Fire Dynamics in Informal Settlements

by
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Declaration

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December 2019

Abstract

In poor and densely populated countries, the rapid growth in population leads to an increase in landlessness. As a result, the number of people residing in informal settlements is increasing on a daily basis. It is estimated that there are currently one billion people living in informal settlements and this number is expected to increase in the coming years. Currently, informal settlements are being ravaged by large fires every day across the globe. Over the past decades, fire related disasters have decreased in the global north, while they have increased in the global south. Since the number of people that reside in informal settlements are expected to increase, it is a cause for serious concern to see how little is done in terms of fire safety in these communities. It is with this in mind that this dissertation focusses on developing an in-depth understanding of fire dynamics in informal settlements, with the hope that it can form the basis for future research and fire safety innovations. In this dissertation four full-scale fire experiments have been carried out: (a) a single steel sheeting clad experiment, (b) a single timber plank clad experiment, (c) a triple dwelling steel sheeting clad experiment and (d) a triple dwelling timber plank clad experiment.

The single dwelling experiments are analysed using two numerical models (i.e. two-zone modelling and Fire Dynamic Simulation (FDS) modelling) to obtain an understanding of the enclosure fire dynamics and heat fluxes emitted from these dwellings. A comparison between the model and experimental results are shown. The effect of different cladding materials (i.e. timber versus steel cladding) on the enclosure fire dynamics and heat fluxes experienced is also presented, where it was found that timber dwellings are more prone to fire spread, with heat fluxes exceeding 200 kW/m^2 at the openings. It was found that the FDS models captured the behaviour of the single dwelling experimental fires well, but that the material properties of the cardboard lining have a substantial effect on how the fire develops, as a result of how the fire spreads across the surface of the cardboard. This was also the most difficult aspect to capture with the numerical models. The FDS models' predictive capabilities were further utilised to determine a preliminary critical separation distance, where it was found to be approximately 3 m between dwellings (i.e. the distance needed for fire spread between dwellings not to occur under wind free conditions).

The dissertation continues by presenting the results of the multi-dwelling experiments, where the basic understandings and findings drawn from the single dwelling experiments were used to examine the effect of different cladding materials on fire spread between dwellings. The multi-dwelling experimental results concurred that the timber dwellings are more prone to fire spread. These results highlighted the dangers of these closely spaced dwellings. For the timber clad dwellings, the overall spread time (i.e. from the start of flashover in the first dwelling to the end of flashover in the last dwelling) was approximately 4 minutes. Simplified FDS models are developed to predict fire spread between multiple dwellings, with the hope that these models can be improved over time so that they can be used to study housing configurations and fire spread interventions.

Opsomming

In arm en digbevolkte lande, lei die vinnige groei in bevolking tot 'n toename in grondloosheid. As ‘n gevolg veroorsaak dit ‘n daaglikse toename in die aantal mense wat in informele nedersettings woon. Daar word beraam dat daar tans een biljoen mense in informele nedersettings woon en dit sal na verwagting in die komende jare toeneem. Tans word informele nedersettings op ‘n dagliks basis wêreldwyd deur groot brande verwoes. Gedurende die afgelope dekades het brandverwante rampe in die noordelike halfrond afgeneem, terwyl dit toegeneem het in die suidelike halfrond. Aangesien die aantal mense wat in informele nedersettings woon na verwagting gaan toeneem, is dit rede vir ernstige kommer om te sien hoe min daar gedoen word in terme van brandveiligheid in hierdie gemeenskappe. Dit is met die bogenoemde in gedagte dat hierdie tesis fokus op die ontwikkeling van 'n indiepte begrip van vuurdinamika in informele nedersettings met die hoop dat dit die basis kan vorm vir toekomstige navorsing en brandveiligheidsinnovasies. In hierdie tesis was vier volskaalse vuur eksperimente uitgevoer: (a) 'n enkelwoning staalplaat-geklede eksperiment, (b) 'n enkelwoning houtplank-geklede eksperiment, (c) 'n drie woning staalplaat-geklede eksperiment, en (d) 'n drie woning houtplank-geklede eksperiment.

Die enkelwoning eksperimente word ontleed met behulp van twee numeriese modelle (namelik tweesone-modellering en Fire Dynamic Simulation (FDS) modellering) om ‘n beter begrip te kry van die kompartement-vuurdinamika en hittevloei wat uit hierdie huise uitgestraal word. 'n Vergelyking tussen die model en eksperimentele resultate word getoon. Die effek van verskillende bekledingsmateriale (d.w.s. hout-bekleding teenoor staal-bekleding) op die kompartement-vuurdinamika en hittevloei wat ervaar was word ook getoon, en daar was gevind dat houthuise meer geneig is tot brandverspreidings met ‘n hittevloei van meer as 200 kW/m^2 by die openinge. Daar is bevind dat die FDS-modelle die gedrag van die enkele woonbrande goed nageboots het, maar dat die materiaal eienskappe van die karton 'n wesenlike effek het op hoe die vuur ontwikkel. Dit is as gevolg van hoe die vuur oor die oppervlak van die karton versprei en dit was ook die moeilikste aspek om na te boots met die numeriese modelle. Die FDS-modelle se voorspellende vermoëns was verder gebruik om 'n voorlopige kritiese skeidingsafstand te bepaal, waar dit gevind was dat daar ongeveer 3 m tussen woonhuise moet wees (d.w.s. die afstand wat nodig is om brandverspreiding tussen wonings te verhoed onder windstil omstandighede).

Die tesis gaan voort deur die resultate van die meervoudige-woning eksperimente aan te bied, waar die basiese begrippe en bevindings wat uit die enkelwoning-eksperimente getrek was, gebruik word om die effek van verskillende bekledingsmateriale op brandverspreidings tussen huise te ondersoek. Die meervoudige-woning eksperimentele resultate het bevestig dat die houthuise meer geneig is tot brandverspreidings en hierdie resultate het die gevaar van hierdie naby gespasieerde wonings beklemtoon. Vir die houtkledewonings ekperiment was die algehele verspreidingstyd ongeveer 4 minute gewees. Vereenvoudigde FDS-modelle was ontwikkel om die verspreiding tussen meervoudige wonings te voorspel, met die hoop dat hierdie modelle oortyd verbeter kan word sodat dit gebruik kan word om behuisingskonfigurasies en brandverspreidingsintervensies te bestudeer.

List of publication by candidate

This dissertation consists of compilation of papers that develop the main goal of understanding fire dynamics in informal settlements. In the development of this work various publications have been produced, but only those that directly address the main goal are included in their entirety, with abstracts of the remaining papers being included in the appendix for reference purposes.

Published journal papers

A. Cicione, M. Beshir, R.S. Walls, D. Rush, Full-scale informal settlement dwelling Fire experiments and development of numerical models, Fire Technology Journal (2019). doi: 10.1007/s10694-019-00894-w **[Included as Chapter 3 in this dissertation]**

A. Cicione, R.S. Walls, C. Kahanji, Experimental Study of Fire Spread Between Multiple Full Scale Informal Settlement Dwellings, Fire Saf. J. (2019). doi: 10.1016/j.firesaf.2019.02.001 **[Included as Chapter 4 in this dissertation]**

C. Kahanji, R.S. Walls, **A. Cicione**, Fire spread analysis for the 2017 Imizamo Yethu informal settlement conflagration in South Africa, Int. J. Disaster Risk Reduct. (2019). **[Abstract included in the Appendix of this dissertation]**

R.S. Walls, R. Eksteen, C. Kahanji, **A. Cicione**, Appraisal of fire safety interventions and strategies for informal settlements in South Africa, Disaster Manag. Prev. In Press (2019) DPM-10-2018-0350. doi:10.1108/DPM-10-2018-0350. **[Abstract included in the Appendix of this dissertation]**

Peer reviewed international conference papers

A. Cicione, R.S. Walls, Towards a simplified fire dynamic simulator model to analyse fire spread between multiple informal settlement dwellings based on full-scale experiments, in: 15th International Conference and Exhibition on Fire Science and Engineering, 2019. **[Included as Chapter 5 in this dissertation]**

A. Cicione, R. Walls, Estimating time to structural collapse of informal settlement dwellings based on structural fire engineering principles, in: SEMC Conference, CRC Press, 2019. **[Abstract included in the Appendix of this dissertation]**

R.S. Walls, C. Kahanji, **A. Cicione**, M. Jansen van Vuuren, Fire dynamics in informal settlement "shacks": Lessons learnt and appraisal of fire behaviour based on full-scale testing, in: 11th Asia-Oceania Symp. Fire Sci. Technol., Taiwan, 2018. **[Abstract included in the Appendix of this dissertation]**

R.S. Walls, **A. Cicione**, B. Messerschmidt, K. Almand, Africa : The next frontier for fire safety engineering?, in: 15th International Conference and Exhibition on Fire Science and Engineering, 2019.

Acknowledgements

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Chapter 1: Introduction

1.1. Introduction to work

Over the past three decades, the population of Africa has increased rapidly from 630 million, exploding to a current population of 1.2 billion (UNECA, 2017). As much as the growth in population over the past three decades seems significant, it is insignificant compared to the expected growth in population in the coming decades, where it is expected that the population of Africa will grow to approximately 2.5 billion people by around 2050. This will result in a working force of approximately 1.1 billion people, which will be greater than the working population of India and China, respectively. In the next few decades, the proportion of African people residing in urban areas is expected to grow by approximately 920 million people. As a result of insufficient housing, it is inevitable that the population residing in informal settlements will also increase. Informal settlements are also known by more derogatory names such as slums, shantytowns or ghettos. Informal settlements and Informal Settlement Dwellings (ISDs) (i.e. informal dwellings typically found in informal settlements) are explained in extensive detail in later chapters, along with some inherent characteristics of these dwellings. Currently, there are approximately 1 billion people living in informal settlements across the globe and according to UN-Habitat (2016), the absolute number of people living in informal settlements are expected to increase to 1.2 billion people in Africa alone by 2050. The issues discussed above are not only relevant to Africa, but also to other continents such as in Asia and South America (Rush et al., 2019). Unfortunately, according to UNECA (2017), the GINI coefficient indicates that 7 of the 10 most unequal countries are in Africa.

In developing countries, informal settlements are spontaneously emerging as distinct and dominant communities. For example, Figure 1.1 (a) depicts an open piece of land in Cape Town, South Africa on July 2014. In just one year, an entire settlement was erected on the piece of land, most probably without government approval, as depicted in Figure 1.1 (b). The problem with erecting an informal settlement over such a short period is that no formal infrastructure could have been built, for example, running water, fire breaks or access roads. The second problem with this scenario is that the government had no control over the erection of the settlement. Consequently, this leaves the population that reside in these settlements extremely vulnerable to fires. Informal settlement fire safety is extremely poor (FPASA, 2017; Zweig et al., 2018) and a single fire incident can leave as much as 10000 people homeless (Kahanji et al., 2019)*.

**The abstract of this citation is included in Appendix A.3 of this dissertation*

Figure 1.1: (a) Greater Khayelitsha 2014/07/30 (left) and (b) Greater Khayelitsha 2015/07/30 (right) (Google, 2018)

Unfortunately, countries in the global south often overlook aspects of fire safety as a result of higher levels of poverty, where societal needs such as healthcare and housing take priority (Walls *et al.*, 2019). According to the national statistics from the Fire Protection Association of South Africa (FPASA, 2017) in 2015 (the 2015 statistics are published in 2017), the total number of fire incidents in South Africa was 5448 incidents in formal dwellings and 5496 incidents in informal dwellings, resulting in 82 and 219 deaths respectively. Thus, the deaths recorded in informal dwellings, as a result of fire incidents, were more than double the deaths recorded in formal dwellings in South Africa for 2015 alone. According to the Western Cape Strategic Framework for Fire and Burn Injury Prevention, South Africa has a burn mortality rate of 8.5 per 100 000, indicating that 8.5 out of a 100 000 people die as a result of severe burns in South Africa (DMFRS, 2015). This is 3.5 per 100 000 more than the world average and 2.5 per 100 000 more than other African regions. In 2015, the total cost of insured fire losses for informal settlements was estimated to be around R133m. Overall, the aforementioned statistics show that informal settlement fires are a major problem, not only in South Africa, but in other third world countries (Rush et al., 2019), and with one billion people residing in informal settlements it is of great concern to see how little work has been done to improve and understand fire safety in these areas.

1.2. Problem statement

It is well known that fire safety regulations and legislations are well established for formal dwellings, where, for example, SANS 10400-T provide guidelines for South Africa. Unfortunately, there are no such regulations or legislations for informal dwellings, because of a shortage of knowledge regarding fire in informal settlements, and the inability to implement construction codes of practice. Additionally, there is negligible literature available on work done in terms of understanding the fire dynamics of both individual ISDs (micro-scale) and entire informal settlements (macro-scale). Furthermore, there is negligible literature available on crucial questions such as: how do ISD enclosure dynamics compare to formal dwellings, what are the maximum temperatures experienced in these dwellings, what are the maximum heat fluxes emitted from these dwellings, how do fires spread between dwellings and how do building materials, geometry and ventilation influence all these questions? Answering these questions will ultimately improve our knowledge regarding informal settlement fire safety, and this work seeks to progressively address many of these issues in the work that follows. Each chapter of this work addresses a substantial number of unknowns that contribute towards a better understanding on informal settlement fire safety. Without any engineering basis or technical understanding of how informal settlement fires behave, local authorities and government cannot adequately address the problem, nor can they implement fire spread interventions to solve the problem (e.g. see Appendix A.1.).

1.3. Project goal and objectives

It is with this backdrop that the main goal of this research project is to understand informal settlement dwelling fire dynamics through experimental testing and numerical modelling, in order to improve the understanding of fire safety in informal settlements. To achieve this goal successfully the objectives of this research are:

I. To conduct four full-scale experiments i.e. (a) a single dwelling cladded with corrugated steel sheeting, (b) a single dwelling cladded with timber planks, (c) three dwellings cladded with corrugated steel sheeting and (d) three dwellings cladded with timber planks.

II. To determine whether current software (i.e. FDS and Ozone) can be used to reliably model ISD fires.

III. To develop detailed numerical models to simulate the enclosure fire behaviour of the experiments conducted in this work, followed by simplified and more practical numerical models to model the fire spread behaviour of the experiments conducted in this work.

IV. To execute a sensitivity investigation on mesh independent parameters using FDS modelling (i.e. of the material properties and model parameters that are critical when predicting fire spread time between dwellings) to study the effect it has on the fire spread rate between dwellings.

1.4. Project exclusions and limitations

This work gives novel insight to informal settlement fire behaviour and the experiments provide ground-breaking insight in terms of enclosure fire dynamics and the measurement of heat fluxes for ISDs, which are crucial for understanding fire spread in these areas. However, as a result of the complexity and scope limitations only a limited number of experiments were conducted in this work. This work can form as a basis for future research regarding ISD fires. The following are limitations or exclusions of the work done in this dissertation:

I. This work will not serve as a solution to fire spread in informal settlements, but just as a basis for understanding the fire dynamics in these areas and the spread mechanisms. It should be noted that a solution to this very complex problem will be a holistic solution across multiple sectors.

II. Heat flux and temperature values obtained during these experiments should not be used as true for all informal settlement fire cases but rather as an idea of the heat fluxes experienced during informal settlement fires with configurations similar to those used in the experiments. Similar limitations apply with regards to the fact that standard timber cribs were used for fuel loads, whereas in reality, a large variety of materials and fuel loads are present.

III. As a result of the sizes of these experiments, the heat release rates could not be measured.

IV. The ventilation conditions, fuel conditions and geometry of the dwellings were simplified to idealize the dwellings for modelling purposes and to have less unknowns when analysing the enclosure fire dynamics and fire spread mechanisms.

V. As a result of current computer limitations, a detailed Fire Dynamic Simulator analysis could not be performed for the larger experiments, thus simplifications had to be made and the results should be interpreted accordingly.

VI. Empirical equations used in this dissertation are constrained to certain assumptions and are mostly only applicable to the specific scenarios in this work. Using the empirical equations for any other cases require validation, or modifications to suit the experimental dataset, and it should be used accordingly.

1.5. Report synopsis

In order to achieve the objectives listed in Section 1.3. above, the following process was followed and consequently forms the structure of this dissertation (note that this dissertation was done by publication and that Chapters 3-5 are exact copies of the journal papers):

I. Literature review (Chapter 2): A literature review was conducted with regards to the fundamentals of enclosure fire dynamics, followed by a brief study on the numerical models used in this work.

II. "Full-scale informal settlement dwelling fire experiments and development of numerical models" (Chapter 3 - This chapter is published in the Fire Technology Journal):

  i. The development of an experimental setup to determine the effect of different cladding materials on the enclosure fire dynamics in an ISD (i.e. timber cladding versus corrugated steel sheeting cladding). Two experiments consisting of a single dwelling were conducted in this work. The dimensions and details pertaining to each experimental setup, instrumentation setup and the materials used are presented in this work (Section 3.3).

  ii. The development of a methodology, which explains how the experiments were conducted, followed by the experimental results of both experiments (i.e. the steel clad dwelling experiment and the timber clad dwelling experiment). This is followed by a summary comparing and discussing the differences between the two experiments.

  iii. The development of numerical modelling setups (Section 3.5 and Section 3.6). The dimensions and details pertaining to the Fire Dynamic Simulator (FDS) models and the Two-zone models are presented in this work (Section 3.5 and Section 3.6, respectively).

  iv. The FDS model results and Two-zone model results versus the experimental results (Section 3.7).

v. A determination of a preliminary critical separation distance between ISDs based on the numerical findings presented in this work (Section 3.8.). It was found that the critical separation distance between ISDs should be approximately 3 meters for fire spread not to occur (i.e. when wind and flammable materials between dwellings are not considered).

The findings of the single dwelling experiments and numerical modelling (Chapter 3) were utilised to study the effect of different cladding materials on fire spread between multi-dwellings, by informing the multi-dwelling experiments conducted in Chapter 4.

