20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements

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Abstract. Large-scale urban conflagrations in informal settlements are a frequent global event, however there is a lack of experimental research and knowledge within literature on how informal settlements fires spread to support local or national intervention strategies. This paper, therefore, presents results and analysis of a full-scale fire spread experiment of a mock 20 dwelling test settlement with a 4 by 5 layout aimed at understanding settlement-scale fire spread behaviour. A "fire line" scenario was created by simultaneously igniting four dwellings in a row, and then allowing the fire to propagate through the settlement to replicate fire disasters involving large numbers of homes. Results highlight the critical hazard posed by the close proximity of neighbouring dwellings (1–2 m), with wind playing a primary role in directing and driving the spread process. Even with a relatively mild wind speed of 15–25 km/h, the fire spread through the entire mock settlement within a mere 5 min. Following ignition of a given dwelling, flashover is reached very quickly, with the temperatures reaching more than 1000°C within 1 min, and downwind neighbour structures igniting less than a minute thereafter. The results suggest that multi-dwelling effects are not dominant in these types of fires, but may become meaningful at a larger scale when branding and topography play a role. Findings show that on a global scale fire behaviour is analogous to a wildfire with a continuous fire front moving through an area, although individual dwellings still do follow the distinct phases of enclosure fires, except that collapse occurs more rapidly than in formal structures. This experiment represents one of the larger urban fire tests conducted to date, and the largest informal settlement fire experiment.

Keywords: Full-scale experiments, Fire tests, Fire spread, Informal settlement fires, Fire dynamics

1. Introduction

Fire is an important source of light and heat in informal settlement dwellings (ISDs), but this ubiquity together with flammable construction materials and the close proximity of neighbouring structures makes these settlements especially vulnerable to disasters related to large, fast spreading fires. A single fire event in the Imizamo Yethu settlement in Cape Town (March 2017) had an estimated cost

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implication of around $10 million for the city, and left almost 10,000 people homeless [1]. Informal settlement dwellings (ISDs) are homes assembled from cheap/easily scavenged materials, with limited application of standardised building codes for structural and fire safety compliance.

Municipal ordinance and building regulations developed partly in response to conflagrations in built-up areas, and have been very effective in reducing fire risk in large cities [2]. Societal knowledge on these effects developed to a large extent in response to large conflagrations experienced in the past [3, 4]. The absence of, and restricted abilities to implement, such measures in informal and semi-formal settlements is one of the primary causes of the scale and frequency of destructive informal settlement fires. With this traditional means of preventing large fires unavailable, alternative, versatile strategies of mitigating the problem need to be explored.

Critical to such an endeavour is a better understanding of the primary factors that drive fire spread at the urban scale. Included among these factors is the combination of dominant spread mechanisms such as flame impingement and radiative heat transfer with environmental factors such as wind and topography [5]. Such insight would in turn inform better judgement of which interventions are worth pursuing, while also serving as quantitative case studies to calibrate computational studies, such as stochastic spread simulations, that aim to identify areas of particularly high risk before a fire occurs [1, 6–8]. Some interventions, such as the compartment of settlements into zones or the use of various fire resistant materials for homes, require an understanding of fire exposure conditions and spread mechanisms to be able to evaluate whether they will improve the situation, or not.

As a phenomenon, fire does not scale well to smaller model sizes [9, 10] meaning that full-scale test are typically required. While experiments can be done using scaled down geometries, full-scale experiments are necessary as reference and to guide the critical parameter choices that are unavoidable [11, 12]. Multi-dwelling fire dynamics simulations are also not practical, as they require significant computational effort [13, 14]. By providing a means of direct observation and measurement, as well as serving as critical benchmarks for numerical simulations, full scale fire experiments are critical if significant advances in understanding fire spread in informal settlements are to be made. Although this work has been developed to provide insight into informal settlement fire behaviour, it still provides useful data for the development of urban fire spread models as it represents one of the larger fire experiments conducted to date.

A series of foregoing studies have established a research framework within which to consider the informal settlement fire problem [1, 7, 15]. An effective standardized informal settlement dwelling fire test [7] has provided a deeper understanding of the fire dynamics associated with single dwellings. Spread to adjacent dwellings was considered in terms of direct impingement in a set of experiments involving a line of three dwellings [1]. Possible larger scale effects, including multiple spread paths and feedback mechanisms [16] can only be captured by experiments involving multiple dwellings burning at the same time, thereby prompting this work which seeks to build upon the aforementioned studies.

This paper details the results of a fire spread experiment involving 20 full-scale informal settlement dwellings. The study was conducted in an effort to (a) obtain quantitative data on the rates, temperatures, and heat flux values associated with fire-spread in a full-scale settlement, and (b) identify the mechanism by which fire spreads from dwelling to dwelling in the context of a large number of burning structures.

A compilation of the salient video footage of the experiment is available online at https://www.youtube.com/watch?v = kkXr6ueakAU. This video provides drone footage, side views and a number of images in excess of that presented below to assist in illustrating spread behavior beyond that which can be depicted in a paper.
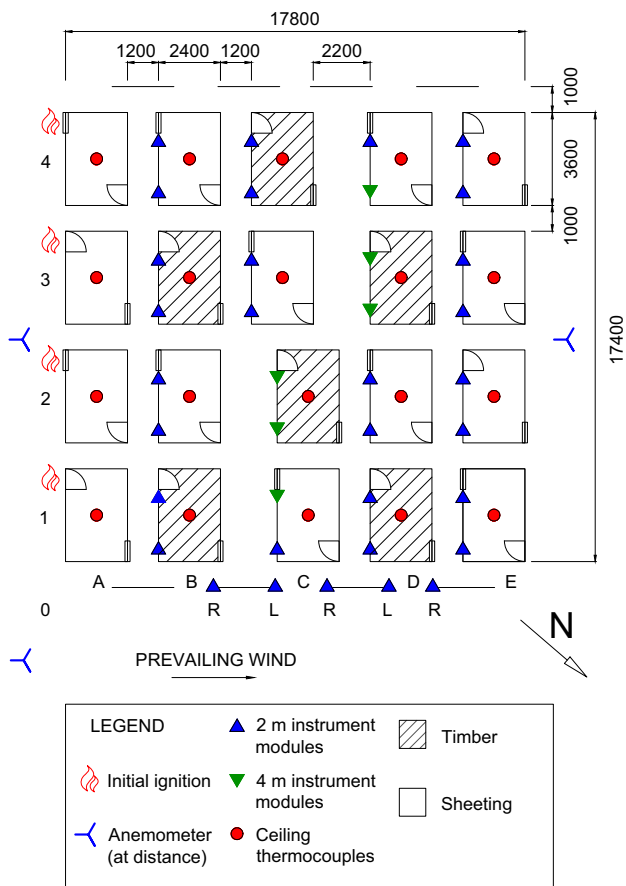
2. Experimental Setup

2.1. Test Site

The experiment was conducted on municipal grounds outside Worcester, South Africa, during the week of 19–23 November, 2018. The facility, which falls under the jurisdiction of the Breede Valley Fire Department, is a flat field inside an old motor racing track (33° 39′ 23.0′′ S 19° 24′ 36.9′′ E), which itself is located on the floodplains of the Breede River with minimal vegetation and no meaningful nearby topography. Local meteorological records for November indicate a south easterly prevailing wind direction (64% likelihood), with north westerly as a secondary direction (30% likelihood), and hot, dry conditions ($< 1\%$ likelihood of rain) [17].

