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An Experimental Study on Fire Propagation and Survival in Informal Settlements

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Abstract

In recent years, the region of Valparaíso has faced devastating fires, notably the Viña del Mar fire on 2 February 2024, which affected 9252 hectares. This study analyzes fire behavior in informal settlements and assesses the effectiveness of different construction materials through scaled prototypes of dwellings made from MDF, OSB, TetraPak, and flame-retardant resin composites. Controlled fire experiments were conducted, recording fire spread times and atmospheric conditions. Results confirm significant differences in fire spread rates and structural survival times between materials, highlighting the practical benefit of fire-resistant alternatives. The Kaplan–Meier survival analysis indicates critical time thresholds for rapid flame escalation and structural collapse under semi-open conditions, supporting the need for improved safety measures. Burn pattern observations further revealed the role of wind, thermal radiation, and material properties in fire dynamics. Overall, this study provides experimental evidence aligned with real fire scenarios, offering quantified insights to enhance fire prevention and response strategies in vulnerable settlements. These findings provide an exploratory basis for understanding fire dynamics in informal settlements but do not constitute definitive design prescriptions.

Keywords: fire propagation; informal settlements; construction materials; fire spread velocity; structural collapse; Kaplan–Meier analysis; small-scale fire experiments; fire-resilient design

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1. Introduction

The increasing frequency and intensity of wildfires—driven by climate change, unregulated urban growth, and socio-environmental vulnerabilities—has significantly impacted informal settlements around the world [1]. These environments, often located at the urban–wildland interface, are highly susceptible to rapid fire propagation due to the use of combustible materials, lack of regulatory oversight, and minimal spacing between dwellings. In Chile, the Valparaíso region has become a critical case study, having experienced multiple large-scale fires over the past decade. The Viña del Mar fire on 2 February 2024, affected over 9200 hectares, marking the most destructive disaster in the country in thirty years [2]. Earlier, in 2017, a similar event consumed 140 homes in densely built informal areas [3].

Comparable incidents have been extensively documented in South Africa and Portugal, where dense informal settlements and wildland–urban interface (WUI) zones have experienced catastrophic fires under high-wind conditions [4–6]. These cases highlight the combined effect of combustible building materials, poor spatial planning, and limited regulatory enforcement, resulting in extreme fire spread rates and large-scale structural loss.

In these settings, fires can destroy dozens of homes within minutes, placing residents and firefighters in extreme danger. The destructive potential of fire in informal settlements extends beyond human loss, damaging ecosystems and severely disrupting already fragile social systems. The rapid escalation of flames is often a direct consequence of fuel load characteristics, construction typologies, and environmental factors such as wind and ambient temperature.

Empirical studies from these regions emphasize the need for experimental evidence that links material selection with realistic fire dynamics in the partially ventilated structures typical of informal dwellings [7,8]. This study builds on this context by providing controlled small-scale experiments that preserve key physical similarity parameters, addressing gaps in the quantification of fire spread velocity and structural endurance.

Whilst studies from countries such as South Africa [6,8] have offered valuable insights into fire behavior in low-income settlements, the literature remains fragmented and insufficient to support comprehensive risk mitigation. Prior research typically follows two paths: post-incident analysis (e.g., [9,10]) or small- and large-scale experimental approaches [4,7]. However, even these works often lack detailed quantification of fire spread dynamics or structural survival under realistic conditions.

Empirical data from real-scale or video-based studies—such as those from South Africa [9] or South Asia [11]—have underscored the importance of fire behavior analysis in informal contexts. These include measurements of spread rates, evaluation of firefighter response, and mapping of human behavior under stress. The implementation of frameworks for fire investigation and community-based resilience planning (e.g., [12,13]) has shown potential but requires further validation through experimental replication.

Among the main obstacles to advancing fire risk science in informal settlements is the lack of accessible, structured data and the difficulty of conducting controlled fire experiments in realistic yet safe conditions. Full-scale tests, while informative, are prohibitively expensive and logistically complex [7]. Scaled-down experiments, if correctly designed and instrumented, offer a feasible alternative that allows for the observation of fire spread mechanisms, material performance, and structural degradation without compromising safety or realism [14].

This study contributes to this gap by analyzing fire propagation in scaled physical models of informal dwellings constructed from the following four materials commonly used in Latin American settlements: MDF, OSB, recycled TetraPak panels, and flame-retardant resin composites. The research evaluates ignition delay, spread velocity, time to rapid flame escalation (semi-open analog), and structural collapse. Moreover, the study applies Kaplan–Meier survival analysis to quantify structural endurance over time and correlates environmental conditions (wind, UV index, pressure) with fire dynamics. The findings aim to support evidence-based improvements in fire resilience, construction material selection, and emergency response planning for informal urban contexts.

2. Materials and Methods

2.1. Experimental Design

The study utilized scaled physical models to simulate fire propagation in informal settlements. The following four construction materials were evaluated: Medium-Density Fiberboard (MDF), Oriented Strand Board (OSB), recycled TetraPak boards, and flame-retardant resin-based composite panels. For each material, nine scaled dwellings (1:5) were arranged in a 3 × 3 grid layout. An initial ignition was induced in the central dwelling of each set (Figure 1), allowing the observation of fire spread across identical environmental and geometric conditions.

Figure 1. Layout of scaled dwelling prototypes in 3 × 3 grid configuration.

All prototypes were based on minimal social housing dimensions provided by TECHO. The full-scale area of each house was 11 m^2, with scaled dimensions constructed accordingly. The scaled dwellings included walls (68 × 45 cm), zinc–aluminum roofs (70 × 70 cm), and rough pine structural elements (pillars and fuel load). Each model featured a partially open door and two small windows (20 × 10 cm), mimicking the ventilation characteristics observed in real informal dwellings (Figure 2).