III. "Experimental study of fire spread between multiple full-scale informal settlement dwellings" (Chapter 4 - This chapter is published in the Fire Safety Journal):
   i. The development of an experimental setup to examine the fire spread mechanism between ISDs and to determine the effect of different cladding materials on fire spread rates (i.e. timber cladding versus corrugated steel sheeting cladding). Two experiments consisting of three dwellings each were conducted in this work. The dimensions and details pertaining to the experimental setups, instrumentation setups and the materials used are presented in this work (Section 4.3).
   ii. The development of a methodology which explains how the experiments were conducted, followed by the experimental results of both experiments (i.e. the triple dwelling steel clad experiment and the triple dwelling timber clad experiment). It was found that timber clad dwellings are more prone to fire spread and the findings highlight the risk associated with these closely spaced dwellings.

Using the knowledge gained form the numerical models developed in Chapter 3, simplified FDS models were constructed to the model multiple ISDs in a sensible time (i.e. with computational time limited to one day on the High Performance Computers of Stellenbosch University, compared to two weeks for the models executed in Chapter 3, which were only for single dwellings). The results of simplified FDS models developed were compared to the results of the two multi-dwelling experiments conducted in Chapter 4.

IV. "Towards a simplified Fire Dynamic Simulator model to analyse fire spread between multiple informal settlement dwellings based on full-scale experiments" (Chapter 5 - This chapter is published in the 15th International Conference and Exhibition on Fire Science and Engineering (Interflam) proceedings and submitted for publication in the special issue of the Fire and Materials Journal.):
   i. The development of a simplified and more practical FDS model of the experiments conducted in Chapter 4 (Section 5.3). It was found that the simplified models captured the fire spread behaviour relatively well for the steel clad dwellings but due to the difficulties associated with modelling the timber cladding, further research is needed to develop a trustworthy model to simulate timber clad dwellings in a simpler, more efficient manner.

ii. The FDS results for the triple dwelling corrugated steel clad experiment and for the triple dwelling timber plank clad experiment are presented in this work (Section 5.4 and Section 5.5, respectively).

iii. A sensitivity study of mesh independent parameters used in the simplified FDS models can be found in Section 5.6, where it is identified that results from simulations of spread between dwellings are extremely sensitive to the material properties of the cardboard lining (i.e. the inner-wall lining material)

The flow of the work, as mentioned above, along with how the work can be used in the future is visually depicted in Figure 1.2.

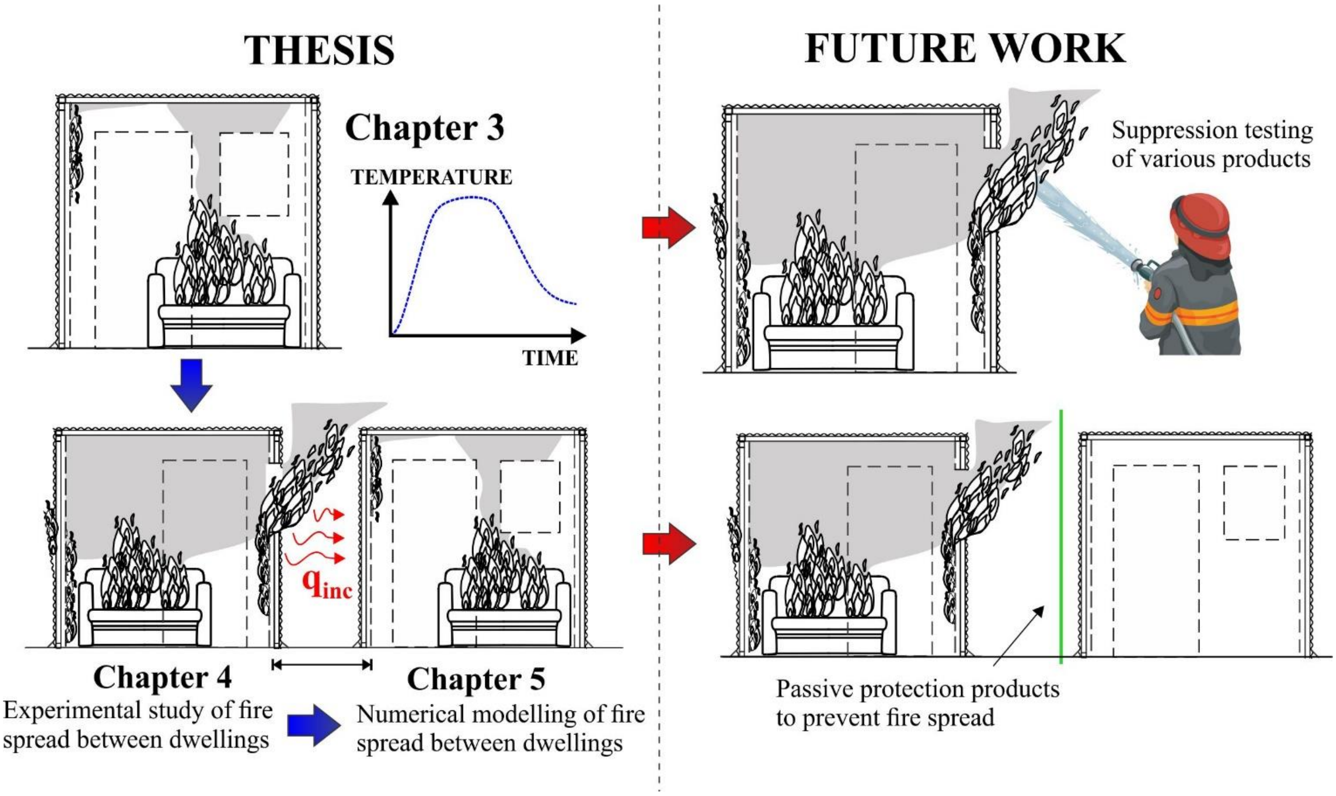

Figure 1.2. Dissertation structure with guidance for future work

It should be noted that because each chapter was published individually, it is necessary to give an introduction to informal settlements in each chapter as well as to give a certain amount of literature regarding fire dynamics.

All Fire Dynamic Simulator codes used in this dissertation can be accessed via the following link: https://github.com/AntonioCicione/AntonioCicione.github.io/tree/master/ISD%20FDS%20models

1.6. References

DMFRS. (2015), 'Western Cape Strategic Framework for Fire and Burn Injury Prevention', *Western Cape Strategic Framework for Fire and Burn Injury Prevention, Western Cape Disaster Management & Fire*

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Zweig, P., Pharoah, R., Eksteen, R. and Walls, R.S. (2018), *Installation of Smoke Alarms in an Informal Settlement Community in Cape Town, South Africa – Final Report*.

Chapter 2: Literature review

2.1. Introduction

This chapter discusses the basic concepts of enclosure fire dynamics needed to understand the work done in subsequent chapters. The field of fire dynamics is broad and complex, so for further information the reader is referred to Karlsson and Quintiere (2000) and Drysdale (2011), from which a significant portion of the work below has been obtained. The chapter starts by defining the combustion process (Section 2.2), which then build towards defining the basic terminology of enclosure fires (Section 2.3 & 2.4). The five stages of a fire's development are defined (Section 2.4). Once the basic concepts are defined, the chapter continues by providing relevant quantifiable fire parameters (Section 2.5). After the basic concepts and parameters are defined and listed, the chapter ends by giving an overview of the Fire Dynamic Simulator software (Section 2.6) which is used for developing analysis models in later chapters.

2.2. Combustion process

Combustion is a chemical reaction that takes place when a substance reacts rapidly with oxygen, releasing heat and light in the process, as depicted in Figure 2.1 (Bengtsson, 1999).

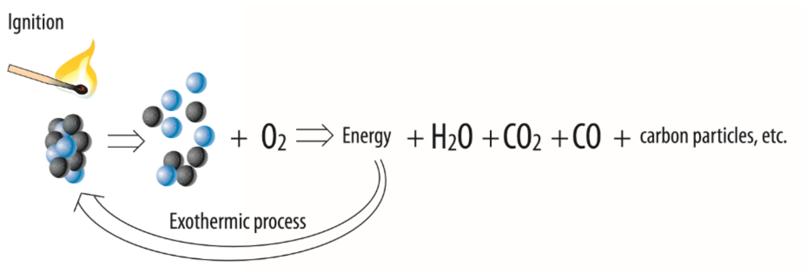

Figure 2.1: Combustion process (Bengtsson, 1999)

As discussed by Karlsson and Quintiere (2000), the combustion process can only take place when the following three components are present:

- Fuel (the combustible material);
- Oxygen supply; and
- Heat.

These three components are known as the fire triangle or combustion triangle, and it is graphically depicted in Figure 2.2. In Figure 2.2, details with regard to ISDs are applied to each component of the combustion triangle to give context to later work. A fourth component is often added to the middle of the triangle, where it is necessary that the combustion reactions be allowed to take place. The components of the combustion triangle have a substantial influence on the characteristics of a developing fire. The combustible materials (fuel) and the ventilation conditions (oxygen supply) pose the greatest limitation to a fire's development.

When a fire is fuel controlled, usually in the ignition and growth stages (Section 2.4.1 & 2.4.2), the heat released is limited by the availability of combustible materials. On the other hand, when a fire is ventilation controlled, usually during the fully developed fire stage (Section 2.4.4), the combustion takes place in the presence of insufficient oxygen (Bengtsson, 1999).

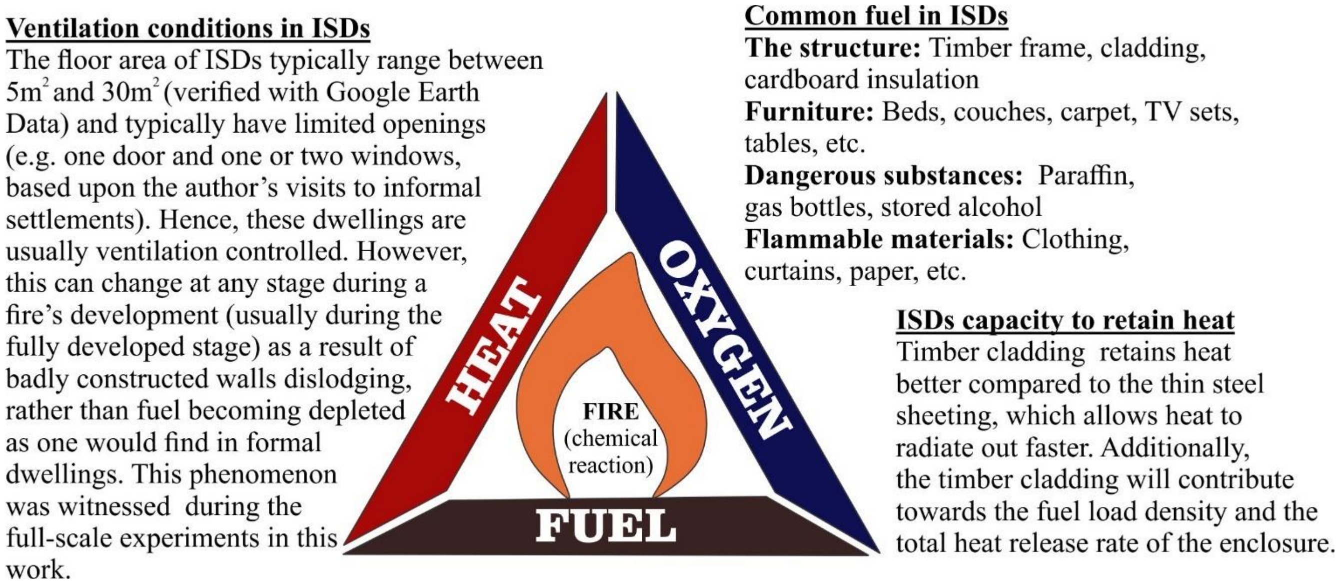

Figure 2.2: Combustion triangle with details regarding ISDs applied to each component

The combustion process can be divided into two distinct types of fire phenomena, namely a smouldering fire and a flaming fire:

- A smouldering fire refers to combustion with a low energy release rate (i.e. when an object burns it releases a certain amount of energy (Figure 2.1), usually in the form of heat, per unit time and is commonly denoted as $\dot{Q}$ and is measured in MW) (Hurley and Rosenbaum, 2015), which takes place when the oxidizing agent and combustible material are not in the same phase, for example, when the fuel is in the form of a solid (Bengtsson, 1999). In ISDs, the main source of smouldering fires appears to be mattresses or upholstered furniture that are ignited by items such as neglected candles or discarded cigarettes (based on interviews conducted with firefighters by the author). As a result of incomplete combustion, more than 10% of the fuel is converted to carbon monoxide, instead of CO_2 (Quintiere, 2011). ISDs are generally small compartments and since carbon monoxide is highly toxic, a smouldering fire may cause asphyxiation, and are of a particular danger to occupants sleeping that may not wake in time.
- A flaming fire refers to combustion with a high-energy release rate (Hurley and Rosenbaum, 2015), which takes place when the oxidizing agent and combustible material are in the same phase, for example, when the fuel is in the form of a gas (Bengtsson, 1999). In some cases, an increased rate of airflow over the surface of the combustible material can convert a smouldering fire into a flaming fire (Quintiere, 2011).

2.3. Heat transfer

There are three modes of heat transfer, namely, conduction, radiation and convection. These modes are visually depicted in Figure 2.3, with the discussion below giving more detail pertaining to each mode. For the purpose of this project, only the basic concepts of conduction, radiation and convection are explained. These sections were sourced from Buchanan and Abu (2017), unless mentioned otherwise.

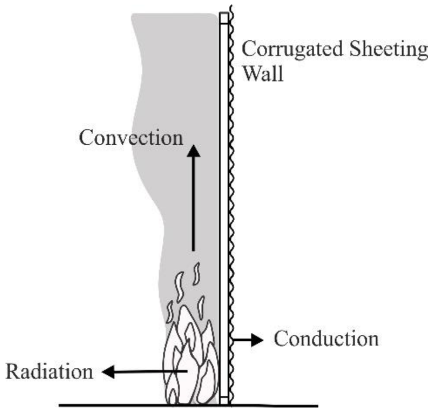

Figure 2.3: Heat transfer methods

2.3.1. Conduction

The mechanism where heat is transferred through a solid material is known as conduction. Heat is transferred by means of free electrons. For this reason, materials that are good heat conductors are also typically good electrical conductors. Heat flow will always flow from a surface with a relatively high temperature to a surface with a relatively low temperature (Quintiere, 2011).

2.3.2. Radiation

Radiation is the main mechanism of heat transfer from flames to the surface of combustible materials and from a burning structure to an adjacent structure. The same holds true for informal dwellings. Radiation is the transfer of energy by means of electromagnetic waves. The electromagnetic waves can pass through transparent liquids, solids or through a vacuum.

2.3.3. Convection

Convection is heat transfer by the flow of fluids (gases or liquids). Convection has a substantial influence on the upward transport of hot gases and smoke to the ceiling level, typically as a result of upwards buoyancy flow. Convection also contributes towards the transportation of hot gases and smoke through openings of a compartment. The rate at which convection heats up or cools down the surface of a specific material is mainly controlled by speed of the fluid at the surface.

2.4. Stages of Fire Development

Karlsson and Quintiere (2000) identify five stages of fire development, namely: ignition, growth, flashover, fully developed fire, and decay. Figure 2.4 depicts a fire development curve, which is a visual representation a time-temperature curve during the five phases of an enclosure fire's development.

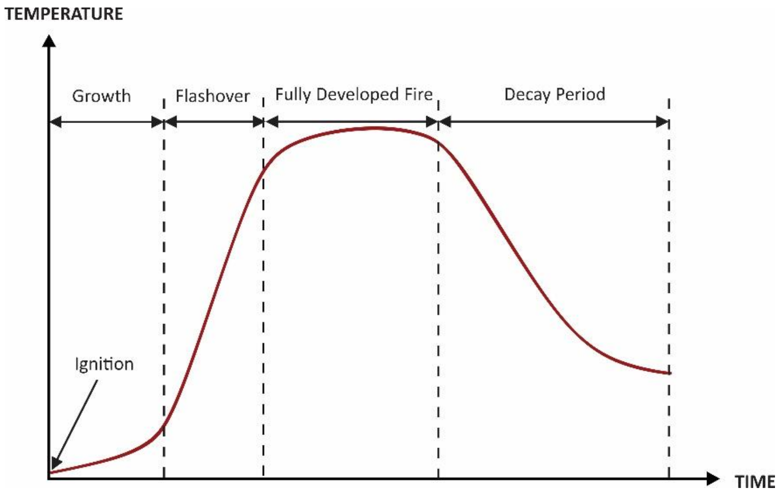

*Figure 2.4: Fire development curve (Cicione and Walls, 2019)**

2.4.1. Ignition

Ignition is the first sign of combustion and can either occur as a result of spontaneous ignition, also known as auto-ignition, or by means of piloted ignition (e.g. ignition by a spark or flaming match). Piloted ignition temperatures range from 250°C to 450°C, whereas spontaneous ignition temperatures require a surface temperature that exceeds 500°C (Bengtsson, 1999). Spontaneous ignition, for solid materials, is a phenomenon that take place once a material's surface reaches a certain temperature, causing the material to ignite spontaneously, without the presence of a flame. For wood to spontaneously ignite, the surface temperature should be between 500°C and 600°C. Quintiere (2011) provide formulae to approximate the time to ignite of a thermally thin solid (i.e. a thickness approximately smaller than 2 mm) and a thermally thick solid, under a constant heat flux (for example, the steady state radiation from an opening of an ISD). For a thermally thick solid the equation is as follows:

$$t_{ig} = C(k\rho c)\frac{(T_{ig}-T_{\infty})^2}{\dot{q}_I"-CHF} \tag{2.1}$$

For thermally thin solid the equation is as follows:

$$t_{ig} = k\rho\tau\frac{(T_{ig}-T_{\infty})}{\dot{q}_I"-CHF} \tag{2.2}$$

where the constant, C, is independent of the material properties and for an ideal case (i.e. when there is no surface heat loss), the constant C is approximately $\frac{\pi}{4}$. For a case with surface heat loss C can be approximated as $2/3$. According to Atreya and Abu-Zaid (1991) and Thomas (1995), the constant, C, is

**Abstract included in Appendix A.2*

however somewhat dependent on the incident heat flux. The product of the conductivity (k), the density (ρ) and the specific heat (c) is commonly known as the thermal inertia. T_{ig} and T_{∞} are the ignition temperature of the material (typically ranging between 200 °C and 500 °C) and the ambient temperature, respectively. $\dot{q}_I{}''$ and CHF are the incident heat flux and the critical heat flux (both measured in kW/m^2), respectively.

