SFPE EUROPE
Q2 2020 ISSUE 18
AN OFFICIAL PUBLICATION OF SFPE

HOW "INFORMAL" IS AN INFORMAL SETTLEMENT FIRE?

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Increasing urbanization, particularly in the Global South, has resulted in a situation where more than 1 billion people currently live in informal settlements.[1] Informal settlements are typified by:

1. 1) Inhabitants lack security of tenure to the land or dwellings they inhabit, with situations ranging from squatting to informal rental housing.
2. 2) Neighbourhoods usually lack in, or are cut off from, basic services and municipal infrastructure.
3. 3) Housing is unlikely to comply with local planning and building regulations and is often situated in geographically and/or environmentally hazardous areas.[2]

In particular, such settlements may face a high risk of large, multiple-dwelling fires due to high settlement densities and extensively distributed combustible materials.[3, 4] In Cape Town, South Africa, alone, some 2,000 fires occurred in informal settlements during 2016–2017. This resulted in damage to at least 5,900 dwellings and a death toll of at least 142.[5] In one notable recent example, on 16th August 2019, thousands of informal settlement dwellings were destroyed in a single fire in Dhaka, Bangladesh, leaving as many as 50,000 people homeless.[6] Conflagrations in informal settlements occur primarily in low- and middle-income countries, which can struggle to fund and implement the long-lasting and systemic changes required to improve the resilience of informal settlements to fire.

Informal settlement dwellings, by their nature, typically do not strictly follow formal national/international codes and regulations, thus their burning behaviour and potential fire-spread mechanisms are uniquely "informal." The fire safety profession's knowledge and experience of informal fires are relatively less than for fires in formal settlements; however, there is increasingly an appreciation that the profession ought to do more. Recent research at the University of Edinburgh (and elsewhere) has begun to establish the requisite technical understanding and provide evidence to increase knowledge from experimental campaigns and numerical simulations through to Geographic Information System (GIS) research, at scales ranging from 0.1 m (0.33 ft) (e.g. materials testing) to 1,000 m (3,281 ft) (e.g. GIS analysis), as illustrated in Figure 1.

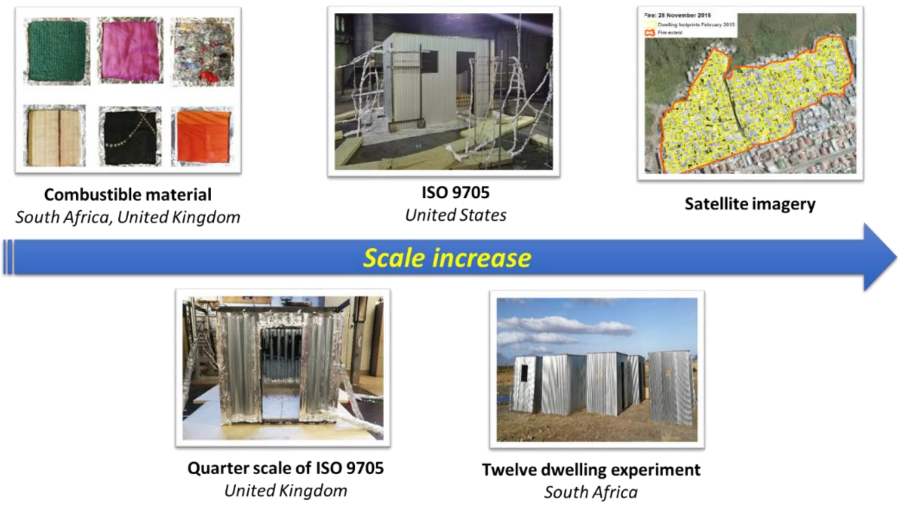

Figure 1. Different Scales of Analysis

Informal in Three Respects

Comparing the formal settlement to the informal one with respect to compartment fire development and urban fire spread issues, at least three clear differences appear:

1. The proportion and locations of combustible materials found in informal settlements
2. Comparatively fast fire development within single informal settlement dwellings (ISDs)
3. Shelter-to-shelter fire spread between ISDs.

