



Wind-Driven Building-to-Building Fire Spread: Experimental Results and Probabilistic Modeling

Faraz Hedayati¹ · Daniel Gorham² · Xareni Monroy¹ · Mohammadrafi Marandi¹ · Evan Sluder¹ · Michael Gollner³ · Wuquan Cui³ · Ali Merhi¹

Received: 30 June 2025 / Accepted: 31 October 2025 / Published online: 28 January 2026
© The Author(s) 2026

Abstract

This study presents a comprehensive experimental and probabilistic analysis of wind-driven building-to-building fire spread, focusing on the interplay between exposure intensity, duration, and material response. Twenty-three full-scale tests were conducted under varied wind speeds, separation distances, and material configurations to capture a spectrum of damage levels and move beyond the conventional binary outcomes of most fire experiments. As fire intensity builds, the target structure experiences increasing heat exposure, while collapse of the source structure during the growth phase disrupts flame dynamics and causes abrupt intensity drops. This deviation from the classic growth, steady, and decay pattern weakens the correlation between observed damage and traditional metrics such as peak heat flux or long-duration heat load. To address this, damage classifications from cosmetic to destroyed were mapped to statistical distributions of energy fluence accumulated over a characteristic intermediate timescale, better reflecting material response under realistic fire conditions. The resulting probabilistic framework supports risk-informed decisions aligned with the acceptable level of risk. At a separation of 10 ft (3 m), the tested building materials showed minimal likelihood of survival when exposed to fires from large, fully loaded sheds. By about 20 ft (6 m), the fire exposure decreases to a level where resilient building components have a fighting chance, and survival probabilities improve substantially at 30 ft (9 m). This framework provides a statistical view based on a physics-based interpretation of ignition thresholds to quantify intermediate damage and assess vulnerability under variable fire exposures, supporting fire-resilient community design and mitigation.

Keywords Wind-driven fire · Conflagration · WUI · Wildfire · Urban fire · Probabilistic modeling · Resiliency · Building to building fire spread

✉ Faraz Hedayati
fhedayati@ibhs.org

¹ Insurance Institute for Business & Home Safety Research Center, Richburg, SC, USA

² Fire Safety Research Institute, UL Research Institutes, Columbia, MD, USA

³ Department of Mechanical Engineering, University of California, Berkeley, CA, USA

1 Introduction

Wildfires that advance into the built environment have caused widespread destruction of homes, businesses, and infrastructure, long-term environmental harm, and tragic loss of life of residents and first responders. Over the past century, urban fires have emerged as a growing global threat, causing widespread structural and economic losses. In Japan, the 1923 Great Kanto Earthquake triggered firestorms that devastated Tokyo's built environment [1]. Decades later, Australia's 1983 Ash Wednesday bushfires destroyed thousands of structures across two states [2]. More recently, the 2016 Fort McMurray Fire in Canada led to the loss of more than 2000 buildings [3]. In the United States, urban fire disasters have escalated in both frequency and scale. The 2018 Camp Fire nearly erased the town of Paradise, California [4]. In 2021, the Marshall Fire swept through dense suburban neighborhoods in Colorado, destroying over 1,000 structures [5]. A fire on Maui devastated the town of Lahaina, becoming one of the deadliest in modern U.S. history [6, 7]. The 2025 Los Angeles County fires have underscored the escalating financial toll of these fires, with estimated economic damage of \$250 billion.¹

Post-event investigations show that initial structure ignitions in affected communities are often caused by accumulated embers or wind-driven burning debris [4, 6, 8, 9]. Under fire conducive conditions, ember ignitions can grow into sporadic large-scale fires, and in extreme fire weather may merge into full scale conflagrations with rapid building to building spread. Urban fire studies have found both localized clusters of destroyed buildings and widespread destruction driven by urban conflagration [10].

Thermal exposure from burning structures depends on environmental conditions, including wind, topography, and the spatial arrangement of fuels and structures. Wind tilts and stretches flames, intensifying radiative and convective heat transfer and promoting rapid spread when flame lengths exceed separation distances. Buildings downstream face the highest combined exposures, while in the crosswind direction wind driven cooling reduces net convective heating and flame contact becomes intermittent. While wind and topography cannot be controlled interventions such as fuel breaks, increased separation distances, and fire resistant construction can substantially reduce the likelihood and rate of community fire spread [6, 11–13].

Building-to-building fire spread has been studied with reduced-scale testing [14], modeling [15, 16], and limited full-scale experiments [12, 15, 17–21]. Previous work focused on radiant heat exposures, simplified geometries, or calm-wind conditions [22–27]. The present study builds on prior work [28] investigating realistic full-scale configurations under controlled wind conditions. A detailed literature review of previous experimental studies is provided in the Supplemental Materials-A.

Much of the standard flammability data available comes from cone calorimeter tests that use small samples, constant radiant heat, and no wind [29–33]. These results support various analyses, including methods that integrate the area under heat flux time history curves to relate material flammability to cumulative heat exposure [16, 32, 34–40]. Steady and uniform heating conditions do not reflect the transient fluxes of wind driven fires, where flame deflection, structural collapse, and convective cooling continually alter exposure intensity and duration. A detailed discussion of these flammability data, ignition mechanisms, and

¹Roger Vincent, "Estimated cost of fire damage balloons to more than \$250 billion," Los Angeles Times, January 24, 2025.

flux time product model assumptions is provided in the Supplemental Materials-B, and their applicability to this study is addressed in the Discussion section.

Structures' resilience to fire exposure is often dictated by their most vulnerable component. Failure of a single component may lead to flame spread, penetration, and ignition of the structure's contents. Effective home hardening must scale with thermal exposure, requiring more robust materials as intensity increases [41]. Some post-fire studies have found that homes with stucco exteriors, dual-paned windows, tile roofs, and fire-resistant decks tend to survive WUI fires [42, 43]. However, Knapp et al. [44] reported that compliance with modern WUI codes (CBC 7A) did not significantly affect survival during the 2018 Camp Fire. Similarly, analysis of the 2023 Lahaina fire by Hedayati et al. [6] emphasized that extreme heat exposure, amplified by close spacing and connective fuels, leaves little fighting chance for even fire-resistant materials. Given that WUI-compliant assemblies are still prone to failure, several critical questions arise:

- Many building codes address only on-property spacing, overlooking proximity to neighboring structures. How should policy reflect real-world structure size and performance under extreme wind and weather?
- At what point does separation distance negate the benefits of fire-resistant materials?
- Do ignition thresholds measured at small scale apply under large scale fire conditions where a building is composed of various materials and subject to multiple damage modes?
- Given the chaotic nature of conflagrations, should they be framed probabilistically, and which variable best captures their intensity, duration, and material response?

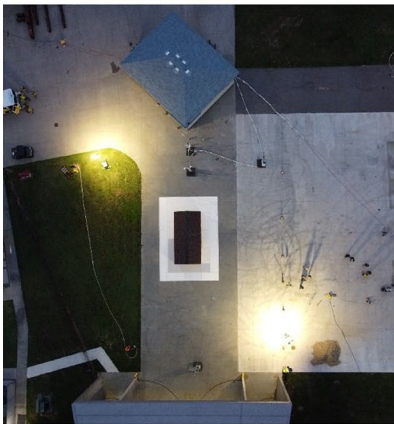
2 Materials and Methods

This experimental campaign examined building-to-building fire spread using ignited 24 ft by 12 ft (7.3 m by 3.6 m) sheds as fire sources and a 40 ft by 35 ft (12.1 m by 10.7 m) downwind building as the target. Unlike traditional post fire investigations that often reveal binary outcomes where structures are either undamaged or destroyed [4] in the absence of suppression, these full-scale tests captured the progression of damage and failure under controlled conditions. Both structures were exposed to controlled wind fields generated by the IBHS wind tunnel, capable of reproducing specific wind time histories [45, 46]. The test variables in this research campaign are summarized in Table 1. Primary factors investigated included: building separation distance; shed construction material (steel or wood); and target building components known to influence fire vulnerability. Wind speed was controlled at two ranges, 20–30 mph for typical conditions and 50–60 mph for extreme fire spread.² Two building orientations relative to wind direction (0° parallel alignment and 45° angular exposure) were also tested, as illustrated in Figure 1. Testing continued until damage stabilized or the structure neared destruction, at which point experiments were terminated to protect equipment.

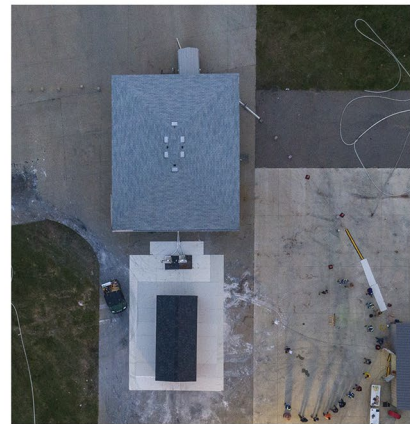
²Results of cold flow measurements are provided in the Supplemental Materials-C.



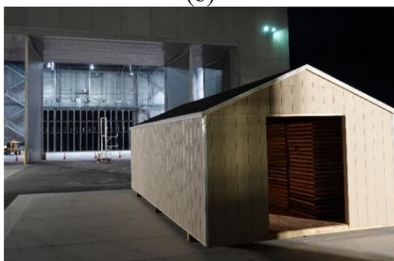
(a)



(b)



(c)



(d)



(e)

Fig. 1 Test configuration views: **a** source and target building with the test chamber in the background (**b**) and (**c**) show aerial views at 20 ft (6 m) separation for 45° and 0° target orientations; **d-e** show ground-level perspectives. In (**e**) the tarp and heated airflow were used to reduce wood moisture

2.1 Source Building and Fuel Load

Two shed types, wood and steel, were used as source buildings. Each measured 24 ft by 12 ft (7.3 m by 3.6 m) with an average roof height of 11 ft (3.3 m). Following [28], each shed contained 15 standardized wood cribs (nominally matching UL 711 Class 6-A) providing a consistent fuel load across tests. The placement of the cribs, however, was not identical between tests. Over the three-year testing period, procurement constraints made sourcing identical sheds challenging, resulting in variations in window and door dimensions that influenced ventilation and collapse behavior. These variations proved beneficial, offering insight into how ventilation affects fire behavior and structural failure. The diversity of configurations better represents the range of shed designs found in real neighborhoods, adding practical relevance to the findings. In all tests, ignition followed a standardized protocol whereby the centrally positioned wood crib was ignited using a pan containing 300 mL of propanol, after which internal fire development led to fire spread to all cribs. Figure 2 shows representative examples of the test configurations, with details for individual tests provided in Appendix A, Table 1, and additional information on fuel load, shed conditions, and uncertainties in heat release rate [47, 48] under wind presented in the Supplemental Materials-D.

