fire

MDPI

Article

Reduced Scale Experiments on Fire Spread Involving Multiple Informal Settlement Dwellings

Vigneshwaran Narayanan, Anene Oguaka and Richard Shaun Walls *

Department of Civil Engineering, Stellenbosch University, Stellenbosch 7599, South Africa
* Correspondence: rwalls@sun.ac.za

Abstract: Fire disasters in informal settlements (also referred to as slums, shantytowns, favelas, etc.) are a major challenge worldwide, with a single incident being able to displace thousands of people. Numerous factors including dwelling spacing, material type, topography, weather, fuel loads, roads, and more influence fire spread. Conducting large-scale experiments to quantify and understand these phenomena is difficult and costly. Hence, it would be beneficial if Reduced Scale Experiments (RSE) could be developed to study the influence of these phenomena. Previous research has demonstrated that a 1/4th scale informal settlement dwelling (ISD) RSE can sufficiently capture the fire behaviour and fire dynamics within dwellings. The objective of this work is to develop a methodology for multi-dwelling ISD scaling such that large-scale spread phenomena can be captured. This paper carries out a series of RSEs to study the influence of (a) the number of dwellings, (b) orientation of dwellings, windows, and door openings, (c) cladding material, (d) wind effects, (e) the distance between dwellings and (f) fuel load on spread. Results are compared to previous large-scale experiments. It is shown that the geometric scaling of distance between dwellings is suitable for capturing spread. It was found that wind and the fuel load contribute significantly to the fire spread, but the type of cladding, distance between dwellings, dwelling orientation, and type of structural members used also affects fire spread rates. The comparative results with full-scale experiments (FSEs) shows that the peak temperatures were comparable and had similar profiles. A good correlation exists between FSEs and RSEs in terms of fire dynamics and spread characteristics, but the spread time (scaled or unscaled) does not correlate well with FSEs. Further work is needed before the work can be reliably used for predicting multi-dwelling spread, especially when wind is involved, due to the complex interaction of parameters and difficulty in scaling flame impingement.

Keywords: informal settlements; enclosure fire dynamics; reduced scale fire experiment; fire spread

Citation: Narayanan, V.; Oguaka, A.; Walls, R.S. Reduced Scale Experiments on Fire Spread Involving Multiple Informal Settlement Dwellings. *Fire* **2022**, *5*, 199. https://doi.org/10.3390/fire5060199

Academic Editor: Tiago Miguel Ferreira

Received: 11 October 2022
Accepted: 21 November 2022
Published: 23 November 2022

1. Introduction

Informal settlements (ISs) can be found all over the world. Nearly one billion people, most of them belonging to lower income bracket, live in these areas [1]. These settlements are usually unplanned, are built over unoccupied lands [2] and the informal settlement dwellings (ISDs) are predominantly make-shift enclosures constructed from thermally thin steel (corrugated) sheets, timber materials, masonry, plastic sheets, or any readily available materials [3,4].

Fires in ISDs are largely underestimated despite being a frequently occurring event. ISs have a wide range of potential ignition sources such as open flames, faulty electrical installations, candles, arson, "other" and "undetermined" causes [4] (the latter two are typically for when the fire services are unable to identify the cause). Fires primarily spread through three main processes: radiation, direct flame impingement, and fire branding [5]. The mitigation of the consequences of fire spread in these settlements demands good understanding of fire development and spread between the dwellings. Fire spread through informal settlement dwellings (ISDs) is a complex process that involves various parameters such as ISD density, fuel load, topography, wind, materials between dwellings, firefighting operations, and construction materials. Thus, it becomes expensive and time consuming to perform a large-scale experimental study on fire spread between ISDs. As a result, reduced-scale experiments (RSEs) need to be developed to simulate fire spread on large-scale ISDs.

In recent years, multiple full-scale fire experiments (FSEs) have been conducted on ISDs. The experimental study on single IS fires has focussed on fire development, and the influence of combustibles on the fire spread in the dwellings [4,6]. Studies on multiple ISs have focussed on the influence of various cladding materials, type of fuel, effect of heat fluxes and building layouts on fire spread between the dwellings [7–12]. In addition, various numerical simulations have been developed especially with steel-clad models. A preliminary FDS model was developed to understand the fire dynamics of ISD (with temperature, flame behaviour, and air velocity near the door) and found good agreement with experimental results [13]. Numerical modelling for ISDs was further developed to predict the fire parameter (such as temperatures, heat fluxes, etc) using FDS and OZone [6]. The paper discusses challenges in addressing compartment fires and its impact in estimating heat fluxes. The OZone model showed good agreement with gas temperatures but failed to predict heat fluxes. A FDS model developed by Cicione et al. [14] to predict fire spread between multiple full-scale ISDs showed good correlation with experimental works, but fire spread rates were seen to be extremely sensitive to the input parameters (such as ignition temperature, specific heat, conductivity, emissivity of the lining material, emissivity of the compartment boundaries, soot yield and radiative fraction). Numerical modelling for combustible cladding was a challenging task because of continuously changing ventilation conditions (i.e., as the side cladding burnt through). Predicting large scale informal settlement fires spread using numerical simulations needs significant research to develop a simple and practical approach. A fire spread analysis was simulated using B-Risk that resulted in good correlation in baseline scenario with the experimental results however, the software overestimated the fire spread rate for model for real informal settlement [15]. A study on fire spread rate has been briefly discussed by Flores Quiroz et al. [16] where lateral fire spread in large urban fires and ISs has been analysed and the average fire spread rate were between 1.2 to 3.6 m/min. Hence, based on the aforementioned discussions, it can be noted that studying fire spread using FSEs and numerical models still pose a challenge and significant variations can be obtained in results.

Reduced scaled dwelling (RSD) fire experiments have been developed to mitigate various challenges linked with full scale ISDs fire experiments and to gain wider understanding of various factors. Scaling of fire behaviour is a complex task as phenomena such as temperature, heat release rates, heat fluxes, convection, mass flows and geometry interact in a non-linear manner. An article from the primary author, investigated the application of scaling methods for thermally thin compartment fires, such as ISDs, through RSEs and Fire Dynamics Simulator (FDS) modelling [17]. Different sizes, namely: 1/4 scale, 1/5 scale, 1/7.5 scale, 1/10 scale, 1/15 scale of reduced scale dwellings were used to assess the behaviour of the RSEs. The results from this study indicated that reduced-scale modelling with RSE models of 1/4 scale and 1/5 scale can be used to replicate an ISD fire with a reasonable level of certainty, depending on the parameter being studied. The results from FDS model predicted the general trend in experimental results and larger RSD models had better agreement with RSE results than smaller RSD model. Another study on reduced scale informal settlement dwelling by Beshir et al. [18], discussed the effect of horizontal opening in the fire dynamics and fire spread of the reduced scale compartment. In addition, a FDS model was developed. The Beshir study concludes that the horizontal opening in the centre of the roof reduces the heat flux from the door opening by a substantial degree. The FDS results reproduced the main trends and fire dynamics of the compartments, but the combustion efficiency and gas temperatures were not effectively captured.

In this paper, 19 RSEs were performed on 1/4th scale dwellings involving multiple ISDs that ranged between two and six dwellings in each experiment. The RSE series aimed to replicate or model previous FSEs in the literature that studied the effect of separation distance on fire spread, fire spread between multiple ISDs, and large-scale fire spread. The experiment series was conducted to investigate the effect of the following parameters: (a) number of dwellings, (b) orientation of dwellings, (c) cladding material, (d) wind effects, and (e) the distance between dwellings. The data from RSEs are analysed and compared with previous full-scale experiments (FSE) on fire spread and based on the comparative results fire spread mechanisms in RSEs are identified and quantified. Initially the paper introduces previous FSEs upon which the work was based. Thereafter an overview of the experimental regime and methodology is given. Results from the different RSEs are presented by comparing time-temperature curves and spread behaviour. The results of the FSEs and RSEs are compared, followed finally with recommendations and conclusions. An extensive database of experimental results and associated analysis are presented below. These have not been split into multiple papers as it is important to compare results between the different experiments such that the influence of parameters and associated trends can be more clearly identified.

2. Overview of the Literature on Full-Scale Experiments Used as Benchmarks

The RSDs and related experiments in this study are based on various FSEs conducted in the past. A brief discussion on each full-scale ISD experiments, namely double and triple dwelling experiments by Cicione et al. [7,9] and a 20-dwelling large scale experiment by de Koker et al. [10] are described in the following sections.

2.1. Double Dwelling FSE Focussing on Separation Distance

Two double dwelling FSEs were conducted by Cicione et al. [9] to investigate the effect of separation distance on fire spread rates between the dwellings. In the experiments two dwellings were placed adjacent to each other and the separating distances between them were varied as shown in Figure 1, along with the varying of parameters such as window position and wall lining material. The full-scale steel-clad dwellings [9] had a floor area identical to the ISO 9705 room of 3.6 m × 2.4 m, but with a height of 2.3 m (rather than 2.4 m). The dwelling of fire origin, denoted as ISD1, had a single door opening of 2.05 m (height) × 0.85 m (width) on the longer side. The other dwelling denoted as ISD2 had two openings, a door of 2.05 m (height) × 0.85 m (width) on the 3.6 m long side and a window of 0.6 m (height) and 0.85 m (width) on the 2.4 m long side 1.25 m from the ground level (sill height). The ISDs were positioned in such a way that the door of ISD-1 was facing the backwall of ISD-2, and the dwellings during these experiments were separated by 1 m and 1.75 m, and the same can be seen in Figure 1.

During the experiments, the ignition wood crib in ISD-1 was ignited, and the impact of flame and heat flux emanating from ISD-1 on ISD-2 was analysed. Parameters such as heat release rate (HRR), gas temperatures inside the compartment at various levels using thermocouple (TC) trees, surface temperatures on the claddings, velocity and temperatures at the openings, and incident heat flux were measured. Each dwelling was loaded with approximately 130 kg of fuel consisting of wood cribs and cardboard lining contributing to a surface-controlled heat release rate of approximately 6.7 MW. The maximum recorded HRR for ISD-1 and ISD-2, based on mass loss data, were 6.5 MW and 8.4 MW, respectively. It was found, as expected, that an increase in separation distance from 1 m to 1.75 m decreased the incident heat flux from ISD-1 onto ISD-2 from 33 kW/m^2 to 27 kW/m^2. Consequently, the ignition time of ISD-2 also increased exponentially as the separating distance increased, consistent with fundamental radiation equations.

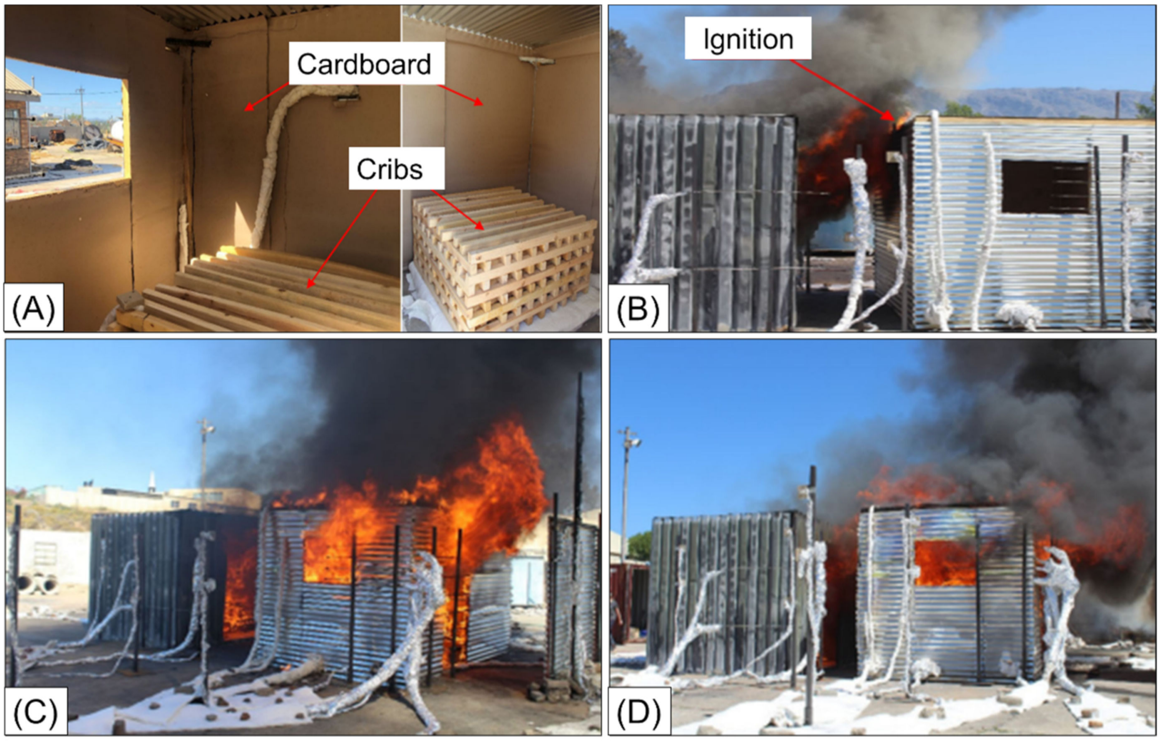

Figure 1. The effect of separation distance between informal dwellings on fire spread rates (**A**) Interior and wood crib arrangement; (**B**) ignition from ISD1 to ISD2; (**C**,**D**) fire spread between dwellings at 1 m and 1.75 m [9].

2.2. Triple Dwelling FSE Focussing on Separation Distance

Similar large-scale studies on ISDs were conducted to understand the fire spread between multiple steel and timber-clad informal settlement dwellings (ISDs) [7] as shown in Figure 2. Two full-scale ISD burn experiments were conducted with (a) three ISDs clad with steel sheeting and (b) three ISDs clad with timber. The heat fluxes and temperatures of both experiments were compared (steel-clad vs. timber-clad) to understand the effect of cladding materials on fire spread. The dwelling size used was 3 m × 3 m × 2.3 m with a door of 0.86 m × 2.03 m and a window of 0.6 m × 0.6 m. To limit the amount of setup variability and number of parameters studied in this paper the RSEs developed below are based on the rectangular 2.4 m × 3.6 m floor plan rather than the 3 m × 3 m floor plan. The paper addressed fire spread behaviour in between different ISDs and primarily focused providing a technical basis with regards to experienced temperatures, fire spread rate, heat fluxes, etc. steel-clad and timber-clad dwellings had similar internal temperature profile. The heat fluxes from timber-clad dwellings ranges from 140 kW/m^2 to 240 kW/m^2 which approximately 1.5 times higher than steel-clad dwellings. The cardboard linings for timber-clad dwellings had reduced effect on fire spread because of combustibility of cladding itself. During full developed phase, the HRR in the steel-clad dwellings was ventilation controlled, whereas for timber-clad dwelling, HRR was limited by the fuel availability. Fire spread times (from the start of flashover in the first dwelling to the end of flashover in the last dwelling) for both experiments (timber and steel) ranged between 4 and 9 min. The paper concludes that the timber-clad dwellings are clearly a higher risk to fire spread defines a critical separation of 3–5 m, based on the studied geometry and fuel specifications, to prevent fire spread between dwellings.