Availability of combustible materials

In most developed countries, furniture and construction materials have controlled fire classifications or ratings that are aimed at providing adequate protection against fire ignition, growth, and spread. In informal settlements, the *ad hoc* use of unregulated combustible materials is often more extensive, ranging from non-fire-retardant PU foam mattresses through to the widespread use of thin timber and plastic sheeting as construction materials (Figure 2).

To understand the fire behaviour of shelters fashioned from such materials, cone-calorimeter tests have been conducted to begin to develop a database of the reaction-to-fire responses of some of the typical combustible materials found in widespread use in informal settlements, initially those of the Western Cape in South Africa.[4, 7] This work has confirmed that different materials can be expected to contribute to fire development, spread, and severity in drastically different ways and phases:

- Inside ISDs, PU foam, carpets and clothing are likely to increase the rate of fire development.
- Clothing, shade netting, and tyres appear to play a key role in fire spread between dwellings.
- Meanwhile, tyres, PU foam, carpets, and Masonite timber increase fire severity inside the dwelling due to comparatively longer burning durations and higher heat release rates (HRRs).

Many of the materials tested thus far have had critical heat fluxes for ignition below 20 kW/m^2. The experimental results provide basic data for theoretical and numerical analysis of compartment fire development and spread within South African informal settlements.

The database is open access (https://doi.org/10.7488/ds/2599) and includes all the original combustion data, including critical heat flux, HRR, and ignition time.

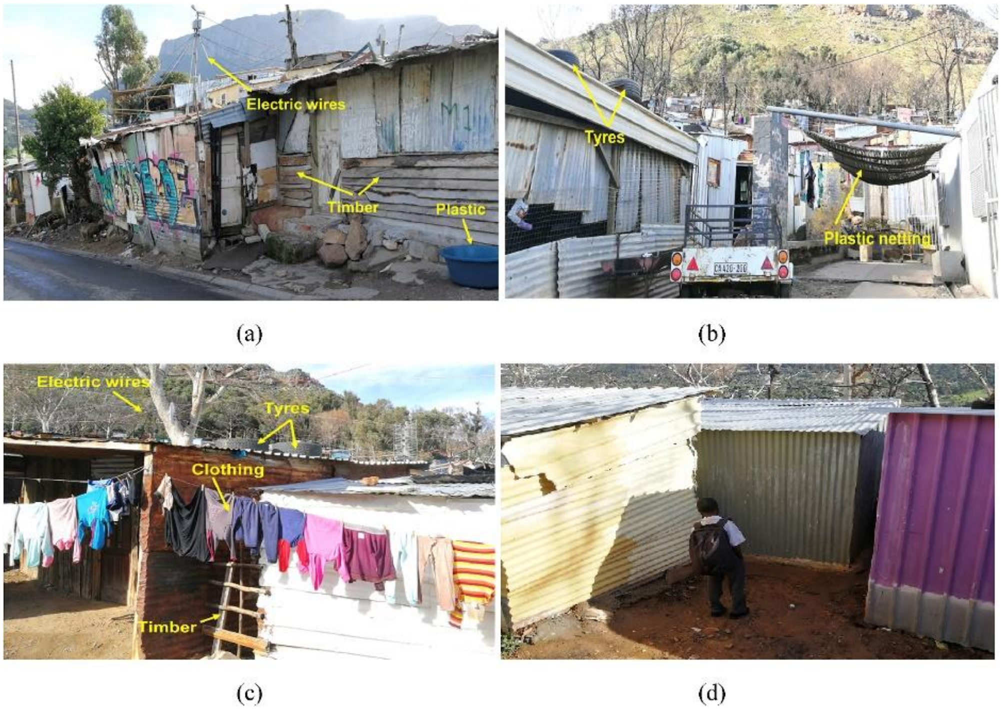

Figure 2. Typical Combustible Materials Widely Found in Informal Settlements of the Western Cape, South Africa[4]

It should be noted that the fuel loads of an ISD are highly variable, in the order of 400–500 MJ/m^2 from a preliminary survey near Stellenbosch, but may be as high as 1,000–3,000 MJ/m^2 for dwellings storing combustible materials and fuels[8], depending on the shelters' inhabitants. Dwelling dimension, shape, number of openings, and location within the settlement are also highly variable, based on 1,000 household surveys of ISDs in Cape Town. However, different settlements and countries present different informal building typologies and fuel characteristics; thus, knowledge needs to be gathered across several different jurisdictions to build a more comprehensive understanding.

