Thermal Resilience of Residential Building with Thermally Anisotropic Building Envelope Connected to Geothermal Sources

Zhenglai Shen, PhD
Associate Member ASHRAE

Som Shrestha, PhD
Member ASHRAE

Daniel Howard, PhD Student
Student Member ASHRAE

Diana Hun, PhD

Sven Mumme

Bandana Kar, PhD

ABSTRACT

Heat waves and cold snaps have become more frequent and more intense because of climate change. A heat wave and a cold snap are a period of excessively hot and cold weather, respectively, that poses severe risks to building occupants' health, especially for vulnerable people. They increase electrical energy consumption and put high stress on the grid which leads to potential power outages. Therefore, it is critical to assess and actively improve the thermal resilience of buildings to cope with heat waves, cold snaps, and power outages.

The thermally anisotropic building envelope (TABE) is a novel active building envelope that can save energy while maintaining thermal comfort in buildings by redirecting heat and coolness from building envelopes to hydronic loops. When connecting to a ground thermal loop (GL), TABE can utilize the relatively stable temperature of the ground to protect the indoor environment during heat waves and cold snaps. This study assesses the thermal resilience of residential buildings that installed TABE and used ground thermal energy to supply the hydronic loops, abbreviated as ground thermal loop or TABE+GL. The simulation and analysis are conducted for the US Department of Energy prototype single-family detached residential building in the hot climate of Miami, Florida and Tucson, Arizona, and the cold climate of Denver, Colorado, and Rochester, Minnesota. Heat waves and cold snaps were obtained from the historical weather data of 1998-2020 for the studied regions. Three thermal resilience metrics, including the standard effective temperature (SET) degree-hours, the Heat Index, and the Hours of Safety (HOS) were used to quantify the effect of TABE+GL. The results showed that buildings installed TABE+GL could significantly reduce the average SET degree-hours above 30°C, increase HOS, and greatly improve thermal resilience.

INTRODUCTION

Climate change, primarily caused by the release of greenhouse gases, is leading to increasingly extreme weather

Zhenglai Shen is R&D associate staff at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. **Som Shrestha** is senior R&D staff at ORNL. **Daniel Howard** is a PhD student at the University of Tennessee, Knoxville, working at ORNL. **Diana Hun** is senior R&D staff and the group leader of the Building Envelope Materials Research group at ORNL. **Sven Mumme** is Supervisory Management and Program Analyst at the US Department of Energy. **Bandana Kar** is an AAAS Science, Technology and Policy Fellow for building decarbonization in the Building Technologies Office at the US Department of Energy.

worldwide. The growing frequency of heatwaves, intense storms, and severe cold snaps places unprecedented strain on existing infrastructures and indoor thermal comfort. Previous research reported that the U.S. electricity customers faced slightly over 8 h of power outage on average in 2020 (Lindstrom and Hoff 2021). A recent study showed that 62.1% of 8+ h outages co-occur with extreme weather events, especially heavy precipitation, hurricanes, and anomalous heat (Do et al. 2023). Also, heat waves lead to more than 700 heat-related deaths and 9235 hospitalizations annually in the United States (The US Center for Disease Control and Prevention 2022), which is much higher than other types of disasters, such as hurricanes, floods, and wildfires. Extreme cold also poses a considerable threat (Texas Department of State Health Services 2021). Therefore, it is necessary to estimate existing buildings' thermal resilience and explore potential mitigation strategies.

Thermal resilience refers to the ability of a building to withstand, and more importantly, adapt to major disruptions owing to extreme weather conditions (Field et al. 2012). Recently, Hong et al. (Hong et al. 2023) explored ten questions on the thermal resilience of buildings aimed at providing insights into current and future research needs on thermal resilience assessment. The authors highlighted the importance of developing a practical standardized methodology for assessing thermal vulnerability and evaluating the benefits of passive and active technologies, as well as occupant behavioral strategies in improving thermal resilience.

Building thermal resilience studies can be classified into two categories: (1) the development of thermal resilience metrics and (2) thermal resilience assessment and improvement. Various thermal resilience metrics have been used and developed to assess the resilience of buildings. For building thermal resilience assessment under heat waves, the commonly used metrics include Indoor Overheating Degree, Ambient Warmness Degree, Standard Effective Temperature (SET), and Heat Index (HI) (Flores-Larsen et al. 2023; Homaei and Hamdy 2021; Ji et al. 2022). For building thermal resilience assessment under cold snaps, researchers have used SET and Hours Of Safety (HOS) (Sheng et al. 2023). A large amount of research efforts are focused on assessing building thermal resilience and comparing different mitigation strategies (Al Assaad et al. 2022; Borghero et al. 2023; Sheng et al. 2023; Sun et al. 2020). For example, researchers studied the effects of passive and active efficiency measures on improving the thermal resilience of a nursing house in Florida (Sun et al. 2020) and an assisted living facility in Texas (Sheng et al. 2023). The passive efficiency measures included building envelope insulation level, cool wall coating, window shading, natural ventilation and more; active efficiency measures included lighting controls, HVAC efficiency, ceiling fan, and plug load control. Similar efficiency measures were also adopted by other researchers to improve building thermal resilience.