2.2. Layout

The basic layout of the mock settlement is shown in Fig. 1. With the overall aim to capture the larger scale effects that occur during settlement fires, a layout was developed that is broad enough to allow for possible lateral effects, and large enough to not be dominated by the boundary effects from the edges of the layout. Such effects include the shielding obstruction to airflow that neighbouring structures would provide, as well as the reduced supply of oxygen in case surrounding structures are also on fire. Hence, the mock settlement sought to some extent to replicate fire development for dwellings in the midst of a larger settlement.

A primary consideration in the layout was to ensure that fire could spread with the wind. With two, opposing dominant wind directions in the area, the layout was designed to be roughly symmetrical, so that the decision regarding locations of initial ignition could be left until close to the burn event itself, informed by short-term weather predictions.

To facilitate unambiguous interpretation of results, the number of added complexities in the layout were kept to a minimum. All dwellings were constructed with a floor area of 3.6 m × 2.4 m (length × width) and a height of 2.2 m (Fig. 2). These dimensions are typical of ISDs, and conform to the previously established standard ISD fire test standard [7], which is based on ISO-9705 specifi-

Figure 1. Overall layout of the model settlement, also indicating instrumentation positions and positions where the experiment was initiated.

cations [18]. Along the longer sides, dwellings were spaced 1.2 m apart, except for four instances where the spacing was 2.2 m. These distances are typical of dwelling spaces found in denser informal settlements [6, 19]. Doors or windows were located on the left hand side of each longitudinal dwelling wall, and alternated to cover door–door, window–window, window–door, and door–window facing wall configurations across transverse alleyways (Fig. 1). This was done to investigate the influence of openings on fire spread, although a side effect of this choice is that fire spread along the axis of the settlement relative to in the lateral direction would be favoured. No doors or windows were installed as they would significantly complicate the analysis, although the presence of such items would potentially slow down fire spread, and results should be interpreted accordingly.

Stand-alone sheeting panels were placed at the ends of the transverse alleyways to act as barriers and mimic the airflow shielding that a larger settlement would
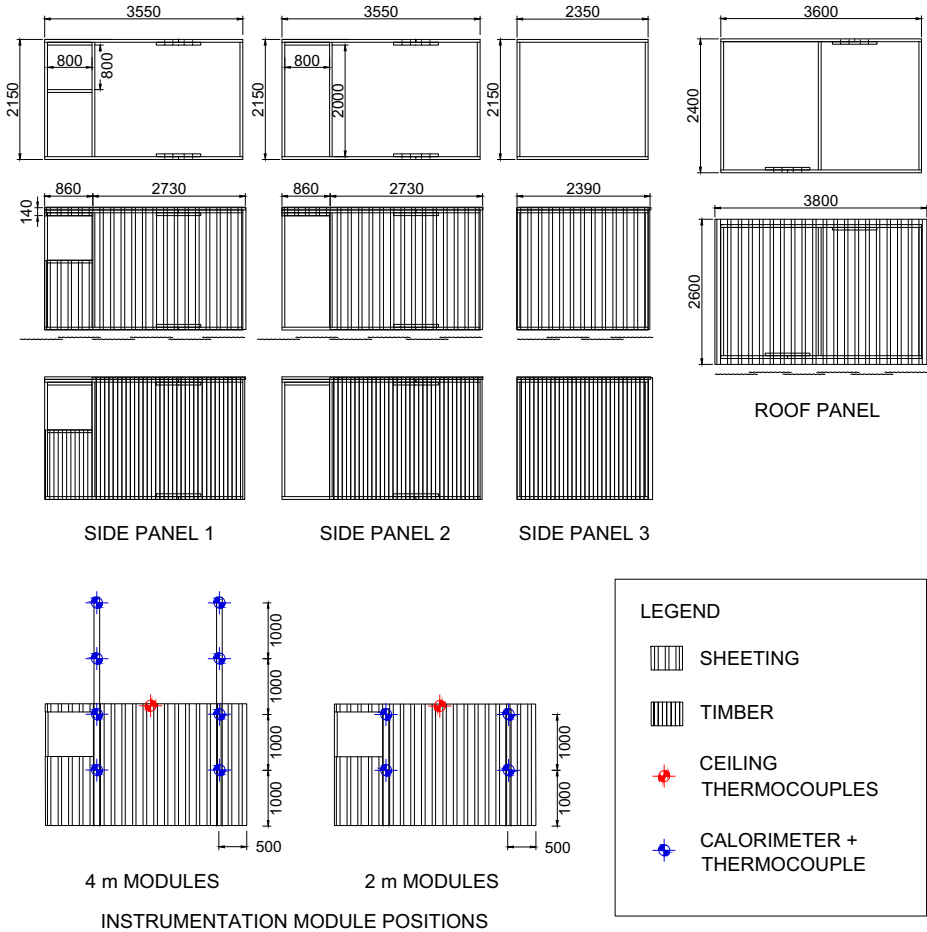
Figure 2. **As-built structural drawings for dwelling frames and assembly, showing both timber-clad and galvanised sheeting-clad side panels. All dwellings had sheeting-clad roof panels. Also shown are the types of instrumentation modules and their positions on the dwelling walls.**

provide (i.e. panels were placed between rows A/B, B/C, C/D and D/E at the top and bottom of Fig. 1). Similar panels were not included on entrances to longitudinal alleyways (parallel to intended burn direction), to allow for visual observations of the experiment.