Fire development in a single ISD

The wall and roof of ISDs in Cape Town are commonly made from corrugated galvanized steel sheets less than 1 mm (.03 in) thick. The interior walls are sometimes lined, for insulation purposes, with combustible insulation materials such as cardboard, newspapers, or timber board. This significantly affects the fire development within an ISD.

During the early stages of a fire, unlined metal walls will heat more rapidly than normal insulation walls found in more formal dwellings. Hot metal walls radiate more energy back to the internal combustible materials and accelerate the occurrence of flashover.[9] This may explain why many informal settlement fires develop so quickly. Conversely, the typical construction method of these dwellings results in natural leakage between the walls and roofs. Once heated, the deformation of the metal wall also tends to form more and larger openings between the metal panels. From the observation of recent ISO 9705 full-scale experiments on exemplar ISDs, as the air leakage changes, the ventilation factor of the compartment changes, and larger maximum HRRs and temperatures are observed during post-flashover ISD fires.[9]

Therefore, the informal boundary conditions of ISDs make most single-dwelling fires less predictable in terms of temperature, HRR, and occurrence of flashover, if one uses contemporary fire safety correlations.[9, 10] New semi-empirical equations for the HRR required for flashover in compartments with thermally thin boundaries and ultra-fast fires have been developed based on ISO 9705 quarter-scale experiments. This demonstrated that the heat transfer on/from the walls of the compartment was dominated by radiation, in contrast to compartments with thermally thick boundaries where wall conductivity typically dominates. Further experimental and numerical work is underway to understand this behaviour for realistic ISDs.

The structural collapse of a wall or roof during burning, which is rare in compartment fire dynamics in formal dwelling scenarios, is common in ISD fires of the typologies studied to date, as illustrated in Figure 3. The collapse of a wall could result in a fire changing from ventilation-controlled to fuel-controlled, similar to the occurrence of window fallout in a formal dwelling.[11] While predicting the collapse phenomenon is not easy, its impact can be significant with a 35 kW/m^2 heat flux at 2.5 m (82 ft) away due to more direct radiation seen from the open flames and with more efficient combustion due to an increase in available oxygen. In certain circumstances, this could potentially ignite many materials around the ISD of fire origin.

Figure 3. Roof and Wall Collapse in Experiments on Exemplar ISDs Modelled after Those Found in the Western Cape, South Africa (Tests Performed by the University of Edinburg Team and Collaborators at UL, Chicago)

Fire spread between ISDs

Flames ejected from openings, and those from potential wall collapses, can be considered as primary fire-spread mechanisms, observed during double and triple ISD experiments conducted in both laboratory and field conditions, respectively.[12, 13] The radiation from a heated metal wall alone was found to be unlikely to ignite adjacent dwellings, and there was no obvious evidence from these experiments that firebrands helped the fire spread (these were qualitatively, rather than quantitively, examined in these experiments).

Fire spread in informal settlements is significantly different from that of formal urban fire scenarios. Factors such as the presence of combustible construction, community interactions, difficult access, high settlement densities, water supply, wind speed, and the presence of potential wildland-urban interfaces contribute to fire spread in real ISD fires.[14] In particular, wind speed has been demonstrated to significantly influence fire spread in informal settlements. As shown in Figure 4, two large, outdoor mock-settlement experiments of 12 and 20 cardboard-lined ISDs were conducted in Worcester, South Africa, in partnership with Stellenbosch University, with fire spread both against — and with — wind direction. In a 12-dwelling experiment, fire spread against the wind from two to eight dwellings occurred in roughly 16.5 minutes, while in a 20-dwelling experiment, spread with the wind from four to twenty dwellings occurred in about 5 minutes.[15, 16] Despite the different experimental conditions, including separation distance and ignition method, the difference caused by wind appears to be significant and warrants additional study.

