Kinetic temperature of structures: a new approach for building resilience assessment

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A New Approach to Understand a Mounting Threat

Extreme climate events (ECEs) present grave natural hazards that are poised to become more frequent [1]. For example, Category 4 and 5 hurricanes, which are responsible for nearly half of the U.S.' historical hurricane damage, became three times as frequent between 1970 and 2004 [2]. In the North Atlantic, the frequency of these severe storms is projected to increase by 75% by 2100 [3].

The threat that ECEs like hurricanes pose to our livelihood and economy has prompted the rise of a new concern in disaster risk analysis: **resilience**, the ability of structures and infrastructure to withstand, respond to, and recover rapidly from ECEs. In a typical resilience framework, damage caused to buildings by ECEs is modeled by **fragility curves.** These curves describe the probability of damage to a structure as a function of hazard intensity (i.e., wind speed for hurricanes). While these curves exist, the definition of damage they provide is often ambiguous [4]. For example, they provide no clear quantitative definition of when structural and non-structural elements fail.

To address this gap, we have developed a molecular-based dynamics model to quantify damage for any building design for structural and non-structural elements [5,6]. In this research brief, we propose a new parameter for diagnosing building damage that can be easily implemented in engineering practices: the **kinetic temperature of structures**.

Key Takeaways:

- The growing frequency and severity of extreme climate events (ECEs) such as hurricanes has prompted an emphasis on structural resilience in disaster risk analysis.
- Fragility curves, which describe the relationship between the likelihood of structural damage and the intensity of a hazard, are important for risk analysis but are typically poorly-defined.
- Kinetic temperature is an important and easy-to-obtain parameter to indicate the failure of structural and non-structural elements of buildings when exposed to hazards like hurricane-force winds and fire.
- Better fragility curves can be obtained by using kinetic temperature as an indicator of building damage. These curves may be used to calculate the cost of maintenance/ repairs in a Life Cycle Cost Assessment (LCCA).

Hurricane-force winds and fires are two hazards to buildings which may be exacerbated by climate change. Considering the kinetic temperature of structures can aid risk analysts in understanding when these hazards can cause structural failure.

Understanding the Concept of Kinetic Temperature

Buildings have a structural makeup that is similar to the structural makeup of materials at the nanoscale, where many strong and weak atoms interact and influence thermal, mechanical, and structural properties. Rather than considering a building to be an ensemble of large elements, like beams, plates, or walls, we propose a new mode of thought: buildings are an ensemble of mass points in space ("atoms") that interact via forces and moments, as the bonds in molecules do. This is the **Molecular Dynamics Model** (MDM).

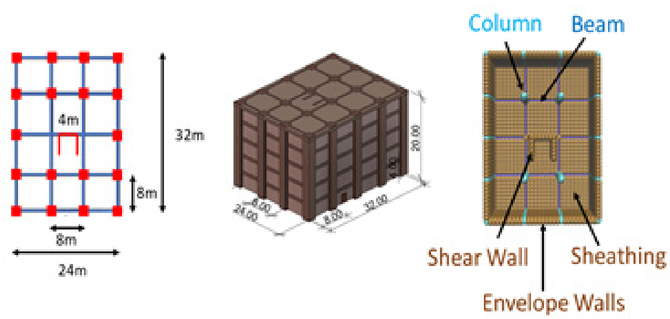

Figure 1. A sample MDM of a five-story wooden building. Left: floor plan. Middle: 3D view of building. Right: molecular model.

To lead us to our conception of the kinetic temperature of structures, we draw upon a principle of gas physics: The kinetic energy of the components of a system can be used to find the system's temperature. The same concept can be applied to buildings, where the kinetic energy experienced by a building during an ECE defines a "building temperature," which we describe as **kinetic temperature.**

From the Zeroth Law of Thermodynamics, we understand that two systems are in thermal equilibrium when they have the same temperature. If the kinetic temperature of a structure is equal to the temperature of the environment, we may assume the structure is stable. However, when kinetic temperature deviates from the ambient temperature, as it might during an ECE, the structure has been damaged.

The kinetic temperature can be obtained from an engineering analysis, while the air temperature can be room temperature or any predetermined value. The flexibility in defining air temperatures can help model structural fires if the ambient temperature is set to the temperature obtained from a burning room, structural codes (e.g., ISO-834, ASTM E-119), or a compartment fire test.

Kinetic Temperature Case Studies: Hurricane-force Winds and Building Fires

Using multiple building case studies, we highlight the versatility of our kinetic temperature approach. In one scenario, a five-story building with wooden elements is subjected to hurricane wind loads. The plot below shows how the kinetic temperature of the structure deviates from ambient temperature as wind loads increase.

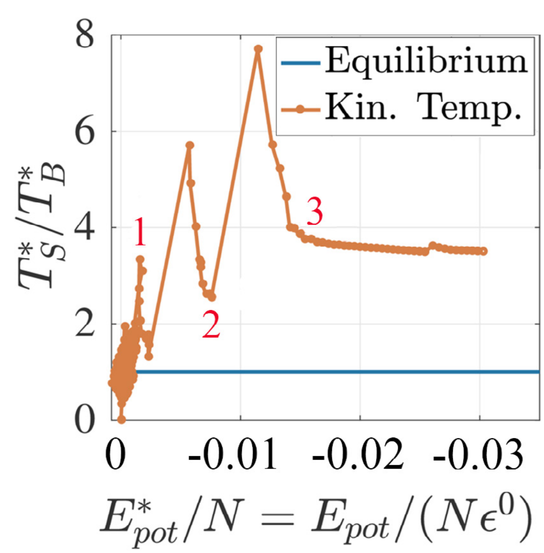

Figure 2. Normalized kinetic temperature-potential energy plot for the five-story wooden building subject to hurricane wind loads. While the structure is stable for zero potential energy (and wind load), the first damage induces a sharp jump (point 1) and an eventual collapse (point 3).