2.2 Target Building

A 1.5-story test structure with a 1,280 ft² (119 m²) footprint was built to the requirements of the California Building Code Chapter 7A Materials and Construction Methods for Exterior Wildfire Exposure [49]. The building featured 9 ft (2.7 m) walls extending to a 13 ft (3.9 m) eave height, with a 2 ft (0.6 m) crawlspace above a 2 ft (0.6 m) elevated steel I-beam base. While the entire exterior was finished to represent a standard residential build-

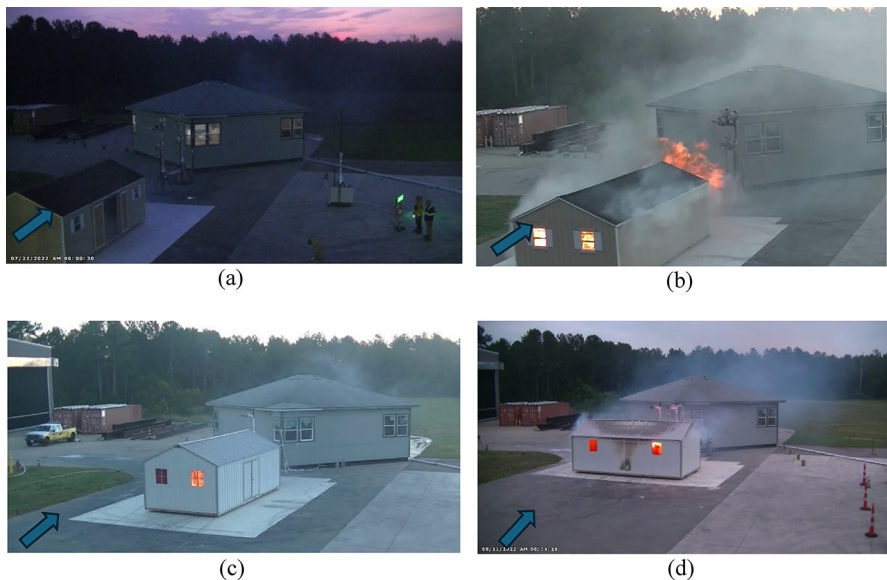


Fig. 2 Examples of shed configurations presented in Table 1 and in Supplemental Materials-D: **a** configuration a- α at 40ft separation; **b** Configuration a- α at 30ft separation; **c** configuration f- α at 20ft separation; and **d** configuration i- α at 20ft separation. The blue arrow indicates wind direction

ing envelope, the interior remained unfinished except along the fire-exposed wall, which received complete interior finishing to accurately assess fire penetration through a realistic building assembly. Prior to testing, all combustible portions of the building were tarped, and a positive-pressure environment was created using heated airflow to reduce the wood moisture content below 10%. The structure represents a California Building Code Chapter 7A compliant home; while Chapter 7A compliance exists along a spectrum, this particular design reflects a mid-range, cost-realistic implementation. Detailed specifications for key components, including the roof assembly, eave configuration, wall construction, and window installations, are provided in Table 2 in Appendix A, with additional information on target building details and construction materials presented in the Supplemental Materials-E.

2.3 Data Collection and Instrumentation

Each experiment used a tailored instrument layout based on the target building's orientation and test objectives. Primary thermal data were collected using water-cooled Schmidt-Boelter heat flux gauges (25 mm, 0–200 or 0–50 kW/m²) positioned at key locations on the target structure and in the interstitial zone (Figure 3). Wind speed was measured with an ultrasonic anemometer at the chamber outlet. Figure 3 shows the sensor layout for tests with target orientations of 45° and 0°, when all calibrated gauges were available. Sensor placement varied between configurations depending on instrument availability, and the specific layouts used in each test are provided in Table 1 and Figure S4. Fixed-position HD cameras were used to record fire behavior and the timing of damage events.

The distributed data system featured a master NI PXIe-1095 chassis and two Ethernet-based cDAQ units (at the chamber outlet and inside the test chamber). The chassis handled sensors on the target, source, and interstitial zone. Wind sensors were connected to their local cDAQs. All units used 24-bit ADC modules to read analog voltage and 4–20 mA current (wind). Data was sampled at 10 Hz for analysis.

3 Results

As summarized in Table 1, most sheds were positioned with the door facing the target building to represent typical residential layouts and allow direct flame exposure through the largest compartment opening. Sheds were generally aligned with the wind, since rotating them



Fig. 3 Sensor layout for tests with target building orientations of (a) 45° and (b) 0°. Data from the sensor outlined in solid lines is used in the discussion section

90° (Figure 2d) disrupted airflow and reduced exposure, as observed in Test 8. Concentrating the fuel load on the leeward side near the shed door increased heating of the target, particularly at a 20 ft (6 m) separation, and this configuration was used in most tests. These arrangements created a wide range of fire intensities and exposure durations across the test matrix. Examples of fire behavior for representative wood and steel sheds are provided in the Supplemental Materials-G.

Fire exposures and the resulting damage were systematically documented across 23 experiments that varied wind speed, separation distance, building orientation, and target materials. Damage outcomes were classified as No Damage, Cosmetic Damage, Envelope Damage, or Destroyed. A detailed discussion of fire dynamics, including flame development and collapse behavior for representative wood and steel sheds, is provided in the Supplemental Materials-G. The following section describes each of these damage categories as observed in the experiments.

3.1 Cosmetic Damage

Figure 4 shows the condition of the target building after tests resulting in cosmetic damage, which does not impact the use or occupancy of the building and is generally less expensive and requires minimal time to repair [50]. Figure 4a shows deformed and detached vinyl glazing. Figure 4b depicts eave vents viewed from the attic where embers accumulated outside on intumescent-coated screens; some cells expanded, and vent replacement may be needed. Figure 4c shows soot accumulation and light charring on rafter tails, removable by pressure washing or sanding.

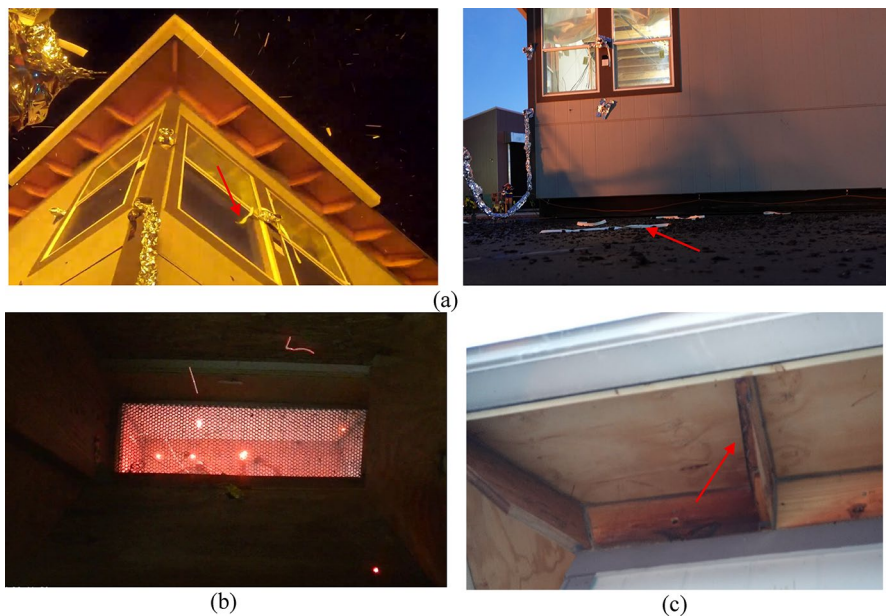


Fig. 4 Cosmetic damage examples: **a** melted vinyl glazing on the ground, **b** partial vent blockage with ember penetration, **c** light charring and soot accumulation on rafter tails

3.2 Envelope Damage

Figure 5 shows the target building condition following tests that resulted in Envelope damage, generally described as requiring moderate repair time and cost, with potential impacts on occupancy of the building. Figure 5a and b show damaged fiber cement siding: thermal exposure caused bowing (7a) and, under higher intensity, visible cracking (7b). Window damage was common in these experiments. In tests with tempered glass windows, deformed and detached vinyl glazing compromised pane retention, and continued heat melted the silicone adhesive, allowing the outer pane to fall out (Figure 5c). In two tests with annealed glass windows, the outer pane fractured (Figure 5e and f). In some cases, the vinyl sash frame deformed and created a gap which might allow flame or ember penetration.



Fig. 5 Example of Envelope damage: **a** fiber cement siding bowing and **(b)** cracking; window damage including **(c** and **d)** pane detachment, **e** glass fracture, and **f** sash deformation

3.3 Destroyed

Figure 6 shows the condition of the target building in tests that were categorized as Destroyed, where repair costs and time equate to full reconstruction, and occupancy of the structure is indefinitely affected. In Figure 6a, the ignition of the fascia board led to gradual roof deck consumption over 10 minutes, prompting test termination. A section of the fascia board shielded by a metal gutter during this test remained intact (Figure 6b). Figure 6c shows the ignition of an eave, which occurred before window failure. Flames from the ignited siding (Figure 6d) entered the attic through both the edge and the field of the eave vent (Figure 6e). Along the edges, gaps allowed early flame entry, highlighting the need for improved sealing, which has since been proposed and approved for inclusion in the 2027 International Wildland Urban Interface Code (IWUIC) code.³ Within the vent field, the intumescent coating activated about 15 seconds later, but the flame intensity was sufficient to ignite low density fuels inside the attic. In some cases, window damage escalated, after outer pane detachment (Figure 6f), the inner pane dropped within the frame, leaving a 2-inch (5-cm) opening (Figure 6g), allowing ember or flame entry.

Additional tests with winds at 50–60 mph (22–27 m/s) revealed a window failure mode that had not previously been observed: heat softened the vinyl window, and wind pressure pushed the sash inward with both panes still in place (Figure 6h).

3.4 Aggregate Results and Observations

Table 2 in the Appendix summarizes damage modes, peak heat flux, failure time, and accumulated heat load for each test. Although damage increased as separation distance decreased, structural collapse altered fire dynamics by reshaping the shed and changing the local wind flow, which affected heating and cooling at the target building. As a result, the typical growth steady decay pattern was disrupted, and several tests showed higher damage levels at lower heat flux values, while exceeding a specific heat flux threshold or heat load level did not consistently discriminate between damage modes. For instance, in Test 6, the windowpane fell out at a heat flux of $\sim 7 \text{ kW m}^{-2}$, while the vinyl glazing melted at $\sim 11 \text{ kW m}^{-2}$. Similar trends in damage appear in Tests 7, 8, 11, 13, 18, and 20. Additionally, in Tests 10, 17, 20, and 21, exposures above 100 kW m^{-2} did not cause immediate ignition of the target building, which instead occurred tens of seconds later at lower heat fluxes, highlighting the role of transient, wind-affected conditions. This delay for tests 10 and 17 was about 60 and 90 seconds, respectively.

Assessing heat load, higher values during an individual test often correlate with greater damage, but no consistent threshold emerges across experiments. Vinyl glazing detached at heat loads ranging from $\sim 0.1 \text{ MJ m}^{-2}$ to $\sim 4 \text{ MJ m}^{-2}$, and windowpane failures occurred between $\sim 5 \text{ MJ m}^{-2}$ and $\sim 15 \text{ MJ m}^{-2}$, depending on exposure duration. Ignition was observed at $\sim 3.2 \text{ MJ m}^{-2}$ in Test 10 but required $\sim 6.4 \text{ MJ m}^{-2}$ to 17 MJ m^{-2} in Tests 17, 23, and 21. Heat load alone does not trend with failures, since similar damage levels can be reached over different timeframes. Incorporating time, such as using the slope of the heat load curve, may offer a more meaningful metric as this can be interpreted as a surrogate for increasing rates of fire heating vs. wind-based cooling. In cases of linear accumulation, the choice of time

³International Code Council. 2024 International Wildland-Urban Interface Code (IWUIC), Version 2.0. Washington, DC: International Code Council, 2024.



Fig. 6 Damage observed on the target building in these experiments corresponds to the destroyed category: **a–b** ignition of the fascia board, **c** ignition of the eave, **d–e** ignition of the siding and flame penetration in to the attic through the vents, **f–g** failure of the first and second window pane, **h** window sash failing inwards

frame has little impact. However, nonlinear behavior requires identifying a characteristic response time that reflects the system's dynamics. Given the variability, fixed thresholds are insufficient; probabilistic approaches offer a better representation. This point is examined further in the Discussion section.

