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Thermal Resilience to Extreme Heat: Preliminary Study on Thermal Fragility Curves

Kyujin Kim[1](✉), Simona Bianchi[1], Thaleia Konstantinou[1], Mauro Overend[1], Jonathan Ciurlanti[2], and Alessandra Luna-Navarro[1]

[1] Delft University of Technology, Julianalaan 134, 2628 BL Delft, The Netherlands
k.j.kim@tudelft.nl
[2] Arup, Naritaweg 118, 1043 CA Amsterdam, The Netherlands

Abstract. The increasing frequency and intensity of heatwaves raises questions about the thermal vulnerability of buildings and, in particular, on how to assess their resilience to extreme heat. In this context, thermal fragility curves, which describe the probability of achieving or exceeding specific temperature thresholds for a building, serve as an effective measure to define the thermal vulnerability of existing buildings and identify tailored retrofit strategies. This study focuses on deriving thermal fragility curves for a case study: a 6-storey residential building constructed in the 1980s with a reinforced concrete structure and masonry infill walls. Dynamic thermal modeling and simulation were conducted over a one-year period using synthetic weather files generated to account for future heatwaves. The simulation results provide useful relationships in particular between: outdoor temperature and indoor Standard Effective Temperature (SET); and between outdoor daily maximum temperature and indoor SET. These relationships were finally analyzed to create and compare fragility curves using maximum likelihood fitting and the so-called Cloud methodology.

Keywords: Climate Resilience · Building Envelope · Thermal Vulnerability · Fragility Curve · Extreme Heat

1 Introduction

Global warming is leading to a heat extremes including heatwaves, that are more intense, more frequent and over longer durations [1, 2]. Climate change and extreme heat have a significant impact on the indoor thermal environment. They increase the risk of overheating and associated thermal discomfort, particularly in naturally ventilated buildings [3]. Thermal resilience to heatwaves refers to the ability of a building to maintain habitable indoor thermal conditions during extreme weather events or building system disruption due to power outages [4]. Resilience involves criteria such as vulnerability, resistance, robustness and recoverability, with vulnerability referring to a building′s sensitivity or propensity to disruptions in comfort conditions [5].

Thermal vulnerability can be assessed using probabilistic methods, which enhances reliability and acknowledges the inherent uncertainties of the heat hazard events.

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Fragility, a concept extensively used in seismic vulnerability assessment, serves as an effective measure for vulnerability evaluation. A fragility curve is described by the conditional probability of an Engineering Demand Parameter (EDP) reaching or exceeding a certain condition (e.g., damage level), given a certain level of Intensity Measure (IM). The analytical formulation of a fragility curve involves several steps. First, a hazard input, represented by IM (e.g., peak ground acceleration for earthquakes), is selected. Then, a dynamic analysis is conducted to assess the response of the building, indicated by the EDP (e.g., story drift ratio or floor acceleration for earthquakes). This is followed by an integration of the expected loss (social, economic, environmental) associated with fragility assessment, whereby probabilistic loss estimates can be provided, referred to as vulnerability. However, the application of fragility for thermal vulnerability assessment remains relatively unexplored, with theoretical fragility curves only recently used for residential building heat vulnerability assessment [6].

When simulating a building′s response to a heatwave, weather data and building operation must be considered carefully. The weather data should account for extreme events. Existing studies have developed procedures to derive weather files for the extreme meteorological year using the regional climate model [7], including extreme temperature events for future conditions based on historical heatwaves [8]. The building′s operational setup must accurately represent the thermal vulnerability of the building fabric, excluding effects such as mechanical cooling. Thermal autonomy, which is both a metric and a design process, addresses these issues by focusing on the relationship among the building fabric, the occupant, and the climate [9]. It quantifies the percentage of time a building can maintain comfortable conditions passively throughout a year, without requiring active system energy inputs [10].

The research gap in thermal vulnerability assessments is in capturing the inherent fragility of buildings by integrating the variability of hazard occurrence and building response. The shortfall in thermal fragility analysis lies in the exploration of the relationship between the heatwave hazard intensity measure and the building′s thermal response, specifically the mathematical representation of its statistical distribution. These gaps lead to the research question: how to create fragility curves that capture the thermal vulnerability of a building for future heatwaves. This question will be addressed through the following steps of fragility curve derivation: 1) selection of the set of fragility parameters 2) development of the energy model and calculation of the building response distribution 3) exploration of fragility analysis methods to create the best fit fragility curve for the given data.