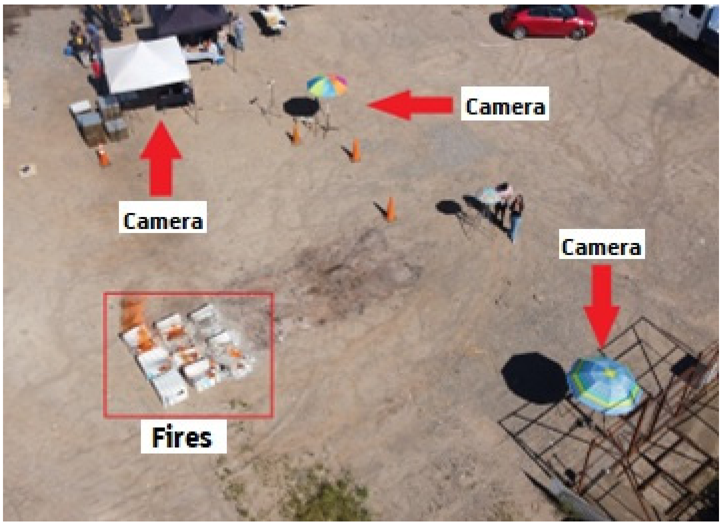

Figure 2. Aerial photograph of the full-scale fire test facility and monitoring setup.

The spatial separation between dwellings was maintained at 30 cm (equivalent to 1.5 m full-scale), based on empirical observations in densely packed settlements.

2.2. Measurement Instrumentation and Data Acquisition

Environmental and fire dynamics variables were continuously recorded using the following calibrated digital instrumentation:

- Thermocouples (Type K, Omega Engineering) for temperature monitoring at multiple interior points (sampling at 1 Hz).

- Pressure sensors (BMP280, Bosch) for both absolute and relative atmospheric pressure (±1 hPa accuracy).
- Anemometer (Testo 410i) for wind speed and gust measurements, recorded at 5 s intervals.
- UV index and light intensity were measured using a Solar Light PMA2100 radiometer, with broadband detectors (UVA/UVB and PAR).
- Visual recordings were obtained from three fixed-angle HD cameras (1080p, 60 fps) for post-experiment fire front tracking and structural collapse analysis.

All sensors were synchronized using a centralized microcontroller data logger (Raspberry Pi + ADS1115 ADC), with timestamps aligned to ignition time.

2.3. Fire Spread Metrics

The following two key fire spread rates were derived:

- Linear fire spread speed (v_l): Defined as the rate (m/s) at which the flame front propagated along a straight line across the grid, measured via frame-by-frame video analysis between house centers (Equation (1)). It is represented as follows:

$$v_l = \frac{d}{\Delta t} \tag{1}$$

where d is the center-to-center distance between houses (in meters) and Δt is the time elapsed between ignition and the arrival of flames at the adjacent dwelling.

- Surface fire spread speed (v_s): Defined as the burned area growth rate (m^2/s), calculated from drone-captured overhead video by segmenting frames and applying 2D image analysis in ImageJ version 1.53t, National Institutes of Health, Bethesda, MD, USA.

2.4. Use of the ISO 834 Standard Fire Curve

The ISO 834 standard [15] fire curve is widely used in Chile (NCh935/1) [16], and it is also used internationally as a mandatory benchmark to evaluate the fire resistance of load-bearing building elements under severe compartment conditions. Although the scaled dwelling prototypes in this study represent semi-open configurations with natural ventilation, the ISO 834 curve was purposefully adopted as a conservative upper-bound reference to characterize and compare the thermal performance of the tested construction materials against the maximum heating rates prescribed by structural fire safety regulations. This normative benchmark provides a consistent frame of reference for assessing whether these materials would meet the minimum fire resistance levels required in the Chilean context. It is acknowledged that the actual thermal evolution diverges from the fully developed compartment scenario; therefore, the real-time experimental temperature profiles are reported alongside the standard curve to transparently illustrate the deviations and the specific fire dynamics relevant to informal settlements. This dual approach aligns with prior experimental practice in small-scale fire modeling where full thermal enclosure is impractical but regulatory comparability remains valuable.

To assess the representativeness of the experimental thermal profiles, temperature–time curves were compared against the ISO 834-1 standard fire curve [15]. This curve is defined by (Equation (2)), which is as follows:

$$T(t) = T_0 + 345 \cdot Log_{10}(8t + 1) \tag{2}$$

The following equation was selected as a benchmark due to its widespread use in structural-fire-resistance testing. Although it represents an idealized fully developed fire in a sealed compartment, its use here serves as a conservative upper bound for evaluating the material thermal response under uncontrolled ventilation.

2.5. Kaplan–Meier Survival Curve Construction

A Kaplan–Meier survival analysis [17] was applied to estimate the probability of structural survivability over time under fire conditions. The event of interest was defined as complete structural collapse of the initial dwelling.

For each material type (n = 4), collapse times were extracted from video recordings and compiled into a survival dataset. Censoring was not required as all experimental units reached the event. The survival function $S(t)$ was computed as (Equation (3)), which is as follows:

$$S(t) = \prod_{t_i \le t} \left(1 - \frac{d_i}{n_i}\right) \quad (3)$$

where d_i is the number of collapses at time t_i and n_i is the number of dwellings at risk prior to t_i. The curve was plotted using the lifelines package (version 0.27.4) in Python (Python Software Foundation, Wilmington, DE, USA.