Among all components, windows sustained damage most frequently, with annealed panes failing at lower heat loads than tempered panes, consistent with prior findings [13, 25]. Annealed panes shattered in place, while tempered panes remained intact but detached as single pieces, highlighting the need to better secure panes to fully utilize tempered glass performance. Exterior walls also played a major role in overall vulnerability, with noncombustible siding showing clear advantages over engineered wood. Under similar heat exposure, fiber cement bowed or cracked, while engineered wood ignited and supported flame spread that extended vertically to rafter tails and the attic and horizontally toward windows. These results show that heat penetration alone is an inadequate metric of performance and support re-evaluation of one hour fire rated provisions in building codes, particularly for exterior wall systems [51]. Similar behavior has been reported in other studies [13, 26]. Exposed combustible rafter tails showed limited resistance to high heat, especially under typical wind conditions where buoyant flame tips were not fully deflected, while at higher wind speeds flame deflection increased, as shown in Fig. 7 where the buoyant region nearly disappeared.

At higher wind speeds 50–60 mph (22–27 m/s; Tests 20–23), the outcome was consistently Destroyed. Under these conditions, the combined effects of flame stretch, intermittent flame contact, and convective cooling became more pronounced. Combustible components of the target structure were exposed to transient heat fluxes exceeding 100 kW m^{-2} , yet ignition did not occur. This shows that short duration, high intensity exposure is not sufficient to trigger ignition when interrupted by convective cooling or when resilient materials possess a high thermal response parameter (TRP) [52]. In all four tests, heat softened the vinyl

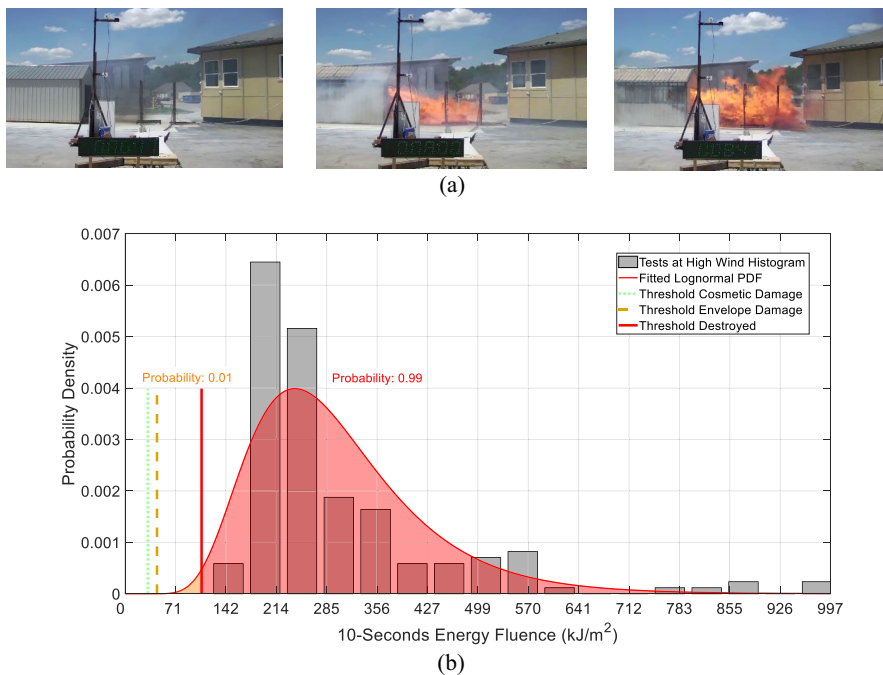


Fig. 7 Energy fluence distributions for high-wind conditions, highlighting extreme exposure despite increased distance

window frames, allowing wind pressure to cause failure while the tempered glass remained intact. These results highlight the need to evaluate window assemblies as integrated systems that account for the combined effects of heat and pressure.

Differences in shed construction also influenced exposure severity. Steel sheds produced less damage than wood sheds at equivalent separation distances. Testing different configurations showed that reorienting openings away from nearby structures helped deflect flames until collapse. This finding has been incorporated into the 2027 IWUIC edition. Although fan input was held constant, wind velocity measured at the outlet, see Table 1, varied with shed opening size, spacing between structures, and target orientation. Target buildings oriented perpendicular to the wind flow (0° , Figure 1c) experienced greater damage than those at 45° (Figure 1b) at the same separation distance, consistent with the heat flux time histories for Tests 13 and 16 shown in Figure 8.

In the 0° configuration, where the target building was oriented perpendicular to the wind, heat flux on the exposure wall increased rapidly, likely due to flow stagnation between the source and target structures. At 45° , the leading corner split the flame path, producing lower and more gradually increasing heat flux compared to the rapid rise at 0° . After about 16 minutes, once the wood sheds were mostly consumed and bluff body effects diminished, heat flux measurements for both orientations converged.

Figure 9a–b shows the setups for Tests 2 and 13, both with sensors 20 ft (6 m) from the fire source. The freestanding sensor in Test 2 recorded higher average and peak heat fluxes than the wall-mounted sensor in Test 13 shown in Figure 9c. Although Test 13's fuel crib was more concentrated toward the target and its upwind windows accelerated fire growth, Test 2 produced greater total energy at the sensor 20 ft (6.1 m) from the fire source. To examine the mechanisms behind these differences, flame length and impingement angle were analyzed during the peak periods (24–32 min for Test 2 and 12–20 min for Test 13), with representative frames in Figure 9c–d showing no statistical difference in visible flame behavior.

Because the visual analysis was used to interpret these thermal differences, image thresholds were set to capture the main flame body given the limitations imposed by the orange sky background and reflections on glass. As a result, intermittent flame contact visible in

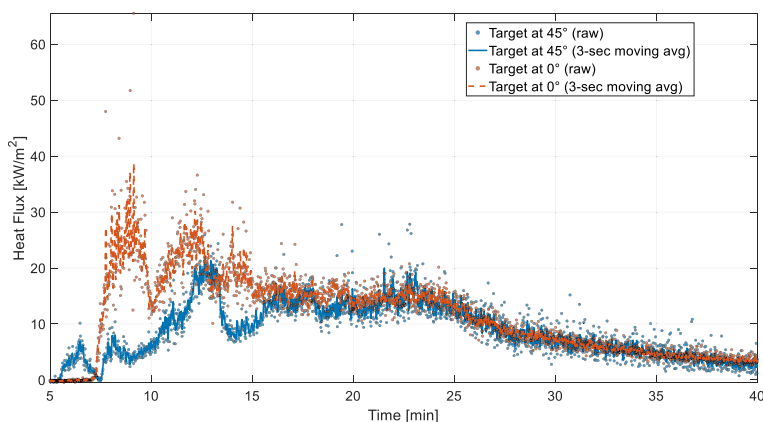


Fig. 8 Comparative heat flux measurements from Tests 13 and 16, two wood shed experiments at 20 ft (6.1 m) separation, highlighting variations caused by flow pattern differences

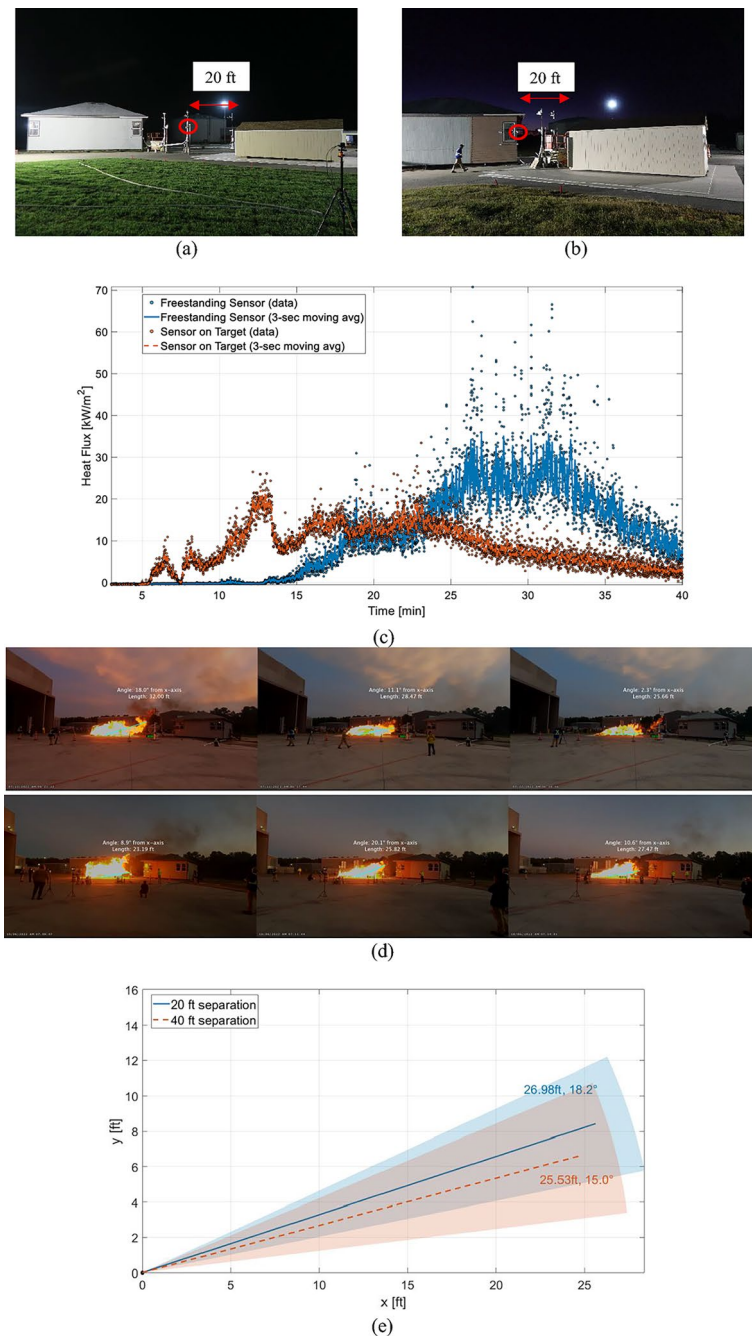


Fig. 9 Influence of bluff-body interactions on heat flux: **a** freestanding sensor setup, **b** wall-mounted sensor setup, **c** corresponding heat flux time histories from Tests 2 and 13, **d** representative frames from the video processing analysis for test 2 and 13 respectively, and **(e)** flame length and angle results during the 8-minute period of peak fire behavior (mean $\pm$ 1 standard deviation; origin is set at the center of the shed)

the last frame was not detected but explains brief heat flux spikes. Beyond these spikes, the freestanding sensor, because of its small projected area, was influenced only by the flow perturbation of the shed, while the sensor on the target building was also affected by turbulence generated by the building itself. This turbulence created transient wind patterns that occasionally pushed flames away, allowing cooler diluted air to pass over the sensors and produce localized convective cooling that lowered the recorded flux values.

Figure 10 shows the probability distribution of damage modes by separation distance, based on the final condition of the target building across Tests 1 to 19 (wind < 30mph (13.4 m/s)). At 10 ft (3 m), exposure to the target structure was severe, causing ignition within about 10 minutes. At 40 ft (12.2 m), no damage was observed, indicating that this distance was sufficient to prevent ignition under similar conditions. At 20 and 30 ft (6 and 9 m), damage probability varied with shed type, building orientation, and target materials. Results suggest that at a separation distance of roughly 20 ft (6 m), retrofits such as noncombustible siding, enclosed eaves, and dual pane tempered windows can substantially reduce ignition likelihood or envelope failure and help break the chain of conflagration.

Damage typically progressed sequentially as exposure increased, with early ignition of siding or eaves followed by window failure. Table 2 includes cases where structures transitioned directly to severe outcomes, skipping intermediate damage modes. In many tests, damage occurred during the decay phase rather than at peak exposure, emphasizing the role of cumulative heating over time. While Figure 10 illustrates the influence of distance on damage severity, its categorical format limits regression or other continuous analysis. This highlights the need for a probabilistic approach that links heat exposure intensity, duration, and material response to better capture how buildings respond to large outdoor fires.