Although passive and active efficiency measures have been increasingly studied, research lacks considering the effects of active building envelopes in building thermal resilience assessment. This paper fills that knowledge gap by focusing on assessing the thermal resilience of residential buildings that installed thermally anisotropic building envelope (TABE) using a geothermal source. A three-step, simulation-based thermal resilience assessment procedure was first developed. This procedure includes the preparation of heat waves and cold snaps, the selection of thermal resilience metrics, and the co-simulation of TABE with a ground loop (GL) using geothermal source energy, or TABE+GL for thermal resilience assessment. Case studies were conducted for the US Department of Energy (DOE) prototype single-family detached residential buildings in the hot climates of Miami, Florida, and Tucson, Arizona, and the cold climates of Denver, Colorado, and Rochester, Minnesota. The results showed that buildings installed TABE+GL could significantly reduce the average SET degree-hours above 30°C, increase HOS, and greatly improve thermal resilience.

METHODOLOGY

To estimate the thermal resilience of residential buildings installed with TABE+GL, a three-step, simulation-based assessment procedure is proposed as shown in Figure 1. In the first step (Step 1), weather files containing heat waves and cold snaps are prepared for the study regions. The heat waves and cold snaps are identified from historical weather data. In the second step (Step 2), the whole-building energy analysis is conducted for the prototype building with and without TABE+GL. During this step, the effects of a power outage are considered relating to the thermal resilience. Lastly, the third step (Step 3) analyzes the thermal resilience and quantifies the metrics of SET, HI, and HOS.

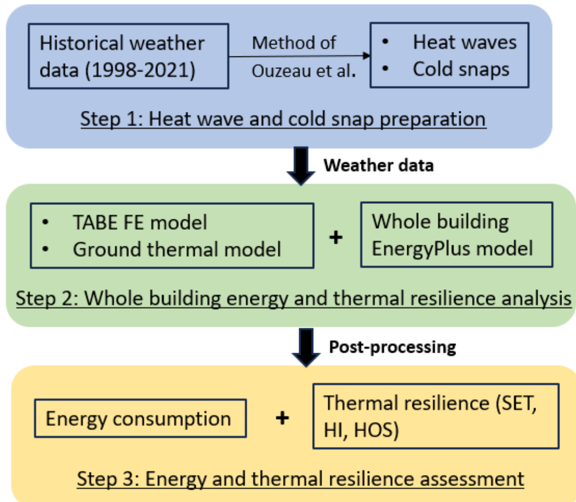

Figure 1 A three-step simulation-based thermal resilience assessment procedure for residential buildings installed TABE+GL

Heat Wave and Cold Snap

A heat wave, also known as extreme heat, is a period of abnormally hot weather lasting 3 days or more. A heat wave is usually measured relative to the normal climate and temperature in the area (Parmesan et al. 2022). The method developed by Ouzeau et al. (Ouzeau et al. 2016) was adopted in this work to identify extreme weather events. The method was based on the analysis of the mean daily temperature and the defined three temperature thresholds: T_{Hpic}, T_{Hdeb}, and T_{Hint}, which were computed as the 99.5th, 97.5th, and 95th percentiles, respectively, among a 30-year mean daily temperature. They were used to find the occurrence, start, and end of the extreme temperature event. A heat wave was found if the daily mean temperature reaches T_{Hpic}, whereas the start and end of a heat wave was determined by T_{Hdeb}. Additionally, two conditions: (1) the temperature below T_{Hdeb} for at least 3 consecutive days; and (2) the temperature below the T_{Hint} at any day were used as interruptions to a heat wave. If either of the two temperature conditions was detected, the heat wave was interrupted. A heat wave is usually characterized by its duration (number of days), intensity (the maximum mean daily temperature reached during the heat wave event), and severity (the aggregated mean daily temperature above T_{Hdeb}).
The study of cold snaps is relatively limited, and no particular method is used to define a cold snap. This study replicated the heat wave determination approach and used three temperature thresholds: T_{Cpic}, T_{Cdeb}, and T_{Cint} as the 0.5th, 2.5th, and 5th percentiles, respectively, among the 30-year mean daily temperature. Similar characteristic values such as duration, intensity, and global severity in heat waves are also applicable.