Figure 2. Fire spread between multiple full-scale informal dwellings. (**Top**) Steel-clad dwellings, (**bottom**) wooden-clad dwelling [7].

2.3. Twenty Dwelling Large-Scale Experiment

This experiment aimed at understanding the settlement-scale fire spread behaviour of informal settlement dwellings (ISDs) [10], using a mock twenty dwelling test settlement. The dwellings were built as simple timber cross member assembled from 48 × 48 mm square pine sections and cladding was attached to these cross members. There were fourteen steel-clad dwellings of 0.5 mm galvanised steel sheets, and the remaining six dwellings were clad with 14 mm thick timber planks. The roof panels of all dwellings were provided with 0.5 mm galvanised steel sheeting. A video of the experiment can be viewed at https://youtu.be/kkXr6ueakAU (accessed on 1 May 2021).

All dwellings were constructed with a floor area of 3.6 m × 2.4 m (length × width) and a height of 2.2 m. The mock settlement consists of four dwellings spaced 1.0 m apart in a row and there were five rows of dwellings spaced 1.2 m apart, except for four instances where the spacing was 2.2 m. Doors or windows were located on the left-hand or right-hand side of each longitudinal dwelling wall (i.e., not on the short edge), and alternated to cover door–door, window–window, window–door, and door–window facing wall configurations across transverse alleyways as in Figure 3. Interiors of the dwellings were covered with a cardboard lining to represent insulation of ISDs.

Cribs from South African pine were chosen as the primary fuel. Each dwelling was loaded with 450 MJ/m^2 of fuel consisting of 1.0 m lengths of the same 48 mm × 48 mm timber arranged into six cribs per dwelling, each stacked as seven alternating transverse layers of four timber lengths.

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 proximity of neighbouring dwellings (1–2 m), with the wind playing a primary role in directing and driving the spread process. Even with a mild wind speed of 15–25 km/h, the fire spread through the entire mock settlement within a short 5 min period. 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 in 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.

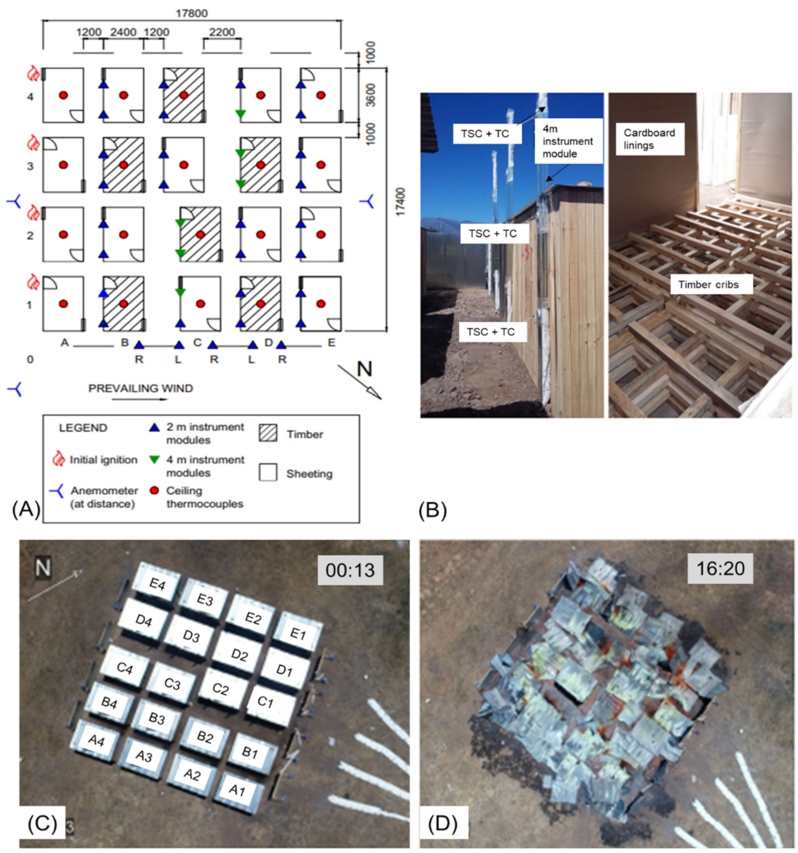

Figure 3. Full-scale fire test on 20 informal dwellings. (**A**) Experiment layout, (**B**) instrumentation and fuel load arrangement, (**C**) aerial image of fire experiment soon after ignition, (**D**) image of fire experiment at 16 min 20 s [10].

3. Reduced Scaled Modelling Methodology

3.1. Scaling Considerations for Ignition

When developing RSEs it must be considered what parameter and behaviour should be captured through an experiment, as discussed above. For informal settlements the occurrence of fire spread between dwellings is of primary concern such that interventions for reducing spread, improving home layouts or enhancing construction materials used can be identified, whilst also enhancing data available for the development of numerical models. Ignition of dwellings typically occurs due to (1) radiation onto target dwellings exceeding critical heat fluxes (or flux-time products for time-variable fluxes), or (2) flame impingement where flames are able to impart sufficient flux to cause ignition. The two mechanisms cannot easily be separated and always occur simultaneously. The first item ignited is typically a material such as cardboard, curtains, plastic linings, and timber cross members in its vicinity due the energy emitted by the flames above openings, cladding, and from fire within a dwelling (i.e., openings).

In terms of quantifying fluxes: (1) the total radiative flux received by a dwelling is based on the summation of the radiative flux emitted from a burning dwelling's flames (i.e., above openings), openings and sidewall cladding (especially for heated steel or burning timber): $\dot{q}''_{radiation} = \dot{q}''_{flames} + \dot{q}''_{openings} + \dot{q}''_{cladding}$. The radiation received from each is a function of the view/configuration factor, $\varnothing$, temperature difference of the emitter and receiver to the fourth power, $\left(T_e^4 - T_r^4\right)$, and emissivity of each component, ϵ. (2) For localised flame impingement there is convective and radiative transfer to the target surface

$\dot{q}''_{impingement} = \dot{q}''_{convective} + \dot{q}''_{radiative}$ responsible for piloted ignition of already pyrolysing combustibles, which is dependent upon flame length and flame height.

From the equations above, it can be observed that even if the only criterion that one seeks to match in RSEs is whether ignition occurs, it is a task involving multiple parameters that interact in a non-linear manner. In some ways scaling radiation is easier, provided that temperatures of emitting items are known, as equations can be more readily applied. The scaling of flame length and height, along with the flux that a smaller flame imparts, is a greater challenge. Hence, this work seeks to identify what can, and cannot, be accomplished through scaling methodologies to capture spread behaviour.

3.2. Wind Considerations

Following discussions that flame behaviour and impingement is important, in real informal settlement incidents wind plays a significant role in directing fire spread. Due to climatic conditions, local terrain, densely packed dwellings and even vegetation there is often significant turbulence and gusting of winds. Furthermore, wind movements around dwellings can lead to localised changes in wind direction and speed. This leads to wind causing flames to pulse from dwelling to dwelling and fluctuate from side to side. Ignition can occur at any time, even during a short-lived wind direction reversal. Such behaviour is extremely difficult to capture. In the tests conducted wind effects were included by testing outside and measuring the average wind speed. However, increased wind speeds may not always lead to increased spread as they can also lead to convective cooling of dwellings, thereby causing increased times to ignition, rather than more rapid ignition, even under favourable wind direction conditions.

3.3. Reduced Scale Dwelling Design and Methodology

The RSEs designed in this paper were based on Froude scaling technique. The scaling correlations of dimensional groups from the conservation equations are based on Quintiere [19]. In this work, the geometry of the Reduced-Scale Dwellings (RSDs) is based on the full-scale ISD experiment introduced above. The RSDs are geometrically scaled according to respective geometric ratios and the vents (doors and windows) are scaled based on ventilation factor scaling according to $A(h)^{0.5} \sim s^2$ as used by Bryner et al. [20] where 's' represents the scaling ratio (i.e., 1/4 as discussed below). For the RSEs, the HRRs were scaled according to $\dot{Q} \sim s^{5/2}$ and subsequently the average burning times were scaled according to $t \sim s^{1/2}$. Wood cribs were used as fuel to represent the anticipated fire load. The design details of the wood cribs for RSEs are discussed in the sections that follow. The steel sheets are considered a thermally thin material (Biot number in order of $10^{-2} < 0.1$), with a thickness of 0.6–0.8 mm, and the thermal properties can be assumed to be homogeneous. This property allows the thickness of steel sheets to be scaled geometrically and the influence of thermal inertia (κρc) to be neglected.

In this research informal settlement dwellings (ISDs) at $\frac{1}{4}^{\text{th}}$ scale of the full-scale experiment (FSE) were constructed for the reduced scale experiments (RSEs). The scaling principles, methodology, and scaling correlations are described in [17]. In this experiment series, two types of reduced-scale dwellings (RSDs) were constructed: (a) Type "D1" with internal dimensions of 0.9 m (length) × 0.6 m (width) × 0.58 m (height) to replicate the double dwelling setup of Cicione et al., and (b) Type "D2" with internal dimensions of 0.9 m × 0.6 m × 0.55 m but also with different ventilation details to represent the 20-dwelling setup of de Koker et al. Each RSD had a door and a window opening which is shown in Figure 4. The dimensions of the openings of full-scale dwellings and RSD along with their associated ventilation condition are provided in Table 1.

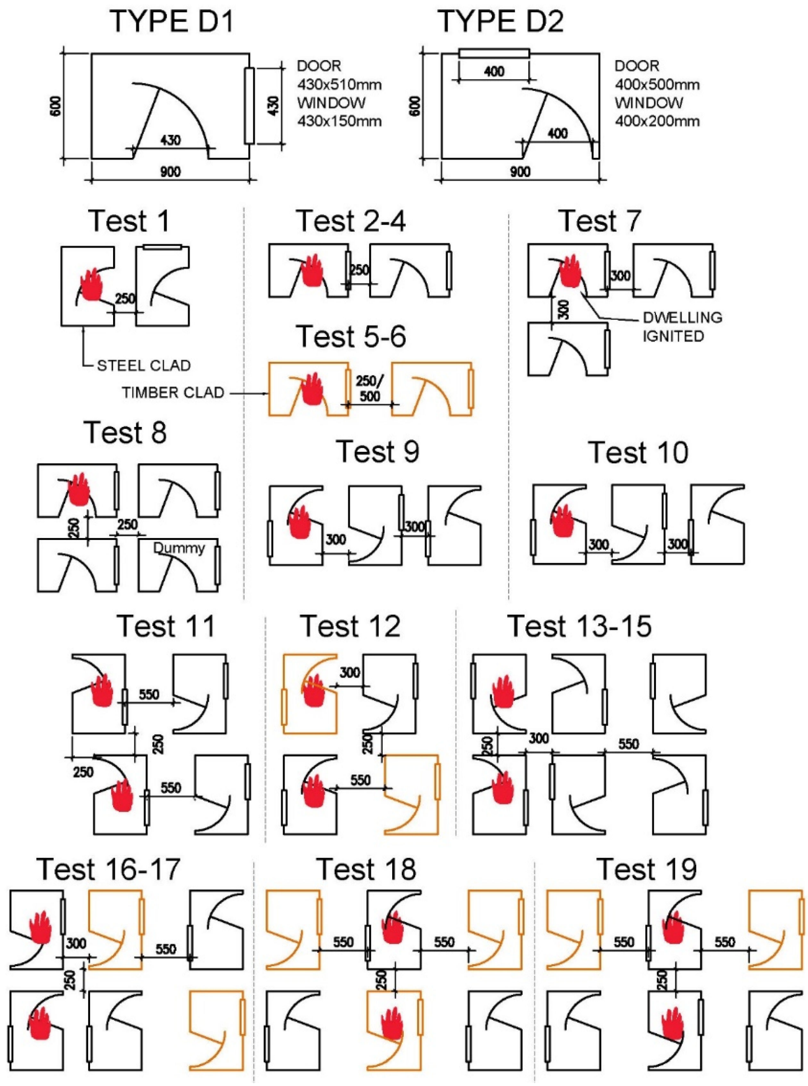

Figure 4. Pictorial representation of 19 test setups showing dwelling layouts (top) and test setups. Steel-clad dwellings are shown in black, timber-clad dwellings in brown and ignited dwellings with the fire symbol.

Table 1. Dimensions of $\frac{1}{4}$th scale reduced scale dwellings.

Scale	Parameter	Dimensions (m)			Total Opening Area (m^2)	Total Opening Height (m)	Total Ventilation Factor ($m^{3/2}$)	Ventilation-Controlled HRR (kW)
		Room	Door	Windows				
Full Scale-1	Length	3.60	-	-	2.253	1.722	2.956	6029
	Width	2.40	0.85	0.85				
	Height	2.30	2.05	0.60				
"D1"—RSD Type-1	Length	0.90	-	-	0.282	0.430	0.185	498
	Width	0.60	0.43	0.43				
	Height	0.58	0.51	0.15				
Full Scale-2	Length	3.60	-	-	2.240	1.657	2.884	7785
	Width	2.40	0.80	0.80				
	Height	2.20	2.00	0.80				
"D2"—RSD Type-2	Length	0.90	-	-	0.280	0.471	0.192	519
	Width	0.60	0.40	0.40				
	Height	0.55	0.50	0.20				

3.4. Reduced Scale Experiment Configurations

The RSDs in these experiments were varied in terms of the cladding materials (14 mm timber strips or 0.5 mm galvanised steel sheet), type of cross member (25 mm × 25 mm timber or steel angles), and positions of windows and doors. All the RSDs were provided with a 1.5 mm thick cardboard layer on the inner side to replicate combustible thermal insulation often used for ISDs. The presence of cardboard significantly influences fire dynamics within dwellings.

An RSD configuration in which the fire spread is observed from the side i.e., from left RSD to right RSD, it is defined as "lateral" and if fire spread is observed from the front door to backwall of a RSD, then it is considered as "longitudinal. The wind directions during experiments were: (1) "favourable" meaning wind that aids fire spread, (2) "opposing" refers to a wind direction that opposes fire spread, (3) "cross wind" means a wind direction that is approximately perpendicular to fire spread, and (4) "circular" refers to a fluctuating wind does not have a specific direction, or which changes its direction all the time. Experiments were conducted outside meaning that it was not possible to control the wind speed and direction. The flashover time during the test was determined by the ceiling temperature of RSDs exceeding 600 °C or the time when the flames were visible through the openings, whichever was observed first. The experimental fire time of an RSD was considered to be a duration between ignition until collapse or until fuel burn out. Ignition is defined based on either observations or a distinct increase in temperature above ambient evidenced by thermocouple data.