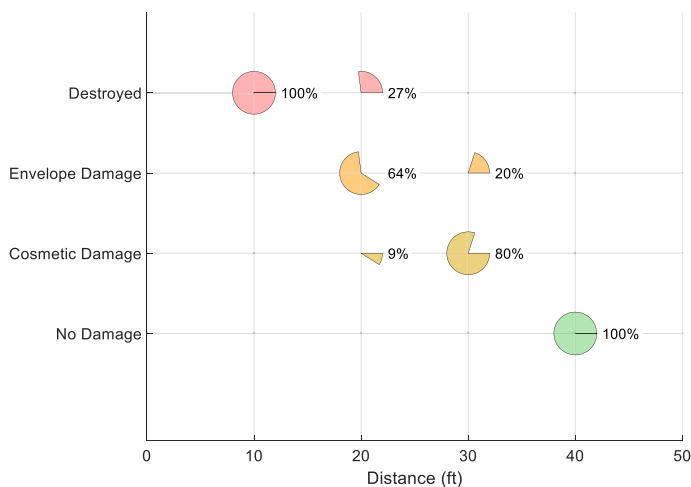


Fig. 10 Maximum observed damage outcomes from wood and steel shed tests (Tests 1–19) conducted under 20–30 mph wind conditions, categorized by separation distance to illustrate the effect of spacing on structure survivability

4 Discussion

When a solid material is exposed to heat, its surface temperature rises rapidly, and energy begins to conduct into the interior. The development of a temperature gradient affects the calculation of an ignition time and depends on the heat source and the material's thermo-physical properties. If a gradient forms, the material is thermally thick; if not, it is thermally thin. When the thermal penetration depth does not reach the rear surface and no heat loss occurs at the back, the material behaves as a semi-infinite solid. Mathematical idealizations are often used to represent thermally thick behavior in building materials [53, 54].

Experimentally, heat flux (kW m^{-2}) is the primary driver of thermal exposure and thus ignition. However, theoretically the potential for ignition is often assumed to occur once a material receives a minimum energy per unit area (kJ m^{-2}), representing the time-integrated heat flux. Under idealized conditions, this energy, referred to here as fluence following [52], is treated as a constant for a given material, linking temperature rise directly to accumulated energy. As temperature increases, materials may undergo physical changes (e.g., softening, fracture) and chemical changes (e.g., pyrolysis, ignition). While many combustibles ignite at similar temperatures, their ignitability differs due to variations in thermal inertia, which governs the rate of temperature rise and the ignition timescale [52]. The following sections examine how damage modes relate to instantaneous heat flux, cumulative energy, and the rate of accumulation.

4.1 Limitations of Conventional Metrics and Motivation for Fluence

Figures 11a and b show incident heat flux and energy time histories at the centerline of the target building for Tests 10, 13, 12, and 2, conducted under 20 to 30 mph wind, and Test 21, conducted under 50 to 60 mph (22–27 m/s) wind for comparison. The tests are arranged by increasing separation distance and represent different damage levels. Test duration varied depending on the observed outcome. If the target building ignited, classified as Destroyed, the test was terminated to protect equipment. Otherwise, it continued to allow for maximum heat absorption and to assess whether a delayed failure mode would occur. These five cases were selected for clarity, although similar trends were observed across all tests.

Regardless of separation distance, the instantaneous heat flux in these examples did not correlate with damage occurrence, either at the theoretical ignition threshold for wood [55] or even the peak levels. Several spikes of 100 kW m^{-2} – 140 kW m^{-2} were recorded at separation distances of 10 ft (3 m) (typical wind) and 20 ft (6 m) (high wind), yet failure did not occur at the time of these peaks. This apparent disconnect is further explained by the fire dynamics observed in the 20-ft test. Although heat flux trends at 10 ft and 20 ft were initially similar, the collapse of the asphalt roof around minute 13 in the 20-ft test restricted airflow, causing a sharp drop in fire intensity. The fire took nearly 8 minutes to recover, by which time much of the fuel was consumed. This collapse reduced the heating rate on the target building, demonstrating that significant heat accumulation can occur without corresponding damage when exposure is interrupted.

Instantaneous heat flux and total accumulated energy typically correlate with damage in conventional growth-steady-decay fires, where heat flux and energy rise proportionally, but these relationships weaken under wind driven, collapse influenced conditions where exposure is irregular, and absorption dynamics are disrupted. Figure 11b shows that steeper

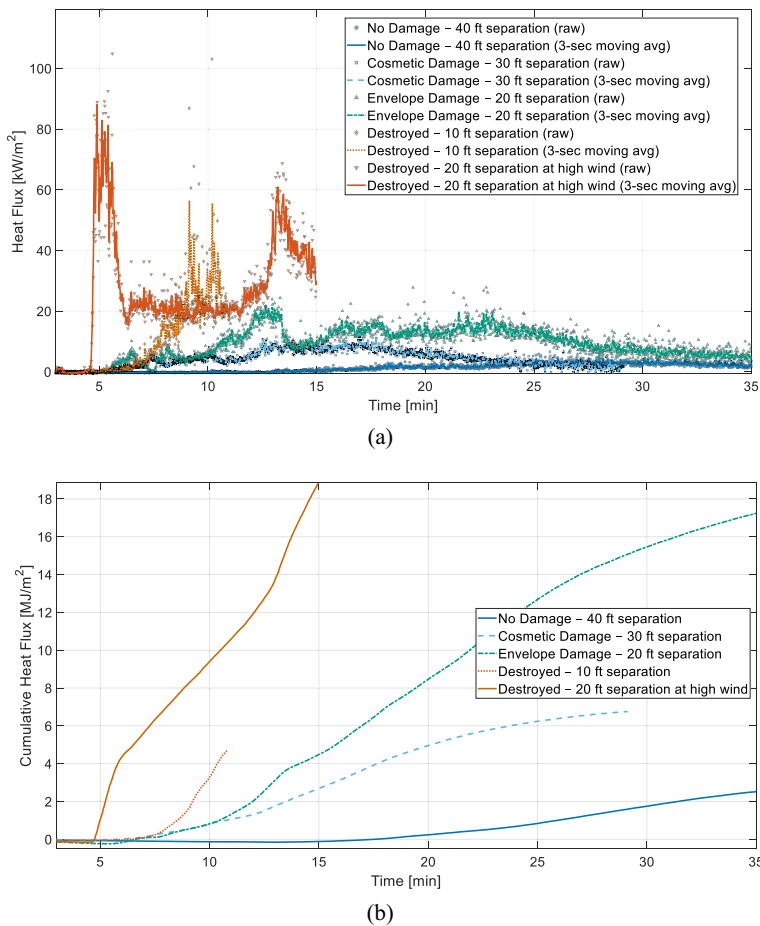


Fig. 11 **a** Down-sampled heat flux time histories (dots) with 3-second moving averages, and **b** integrated energy accumulation time histories from five tests with varying separation distances and wind conditions

slopes in the energy accumulation curves correspond to more severe damage. The slope represents the balance between heating and cooling. Over a fixed interval, a steeper slope indicates higher average heat flux and greater energy absorption, or a larger area under the heat flux curve during that period. The relevant time scale for evaluating this balance can be defined by the characteristic thermal response time (Δt), which provides a basis for calculating energy fluence in a way that couples fire exposure with material behavior: the heat flux reflects fire intensity, and Δt represents the material's ability to absorb and respond to heat. Mathematically, this relationship is expressed as: $\Phi(t, \Delta t) = \int_t^{t+\Delta t} q''(\tau) d\tau$, where $q''(\tau)$ is governed by the fire, and Δt by the materials. This approach focuses on physically meaningful intervals, capturing not just how much energy is accumulated, but how quickly it is delivered.

4.2 Physical Basis of Energy Fluence at Characteristic Time Scale

Thermal response time, also referred to as ignition delay time, friction time, or time to ignition, represents the transient period during which a material absorbs enough heat to reach ignition. This concept is widely applied in wildfire research and other engineering fields to characterize how solid fuels respond to thermal exposure [56]. The response is primarily governed by three factors: incident heat flux, exposure duration, and material thermal inertia. Depending on the process scale, from molecular reactions to atmospheric boundary layer behavior, relevant times range from atto-seconds to mega-seconds [56].

In engineering contexts, ignition studies usually assume steady state heat flux, yielding well established models for thermally thick and thermally thin materials. For thermally thick materials, ignition time varies inversely with the square of heat flux, while for thermally thin materials it varies inversely with heat flux [57]. For example, reducing the incident heat flux from 70 kW m^{-2} to 20 kW m^{-2} increases ignition time for engineered wood from a few seconds to several minutes. More recent models incorporate time varying flux profiles, such as linear or exponential ramps, to better represent fire growth [58, 59].

In WUI fires, heat flux is highly variable (Figure 11a), often showing extended sub-ignition preheating, rapid spikes, and sharp drops due to structural fuel collapse, changes in the wind speed/direction, and flame geometry shifts. Under such dynamic conditions, the thermophysical diversity of building envelope components precludes the use of a single, fixed thermal response time. However, selecting a characteristic response time for the structure allows the nonlinear behavior to be discretized into smaller, quasi-stationary intervals, enabling evaluation of the nominal energy absorbed during each period. Although a single fluence value may not correlate directly with damage, the statistical distribution of these fluences provides a probabilistic basis for distinguishing damage modes.

For generality, a 10 second thermal response time window, approximately the average value from Table 3, was used in this analysis. While other durations could be used, the selected window is not arbitrary; it lies within the physically justified range of the materials response times modeled as a semi-infinite solid exposed to different heating ramps. This choice is further supported by prior empirical and modeling studies, which show that the “overall” characteristic time for fire behavior spread between structures occurs over 5 seconds to 150 seconds [15]. For large-scale radiative and convective exposures, numerical models commonly assume response times in the range of 10 seconds to 100 seconds [56]. Similarly, Quintiere [55] reports that ignition of typical furniture under compartment fire conditions occurs around the one-minute mark. The sensitivity and detailed reasoning of this assumption is explored in Appendix B.

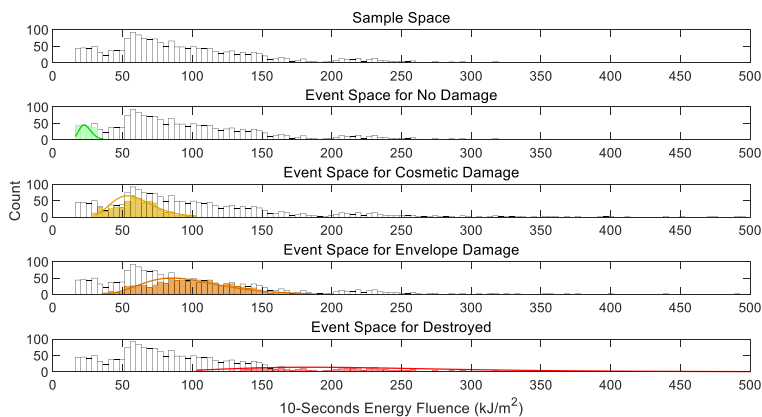
4.3 Statistical Relationship Between Fluence and Damage

Physical systems can exhibit both deterministic and probabilistic behaviors. While deterministic systems, like those governed by Fourier’s Law, exhibit deterministic behavior, wind-driven wildfires are fundamentally chaotic due to nonlinear interactions among fuels, atmospheric dynamics, and localized variability, which effectively “destroys the deterministic prediction” [60]. In such systems, probabilistic modeling becomes essential to capture uncertainty and improve predictive reliability [61]. A core component of probabilistic modeling is the use of random variables, numerical representations of phenomena rooted in

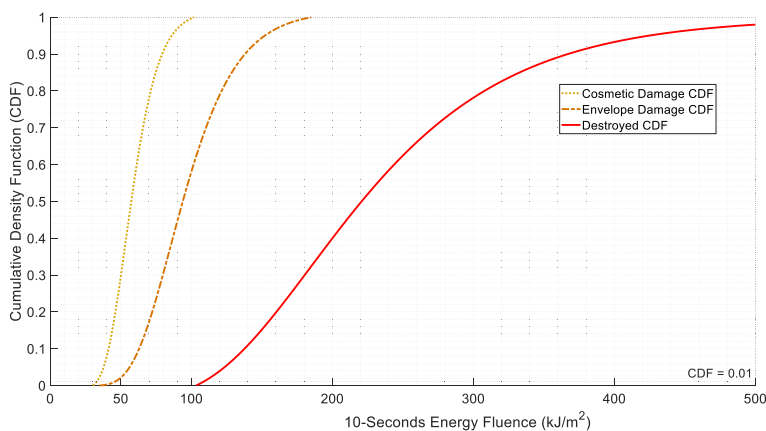
physical processes, defined over a sample space that includes all possible outcomes. Each outcome forms an event with an assigned probability between zero and one, described by a probability density function (PDF).