2.3. Dwelling Structure and Assembly

As-built drawings for the informal dwellings used in this experiment are given in Fig. 2. Dwellings had dimensions determined according to the previously established ISD fire experiments [1, 7]. Consistent with common construction tech-

niques used in South African informal settlements, dwellings were built as simple timber frames assembled from 48×48 mm square pine sections. Cladding was attached to these frames, also acting as the primary means of stabilization (bracing). Openings were left to represent doors and windows on opposing corners (actual doors and windows were not fitted). All dwellings were provided with 0.5 mm galvanized steel sheeting roof panels. 14 dwellings had galvanized sheeting as side cladding as well, with the remaining 6 clad with 12 mm thick timber planks.

The dwelling structure implies a ventilation factor of 0.07, calculated as $A_v\sqrt{H_v}/A_t$ [20], with H_v the area-weighted equivalent opening height (1.66 m), A_v the total opening area (2.24 m^2), and A_t the total area of internal bounding surfaces (43.7 m^2).

For practical reasons of constructability, timber cladding was fitted vertically and did not overlap, while steel sheets were overlapped by 2–3 flutes. This meant that a small area of cardboard was exposed to the outside through gaps between timber planks, which was not the case with sheeting-clad dwellings, and also implies marginally increased ventilation once cardboard has burned away (refer to Sect. 2.5 for details on the fuel load and materials).

For reasons related to security, safety, and economy, dwelling structures were designed specifically for speed of assembly. Panels for the entire experimental settlement were pre-assembled from pre-cut timber and sheeting in a municipal warehouse, after which they were transported to the test site and erected within a single day. Two further days were necessary to furnish the dwellings with inner cardboard lining and timber cribs as fuel load, and to install instrumentation, as discussed in the following subsections.

2.4. Instrumentation

The locations of sensors installed for the experiment are shown in Figs. 1 and 2. Inconel sheathed K-type thermocouples (1.5 mm diameter tip) and thin-skin calorimeters (TSC) manufactured following [21] were the primary sensors used. TSCs were calibrated and validated against a water-cooled heat flux gauge, providing heat flux measurements to within 10% accuracy, with a measuring range up to 200 kW/m^2 [1]. Thermocouples are certified to be accurate to within 0.75% by the supplier. Temperature values were logged at 10 values per minute, i.e. every 6 s.

Instruments were fitted into pre-assembled units, which were attached to the dwellings (Figs. 2 and 3) to face in the direction of the oncoming fire (two modules per dwelling, except in row A, where the fire was initiated). The positions of the instrumentation units on the dwellings are indicated in Fig. 2. Instrumentation units were also attached to the edges of selected side panels (Fig. 1). Standard units had two thermocouple-TSC pairs at 1 m and 2 m above the ground, respectively; six units were extended to reach 2 m above the roof of the dwelling (Fig. 3a), with two additional instrument pairs at 3 m and 4 m above the ground. In addition, each dwelling was fitted with two thermocouples measuring gas temperatures at about 5 cm below the ceiling, placed approximately 50 cm apart in the centre of the dwelling.
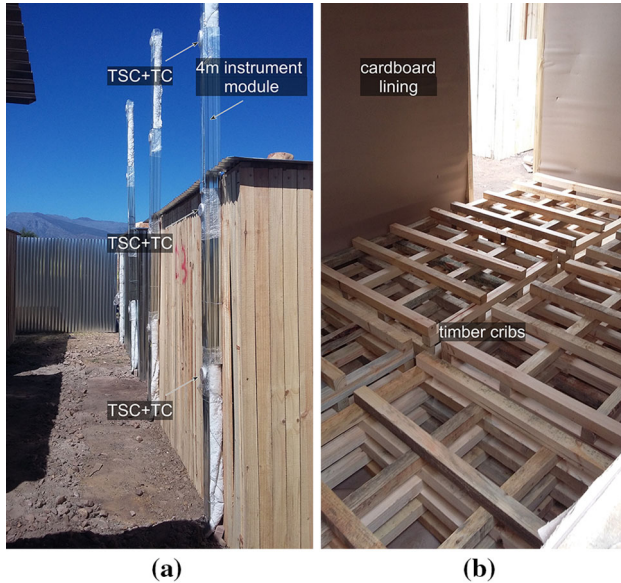
Figure 3. (a) Thermocouples (TC) and thin-skin calorimeters (TSC) are fixed in position via modular instrumentation units pre-assembled using cold-formed steel conduits and fire-retarding blanket. Plastic wrapping was removed prior to the experiment. (b) Dwelling interior prior to burning, showing carboard linings and six timber cribs stacked from 48 × 48 mm 1.0 m lengths of South African pine.

Instrumentation modules were assembled from 100 × 100 mm galvanized cold formed open square sections, generally sold in South Africa for use as rainwater gutters. Thermocouple wiring for each instrument was rolled into fire resistant mineral wool blanket and tucked inside the square sections, which led into ∼ 50 cm deep trenches running from the base of each tree out of the settlement to the computer logging station along the transverse alleyways. Thermocouple extension wires buried in the trenches were also covered with mineral wool prior to replacing the soil.

Three hemispherical cup-type anemometers were stationed about 20 m from the settlement (Fig. 1), in each case 1.6 m off the ground and with as little exposure to obstruction as possible. One was placed upwind of the settlement, one downwind, and one to the side as a reference station.

Finally, a remote controlled drone provided video footage of the fire from a safe height overhead. This footage was used to track and confirm the main events of the experiment, to identify times of collapse of each dwelling, and as a source of qualitative data on the mechanisms by which fire spread from dwelling to dwelling. This data is presented in the online video introduced previously.

2.5. *Fuel Load*

Following on the standard shack-fire test developed by [7], each dwelling was fitted with a representative fire-load consisting of cardboard lining of the inner walls and 6 regularly stacked timber cribs (Fig. 3b). Surveys have shown that South African informal dwellings have contents covering a range of fuel loads between 370 MJ/m^2 and 3000 MJ/m^2 [6]. Dwellings are typically insulated using cardboard linings on the inner walls [7]. A relatively low target fuel load of 450 MJ/m^2 was chosen for the current experiment, as higher fuel loads have been shown only to affect the duration of the fire, not the initial development or spread [1] (the calculated ventilation factor 0.07 indicates dwellings in the current experiment to be ventilation controlled).

1.0 m lengths of the same 48 × 48 mm timber used in constructing the dwelling frames were also used as the primary fuel load, arranged into 6 cribs per dwelling, each stacked as 7 alternating layers of 4 lengths. Timber was kiln dried the week before delivery to site, with 6 samples analysed in bomb calorimeter tests yielding mean density of 520 kg/m^3, heat of combustion of 16.8 MJ/kg, and water content of 5.4 wt%. These values imply an actual mean fuel load of 392 MJ/m^2.