At this stage the enclosure has no effect on the fire, meaning that the fire is fuel controlled. Thus, the combustible materials are a crucial factor in the ignition stage and the thermal properties of the materials will affect the characteristics of the fire. For example, dense materials such as heavy wood will generally result in a smouldering fire, where less dense materials such as curtains will generally result in a flaming fire. The ignition of a material mostly depends on the surface temperature, whereas surface fire spread primarily depends on the thermal inertia of the material. Bengtsson (1999) identifies four factors that influence the rate of fire spread over the surface of a specific material. Although, this is focused on fire spread over a surface of a material, fire spread will occur in the same manner in an enclosure that is close to flashover.

1. **Thermal inertia:** This is one of the thermal properties of a material. The smaller the thermal inertia of a material the faster the rate of flame spread over the surface of the material. In general, for solid materials, the denser the material the higher the thermal conductivity (k), and according to Drysdale (2011) the thermal conductivity is approximately proportional to the density. This implies that the flame spread rate is directly proportional to ρ^{-2}. Thus, the flame spread across the surface of dense materials is typically significantly slower.
2. **Surface direction:** The flame spread rate over a material's surface is predominantly vertically upwards. For upward vertical (typically known as concurrent flow) fire spread, the flame height for materials like wood approximately doubles each time the time period doubles (e.g. if a flame is 2 meters high after 1 minute, it will be approximately 4 meters high after 2 minutes). Vertical downward flame spread, known as “creeping” or opposed flow, is slower as compared to upwards flame spread. This implies that if a fire is ignited on an upper part of a material's surface the flame will spread at a slower rate. In the case of informal settlements, most ignitions appear to be a result of paraffin lamps or candles that are accidentally pushed over, however cause of ignition details are generally not well defined in the literature. The cause of ignition is discussed in more detail when statistics are given regarding the causes of informal settlement fires (Chapter 4). Thus, most fires in informal settlements tend to be ignited at a lower level in a home, which ultimately means that the initial enclosure fire spread will occur at a more rapid rate.
3. **Surface geometry:** Flames exposed to more than one surface will have an increased rate of fire spread, for example, a flame in the corner of a compartment will spread more rapidly compared to a flame in the middle of a compartment wall.
4. **Surrounding Environment:** The rate of flame spread increases as the material's temperature increases. The higher the fire temperature from ignition the faster the flame spread rate.

2.4.2. Growth

The period between ignition and the start of the flashover phase (Figure 2.5) is known as early fire development, or the growth stage. During the growth stage, the fire is fuel controlled, meaning that the available oxygen in the enclosure is still sufficient. A fire's growth rate will range between slow and ultrafast (based on the definition of a t^2 fire growth rate) depending on the combustible material, type of combustion and oxygen supply (Karlsson and Quintiere, 2000). The fire growth is typically governed by the flame spread rate during this phase (Hurley and Rosenbaum, 2015). Because the growth phase is still part of early fire development, the fire intensity is still increasing as the heat release rate and the accompanying mass loss rate increase (Bengtsson, 1999). The heat release rate refers to the amount of energy, in the form of heat, released over a period of time during the combustion of an object, as mentioned earlier. The fire growth stage ends when the fire becomes either fuel controlled (i.e. the fire growth ceases because the fire has grown to its maximum size, meaning the fire is not able to ignite additional fuels, or the fuel supply is depleted.) or ventilation controlled (Hurley and Rosenbaum, 2015).

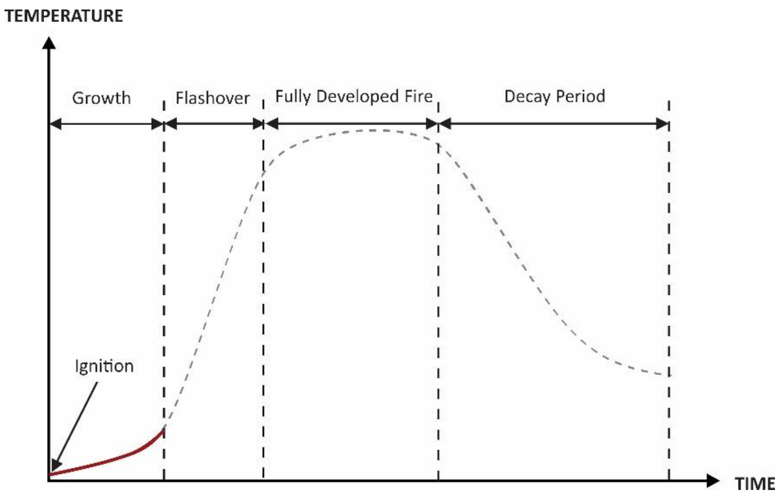

Figure 2.5: Growth stage

During the growth stage, combustion products are released into the environment in a gaseous form, as a result of the combustion of fuel taking place. These gaseous products released are known as combustion gases, whereas the reaction that occurs when a solid is heated, ultimately releasing gaseous fuel is known as pyrolysis (Quintiere, 2006). Pyrolysis usually takes place when the surface temperature of the material is between 100°C and 250°C (Bengtsson, 1999). During the pyrolysis process, the fuel undergoes a chemical decomposition from complex components to simpler elements. The pyrolysis gases start burning when they are mixed with oxygen and have sufficient energy to react. Not all the gases that accumulate at the surface of the material will combust, and those that do not are known as unburned gases. Because some of these unburned gases are less dense compared to the surrounding atmosphere and that they are heated compared to the surroundings, they will move with the fire plume and rise to the top of the enclosure. According to Karlsson and Quintiere (2000) a fire plume can be defined as the hot gas flow forming above and within the flame source. Similarly, Heskestad (2016) defines a fire plume as the buoyant gas flow accompanied by any flames above the flame source. As the combustion gases accumulate at the top of the enclosure, they form a hot layer. A hot layer and a fire plume are visually depicted in Figure 2.6.

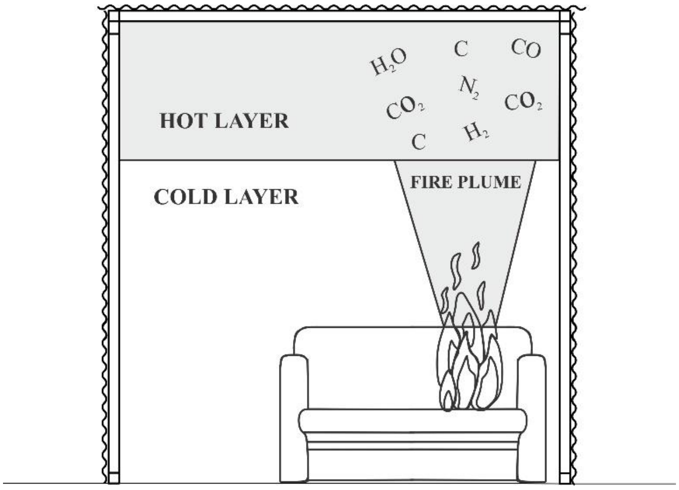

Figure 2.6: Fire plume and a hot layer (Cicione and Walls, 2019)*

2.4.3. Flashover

In the case of sufficient fuel and openings inside the enclosure, a fire is presented with the opportunity to progress to flashover. Flashover is reached when the hot surfaces of the enclosure and the hot combustion gases cause all the combustible materials in the enclosure to ignite, i.e. all exposed surfaces in an enclosure start to burn. The flashover stage is depicted in the time-temperature curve given in Figure 2.7. It should, however, be mentioned that the definition of flashover varies in the literature and in some cases, flashover is seen as a single point of transition between the growth stage and the fully developed stage, rather than a phase.

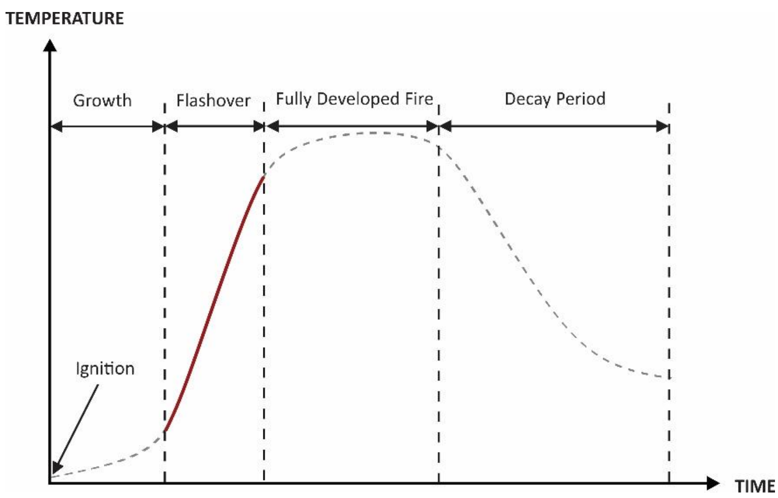

Figure 2.7: Time-temperature curve during the flashover stage

Flashover is actualized in the following sequence as sourced from Karlsson and Quintiere (2000) and Buchanan and Abu (2017):

- Combustion gases accumulate, at the top of the enclosure, during the growth stage;

- as the combustion of fuel continues to take place, the combustion gases continue to accumulate in the enclosure, causing the temperature to rise;
- as a result, the hot layer descends lower into the enclosure; and
- through increasing radiated heat fluxes, the heat in the hot layer is transferred by means of radiation into the cold layer, increasing the energy release rate onto surrounding combustible materials within the enclosure, causing these combustible materials to ignite.

According to Drysdale (2011), for an enclosure fire to progress to flashover the enclosure should have sufficient fuel and oxygen, the hot gases must be sufficiently trapped at ceiling level and the enclosure geometry should be in such as a way that it allows the fuel level to reach critical ignition temperatures by virtue of radiant heat flux from the hot layer. Flashover typically occurs when the upper layer reaches 500-600 °C, which corresponds to a radiative heat flux at the floor level of 15-20 kW/m^2.

2.4.4. Fully Developed Fire

After flashover the fully developed fire phase commences. At this stage the fire is usually ventilation controlled and the fire reaches its maximum energy release rate. The temperature within the enclosure typically ranges from 700-1200 °C during this stage (Karlsson and Quintiere, 2000). The fully developed fire phase is depicted in the time-temperature curve given in Figure 2.8.

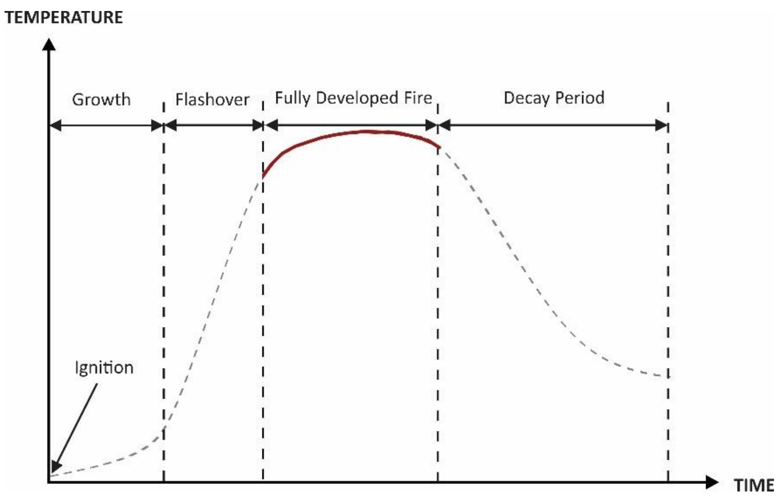

Figure 2.8: Time-temperature curve during the fully developed fire stage

When the enclosure fire is ventilation controlled, it produces an excess of unburnt gases, smoke, CO and energy (Quintiere, 2011). The unburnt gases accumulate at ceiling level and as they leave the enclosure through openings, they ignite once in contact with oxygen. As a result, flames emerge out of the building's openings. For informal dwellings one might find that the fire can become fuel controlled again if the dwelling is poorly constructed, and panels dislodge and collapse onto the fire. In other words, the fire would become fuel controlled if a "wall" of an ISD dislodges. Another phenomenon called backdraft can also occur, as observed during the experiments conducted in this work. As fuel-rich gases accumulate in the enclosure, a sudden exposure to oxygen will cause the gases to ignite. This phenomenon can release high

*Abstract included in Appendix A.2

levels of energy in a short time, as a result of premixed flames moving rapidly through gas. This causes an increase in pressure in the compartment, which creates a flame rapidly emerging from a dwelling (Quintiere, 2011).

2.4.5. Decay

At this stage the limiting factor controlling the fire's behaviour usually changes from ventilation controlled to fuel controlled, and as the amount of combustible material is depleted the fully developed fire cannot be sustained. This leads to a temperature decrease, as depicted in Figure 2.9.

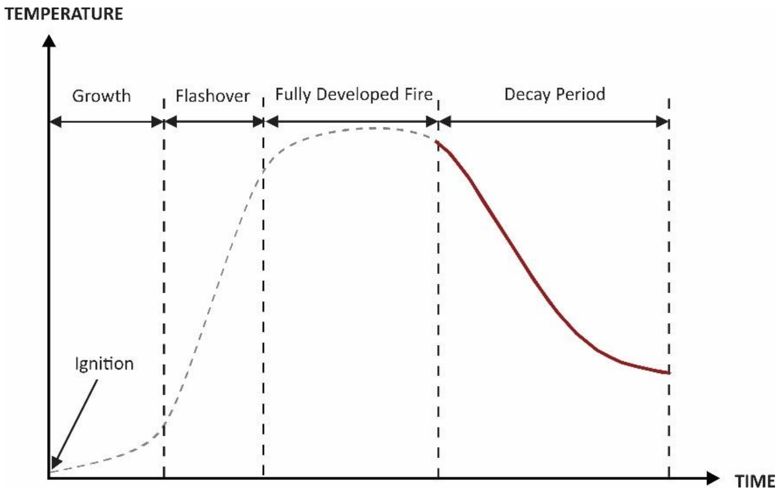

Figure 2.9: Time-temperature curve during the decay stage

2.5. Quantifiable Fire Parameters

The following section introduce concepts necessary for numerical modelling of fire behaviour.

2.5.1. Net calorific value or heat of combustion

The calorific value (commonly known as the heat of combustion) of a material refers to the energy that it contains. This is determined by measuring the heat that is produced during the complete combustion of a specific quantity of the combustible material (Buchanan and Abu, 2017). Thus, the higher the calorific value, the more heat is released during combustion. The calorific value (ΔH_c) is measured in megajoules per kilogram [MJ/kg], which usually range between 15-50 MJ/kg for the majority of combustible materials (Buchanan and Abu, 2017). Table 2.1 depicts the calorific values of common combustible materials.

Table 2.1: Net calorific value for common combustible materials [MJ/kg] (CEN, 2002)

Chemicals	
Paraffin series: Methane, Ethane, Propane, Butane	50
Olefin series: Ethylene, Propylene, Butene	45
Fuels: Gasoline, Petroleum, Diesel	45
Pure hydrocarbon plastics: Polyethylene, Polystyrene, Polypropylene	40
Aromatic series: Benzene, Toluene	40
Alcohols: Methanol, Ethanol, Ethyl alcohol	30
Solids	
Carbon: Anthracite, Charcoal, Coal	30
Other cellulosic materials: Clothes, Cork, Cotton, Paper, Cardboard, Silk, Straw, Wool	20
Wood	17.5
Other products	
Bitumen, Asphalt	40
ABS (plastic)	35
Polyester (plastic), Rubber tyre	30
Polyisocyanurate and polyurethane (plastics)	25
Polyvinylchloride, PVC (plastic), Leather, Linoleum	20

In some cases, combustible materials contain moisture, therefore the effective calorific value or effective heat of combustion (ΔH_{eff}) can be calculated based on the percentage moisture the material contains and is given by the following equation:

$$\Delta H_{eff} = \Delta H_c(1 - 0.01m_w) - 0.025m_w \qquad (2.3)$$

where m_w is the percentage moisture by weight of the material.

2.5.2. Fire Load Energy Density

Fire load density, e_f (measured in MJ/m^2), is calculated by dividing the maximum energy contained in the fuel by the floor area of the enclosure (Buchanan and Abu, 2017). If the calorific value is known for a specific fuel, it is then possible to calculate the maximum amount of energy, E (measured in MJ), that the specific fuel can release during combustion and is given by the following equation:

$$E = M\Delta H_{eff} \qquad (2.4)$$

where M is the initial mass of the fuel, measured in kg. Once the maximum amount of energy is calculated, the fire load density can be calculated as a result, using the following equations:

$$e_f = E/A_f \qquad (2.5)$$

where A_f is the floor area of the enclosure, measured in m^2.

2.5.3. Heat Release Rate

This concept was introduced in Section 2.4.3. The heat release rate, $\dot{Q}$ (measured in MW), typically increases gradually to a peak and dies out after sufficient fuel has been consumed. The heat release rate (HRR) is the single most important variable of the intensity of a fire (Babrauskas and Peacock, 1992). Buchanan and Abu, (2017) give the following equation to calculate the heat release rate:

$$\dot{Q} = E/t \tag{2.6}$$

where t is the time elapsed during combustion, measured in seconds. By substituting Equation 2.4 into Equation 2.6, the heat release rate equation can be rewritten in a well-known form, typically used in the fire community:

$$\dot{Q} = \dot{m}\Delta H_{eff} \tag{2.7}$$

where $\dot{m}$ is the mass loss rate (MLR), measured in kg/s. If an enclosure is ventilation controlled the mass loss rate can be approximated as (Babrauskas, 2016):

$$\dot{m} = 0.12A_v\sqrt{h_v} \tag{2.8}$$

where $A_v\sqrt{h_v}$ is typically known as the ventilation factor, A_v is the area of the opening in the compartment (measured in m^2) and h_v is the height of the opening in the compartment (measure in m). If a compartment has more than one opening, A_v and h_v become the sum of the areas and the weighted average of the heights of the openings, respectively.