The blue line on Figure 2 shows where kinetic temperature (TS) and air temperature (TB) are in equilibrium. When there are no hurricane wind loads, the structure is stable, as may be seen by the cluster of points around 0 on the X-axis. However, increasing wind speeds cause damage to the structure, as may be observed by the distance between the labelled point 1 and the equilibrium line. Continuing to read the plot from right to left, we observe that the stiffness of the structure allows the structure's kinetic temperature to get closer to equilibrium at point 2. Wind loads then increase, causing more damage and an even greater spike in kinetic temperature, causing the structure to collapse at point 3.

Our kinetic temperature approach is also useful for evaluating the strength of different structural materials in the event of a fire. We compared the fire performance of three different building designs obtained from a neighborhood block in Sacramento, CA: a typical wood structure, a fortified wood structure, and a concrete structure).

In this scenario (represented by Figure 3), the blue line again indicates an equilibrium between the kinetic temperature of the structure and the air temperature, which has been set to the temperature of a burning room. When non-structural elements of each building are damaged, the kinetic temperature of each increases by a small amount, as exhibited by each point labelled with an "ns," or non-structural, subscript. As the fire propagates, the weaker wood building begins to suffer structural damage, as demonstrated by the kinetic temperature jump at point 1s. During the simulation, the stronger wood and concrete structures do not suffer structural damage, so their kinetic temperatures remain fairly close to the blue equilibrium line.

As we will explore in our future work, **kinetic temperature may be useful for understanding the risk of a given structure to hazards of different intensities.** As it can help indicate the severity of damage, kinetic temperature can assist in creating better fragility curves, which can then be used to inform the cost of maintenance and repairs in building life cycle assessments (LCAs) and life cycle cost assessments (LCCAs). In this manner, it can assist engineers and architects in selecting building materials (e.g., concrete) more resistant to regionally applicable ECEs.

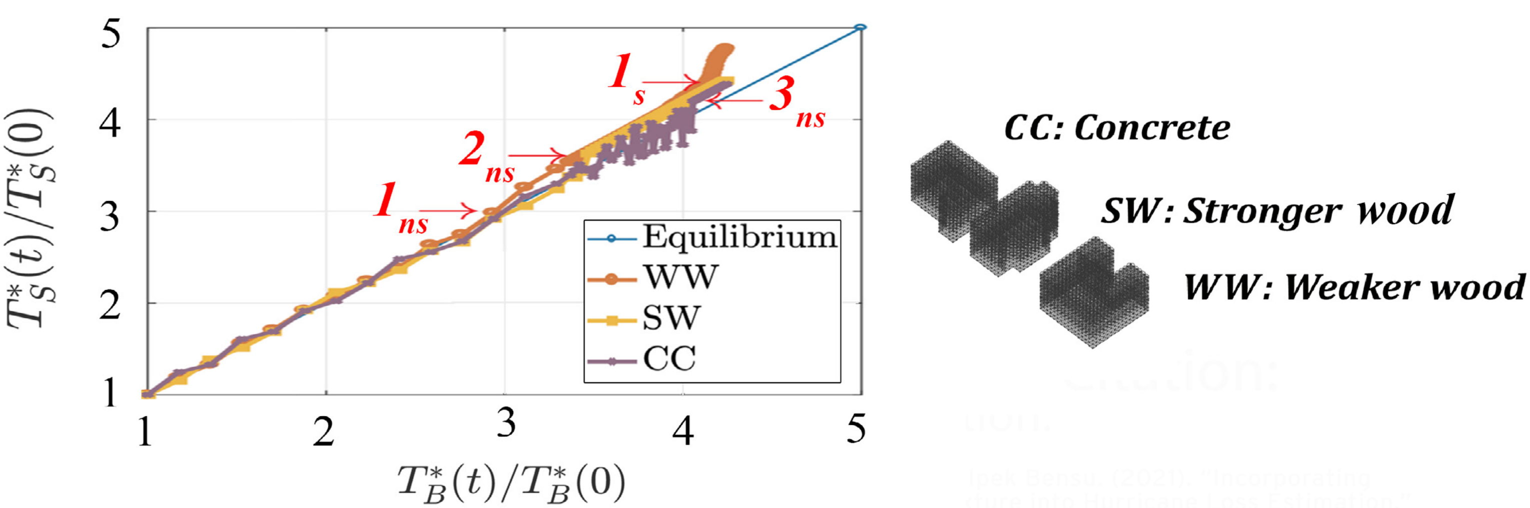

Figure 3: Normalized kinetic temperature of different buildings from a Sacramento, CA block versus normalized room fire temperature. A small deviation appears when non-structural damage occurs for each design (observe the points with "ns" subscript), while a large deviation appears when structural damage occurs on the weaker wood building.

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Related Links:

- MIT News, "Studying floods to better predict their dangers"
- MIT News, "Hurricane-resistant construction may be undervalued by billions of dollars annually"
- MIT CSHub, "Molecular Dynamics-based Resilience Assessment of Structures"

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