2.6. *Burn Experiment*

All instruments were tested and referenced directly prior to the start of the experiment. Around noon, the burn experiment itself was started by simultaneously igniting four bundles of hessian fabric (burlap) soaked in paraffin (kerosene liquid) placed inside the dwellings at the locations shown in Fig. 1.

The Breede Valley Fire Department was on site with a fire-engine and a team of fire fighters for the duration of the experiment, while a wildfire spotting team was stationed down-wind of the site, in case branding caused ignition of the surrounding brush. Fortunately, no intervention was necessary, and the experiment was allowed to run to completion.

3. Results

3.1. *Fire Spread Observations*

A series of snapshots from the drone footage is shown in Fig. 4. Of especial note is (1) how swiftly the fire spreads with the wind, (2) the ∼ 1.0–2.0 m flame lengths emerging from the doors and window openings, and (3) the fact that after about 5 min the entire test settlement is on fire. Inspection of the drone footage indicates that all ignition events occur directly from the upwind dwelling, rather than via indirect sideways ignition. Throughout the course of the experiment, wind fluctuated between 15 and 25 km/h from a SSW direction (Fig. 5), and about 10° to 20° off the primary axis of the settlement, as shown by the direction of the smoke in the drone footage.

A timeline of ignition, end of flashover, and collapse for each dwelling is shown in Fig. 6. Note that to identify ignition and flashover, the time–temperature curves shown in Fig. 7 are smoothed via a 3-value running average filter. Ignition is iden-
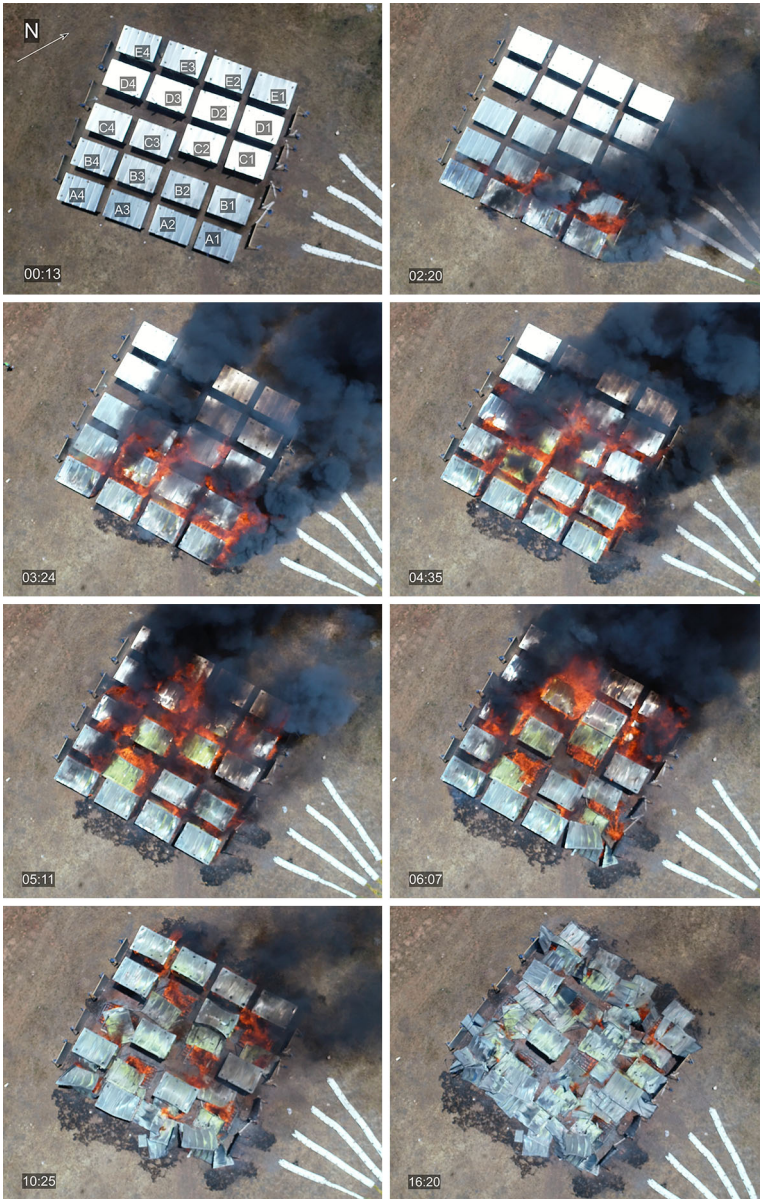
Figure 4. Snapshots from overhead drone footage, starting from soon after ignition to just before the final dwelling collapse. Times are indicated relative to point of ignition.