2 Method

Figure 1 presents the research workflow for developing a thermal fragility curve for a building type with reinforced concrete frame structure and masonry infill walls. Considering a single residential unit on a typical floor of the case-study building, the dynamic thermal modelling and simulation are implemented by using synthetic weather files which account for future heatwaves. This process generates two sets of data pairs of IMs and EDP. Two distinct methods of fragility analysis, multiple stripe analysis [11] and cloud analysis [12], are applied to these datasets to derive fragility curves. During fragility analysis, different thresholds of EDPs are considered to derive the fragility curves, which represent thermal limit states ranging from acceptable to uninhabitable conditions. The next subsections describe in detail each workflow step.

The intensity level of heatwaves is indicated by the outdoor Dry Bulb Temperature (DBT) and daily maximum DBT, which are selected as IMs. The EDP, which indicates the extent to which the indoor environment is habitable for occupants, is represented by the Standard Effective Temperature (SET), a model of human response to the thermal environment. SET is defined as the dry-bulb temperature in a hypothetical environment with 50% relative humidity, assuming appropriate clothing is worn for the activity [13]. A building is considered vulnerable to a heatwave when the SET reaches a certain limit state. Based on literature [14–16], this research classifies SET thresholds of 22 °C, 26 °C, 28 °C, and 30 °C as acceptable, slightly unacceptable, discomfort, and unliveable limit states, respectively.

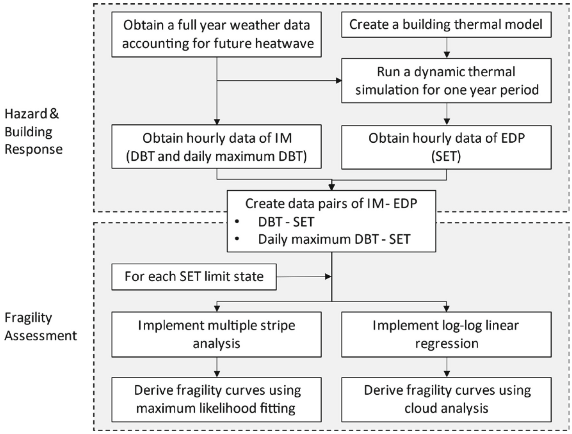
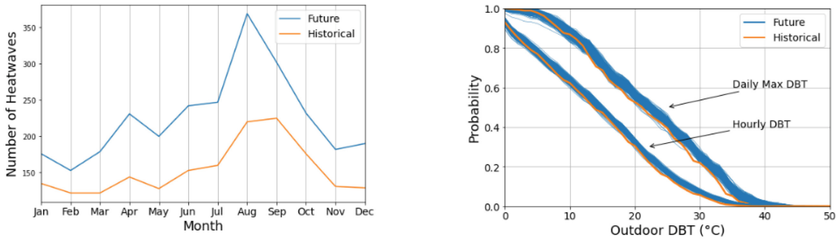


Fig. 1. Research workflow for deriving thermal fragility curves. It examines two sets of relationships between the IMs and EDP, using maximum likelihood fitting and cloud analysis method.

2.1 Extreme Heat Hazard

To conduct a thermal fragility assessment for future extreme heat events, weather data containing multiple heatwaves of varying intensity levels are generated through the Multi-scenario Extreme Weather Simulator (MEWS). MEWS is a python package [17] integrating extreme weather events into existing weather data to investigate future heatwave effects on buildings. In MEWS, heatwaves are defined as periods when daily maximum and minimum temperatures exceed their climate norm thresholds [18]. These are identified in historical weather data and adjusted to match IPCC projections [1] for increased frequency and intensity of climate scenarios. The focus of this paper is on developing fragility curves for a specific building envelope type, with consideration for varied locations. The case study is located in Albuquerque, US, due to the availability of the future year 2035 sourced from the MEWs database [19]. Figure 2(a) shows the number of heatwaves for the historical period and the projected scenario for 2035, as generated by MEWS. For these identified heatwaves, the MEWS stochastic model runs over 299 realizations. Figure 2(b) presents the hazard curve of each IMs, indicating the probability of observing a specific DBT for a given number of hours in a year.