Table 2 lists the testing regime which includes all experiments, relevant variable factors that can affect the fire spread in-between the dwellings, and a unique test identification number consisting of all the data provided in the table. The experiment ID is unique for all test setups to identify dwellings arrangement to assist the reader in sections that follow. For example, "1-2D-S-250-F" represents the test number (e.g., 1); number of 'D'wellings involved (2D to 6D); type of cladding ('S'teel or 'T'imber); spacing of RSDs (e.g., 250 mm); and wind condition ('F'avourable, 'O'pposing, Crosswind 'K', 'C'ircular, not applicable or negligible '/'). Figure 4 provides the pictorial representation of the 19 setups with unique RSD ID that are provided on the top of each test setups. In Experiment 8, a dummy dwelling was included which had no fuel load or cladding, and simply served as a flame barrier.

Table 2. Summary of testing regime.

<table>
<tr><th>Experiment Id</th><th>Test No</th><th>No of RSD</th><th>Cladding</th><th>Fire Load (kW)</th><th>RSDs Spacing (mm)</th><th>Type of RSDs</th><th>Wind Condition</th></tr>
<tr><td>1-2D-S-250-/</td><td>1</td><td rowspan="6">2</td><td rowspan="3">S</td><td rowspan="3">520</td><td rowspan="3">250</td><td rowspan="6">D1</td><td>/</td></tr>
<tr><td>2-2D-S-250-K</td><td>2</td><td>Cross</td></tr>
<tr><td>3-2D-S-250-C</td><td>3</td><td>Circular</td></tr>
<tr><td>4-2D-S-250-F</td><td>4</td><td rowspan="3">T</td><td rowspan="3">402</td><td rowspan="3">500</td><td>Favourable</td></tr>
<tr><td>5-2D-T-250-C</td><td>5</td><td>Circular</td></tr>
<tr><td>6-2D-T-500-O</td><td>6</td><td>Opposing</td></tr>
<tr><td>7-3D-S-300-F</td><td>7</td><td rowspan="4">3</td><td rowspan="4">S</td><td rowspan="4">520</td><td>300</td><td rowspan="2">D1</td><td>Favourable</td></tr>
<tr><td>8-3D-S-250-O</td><td>8</td><td>250</td><td>Opposing</td></tr>
<tr><td>9-3D-S-300-O</td><td>9</td><td rowspan="2">300</td><td rowspan="2">D2</td><td>Opposing</td></tr>
<tr><td>10-3D-S-300-/</td><td>10</td><td>/</td></tr>
<tr><td>11-4D-S-550-/</td><td>11</td><td rowspan="2">4</td><td>S</td><td>520</td><td>550</td><td>D1/D2</td><td>/</td></tr>
<tr><td>12-4D-2S/2T-250/550-F</td><td>12</td><td>2S/2T</td><td>402</td><td>250/500</td><td>D2</td><td>Favourable</td></tr>
</table>

Table 2. *Cont.*

Experiment Id	Test No	No of RSD	Cladding	Fire Load (kW)	RSDs Spacing (mm)	Type of RSDs	Wind Condition
13-6D-S-300/550-O	13	6	S	402	300/550	D2	Opposing
14-6D-S-300/550-F	14					D2	Favourable
15-6D-S-300/550-K	15					D2	Cross
16-6D-4S/2T-300/550-O	16		4S/2T	402	300/550	D2	Opposing
17-6D-4S/2T-300/550-O	17					D2	Opposing
18-6D-3S/3T-550-/	18		3S/3T	402	500	D2	/
19-6D-4S/2T-550-/	19		4S/2T			D2	/

3.5. Fuel Source

From the previous work on ISDs, it was seen that the fuel load in an informal dwelling range between 400 MJ/m^2 to 2000 MJ/m^2 [4]. Although the fuel load range varies significantly, fires in these dwellings are typically ventilation controlled and they collapse before the fuel burns out, indicating the role of other factors that could play a substantial effect on fire dynamics inside an ISD. For all RSEs, the cross-sectional (b_w) dimension, number of stick levels (n_{level}) of wood cribs were obtained by scaling according to $b_w \sim s^{1/3}$ and $n_{level} \sim s^{1/3}$, respectively, whereas the length of each stick and number of sticks per level were changed to obtain the desired HRR. The HRR (Q) of the cribs were calculated as per [21].

In this work, untreated and kiln dried wood cribs from South African pine were used as the fuel. The density of wood used for the cribs was approximately 580 kg/m^3, the heat of combustion was ΔH_c = 22.5 MJ/kg as measured in a bomb calorimeter, and the moisture content was less than 12%. There were three different fuel loads based on the different sizes of the wood cribs used in the experiment that are listed in the respective sections. The maximum surface-controlled heat release rate of wood cribs used in this experiment series was 520 kW (21 mm × 21 mm × 450 mm × 48 Nos), 402 kW (25 mm × 25 mm × 500 mm × 30 Nos), and 536 kW (25 mm × 25 mm × 500 mm × 40 Nos). Due to the limited availability of timber fuel the member sizes slightly vary between tests (21 mm vs. 25 mm). The ventilation controlled HRR for each RSD is provided in Table 1. A timber cladding of thickness 14 mm was used in the experiment, which had a density of 542 kg/m^3 and the heat of combustion of 18.1 MJ/kg as measured in a bomb calorimeter.

3.6. Instrumentation

K-type (1.5 mm tip diameter) thermocouples were used as the primary device for measuring temperature. Each RSD had four thermocouples, two placed at 5 mm below ceiling, one at window and door soffit. The measurements of the experiments were recorded with a data logger at every 1 Hz. The instrumentation layout of the experiment is depicted in Figure 5. Videography and photography were primary evidence to trace the fire spread patterns. The video cameras were placed at multiple angles to capture all moments of fire spread.

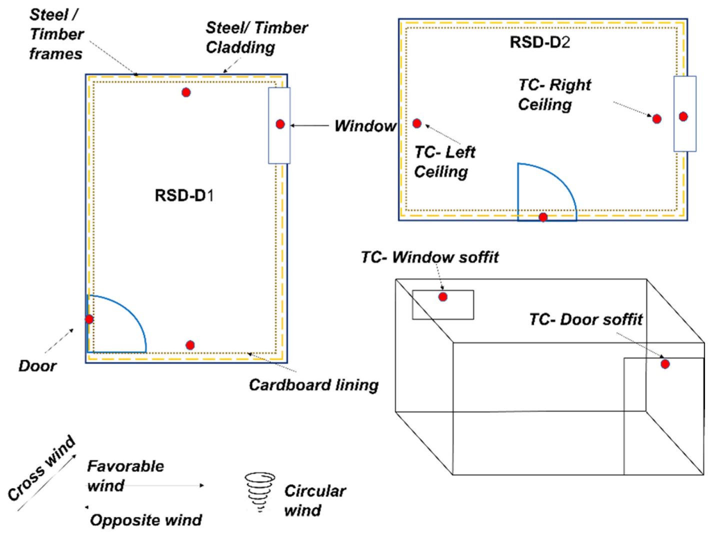

Figure 5. Instrumentation layout of an RSDs.

4. RSE Results and Discussion

The testing regime of the experiments is listed in the following sections where the experiments are discussed according to the number of dwellings tested at a time.

4.1. Two RSD Experiments

The testing matrix of double dwellings experiments shown in Table 3 and the detailed analysis has been provided in the following sections. In this two RSD test, the RSD on the left was considered as RSD-1, whereas the RSD on the right as RSD-2 and each test began with igniting the RSD-1 and fire spread to the RSD-2 was studied. The calculated fire spread rate highlights how the timber dwellings have much faster spread than steel dwellings. For the crosswind condition (Test 2) no spread occurred, whilst spread occurred very slowly with a fluctuating circular wind (Test 3).

Table 3. Test matrix of two RSD experiments.

Test No	RSD Id	RSD Configuration	Wind Speed	Fire Spread Rate (m/min)
1	1-2D-S-250-/	Steel-clad RSDs with timber cross member placed laterally.	Negligible	0.137
2	2-2D-S-250-K	Steel-clad RSDs with timber cross member placed longitudinally.	13 kmph cross	No spread
3	3-2D-S-250-C		15 kmph circular	0.008
4	4-2D-S-250-F		17 kmph favourable	0.07
5	5-2D-T-250-C	Timber-clad RSDs placed longitudinally.	11 kmph circular	0.123
6	6-2D-T-500-O		14 kmph opposing	0.121

4.1.1. Longitudinal Fire Spread between Two Steel-Clad RSDs (Test 1)

Test 1 (negligible wind): The influence of wind was minimal throughout the duration of the experiment. An initial peak in temperature was recorded at 200 s of RSD-2 came from smoke entrainment inside the dwelling from RSD-1 through the gaps between backwall and roof panel. At 561 s, flames started impinging on the wall of RSD-2 that heated the timber cross member and ignited the cardboard linings. The cardboard then allowed the fire to spread throughout the compartment leading to the ignition of the wood crib, and the RSD-2 was fully involved in fire. The fire in RSD-2 lasted for 800 s from ignition till collapse. The increase in fuel load in Test 11 prolonged the burning time relative to the tests below. However, despite the slightly higher fuel load, the wind speed is also dominant in influencing spread behaviour.

The comparative results from RSEs and FSE [9] has been provided in the Table 4. The peak roof temperatures of the RSEs in RSD-1 was 11% lower than in RSD-2, whereas this difference in peak roof temperature was 8% in FSE. This temperature difference between these dwelling was a result of limited ventilation condition. The roof temperature difference in RSEs were 28% lower than the FSEs as a result of higher heat losses and lower smoke layer thickness.

Table 4. Comparative results from longitudinal fire spread between two steel-clad dwellings.

Steel-Clad ISDs	Full-Scale ISD [9]		Reduced-Scale ISD	
	ISD-1	ISD-2	RSD-1	RSD-2
Fire spread mechanism	Dwelling of fire origin	Flame impingement from RSD-1 on exposed timber cross member of RSD-2	Dwelling of fire origin	Flame impingement from RSD-1 on exposed timber cross member of RSD-2
Maximum ceiling temperature	963 °C	1040 °C	685 °C	763 °C
Ventilation	Door	Door and windows	Door	Door and windows
Time from the start to flashover	360 s	160 s	210 s	480 s
Scaled time from the start to flashover	-	-	420 s	960 s
Time from start of ignition to collapse	660 s	440 s	587 s	840 s
Scaled time from start of ignition to collapse	-	-	1174 s	1680 s
Time to fire spread to RSD-2 from flashover of RSD-1	-	80 s	-	110 s
Scaled time to fire spread to RSD-2 from flashover of RSD-1	-	-	-	220 s

The time from ignition to flashover was 360 s and 160 s vs. 210 s and 480 s for the FSE and RSE, respectively, where the latter scaled to 420 s and 960 s ($t \sim s^{\frac{1}{2}}$). The spread time for the FSE was 80 s from flashover of RSD-1, whereas it was 110 s and 220 s for the unscaled and scaled times for the RSE. In case of RSD-2, the growth phase was largely smouldering after the ignition of cardboard; thus, time to flashover was substantially longer in the experiment time. The fire spread rate in Test 1 was 0.167 m/min which after scaling was approximately three times larger than in FSE at 0.84 m/min. Hence, overall temperatures, flame behaviour, spread mechanisms and fire development trends were reasonably well captured, but spread rates and experiment times were not. This is a consistent theme that follows through the experiments below.

4.1.2. Lateral Fire Spread between Two Steel-Clad RSDs (Tests 2–4)

In Test 2 (2-2D-S-250-K), Test 3 (3-2D-S-250-C) and Test 4 (4-2D-S-250-F), both RSDs were steel-clad with timber cross members. The window was introduced in RSD-1 such that the dwelling is identical to RSD-2. This updated test was proposed with a slightly lower fuel load and the RSDs were positioned laterally at 250 mm from each other. These tests were conducted outdoors with varying wind conditions to assess the impact of wind conditions. Figure 6 shows a test setup and the temperature-time results of the tests.

Test 2 (cross wind): The flames started to emerge from the openings of RSD-1 within 2 min after ignition and the flashover was observed shortly thereafter. The cross wind swept the hot gases and flames away from the adjacent RSD-2 and no fire spread was observed to the RSD-2.

Test 3 (circular wind): Flashover was observed within 2 min and flames from the openings of RSD-1 started impinging on the cladding of RSD-2. The movement of hot gases and flames in the open environment was dependent on the direction of wind, which kept changing throughout the experiment. There was a continuous heat flux (radiative and convective) from windows of RSD-1 to the steel cladding that initiated the smouldering of cardboard linings of RSD-2. The flame impingement was seen for a short span that ignited the smouldering cardboard through gaps in the RSDs. After the ignition of cardboard, the adjacent RSD was in a smouldering phase for 1550 s and later the adjacent RSD was involved in the fire.

Test 4 (favourable wind): This test was unique where a wind of 24 kmph was observed from RSD-1 towards RSD-2. After the ignition of RSD-1, all the hot gases were driven towards the direction of RSD-2. RSD-1 reached a flashover in less than 90 s and the flames emerging out of RSD-1 started impinging onto the steel cladding of RSD-2. A smouldering of cardboard in RSD-2 was seen at 185 s after ignition in RSD-1 and within a few seconds the cardboard was ignited which spread the fire to the other regions of the RSD including the wood cribs. Despite being a successful experiment in terms of fire spread to the adjacent RSD, the data could not be extracted due to technical failure, hence only videographic information was used for analysis.