The top row of Figure 12a displays the distribution of 10-second energy fluences across all experiments. The subsequent rows show corresponding events for each damage mode, along with their fitted lognormal PDFs. The lognormal distribution was selected to model energy fluence due to its physical basis and strong empirical support in fire research [57]. Additionally, the Bayesian Information Criterion [62, 63], as detailed in the Supplemental Materials-H, strongly favors the lognormal model.

Energy fluence values were computed by integrating heat flux at the center of the target building over 10-second intervals, excluding flux values below 1 kW m^{-2} . Intervals overlapped by 25% to account for temporal correlation. A percentile-based trimming method was applied to reduce the influence of outliers, removing the lowest 25% and highest 5%



(a)



(b)

Fig. 12 Energy fluence distributions and fragility curves: **a** histograms and lognormal fits for damage categories from No Damage to Destroyed; **b** cumulative distributions defining probabilistic damage thresholds

of values. This asymmetric approach aligns with robust statistical practices [64, 65] and reflects the characteristics of positively skewed distributions such as the lognormal, where the upper tail spans a much wider range than the lower [66]. In fire engineering research, smaller heat flux and energy values are often excluded due to high measurement uncertainty, limited structural impact, or their role primarily in preheating [32, 67, 68].

The first row of Figure 12a represents the full sample space of all calculated energy fluence values obtained from the 23 tests. Fluence levels below 30 kJ m^{-2} have no observable effect on target materials, as such exposures either dissipate or produce negligible temperature rise. Cosmetic and Envelope damage appears only within the relevant statistical ranges shown in the second and third rows of Figure 12a. Some overlap between these distributions is expected, with the upper tail of the Cosmetic range aligning with the central region of the Envelope range. For example, a fluence of about 100 kJ m^{-2} results in near certain Cosmetic damage, while Envelope damage remains possible but less likely. Fluence values must exceed 108 kJ m^{-2} to reach the lower bound of the Destroyed category (bottom row of Figure 12a). Fluence levels below this threshold may contribute to preheating or intermediate damage limits but are insufficient to cause escalation without subsequent higher exposure. Each fluence value represents the total energy received during the 10 second window, and its position within overlapping distributions determines the likelihood of a particular damage level.

Fluence values after the Destroyed condition were excluded since tests ended at that point. For intermediate damage levels, data were kept to capture progression and overlap between modes; as fluence increased to the next distribution, the preceding mode had already occurred, reinforcing rather than biasing the probability. Pairwise Kolmogorov Smirnov [69] tests confirm that the four damage categories arise from significantly different distributions (see the Supplemental Materials-H).

Figure 12b presents the cumulative distribution functions (CDFs) for the three main damage modes. Although CDF thresholds can be adjusted to reflect risk tolerance, lower thresholds are typically applied for mission-critical outcomes such as destruction. For consistency, a uniform threshold of 0.01 was used for all damage modes, though different risk tolerances could be adopted for other applications.

These thresholds yield critical energy fluence magnitudes of 32 kJ m^{-2} , 45 kJ m^{-2} , and 108 kJ m^{-2} for Cosmetic, Envelope, and Destroyed distributions, respectively. While the 108 kJ m^{-2} threshold is statistically derived, it carries physical significance as it closely corresponds to the 11 kW m^{-2} heat flux threshold commonly associated with transition to ignition. For additional details on the relationship between fluence levels and damage modes, see Appendix B.

4.3.1 Damage Probability by Separation Distance

Identifying the statistical threshold among all possible energy fluence values enables analysis of their distribution at different separation distances. Figure 13 shows the distributions for tests conducted at 10, 20, 30, and 40 ft (3, 6, 9.1, and 12.2 m). At a 10-foot (3 m) separation, the probabilistic analysis produces a deterministic result, with all energy fluence values exceeding the 108 kJ m^{-2} destruction threshold. This indicates that, under typical wind driven conditions, a structure with similar fire-resistant features to the target building would be destroyed when exposed to a comparably fueled shed. At distances of 20, 30, and 40 ft, a

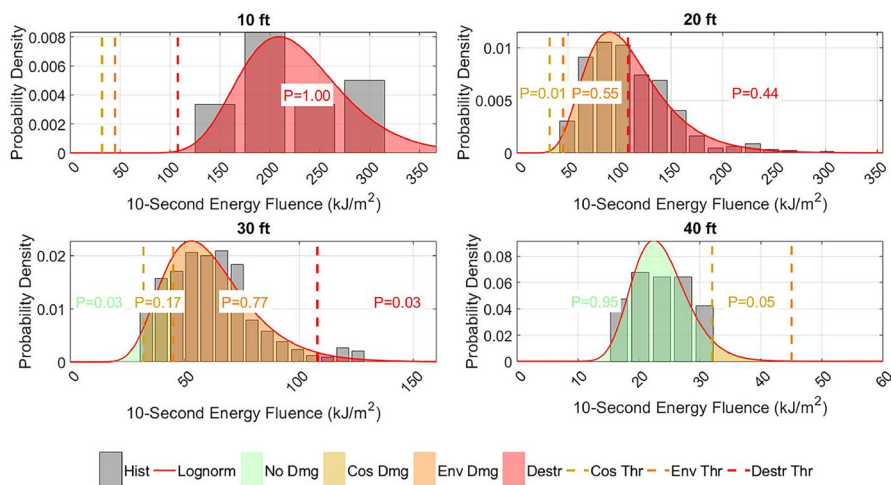


Fig. 13 Energy fluence distribution by separation distance showing declining fluence with distance

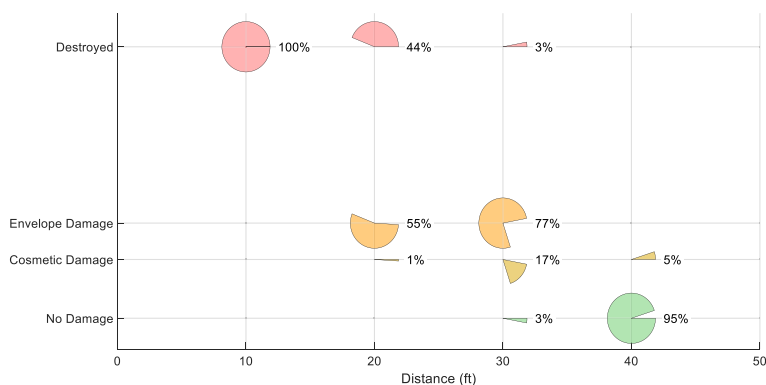


Fig. 14 Damage mode probabilities as a function of separation distance, assuming independent events and using the thresholds identified for each damage category at CDF = 0.01

broader range of outcomes appear, with probabilities shifting toward lower damage modes. At 40 ft (12.2 m), nearly all exposures fall below the Cosmetic damage threshold, demonstrating the risk reduction achieved through increased separation.

Figure 14 illustrates how damage probability varies with separation distance, using the thresholds identified in Figure 12b. Each category is treated independently, with only one damage mode assigned per test. Alternatively, to capture consecutive or overlapping damage modes within this framework, the maximum fluence from each test can be referenced against the CDF curves to determine the proportion of each damage mode represented in a single exposure. The data-driven results follow trends similar to Figure 10 but are skewed toward more severe outcomes because of the conservative threshold (CDF = 0.01); relaxing it to CDF = 0.1 yields closer agreement with Figure 10. By assigning numerical values to each damage category, regression analysis between damage and distance becomes possible. Using weighted averages, one can estimate either the expected damage level at a given

distance (weighted average per distance) or the typical distance at which a given damage category is most likely to occur (weighted average per category).

4.3.2 Effects of Extreme Wind on Exposure and Damage

To examine the effects of extreme wind, four additional tests were conducted at 50 to 60 mph (22–27 m/s). Under these conditions, the buoyant upward flow was largely overpowered by the wind when the target building was oriented at 45° (Figure 7a), causing flames and heat to be redirected horizontally toward the target structure. The exposure softened window frames and the wind pressure pushed window assemblies inward, breaching the building envelope. Figure 7b shows the energy fluence distributions from these high wind tests at 20 and 30 ft (6.1 and 9.1 m) separations. Exposure levels exceeded the critical threshold, and all cases were classified as Destroyed. These results highlight the potential for unique system level failures in full scale fire exposures and the need for performance based standards for complete window systems, including both glazing and framing, and emphasize the importance of a layered mitigation strategy that combines greater separation between combustibles, noncombustible fencing, removal of flammable materials between structures, and fire resistant retrofits. Only through such measures do materials have a fighting chance under extreme wind driven fire conditions.

4.4 Component-Level Vulnerability

Building codes typically regulate individual materials or components. In WUI fire conditions, however, the weakest part of the building envelope often determines overall structure vulnerability, particularly in the absence of active suppression. The proposed probabilistic framework addresses this by classifying structural damage based on the most vulnerable element and allowing statistical comparison of component level performance under equivalent energy fluence.

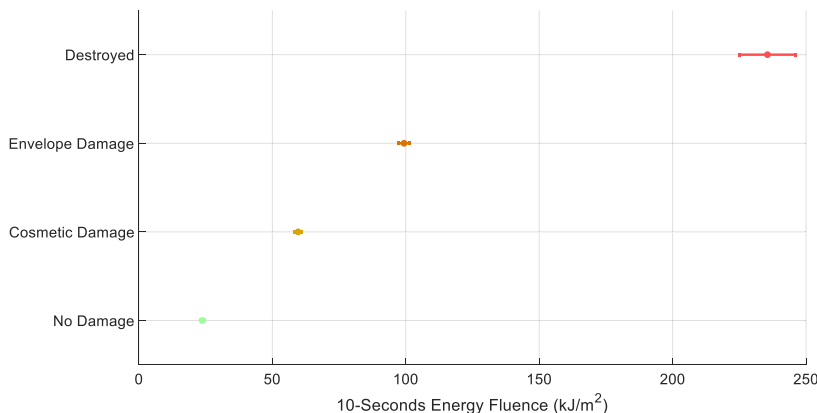
Two tests were conducted under identical conditions, differing only in siding material. One target building featured a split façade, half combustible and half noncombustible, while the other was fully clad in noncombustible siding. As shown in Table 2 (Tests 17 and 18), both experienced similar heat flux profiles until the combustible siding ignited, leading to a Destroyed classification, whereas the fully noncombustible structure sustained only Envelope Damage (Figure 15a). Despite comparable energy fluence, the difference in siding material shifted the outcome from Destroyed to Envelope Damage. The mean and standard deviation of the corresponding damage distributions (Figure 15b) differ by approximately 37–52%, highlighting the strong influence of siding configuration on overall damage outcomes in these experiments. Further validation through additional tests and real-world observations is needed to confirm these ranges.