This approach provides a probabilistic estimate of structural integrity over time, which is useful for emergency response planning and material performance comparison.

2.6. Scaling Validity and Physical Similarity

The experiments were conducted at a 1:5 geometric scale. Although thermal and fluid dynamics cannot be perfectly preserved at a reduced scale, the following key dimensionless groups were qualitatively respected:

- Froude number similarity for gravity-driven flows.
- Biot number for thermal penetration consistency.
- Characteristic time ratio for combustion progression.

No direct application of dimensional analysis (e.g., Buckingham π theorem) was performed, but the experimental fire behavior was visually validated against real events (see Section 4) and literature profiles [18,19].

Further work should consider applying quantitative similarity analysis for more rigorous extrapolation to full-scale scenarios.

2.7. Dimensional Analysis and Physical Similarity

To ensure physical similarity between the scaled prototypes and real informal dwellings, key dimensionless groups were preserved. Following refs. [14,20], the Froude number was used to maintain buoyancy-driven flow similarity as flame plume dynamics in compartment or semi-open fires are primarily governed by gravitational forces. For this condition, the gas flow velocity u scales with the square root of the length scale s as is shown in (Equation (4)):

$$F_r \frac{u}{\sqrt{gs}} \approx constant, \quad (4)$$

Accordingly, the characteristic time scale ttt is derived as follows in (Equation (5)):

$$t \sim \sqrt{\frac{s}{g}}, \quad (5)$$

where s is the length scale and g is gravitational acceleration. For this study, a geometric scale ratio of 1:5 was selected, implying that velocities and time scales respect the following proportionality (Equation (6)):

$$\frac{u_m}{u_p} = \sqrt{\frac{s_m}{s_p}}\,;\ \frac{t_m}{t_p} = \sqrt{\frac{s_m}{s_p}} \tag{6}$$

where subscripts m and p denote model and prototype, respectively. This guarantees that flame height growth and fire spread dynamics are comparable in relative terms, within acceptable experimental uncertainty. Additional estimates of Biot and Peclet numbers confirmed consistency in thermal conduction and heat-transfer behavior across scales.

The complete set of scale factors applied to the key physical quantities in this study is summarized in Table 1.

Table 1. Scale factors for key physical quantities used in the physical similarity analysis.

Quantity	Symbol	Scale Factor
Length	L	s
Mass	m	s^3
Density	ρ	s^0
Heat generation rate	Q	$s^{(5/2)}$
Heat loss index	q̇	$s^{(5/2)}$
Temperature	T	s^0
Time	t	$s^{(1/2)}$
Strain	ε	s^0
Stress	σ	s^0
Modulus of elasticity	E	s^0
Force	F or P	s^2
Displacement	v	s
Area	A	s^2
Volume	V	s^3

3. Results

3.1. Correlation Analysis of Fire Behavior and Atmospheric Variables

Figure 3 presents a Pearson correlation heatmap between construction materials, fire development times, and atmospheric conditions. Strong positive correlations were observed between wind speed (including gusts) and fire spread times, particularly surface spread velocity. UV index and light intensity showed moderate associations with the rate of ignition, likely due to their influence on ambient temperature during tests conducted under natural light conditions.

Materials with lower thermal inertia (e.g., MDF, OSB) correlated with earlier rapid flame escalation and collapse times, whereas flame-retardant composites showed delayed ignition and collapse. This supports the hypothesis that intrinsic material properties substantially affect fire progression and structural survivability.