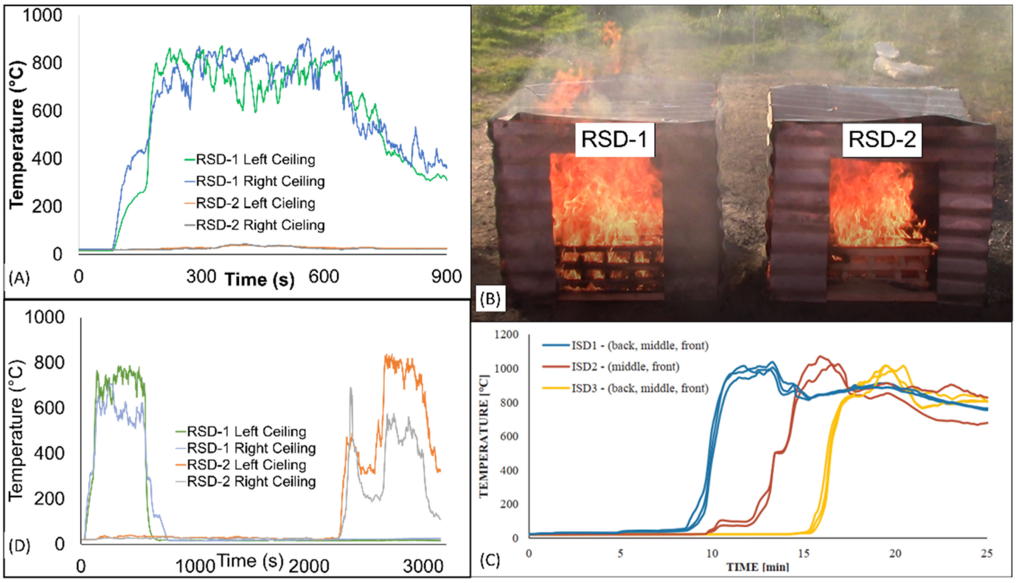

Figure 6. Longitudinal fire spread results. Left top clockwise—(**A**) Test 2: ceiling temperature on cross wind condition, (**B**) RSEs on steel-clad dwellings, (**C**) FSE results on steel-clad dwelling [7], (**D**) test 3: ceiling temperature on circular wind condition.

Figure 6 shows the results of ceiling temperature profiles of various RSEs and FSEs from multiple steel-clad dwelling tests. The experimental results from RSDs are compared with full scale experiment [7] and provided in Table 5. The temperature time curve in RSE correlate well with the FSE. Theoretically, the temperatures should be scaled for the RSEs. The ceiling temperatures in the RSEs from available data were ranging from 830 to 900 °C and found to be around 20% lower than the FSEs. A similar drop in ceiling temperatures was recorded in past work [17].

Table 5. Comparison on RSEs and FSEs results on fire spread between multiple steel-clad reduced scale dwelling.

Steel-Clad ISDs	Full-Scale ISD [7]		Reduced-Scale ISD					
	Favourable Wind		Test 2 (Cross Wind)		Test 3 (Circular Wind)		Test 4 (Favourable Wind)	
	ISD-1	ISD-2	RSD-1	RSD-1	RSD-1	RSD-2	RSD-1	RSD-2
Maximum ceiling temperature	1037 °C	1070 °C	900 °C	No spread	838 °C	840 °C	No Data	No Data
Time from start of ignition to collapse	1080 s	1140 s	537 s	No Ignition	570 s	574 s	553 s	637 s
Scaled time from start of ignition to collapse	-	-	1074 s	-	1140 s	1148 s	1106 s	1274 s
Time from the flashover to collapse	510 s	378 s	311 s	No Ignition	485 s	497 s	445 s	524 s
Scaled time from the flashover to collapse	-	-	622 s	-	970 s	994 s	890 s	1048 s
Time to fire spread to RSD-2 from flashover of RSD-1	-	240 s	-	No Spread	-	2259 s	-	319 s
Scaled time to fire spread to RSD-2 from flashover of RSD-1	-	-	-	No Spread	-	4518 s	-	638 s

It was observed that the experiment time in all RSEs followed scaled correlation ($t{\sim}s^{1/2}$) in all wind conditions with a maximum error margin of 11% in test 4. The time to flashover in each case was different and deviated up to 100% from the full-scale experimental results. This shows the limit of scaling hypothesis in which all phenomena cannot preserved. The time for spread from flashover in the FSE was 240 s which is not comparable to the unscaled RSE values (No spread, 2259 s, 319 s) and the scaled values (No spread, 4518 s, 638 s).

In both FSE and RSE, the fire spread from the dwelling on fire adjacent RSE was due to ignition of cardboard because of flame impingement through the gaps and constant heat flux that led to ignition. This burning cardboard then spread fire to entire dwelling. The fire spread in Test 4 (favourable) was faster than in other tests due to favourable wind currents. In Test 3 (circular), as seen in Figure 6D, although fire spread was delayed it was interesting to see an evolution of smouldering fire that subsequently led to the collapse of the RSD and spread only occurred after that. This confirms the possibility of restarting IS fires despite the original dwelling on fire is attended. In all cases, the fire spread time in the FSE was significantly lower than the RSEs by 95 and 62%.

4.1.3. Lateral Fire Spread between Two Timber-Clad RSDs (Tests 5–6)

Tests 5 to 6 were carried out to understand the influence of combustible cladding, namely 14 mm thick timber planks. Since combustible cladding is known to cause increased fire spread in settlements a large separation distance of 500 mm was also used. Low wind speeds that were circular or opposing wind spread occurred during the testing.

Test 5 (250 mm spacing): Upon ignition RSD-1 was engulfed in fire within 100 s and the hot smoke and flames emitted convective and radiative heat fluxes on to the adjacent RSD that aids in pyrolysing the timber cladding of RSD-2. Although the wind was in circular motion throughout the experiment, the adjacent RSD took less than 121 s to ignite. The entire experiment was completed within a period of 800 s that completely burned down the RSDs ending the experiment.

Test 6 (500 mm spacing): Spread from RSD to RSD took 427 s from ignition, which is approximately double that of Test 5. The total duration of an experiment was little over 1100 s.

Figure 7 shows the comparison between FSEs and RSEs. The experimental results from RSDs are compared with full scale experiment [7] and provided in Table 6. The experimental time temperature curve for FSE and RSEs had similar pattern indicating that general behaviour was captured. However, the peak temperature in both RSEs tests was lower by around 10%. The temperature profile followed in the FSD graph, as shown in Figure 7A, and is similar to the timber-clad RSEs temperature results for both Test 5 and 6. The adjacent RSDs in both the tests became involved in fire once the burning FSD reached the fully developed phase. As shown in Figure 7E, in RSEs with 250 mm separation distance experiment, RSD-2 ignited during the final stages of fully developed phase of RSD-1 closely representing full scale experiment. However, ignition of RSDs with 500 mm separation distance was delayed where the ignition phase of RSD-2 was coinciding with decay phase of fire in RSD-1 as seen in Figure 7D as the wind was opposing the fire spread. Hence, in this instance geometric scaling was suitable for capturing spread behaviour.

Table 6. Results from fire spread between timber-clad dwelling in full scale experiment and reduced scale experiment.

Timber-Clad RSD Informal Settlement Dwelling	Full-Scale ISD [7]		Reduced Scale ISD			
	Mild Favourable Wind		Favourable Wind, Spacing—250 mm		Favourable Wind, Spacing—500 mm	
	ISD-1	ISD-2	RSD-1	RSD-2	RSD-1	RSD-2
Maximum ceiling temperature	1104 °C	1176 °C	1016 °C	957 °C	1000 °C	974 °C
Time from start of ignition to collapse	798 s	858 s	580 s	420 s	780 s	410 s
Scaled time from start of ignition to collapse	-	-	1160 s	840 s	1560 s	820 s
Time from the start to flashover to collapse	306 s	318 s	480 s	390 s	600 s	359 s
Scaled time from the start to flashover to collapse	-	-	960 s	780 s	1200 s	718 s
Time to fire spread to RSD-2 from flashover of RSD-1	-	82 s	-	121 s	-	247 s
Scaled time to fire spread to RSD-2 from flashover of RSD-1	-	-	-	242 s	-	494 s

In the FSEs, the wind current was favourable to fire spread, whereas in the RSEs, they were either circular or opposing the fire spread, potentially leading to the discrepancy in spread times. The duration in each RSD from ignition to collapse was recorded as twice that of FSEs in the unfavourable wind condition. The fire spread to and adjacent RSD from a timber-clad RSEs is largely due to flame impingement and heat fluxes that ignite cardboard and also pyrolyse the timber cladding. At this scale, the fire spread time is approximately linearly dependent on separation distance between the dwellings, but this is likely to be influenced by multiple factors. The time to spread from flashover was 82 s for the FSE which is faster than the RSE unscaled (121 s, 242 s) and scaled (247 s, 494 s) values.

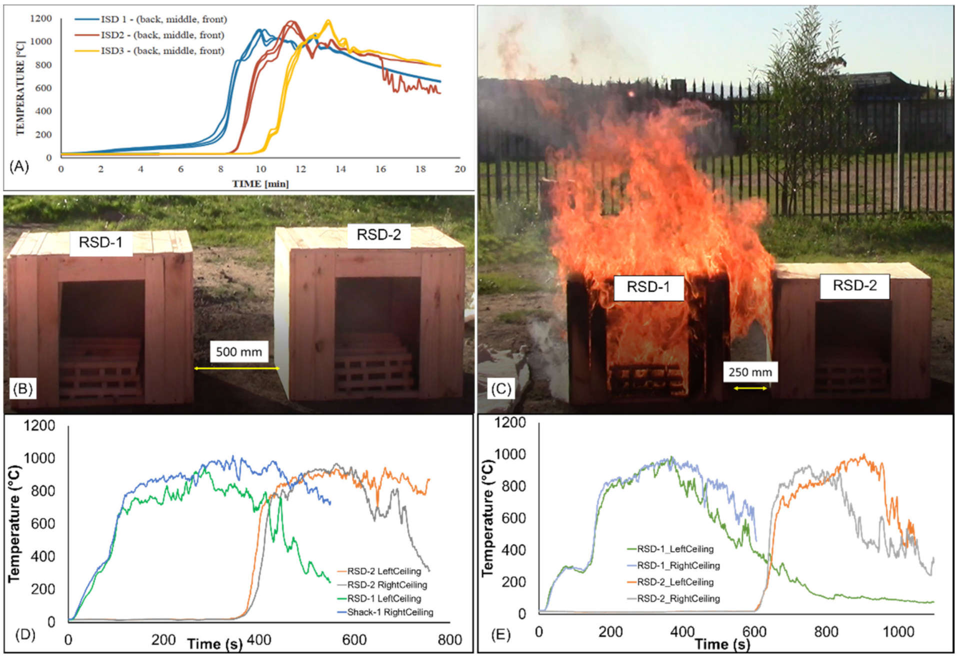

Figure 7. Results from various muti dwelling tests. Clockwise—(**A**) FSE results on timber-clad dwelling [7], (**B**) test 6: RSEs on timber-clad dwellings at 500 mm, (**C**) test 5: RSEs on timber-clad dwellings at 250 mm, (**D**) test 6: ceiling temperature in timber-clad dwelling placed at 500 mm, (**E**) test 5: ceiling temperature in timber-clad dwelling placed at 250 mm.

4.2. Three RSD Experiments

In continuation to the two RSD experiments, a third dwelling was added on the adjacent side, see Figure 8, such that the fire spread from the door and window can be analysed. In these experiments, the impact of combustible cross members with varying wind conditions has been analysed. In this series three sets of experiments were conducted that are listed in the following section and the testing matrix has been provided in Table 7. The wind speed in all tests was low at around less than 5 kmph, which led to only wind direction being captured accurately.

Table 7. Testing matrix of three RSD experiment.

Test No	RSD Id	RSD Configuration	Wind	Fire Spread Rate (m/min)
7	7-3D-S-H-300-F	Steel-clad RSDs with steel cross member spaced at 300 mm from each other, in 'L' shape.	Favourable <5 kmph	0.15
8	8-3D-S-H-250-O	Repeated above test with timber cross member. Dummy RSDs added.	Opposing <5 kmph	0.136
9	9-3D-S-H-300-O	Steel-clad RSDs 3 with timber cross member spaced laterally	Opposing <5 kmph	No spread
10	10-3D-S-H-300-R	Repeated above test in restricted wind condition	/	0.15

Test 7 (steel frame): Three steel-clad RSDs were located equidistant of 300 mm from each other in a 'L' shape. The 300 mm spacing is based on geometrically scaling the 1.2 m distance between dwellings in the FSE used for comparison. RSD-A1 was ignited and the fire spread was observed in RSD-A2 and RSD B1. The flames from door and windows of RSD-A1 started impinging on adjacent RSDs at 270 s. The constant flame impingement on backwall of RSD-B1 led to the smouldering of its cardboard lining for more than 100 s then subsequently ignited the cardboard at 450 s as seen in Figure 8. The fire quickly spread throughout the RSD-B1 including the wood cribs. The fire in RSD-A1 burned away before the fire in the adjacent RSD-B1 could establish and the fire development inside the RSD-B1 was aborted.

In addition, there was no combustible cross members which in real fires contribute to faster fire spread. The flames from the window of RSD-A1 was not steady while impinging on the window of RSD-A2. The flames were pushed away by air movement in the alley between the RSDs; thus, the flames were not able to ignite the cardboard of RSD-A2; however, smouldering gases from the RSD were seen throughout the experiment. The intensity of flame impingement represented as a temperature profile in adjacent dwellings has been provided in Figure 9A where the roof temperature of RSD-B1 indicated the ignition of the shack and window temperature of RSD-A2 indicates the temperature of pyrolysis gases.

Based on the results from Test 7, Test 8 was then used to study the influence of reduced spacing and timber frames; Test 9 considered the same spacing and timber frames whilst Test 10 was a repeat of Test 9 but was carried out with negligible air movement. Tests 9 and 10 were carried out as a single line of dwellings to ensure one-dimensional spread and effects could be ensured.

Test 8 (timber frame, 250 mm spacing): The same experimental set-up was repeated by reducing the separation distance between the RSDs from 300 mm to 250 mm. One dummy RSD added ahead of RSD-A2 such that it becomes 4-RSD arrangement that will restrict the wind near the windows. The unfavourable wind condition pushed flames away from the RSD-A2 and no significant difference was found in fire spread rates from Test 7.

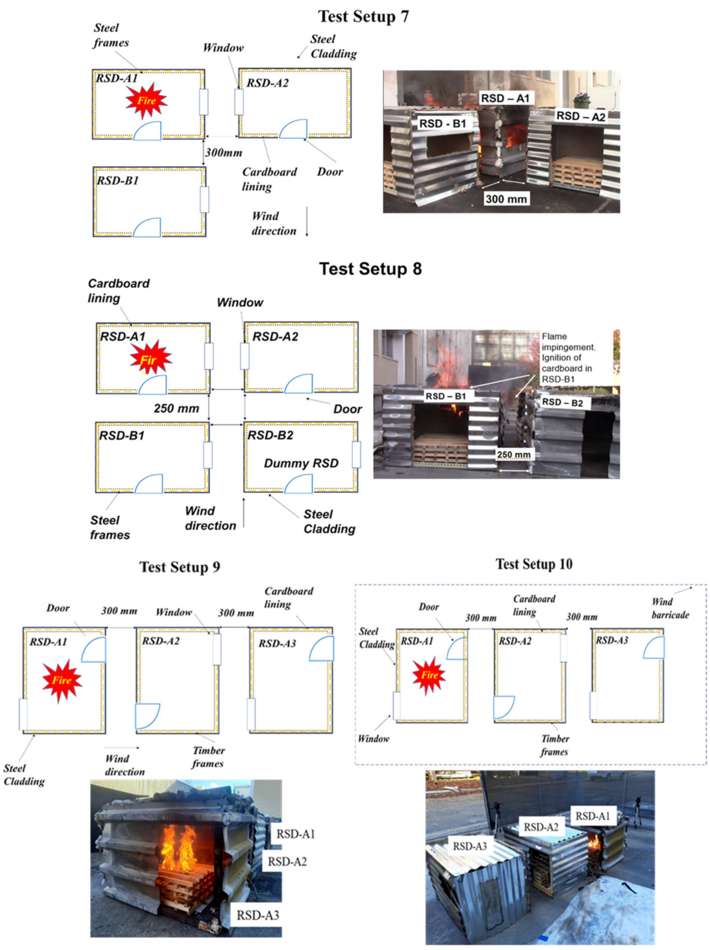

Figure 8. Tests 7 to 10 showing layouts and images during testing.