(a) (b)

Fig. 2. (a) Number of historical and future heatwaves, and (b) the hazard curves of outdoor DBT and daily maximum DBT derived from 299 future heatwave weather files.

2.2 Building and Occupant Thermal Response

A building thermal model was developed using Honeybee [20]. Then, a dynamic thermal simulation was conducted over a year using EnergyPlus [21], applying multiple weather files via the EnergyPlus-Launch group simulation. The SET was calculated using the 'pythermalcomfort' Python package [22], based on the temperature output variables. Conservative estimates were used for variables related to human comfort, including an air speed of 0.1 m/s, a metabolic rate of 1 met, clothing insulation of 0.5 clo, and a body surface area of 1.8 m^2.

A six-storey residential building built in the 1980s with a reinforced concrete frame structure, was used as a case study. The analysis focused on the impact of heatwaves on localized thermal effects within occupants' living spaces. Therefore, the simulation was conducted for a residential unit with a floor area of 80.92 m^2, located on a typical floor within the building. This unit has a southwest-facing exterior wall with a window-to-wall ratio of 27%, and shares internal walls with another unit on the north and east sides. The building envelope consists of infill wall, composed of brick block and lapillus block with an air gap in between (Thickness = 0.35 m, U-value = 0.56 W/m^2K). The windows are made of aluminium frames with single-pane glass (U-Value: 4.36 W/m^2K, SHGC: 0.61). The building operates in a free-running mode, aligning with the goal of measuring thermal autonomy. As a passive measure, the building utilizes natural ventilation through operable windows, where it is assumed that occupants open these windows ideally when the indoor temperature exceeds 23 °C [13]. Other preset values and the occupancy schedule, were obtained from the mid-rise apartment program type from the Honeybee building program library.

2.3 Fragility Assessment

Two sets of data pairs - outdoor DBT to Indoor SET and outdoor daily maximum DBT to indoor SET - were used for fragility assessment. The dataset was generated by running thermal simulations for 299 future heatwave weather files, with Indoor SET measured at hourly timesteps throughout the year (299 × 8760).

Multiple stripe analysis involves conducting a fragility assessment for discrete IM levels, referred to as 'stripes' [11]. The probability of observing the EDP reaching or exceeding the EDP threshold at a particular stripe (IM $= x_j$) can be expressed as:

$$P\left(EDP \geq \text{threshold} \mid \text{IM} = x_j\right)_{\text{observed}} = \frac{\text{hours exceedence when IM} = x_j}{\text{total hours when IM} = x_j} \quad (1)$$

For each outdoor DBT, the fraction of hours where SET is at or above the SET threshold out of the total hours for that given outdoor DBT is counted. Based on the observed probabilities, a fragility curve, assuming a lognormal cumulative distribution function, is then fitted. The fitting process entails estimating function parameters that maximize the likelihood of producing the observed data.

Cloud analysis employs a regression model on a logarithmic scale between EDP and IM [12]. The resulting fragility, which denotes the probability of EDP reaching or surpassing a specific threshold, can be expressed as follows:

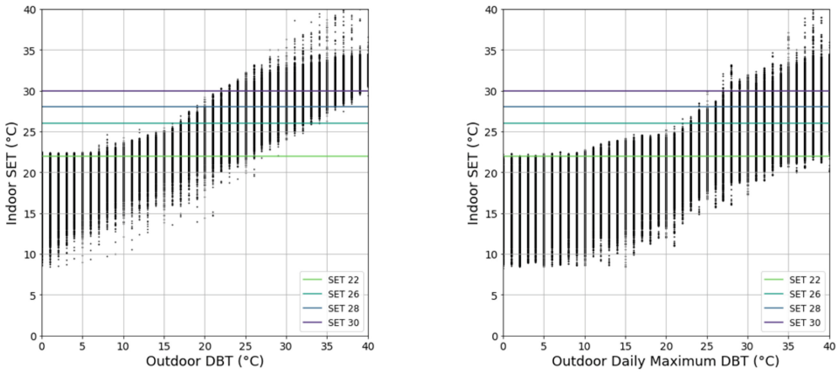
$$\text{P}(\text{EDP} \geq \text{threshold} \mid \text{IM}) = \Phi\left(\frac{\ln \eta_{\text{EDP|IM}}}{\sigma_{\ln \text{EDP|IM}}}\right) \quad (2)$$

From the linear regression model, the parameters $\boldsymbol{\eta}_{\text{EDP|IM}}$ and $\boldsymbol{\sigma}_{\textbf{ln}\text{EDP|IM}}$ which represent the median and logarithmic standard deviation for EDP given IM, are derived. These parameters are then used to create a fragility curve.