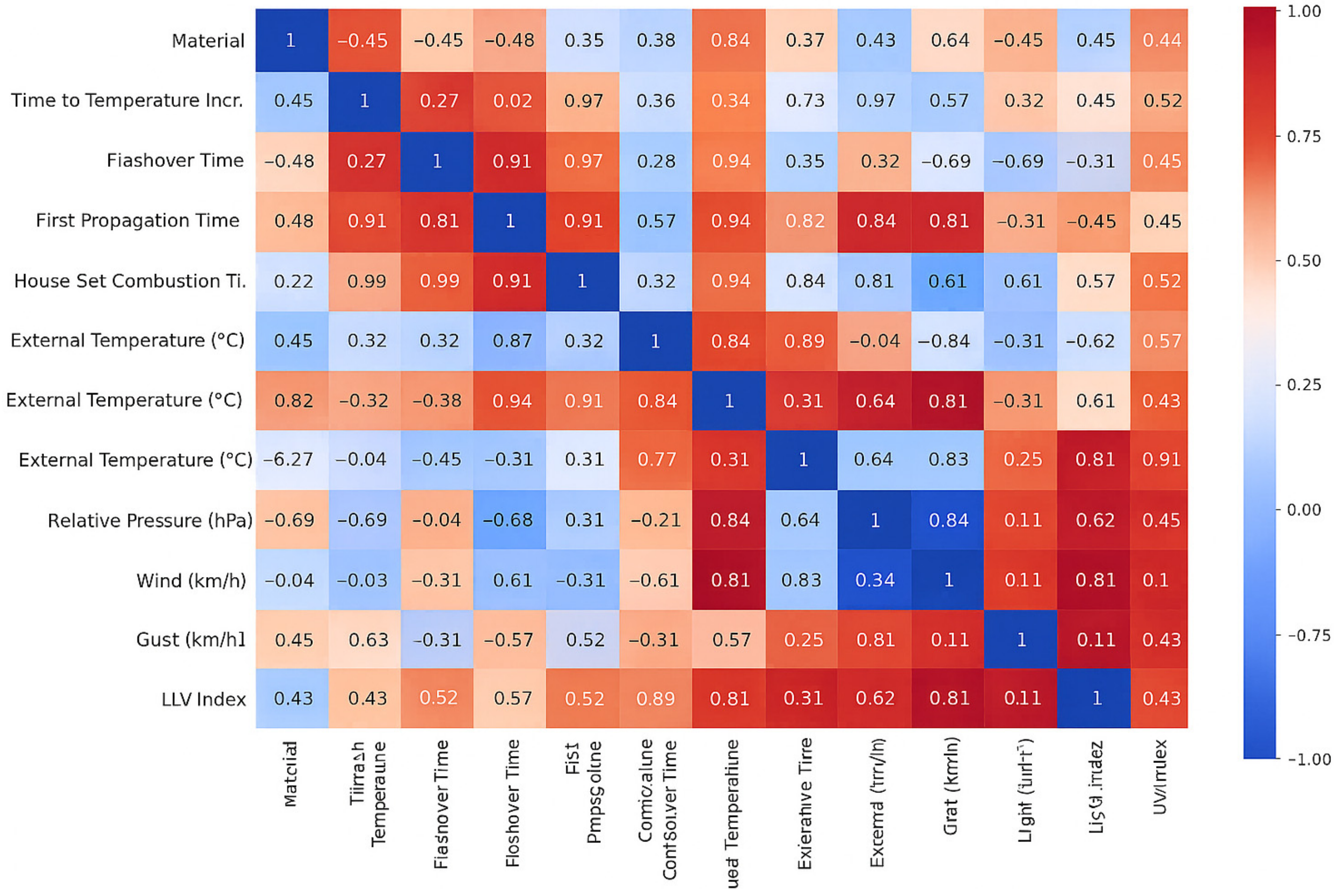

Figure 3. Correlation heatmap of fire behavior and atmospheric variables.

3.2. Thermal Response: Natural vs. Standard Fire Curves

Figures 4–7 compare the experimentally recorded temperature–time curves for each material with the ISO 834 standard fire curve.

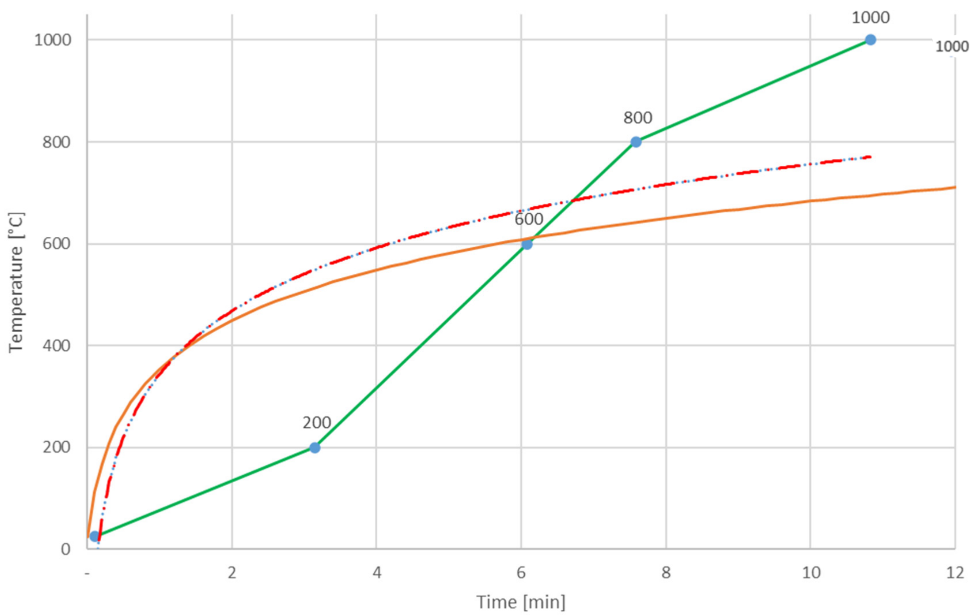

Figure 4. Temperature–time curve for MDF dwellings under fire condition.

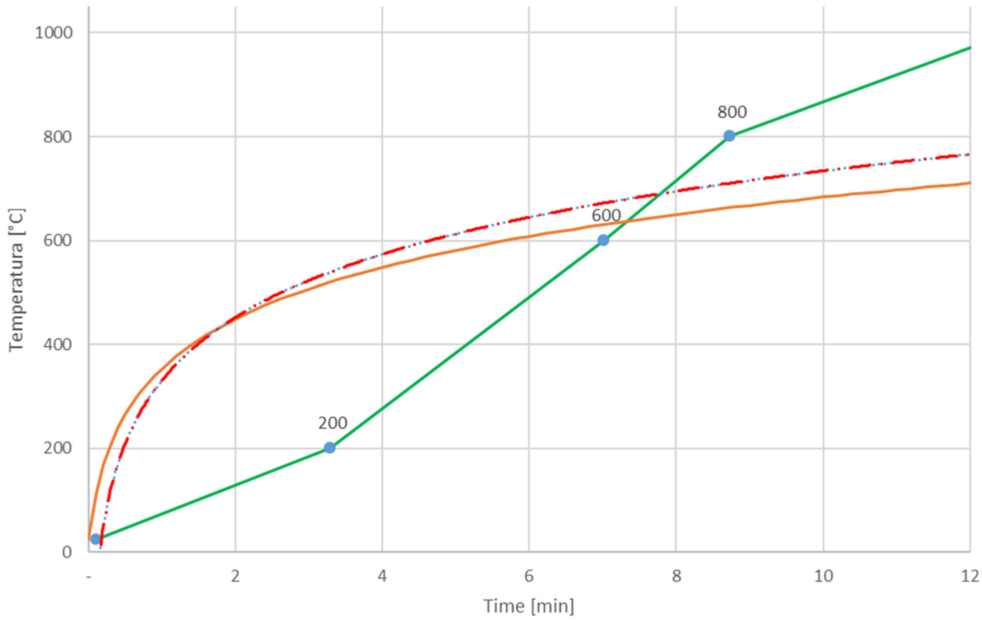

Figure 5. Temperature–time curve for OSB dwellings under fire condition.