5 Limitations and Future Research

This study is limited by its focus on specific construction materials and the fire intensities associated with the tested shed configurations. Fire exposures were intentionally selected at the upper end of the intensity range to represent worst case scenarios. While the proposed



(a)



(b)

Fig. 15 Impact of siding retrofit: **a** outcome photos comparing combustible and non-combustible façades, **b** probabilistic damage distributions with 95% confidence intervals

statistical framework allows the selection of different risk thresholds, the results presented here reflect a conservative case based on the tested conditions.

Although the framework is expected to remain valid under broader scenarios, its applicability is constrained when conditions differ from the tested single compartment fires, including variations in building geometry, material systems, connected fuels such as vehicles, fences, or landscaping, and differing wind environments. Uncertainty in heat flux measurements should also be acknowledged, as each gauge provides only a point measurement, and spatial variability across even a few meters can result in different heat flux time histories under these conditions. However, by selecting an appropriate risk threshold, such variability can be accounted for within the probabilistic framework. The current analysis also considers only flame driven hazards and does not account for ember exposure. Sensitivity analyses indicate that uncertainties in distribution fitting and variations in the selected response time window produce about a five percent change in the final damage classification probabilities.

To address these limitations, ongoing work includes full scale fire spread testing from larger source structures, such as furnished accessory dwelling units (ADUs), under varied wind and construction conditions. Complementary radiant panel testing is also underway

to develop material specific thermal resistance functions that will extend and generalize the probabilistic framework.

6 Summary and Conclusion

This study presents a series of full scale, wind driven building to building fire spread experiments aimed at quantifying the effect of separation distance on damage modes. While greater separation reduces the risk of conflagration, land use and infrastructure constraints often limit its feasibility. This raises a central question: what is the minimum separation distance at which resilient materials begin to perform effectively, where their benefits are not overwhelmed by heat exposure, thereby preventing ignition and breaking the chain of conflagration? The findings have direct implications for performance based design and the development of risk informed community standards in WUI codes.

The experimental results highlight the limitations of conventional metrics such as instantaneous or peak heat flux and total heat load, which do not consistently correlate with damage when materials are exposed to fires that deviate from the typical growth steady decay pattern. By treating buildings as thermally thick systems and analyzing energy accumulation over a characteristic response time of tens of seconds, a stronger statistical link to damage severity was established. This approach reframes the characterization of fire induced building damage through a single variable probabilistic framework grounded in the physical relationship between heat intensity, duration, and material thermophysical properties, represented by energy fluence. It captures the full continuum of damage, from no damage to destruction, and supports risk informed design by allowing users to define acceptable performance thresholds.

Results show that structures built with typical fire resistant materials are unlikely to survive at a 10 ft (3m) separation when exposed to fully involved shed. At 20 ft (6.1 m), fire resistant assemblies begin to perform effectively, while unmitigated structures still face high failure probabilities. At 30 ft (9.1 m), ignition risk is substantially reduced for all configurations, and at 40 ft (12.2 m), exposures in this study produced only Cosmetic damage.

The variety of failure modes observed demonstrates that no single mitigation measure can ensure structural resilience under wind driven fire exposure, especially given the trade-off between separation distance, land use, and housing density. Despite these challenges, structure separation remains a primary risk driver. New developments should tailor separation distances to material use, while existing dense communities should maximize hardening and minimize potential exposures by eliminating connective fuels, including outbuildings such as sheds.

Appendix A

Test Configurations, Component Details, and Thermal Measurements

See Table 1

Table 1 Combinations of test parameters including shed type, separation distance, target orientation, building components, and wind speed

Test number	Shed Configuration-Sensor Configuration	Separation distance (ft)	Target building angle (deg)	Target building components	Wind speed (mph)
1	a- α	40	45	Noncombustible with Open Eaves, Tempered Windows	23.3 $\pm$ 3.0
2	a- α	40	45	Noncombustible with Open Eaves, Tempered and annealed Windows	27.0 $\pm$ 3.4
3	a- α	30	45	Noncombustible with Open Eaves, Tempered Windows	25.9 $\pm$ 3.4
4	b- α	30	45	Noncombustible with Open Eaves, Tempered Windows	27.1 $\pm$ 2.3
5	f- α	20	45	Noncombustible with Open Eaves, Tempered Windows	26.0 $\pm$ 2.9
6	g- α	20	45	Noncombustible with Open Eaves, Tempered Windows	26.6 $\pm$ 2.7
7	h- α	20	45	Noncombustible with Open Eaves, Tempered Windows	26.1 $\pm$ 2.8
8	i- α	20	45	Noncombustible with Open Eaves, Tempered and annealed Windows	27.4 $\pm$ 2.0
9	c- α	20	45	Noncombustible with Open Eaves, Tempered Windows	27.0 $\pm$ 2.0
10	g- α	10	45	Noncombustible with Open Eaves, Tempered Windows	26.8 $\pm$ 2.3
11	h- α	20	45	Noncombustible with Open Eaves, Tempered Windows	23.3 $\pm$ 2.1
12	d- α	30	45	Combustible with Open Eaves, Tempered Windows	25.9 $\pm$ 1.2
13	c- α	20	45	Combustible with Open Eaves, Tempered Windows	27.3 $\pm$ 2.1
14	c- ε	20	0	Combustible and Noncombustible Open Eaves, Tempered and annealed Windows	24.2 $\pm$ 2.3
15	e- δ	30	0	Combustible and Noncombustible Open Eaves, Tempered Windows	22.5 $\pm$ 1.6
16	e- δ	20	0	Combustible and Noncombustible Open Eaves, Tempered Windows	22.1 $\pm$ 1.5
17	j- δ	20	0	Combustible and Noncombustible, Open Eaves, Tempered Windows	22.9 $\pm$ 1.5
18	j- ε	20	0	Noncombustible with Closed Eaves, Tempered Windows	20.1 $\pm$ 1.0
19	j- ε	30	0	Noncombustible with Closed Eaves, Tempered Windows	21.6 $\pm$ 1.0
20	e- ε	20	0	Noncombustible with Closed Eaves, Tempered Windows	56.6 $\pm$ 1.1
21	e- β	20	45	Combustible and Noncombustible Closed Eaves, Tempered Windows	56.4 $\pm$ 1.2
22	e- α	30	45	Combustible and Noncombustible Closed Eaves, Tempered Windows	60.2 $\pm$ 1.4
23	j- γ	20	45	Noncombustible with Closed Eaves, Tempered Windows	59.9 $\pm$ 1.2

The letter codes for shed and sensor configuration are described in the Supplementary Material

See Table 2

Table 2 Summary of damage modes and associated heat flux (HF) and heat load (HL)

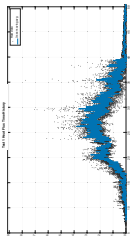
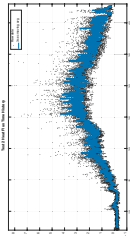
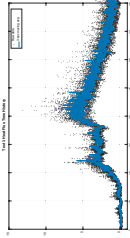
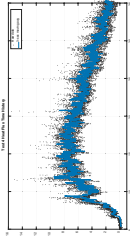
TEST	Shed material-Separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glazing HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
1	Wood-40	No Damage	6.7(29)	No	No	No	No	No		
2	Wood-40		7.3(30)	No	No	No	No	No		
3	Wood-30	Cosmetic	13(26)	6-2.7(26:40)	No	No	No	No		
4	Wood-30	Cosmetic	16(20)	6-0.8-(10:48)	No	No	No	No		

Table 2 (continued)

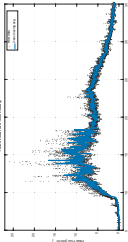
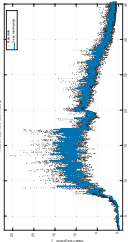
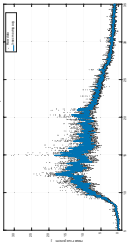
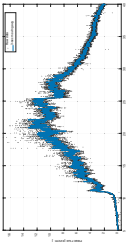
TEST	Shed materi- al-Separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glaz- ing detached HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
5	Steel-20	Cosmetic	27(14)	15-1.7- (13:38)	No	No	No	No		
6	Steel-20	Envelope	28(13)	11-2.1- (11:35)	7-6.7- (18:35)	No	No	No		
7	Steel-20	Envelope	33(15)	9-0.6-(11)	9-6.1-(19)	No	No	No		
8	Steel-20	Envelope	17(19)	13-4.4- (21:25)	5-10.4- (32:41)	No	No	No		

Table 2 (continued)

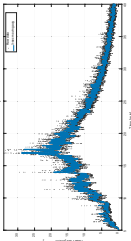
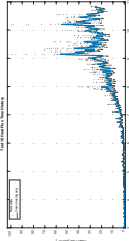
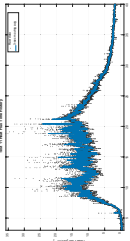
TEST	Shed materi- al-Separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glaz- ing detached HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
9	Wood-20	Envelope	34(17)	5-1.1-(10:25)	21-8- (18:30)	Yes, unknown time	No	No		
10	Steel-10	Destroyed	102(9)	18-0.9-(8:20)	No	No	No	28-3.2- (10)		
11	Steel-20	Envelope	36(19)	11-1.7- (10:06)	12-11.8- (23:04)	No	No	No		

Table 2 (continued)

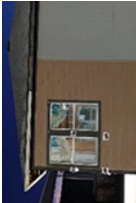
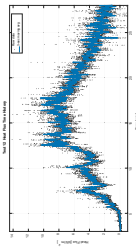
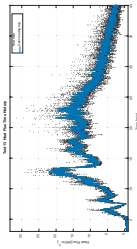
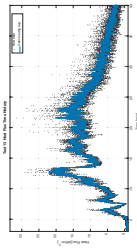
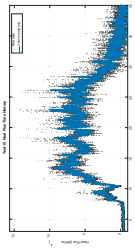
TEST	Shed material-separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glazing detached HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
12	Wood-30	Cosmetic	14(12)	7-1.9-(13:03)	No	No	No	No		 
13	Wood-20	Envelope	33(23)	12-1.7-(11:41)	11-12.7-(23:05)	No	No	No		
14	Wood-20	Destroyed	unk (unknown)	unk- unk-(7:40)	unk- unk-(9:25)	No	No	unk-unk-(7:35)		DAQ failed during the experiment
15	Wood-30	Cosmetic	15(23)	2.3-0.1-(10:25)	No	No	No	No		

Table 2 (continued)

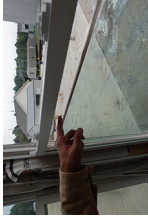
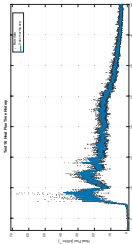
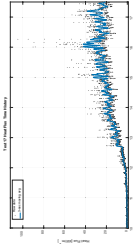
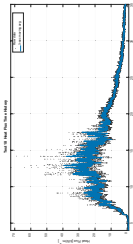
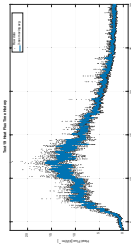
TEST	Shed material-separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glazing detached HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
16	Wood-20	Destroyed	71(9)	11-0.1-(7:30)	17-7.1-(13)	Yes, unknown time	Yes, unknown time	No		
17 ^b	Steel-20	Destroyed	112(12)	8-0.3-(9)	No ^c	No	No	23-6.4-(13:52 ^d)		
18	Steel-20	Envelope	72(13)	24-0.2-(7:20)	13-14.8-(20)	Yes, unknown time	No	No (NC)		
19	Steel-30	Envelope	24(12)	8.3-0.8-(7:40)	8-6.5-(16:38)	Yes, unknown time	No	No ⁶		