tified as the point where recorded ceiling temperatures rise above 80°C, so that true ignition would have occurred about 10–15 s earlier than the recorded times; the end of flashover is identified as the point where the temperature first exceeds
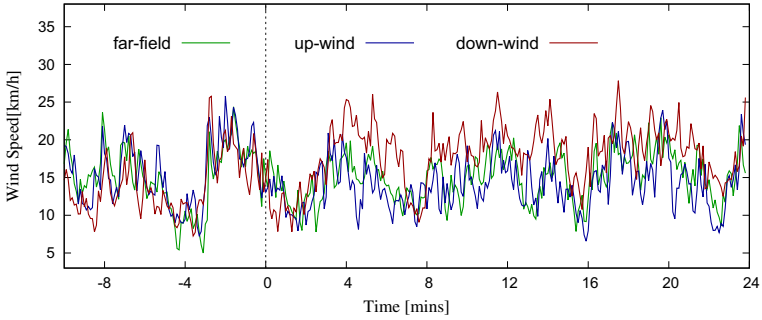
Figure 5. Wind speed traces as recorded by the three anemometers, with time relative to the start of the fire. Note the decoupling of the windspeed down-wind from the fire to the up-wind and far-field traces as the fire reaches full intensity.
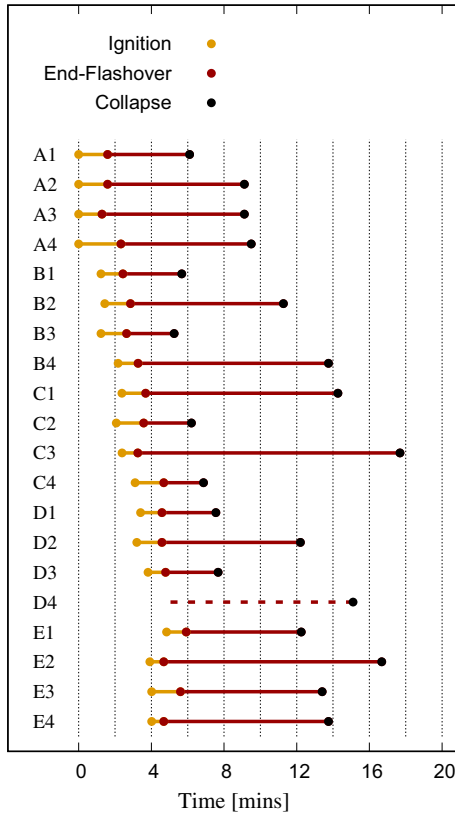
Figure 6. Summary of timeline for the experiment. Dashed line indicates timeline based only on video footage, where the thermocouples fitted to the ceiling malfunctioned.
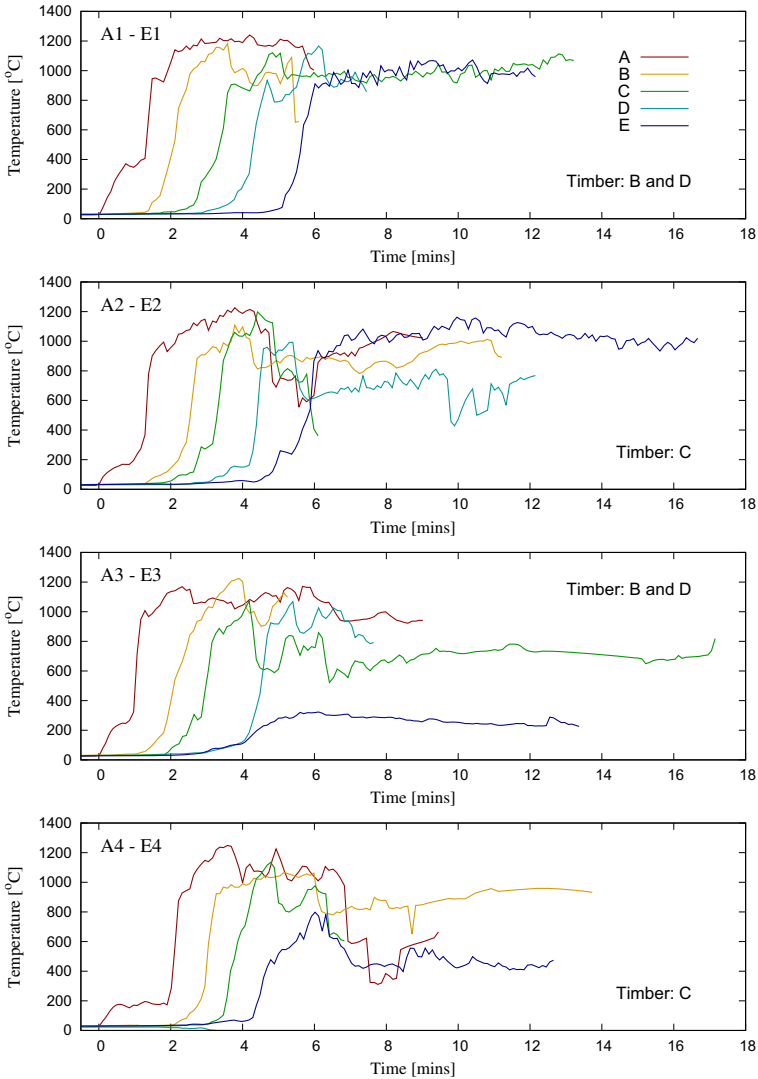
Figure 7. Average ceiling temperatures inside each dwelling, clearly illustrating how down-wind ignition follows shortly after flashover of a given dwelling.

800°C. The value used to identify ignition is chosen to avoid incorrectly identifying ignition from a local spurious temperature rise; flashover is not viewed as an event but as a period in which temperature rises rapidly, with 800°C representative of values where the rise starts to slow.

Ceiling time–temperature data for each dwelling are reported in Fig. 7. Curves indicate that dwellings reach the end-of-flashover very quickly after ignition and sustain a fully developed fire state at about 1100°C thereafter. Temperatures

recorded above roof level (on 4 m instrument units) indicate the rising plume of the burning up-wind neighbour is first seen by the uppermost thermocouple, with smoke temperatures of 400–600°C. This indicates that such dwellings are almost at the fully developed stage and flames would be emerging from openings.

The simple numerical definitions for identifying ignition and flashover were necessary due to the difficulty associated with visually assessing fire behaviour. Calculated ignition and flashover times would vary slightly if different criteria or temperature signatures were used. Furthermore, because of the close spacing of dwellings and the small dwelling sizes, the possibility exists of spuriously relating air temperatures associated with a burning neighbouring dwelling to the dwelling where a thermocouple is mounted, and subsequently mis-identifying the ignition time. However, as such influences will fluctuate significantly, the running average filter applied in identifying ignition can be expected to remove this effect almost entirely. Where possible the aerial footage was utilised to validate findings.

Notice in Fig. 6 that around 5 min into the experiment, every single dwelling was fully involved. The distribution of times between ignition and the end of flashover, between end of flashover and collapse, and between end of flashover and ignition of the down-wind neighbour, is summarized in Fig. 8. With the exception of dwellings in Row A where the experiment was initiated, flashover was reached very quickly, within less than a minute after ignition of the dwelling. Of all the dwellings, nine experienced time from ignition as defined above to end of flashover of 1¼ min or less, seven at 1½ min, and only three dwellings required longer than this (note that dwelling D4 was not included due to equipment malfunction). Dwelling A4 took longer than the other ignited dwellings to reach flashover, presumably due to flames within the dwelling not impinging on cardboard as quickly as dwellings A1–A3. As seen in previous experiments [1] the time to flashover closely correlates to the full ignition of the cardboard insulation.

Timber-clad dwellings collapsed soon after the start of the fully developed phase as a result of lost bracing shown by 5 dwellings collapsing in around 2½ min, whilst the final one (B1) required around 3¾ min. From Fig. 8 the ignition of the down-wind neighbour occurs within less than a minute of the end of flashover, with 2 dwellings downwind igniting even before the end-of-flashover criteria was achieved, with a further 8 instances of fire spread events occurring within 20 s, and the final 4 in under a minute. This highlights how the ignition and development stages up to flashover are critical for predicting fire spread. The total fuel load within a dwelling is of less importance compared to how easily items can catch fire and how fast ignition transitions to flashover.