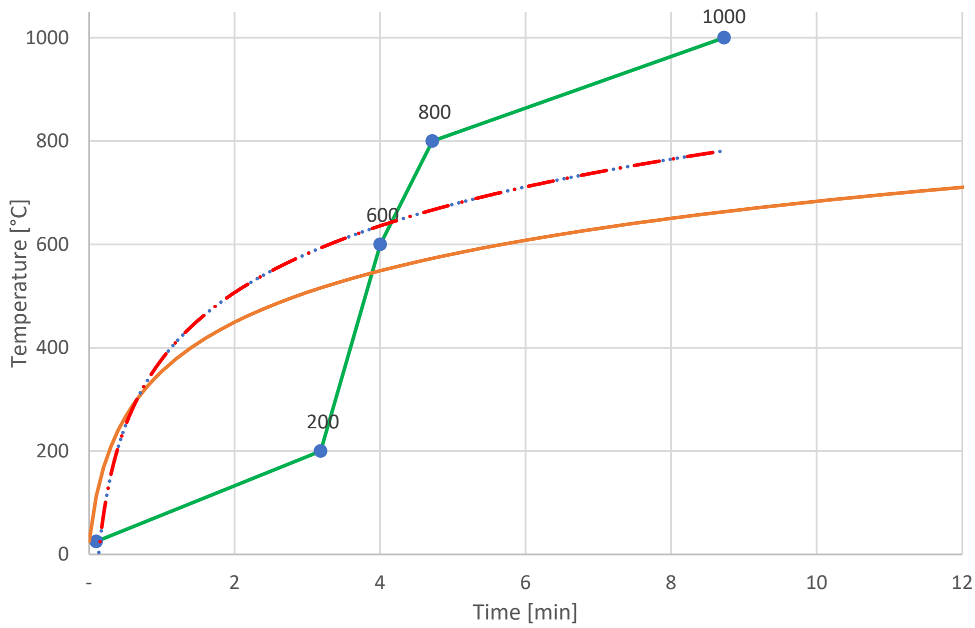

Figure 6. Temperature–time curve for TetraPak dwellings under fire condition.

Figure 4 compares the natural temperature evolution of MDF structures to the ISO 834 curve. The orange solid line represents the standardized fire, the green solid line reflects the actual thermal response, and the red dash-dot line represents the fit to experimental data.

Figure 5 compares the natural temperature evolution of OSB structures to the ISO 834 curve. The orange solid line represents the standardized fire, the green solid line reflects the actual thermal response, and the red dash-dot line represents the fit to experimental data.

Figure 6 compares the natural temperature evolution of TetraPak structures to the ISO 834 curve. The orange solid line represents the standardized fire, the green solid line reflects the actual thermal response, and the red dash-dot line represents the fit to experimental data

Figure 7 compares the natural temperature evolution of composite structures to the ISO 834 curve. The orange solid line represents the standardized fire, the green solid line reflects the actual thermal response, and the red dash-dot line represents the fit to experimental data.

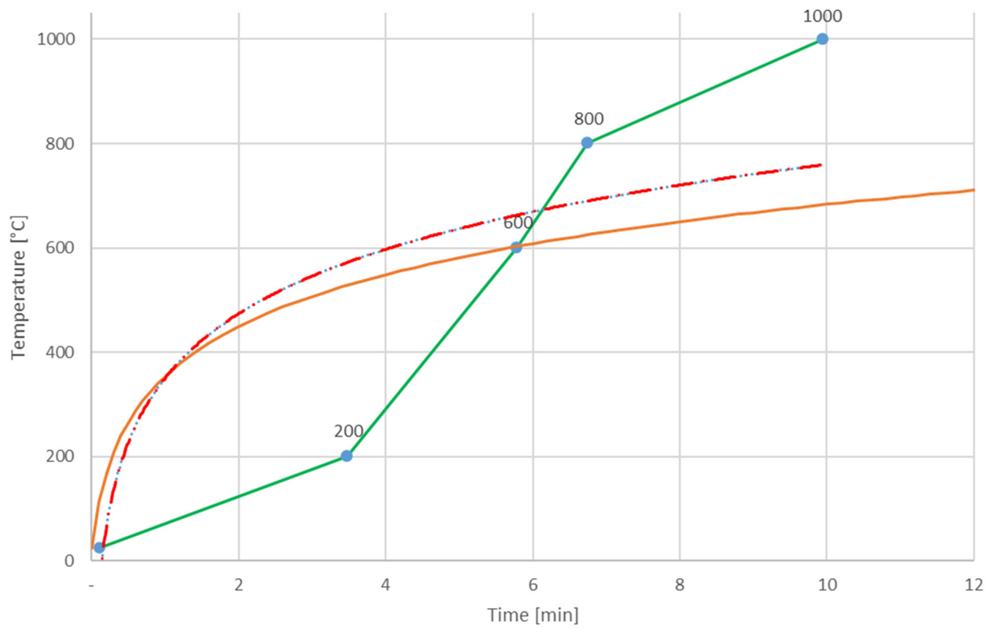

Figure 7. Temperature–time curve for composite panel dwellings under fire condition.