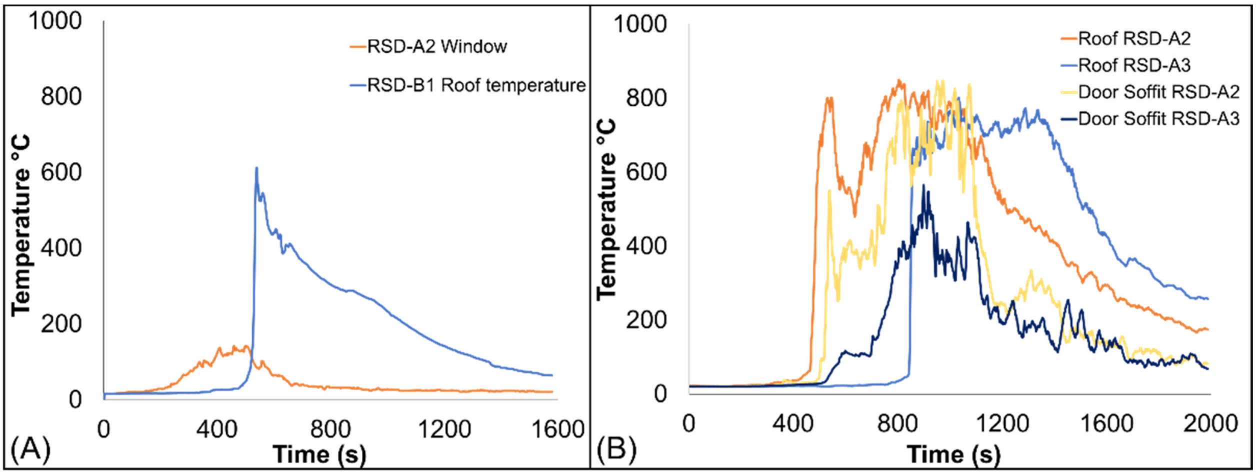

Figure 9. Three RSD experiment: (**A**) test 7: fire spread by RSD-01; (**B**) test 10: roof temperatures and door soffit temperatures.

Test 9 (timber frame, 300 mm spacing): There was no fire spread observed in Test 9 despite the presence of combustible cross members due a light unfavourable wind. Hence, depending on wind direction spread is unlikely to occur with a spacing of 300 to 400 mm based on the geometry of RSD-A1.

Test 10 (as Test 9 with no air movement): The same test was repeated as Test 10 but with barricading the experimental area with porous screen to considerably reduce the influence of wind. Fire spread was observed in all the RSDs and a fire development pattern observed with one RSD igniting the other in every 400 s as shown in Figure 9B. This test again highlights both the importance of combustible cross member and influence of wind conditions in ISDs fire spread.

From Table 7 it can be observed that the spread rate was surprisingly consistent between the different tests at around 0.136–0.15 m/min, considering the variable conditions and parameters, but of the same order as the tests with more rapid spread for the double dwelling RSDs above.

4.3. Four RSD Experiments

The four RSD experiments were conducted with varying distances and staggered arrangements of RSDs. The details of the test setups have been provided in Table 8. In these experiments, the impact of distance, cladding, and positioning of RSDs with varying wind conditions have been analysed. Setups have been designed to mimic a section of the 20-dwelling experiment presented in Section 5.2.3 [10], and the results will be analysed and presented further in the following sections.

Table 8. Testing matrix of four RSD experiment.

Test No	RSD Id	RSD Configuration	Wind Speed	Fire Spread Rate (m/min)
11	11-4D-S-550-/	Steel-clad RSDs in staggered arrangement spaced equidistant from each other such that there are 2 rows of 2 Nos RSDs. The wind condition was restricted	/	0.225
12	12-4D-2S/2T-250/550-F	Steel-clad RSDs spaced equidistant from each other such that there are 2 rows of 2 RSDs.	9 kmph favourable	0.194

Test 11 (negligible wind): The steel-clad RSDs were arranged in staggered positions with two rows of two numbers of RSDs as shown in Figure 10. The adjacent dwellings were positioned 250 mm part and the next row was placed at 550 mm away from the first row. The influence of wind during the test was restricted by a porous barricade on the test site perimeter.

RSD-A1 and RSD-A2 were ignited simultaneously, and the fire spread to adjacent rows was observed. At 400 s after ignition, the flames were seen projecting outside the RSD-A1 and were directly impinging onto backwall of RSD-B1. Then RSD-A2 became fully involved in fire at 485 s and the flames from its door opening were now impinging on the back wall of RSD-B2 and initiated the pyrolysis of the cardboard lining near its windows. The cardboard lining near the timber cross member of the backwall of RSD-B2 was ignited by the impinging flames from RSD-A2 and within 60 s the fire was spread inside the dwelling. The entire test lasted for approximately 20 min but there was no ignition or fire spread observed to RSD-B1 despite a constant flame impingement for 600 s. It is also interesting to observe that the door opening in RSD-A1 and the window opening of RSD-B1 were located on opposite sides and could be the reason for no fire spread in the test as flames were not able to trigger the ignition of the cardboard linings. In addition, the RSDs with different dwelling profile such as RSD-A1 (Type D2) and RSD-A2 (Type D1) in this section provided different results in fire spread under the same environmental conditions.

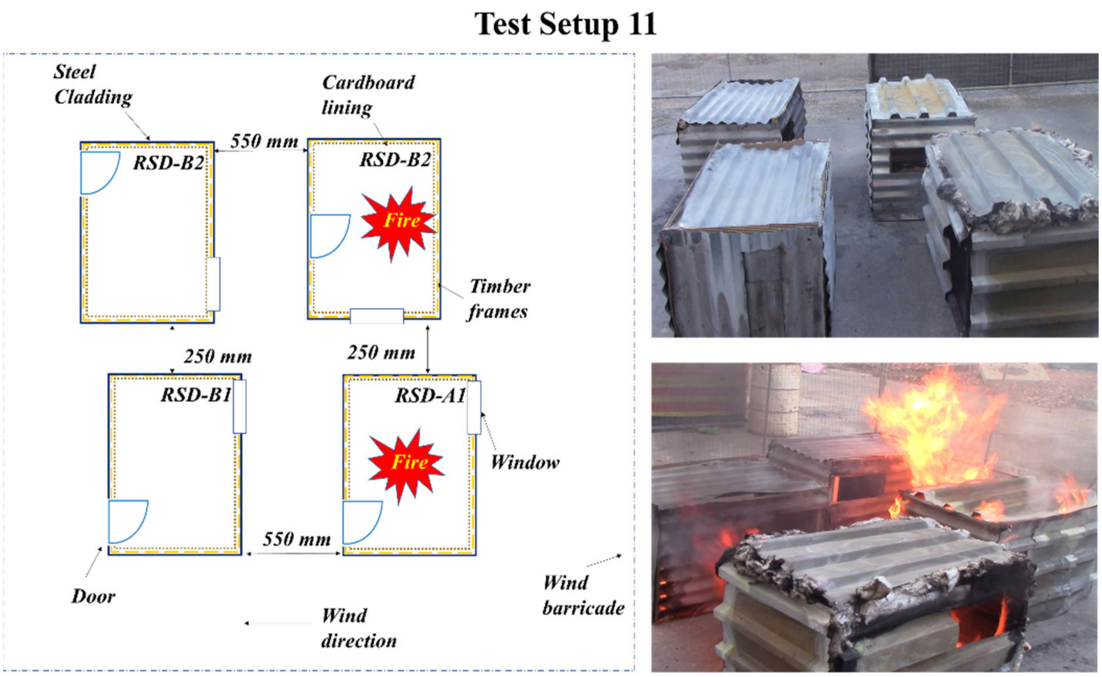

Figure 10. Four RSD experiment: test setup 12; clockwise—schematic view; test setup-12 @ 0 min; flame impingement from RSD-A2 at 11 min.

Test 12: The RSDs in each row was separated by 250 mm and RSDs in the next row were placed at 300 mm and 550 mm as shown in Figure 11. Each row consisted of one steel-clad RSD and one timber-clad. In the beginning, RSDs of row B was ignited and within 40 s the RSDs reached the fully developed stage. The ignition of combustible cladding of timber in RSD-B2 resulted in larger influence of convective and radiative heat flux in the vicinity.

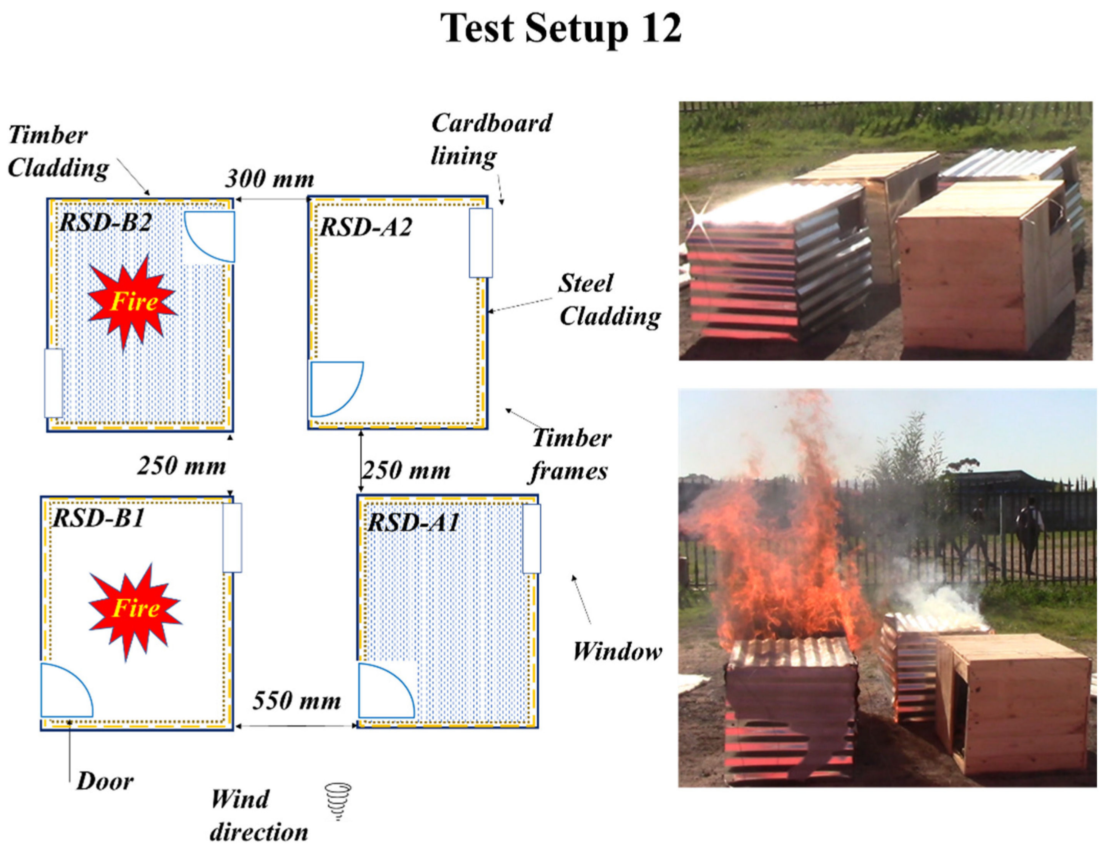

Figure 11. Four RSD experiment: test setup 12; clockwise—schematic view; test setup-11 @ 0 min; @ 6 min.

This heat flux triggered the ignition of steel-clad RSD-A2 in the next row as seen in Figure 11. The heat flux and flame impingement from the door of RSD-B2 aided in faster burning of combustibles in the dwelling RSD-A2. As a result, the total burn time of RSD-A2 reduced to 400 s. The RSD-B2 also influenced the timber RSD-A1 that was on the opposite side. The flame impingement and heat flux from the steel-clad RSD-B1 of first row, heated the timber cladding of RSD-A1 in second row which resulted in pyrolysed and charred cladding surface on the RSD. However, there was no ignition seen in the timber dwelling.

Discussion on Fire Spread Comparative Results in 4 Nos RSD Test (Tests 12) and FSE

A section of the 20 dwelling large scale experiments has been represented by the 4 RSDs in Test 11 and 12. The experimental setup in full scale experiment and reduced scale experiment with fire spread patterns are shown in Figure 12. The chosen section in the full-scale experiment was surrounded by burning dwellings which enhanced burning rate due to continuous flame impingement onto the RSD and higher heat transfer from dwellings on fire to adjacent dwelling. This phenomenon has enhanced the time to flashover and supported faster fire spread in the IS dwellings.

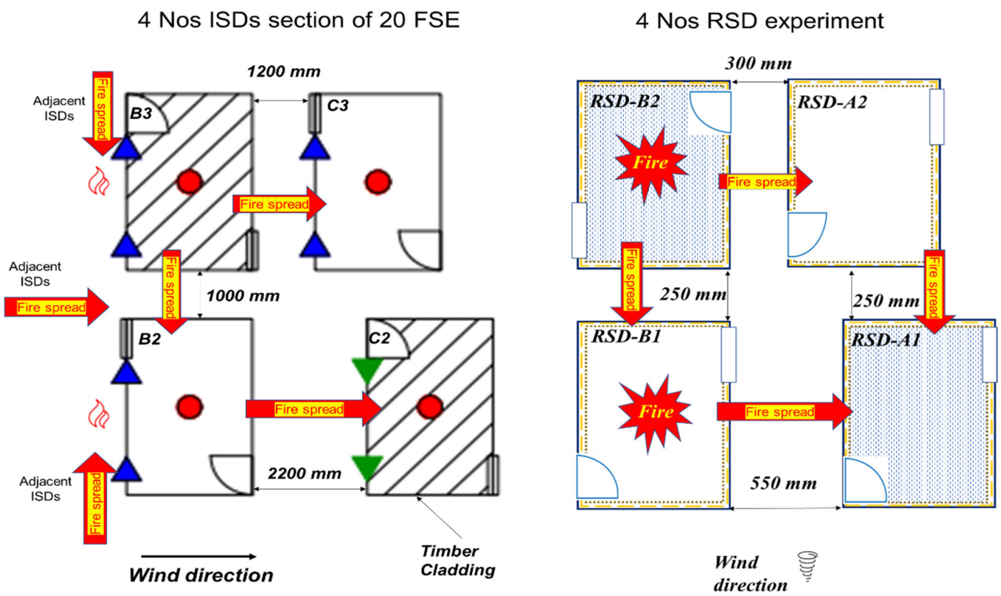

Figure 12. Fire spread in FSEs and 4 Nos RSD test.