Figure 9 shows a number of photos taken during the experiment. Of especial note is (a) the presence of flame impingement as a likely fire spread mechanism, and (b) flame lengths extending 2.5–3 m above the dwellings during the fully developed stage. The equipment trees which were 4 m tall were fully engulfed in flames, and flame lengths that would cross typical settlement pathways easily occurred. Dwellings are often not well sealed, and in many instances have combustible material such as newspaper compacted and pushed into openings to prevent drafts, meaning that they would readily ignite when exposed to flame
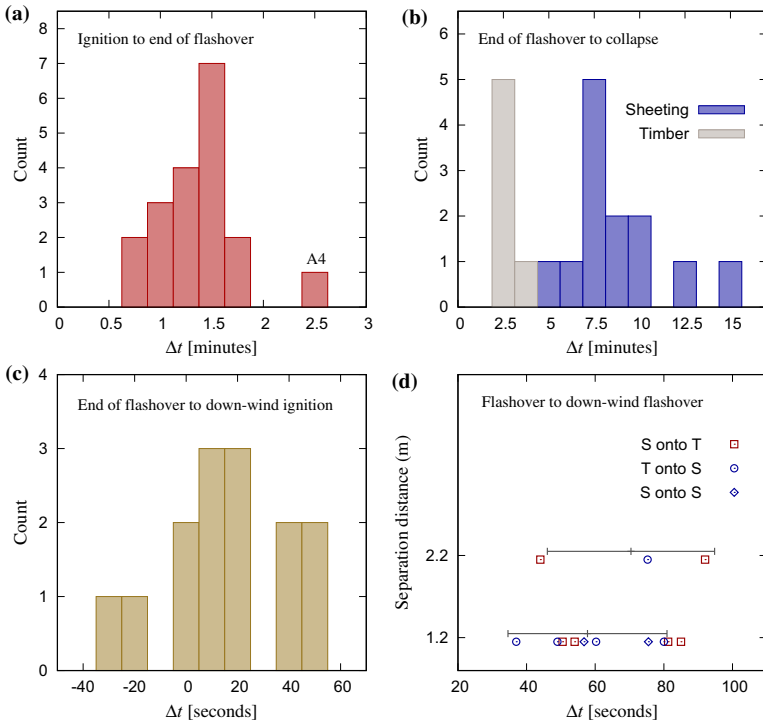
Figure 8. (a)–(c) Frequency distributions of time between salient events during the burning of individual dwellings and fire spread to down-wind neighbours. (d) Comparison of time lag between temperature traces (represented by time between end of flashover events) for different separation distances, with error bars representing one standard deviation.

impingement; in this experiment the flames emerging from the on-fire dwellings would impinge onto a wall, rather than onto/through an opening.

Recordings of wind speed with time are compared for the three anemometers in Fig. 5. Note the contrast in the readings before initial ignition of the experiment versus once the fire has spread into the settlement. Readings follow one another closely prior to ignition, but as the fire reaches full intensity the downwind recorded wind speeds are notably higher than the upwind and reference values. This effect requires more research and experimentation, as it is not necessarily the same phenomena as observed in wildland fires, although the scale of such experiments is much larger so it is difficult to make direct comparisons. This effect may have been influenced by the size and geometry of the setup, or affected by the rising buoyant air from the fire.

Figure 9. Photographic evidence documenting fire spread by direct flame impingement (FI), flame lengths out of dwelling vents (FL), and flame heights above roof level (FH), with 4 m tall instrument units (IU) pointed out for reference. Where times are not obtainable from the source footage, it is estimated based on correlation to other footage, and indicated as approximate (indicated with ~).
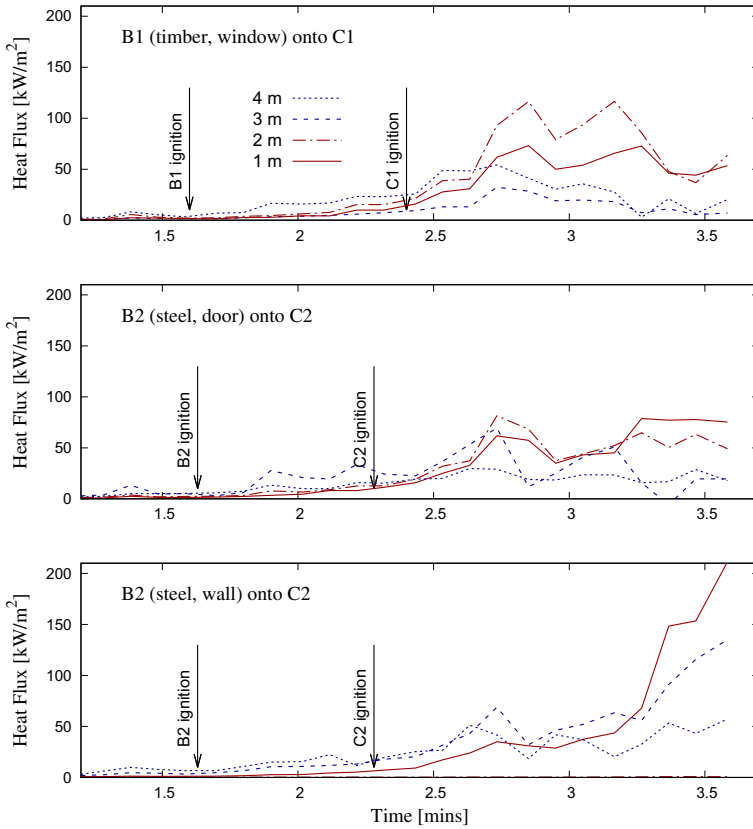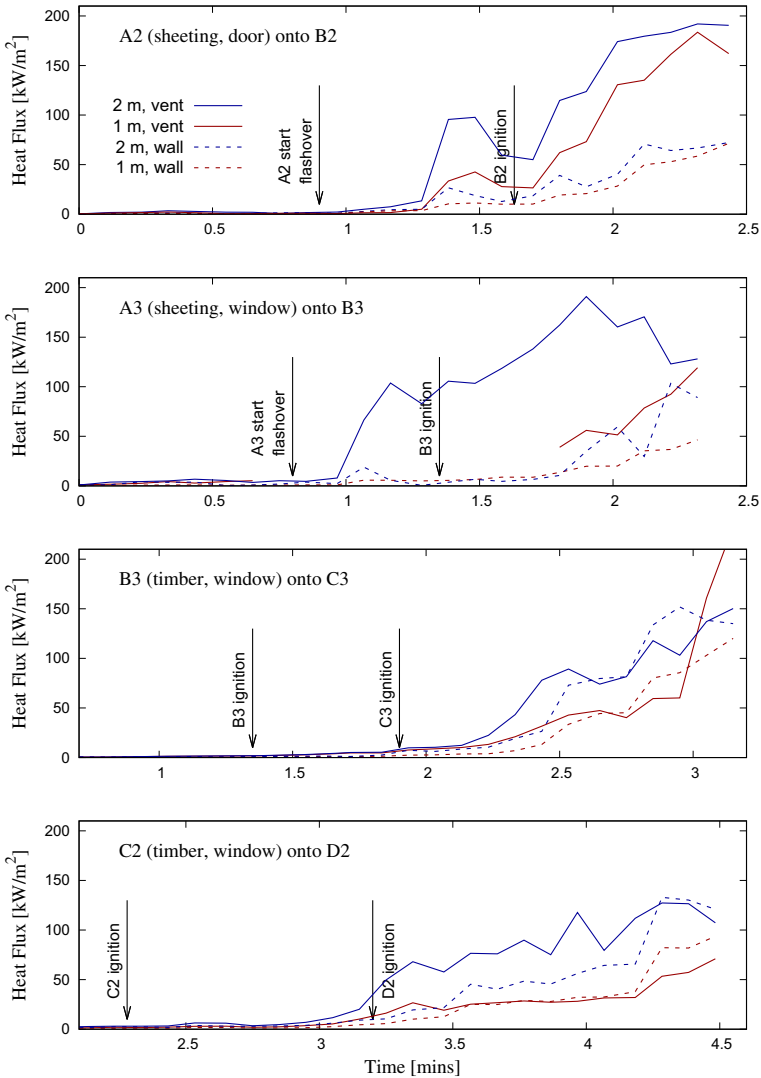
Figure 10. Heat flux recorded across a 2.2 m distance separating the 4-instrument units on dwellings C1 and C2, facing dwellings B1 and B2, respectively.