3 Results

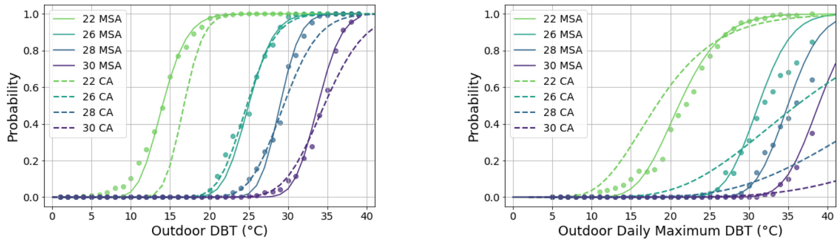
Figure 3 shows the distribution of IM-EDP pairs used for the fragility assessment. Figure 3(a) shows the indoor SET across outdoor DBTs, while Fig. 3(b) shows the indoor SET across outdoor daily maximum DBTs. The lower dispersion and steeper regression slope of SET across outdoor temperature in Fig. 3(a) suggest a potentially higher correlation of the IM-EDP pairs.

Figure 4 shows the fragility curves derived from the two methods. The accuracy of the resulting fragility curves depend on the extent to which the distribution follows its assumed path i.e. whether it followed a lognormal distribution (as in multiple stripe analysis) or exhibited linearity in the log space (as in cloud analysis). The comparison between Fig. 4(a) Fig. 4(b) reveals that with DBT, the dispersion of the fragility curve is larger. This suggests that when using the daily maximum temperature as the intensity measure, the resulting indoor thermal condition under a heatwave is estimated to be less severe. As shown in Fig. 4(a), when assessing the probability of indoor SET reaching the discomfort state (SET threshold of 28 °C) at a given outdoor temperature, the multiple stripe analysis overestimates the probability by approximately 10% when compared to the cloud analysis. This indicates that fragility curves derived using multiple stripe analysis are more conservative than those from cloud analysis.



(a) (b)

Fig. 3. Scatter plots of IM - EDP pairs: (a) Relationship between outdoor DBT and indoor SET, (b) Relationship between outdoor daily maximum DBT and indoor SET.



(a) (b)

Fig. 4. Fragility curves and the fraction of observed likelihood using both Multiple Stripe Analysis (MSA) and Cloud Analysis (CA). These are shown for different SET thresholds for data pairs of (a) outdoor Dry Bulb Temperature (DBT) and indoor Standard Effective Temperature (SET), and (b) outdoor daily maximum DBT and indoor SET.

4 Conclusion

This study set out to derive thermal fragility curves for a residential building with reinforced concrete frame structure and masonry infill walls. This is achieved by identifying the relationship between the intensity measure (IM) and engineering demand parameter (EDP). The outdoor dry bulb temperature (DBT) and daily maximum DBT were selected as IMs, and the indoor standard effective temperature (SET) was chosen as an EDP. Two different fragility analysis methods, multiple stripe analysis and cloud analysis, were applied to these pairs of IM and EDP at various temperature thresholds. The derivation process involved assessing the building′s indoor thermal condition in response to heatwaves, using synthetically generated weather files. These assessments were carried out in a free-running operational setting with natural ventilation.

This study presented a methodology for deriving a thermal fragility curve using an existing fragility analysis method, contributing to initial research on developing a fragility curve for thermal vulnerability assessment. However, the complex dynamics between heat hazard and indoor thermal condition, which cannot be simplified by treating temperature and time as independent, were also revealed. Future research should explore more precise pairs of IM and EDP to accurately reflect the dynamics of thermal conditions, including the effects of thermal history. Additionally, fragility analysis should incorporate uncertainties related to natural ventilation operation, building envelope materials and construction types, and assessment zone properties such as orientation and size. This will allow for a comprehensive representation of thermal vulnerability to heatwaves.

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