In contrast, the reduced scale experiments had no influence of added heat transfer or flame impingement from adjacent RSD and unlike in full-scale experiment where wind direction was favourable to fire spread, in the RSEs the wind direction was changing throughout the experiment. This condition diverted the flames and heat away from the RSDs in row A. However, the effect of timber dwelling RSD-B2 dominated the wind effect and ignited the RSD-A2 within 200 s as seen in the graph B of below Figure 13. The graphs represent the ceiling temperature of dwellings in full scale experiment (top) and reduced scale experiment (bottom). Table 9 lists the difference in time to flashover, duration of dwelling to collapse, and maximum ceiling temperature.

The ceiling temperatures in full scale experiments were over 25% higher than the reduced scale experiments due to higher smoke layer build-up. In both type of experiments, the ignition to flashover to fully developed was achieved in short duration with little over a minute. However, this transition was achieved more quickly due to the impact of burning adjacent RSD. In the four RSD experiment the influence of burning adjacent RSD are clearly visible in burning time. The fire spread to adjacent row is evident in the graphs of reduced scale experiment but in the section of full-scale experiment, the burning behaviour was a collective phenomenon involving fires at multiple FSDs.

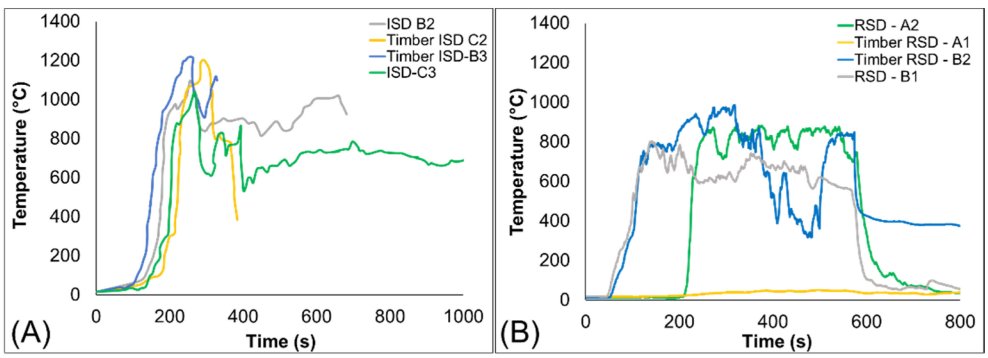

Figure 13. Ceiling temperature of 4 Nos RSDs in (**A**) FSEs, and (**B**) RSEs.

Table 9. Comparative results from 4 Nos RSEs (Test-12) and FSEs.

RSD Nos		Maximum Ceiling Temperature (°C)	Time from the Start to Flashover (s)	Scaled Time from the Start to Flashover (s)	Time from Start of Ignition to Collapse (s)	Scaled Time from Start of Ignition to Collapse (s)	Time to Fire Spread to Adjacent RSD from Flashover of RSD in 1st Row (s)	Scaled time to Fire Spread to Adjacent RSD from Flashover of RSD in 1st Row (s)
Full-Scale ISD	B2	1203	60	-	600	-	-	-
	B3	1213	60	-	240	-	-	-
	C2	1170	60	-	250	-	100	-
	C3	1039	40	-	940	-	90	-
Reduced Scale ISD	B2	986	55	110	550	1100	-	-
	B1	801	60	120	513	1026	-	-
	A2	881	87	174	490	980	677	1354
	A1	50	Nil	-	Nil	-	-	-

4.4. Six RSD Experiments

The six RSD experiment tests below provide an understanding on behaviour of fire spread between multiple mixed-clad dwellings. The influence of cladding material, fire load, wind conditions, and separating distance between RSDs on fire spread among multiple dwellings has been recorded. The testing matrix has been provided in the Table 10 and the detailed analysis has been provided in the following sections, with layouts provided in Figures 14–19. After the results from all the six dwelling experiments have been presented, they will be compared with the FSE results below.

Table 10. Testing matrix of six RSD experiment.

Test No	RSD Id	RSD Configuration	Wind Speed	Fire Spread Rate (m/min)
13	13-6D-S-300/550-O	Longitudinally placed 2 Nos Steel-clad RSDs in 3 rows spaced at 300 mm and 550 mm.	30 kmph	No spread
14	14-6D-S-300/550-F		28 kmph	
15	15-6D-S-300/550-K	Repeated above test with increased fuel load	24 kmph	0.15
16	16-6D-4S/2T-300/550-O	Repeated above test but steel RSDs were replaced with timber-clad RSD in the either side of middle and last row.	11 kmph	0.13/0.04
17	17-6D-4S/2T-300/550-O		13 kmph	0.058/0.015
18	18-6D-3S/3T-550-/	The same test was repeated but RSDs rows spaced at equal distance. The fire was ignited in the second row to avoid the influence of wind.	/	0.273/0.34
19	19-6D-4S/2T-550-/		/	0.114

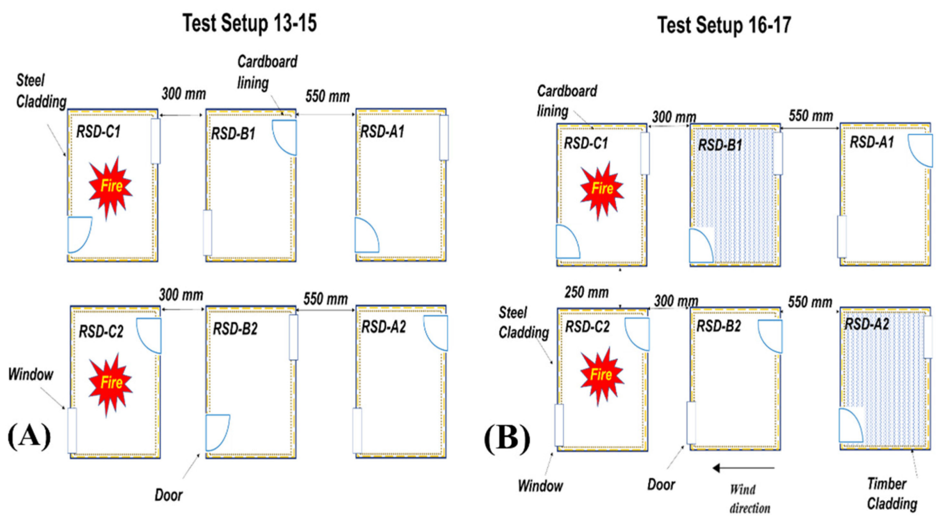

Figure 14. Six RSD experiment—(**A**) test setup 13–15, (**B**) test setup 16–17.

4.4.1. Tests 13–15—Steel Only Dwellings

Test-13 (opposed wind): In the first test, RSD-C1 and RSD-C2 of first row were ignited. The fire quickly reached flashover state and the fire became fully developed within 90 s. The wind was blowing strongly in the opposite direction of expected flame spread which drove away all the hot gases and flames away from second row RSDs. This led to loss of convective and radiative heat flux that play a crucial role in pyrolysis of available combustibles. Furthermore, the impinging flames were also diverted away from second row RSDs that would ignite the already pyrolysing combustibles inside them. No fire spread occurred to the adjacent rows.

Test 14 (favourable wind): The same test was repeated with favourable wind conditions blowing strongly at 28 kmph that directs all the hot gases towards the second row of RSDs. The flames from the ignited RSD-C1 and RSD-C2 were also seen to be carried over by the wind. The strong favourable wind current also caused the burning of the fuel at a faster rate. On the other hand, the heat losses in the burning RSDs increased due to mixing of cold air with hot gases. As a result of losing essential heat fluxes in this way, there was no effective fire spread to adjacent rows of RSDs. Though substantial flame impingement was seen towards second row RSDs, but it was inadequate to ignite the combustible materials. This is interesting given that the previous test with unfavourable wind conditions had spread across the 300 mm space to the second row.

Test 15 (crosswind and increased fuel load): There was no modifications made in geometry of the RSDs, but the fuel load was increased by two layers. There was heavy cross wind which blew the hot gases partially towards the second row of RSDs. There was a sustained flame impingement due to continuous favourable wind current and increased fire load. This aided in the fire spread onto the RSDs in the second row which was ignited after 4 min. The flames were also seen going over the RSDs and not impinging on the steel cladding. The temperature development for this test setup are shown in Figure 15 in which each RSD after its ignition, takes around 100 s to reach ceiling temperature of 600 °C indicating the flashover stage (in addition flames appear outside the RSD openings) and the total duration of each burning RSD is around 500 s. Additionally, ignition of RSDs in each row can be clearly seen in graphs where second row was ignited at around 300 s. Although from the Figure 15, it can be seen that the third row has recorded elevated temperatures in the openings but the flames from second row were inadequate to ignite the combustibles in the third row of RSDs. Thus, wind current with an optimum speed and favourable direction, and an increased fuel load, possess a higher possibility of fire spread through flame impingement and heat fluxes than from the hot gases.

Overall, only Test 15 resulted in spread through the 6 dwellings, with a rate of 0.15 m/min, which is similar to spread rates above. Both the increased fuel load and effect of wind influenced this result.

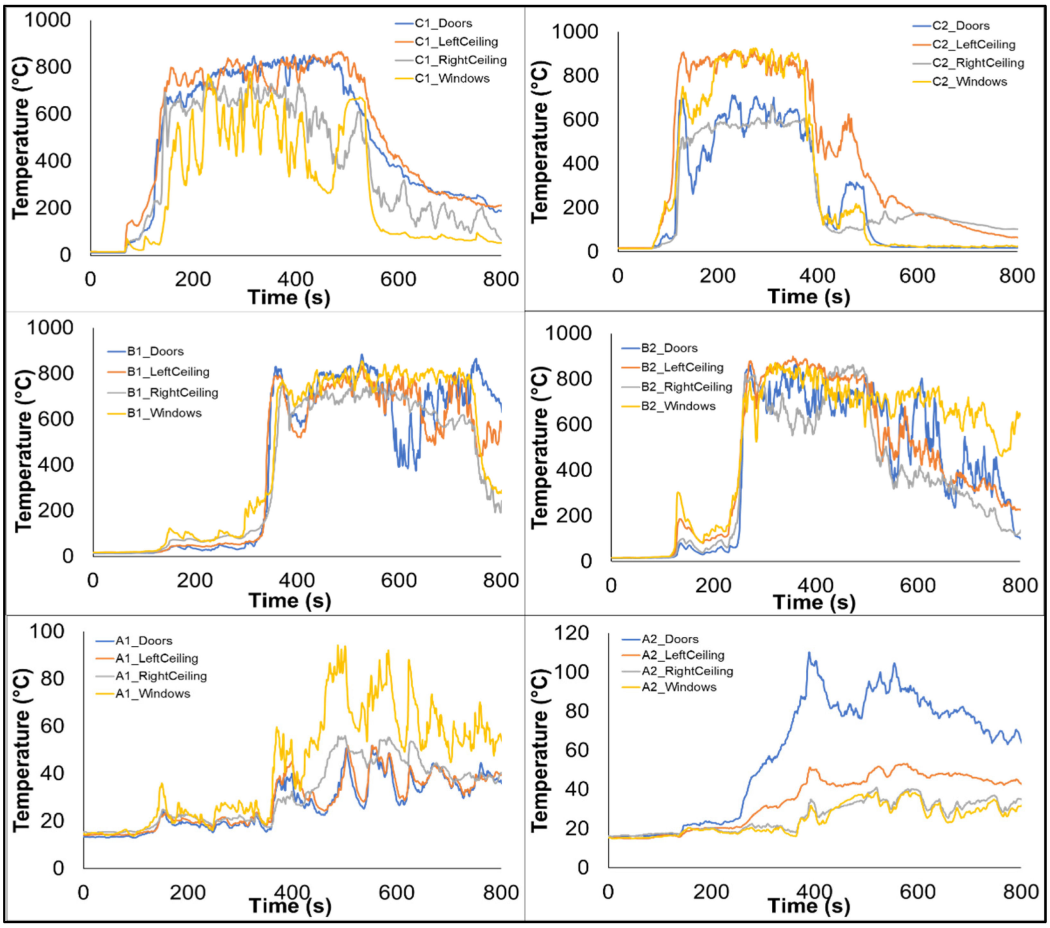

Figure 15. Six RSD experiment: temperature profiles of each RSD in Test 15.

4.4.2. Tests 16–17—Mixed Steel and Timber Dwellings

Test-16 (16-6D-4S/2T-300/550-O): The previous tests were modified with the inclusion of two timber-clad RSDs placed in second and third rows. The test was initiated by igniting two RSDs of first (C) row and within 90 s, the fire quickly reached fully developed stage. There was an opposing wind current driving all the hot gases away from the second row of RSDs. The flames were also diminished and fluctuated by the wind. Despite this factor, the timber dwelling RSD–B1 in the second row ignited at ^{6t}h minute and the heat flux from the flaming timber cladding led to steel ISD in the second row, RSD–B2 to ignite. The heat flux and flames from RSD—B1 and B2 together started pyrolysing the timber cladding of RSD–A2 in the third row. However, due to insufficient flame lengths owing to opposing wind condition, the third row was not involved in fire. This test was therefore repeated to confirm the repeatability of the results of the reduced scale experiments.

Test 17 (repeat): In this test the fire in the two dwellings of the first row namely RSD-C1 and RSD-C2 became fully developed within 60 s which is earlier than Test 16. The wind current flowing at 13 kmph was opposing the fire spread to the second row RSDs. The results such as fire spread, flashover time and test duration between from Tests 16 and 17 were similar as shown in Table 11. In both cases, the timber RSD–B2 was first to ignite in the second row due to continuous heat flux on timber cladding and an ignition by a flame from RSDs the first row. Similarly, in the test-17, the RSD–B1 took longer to ignite due to opposing wind conditions. In this test spread did occur to the third line of dwellings.