MDF and OSB exhibited steep thermal rises, surpassing 600 °C within 5–6 min.

TetraPak reached rapid flame escalation slightly later but demonstrated sustained burning behavior.

Composite panels maintained temperatures below 450 °C for the entire duration, showing self-limiting combustion due to flame retardants.

The logarithmic fit to each temperature curve confirms the expected exponential fire growth dynamics, validating the physical realism of the tests.

3.3. Fire Spread Velocity

3.3.1. Linear Fire Spread

As shown in Figure 8, linear fire spread velocity was fastest for MDF (0.065 m/s) and OSB (0.061 m/s), while TetraPak and composite materials showed significantly slower propagation (0.042 m/s and 0.031 m/s, respectively). The composite dwellings consistently delayed horizontal fire transmission beyond 3 min post-ignition.

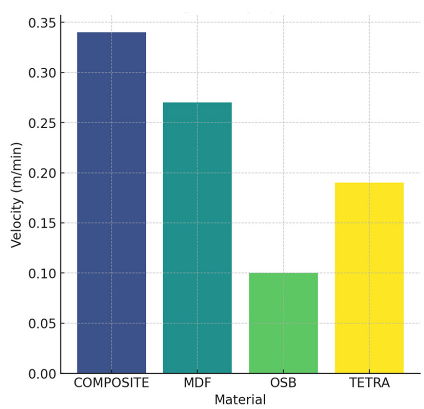

Figure 8. Linear fire spread velocity by construction material.

These values were obtained from high-frame-rate video footage, with spread distances measured center-to-center between adjacent units. Flame arrival was defined as visible sustained ignition at façade level.

3.3.2. Surface Fire Spread

Figure 9 illustrates the surface fire spread area over time. Composite materials yielded the slowest areal expansion, reaching full grid involvement at ~9.1 min versus MDF at ~5.6 min. The anisotropic spread pattern observed in composite and TetraPak panels is attributed to variable heat conduction and intermittent flame fronts.

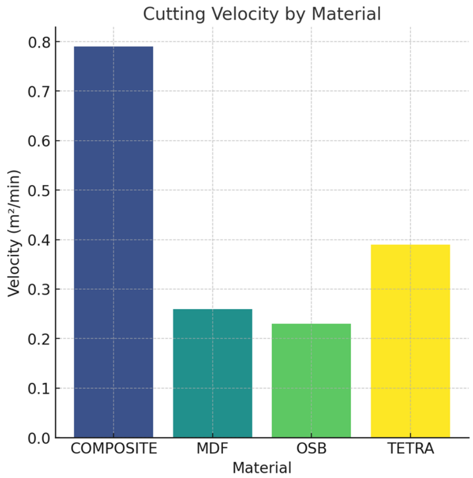

Figure 9. Surface area affected over time by material type.

3.4. Kaplan–Meier Survival Analysis

Figure 10 displays Kaplan–Meier survival curves for each material, where the event was defined as complete structural collapse of the initially ignited dwelling. The median survival times were as follows:

- Composite: 8.8 min.
- TetraPak: 7.1 min.
- OSB: 6.4 min.
- MDF: 5.9 min.

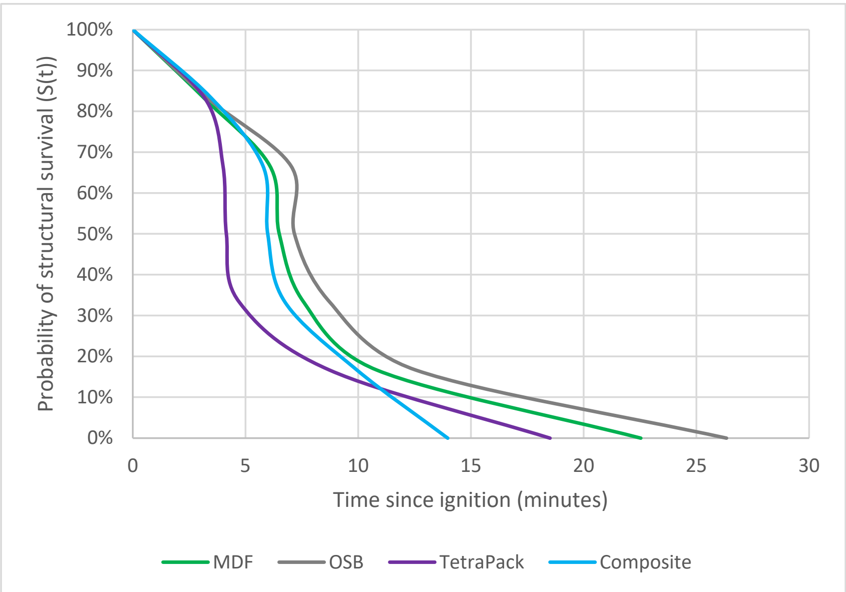

Figure 10. Kaplan–Meier survival curves of structural integrity by material type.

Confidence intervals (95%) were computed via Greenwood's formula. Log-rank tests confirm significant differences in survival distributions across materials ($p < 0.01$). The steeper descent in MDF/OSB curves reflects their rapid loss of structural integrity under fire loading.

This survival model provides a probabilistic framework for estimating evacuation windows in fire scenarios involving lightweight dwellings.