Whole Building Energy and Thermal Resilience Analysis of TABE+GL

The DOE prototype single-family detached house (U.S. Department of Energy 2018) complies with the International Energy Conservation Code (IECC) 2006 and was selected as the baseline building to assess the thermal resilience of TABE+GL. The baseline building was a two-story building, oriented toward the south and had a total floor area of 223 m^2 (2400 ft^2), as shown in Figure 2. For the HVAC system, it used an electric variable air volume reheat system, which was complemented by a heat pump for heating and cooling purposes. The setpoints for heating and cooling were 22.2°C (72°F) and 23.9°C (75°F) respectively. Additionally, the occupancy, lighting, equipment, and ventilation settings and schedules had been adopted from the prototype building (U.S. Department of Energy 2018).

For the building installed TABE+GL, the baseline building walls were replaced with TABE wall panels (Figure 2). The TABE wall panels used nominal 5.0 × 10.1 cm [2 × 4 in.] wood studs spaced at 40.6 cm [16 in.] on the center. It comprised five layers: an interior 1.3 cm [0.5 in.] gypsum board, fiberglass bat insulation in the cavities, two layers of 1.3 cm [0.5 in.] polyisocyanurate insulation, and exterior horizontal vinyl siding. The R-values of the panels were 1.88 W/(m^2·K) (10.65 [h·ft^2·°F]/Btu) and 2.76 W/(m^2·K) (15.62 [h·ft^2·°F]/Btu) for ASHRAE climate zones 1 and 2 and 5 and 6, respectively, which met the IECC 2006 requirements. Interior and exterior thermal loops (ILs and ELs) were integrated into the TABE using thin aluminum sheets to accelerate the heat dissipation rates. The ground heat exchange system, modeled in EnergyPlus, used two boreholes each with a depth of 110 m to enable the ground to water heat exchange. Supplying geothermal source energy to the TABE through the GL could be served by two purposes depending on the geothermal source temperature (close to a constant when the ground depth is larger than 6.1 m [20 ft] (Xing et al. 2017)). First, when activating the EL, it functions as an active barrier, separating the indoor environment from the outdoor environment. Second, when activating the IL, it can serve as a source for heating or cooling to regulate the indoor environment's temperature. In essence, the TABE+GL enables the building envelope to proactively respond to the outdoor environment. The thermal loops were closed water loops and a pump with input power of 33.1 W was used to circulate water in it. When there is a power outage, a backup battery was used to run the pump. The TABE was developed to enhance the thermal management of the building envelope (Biswas et al. 2019a; b; Shrestha et al. 2020). Also, the finite element model (FEM) of TABE was calibrated by using the field evaluation data (Howard et al. 2023) and a machine learning assisted method was developed to predict the heat flux of TABE wall using geothermal source (Shen et al. 2023). The details of the heat balance and finite element modeling can be found in (Howard et al. 2023; Shen et al. 2023).