However, it must be understood that it is often difficult to exactly define the HRR of a real fire scenario, so in many cases approximate models are used. Delichatsios (1976) has developed a method to approximate the HRR of timber cribs which makes used of Equation 2.7 and where the MLR is governed by the porosity of the crib, the exposed surface area of the timber pieces or the ventilation conditions of the enclosure. This method is discussed more recently by Babrauskas (2016). A simpler method, and more widely used, is the well-known t-squared fire method.

2.5.4. t-squared fires

A t-squared fire is a parametric fire curve that characterises the growth rate of the fire. It is determined by setting the heat release rate proportional to time squared. In other words, one can visualize an object burning with a constant heat release rate per unit area, and the fire is spreading at a constant radial flame speed in a circular pattern (Buchanan and Abu, 2017). Karlsson and Quintiere (2000) gives the following equation to calculate heat release rate for a t-squared fire:

$$\dot{Q} = \alpha t^2 \tag{2.9}$$

where α is the growth factor, measured in kW/s^2, and t is time, measure in seconds. Table 2.2 give the values for α for a slow to ultrafast fire growth rate. The α values were numerically determined and refer to the time it takes the fire to reach a size of 1.055MW. Based on the geometry of the fuel an α value can be obtained by using Table 2.2.

Table 2.2: Values of α for different fire scenarios (NFPA, 1985)

Growth rate	α	Fire scenario
slow	2.93×10^{-6}	Densely packed wooden products
medium	1.17×10^{-6}	Individual furniture with some amount of plastic or solid wood furniture
fast	4.66×10^{-5}	Carton on pallets, high stacked pallets or some upholstery furniture
ultra	1.874×10^{-4}	Thin wooden furniture or most upholstery furniture and high stacked plastic materials

2.6. Overview of FDS modelling

The numerical modelling carried out in this work was done with a software known as Fire Dynamic Simulator (FDS) created by NIST (McGrattan et al., 2013). FDS models were used to model (a) the enclosure fire dynamics of the ISD experiments done in this work, to (b) predict the fire spread mechanisms between ISDs based on the experiments done in this work, and to (c) study the effect of mesh independent parameters on the fire spread rate and the enclosure dynamics by means of a parametric study.

The objective of this section is to highlight the important features of the solution procedure used in FDS models that make it possible for fire simulations to be solved. The details below are primarily based on the work done by McGrattan et al. (2013) unless mentioned otherwise. FDS is a Computational Fluid Dynamics (CFD) program but with prominence given to fire-driven fluid flow and it is accompanied by an additional program called Smokeview, that is used to visually present the FDS simulation predictions (Forney, 2018). CFD modelling is a technique based on three-dimensional, time-dependent solutions of the fundamental conservation laws. The volume, commonly known as the domain, of interest is divided into sub-volume elements (known as cells) and the basic energy, mass and momentum conservation laws are calculated for each sub-volume element. The Navier-Stokes equations are derived by substituting the viscous stress components (contained as further unknown in the conservation equations) into the momentum conservation equation (Karlsson and Quintiere, 2000). The solving of the Navier-Stokes equations is the purpose of any CFD code. FDS numerically solve the sections of the Navier-Stokes equations that are applicable to fires with prominence given to heat and smoke transport. Rehm and Baum (1978) developed this approximate form of the Navier-Stokes equations that describe the fire-driven fluid flow for a low Mach number (i.e. when the relationship between the speed of an object to the speed of sound in the surrounding medium is less than 0.3 (Mcgrattan et al., 2017)). The conservation equations are as follows:

- Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = \dot{m}_b''' \tag{2.10}$$

where t is the time, ρ is the density of air, u is velocity and $\dot{m}_b'''$ is the production rate of species by evaporating droplets or particles.

- Momentum conservation equation:

$$\frac{\partial u}{\partial t} - u \times \omega + \nabla H - \tilde{p}\nabla(1/\rho) = \frac{1}{\rho}[(\rho - \rho_0)g + f_b + \nabla \cdot \tau] \tag{2.11}$$

where ω is the vorticity vector, H is the stagnation energy per unit mass, $\tilde{p}$ is the perturbation pressure, f_b is the drag force applied by the droplets and particles on the Sub-Grid Scale (SGS) and τ is the viscous stress tensor which is closed by means of gradient diffusion and where the turbulent viscosity (that is explained below) is obtained from the default viscosity model implemented by FDS, known as the Deardorff eddy viscosity model.

- Energy conservation equation:

$$\frac{\partial(\rho h_s)}{\partial t} + \nabla \cdot (\rho h_s u) = \frac{D\bar{p}}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla \cdot \dot{q}'' \tag{2.12}$$

where h_s is the sensible enthalpy, $\bar{p}$ the background pressure, $\dot{q}'''$ is the heat release rate per unit volume from a chemical reaction, $\dot{q}_b'''$ is the energy transferred to SGS droplets and particles, and the term $\dot{q}''$represents the total heat flux.

The thought behind this approach was to remove acoustic waves (i.e. by means of applying a filter) while the large alterations in temperature and density found in fire-driven fluid flow are explicitly considered. The main assumptions made to develop this model are hydrodynamic flow (meaning the material under consideration cannot compress), Low Mach number flow (implying that the acoustic waves are not considered as described above), as a result of some approximations of divergence the pressure is constrained by strict boundaries and the altitude does not have an effect on the pressure, baroclinic torque is not considered implying that the viscosity of the flow and buoyancy dominate the vorticity, and the SGS eddy viscosity is calculated by assuming that the small scales are in equilibrium (i.e. energy in is equal to energy out) (Rehm and Baum, 1978). The fire's behaviour is predicted across the entire computational domain by solving the Navier-Stokes equations for each sub-volume (cell) at every time-step.

2.6.1. Turbulence modelling

Once fluid flow surpasses a certain Reynolds number the flow becomes unstable, and this is known as turbulent flow. Turbulence is associated with velocity fluctuations that induce additional stresses, known as Reynolds stresses, on the fluid. Visual studies of turbulent flow revealed rotational flow structures, known as turbulent eddies (Karlsson and Quintiere, 2000). For very high Reynolds numbers, the length scales of the eddies may be as small as 10^{-6} m. The velocity fluctuations can have a frequency as high as 10 kHz. Thus, the direct solution of the Navier–Stokes equations over time for fully turbulent flows, when considering high Reynolds numbers, would necessitate very small-time steps and very small geometric grids. Even with current technology, the direct solution would be truly phenomenal as a result of the computational effort that would be needed. As a result of the above mention, a CFD code must (a) be economical to run, (b) have wide applicability and (c) be accurate in order for a turbulent model to be practically useful. Over the past few decades more economical turbulent models have been developed by introducing specific assumptions that eliminates the need to predict the effects of every single eddy in the domain. The turbulence model mostly used for CFD application, is the Reynolds Averaged Navier–Stokes (RANS) equations, which form the basis of most commercial CFD codes, including the well-known κ-ε turbulence model (pioneered by Pantakar (1980)), which is also the most validated and poplar turbulence model for CFD models in general (Versteeg and Malalasekera, 2007; Wang et al., 2001). A common method employed by the fire community for turbulent modelling is known as the Large Eddy Simulation (LES) model. In order to derive the equations of the LES model, a low-pass filtering of width Δ are applied to the Direct Numerical Simulation (DNS) equations. In other words, phenomena taking place on scales larger than the filtered width (note that the cell size, δ, are equal to filtered width, Δ, in FDS) are calculated directly, and those on the SGS are approximated or modelled. Consider the following equation, that represents a one-dimensional example where the filtered density for a cell with a width Δ is:

$$\bar{\rho}(x,t) = \frac{1}{\Delta}\int_{x-\frac{1}{\Delta}}^{x+\frac{1}{\Delta}} \rho(r,t)dr \tag{2.13}$$

Note that x is the Cartesian coordinate system and r is the Radial coordinate system. Numerical diffusion is not necessarily implied for indirect filtering, instead for turbulent stress, physically-based closure momentum is solved using kinetic energy-conserving central difference schemes in FDS.

For smoke and fire modelling, the capacity to model time-dependent events, for example, large buoyant eddies formed in plumes, is the biggest benefit of the LES technique which is typically not possible in other turbulent models. There are numerous variations of the SGS models for viscosity and they vary from the early Smagorinsky model (Smagorinksy, 1963) to the dynamic viscosity models developed by Germono (1991). FDS employs the Deardorff's model by default to model turbulent viscosity (Deardorff, 1972).

2.6.2. Mass and species transport

FDS typically takes a simplified approach to model combustion by limiting the number of fuels in a single model to one and the number of reactions to a maximum of two. Even with the limitations there are still at least 6 gas species (i.e. fuel, O_2, H_2O, CO_2, CO, N_2) plus soot particulate. For a single-step reaction FDS does not explicitly solve 7 transport equations, it rather assumes that everything is air that is neither fuel nor products. Thus, the products and air are referred to as "lumped species" and the fuel is a single gas species. A lumped species refers to a mixture of gas species that are transported together and react together, and thus

FDS treats a lumped species as a single species (e.g. air is a lumped species that consists of oxygen, carbon dioxide, nitrogen and water vapor). This leads to the following equation:

$$Z_A = 1 - Z_F - Z_P \tag{2.14}$$

where Z_A, Z_F and Z_P are the mass fractions of air, fuel and products, respectively. A simple matrix multiplication can be performed to convert lumped species mass fractions to primitive species mass fractions, Y_α, because of their linear relationship. Consider the complete combustion of methane as an example:

$$CH_4 + 2(O_2 + 3.76N_2) \ \rightarrow \ CO_2 + 2H_4O + 7.52N_2 \tag{2.15}$$

this can be expressed as Fuel + 2Air → Products and from the lumped species the primitive species can be obtained as follows:

$$\begin{bmatrix} 0.77 & 0 & 0.73 \\ 0.23 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.15 \\ 0 & 0 & 0.12 \end{bmatrix} \begin{bmatrix} Z_A \\ Z_F \\ Z_P \end{bmatrix} = \begin{bmatrix} Y_{N_2} \\ Y_{O_2} \\ Y_{CH_4} \\ Y_{CO_2} \\ Y_{H_2O} \end{bmatrix} \tag{2.16}$$

The mass transport equation for total mass is still given by Equation 2.10 and is not affected by this approach.

2.6.3. Combustion

The combustion source term, $\dot{q}'''$, is introduced into the controlling equations by virtue of the energy transport equation. Since the energy equation is solved implicitly, this term finds its way into the expression for the divergence. Typically, FDS uses a combustion model based on the mixing-limited (i.e. by limiting the number of fuels in a single model, as mentioned above) for infinitely fast reaction of lumped species. Although the reaction of oxygen and fuel is not usually complete and instantaneous, there are multiple methods developed to estimate the degree of combustion in oxygen-controlled environments. In a given cell, the product species are converted from reactant species at a rate determined by a characteristic mixing time (τ_{mix}), for an infinitely-fast reaction. The characteristic mixing time is discussed in more detail in McGrattan et al. (2013). The HRR (also determined by the combustion model) is a quantity that is fundamentally important in the fire physics, and in most cases, it has a substantial contribution to the velocity divergence. Once the mass production rate of species per unit volume, $\dot{m}_\alpha'''$, has been determined, the HRR can be calculated by multiplying each species heats of formation with their respective sum of the mass production rates:

$$\dot{q}''' = -\sum_\alpha \dot{m}_\alpha''' \Delta h_{f,\alpha} \tag{2.17}$$

2.6.4. Radiation

Similar to combustion, the radiation source term, $\dot{q}_r'''$, is also introduced into the controlling equations by virtue of energy transport equation. Since the energy equation is solved implicitly, as mentioned above, this term also finds its way into the expression for the divergence. The radiation equation is solved using a technique known as the Finite Volume Method (FVM), which is similar to the FVM for convective transport, by using 100 discrete angles (by default) that are updated over multiple time steps. The net contribution from thermal radiation in the energy equation is defined by (in words, the difference between the radiation absorbed and emitted, is the net radiation gained by a grid cell):

$$\dot{q}_r''' = -\dot{q}_r''(x) = \kappa(x)[U(x) - 4\pi I_b(x)] \tag{2.18}$$

where $\kappa(x)$ is the absorption coefficient (can be calculated using a narrow-band method known as RadCal (Grosshandler, 1993)), $\mathrm{U(x)} = \int_{4\pi} \mathrm{I(x, s')ds'}$, $I_b(x)$ is the source term, and I(x,s) is the solution of the radiation transport equation for a non-scattering gray gas.

2.6.5. Application of FDS in past research

Negligible research has been found on FDS modelling for informal settlement or ISDs. There are, however, numerous studies that have validated FDS for compartment fires. Welch et al. (2007) used a series of full-scale experimental results to develop a well-characterised dataset of physical parameters to account for various uncertainties in experimental measurements, such as the radiation errors in thermocouple measurements, and these can be used for model validation. Yang et al. (2010) compared FDS predictions based on different combustion models with measured data for enclosure fires. They compared upper-layer temperature, CO yield and HRR to the experimental measurements considering each parameter’s sensitivity to the (a) mixing time scale, (b) lower limit of fuel, and (c) the turbulent model constants. Jahn et al. (2007) and Rein et al. (2007) constructed a priori and a posteriori FDS models, respectively, for the well-known Dalmarnock Fire Tests. Merci and Van Maele (2008) conducted numerical simulations of full-scale enclosure fires in a small compartment with natural roof ventilation, where it was found that the model HRR input has the largest influence on the hot smoke layer average temperature rise, while the area of the fire and the roof opening had a less significant affect.

For enclosure fire experiment, in general, FDS tends to show good correlation to the experimental results. Modelling fire spread on the other hand has proven to be more difficult. Hietaniemi et al. (2004) established a set of material parameter values for engineering use in FDS, when modelling flame spread, and the parameters are summarised in Appendix A of Hietaniemi et al. (2004). The study further unveiled some discrepancies in the FDS results compared to the measured experimental results.

There are numerous studies on the numerical modelling of timber cribs, which is also done in this work. Recent work by Janardhan and Hostikka (2019) investigated the influence of various parameters on fire spread in large openings. Janardhan and Hostikka (2019) found that, with the help of the surface area correction, the fine-mesh predictions of the heat release rate can be reproduced with coarser meshes for timber cribs, decreasing the computational time substantially. Zhang et al. (2015) studied the fire behavior of timber cribs in confined spaces using FDS. They found that the surface HRR input in FDS, obtained from cone calorimeter tests with different external heat flux (35-50 kW/m^2) had a negligible effect on the simulation results. The output HRR of the cribs showed good correlation with the experimentally measured HRR, where the largest difference was found to be 13.9 % from the peak value. A number of recent works has been devoted to FDS models of travelling fires (Anderson et al., 2019; Horová et al., 2013).

NIST (Linteris et al., 2005) published a report looking at parameters that have an effect on model results, specifically when modelling the burning of solid materials. They found that (a) the grid and domain size both have a large effect the HRR in the gas phase, (b) the selection of DNS or LES does not have a substantial effect using current calculations and (c) that the ignition temperature, activation energy, and the heat of vaporization all effected the burning rate by approximately 10%. Lastly, Jahn et al. (2008) investigated the effect of model parameters on the simulation of fire dynamics, with emphasis placed on the prediction of secondary ignition and time to flashover. The study found that if the HRR is kept constant, the FDS results are relatively insensitive to the calorific value of the material (note that this will affect the mass loss rate), the soot yield and the heating from the smoke layer. Jahn et al. (2008) concluded that future development in FDS should focus on the global HRR as well as the important parameters identified in the paper.

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Chapter 3: Full-scale informal settlement dwelling fire experiments and development of numerical models

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	Extent of contribution (%)
Planning, ordering, preparation and execution of experiments. Writing the manuscript, establishing methodology, data analysis and preparing figures and tables. Lead the modelling work done in the paper and did the data analysis of the modelling results.	74%

The following co-authors have contributed to as follows:

Name and e-mails	Nature of contribution	Extent of contribution (%)
Mohamed Beshir (m.beshir@ed.ac.uk)	Assisted with the FDS modelling (joint collaboration between the candidate and Mohamed) and reviewed the manuscript. Did the FPA tests at the University of Edinburgh	17%
Richard Shaun Walls (rwalls@sun.ac.za)	Supervised the work, assisted with experiments, advised on the work and reviewed the manuscript.	6%
David Rush (d.rush@ed.ac.uk)	Supervisor of Mohamed Beshir, advised on the work, and reviewed the manuscript.	3%

Signature of candidate:

Date:

The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 3,
2. no other authors contributed to Chapter 3 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3 of this dissertation.

Signature	Institutional affiliation	Date
	University of Edinburgh	
	Stellenbosch University	
	University of Edinburgh	

This chapter is an exact copy of the journal paper referred to above

Contribution of chapter to dissertation

In this chapter full-scale fire experiments are conducted on single dwellings, and from these results numerical models are developed. This work is then built upon in Chapter 4 where larger experiments are conducted with three dwellings in a single experiment. In this chapter a statistical model is proposed to estimate a required separation distance between dwellings. This estimation of a safe separation distance is based on the numerical results obtained in this chapter. Chapter 4 repeats the exercise of obtaining a critical separation distance, but by means of analytical equations. The separation distance of 3 m obtained in this chapter is based on the average heat flux values obtained during the single dwelling experiments, whereas the separation distance of 3.8 m obtained in Chapter 4 (i.e. by using analytical equations) are based on maximum heat flux values (as opposed to the average heat flux values) obtained during the multi-dwelling experiments. The numerical models from this chapter are simplified in Chapter 5 to allow for the analysis of spread between multiple dwellings and to make the simulations more practical (i.e. in terms of computational effort) to study different housing configurations, fire breaks or different forms of passive fire protection.