3.5. Burn Pattern Analysis Under Wind Influence

Figure 11 presents qualitative diagrams of burn progression under varied wind directions for each material. Burn asymmetry was particularly evident in OSB and MDF configurations under crosswind conditions (angle > 45°). Flame directionality aligned consistently with prevailing wind, confirming strong coupling between wind vectors and fire front advancement.

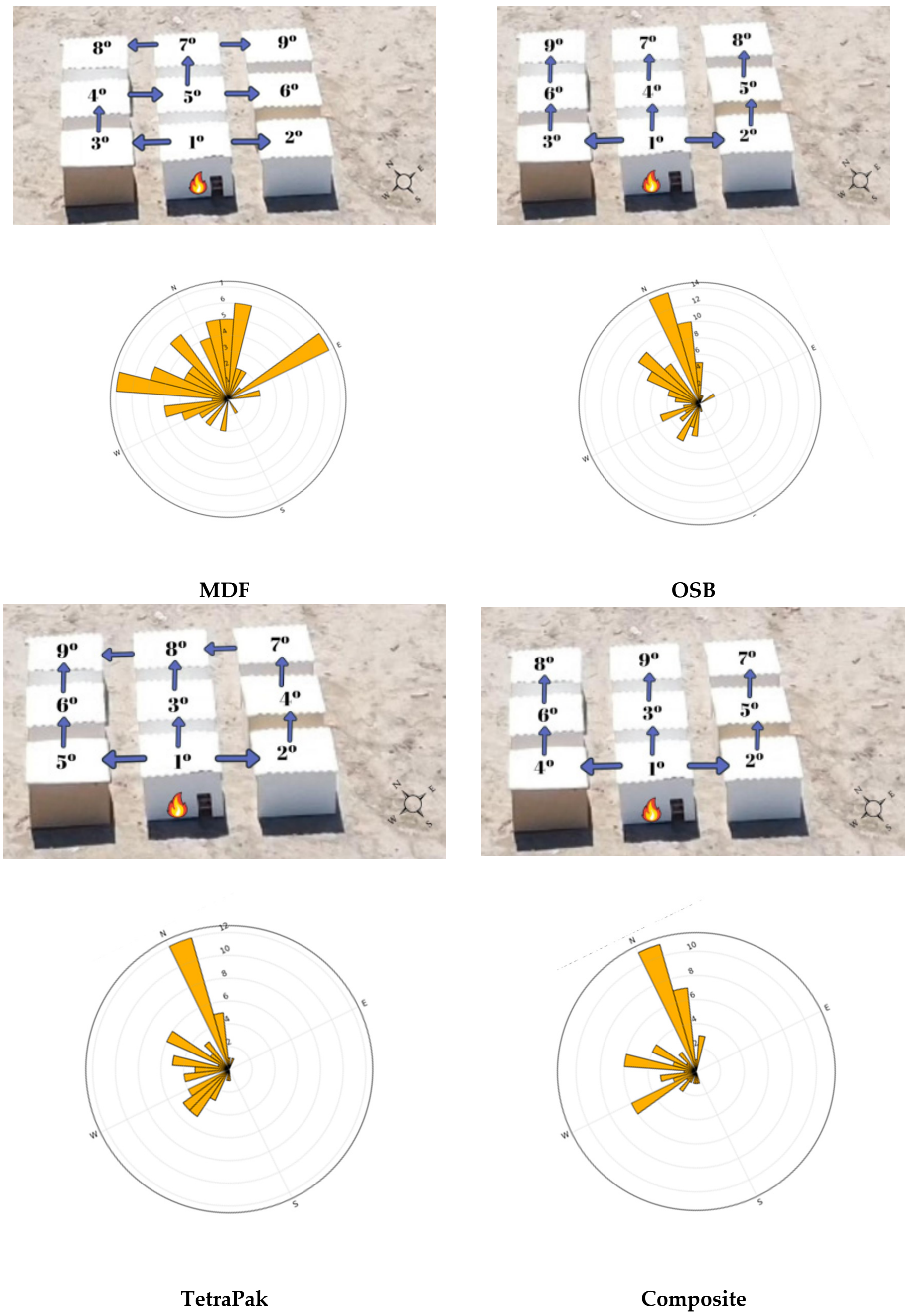

Figure 11. Burn pattern visualization under different wind directions and material types.

Whilst burn patterns in composite materials remained more isotropic, minor directional biases were still visible. These findings suggest that wind not only affects the rate of spread but also the spatial distribution of flame intensity and structural failure zones.

Future work should incorporate quantitative thermal maps and use of thermographic imaging to extract isotherms and damage gradients.

4. Discussion

The experimental results provide robust evidence that both the intrinsic properties of construction materials and external atmospheric conditions play a decisive role in fire development and structural survivability in informal dwellings. The discussion below examines these findings from the following three key perspectives: thermal dynamics, material performance, and practical implications for fire risk mitigation.

4.1. Influence of Material Composition on Fire Behavior

Materials such as MDF and OSB demonstrated high fire propagation velocities and early structural failure, consistent with their homogeneous, porous nature and lack of thermal insulation. Their capacity for sustained pyrolysis under moderate heat fluxes leads to rapid flame spread and intense thermal degradation. These findings align with previous full-scale studies in similar urban contexts [4,6].

In contrast, the flame-retardant composite panels [21] maintained lower peak temperatures and delayed both rapid flame escalation under semi-open conditions and collapse. This performance is attributed to the presence of fire-inhibiting additives and a higher thermal inertia, which retards heat transfer and flame propagation. These results validate the composite material's suitability for passive fire protection in vulnerable housing contexts.