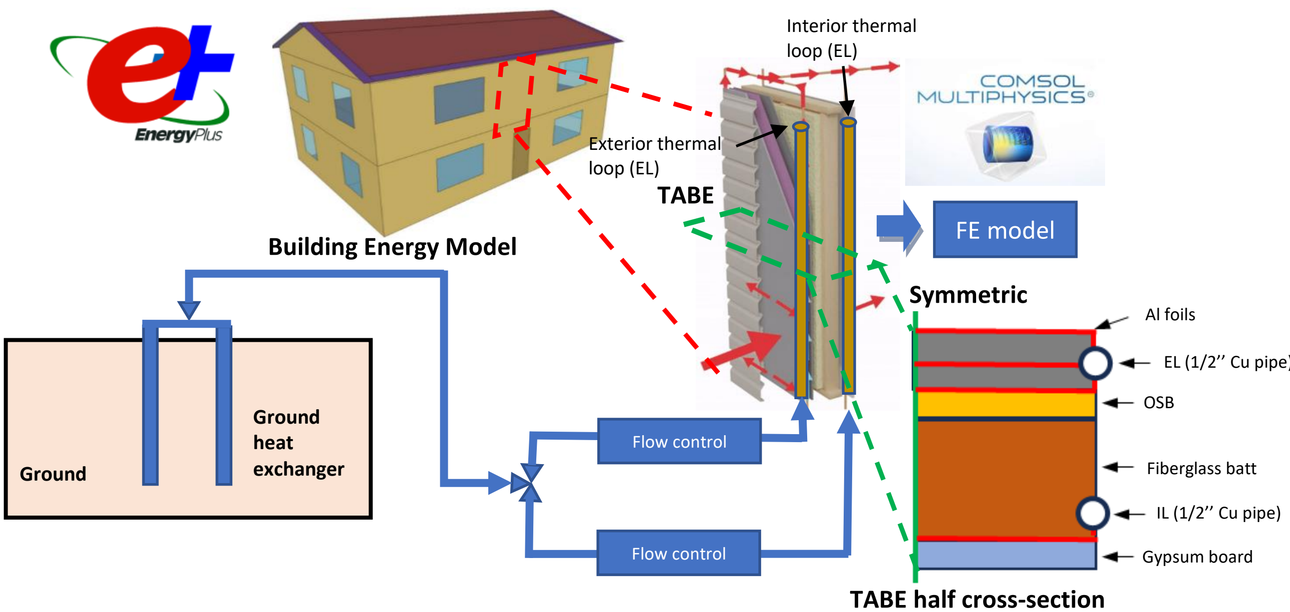

Figure 2 Co-simulation of TABE+GL with whole building energy analysis

Thermal Resilience Metrics

The thermal resilience metrics used in this study, included SET, HI, and HOS. SET is a comprehensive comfort index based on heat-balance equations and considers relative humidity, mean radiant temperature, air velocity, the anticipated activity rate and clothing levels, which are suitable to assess the thermal resilience during both hot and cold

events. ASHRAE 55-2010 defines SET as "the temperature of an imaginary environment at 50% relative humidity, < 0.1 m/s (0.33 ft/s) average air speed, and mean radiant temperature equal to average air temperature, in which total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level" (ASHRAE 55 2012).
HI combines air temperature and relative humidity to calculate a human-perceived equivalent temperature. The US Occupational Safety and Health Administration (OSHA) uses HI as an indicator to assess heat stress (OSHA 2008). Four heat stress levels were defined: caution, extreme caution, danger, and extreme danger as shown in Table 1. EnergyPlus can output the HI Hours (accumulated hours for a space) and HI occupant hours (accumulated hours for the sum of all occupants in a space) of each level for each zone.

Table 1. Definition of four HI levels

HI	HI Level
Less than 26.7°C (<80°F)	Safe: no risk of heat hazard
26.7°C – 32.2°C (80°F – 90°F)	Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32.2°C – 39.4°C (90°F – 103°F)	Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
39.4°C – 51.7°C (103°F – 125°F)	Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
Over 51.7°C (>125°F)	Extreme danger: heat stroke is imminent.

HOS was developed by the US Environmental Protection Agency and the Rocky Mountain Institute to estimate how long a building is in safe conditions before reaching unsafe indoor temperature levels (Ayyagari et al. 2020). It uses predefined cold stress temperature thresholds to indicate safe and unsafe levels for vulnerable and healthy populations (see Table 2). For example, an indoor air temperature above 17.78°C is safe for all populations, but below this temperature is unsafe for vulnerable populations. When temperature drops below 4.44°C, is the conditions are severe for all populations because of the increased hypothermia risk. The HOS metric is simple and easily obtained through post-processing the indoor air temperature results obtained by EnergyPlus simulations.

Table 2. Cold stress levels for HOS (Ayyagari et al. 2020)

Cold stress levels	Indoor air temperature
Safe for all populations	Above 17.78°C (>64°F)
Unsafe for vulnerable populations	Below 17.78°C (<64°F)
Mild for healthy populations	10°C – 15.56°C (50°F – 60°F)
Moderate for healthy populations	4.44°C – 10°C (40°F – 50°F)
Severe for healthy populations	Below 4.44°C (<40°F)

In this study, HI and SET were used for heat wave while HOS and SET were used for cold snaps. The reason for using HI and SET for heat waves is because HI is a more comprehensive index categorized as safe, caution, extreme caution, danger, and extreme danger based on different temperature ranges, while SET has only one threshold. Similar reasoning applies to the use of HOS and SET.

RESULTS AND DISCUSSIONS

Heat Waves and Cold Snaps

This study used the historical weather data from the National Solar Radiation Database from the National Renewable Energy Laboratory. It includes 23 years of data from 1998 to 2021 for various locations in the United States. Using the method from Ouzeau et al. (Ouzeau et al. 2016), the heat waves and cold snaps for Miami, Florida; Tucson, Arizona; Denver, Colorado; and Rochester, Minnesota, as shown in Figure 3. The selected heat waves and cold snaps have a duration of one week. The peak air temperature of Miami is much lower than in Tucson, but Miami has a much higher relative humidity at around 70%. This elevated humidity level can create discomfort for people in the indoor environment.