Table 11. Comparative results of test-16 and 17 with FSE.

RSD Nos		Maximum Ceiling Temperature (°C)	Time from the Start to Flashover (s)	Scaled Time from the Start to Flashover (s)	Time from Start of Ignition to Collapse (s)	Scaled Time from Start of Ignition to Collapse (s)	Time to Fire Spread to Adjacent RSD from Flashover of RSD in 1st Row (s)	Scaled Time to Fire Spread to Adjacent RSD from Flashover of RSD in 1st Row (s)
Test Setup-16	A1	51	Nil	-	Nil	-	-	-
	A2	52	Nil	-	Nil	-	-	-
	B1	967	45	90	379	758	206	412
	B2	873	42	84	400	800	390	780
	C1	899	41	82	473	946	-	-
	C2	902	45	90	414	828	-	-
Test Setup-17	A1	51	Nil	-	Nil	-	-	-
	A2	52	Nil	-	Nil	-	-	-
	B1	902	40	80	368	736	309	618
	B2	880	56	112	404	808	992	1984
	C1	817	66	132	492	984	-	-
	C2	979	67	134	489	978	-	-
Full-Scale ISD	A1	1240	100	-	500	-	-	-
	A2	1220	40	-	600	-	-	-
	B1	1170	70	-	300	-	90	-
	B2	1100	100	-	600	-	100	-
	C1	1150	90	-	720	-	130	-
	C2	1205	100	-	250	-	120	-

This similarity in temperature trends is graphically represented in Figure 16 where ceiling temperatures of ignited RSDs are presented. Despite this set of tests having a lower fuel load and opposing wind, the addition of timber-clad RSD changed the entire dynamics of fire spread. The test was initially planned to be favourable wind condition but due to sudden change in wind direction, the same test was repeated with opposing wind. However, it was interesting to see comparable results of Test 16 and Test 17, but difference in steel-clad dwelling (RSD-B2) of second row where time to fire spread was different. For the FSE the spread times were 0.8 m/min, whereas they were on average 0.05 m/min for the RSEs.

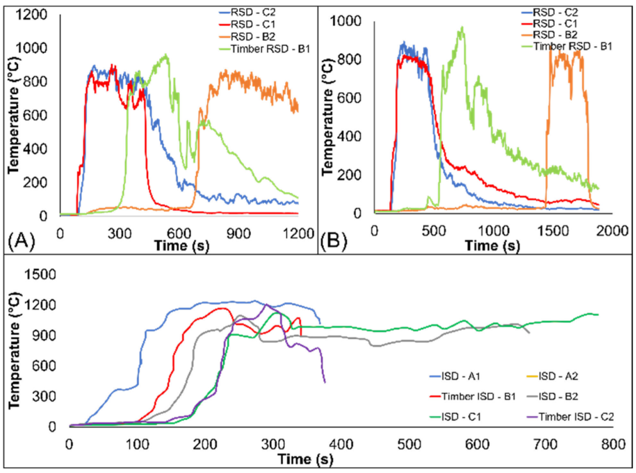

Figure 16. Six RSD experiments: ceiling temperature: top—temperature profiles of each RSD in (**A**) test 16, and (**B**) test 17, bottom—6 Nos ISDs from section of 20 FSE.

4.4.3. Comparative Study with FSE and RSE (Test-16, 17) in Six RSD Experiments

In this comparison study, six ISDs from twenty full scale dwelling experiment was considered and the relevant section is highlighted in Figure 17. The selected section consists of four steel-clad dwellings and two timber-clad dwellings. There were three rows of dwellings and each row had two dwellings. The timber-clad dwellings were placed on opposite side of second and third rows. The study will be focussing on parameters such as temperatures inside the dwellings, timelines of burning, fire spread patterns and so on.

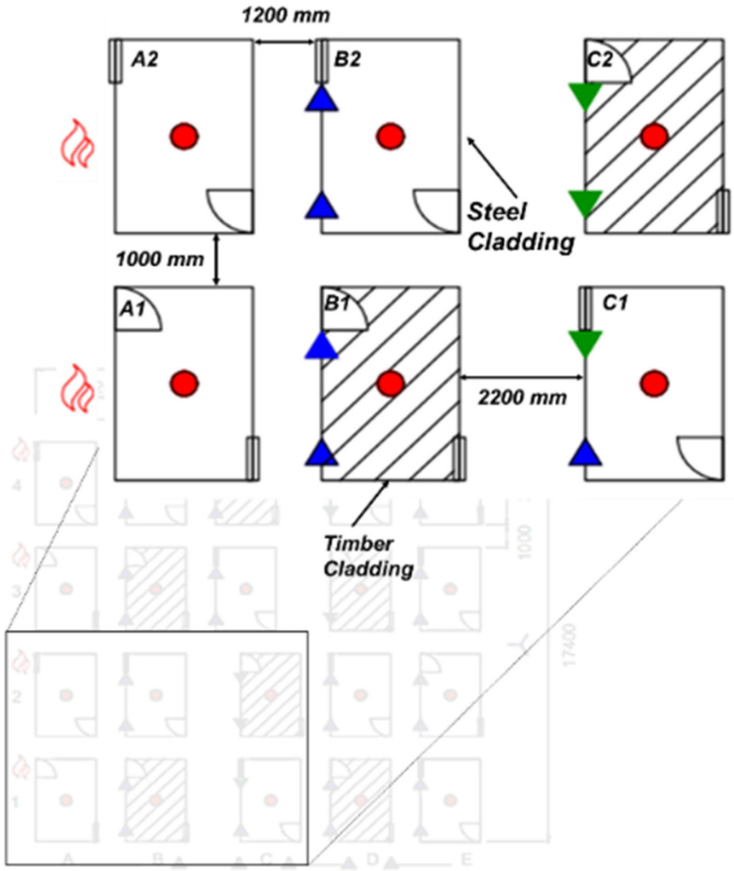

Figure 17. Section of 20 large-scale dwelling FSE on fire spread in ISDs considered for 6 Nos RSEs.

In the full-scale experiment, first row ('A' row) of dwellings were ignited and the fire spread behaviour to other rows were studied. Soon after the ISD-A1 reached flashover, the timber ISD–B1 was ignited and reached flashover even before igniting ISD–A2. The ignition of timber ISD–B1 changed the dynamics of fire spread and within 100 s other ISDs were involved in the fire. The fire spread rate as observed in FSE was 3.6 m/min. It should be noted that the adjacent section with burning ISDs also influenced the fire spread. The graph for the full-scale experiment as shown in Figure 16 (Bottom) shows that each dwelling was involved in the fire individually and there was no clear distinction of fire spread in different rows.

A section of the full-scale experimental setup as shown in Figure 17 was replicated in the reduced scale experiment. Table 11 provides comparative results on burning time and ceiling temperatures from FSEs and six RSDs. Figure 16 provides a graphical representation of ceiling temperatures in FSEs and RSDs. The first row of steel-clad RSDs was ignited, and they reached flashover stage around 50 s of ignition. At the same time, the timber-clad dwelling RSD–B1 was ignited, and it became fully developed in next 52 s. The dwelling continued to burn for the next 520 s. Meanwhile RSD–B2 was smouldering throughout the burning of the timber-clad RSD-B1 and started burning during decay phase of RSD–B1.

Unlike in the FSE, there was a clear distinction seen in burning pattern of the RSEs. Figure 18 shows the comparative pictorial representation of fire spread in-between the dwellings of FSEs and RSEs. The temperatures in the RSEs were 30% lower than that of FSEs and the total burning time in both FSEs and RSEs were almost similar for each dwelling. The higher temperatures and reduction in burning time could be a result of thermal influence from other section of the FSEs and higher smoke build-up that was clearly missing in the RSEs. The fire spread in RSE was ranging from 0.05 to 0.09 m/min in longitudinal direction and 0.01 to 0.05 m/min in lateral direction, whereas fire spread rate as observed in FSE was 3.6 m/min. The fire spread rate obtained in RSEs were negligible when compared with FSE. This could be a result of favourable wind current in FSEs, whereas in RSEs the wind was opposing fire spread, and thus, the third row in RSEs was not involved in fire and only charring was seen in the timber cladding of RSD–A2.

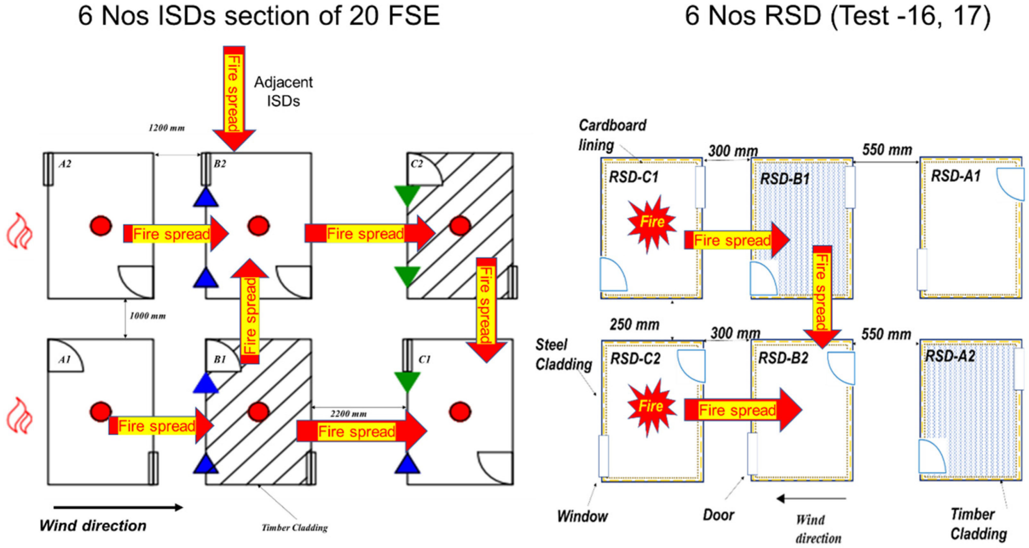

Figure 18. Fire spread in FSEs and 6 Nos RSD test (Test 16 and 17).

4.4.4. Test Setups—18 and 19—Bi-Directional Fire Spread

Test 18 (bi-directional spread, 3S/3T): From above tests it was seen that wind direction was crucial for fire spread, to reduce the dependency of that parameter, a test was setup as shown in Figure 19. The RSDs were arranged in three rows with two RSDs per row where each row was placed 550 mm apart. The steel and a timber-clad RSDs in the test setup were arranged in an alternating pattern. The fire was set-up in the second row to limit the dependency of wind direction and fire spread in both directions can be studied. From the test it was seen that timber cladding in the second row played a crucial role in the fire spread. It was seen that strong wind was driving the hot gases and the flames in the direction of wind current. This individual timber-clad RSD-B2 in the middle row triggered the ignition of timber-clad RSDs, RSD-C1 and RSD-A1 on either side of the adjacent rows.

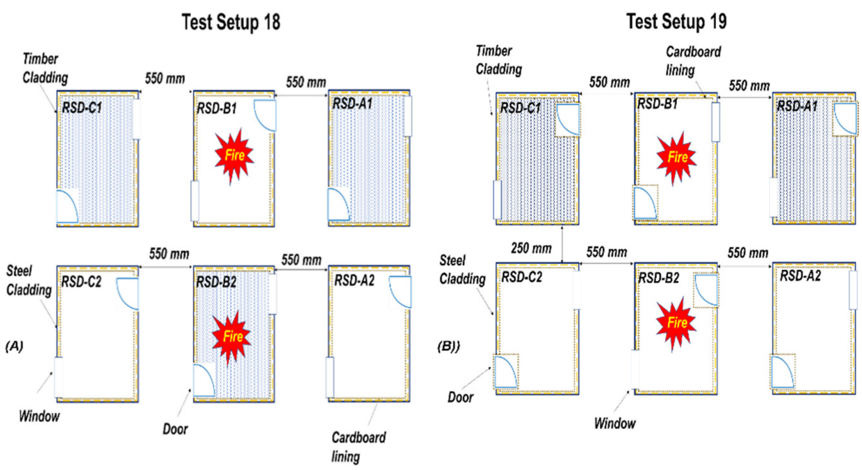

Figure 19. Six RSD experiment—(**A**) test setup 18, (**B**) test setup 19.

The temperature curve for the Test 18 is shown in Figure 20. As seen in the graph, middle row RSDs were ignited and, in that timber-clad RSD was burning at faster rate due to higher fuel load. Surprisingly, the timber-clad RSDs on either side of the adjacent rows were the first to ignite rather than the nearest steel-clad dwellings, demonstrating the impact of timber RSDs in fire spread in the test arrangement. The overall time of each RSD burning was approximately 400–450 s, and so no difference in burn duration was seen between steel-clad and timber-clad RSDs.

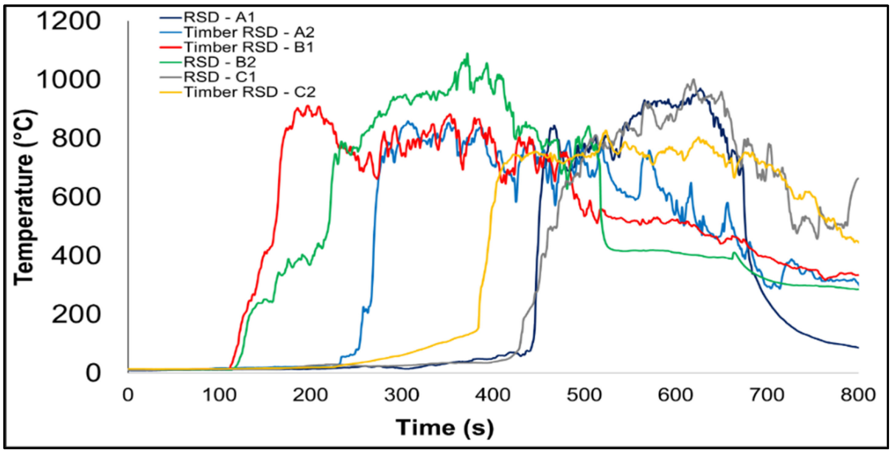

Figure 20. Ceiling temperature of each RSD in test setup 18.

Therefore, it can be said that the timber-clad RSDs influence fire spread fire in the ISD community due to high fuel load that has the potential to emit heat fluxes in all directions and project the continuous flames as compared to steel-clad RSDs. While burning in a fully developed stage, it has a potential to ignite all the combustible in its vicinity even at 550 mm (2200 m in FSE) and can alter the dynamics of fire spreading.

Test 19 (bi-directional spread, 4S/2T): In previous sections, it has been shown that timber cladding has a big influence on fire spread. However, to assess the importance of timber-clad RSD in the middle row, the wood-clad RSD was replaced by steel-clad RSD in the repeat test as shown in Figure 20.