3.2. Heat Flux Measurements

Incident radiant heat flux values onto downwind facades facing a burning dwelling, measured via the TSCs mounted on the downwind dwelling, are shown in Figs. 10 and 11, with measurements on side panels shown in Fig. 12. This set of heat flux values shown is representative of all dwellings for which useful heat flux values were obtained, and shows the salient behaviour most clearly. Heat flux values for all dwellings reach values of 50–100 kW/m² opposite vents (doors/windows) of the dwelling immediately downwind (distance of either 1.2 m or 2.2 m; see Fig. 1), once it reaches the fully-developed fire stage. Values are only considered meaningful while they are below the calibration limit of the TSCs.

Three notable observations emerge from the values recorded prior to flame impingement. Firstly, heat flux at the lowest TSC (1 m from the ground) is consistently the lowest of the recorded values at a given time on a given instrument

Figure 11. Heat flux recorded across a 1.2 m distance separating the 2-instrument units on dwellings B2, B3, C3, and D2, facing dwellings A2, A3, B3, and C2, respectively.

unit; instruments above roof level do not record very high values, but see the temperature rise due to the plume from the upwind fire first.

Secondly, when the cladding itself is not burning (i.e. for galvanized sheeting walls/facades) heat flux opposite doors/windows reach higher values notably sooner than values opposite the part of the wall with no vents, caused by the flames emerging from openings. In contrast heat flux opposite timber facades depends primarily on height above the ground, with only minor effects from the
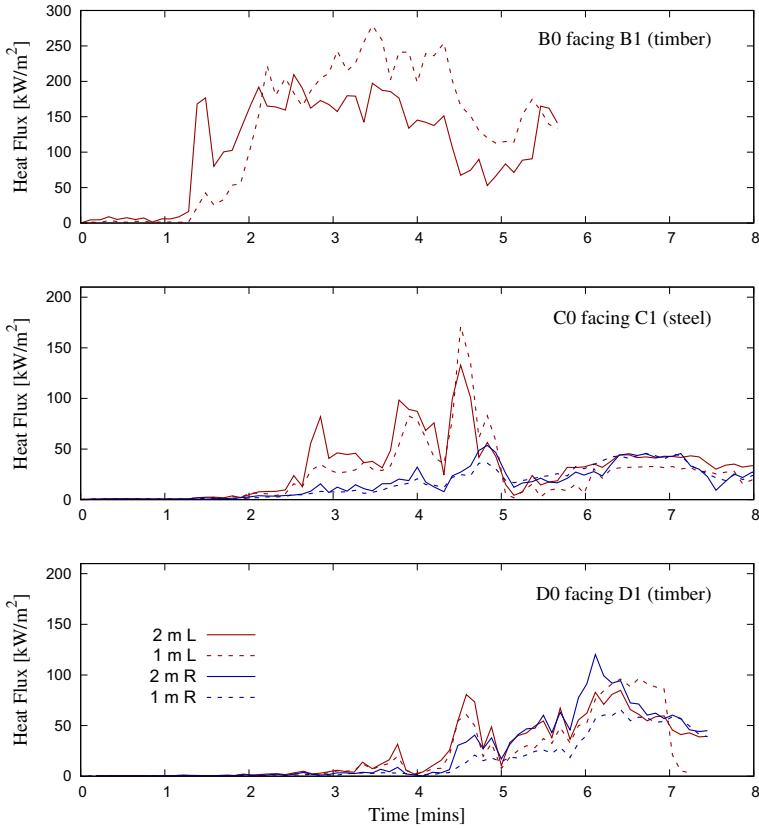
Figure 12. **Heat flux onto side panels, as labelled in Fig. 1. High heat flux values on B0 correspond to direct flame impingement.**

position of the vent. This is due to the timber cladding on walls exerting a high heat flux as it burns, potentially approaching the magnitude of the flux from the flames emerging from openings, meaning that such walls exert a more consistent flux across the entire wall area.

Thirdly, ignition of the target dwellings occurs when the heat flux exposure is still relatively low (< 30 kW/m^2). Higher heat flux values are seen as the upwind dwelling continues to burn, in some cases directly associated with flame impingement on the TSCs (e.g. B0, Fig. 12). In such cases heat fluxes range between 100 and 250 kW/m^2, with upper values consistent with observations in post-flashover enclosures. Note that the maximum heat fluxes recorded are outside of the range that instruments can be calibrated for, and results should be interpreted accordingly. Readings have been adjusted to account for convective exposure, but this may also influence instrument accuracy.

4. Discussion

The combination of drone footage and temperature profiles illustrate the primary role played by the wind in aiding fire spread in informal settlements. All spread events occurred in the direction of the wind, despite transverse dwelling separation being only 1 m. Multi-dwelling spread mechanisms, in which a downwind dwelling is ignited from a transverse direction rather than directly from the upwind neighbour, therefore do not appear to be significant in the presence of a mild wind. Ignoring the width of the last row of dwellings, the results imply a mean spread rate of about 3.6 m/min. This value is notably smaller than the wildfire spread rate of 20–35 m/min expected for a 17 km/h average wind speed [22], but reasonably comparable to the maximum spread rate of 2.3 m/min estimated for the Imizamu Yethu settlement fire [19], a far more complex fire spread situation which includes efforts to intervene and slow its progress.