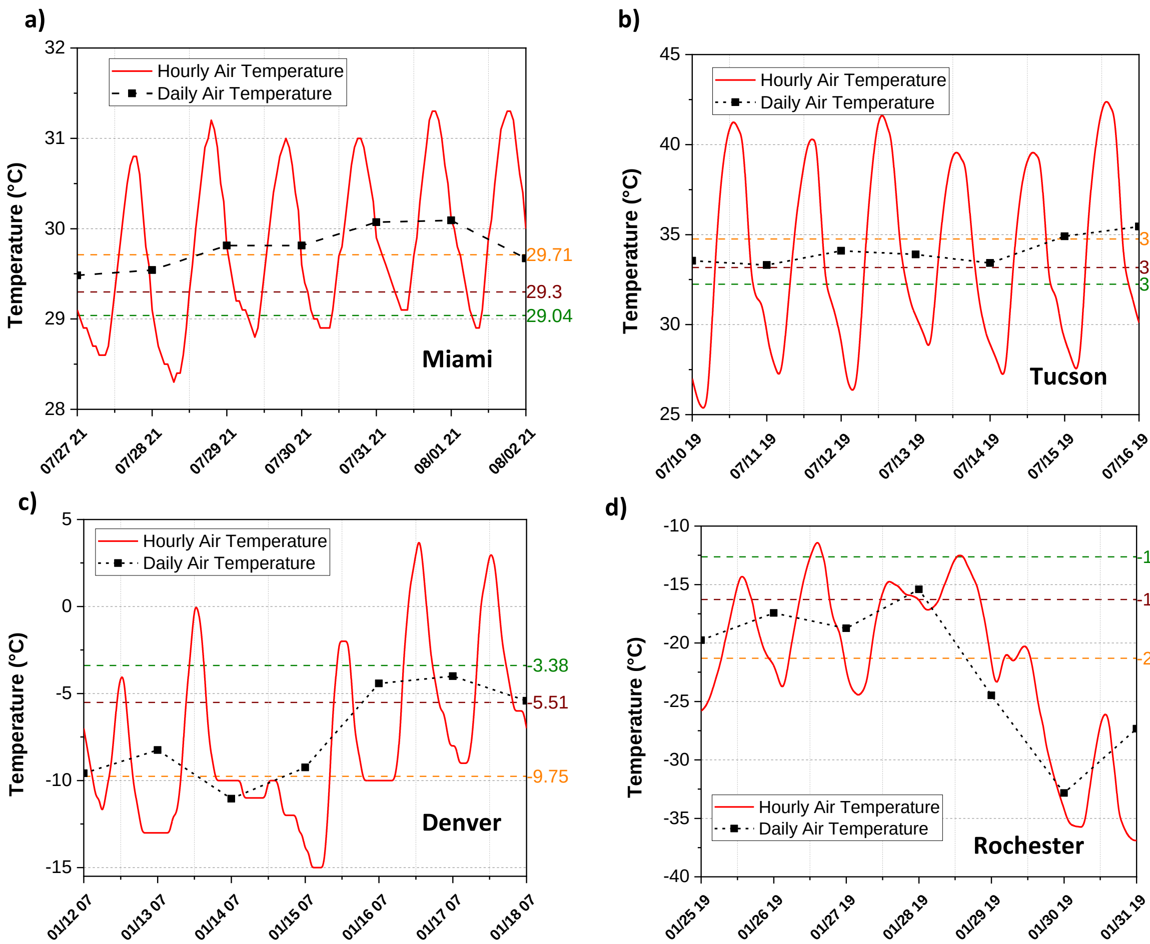

Figure 3 Heat waves and cold snaps for: (a) Miami; (b) Tucson; (c) Denver; and (d) Rochester. The orange, wine, and olive dashed lines represent Tpic, Tdeb, and Tint respectively.

Energy consumption and Thermal resilience

HVAC energy consumption during the heat wave week in Miami and Tucson and cold snap week in Denver and Rochester are presented in Table 3. In Miami and Tucson, activating the TABE+GL IL results in greater energy savings compared with activating the EL during the heat wave week. Miami achieves approximately 11.5% energy savings, and Tucson attains a substantial 21.0% reduction in HVAC energy consumption. This is primarily attributed to the higher temperature of the interior wall surface compared with that of the geothermal source (25.1°C for Miami and 23.7°C for Tucson). Geothermal source temperatures were determined using the method developed by Xing et al. (Xing et al. 2017). Conversely, during cold snaps in Denver and Rochester, activating the TABE+GL EL is the preferred choice. Denver experiences savings of around 10.7%, and Rochester achieves a 6.0% reduction in HVAC energy consumption. This preference is primarily because of the protective qualities of the EL, which slightly elevates the temperature of the cold exterior surface and reduces heat loss. Notably, activating the IL leads to increased heating energy consumption, because the geothermal source temperatures in Denver and Rochester are relatively colder at 11.5°C [52.7°F] and 12.8°C [55.0°F], respectively.