3.1. Abstract

While fire-related injuries and deaths decreased in the global north over the past few years, they have increased in the global south. With more than one billion people residing in informal settlements (sometimes known as slums, ghettos or shantytowns), it is necessary that greater effort be placed on addressing and developing means for improving fire safety in these areas. As a result of advances made in computer technologies, emerging performance-based regulations and an increase in building complexity in the global north, the use of computer models simulating enclosure fires have increased dramatically. In this work an experimental investigation is presented for (a) a full-scale corrugated steel sheeting clad informal dwelling experiment and (b) a full-scale timber clad informal dwelling experiment. The experimental results are then compared to numerical models consisting of both simple two-zone (OZone) and computational fluid dynamic models. Currently, there is negligible literature available on Fire Dynamic Simulator (FDS) modelling of informal settlement dwellings (sometimes known as shacks or shanties) fires. This paper evaluates the plausibility of using FDS v6.7 and zonal models to predict certain fire parameters (i.e. ceiling temperatures, heat fluxes, etc.) for Informal Settlement Dwellings (ISDs) and to study the plausibility of using FDS to estimate the probability of fire spread. In this paper an introduction to ISDs is given with details pertaining to construction materials and considerations needed for numerical modelling of informal dwellings (i.e. thin permeable boundaries or combustible boundaries). Models are based upon (a) a prescribed Heat Release Rate Per Unit Area (HRRPUA) in FDS using data obtained from a Fire Propagation Apparatus (FPA) test, and (b) an empirical two-zone model using OZone. The FDS validation guide was used to quantify the model uncertainties in order to give a critical separation distance at which fire spread between dwellings will not occur. It was found that at three meters spacing between ISDs there is an 6% chance (based on the model uncertainties) that fire spread can occur. This is an important finding that highlights the danger associated with these closely spaced dwellings and the hope is that it can guide local government and Non-Governmental Organizations (NGOs) in future decision making. Three meters spacing between dwellings, however, may not be possible due to the socio-cultural-political-economic issues associated with informal settlements. This is one of the first papers to demonstrate FDS models against full-scale ISD experiments.

KEYWORDS: informal settlements, Computational Fluid Dynamics, enclosure fire dynamics, full-scale fire experiments, two zone modelling.

3.2. Introduction

In the world, there are currently an estimated 300 000 fire-related deaths per year with more than 95% of those deaths occurring in middle to lower-income groups [1]. The rapid population growth in cities that is being observed more acutely in the global south, has the potential for more people to reside in informal settlements. An informal settlement refers to dwellings (mostly informal dwellings) erected on land that has not been proclaimed as residential [2]. Informal settlements are also known by other names such as slums, squatter camps or shantytowns in other parts of the world. Informal settlement dwellings (ISDs) are makeshift structures that are typically cladded with immediately available building materials like steel sheeting, plastic sheets or timber; insulated with timber or cardboard; and are often constructed with timber frames. Figure 3.1 provides an overview of a typical ISD with details pertaining to construction practices and considerations needed for numerical modelling. The details given in Figure 3.1 are based on the authors' visits to informal settlements, interviews conducted with firefighters in South Africa by the authors and the literature [3–5]. Therefore, people residing in informal settlements are vulnerable to fire since these areas can be characterized by poorly constructed dwellings, a lack of basic services and are more densely populated than formal settlements [6].

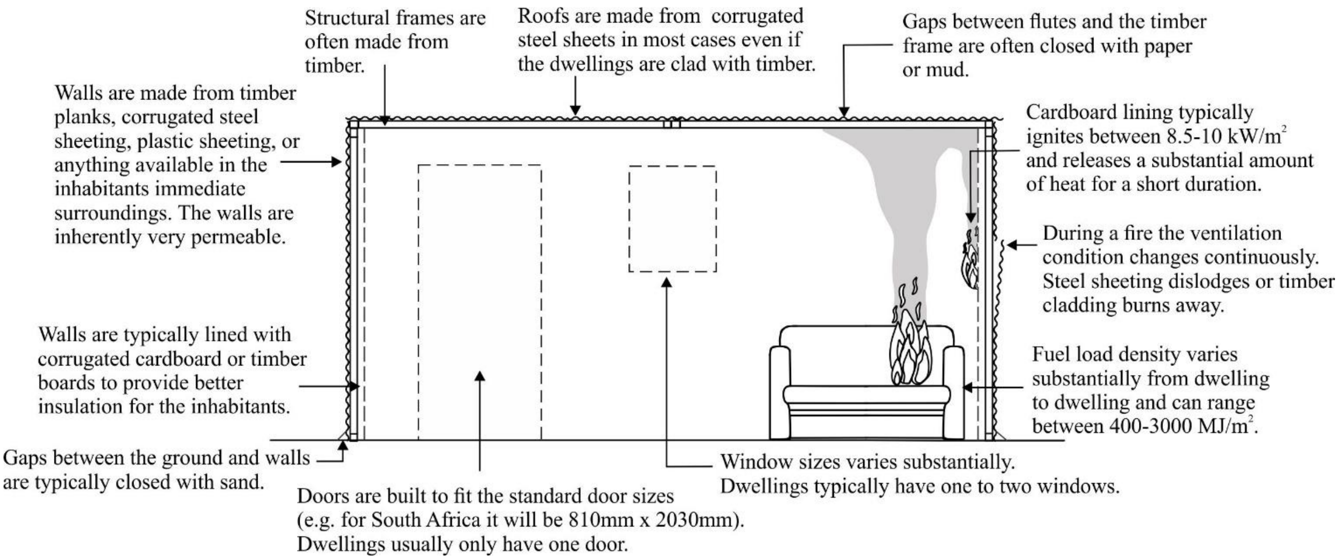

Figure. 3.1: Typical informal settlement dwelling with details needed to understand the fire dynamic behaviour of the dwelling

The number of people that reside in informal settlements is expected to increase from one billion worldwide to 1.2 billion people in Africa alone by 2050 [6]. It is of concern, therefore, to see how little work is being done to improve the fire safety in these communities. There are numerous fire incidents illustrating the scale of the problem. For example, In Nepal, 38924 homes were destroyed by fire incidences between 1990 and 1996 [7]. In January 2005, February 2008 and March 2009 more than 3600 homes were destroyed, leaving more than 13000 people homeless in the Joe Slovo informal settlement in Cape Town [8]. In May 2012 a fire ravaged an informal settlement in Accra, Ghana, leaving approximately 3500 people homeless [9]. In April 2014, in Valparaíso, approximately 2500 homes were destroyed by a fire, leaving 12500 people homeless [10]. In 2017, approximately 2200 homes were razed, affecting approximately 9700 people in the Imizamo Yethu informal settlement in Cape Town [11]. These fires do not just cause loss of life in these communities, but significant morbidity with over 10M disability adjusted life years lost each year due to fire, and loss of belongings (such as official documents, educational material) and livelihoods.

The development and validation of Computational Fluid Dynamics (CFD) models in the fire community has so far generally focused on small-scale fire behaviour and smoke movement [12–15] with some validations of post-flashover compartment fires [12,16–18]. All of these studies are based on formal structures (i.e. dwellings with no wall permeability, thick walls, typically not lined with flammable materials, no structural collapse, etc.) and there is negligible literature available on CFD modelling for ISDs. It is with this backdrop that this paper seeks to (a) demonstrate different numerical modelling techniques by comparing the modelling results to full-scale ISD burn experimental results, (b) to provide an understanding of the fire behaviour of ISDs as well as the effect of different cladding materials (i.e. corrugated steel cladding versus timber cladding) and (c) to provide a Fire Dynamics Simulator (FDS) based solution to evaluate the critical separation distance between dwellings. This work forms part of an overall project to understand fire behaviour in informal settlements. Previous work has focused on results from preliminary single dwellings experiments [5], results from multi-dwelling experiments considering inter-dwelling spread [19]*, the development of a simplified FDS model to describe the aforementioned multi-dwelling experiment [20]**, analysis of large-scale spread in real fire disaster that affected over 2000 homes [11]***, and the appraisal of fire safety interventions to be used in such settlements [21]****.

3.3. Experimental set-up

Two full-scale ISD fire experiments were conducted at the Breede Valley Fire Department in Worcester, South Africa; namely (a) a corrugated steel sheeting clad experiment and (b) a timber clad experiment. The thermocouples used were K-Type thermocouples and the Thin Skin Calorimeters (TSCs) used were constructed according to [14] and have an accuracy of ±10% and a measuring range of approximately 0-200 kW/m^2. The TSCs used in the experiments were validated and calibrated against a water-cooled heat flux gauge. The timber fuel (i.e. Pine) used had a density of 536 kg/m^3 with a gross heat of combustion of 18MJ/kg, the cardboard used had an approximate thickness of 1.5 mm with a density of approximately 180 kg/m^3 and a gross heat of combustion of 16.9 MJ/kg. The gross heat of combustion of the timber and cardboard were measured with a bomb calorimeter. For both experiments, the roofs were made from corrugated steel sheeting with a thickness of 0.47 mm and the frames of both experiments were constructed from 50 mm × 50 mm timber sections (i.e. Pine). The timber clad dwelling was cladded with 12 × 100 mm (thickness × width) timber planks. The corrugated steel sheeting dwelling was cladded with 0.47 mm thick sheeting with a flute height of 17mm. Figure 3.2 depicts the details pertaining to the two experiments. All the equipment was not present in each experiment, after the first experiment (i.e. the steel clad dwelling experiment) and the analysis of the data, the equipment layout was adjusted based upon the authors' observations and findings. It was decided that an equipment tree at 1 m away from the window should be added for the timber clad dwelling experiment. This was decided to ensure that more data could be collected at a distance, which is important when considering fire spread.

**Refers to Chapter 4 of this dissertation. **Refers to Chapter 5 of this dissertation.*
****Abstract included in Appendix A.3. ****Abstract included in Appendix A.1.*

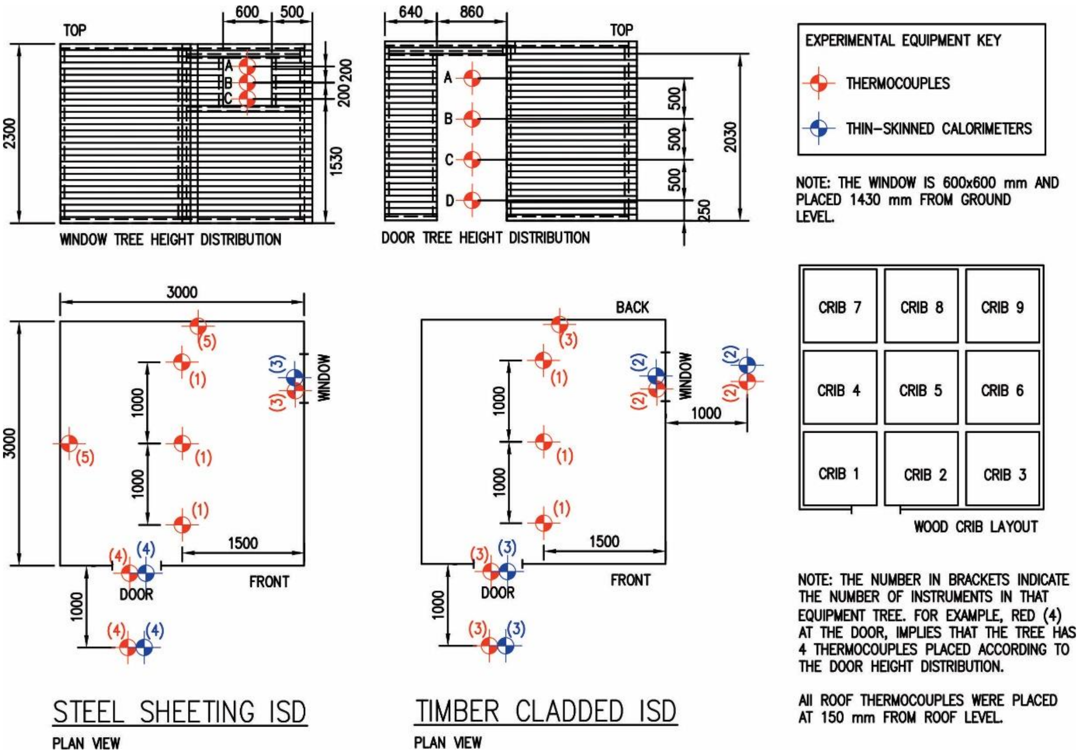

Figure 3.2: Experimental setup: Floor plans with experimental layout are depicted by the bottom left layouts and the height distributions of window trees and door trees are depicted by the top left layouts. All trees, not placed in front of a door or window, were distributed according to the door tree height distribution, unless stated otherwise.

Note that all TSCs were orientated at the dwelling, with the direction parallel to the ground, facing into the door or window. The only difference between the two experiments was the cladding material of the walls. Figure 3.3 visually depicts the steel clad dwelling and timber clad dwelling.

Figure 3.3: Steel clad dwelling setup (left image) and timber clad dwelling setup (right image)

3.3.1. Fuel load

In 2015, a survey was conducted in an informal settlement through the University of Stellenbosch, where it was found that the average fire load density was 410 MJ/m^2 with a standard deviation of 140 MJ/m^2 [22]. However, the sample size was too small to be considered fully reliable. In 2017, interviews were conducted at the Breede Valley Fire Department by the authors. The firefighters that were interviewed fought more than 2000 informal settlement fires incidents combined. According to them, the average fire load density in an ISD is higher than formal dwellings (i.e. probably higher than 780 MJ/m^2 as stipulated in EN 1991-1-2 (CEN 2009). In some cases, the fire load densities can be as high as 1000-2000 MJ/m^2 depending on the occupation of the resident of the dwelling (e.g. inhabitants storing paraffin, wood or tyres) [4,5]. The fire load densities vary substantially from settlement to settlement as a result of the building materials available in the immediate surroundings of a particular settlement and also as a result of variation in income levels. In this work it was decided to use the average fire load density of 780 MJ/m^2 as specified by [9] for formal dwellings. In order to mimic reality, cardboard insulation was added to the inside of the walls of the dwelling as one would typically find in these dwellings. Additionally, polystyrene was added to the wood cribs to increase the fire spread rate, although during the experiment it was noted that the polystyrene had a negligible effect on the spread rate, and it is not recommended for future work. The wood cribs and cardboard insulation are depicted in Figure 3.4. There were 36 timber pieces (40×60×900 mm) per crib and the crib configuration is also shown Figure 3.4.

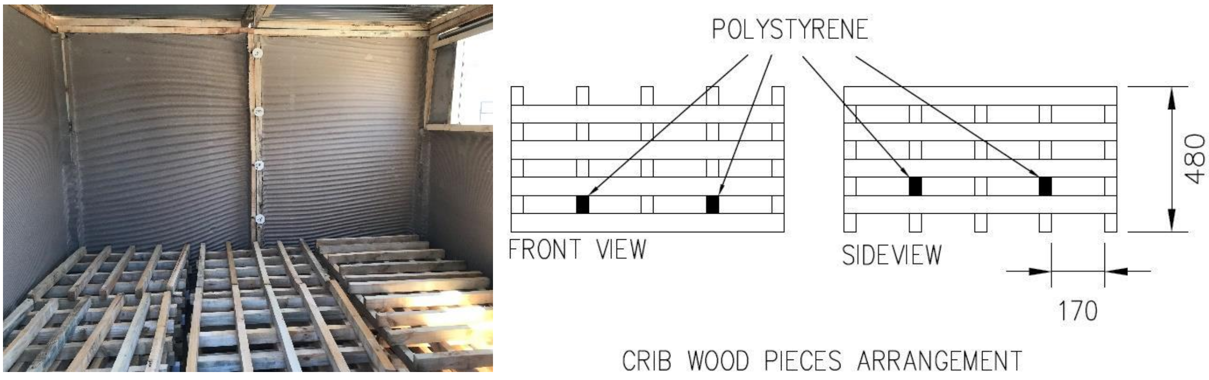

Figure 3.4:. Fuel load for both steel sheeting clad ISD and timber clad ISD experiments (Note that all dimensions are in mm)

The dwellings were ignited by igniting a tin can (100 mm in diameter and 200mm high) filled with approximately 1.5 L paraffin (kerosene). The tin can was placed in the middle front crib (i.e. crib 2 as depicted in Figure 3.2). For the steel clad experiment, two timber pieces placed at the top of crib 2, above the can, were partially dipped (i.e. approximately 200 mm of the tip of the timber piece) in paraffin to increase the initial growth phase. However, the fire brigade did allow some of the paraffin to drip on the crib as they placed the timber pieces back in position. After the first experiment (i.e. the steel clad experiment) it was decided to increase (double) the number of timber pieces dipped in paraffin to increase the initial growth phase.

3.4. Experimental results

3.4.1. Corrugated steel sheeting clad ISD results

As introduced above, the corrugated steel clad experiment was conducted at the Breede Valley Fire Department in Worcester, South Africa. The ambient temperature was 29°C and a very light North Westerly breeze (i.e. from the front left to the back right of the test setup as depicted in Figure 3.2), with wind speeds fluctuating between being negligible and 2 m/s, based on the local wind readings. Approximately 11 minutes after the paraffin source was ignited, the flames had grown high enough to just reach the cardboard lining, at this point the cardboard on the front wall caught fire and flashover ensued approximately 12 seconds later. Flashover in this paper refers to the transition phase between the growth stage and the fully developed fire stage. The fire in the compartment attained a fully developed state seconds after flashover was reached. The flames could be seen emerging out of the door and the window. Flames from the door and window of 3-4 meters high, from ground level, were recorded. Figure 3.5 and 3.6 depict the experimental ceiling and back wall temperatures, respectively. The thermocouple (TC) heights shown in Figure 3.6 are from ground level. Note that the height distributions of instruments placed (a) in front of the door, (b) in front of the window or (c) at ceiling level, are presented in Figure 3.2. Due to the intensity of the fire and because of structural collapse, a number of the thermocouples and Thin Skin Calorimeters (TSCs) got damaged during the experiments. Thus, if a measurement at certain instrument position is not portrayed, it can be assumed that the instrument was damaged at that particular position.