Ignition can occur as a result of either direct flame impingement onto flammable material (cardboard or timber frames through gaps and vents; timber cladding; especially opposite vents and openings of adjacent structures), or by receiving sufficient radiation to exceed the critical heat flux of any of the materials present. Due to the large size of this experiment it is not possible to accurately measure behaviour at all positions, meaning that in some cases it is difficult to identify ignition mechanisms with absolute certainty. Photographic evidence (Fig. 9) suggests that flame impingement was certainly present, and may well have been a dominant mechanism for fire spread in this experiment, although ignition by radiative exposure cannot be ruled out for all dwellings. The small dwelling spacings (< 2 m) common in these settlements provide ample opportunity for direct flame impingement to spread the fire from dwelling to dwelling, with the combination of large fuel loads and small, reasonably ventilated enclosures resulting in very quick development times from ignition through flashover into fully developed stages. As a result, fires can spread into multiple dwellings extremely quickly.

Predictions for a thermally-thick medium ignition model for timber suggest that even in the absence of direct flame impingement, heat flux values of around 25 kW/m^2 would result in ignition within less than a minute [3], while the measured heat flux values around the recorded times of ignition are in excess of self-igniting heat flux values for most common household materials (8–20 kW/m^2 [5]). Although this suggests that radiation-induced self-ignition might be the dominant mechanism for fire spread, photographic evidence indicates that direct flame impingement was also present. Larger heat flux values likely represent direct flame impingement on the TSC disks, an observation which is confirmed for a number of the dwellings from the drone footage. Flame impingement is also supported by the observed spreading times, with no statistically significant difference in spreading rate between the 1.2 m and 2.2 m spaced dwellings visible in the overall results (Fig. 8). Given the small time of spread and the proximity of dwellings, both mechanisms therefore contributed to the rapid spread observed. Dwelling spacing in typical dense informal settlements (1.0–1.5 m) are far smaller than the critical separation necessary to prevent rapid fire spread.

The observed temperature curves are consistent with the observations of Magnusson [23] for enclosures with intermediate ventilation factor values (0.07 in this case, see above). The mock dwellings in this experiment are initially well ventilated, before fires become marginally ventilation controlled and plateaux around 1100°C. Of course, the uniform nature and distribution of the fuel load used in this experiment is only representative of household items in an average sense, and do not capture the effect items such as cooking oil, aerosol cans, and stored fuel would contribute [6].

It is possible that the importance of ventilation shows up as a larger-scale effect in the observed results: consider that dwelling C3 was surrounded by timber-clad dwellings on all four sides, and was the dwelling with the longest survival time. Intuitively it would be expected that C3 would experience intense fire exposure from the neighbouring timber structures and collapse rapidly. However, the intense burning of its timber-clad neighbours may have deprived its oxygen supply for a period, delaying the collapse of its timber frame structure. This hypothesis is supported by the ~ 350°C drop in the recorded ceiling temperature in C3 just as dwelling D3 goes into the flashover phase (green line in panel 3 of Fig. 7).

Figure 5 presents the wind speed at the anemometer positions during the period of the experiment, presenting data both before and during the experiment. As would be expected in a real-life experiment the wind speed fluctuated continuously, with typical values between 10 and 20 km/h, with gusts reaching around 25 km/h. Of great interest is the wind speed at the down-wind anemometer position, which is shown to increase at around 4 min into the experiment, when the first 16 homes had ignited, and continues until around 23 min after ignition, but less markedly towards the end. This apparent accelerating effect of the fire on average wind speed down-wind of the fire has in the past been associated with wildland fire [24, 25], and could possibly affect spread rates and ignition over longer distances through branding if intensified in a larger fire. Large conflagrations are known to modify wind conditions markedly [26, 27], so that this observation may reflect a similar effect at the lower end of the size scale. In such large fires branding becomes an important means of fire-spread, although the spatial extent of the mock settlement used in the present experiment is not sufficient for the effect of branding be observed. Additional factors not accounted for in the experiment, such as topography and multi-storey structures, are also expected to affect the rate of fire spread and fire-wind interaction. This does highlight how in larger informal settlement fires, such as when hundreds of dwellings burn in a single disaster, it may be possible that fire phenomena associated with wildland fire behaviour may occur [28].

5. Conclusion

A full-scale fire spread experiment of a mock 20-dwelling mock settlement emphasises the critical hazard posed by the close proximity of dwellings in informal settlements. Combined with a mild wind in driving and directing the process, fire spread through the mock settlement within 5 min. The small dwelling spacings

(< 2 m) that are common in these settlements results in both direct flame impinge-ment and radiation-induces auto ignition as the dominant mechanisms for fire spread from dwelling to dwelling, with the combination of large fuel loads and small, reasonably ventilated enclosures resulting in very quick development times from ignition through flashover into fully developed stages.

The results provide an initial set of observations against which event-based modelling of fire spread through informal settlements can be benchmarked and calibrated. However, factors resulting from human interaction with the fire, for example the effectiveness of firefighting efforts, and relocation of household items and furniture in response to an oncoming fire, will require a combination of fire dynamics and agent-based simulation techniques. Building on these observations, future experiments will be aimed specifically at (a) complicating factors such as branding, topography, multi-storey structures, and fluctuating wind, and at (b) developing potential measures of intervention that can delay the speed with which fire spread occurs.

On a macro-scale the fire spread is analogous to that observed in wildland fires, with the fire front moving progressively through combustible material. This beha-viour would be aided if additional fuels were stacked between dwellings, as is often the case in real informal settlements where piles of tyres, rubbish, stored wooden pallets and broken equipment can be found. However, on an individual home level the distinct stages of enclosure fire development are recorded for dwell-ings. Hence, modelling of fire spread on global scale could range from between using simplified models with average spread rates defined by empirical terms that are a function of fuel type, home density, topography and wind. Alternatively, detailed computational fluid dynamics models, or one/two-zone models could be utilised to predict spread between individual dwellings, and such data used as sub-models within global analyses considering each home individually. However, the challenge with all modelling techniques is that information about fuel load and settlement configuration is typically not known accurately, negating the potential to "accurately" calculate spread rates. Nevertheless, predictions about fire spread are still useful for potentially identifying how settlement layouts, construction types, fire safety interventions, and disaster preparedness may be improved.

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