Table 3. Ground temperature, weekly HVAC energy consumption, and weekly SET safe hours

Regions	Ground temperature	Weekly HVAC energy consumption			SET safe hours		
		Baseline (kWh)	IL (kWh)	EL (kWh)	Baseline (h)	IL (h)	EL (h)
Miami	25.1°C (77.2°F)	274.4	248.3	257.7	9	53	14
Tucson	23.7°C (74.7°F)	299.6	242.2	273.9	52	100	64
Denver	11.5°C (52.7°F)	694.9	1053.3	626.1	50	95	62
Rochester	12.8°C (55.0°F)	2055.5	2223.0	1937.8	1	3	1

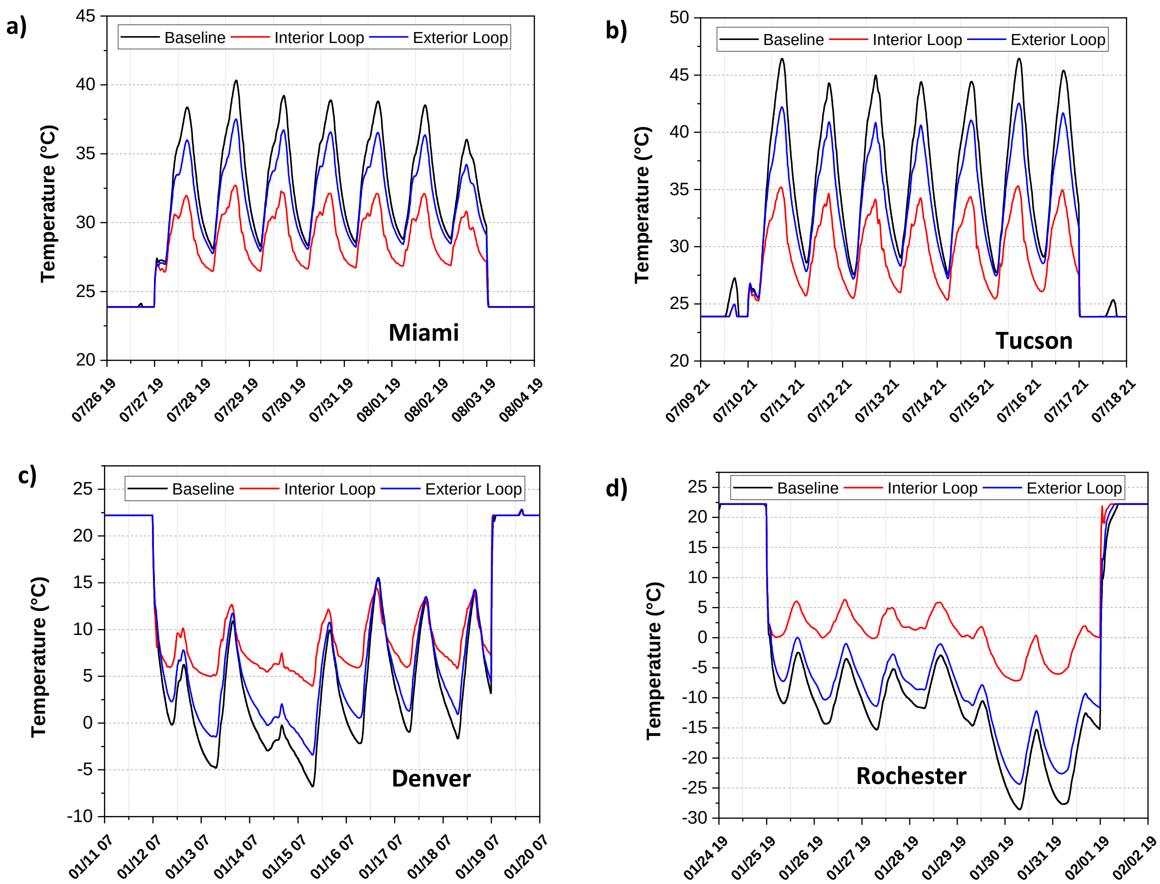

Figure 4 Indoor air temperature of the baseline and TABE with IL or EL during heat wave or cold snap week: (a) Miami; (b) Tucson; (c) Denver; and (d) Rochester.