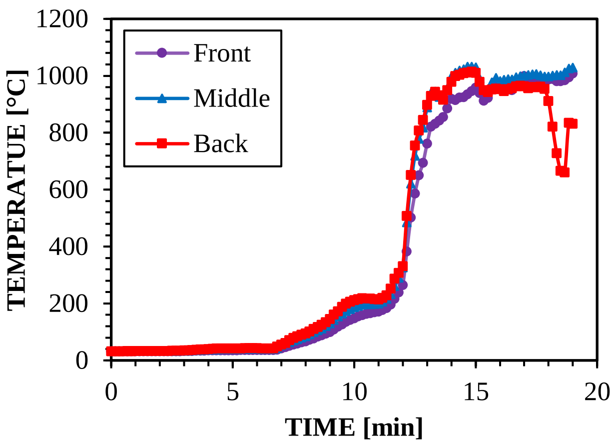

Figure 3.5: Experimental ceiling temperatures

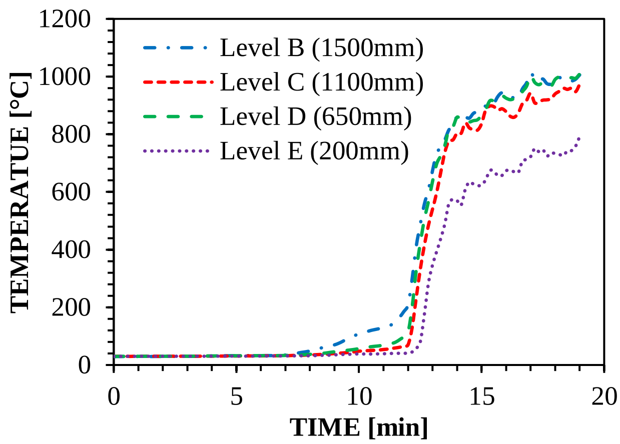

Figure 3.6: Experimental back wall temperatures

It is important to note that structural collapse occurred at approximately 19 minutes and that no data is considered after collapse for the rest of the discussion that follows. The temperatures across the ceiling were relatively uniform with an average steady state temperature of 1000°C and a maximum temperature of 1032°C, as depicted in Figure 3.5. It is also clear that this dwelling was ventilation controlled once the fully developed stage was reached as indicated by the plateau in Figure 3.5. After flashover the temperatures over the height of the compartment were relatively uniform, as depicted in Figure 3.6, with the only cooler part being at the bottom of the timber cribs. Figures 3.7-3.9 depict the heat flux curves at the door, at 1 meter away from the door and at the window, respectively.

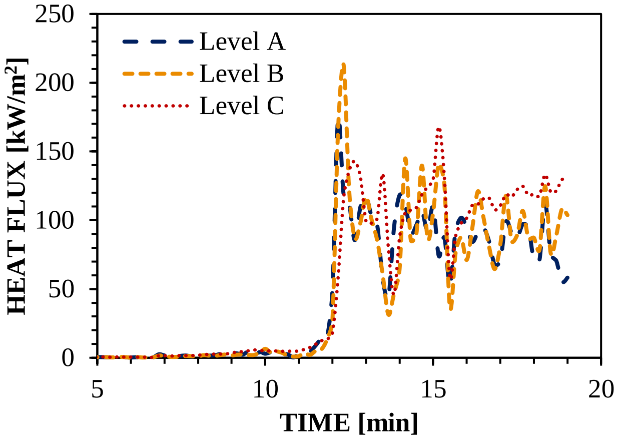

Figure 3.7: Heat flux curves at the door

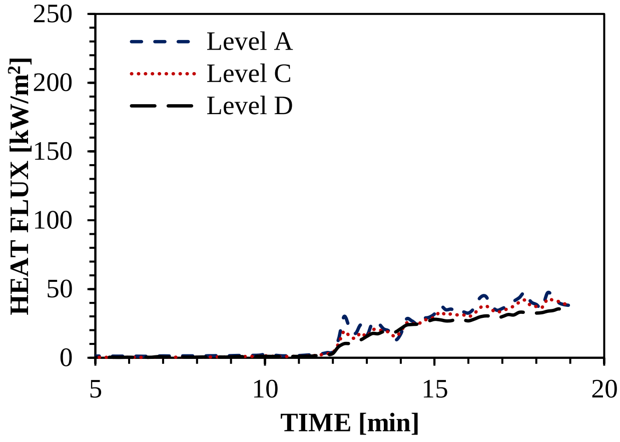

Figure 3.8: Heat flux curve at 1 meter away from the door

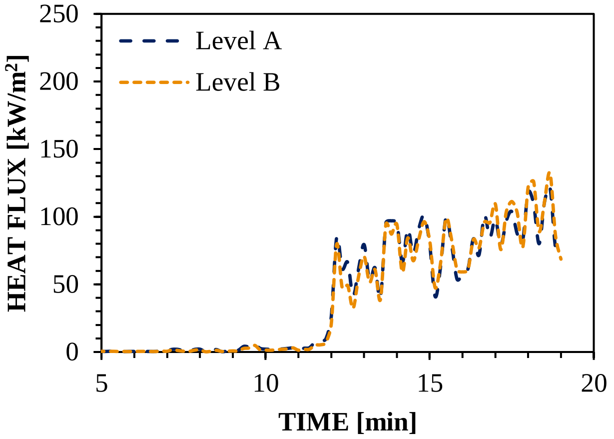

Figure. 3.9: Heat flux curves at the window

The heat flux at the door reached a maximum of 213 kW/m^2, which is beyond the calibration limits and should be interpreted accordingly. This peak corresponds with the complete ignition of the cardboard lining. The average steady state heat flux at the door (Level A) was 88 kW/m^2, as depicted in Figure 3.7. The average steady state heat flux at the window (Level A) of 80kW/m^2 is relatively similar to the heat fluxes experienced at the door. However, the maximum of 132 kW/m^2 is less than the peak experienced at the door. The heat flux curves at the window show no peak that corresponds with the complete ignition of the cardboard. The average steady state heat flux at 1 meter away from the door (Level A) was 32 kW/m^2. The heat fluxes experienced in this experiment are extremely high when considering the Critical Heat Flux (CHF) of cardboard of 8-10 kW/m^2 [23,24] (i.e. a common lining material used in ISDs). The cardboard of an adjacent dwelling is typically exposed to these heat fluxes as a result of poor construction methods, or gaps as a result of the flutes [19]. This indicates that at 1 meter spacing between dwellings, rapid fire spread will occur, highlighting the risk of these closely spaced dwellings.

3.4.2. Timber clad ISD results

The second experiment was also conducted at the Breede Valley Fire Department in Worcester, South Africa, but on a different day. The ambient temperature was 28°C and a very light North Westerly breeze (i.e. from the front left to the back right of the test setup as depicted in Figure 3.2), with wind speeds fluctuating between being negligible and 2 m/s. Approximately 3.2 minutes after the paraffin source was ignited, the flames had grown enough to just reach the cardboard lining, at this point the cardboard on the front wall caught fire and flashover ensued approximately 5 seconds later. The fire in the compartment attained a fully developed state seconds after flashover was reached. The flames could be seen emerging out of the door and the window. Flames from the door and window of 3-4 meters high were recorded. Figure 3.10 and 3.11 depict the experimental ceiling and back wall temperatures, respectively. The thermocouple (TC) heights shown in Figure 3.11 are from ground level.

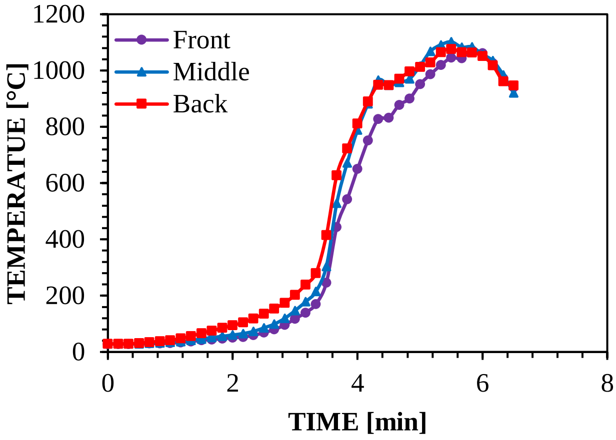

Figure 3.10: Experimental ceiling temperatures

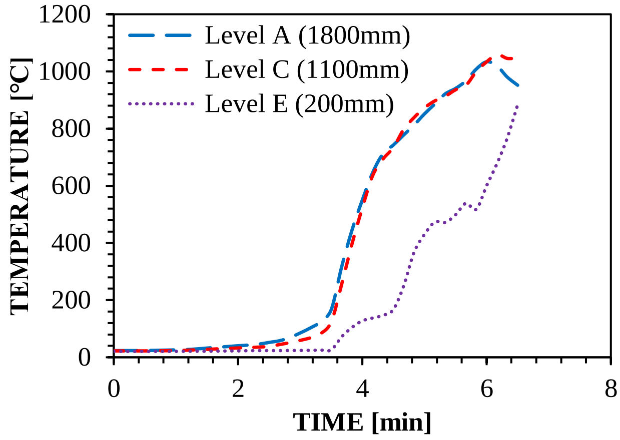

Figure 3.11: Experimental back wall temperatures

It is important to note that structural collapse occurred at approximately 6.4 minutes and that no data is considered after collapse for the rest of the discussion that follows. The temperatures across the ceiling were relatively uniform with a maximum temperature of 1102°C, as depicted in Figure 3.10. This dwelling temperature never reached a steady state as a result of the burning of timber cladding. After flashover was reached the timber cladding ignited and contributed significantly to the total heat release rate. The peak temperature corresponds with the complete ignition of the top timber cladding, as depicted in the top left images in Figure 3.12. During the fully developed stage the controlling factor quickly changed from ventilation controlled to fuel control as the timber cladding started to burn away at approximately 4.6 minutes. This is clearly demonstrated by a sudden drop in heat flux as depicted in Figure 3.13 to 3.16 and is visually depicted in Figure 3.12. The experimental ceiling temperature was, however, not affected by the large openings arising as a result of the cladding burning away. This might be as a result of the heat from the burning cribs directly underneath the thermocouple, as shown in Figure 3.12 (note that the images are approximately 10s apart).

Figure 3.12: Ventilation openings forming in the timber clad dwelling experiment as a result of the cladding burning away, showing images at approximately 10 second intervals

Figures 3.13-3.16 depict the heat flux curves at door, at 1 meter away from the door, at the window and at 1 meter away from the window, respectively.

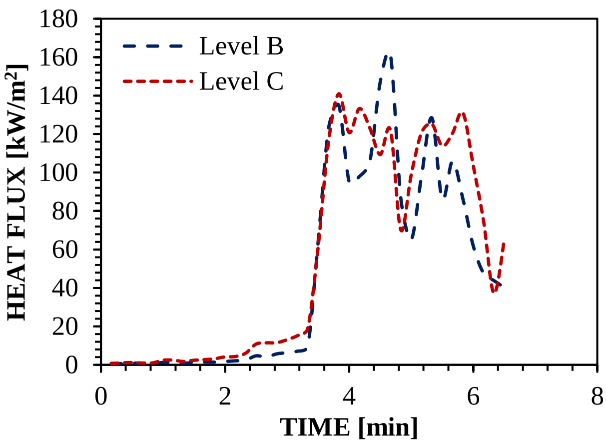

Figure 3.13: Heat flux curves at the door

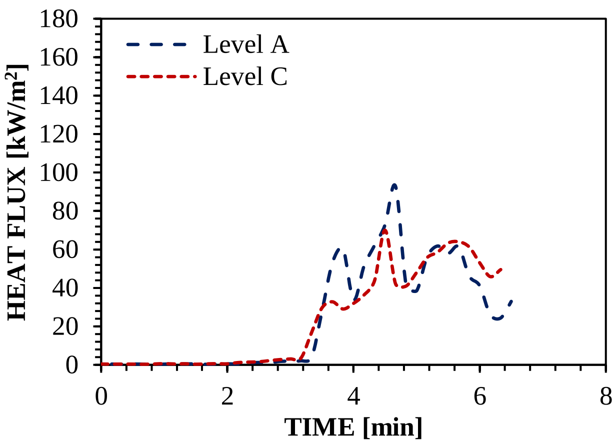

*Figure 3.14**:** Heat flux curves at 1 meter away from the door*

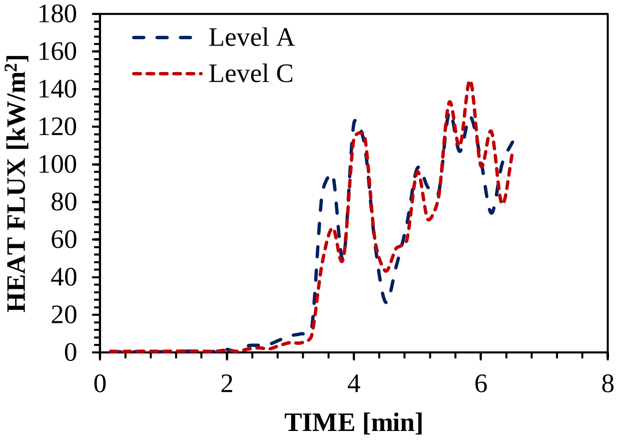

Figure 3.15: Heat flux curves at the window

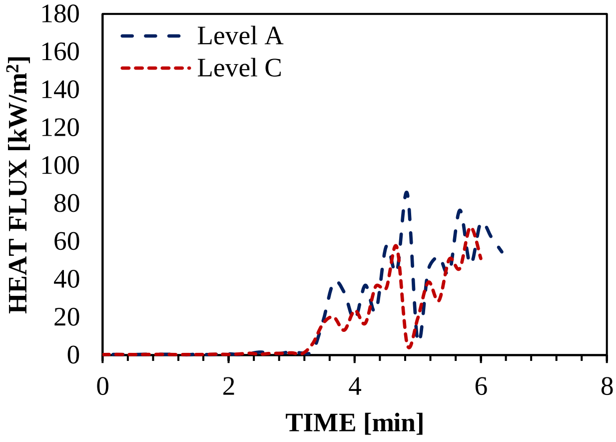

Figure 3.16: Heat flux curves at 1 meter away from the window

The heat flux at the door reached a maximum of 106 kW/m^2. Because this dwelling did not reach a steady state, the average heat flux values during the fully developed fire stage were considered. The average fully developed heat flux at the door (Level B) was 93 kW/m^2, as depicted in Figure 3.13. The average fully developed stage heat flux at the window (Level A) of 88 kW/m^2 is relatively similar to the heat fluxes experienced at the door. The average fully developed stage heat flux at 1 meter away from the door (Level A) and window (Level A) was 43 kW/m^2 and 50 kW/m^2, respectively.

3.4.3. Steel clad experiment versus timber clad experiment

Table 3.1 provides a summary of important parameters pertaining to both experiments such as maximum ceiling temperatures, collapse times and heat fluxes, with details being discussed in the section that follows. Data readings after structural collapse were not considered. Note that the terminology steel clad dwelling and corrugated steel clad dwelling refer to the same experiment.

Table 3.1: A comparison between the corrugated steel clad experiment and the timber clad experiment

	STEEL CLAD EXPERIMENT	**TIMBER CLAD EXPERIMENT**
Maximum ceiling temperature	1032°C	1102°C
Time from the start of flashover to collapse	7 minutes	3.2 minutes
Heat flux (HF) at the door	95 kW/m^2 (Level B)	93 kW/m^2 (Level B)
HF 1 meter away from the door	32 kW/m^2	43 kW/m^2
HF at the window	80 kW/m^2	88 kW/m^2
HF 1 meter away from the window	n/a	50 kW/m^2

*All heat flux values are the average heat flux value during the fully developed stage obtained at Level A of the specified position unless specified otherwise.

As mentioned earlier, the timber clad dwelling had more crib timber pieces partially dipped in paraffin that contributed significantly towards the early fire growth of the timber dwelling. This is clear when comparing the time to flashover of 7 minutes for the corrugated steel clad dwelling to the 3.2 minutes of the timber clad dwelling. Because the timber pieces used for cladding were so thin, it burned away very quickly after it ignited. This left the timber dwelling without lateral support and as a result of eccentricities inherent in the structure the timber dwelling experienced a sway collapse. In general, the heat fluxes experienced during the timber clad experiment were higher than the steel clad experiment, as listed in Table 3.1, indicating that fire spread to an adjacent dwelling is more likely to occur for the timber dwellings. This is similar to the findings in [19]. The timber dwelling did, however, experience a quicker time to collapse (similar to the findings in [25]), indicating that the heat flux experienced by an adjacent dwelling will be over a shorter period. Additionally, as a result of continuously changing ventilation conditions, the timber clad dwelling had substantial fluctuations in heat flux values, whereas the steel clad dwelling reached a steady state seconds after flashover. Regardless of the factors mentioned above, the average heat flux values for timber dwelling are still enough to ignite adjacent dwellings and are more prone to fire spread than steel dwellings, even if the burning period is only 3 minutes [19].

3.5. Fire dynamic simulator model set-up

Two FDS models (i.e. a timber clad dwelling model and steel clad dwelling model) were created and the details pertaining to each model are discussed in more detail below.

3.5.1. Geometry, computational domain and cell size

The geometry of the dwellings was constructed according to Figure 3.2 for both models (the only difference being the cladding material). Both models had a domain size of 5×5×3 m (i.e. width × breadth × height) with a corresponding cell size of 50mm^3, giving a total of 600000 cells. In this case, the timber pieces used in the cribs had a cross sectional area of 60×40 mm, which governed the cell size. In order to simplify the cell size ratios, it was decided to model the timber pieces as 50×50 mm, thus simplifying the cell size to 50×50×50 mm, rather than 60×40×40 mm. Alternatively, a cell size of 20 mm^3 could have been used, however that would have increased the computational time dramatically making it computationally difficult to simulate the informal settlement dwelling fires. In order to account for the change in volume of the timber pieces, the density of the timber used for the cribs in the simulations was adjusted to 515 kg/m^3. The same problem occurred for the cardboard. The actual thickness of the cardboard was 1.5 mm, but the cell size of 50 mm would not allow such a thin obstruction. The cardboard was thus modeled as 50 mm thick (i.e. to be at least one cell size thick which allows the obstruction to have full functionality [26]) and the density modified to account for the change in volume of the obstruction. Figure 3.17 depicts the setup as a Smokeview image [27]. The walls surface properties (i.e. the HVAC system and the slots between timber layers) are explained in the section that follows. Note that wind was not accounted for in the models and that the domain boundaries were modeled as open.