4.2. Atmospheric Conditions and Fire Spread

The correlation matrix revealed a strong relationship between wind speed and fire spread, supporting existing models where convective transport and flame tilting accelerate lateral ignition [19]. Gust wind events were particularly impactful, often triggering directional flame jets that bypassed vertical ignition paths and ignited roofs or rear façades prematurely.

Interestingly, ambient UV index and light intensity—usually dismissed in indoor compartment fires—both showed a moderate influence on ignition delays, likely due to their indirect contribution to the pre-heating of external surfaces prior to ignition.

These environmental factors should be formally included in urban fire modeling efforts, particularly in settlements with unregulated building envelopes exposed to direct solar radiation and natural ventilation [22].

4.3. Representativity and Validity of the Experimental Model

The temperature–time profiles closely matched the ISO 834 curve during the early growth phase but diverged after the rapid flame escalation phase (semi-open analog), highlighting the partial ventilation effect of the scaled models. Despite this, the thermal evolution and collapse patterns are representative of real-world informal fires documented in South Africa and Latin America [8,9].

Whilst the lack of a fully sealed compartment [23] precludes classical flashover, the observed rapid flame escalation is functionally analogous. The thermal transition and flame engulfment confirm this analogy. However, future work should differentiate between compartment-based rapid flame escalation and "open-flame escalation" phenomena under partial ventilation.

4.4. Probabilistic Modeling and Evacuation Windows

The Kaplan–Meier survival analysis proved to be a valuable tool for quantifying structural endurance over time. The marked differences in median collapse times between materials highlight its utility in comparing fire resilience, even in small-scale tests.

This statistical framework can be adapted to simulate evacuation time thresholds, integrate with human response modeling, and inform design codes or emergency protocols in low-resource urban contexts. Nonetheless, its application must be accompanied by rigorous event definition, complete censoring data, and sensitivity analysis—elements which are currently limited in this pilot study.

4.5. Burn Patterns and Wind Directionality

The burn pattern diagrams revealed significant asymmetry in fire spread depending on material and wind exposure. Materials with high thermal conductivity or structural rigidity (e.g., OSB) exhibited unidirectional collapse trajectories, suggesting that certain material–wind configurations create predictable paths of failure.

This emphasizes the need to incorporate directional wind analysis into urban planning for informal settlements, potentially influencing building orientation, clustering geometry, and spacing regulations.

4.6. Limitations and Future Work

The current study provides essential insights but is not without the following limitations:

- Instrumentation granularity could be improved with distributed thermocouple arrays and heat flux sensors.
- Dimensional analysis was limited; future experiments should be governed by similarity laws (e.g., Froude, Reynolds, Peclet numbers) to enable formal upscaling.
- Human behavior and occupant dynamics were excluded from the analysis. Fire safety in informal housing also depends on mobility constraints, alert systems, and social dynamics during fire emergencies.

In summary, the results validate the experimental approach and offer both quantitative and probabilistic indicators of fire behavior. They support the urgent need for performance-based criteria to support construction material selection by vulnerable populations, which go beyond traditional prescriptive standards.

5. Conclusions

This study presents a systematic experimental analysis of fire propagation and structural survivability in scaled dwellings constructed from four different materials commonly found in informal settlements. The main conclusions are as follows:

5.1. Material Impact on Fire Behavior

Composite panels exhibited the lowest fire spread velocities (linear and surface) and the longest survival times, confirming their superior fire-retardant performance. These results underscore their viability as a high-priority material for fire-resilient construction in vulnerable contexts.

MDF and OSB, whilst commonly used for economic reasons, presented rapid ignition, early rapid flame escalation (as a semi-open analog), and structural collapse within 7 min, making them unsuitable without passive fire protection or separation strategies.

TetraPak boards demonstrated intermediate behavior, offering better resistance than wood-based panels but worse resistance than engineered composites.

5.2. Environmental and Structural Interaction

Wind speed and gusts showed strong positive correlations with fire spread rates, confirming their role as primary accelerants in open-structure fire dynamics.

The influence of atmospheric parameters such as UV index and light intensity, although moderate, suggests that environmental preheating should not be neglected in outdoor fire risk models.

5.3. Methodological Validity

The experimental fire curves showed acceptable similarity to ISO 834 during initial stages, validating the thermal realism of the reduced-scale experiments.

Although the ventilation conditions deviate from sealed compartments, the fire growth dynamics and burn patterns are functionally representative of informal dwelling fires observed in the field.

5.4. Survival Modeling and Application

Kaplan–Meier analyses provided meaningful insight into structural survival probabilities under fire conditions. Median collapse times ranged from 5.9 to 8.8 min, offering a quantified estimate of available evacuation time by material.

This approach introduces a valuable probabilistic framework for future integration into risk-based evacuation planning and fire safety engineering for informal housing.

5.5. Practical Implications

The results justify the urgent implementation of fire-resistant materials in social housing, particularly in regions with high wind exposure and dense clustering.

Building layouts should incorporate directional wind analysis and minimum separation distances to delay lateral fire transmission and reduce structural interdependence.

Policymakers and NGOs should consider these findings when formulating material subsidies, urban layout regulations, and community fire risk management strategies.

5.6. Recommendations for Future Work

Scale refinement using dimensional analysis and computational modeling is recommended to extrapolate the results to full-scale predictions.

Future studies should integrate human factors, including detection time, evacuation delays, and behavioral variability during fires.

Burn pattern quantification via thermographic imaging and heat flux mapping would enhance the objectivity of directional fire spread assessments.

This work contributes experimental evidence and probabilistic insight into fire dynamics in low-income urban environments, providing actionable guidance for improving material selection, risk assessment, and structural resilience in informal settlements.

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