The thermal resilience analysis was also conducted considering the baseline and TABE+GL with IL and EL coincidence with power outage. Figure 4 compares the indoor air temperature between the baseline and the IL and EL settings. Based on the results, activating the IL is desired for all the studied regions because it acts as an energy source to directly supply cold or heat energy. Alternatively, activating the EL has a limited effect on the indoor air temperature because of the large heat gain or loss from the openings (windows and doors). The SET results (see

Table 3) showed that the activating IL achieves 100 and 95 safe hours for Tucson and Denver, which doubles the safe hours of the baseline. In Miami, it also significantly increases the SET safe hours, from 9 hours of the baseline to 53 hours. In Rochester, it has a limited effects owing to the very low outdoor air temperature (see Figure 4 (d)). The effects of IL on thermal resilience also reflected in the HI and HOS as shown in Figure 5. In Tucson, IL significantly reduces the extreme caution and danger hours of HI—only 10% hours in extreme caution. In Denver, only 2.3% is in the severe hours of HOS.

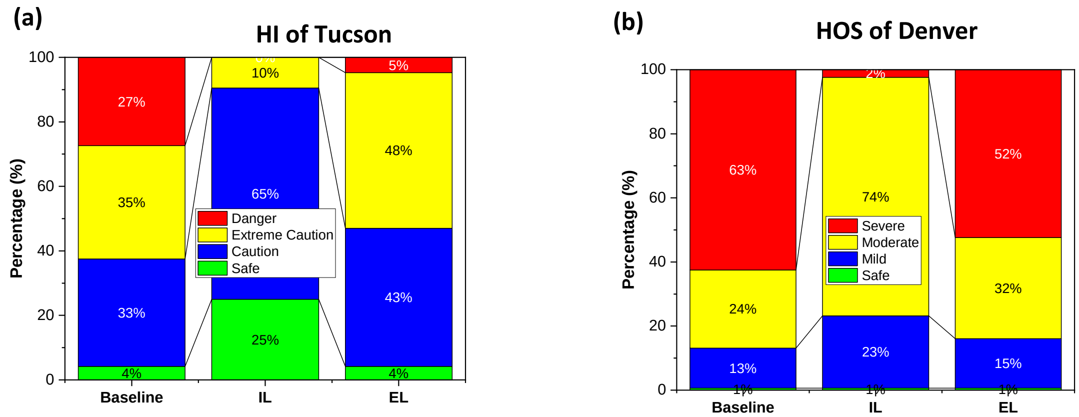

Figure 5 HI and HOS for: (a) Tucson; and (b) Denver.

CONCLUSION

In this paper, a three-step simulation-based thermal resilience assessment procedure was established for residential buildings installed with TABE+GL using a geothermal source. Heat wave and cold snap weeks were identified from historical weather data. The baseline and TABE+GL with IL and EL were considered for the energy and thermal resilience assessment. The following conclusions can be drawn:

1. Activating the IL of TABE+GL leads to higher HVAC energy savings than activating the EL even if the geothermal source temperature is relatively high in Miami and Tucson. Activating the EL is necessary to save HVAC energy in Denver and Rochester.
2. During a heat wave and cold snap coincident with power outage, activating IL is desired for all the studied regions to improve the thermal resilience. However, activating EL has a limited effect.
3. Activating IL could significantly reduce the average SET degree-hours above 30°C, increase HOS, and greatly improve thermal resilience for Tucson and Denver.

Future research can be orientated to the following three aspects: (1) studying the effects of power outage time on the thermal resilience of TABE+GL; (2) estimate the minimum backup power needed for power outage in different regions; and (3) estimating the effects of TABE+GL on peak load shaving.

ACKNOWLEDGMENTS

This manuscript has been authored in part by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

REFERENCES

ASHRAE 55. 2012. *Thermal Environmental Conditions for Human Occupancy*.

Al Assaad, D., A. Sengupta, and H. Breesch. 2022. "Demand-controlled ventilation in educational buildings: Energy efficient but is it resilient?" *Build. Environ.*, 226 (November): 109778. Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2022.109778.

Ayyagari, S., M. Gartman, and J. Corvidae. 2020. *Hours of Safety in Cold Weather: a Framework for Considering Resilience in Building Envelope Design and Construction*.