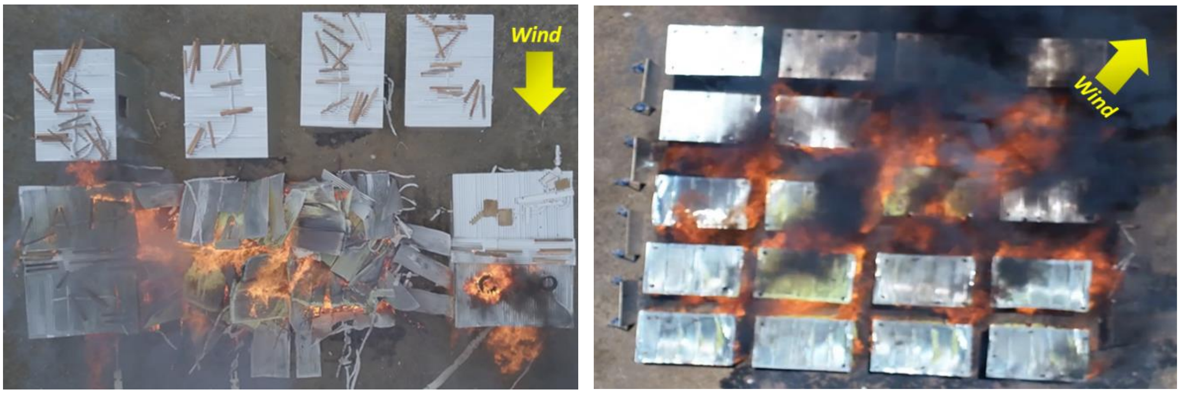

Figure 4. Overhead Photos of 12- and 20-Dwelling Full-Scale Experiments, a Cooperation between the University of Edinburgh, UK, and Stellenbosch University, South Africa

GIS tools and applications

In real informal settlements with thousands or more dwellings, GIS can be an effective tool to undertake community-level fire spread hazard analysis. Recent research has shown that it is possible to map historic informal settlement fires based on the changes in reflectance in the Blue Band of Sentinel-2 satellite imagery, and that this can aid in fire spread risk assessments of informal settlements.[17, 18] By combining GIS and fire science, the critical separation distances between dwellings in informal settlements can be investigated. For instance, from four real informal settlement fires between 2014–2015 in Masiphumelele, South Africa, through both GIS and a physics-based model from fire experimental data, the ignition probability at 1.0, 2.0, and 3.0 m (3.3 ft, 6.6 ft, and 9.8 ft) was estimated as 97%, 52%, and 5%, respectively. This is consistent with double- and triple-dwelling experiments:

- At 1 m (3.3 ft) distances, the fire spread whereas for a 12-dwelling experiment at 1 m distance the fire spread.
- However, at 2 m (6.6 ft) distance, the fire spread to only one of the two dwellings.

This provides evidence to assist communities in redesigning their informal settlements to reduce fire spread hazards, with ISD separation distance (unsurprisingly) being a key consideration — and notwithstanding obvious challenges in applying such measures in practice. However, more robust fire-spread models are needed, considering other factors such as fire fighting interventions (by brigades or by inhabitants), wind speed and direction, and topography.

Conclusions and Closing Remarks

Different scales of research are underway to deepen the understanding of ISD fire development and fire spread. Informal-settlement dwelling fire dynamics are significantly different from formal-settlement compartment fires as they are currently understood, with three significant differentiating factors related to fuel load and distribution, single dwelling fire development, and fire spread between dwellings. Contemporary formal compartment fire and urban fire models fail to adequately capture the characteristics of informal settlement fires. Experimental data have been collected at different scales and with different boundary conditions through both field and laboratory experiments. Combining these data with GIS analyses may, in the future, provide useful tools to predict — and mitigate — the likelihood of fire spread in such settings. However, new theoretical and numerical models are needed to develop such tools in an evidence-based and robust manner. Additionally, to be able to implement any of these fire safety findings in real world situations, the fire science community will need to engage with colleagues from the social sciences, as well as with the communities at risk from these large-scale conflagrations.

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