Table 2 (continued)

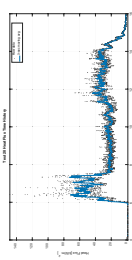
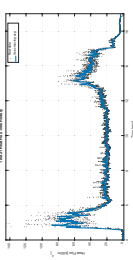
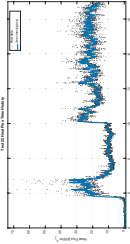
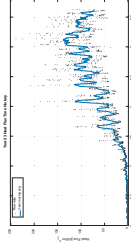
TEST	Shed material-separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glazing detached HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
20	Wood-20	Destroyed	148(6)	48-0.08-(6:15)	21-5.7-(8:55)	Yes, unknown time	29-13.1-(13:30)	No ^e		
21	Wood-20	Destroyed	144(5)	31-0.1-(4:44)	16-4.7-(6:20)	Yes, unknown time	43-14.7-(13:18)	42-17-(14:30) ^f		

Table 2 (continued)

TEST	Shed material-separation distance (ft)	Damage Category	Peak HF (Time)	vinyl glazing detached HF-HL (Time)	window pane failed HF-HL (Time)	window frame deformed HF-HL (Time)	window assembly failed HF-HL (Time)	Ignition HF-HL (Time)	Photo of the damage	Heat flux Time History ^a
22	Wood-30	Destroyed	74(7)	21-1.1-(6:45)	19-10-(15:20)	Yes, unknown time	13-12-(16:50)	No		
23	Steel-20	Destroyed	207 (8)	87-0.9-(7:40)	168-10-(9:30)	Yes, unknown time	No	94-4.8-(8:40)		

Heat flux is reported in kW m⁻², heat load in MJ m⁻², and time in minutes: seconds)
Due to flame and smoke obstructions, some timings are approximate estimates.

^aThree second moving average

^b4 minutes of background data was collected

^cWindow pane slid down but did not fall

^dStarted off-gassing around t=12 min

^eFiber-cement siding

^fSome off gassing, no ignition

Appendix B

Sensitivity to Time Window

The proposed framework builds on the methodology described in Himoto [57], which models fire spread as the probability that external heating (H) exceeds the resistance (R) of nearby structures. Due to variability in heating and construction, fully capturing this behavior in real fires is impractical. The main challenge is identifying statistically and physically meaningful variables for H and R with common units that allow direct comparison and support the development of vulnerability curves at both component and system levels, similar to those used for wind, earthquake, and tsunami design [70–72].

As with wind design standards, where the United States uses a three second gust, Japan a ten minute average, and Australia a 0.2 second peak gust [73, 74], there is likely no single universal metric for characterizing material response to external heating from large outdoor fires. The probabilistic framework integrates the heat flux signal over a finite time window to calculate energy fluence. Selecting an appropriate window length is critical: if it is too short, brief high flux spikes dominate; if too long, meaningful transients become diluted, masking materials with lower thermal inertia.

Most engineering models assume uniform or idealized heating, with some incorporating linear or exponential heat flux profiles. Among these, a linearly increasing heat flux is often the most practical approximation of real fire behavior, balancing realism with computational and conceptual simplicity. This assumption and its related mathematical treatment are discussed further in Reszka et al. [75].

The temperature distribution, $\theta(x, t)$, in semi-infinite solids, a common assumption for building materials [55, 57], is governed by:

$$\frac{\partial \theta(x, t)}{\partial t} = \alpha \frac{\partial^2 \theta(x, t)}{\partial x^2}$$

where α is the thermal diffusivity of the material, and $\theta(x, t) = T(x, t) - T_\infty$. For a semi-infinite solid exposed to a linearly increasing heat flux, with no loss and an initial uniform temperature, the boundary and initial conditions are:

$$q''_{net}(t) = mt; \theta(x, t) = 0, x \rightarrow \infty; \theta(x, 0) = T_i$$

The expression for the time to ignition under these conditions is presented in Reszka et al. [75], and with some algebraic substitutions and manipulations, the closed-form solution for this equation becomes:

$$t_{ig} = \left[\frac{3\sqrt{\pi}\theta_{ig}(k\rho c_p)^{1/2}}{4m} \right]^{2/3}$$

Table 3 Thermal response time (sec) of materials to reach the average mentioned failure temperature range in seconds (failure time) from initial temperature of 20°C

Ramp rate (W/m ² ·s)	Window glass pane (93–265°C) [77]	Plywood (300– 365°C) [78]	PVC (115– 245°C) ^a [79]	Fiber ce- ment boards (>400°C) [80]
1000	49.5	25.4	19.4	33.9
2000	31.2	16	12.2	21.3
3000	23.8	12.2	9.3	16.3
4000	19.6	10.1	7.7	13.3
5000	16.9	8.6	6.6	11.6
6000	15	7.8	5.9	10.3
7000	13.5	6.9	5.3	9.2

Thermal properties are taken from: [76] & UL-FSRI material library

^aDepending on the size and perfection of the crystallites

where k is the thermal conductivity, ρ is the density, c_p is the specific heat (numerical values can be found in Himoto [57], θ is the ignition temperature, and m is the heating ramp rate.

Heat ramps were calculated in all tests from the heat flux curves. The 75th percentile ranged from $-2 \text{ kW m}^{-2} \text{ s}^{-1}$ to $7 \text{ kW m}^{-2} \text{ s}^{-1}$, with most values between $0.9 \text{ kW m}^{-2} \text{ s}^{-1}$ and $7 \text{ kW m}^{-2} \text{ s}^{-1}$. Using the positive ramp range, estimated times to reach failure temperatures for target materials are presented in Table 3. Although the exact failure times vary among materials, the key finding is that nominal thermal response times fall between instantaneous heating and the full burn duration, depending on the applied heat-flux ramp rate, consistent with the trends shown in Figure 10.

A 10 second window, approximately the median value from Table 3, was used in this study, but the framework remains robust across reasonable time variations. Long integration windows greater than 100 seconds can obscure critical fluctuations by averaging transient fire behavior, often missing intermediate damage and emphasizing late stage heat transfer. They also group a wide range of values into single bins, introducing discontinuities and reducing the reliability of probability density fitting. Shorter windows avoid this but have their own limitations. Brief, high intensity spikes from intermittent flame contact (Figure 10) in Envelope damage tests do not cause failure yet disproportionately shift the statistical distribution to the right. While short windows are not invalid, their correlation with damage is less reliable when fluence is treated as an independent random variable. In this study, it was not necessary to incorporate heating history beyond the building's characteristic thermal response time, as the probabilistic framework produced stable results using the 10-second fluence. Nonetheless, the concept of effective fluence, which accounts for cumulative heating through an exponential memory term, is discussed in the Supplemental Materials-I as an extension for more variable or gust-driven conditions. Supplemental Materials-I also presents a sensitivity analysis of fluence duration, showing that variations in integration window length influence the resulting probabilities by less than 5%, with detailed damage distributions summarized in Table S4.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10694-025-01854-3>.

Acknowledgement The authors would like to express their deep gratitude to the executive leadership of the Insurance Institute for Business & Home Safety (IBHS) for their support and commitment throughout the four-year duration of this project. This work would not have been possible without the invaluable contributions of numerous IBHS staff members, whose dedication, expertise, and effort greatly enhanced every

stage of the project. We are honored to acknowledge the following individuals, listed in alphabetical order: Danny Baker, Rick Baker, Mary Anne Byrd, Sarah Dillingham, Robert Ealey, Conrad Estes, Lucas Faulkner, Katie Fischer, Chris Gay, Rachael Gauthier, Christina Gropp, Carlos Gutierrez, Shawn Macomber, Ross Maiden, Katy Martin, Aubery Marcinko, David McClain, Brenna Meisenzahl, Sherry Melton, David Morris, Aaron Prabhakaran, Justin Privette, Nasim Rashidi, Milad Shabani, Aaron Shell, Courtney Schultz, Junior Stewart, Josh Sturgis, Tom Trout, David Trull, Amanda West, T.J. Wilson. We are grateful to the leadership at CALFIRE for their financial support, which significantly contributed to the successful execution of this research. We are sincerely appreciative of the Richburg Fire Department for their essential on-site support, which was critical to the safe and successful completion of these tests. We would also like to thank Jose Rivera at the Berkeley Fire Research Lab and Roddy Mell at the U.S. Forest Service Pacific Wildland Fire Sciences Lab for their contributions. We wish to acknowledge our colleagues at the National Institute of Standards and Technology (NIST) for their collaboration during the planning phases. In particular, we thank Matthew Bundy, Matthew Hoehler, Eric Link, Alexander Maranghides, and Shonali Nazare, listed here in alphabetical order, for their thoughtful insights. Finally, we also thank the anonymous reviewers for their constructive feedback and suggestions, which helped improve the clarity and quality of this work.

Funding This research was jointly funded by the California Department of Forestry and Fire Protection (CAL FIRE) and the Insurance Institute for Business & Home Safety (IBHS) through a Collection Agreement with the U.S. Forest Service. The funding agencies had no role in the preparation of the data, the manuscript, or the decision to submit for publication.

Data Availability Data supporting the findings of this study are available upon request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

References

1. Sekizawa A (2023) 1923 Great Kanto earthquake: fire damage and lessons learned. *J Disaster Res* 18(6):558–561
2. Blanchi R, Leonard J, Haynes K, Opie K, James M, de Oliveira FD (2014) Environmental circumstances surrounding bushfire fatalities in Australia 1901–2011. *Environ Sci Policy* 37:192–203
3. Landis MS, Edgerton ES, White EM, Wentworth GR, Sullivan AP, Dillner AM (2018) The impact of the 2016 Fort McMurray Horse River wildfire on ambient air pollution levels in the Athabasca Oil Sands Region, Alberta, Canada. *Sci Total Environ* 618:1665–1676
4. Maranghides A, Link E, Hawks S, Wilson M, Brewer W, Brown C, et al (2021) A Case study of the camp fire–fire progression timeline appendix C. Community WUI Fire Hazard Evaluation Framework.
5. Sharma R, Arneson E, Valdes-Vasquez R, Bhattarai N (2024) Marshall fire's impact on Colorado housing market.
6. Hedayati F, Monroy X, Sluder E, Fallahian H, SHabani M (2024) The 2023 Lahaina Conflagration. Richburg, SC: Insurance Institute for Business & Home Safety.
7. Kerber S, Alkonis D (2024) Lahaina fire comprehensive timeline report. Fire Safety Reserach Institute.