Biswas, K., S. Shrestha, D. Hun, and J. Atchley. 2019a. "Thermally Anisotropic Composites for Improving the Energy Efficiency of Building Envelopes." *energies*, 12 (19): 195–209. https://doi.org/https://doi.org/10.3390/en12193783.

Biswas, K., S. Shrestha, D. Hun, and J. Atchley. 2019b. "Thermally Anisotropic Composites for Heat Redirection and Thermal Management in Building Envelopes." *2019 Therm. Perform. Exter. Envel. Whole Build. XIV Int. Conf.* Clearwater, Florida.

Borghero, L., E. Clèries, T. Péan, J. Ortiz, and J. Salom. 2023. "Comparing cooling strategies to assess thermal comfort resilience of residential buildings in Barcelona for present and future heatwaves." *Build. Environ.*, 231 (January): 110043. https://doi.org/10.1016/j.buildenv.2023.110043.

Do, V., H. McBrien, N. M. Flores, A. J. Northrop, J. Schlegelmilch, M. V. Kiang, and J. A. Casey. 2023. "Spatiotemporal distribution of power outages with climate events and social vulnerability in the USA." *Nat. Commun.*, 14 (1). Springer US. https://doi.org/10.1038/s41467-023-38084-6.

Field, C., V. Barros, T. Stocker, and Q. Dahe. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Flores-Larsen, S., C. Filippín, and F. Bre. 2023. "New metrics for thermal resilience of passive buildings during heat events." *Build. Environ.*, 230 (November 2022): 109990. Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2023.109990.

Homaei, S., and M. Hamdy. 2021. "Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric." *Build. Environ.*, 201 (May): 108022. Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2021.108022.

Hong, T., J. Malik, A. Krelling, W. O'Brien, K. Sun, R. Lamberts, and M. Wei. 2023. "Ten questions concerning thermal resilience of buildings and occupants for climate adaptation." *Build. Environ.*, 244 (July). Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2023.110806.

Howard, D., S. Shrestha, Z. Shen, and T. Feng. 2023. "Field Evaluation and Numerical Study to Determine the Energy Saving Potential of Thermally Anisotropic Building Envelope." *J. Build. Perform. Simul.*

Ji, W., Y. Zhu, H. Du, B. Cao, Z. Lian, Y. Geng, S. Liu, J. Xiong, and C. Yang. 2022. "Interpretation of standard effective temperature (SET) and explorations on its modification and development." *Build. Environ.*, 210 (December 2021). Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2021.108714.

Lindstrom, A., and S. Hoff. 2021. "U.S. electricity customers experienced eight hours of power interruptions in 2020." *U.S. Energy Inf. Adm.* Accessed September 25, 2023. http://www.eia.gov/todayinenergy/detail.php?id=50316.

OSHA. 2008. *Using the Heat Index: A Guide for Employers Introduction*.

Ouzeau, G., J. M. Soubeyroux, M. Schneider, R. Vautard, and S. Planton. 2016. "Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble." *Clim. Serv.*, 4: 1–12. The Authors. https://doi.org/10.1016/j.cliser.2016.09.002.

Parmesan, C., M. D. Morecroft, and Y. Trisurat. 2022. *Climate Change 2022: Impacts, Adaption and Vulnerability*. Cambridge University Press.

Shen, Z., S. Shrestha, D. Howard, T. Feng, D. Hun, and B. She. 2023. "Machine learning – assisted prediction of heat fluxes through thermally anisotropic building envelopes." *Build. Environ.*, 234 (February): 110157. Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2023.110157.

Sheng, M., M. Reiner, K. Sun, and T. Hong. 2023. "Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages." *Build. Environ.*, 230 (January): 110001. Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2023.110001.

Shrestha, S., K. Biswas, D. Hun, and J. Atchley. 2020. "Thermally Anisotropic Composites for Thermal Management in Building Environments." USA.

Sun, K., M. Specian, and T. Hong. 2020. "Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home." *Build. Environ.*, 177. https://doi.org/10.1016/j.buildenv.2020.106842.

Texas Department of State Health Services. 2021. *February 2021 Winter Storm-Related Deaths - Texas*.

The US Center for Disease Control and Prevention. 2022. *CDC's Heat & Health Tracker*.

U.S. Department of Energy. 2018. "Prototype Building Models." Accessed October 25, 2022. https://www.energycodes.gov/prototype-building-models.

Xing, L., J. D. Spitler, and A. Bandyopadhyay. 2017. "Prediction of undisturbed ground temperature using analytical and numerical modeling. Part III: Experimental validation of a world-wide dataset." *Sci. Technol. Built Environ.*, 23 (5): 826–842. Taylor & Francis. https://doi.org/10.1080/23744731.2016.1253978.