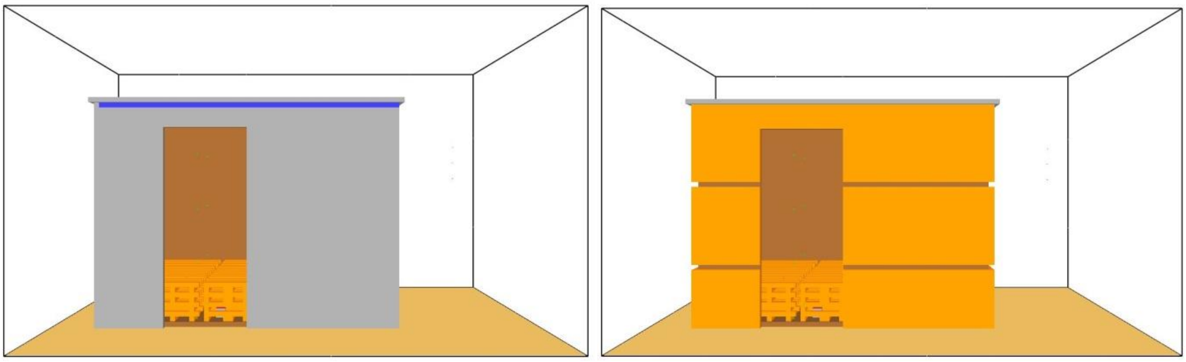

Figure 3.17: Geometry of the steel clad dwelling (left) and the timber clad dwelling (right) used in the numerical simulation (Smokeview)

Unfortunately, as a result of limitations on both the University of Edinburgh and Stellenbosch University's High Performance Computers (HPCs), a cell sensitivity study could not be done. Decreasing the cell size to 25 mm^3, increased the number of cells to 4.8 million. After running the simulation for one month the simulation did still not reach the flashover stage. A model with such a refined mesh is economically unpractical and will make it difficult to use the developed model for parametric studies. Since, the cell size is governed by the thickness of the timber pieces, a bigger cell size could also not be considered for the cell sensitivity study. The cell size used in the models developed in this work is significantly smaller than 0.1D* (i.e. a theoretical value for the maximum cell size for plume fires according to [28]). Where D* can be calculated as follows:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty T_\infty c_p \sqrt{g}}\right)^{2/5} \tag{3.1}$$

where D^* is the characteristic length scale of the fire plume, $\dot{Q}$ is the heat release rate [kW], ρ_∞, T_∞ and C_p are the ambient air density [kg/m^3], specific heat of air [kJ/(kg·K)] and ambient temperature [K], respectively and g is the gravitational acceleration [m/s^2]. For $\dot{Q}$ = 10250 kW (i.e. for the nine cribs in this case, calculated according to Babrauskas's HRR for cribs method [29]), a characteristic fire diameter of D* = 2.4 m is obtained, meaning a minimum cell size of 0.1D* = 0.24 m is required according to [28]. In this work, a cell size of 0.05 m was used, which is significantly smaller than 0.1D*. The 0.1D* method is widely used in the fire community and has shown good results in past studies [30–34]. The method also showed good results for timber crib models [35,36]. Additionally, the authors conducted a cell sensitivity study in [20], where the model consisted of multiple ISDs with the same (i.e. compared to the current models) cladding materials and cardboard lining and it was found that a cell size of 0.1 m (a cell size of 0.05 m was used in this work) was sufficient to capture the ceiling temperatures, heat fluxes emitted from the dwelling and the cardboard behaviour. Thus, with all of the factors mentioned above, it can be assumed with reasonable certainty that the cell size used in this work is sufficient enough to capture the fire behaviour with reasonable accuracy.

3.5.2. Material and surface properties

Table 3.2 gives the properties of the materials used in the FDS models. The material properties of the steel, cardboard and wood were taken from [37,38], [24,39] and [40,41], respectively.

Table 3.2: Material properties used in the FDS models

Properties	Steel	Corrugated cardboard	Wood
Density [kg/m^3]	7850	180 (actual) – 5.4 (used in FDS)	536 (actual), 515 (used in FDS)
Specific Heat [kJ/(kg·K)]	0.6	2.7	1.3
Conductivity [W/(m·K)]	45	0.42	0.14
Emissivity	0.42 [38] (i.e. for new galvanised steel)	0.9	0.9
Ignition Temperature [°C]	n/a	293	350

For both the steel clad dwelling and timber clad dwelling model, the timber crib pieces and cardboard both had a prescribed surface thickness of 25mm applied to all faces, with a void backing condition. To model the timber pieces that were dipped in paraffin an ignition temperature of 30°C was prescribed to start the burning of those pieces immediately. It should be noted that the time to flashover is relatively sensitive to the quantity of timber pieces modelled as dipped in paraffin. Because this was difficult to quantify, the number of timber pieces modelled as dipped were increased to enable the model to reach flashover earlier in order to reduce the computational time of the simulation, thus allowing for multiple scenarios to be studied within a reasonable time (note that a simulation still took 2-3 weeks on the HPCs). The results were offset in order for the flashover phases to match.

For the steel sheeting clad dwelling model, the flutes created additional openings (i.e. at wall and roof connections) which are smaller than the cell size but are typical of ISDs. The leakage was modelled in FDS by using HVAC systems, using its 'leak' functionality. The leak area and flow loss were specified as 0.0255 m^2 and 0, respectively for the steel clad model [a]. The steel sheets were modeled as flat sheets with a surface thickness of 0.025 mm applied to all faces and a backing condition of exposed.

For the timber clad dwelling model, the walls were modeled as 50 mm thick to be at least one cell size thick with the density modified to account for the change in volume of the obstruction. A surface thickness of 25 mm was applied to all surfaces with a backing condition of air gap. A horizontal 50 mm gap was specified over the width of all walls at 800 mm and 1500 mm from ground level of the walls, as depicted in Figure 3.17. This was to account for the small gaps between each 100 mm cladding timber plank, as seen in the top left image in Figure 3.12. The positions of the gaps (i.e. the gaps at 800 mm and 1500 mm) were arbitrarily decided on. The positions of these gaps will affect the ceiling temperatures but will not have a substantial effect on the heat fluxes experienced in front of the door and window [b].

[a,b] *More information is provided in Appendix C*

3.5.3. Prescribed heat release rate obtained through FPA test

The Heat Release Rate per Unit Area (HRRPUA) curves for these models were obtained by means of a Fire Propagation Apparatus (FPA) test and are depicted in Figure 3.18. The FPA is an apparatus that can be used to quantify the convective, chemical and overall heat release rate, mass loss rate and the effective heat of combustion of a material. For a detailed description of the FPA the reader is refer to [42]. Since the heat flux emitted onto the timber cribs and cardboard are expected to be 50 kW/m^2 or higher, the heat flux used during the FPA test was 50 kW/m^2. According to previous studies (e.g. [35]), the HRRPUA output from FPA or cone calorimeter tests are similar for higher heat flux values (e.g. 50 kW/m^2 as used in this work). The exact values (i.e. from Figure 3.18) were used as an input in FDS to prescribe the HRRPUA of the two fuel materials.

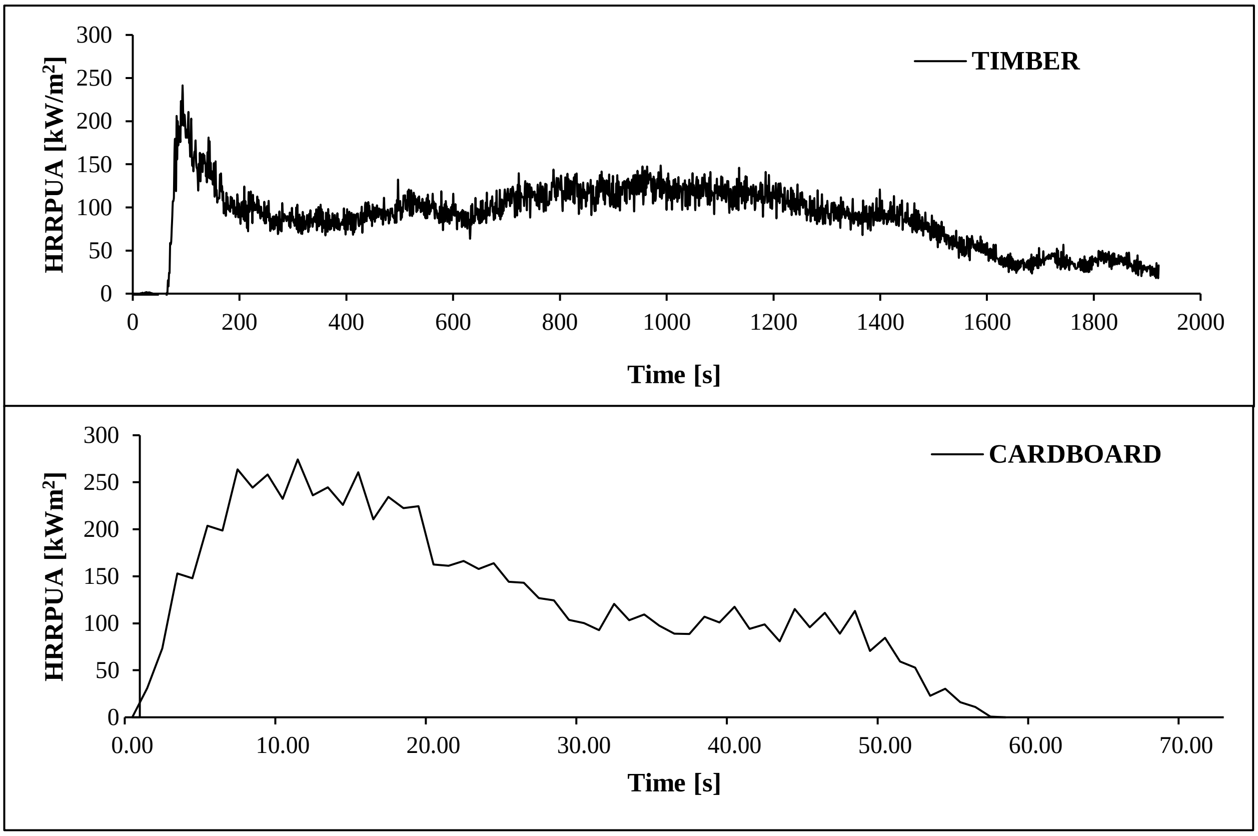

Figure 3.18: Heat release rate per unit area curve for timber (top graph) and cardboard (bottom graph)

The value of the heat release rate (HRR) of the timber cribs according to the SFPE timber crib calculations by Babrauskas [29] are prescribed by the following very well-known HRR formula:

$$\dot{Q} = \dot{m}\Delta H_{eff} \tag{3.2}$$

where $\dot{m}$ is the mass loss rate measured in kg/s and ΔH_{eff} is the effective heat of combustion measured in kJ/kg. The mass loss rate, $\dot{m}$, is taken as the lesser of the surface-controlled mass loss rate

$$\dot{m} = \frac{4}{D} m_0 v_p \left(1 - \frac{2v_p t}{D}\right) \tag{3.3}$$

and porosity-controlled mass loss rate

$$\dot{m} = 4.4 \times 10^{-4} \left(\frac{S}{h_c}\right)\left(\frac{m_0}{D}\right) \tag{3.4}$$

For the cribs used in this experiments, the stick thickness was D = 0.04 m, the clear spacing was S = 0.175 m, the crib height was h_c = 0.48 m, the number of sticks per row was n = 5, the initial crib mass was m_0 = 41.67 kg, $v_p = 2.2\times10^{-6}D^{-0.6}$ according to [29] and the heat of combustion was ΔH_{eff} = 18 MJ/kg (assuming a combustion efficiency of 1, the effective heat of combustion equals the gross heat of combustion). This gave an experimental surface-controlled mass loss rate with a limiting HRR of 1138.37 kW.

In the modelling, to simplify the cell size ratio and reduce the computational time the stick thickness was changed to D = 0.05 m as discussed above, the clear spacing to S = 0.1625 m and the crib height to h_c = 0.4 m. Using Equations 3.2-3.4 the modelling HRR would be 769.57 kW. Thus, by using a cross sectional area of 50×50 mm rather than 60×40 mm leads to a 32% decrease in the HRR of the cribs according to Babrauskas' formulas. To account for this within the model, the heat of combustion on the material line (i.e. in FDS) was increased by 32%, giving a heat of combustion of 23.8 MJ/kg, to obtain the same HRR one would expect for the experimental timber cribs. The reaction line for both models looked as follows: &REAC ID='WOOD', FUEL='REAC_FUEL', C=3.4, H=6.2, O=2.5, SOOT_H_FRACTION=0.0, SOOT_YIELD=0.03, HEAT_OF_COMBUSTION=1.8E4/. The simple chemical composition and soot yield values used on the reaction line (in FDS) were obtained from [43,44].

3.6. Two-zone model set-up

It would be advantageous for the development of interventions for ISD fire safety if simple two zone models could be used to quickly obtain estimates of fire behaviour, rather than a CFD model being utilized each time. This also would allow parametric and statistical analyses to be carried out more easily. Hence, OZone v3 [45] was also used to model both the steel clad and timber clad ISD experiments. OZone is a one and two zonal fire modelling software designed by the University of Liège in Belgium. During the duration of a fire, the temperature development of gases inside the enclosure are evaluated by zone models. The compartment under consideration is divided into zones and the main hypothesis made is that the temperature distribution is uniform in each zone at any time. The temperature, species concentration and size of each zone are calculated with a dynamic process as the fire progresses, together with the smoke movement through openings in the compartment boundaries, by applying the moment, mass and energy conservation laws to each zone. Since, zone models cannot calculate fire spread it requires certain inputs such as the fire growth rate. For OZone outputs typically include the zone height and gas temperatures. For more information regarding the formulations of OZone, the reader is referred to [45]. In general, the OZone default values were used. The user is able to choose between four air entrainment models in OZone and the following should be considered:

- *McCaffrey* [46]*:* This air entrained model considers the all the regions (i.e. plume region, flame region and the intermittent region).

- *Heskestad* [47]*:* This air entrained model considers only the plume region and the flame region and does not consider the intermittent region as in [46]. This is the default air entrained model in OZone and is implicitly used in the manual calculation method.
- *Thomas* [48]*:* This air entrained model is best suited for use in the vicinity of a flame region.
- *Zukoski* [49]*:* This air entrained model is theoretically only suitable for the plume region and the use of this model is questionable for zone models with low ceilings (e.g. for ISDs).

Since there is insufficient space for a complete plume to develop above the fire region and because the fire region will extend across the entire enclosure the air entrained models which consider the flame and intermittent regions (i.e. [46]) will describe the air entrainment best. It was decided to use the McCaffrey model [46] in this work.

For the steel dwelling model, a HRRPUA of 1138.37 kW/m^2, a fire growth rate of 233.8 seconds and a fire load density of 750.23 MJ/m^2 (i.e. the timber cribs fire load density) plus 17.5 MJ/m^2 (i.e. cardboard lining fire load density) were specified. The heat release rate of 10245.31 kW was calculated according to the SPFE HRR wood crib calculations by Babrauskas [29], where the stick thickness is 0.04 m, the clear spacing is 0.175 m, the crib height is 0.48 m, number of sticks per row is 15, initial crib weight is 375.03 kg and the heat of combustion is 18 MJ/kg. To convert the HRR to a HRRPUA the floor area of 9 m^2 was used to obtain the 1138.37 kW/m^2 value as seen above. It should be noted that OZone does not have the capability to simulate fire spread and thus it is necessary to include a growth rate in the model, although for it, and other methods, analytical methods could be used to provide predicted heat fluxes. The fire growth rate was obtained through a t-squared fire calculation and by setting the fire intensity coefficient equal to 'ultrafast' (i.e. 1.874×10^{-5}). Although wood cribs on their own are better prescribed by a 'fast' fire intensity coefficient (e.g. [50]), 'ultrafast' was used to account for the cardboard lining. The walls were defined as one layer set to Steel [EN1994-1-2] with a thickness of 0.047 mm. The roof and floor were set to Steel [EN1994-1-2] with a thickness of 0.047 mm and concrete with a thickness of 200 mm, respectively. Due to construction tolerances and steel sheeting profiles wall-wall and wall-roof connections were modeled with an 8.5 mm gap. Both the window and door were modeled as open.

For the timber dwelling model, a HRRPUA of 1138.37 kW/m^2, a fire growth rate of 233.8 seconds and a fire load density of 750.23 MJ/m^2 (i.e. the timber cribs fire load density) plus 17.5 MJ/m^2 (i.e. cardboard lining fire load density) plus 546.6 MJ/m^2 (i.e. timber cladding fire load density) were specified. The roof and floor had the same input parameters as for the corrugated steel clad dwelling model. The walls were set to timber with a 12 mm thickness, 536 kg/m^3 density, 0.14 W/(m·K) conductivity, 1300 J/(kg·K) specific heat and an emissivity of 0.9 (see Table 3.3). Due to the construction configuration the wall-wall and wall-roof connections were modeled with an 8.5 mm gap. OZone is limited to 3 openings per wall and thus a small gap between each timber plank (i.e. the timber cladding) is not able to be modeled and to account for this the wall-roof connection gap was increased from 8.5mm to 100 mm (i.e. to account for all the small gaps between the timber cladding, similarly to what was done in the FDS model). Both the window and door were modeled as open.

3.7. Numerical modelling results and comparison

This section is divided into two subsections; (a) the corrugated steel sheeting clad model results and comparison and (b) the timber clad model results and comparison.

