy saving and human comfort.

Acknowledgment

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