8. Cohen JD, Stratton RD (2008) Home destruction examination: Grass valley fire, Lake Arrowhead, California. Tech Paper R5-TP-026b Vallejo, CA: US Department of Agriculture, Forest Service, Pacific Southwest Region (Region 5) 26 p
9. Potter M, Leonard J (2011) Spray system design for ember attack-Research findings and discussion paper.
10. Giammanco I, Hedayati F, Hawks S, Monroy X, Evan S (2023) The return of conflagration in our built environment. IBHS.
11. Nazare S, Leventon I, Davis R (2021) Ignitibility of structural wood products exposed to embers during wildland fires: a review of literature. National Institute of Standards and Technology, Gaithersburg
12. Yuan S, Xiang K, Yan F, Liu Q, Sun X, Li Y et al (2022) Characteristics and mechanism of fire spread between full-scale wooden houses from internal fires. *Buildings* 12(5):575
13. Cohen JD. Structure ignition assessment model (SIAM). In: Weise, David R; Martin, Robert E, technical coordinators The Biswell symposium: fire issues and solutions in urban interface and wildland ecosystems; February 15-17, 1994; Walnut Creek, California Gen Tech Rep PSW-GTR-158 Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture; p 85-921995.
14. Narayanan V, Oguaka A, Walls RS (2022) Reduced scale experiments on fire spread involving multiple informal settlement dwellings. *Fire* 5(6):199
15. Himoto K, Shinohara M, Sekizawa A, Takashi K-i, Saiki H (2018) A field experiment on fire spread within a group of model houses. *Fire Saf J* 96:105–114
16. Masoudvaziri N, Bardales FS, Keskin OK, Sarreshtehdari A, Sun K, Elhami-Khorasani N (2021) Streamlined wildland-urban interface fire tracing (SWUIFT): modeling wildfire spread in communities. *Environ Model Softw* 143:105097
17. Regan JW, Bryant J, Weinschenk CG (2020) Analysis of the coordination of suppression and ventilation in single-family homes. Underwriters Laboratory, Firefighter Safety Research Institute.
18. Hasemi Y (1997) Full-scale burn test of wooden three-story apartment building. *Fire Sci Technol* 17(1):78–92
19. Cicione A, Walls RS, Kahanji C (2019) Experimental study of fire spread between multiple full scale informal settlement dwellings. *Fire Saf J* 105:19–27
20. Maranghides A, Nazare S, Link E, Bundy M, Chernovsky A, Johnsson E et al (2022) NIST outdoor structure separation experiments (NOSSE): preliminary test plan. US Department of Commerce, National Institute of Standards and Technology, Gaithersburg
21. Maranghides A, Nazare S, Link E, Butler K, Johnsson EL, Bundy M et al (2023) NIST Outdoor Structure Separation Experiments (NOSSE) with Wind. US Department of Commerce, National Institute of Standards and Technology, Gaithersburg
22. Maranghides A, Johnsson EL, Maranghides A (2008) Residential structure separation fire experiments. US Department of Commerce, National Institute of Standards and Technology, Gaithersburg
23. Lee Y-P, Delichatsios M, Ohmiya Y, Wakatsuki K, Yanagisawa A, Goto D (2009) Heat fluxes on opposite building wall by flames emerging from an enclosure. *Proc Combust Inst* 32(2):2551–2558
24. Yuen ACY, Chen TBY, Li A, De Cachinho Cordeiro IM, Liu L, Liu H et al (2021) Evaluating the fire risk associated with cladding panels: an overview of fire incidents, policies, and future perspective in fire standards. *Fire Mater* 45(5):663–689
25. Willi JM, Gorham DJ, Horn GP (2024) Window pane failure during exterior fire exposure. *Fire Technol*. <https://doi.org/10.1007/s10694-024-01656-z>
26. Gorham DJ, Willi JM, Horn GP (2025) Residential exterior wall reaction to post-flashover compartment fires. *Fire Mater*. <https://doi.org/10.1002/fam.3278>
27. Wang Y, Gibson L, Beshir M, Rush D (2021) Determination of critical separation distance between dwellings in informal settlements fire. *Fire Technol* 57(3):987–1014
28. Maranghides A, Nazare S, Hedayati F, Gorham D, Link E, Hoehler M, et al (2022) Structure Separation Experiments: Shed Burns without Wind.
29. Babrauskas V (2003) Ignition handbook: principles and applications to fire safety engineering, fire investigation, risk management and forensic science. Fire Science Publishers, Issaquah
30. Babrauskas V (2002) Ignition of wood: a review of the state of the art. *J Fire Prot Eng* 12(3):163–189
31. Simms DL (1963) On the pilot ignition of wood by radiation. *Combust Flame* 7:253–261
32. Cohen JD (2004) Relating flame radiation to home ignition using modeling and experimental crown fires. *Can J Forest Res* 34(8):1616–1626
33. Quintiere JG (2006) Fundamentals of fire phenomena.
34. Vacca P, Caballero D, Pastor E, Planas E (2020) WUI fire risk mitigation in Europe: a performance-based design approach at home-owner level. *J Saf Sci Resil* 1(2):97–105
35. Willi JM, Gorham DJ, Horn GP (2025) Window pane failure during exterior fire exposure: window pane failure during exterior fire exposure. *Fire Technol* 61(4):1613–1645

36. Gorham DJ, Willi JM, Horn GP (2025) Residential exterior wall reaction to post-flashover compartment fires. *Fire Mater*. <https://doi.org/10.1002/fam.3278>
37. Shields T, Silcock G, Murray J (1994) Evaluating ignition data using the flux time product. *Fire Mater* 18(4):243–254
38. Moyssey E, Muir W (1968) Pilot ignition of building materials by radiation. *Fire Technol* 4(1):46–50
39. Hedayati F, Yang W, Zhou A (2018) Effects of moisture content and heating condition on pyrolysis and combustion properties of structural fuels. *Fire Mater* 42(7):741–749
40. Brown CU, Maranghides A, Nazare S, Di Cristina G, Bailey DM, Fox L et al (2024) NIST eave and vent experiments (EaVE) EaVEs phase a: test plan. US Department of Commerce, National Institute of Standards and Technology, Gaithersburg
41. Maranghides A, Link ED, Nazare S, Hawks S, McDougald J, Quarles S, et al. WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology. NIST Technical Note2022.
42. Syphard AD, Brennan TJ, Keeley JE (2017) The importance of building construction materials relative to other factors affecting structure survival during wildfire. *Int J Disaster Risk Reduct* 21:140–147
43. Dossi S, Messerschmidt B, Ribeiro LM, Almeida M, Rein G (2022) Relationships between building features and wildfire damage in California, USA and Pedrógão Grande, Portugal. *Int J Wildland Fire*. <https://doi.org/10.1071/WF22095>
44. Knapp EE, Valachovic YS, Quarles SL, Johnson NG (2021) Housing arrangement and vegetation factors associated with single-family home survival in the 2018 Camp Fire, California. *Fire Ecol* 17(1):1–19. <https://doi.org/10.1186/s42408-021-00117-0>
45. Standohar-Alfano C, Estes H, Johnston T, Morrison M, Brown-Giammanco T (2017) Reducing losses from wind-related natural perils: research at the IBHS research center frontiers in built environment.
46. Hedayati F, Merhi A, Morrison M (2023) Reconstruction of wind field measurements: a machine learning approach. 16th International Conference on Wind Engineering. Florence
47. McGrattan K, McGrattan K (2020) Heat release rates of multiple transient combustibles. US Department of Commerce, National Institute of Standards and Technology, Gaithersburg
48. Backstrom B, Sloan D, Gandhi P (2012) Effect of rack mounted photovoltaic modules on the fire classification rating of roofing assemblies phase 2. Underwriters' Laboratories, Northbrook
49. California State Fire Marshal. Materials and Construction Methods for Exterior Wildfire Exposure. In: California Building Standards Commission, editor. Title 24; Part 2. Club Hills, Illinois: International Code Council, Inc.; 2022.
50. van de Lindt JW, Dao TN (2009) Performance-based wind engineering for wood-frame buildings. *J Struct Eng* 135(2):169–177
51. ASTM-E119 (2022) ASTM E119-24: Standard test methods for fire tests of building construction and materials. West Conshohocken
52. Babrauskas V (2003) Ignition handbook. Fire Science Publishers, Issaquah
53. Hurley MJ, Gottuk DT, Hall JR Jr, Harada K, Kuligowski ED, Puchovsky M et al (2015) SFPE handbook of fire protection engineering. Springer, Berlin
54. Drysdale D (2011) An introduction to fire dynamics. Wiley, Hoboken
55. Quintiere JG (2006) Ignition of solids. *Fundamentals of Fire Phenomena*. p. 159-90.
56. Sullivan AL (2009) Wildland surface fire spread modelling, 19902007. 1: Physical and quasi-physical models. *Int J Wildland Fire* 18(4):349–368. <https://doi.org/10.1071/WF06143>
57. Himoto K (2022) Large outdoor fire dynamics. CRC Press, Boca Raton
58. Parot R, Rivera JI, Reszka P, Torero JL, Fuentes A (2022) A simplified analytical model for radiation dominated ignition of solid fuels exposed to multiple non-steady heat fluxes. *Combust Flame* 237:111866
59. Zhai C, Gong J, Zhou X, Peng F, Yang L (2017) Pyrolysis and spontaneous ignition of wood under time-dependent heat flux. *J Anal Appl Pyrolysis* 125:100–108
60. Danta JM, Egorova VN, Pagnini G (2024) Predicting the arrival of the unpredictable: an approach for foreseeing the transition to chaos of wildfire propagation. *Commun Nonlinear Sci Numer Simul* 138:108190
61. Bendat JS, Piersol AG (2011) Random data: analysis and measurement procedures. Wiley, Hoboken
62. Chakrabarti A, Ghosh JK (2011) AIC, BIC and recent advances in model selection. *Philosophy of statistics*. 583-605.
63. Kass RE, Raftery AE (1995) Bayes factors. *J Am Stat Assoc* 90(430):773–795
64. Wilcox R (2017) Modern statistics for the social and behavioral sciences: a practical introduction. Chapman and Hall/CRC, Boca Raton
65. Maronna RA, Martin RD, Yohai VJ, Salibián-Barrera M (2019) Robust statistics: theory and methods (with R). Wiley, Hoboken
66. Cheng K, Young DS (2023) An approach for specifying trimming and winsorization cutoffs. *J Agric Biol Environ Stat* 28(2):299–323

67. Babrauskas V (1995) Specimen heat fluxes for bench-scale heat release rate testing. *Fire Mater* 19(6):243–252
68. Torero JL, Majdalani AH, Abecassis-Empis C, Cowlard A (2014) Revisiting the compartment fire. *Fire Saf Sci* 11:28–45
69. Press WH (2007) Numerical recipes 3rd edition: the art of scientific computing. Cambridge University Press. Cambridge
70. Merhi A, Andow B, Cruzado H, Letchford C, Lombardo F (2025) A framework for post-windstorm functional recovery of non-residential buildings applied to hospitals. *Reliab Eng Syst Saf* 253:110508
71. Koshimura S, Namegaya Y, Yanagisawa H (2009) Tsunami fragility: a new measure to identify tsunami damage. *J Disaster Res* 4(6):479–488
72. Shinozuka M, Feng MQ, Lee J, Naganuma T (2000) Statistical analysis of fragility curves. *J Eng Mech* 126(12):1224–1231
73. Okada H, Okuda Y, Kikitsu H (2002) Wind load provisions of the revised building code in Japan. *Tech Note Natl Inst Land Infrastruct Manag* 41:67–71
74. Lombardo FT (2021) History of the peak three-second gust. *J Wind Eng Ind Aerodyn* 208:104447
75. Reszka P, Borowiec P, Steinhaus T, Torero J (2012) A methodology for the estimation of ignition delay times in forest fire modelling. *Combust Flame* 159(12):3652–3657
76. Incropera FP, DeWitt DP, Bergman TL, Lavine AS (1996) Fundamentals of heat and mass transfer. Wiley, New York
77. Mowrer FW, Mowrer FW (1998) Window breakage induced by exterior fires. National Institute of Standards and Technology Gaithersburg, Gaithersburg
78. Atreya A (1998) Ignition of fires. *Philos Trans R Soc London, Ser A* 356(1748):2787–2813
79. Summers JW (2008) The melting temperature (or not melting) of poly (vinyl chloride). *J Vinyl Addit Technol* 14(3):105–109
80. Szymków M (2018) Identification of the degree of destruction of fiber-cement boards under the effects of high temperature, Raport serii PRE nr 9/2018. Wydział Budownictwa Lądowego i Wodnego, Politechnika Wrocławska Wrocławska.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.