As in Test 19, the RSDs in the middle row were ignited. The heat fluxes from the hot gases and flames of the steel-clad RSDs were continuously pyrolysing the timber cladding of RSD in first and third row. After 8 min of ignition, the back wall of the RSD-B1 collapsed near the timber-clad RSD–A1 with some of its residual cross members still burning as shown in Figure 21. The pyrolysing of timber cladding in RSD–A1 was increased due to sudden exposure to higher heat fluxes from burning RSD–B1 owing to the collapse of the back wall. At the 9th minute of the test, pyrolysis gas was ignited by residual cross members of the back wall, such that RSD–A1 started burning and it continued burning for the next 10 min. Despite exposure to higher heat fluxes in the vicinity, the steel-clad RSD–A2 of third row was smouldering for 15 min and then with a sudden gust of wind it started burning and after 5 min the dwelling collapsed. Throughout the test, the first row remained unaffected as the heat fluxes and the flames were driven by wind currents towards the third row of dwellings.

Thus, absence of timber-clad dwelling from the middle row, reduced the fuel load and heat release rate consequently reducing the radiative and convective heat flux that enhances the fire spread. A timber-clad RSD (or other combustible cladding) in the settlement is a key contributor to fire spread. In the absence of timber-clad dwellings, fire spread is primarily dependent on the direction of wind current. It was also interesting to see that despite the fire being suppressed in dwellings, the remnants of burning RSD can trigger smouldering of combustible in its vicinity that can start another informal settlement dwelling fire.

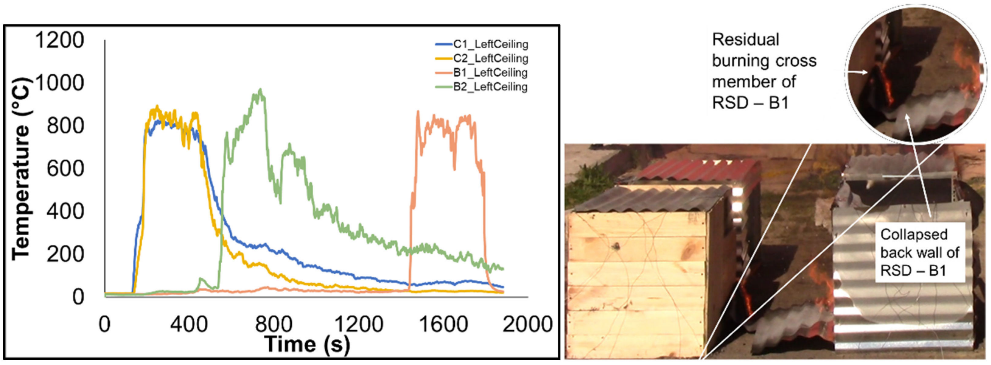

Figure 21. Six RSD experiments—left: ceiling temperatures of RSDs in test 19; right: burning of residual cross members.

5. Conclusions

This paper investigated fire spread using reduced scale dwellings at 1/4th of full-scale informal settlement experiments. The objective of the study was to identify the impact of factors such as cladding material, wind current and separation distance. The study also investigated the relevance of previous multiple-dwelling full-scale experiments in reduced scaling of informal settlement dwellings. The study involved fire spread between two, three, four, and six sets of reduced scaled dwellings with various orientations, separation distances, and cladding materials. Although primarily flame impingement, and secondarily heat flux, are responsible for fire spread to a greater extent, burning remnants from a collapsed dwelling have potential to ignite a new dwelling.

The direction of wind current plays a crucial role in directing flames and driving heat fluxes in both FSEs and RSEs. An optimum wind speed can aid in faster fire spread between the dwellings. However, a strong favourable wind current may also increase the heat losses in the burning RSDs, leading to no effective fire spread to adjacent rows (Test 14), as discussed in Section 3.2. In some instances, the flames were also seen going over the RSDs instead of hitting the roof panel. Wind can become a dominant factor to fire spread for inter dwelling spacing above 300 mm. Although, wind direction and speed measured at the beginning of each test fluctuations in wind current during most of the test was visible. Since this factor is so dominant, it will be beneficial to conduct such experiments in a wind tunnel in the future where the wind speed can be regulated. Additionally, capturing localised wind effects in between rows of dwellings can support the predication of fire spread and the pulsating behaviour of flame length and flame heights emerging from the openings.

The possibility of ignition is further increased due to the availability of timber cross members (Test 8) and combustible lining inside the dwelling walls. The exposed combustible cross members in the event of fire become involved in fire in the early stage, and they also contribute to fire spread to other combustibles inside the dwelling. The dwelling with higher fuel tends to have longer burning time. A dwelling is likely to be ignited as the increased burning time enhances the devolatilisation process and flame impingement due to longer exposure time. In addition, timber-cladded dwellings increase the risk of ignition in the vicinity to substantial level (Tests 5–6). The timber-clad RSDs have a significant impact on spread fire in ISs. They have the potential to ignite all the combustibles in its vicinity even at 550 mm (2.2 m in FSE) and can alter the dynamics of fire spreading despite having opposing wind currents.

The time to flashover in each case was different and deviated up to 100% from the full-scale experimental results, with RSEs typically ranging between 30 s and 180 s depending upon type of test and location of the RSD. The fire spread time between the dwellings increased with an increase in their separation distances, as would be expected. It was seen from the test that the fire spread due to flame impingement through the door opening contributes more than the window openings. The dwelling with windows on shorter side walls has greater fire spread prospects than the dwelling windows on longer back wall.

The addition of an opening has negligible impact on fire spread to the adjacent dwelling, but fire spread in type-1,2 RSDs provided different results under the same environmental conditions, proving the influence of the location of openings in a dwelling (test 11).

The average fire spread rate from all 19 RSEs was 0.092 m/min, ranging from 0.007 m/min in Test 3 to 0.27 m/min in Test 17 (FSE—0.137 m/min), which is significantly lower than the range of 1.2–3.6 m/min as found for real incidents and large-scale experiments. The scaled spread rates varied between 0.14 m/min and 0.55 m/min between rows of dwellings, in comparison to FSEs where spread times ranged between 0.167 m/min and 3.6 m/min. This highlights that even though trends, temperatures, and general fire dynamic behaviour can be captured, RSEs cannot currently be used for quantifying spread rates for informal settlement fires, although the occurrence of spread can be captured to a certain degree.

It was observed that the temperature profile for both FSE and RSEs were comparable with similar profiles, but the peak temperature was lower in RSEs than FSE, by around 10–20%. The experiment time from ignition to collapse in all wind conditions and for all RSDs was similar to FSE, but the flashover time in each case was different and deviated from the full-scale experimental results. The time variable in the RSEs was predominantly influenced by wind currents that affected the scaling of experimental time, flashover time, and fire spread rate. However, in few instances where wind current was similar to FSE, time variable was scaled well. Heat flux data in RSEs were not captured which would have further provided details to understand the FSEs and RSEs quantitatively. The results from individual RSEs (test-1–6) provided more comparable results with FSEs than the test with multiple rows, as greater numbers of steps in the flame paths leads to higher levels of uncertainty. It was observed that thermal influence from adjacent section with burning ISDs had great impact on the fire spread, and the same was missing in RSEs. In the experiments with six RSDs, each dwelling was involved in the fire individually and there was no clear distinction of fire spread in different rows.

To sum up, (a) wind, combustible cladding, and separation distance between dwellings significantly influence results. However, (b) the influence of cross member, fuel load inside the dwelling, and type of dwellings also had an impact on fire spread. (c) The comparative results from FSEs and RSEs demonstrate good fire dynamic correlations within the dwellings and in between the dwellings with comparable profiles but (d) have limited correlation to the fire spread rate. The database presented in this work provides a useful basis for enhancing scaling methodologies, but further data are needed before the results can be consistently applied due to the variability encountered. A study on the flame length and flame height emerging from the RSDs with various wind conditions would be beneficial to understand the impact of these parameters on fire spread. By quantifying flame length and height, and developing analytical equations for scaled dwellings, it is hypothesised that the behaviour observed in this paper can be more accurately defined, especially if equations can account for (albeit approximate) wind conditions. It is envisaged that separation distances between dwellings could be specified based on FSEs and RSEs causing the same level of flame impingement on the target dwellings.

Based on the results above, and observations of real informal settlement incidents, more research and testing are needed before large-scale multi-dwelling spread will be predicted accurately. Nevertheless, in future, these experiments can further be extended by changing selected parameters and studying the relative change in the test results using an initial test as a validated benchmark (i.e., all tests conducted at $\frac{1}{4}$ scale but the relative change in spread rate can be readily quantified by adjusting parameters). Such results can assist in quantifying empirical correlations to predict fire spread mechanisms in relation to multiple informal dwellings with reduced scale experiments considering various parameters. In addition, a numerical simulation can be developed that can predict the influence of numerous variables that can influence fire spread involving a large number of dwellings. As noted above, tests in a wind tunnel would be ideal for more accurately quantifying spread rates and comparing the influence of parameters. This work would serve as preliminary guidance for such a study.

Author Contributions: Investigation, Methodology—V.N.; Testing—V.N., A.O.; Writing and Editing—V.N., R.S.W.; Review—R.S.W. and A.O. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to acknowledge the financial support of (a) the Lloyd's Register Foundation under the "Fire Engineering Education for Africa" project (Grant GA 100093), and (b) the Royal Academy of Engineering/Lloyd's Register Foundation under the "Engineering Skills Where They are Most Needed" grant (Grant ESMN 192-1-141).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to Klapmuts Fire Department for their extended support to conduct the experiments on their premises.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations (UN). 'Population 2030: Demographic Challenges and Opportunities for Sustainable Development Planning', New York. 2015. Available online: http://www.un.org/en/development/desa/population/publications/pdf/trends/Population2030.pdf (accessed on 11 July 2022).
2. Statistics South Africa (Stats SA). Concepts and Definition. Available online: www.statssa.gov.za (accessed on 11 July 2022).
3. Walls, R.; Zweig, P. Towards Sustainable Slums: Understanding Fire. In *Advanced Technologies for Sustainable Systems*; Springer: Berlin, Germany, 2017; pp. 93–98. [CrossRef]
4. Walls, R.; Olivier, G.; Eksteen, R. Informal settlement fires in South Africa: Fire engineering overview and full-scale tests on "shacks". *Fire Saf. J.* **2017**, *91*, 997–1006. [CrossRef]
5. Moradi, A. *A Physics-Based Model for Fire Spreading in Low Cost Housing in South African*; Stellenbosch University: Stellenbosch, South Africa, 2016.
6. Cicione, A.; Beshir, M.; Walls, R.S.; Rush, D. Full-Scale Informal Settlement Dwelling Fire Experiments and Development of Numerical Models. *Fire Technol.* **2019**, *56*, 639–672. [CrossRef]
7. Cicione, A.; Walls, R.; Kahanji, C. Experimental study of fire spread between multiple full scale informal settlement dwellings. *Fire Saf. J.* **2019**, *105*, 19–27. [CrossRef]
8. Cicione, A.; Walls, R.; Stevens, S.; Sander, Z.; Flores, N.; Narayanan, V.; Rush, D. An Experimental and Numerical Study on the Effects of Leakages and Ventilation Conditions on Informal Settlement Fire Dynamics. *Fire Technol.* **2021**, *58*, 217–250. [CrossRef]
9. Cicione, A.; Walls, R.; Sander, Z.; Flores, N.; Narayanan, V.; Stevens, S.; Rush, D. The Effect of Separation Distance Between Informal Dwellings on Fire Spread Rates Based on Experimental Data and Analytical Equations. *Fire Technol.* **2021**, *57*, 873–909. [CrossRef]
10. De Koker, N.; Walls, R.S.; Cicione, A.; Sander, Z.R.; Löffel, S.; Claasen, J.J.; Fourie, S.J.; Croukamp, L.; Rush, D. 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements. *Fire Technol.* **2020**, *56*, 1599–1620. [CrossRef]
11. Wang, Y.; Gibson, L.; Beshir, M.; Rush, D. Determination of Critical Separation Distance Between Dwellings in Informal Settlements Fire. *Fire Technol.* **2021**, *57*, 987–1014. [CrossRef]
12. Beshir, M.; Wang, Y.; Centeno, F.; Hadden, R.; Welch, S.; Rush, D. Semi-empirical model for estimating the heat release rate required for flashover in compartments with thermally-thin boundaries and ultra-fast fires. *Fire Saf. J.* **2021**, *120*, 103124. [CrossRef]
13. Walls, R.; Kahanji, C.; Cicione, A.; Vuuren, M.J.V. Fire dynamics in informal settlement "shacks": Lessons learnt and appraisal of fire behavior based on full-scale testing. In *Asia-Oceania Symposium on Fire Science and Technology*; Springer: Singapore, 2018; pp. 15–27.
14. Cicione, A.; Walls, R.S. Towards a simplified fire dynamic simulator model to analyse fire spread between multiple informal settlement dwellings based on full-scale experiments. *Fire Mater.* **2020**, *45*, 720–736. [CrossRef]
15. Cicione, A.; Wade, C.; Spearpoint, M.; Gibson, L.; Walls, R.; Rush, D. A preliminary investigation to develop a semi-probabilistic model of informal settlement fire spread using B-RISK. *Fire Saf. J.* **2020**, *120*, 103115. [CrossRef]
16. Quiroz, N.F.; Walls, R.; Cicione, A.; Smith, M. Fire incident analysis of a large-scale informal settlement fire based on video imagery. *Int. J. Disaster Risk Reduct.* **2021**, *55*, 102107. [CrossRef]
17. Narayanan, V.; Cicicone, A.; Botha, A.D.; Walls, R.S. Reduced-scale experiments and numerical simulations of informal settlement dwelling fires. *Int. J. Prog. Scale Model. Int. J.* **2022**, *3*, 3023. [CrossRef]
18. Beshir, M.; Omar, K.; Centeno, F.; Stevens, S.; Gibson, L.; Rush, D. Experimental and Numerical Study for the Effect of Horizontal Openings on the External Plume and Potential Fire Spread in Informal Settlements. *Appl. Sci.* **2021**, *11*, 2380. [CrossRef]
19. Quintiere, J.G. *Fundamentals of Fire Phenomena*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2006.

20. Bryner, N.; Johnsson, E.L.; Pitts, W. Carbon Monoxide Fires—Production in Compartment Reduced-Scale Enclosure Test Facility, NIST, NSTIR 5568. 1994. Available online: https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nistir5568.pdf (accessed on 11 July 2022).
21. Babrauskas, V. Heat release rates. In *SFPE Handbook of Fire Protection Engineering, 5th ed*; Springer: New York, NY, USA, 2016; pp. 799–904. [CrossRef]