3.7.1. Corrugated steel sheeting clad results and comparison

Table 3.3 provides a summary of important parameters pertaining to the experiment, the FDS model and the two-zone model such as maximum ceiling temperatures, collapse times and heat fluxes (HF), with details being discussed in the sections that follow. Data readings after structural collapse were not considered.

Table 3.3: Summary of selected data from (a) experimental results, (b) FDS model results and (c) Two-zone model results.

	EXPERIMENT	FDS MODEL	TWO-ZONE MODEL
Maximum ceiling temperature	1032°C	985°C	1085°C
Time from the start of flashover to collapse	7 minutes	n/a	n/a
Heat flux (HF) at the door	88 kW/m^2	105 kW/m^2	n/a
HF 1 meter away from the door	32 kW/m^2	34 kW/m^2	n/a
HF at the window	80 kW/m^2	84 kW/m^2	n/a

*All heat flux values are the average steady state heat flux value obtained at Level A of the specified position. Note that where steady state was not reached, the average heat flux during the fully developed stage was used.

The ceiling time-temperature curve of the FDS model, two zone model and the experimental results are depicted in Figure 3.19. The ceiling temperatures for the experimental results were measured in the middle of the dwelling and are referred to as the experimental TC results in Figure 3.19.

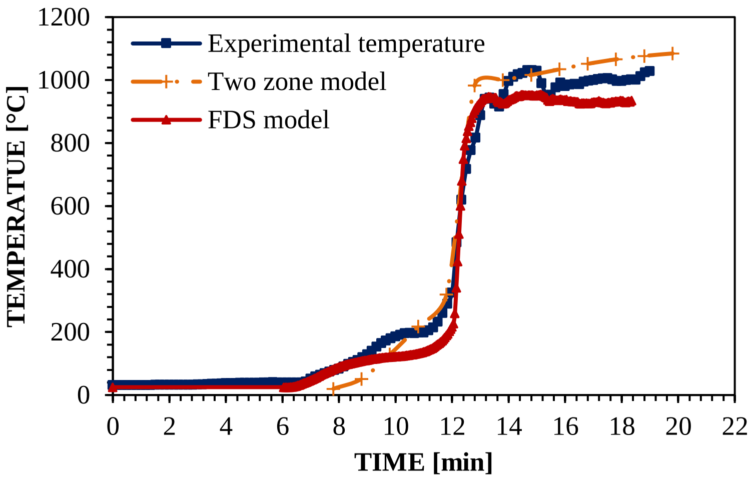

Figure 3.19: Ceiling temperatures for the corrugated steel clad ISD

The initial growth phase of a fire cannot be modeled in OZone (one of the limitations of two-zone modelling), so the two-zone model results were offset by 7.8 minutes for the flashover stages of the model and experiment to align. The two-zone model compares well to the experiment (considering the simple nature of the model), with the plateau following the correct trend and the temperatures reached have a maximum deviation of approximately 8% during the fully developed fire stage. The FDS model captures the behaviour of the cardboard lining quite well. From the temperature slice files, it is clear that flashover occurred as a result of radiation from the flames of the burning cardboard, as depicted in Figure 3.20, similar to what was observed during the experiments. This is clear when considering the hot layer build up before the cardboard ignites, and then considering the hot layer during the burning of cardboard. The radiation from the hot layer did still contribute towards the ignition of the cribs, but in a less substantial way in comparison to the radiation from the cardboard, similar to the findings in [19]. The ceiling temperatures predicted by the FDS model are slightly underpredicted, but the general trend compares well to the experiment i.e. when considering the growth stage, flashover, and the trend of the plateaus. The FDS model has a slightly steeper slope during the flashover stage; this is as a result of the approximate cardboard properties used in FDS (e.g. using a slightly higher ignition temperature will result in slower fire spread across the surface of the cardboard, and as a result it causes flashover to happen less rapidly, the conduction, specific heat and density of the cardboard can also affect this behaviour). Comparing the surface spread rate of the cardboard in the model to the experimental surface spread rate, it is clear that the fire spreads faster in the model. From the experimental results it is clear that this dwelling was ventilation controlled and it is also portrayed by the two-zone and FDS models.

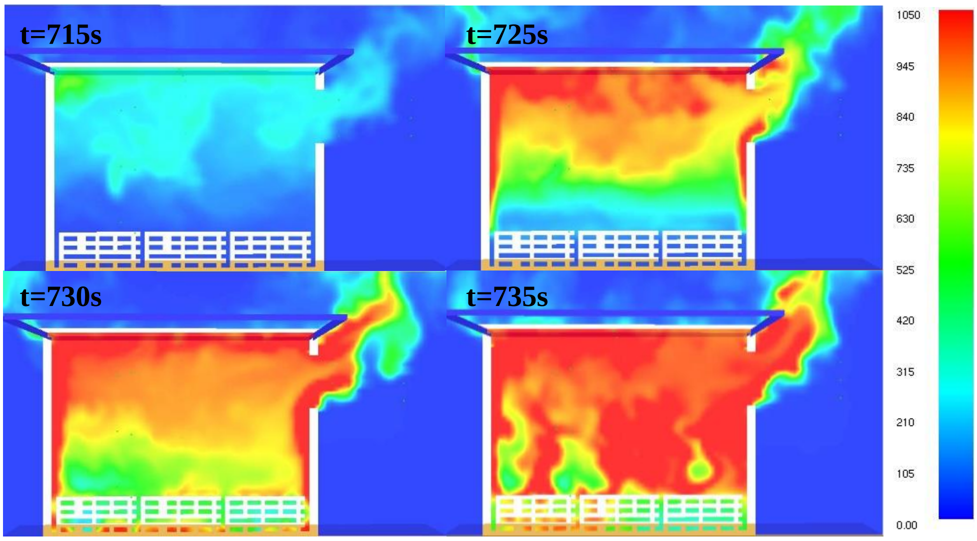

Figure 3.20: Temperature slice file from FDS at the window for the steel clad dwelling, showing the heat emitted from the cardboard lining.

The heat flux curves at the door and at 1 m away from the door of the FDS model and the experimental results are depicted in Figure 3.21 and 3.22, respectively. OZone models do not have the capability to predict heat flux values and are thus not discussed further in this section. This is another limitation of two-zone models. Heat fluxes are an extremely important parameter when studying fire spread and the intensity of the fire.

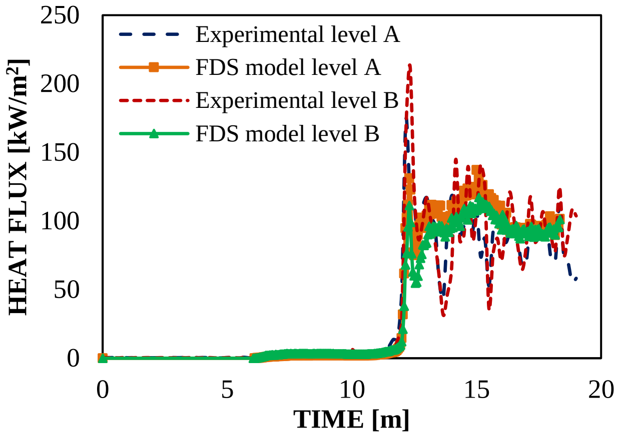

Figure 3.21: Heat fluxes at the door

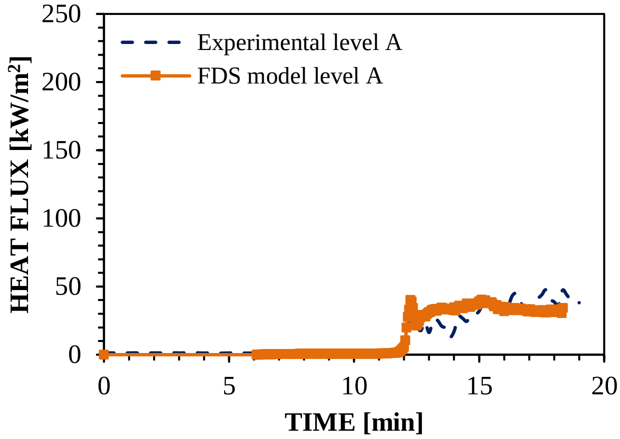

Figure 3.22: Heat fluxes at 1 meter away from the door

The heat fluxes at the door of the FDS model compare relatively well to the experimental values, as depicted in Figure 3.21. Considering the heat flux curve at Level A and B of the FDS model and of the experiment, it is clear that the overall trend is captured by FDS. Although the peak heat flux values at approximately 12 minutes (i.e. where the cardboard was completely engulfed with flames) are lower for the FDS model, the model does capture the behaviour of the peak corresponding to this complete ignition of the cardboard lining well. Although the model underpredicted the peak corresponding to the burning of the cardboard at the door, the model overpredicted this same peak at 1 meter away from the door (Figure 3.22) and also at the window (Figure 3.23). The average steady state heat flux of the FDS model at the door is 105 kW/m^2 which is 19% higher that the experimental average steady state heat flux of 88 kW/m^2. The average heat flux during the steady state stage, at 1 meter away from the door, for the model is 34 kW/m^2 which compares very well to the experimental average heat flux during the fully developed fire stage of 32 kW/m^2. Although there are some deviations between the two curves, the overall trend is capture relatively well by the model. The slight deviations might be as a result of (a) the light breeze/wind not being included in the simulation, (b) the assumptions made to model the cardboard lining (i.e. allowing the cardboard to be one cell size thick, and a result reducing the density as explained above), or (c) assumptions made to simplify the timber cribs.

The heat flux curve at the window for the FDS model and the experimental results are depicted in Figure 3.23.

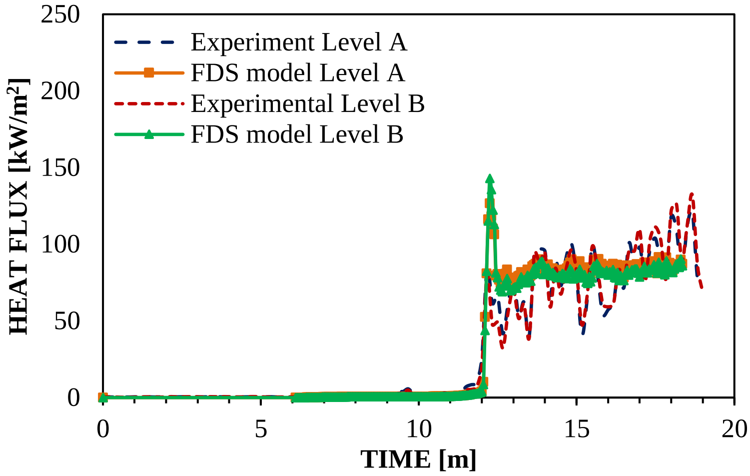

Figure 3.23: Heat fluxes at the window

The average steady state heat flux at the widow of the FDS model is 84 kW/m^2 and compares well to the experimental value of 80 kW/m^2, as depicted in Figure 3.23. Considering the heat flux curve at Level A and B of the FDS model and of the experiment, it is clear that the overall trend is captured well by FDS. The experimental results do not show a peak value at approximately 12 minutes, whereas the FDS model does.

3.7.2. Timber clad model results and comparison

Table 3.4 provides a summary of important parameters pertaining to the experiment, the FDS model and the two-zone model such as maximum ceiling temperatures, collapse times and heat fluxes, with details being discussed in the sections that follow. Data readings after structural collapse were not considered.

Table 3.4: Summary of data from (a) experimental results, (b) FDS model results and (c) Two-zone model results.

	EXPERIMENT	**FDS MODEL**	**TWO-ZONE MODEL**
Maximum ceiling temperature	1102°C	1161°C	1189°C
Time from the start of flashover to collapse	3.2 minutes	n/a	n/a
Heat flux (HF) at the door	93 kW/m^2 (Level B)	111 kW/m^2 (Level B)	n/a
HF 1 meter away from the door	43 kW/m^2	51 kW/m^2	n/a
HF at the window	88 kW/m^2	108 kW/m^2	n/a
HF 1 meter away from the window	50 kW/m^2	49 kW/m^2	n/a

*All heat flux values are the average heat flux value during the fully developed stage obtained at Level A of the specified position unless specified otherwise.

It is difficult to define a steady state heat flux for the timber experiment because the ventilation conditions changed continuously. Thus, it was decided to use the average heat flux during the fully developed stage in order to compare the model results to the experiment results.

The ceiling time-temperature curve of the FDS model, two zone model and the experimental results are depicted in Figure 3.24.

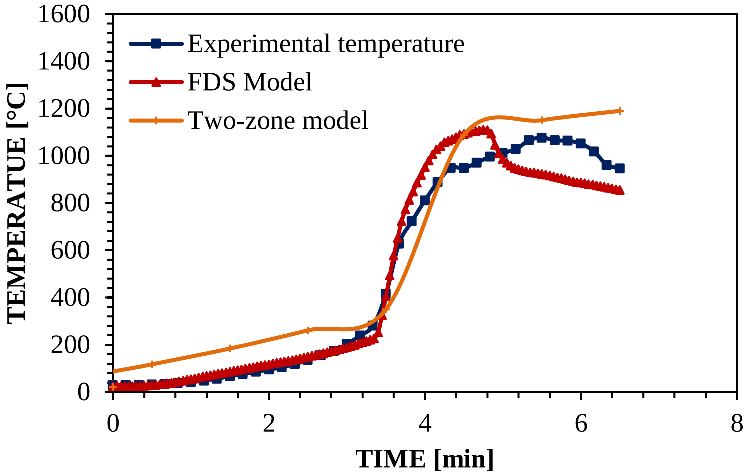

Figure 3.24: Ceiling temperatures for the timber clad ISD experiment

The two-zone model slightly overpredicted the ceiling temperature, as compared to the experimental temperatures. The predicted temperatures have a maximum deviation of 25%. This overprediction is likely a result of how the leakages were modelled in OZone. As mentioned earlier, OZone is limited to 3 openings per wall, thus multiple small openings between timber cladding pieces could not be modelled accurately. The FDS model captures the behaviour of the cardboard lining quite well (similar to the steel clad dwelling). Flashover starts at approximately the same ceiling temperature (i.e. both ceiling temperature approximately at 280°C). The FDS model initially overpredicts the initial ceiling temperature, reaching approximately the same temperatures as the two-zone model. This is likely as a result of the steeper curve during flashover. As mentioned earlier, this is because FDS slightly overpredicts the spread rate across the surface of the cardboard. At 4.9 minutes the bottom 2/3^{rds} of all the walls were set to instantaneously disappear, in the FDS model, to account for the cladding burning away in the experiment. This could have also been done with a ramp function, or by selecting specific sections to disappear at specific times. However, with all the unknowns such as: which wall started to burn away first, what was the rate at which the walls burned away and where in the wall the gaps first appear, it was arbitrarily decided (i.e. for simplicity and practicality) to allow the same sections of all the walls to disappear at the same time. Because of this sudden change in ventilation, the FDS ceiling temperatures experienced a sudden dip, rather than a gradual decrease as observe in the experimental results. However, this sudden dip allows the model to capture the heat flux behaviour better and was thus decided to keep to this method of modelling the cladding. The modelling of this complex phenomena will remain a challenge in future work.

The heat flux curves at the door and at 1 m away from the door of the FDS model and the experimental results are depicted in Figure 3.25 and 3.26, respectively.

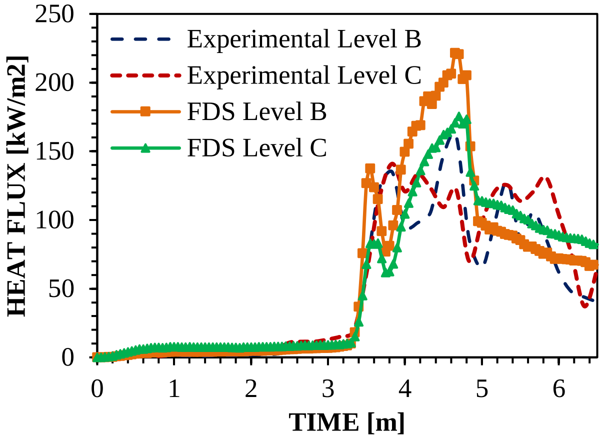

Figure 3.25: Heat fluxes at the door

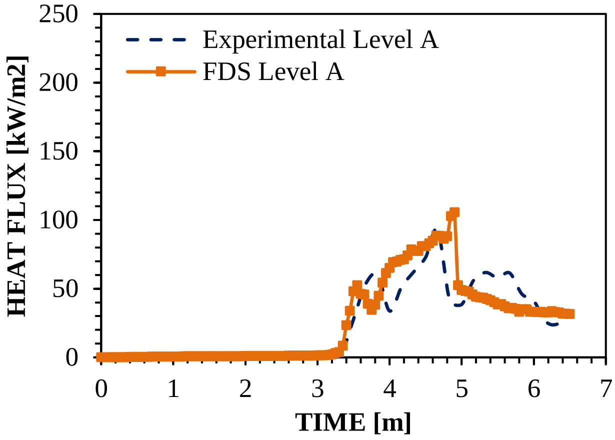

Figure 3.26: Heat fluxes at 1 meter away from the door

The heat fluxes at the door of the FDS model compare relatively well to the experimental values, as depicted in Figure 3.25. Considering the heat flux curve at Level B and C (Level A was damaged) of the FDS model and of the experiment, it is clear that the overall trend is captured by FDS. The model also captured the peak corresponding to the complete ignition of the cardboard, but overpredicts the peak corresponding with the complete ignition of the timber cladding (i.e. at approximately 4.8 minutes). The average heat flux during the fully developed stage (i.e. from the end of flashover to collapse) of the model (Level B) is 111 kW/m^2 which is higher than the average heat flux during the fully developed stage of 93 kW/m^2 for the experiment (Level B). It should be noted that the assumptions made to model the timber cladding will have an influence on the results. As depicted in Figure 3.26, the curve predicted by FDS captures the experimental curve well with an average heat flux during the fully developed fire stage of 51 kW/m^2 compared to 43 kW/m^2. The overall trend at 1 m away from the door is well captured by the FDS model. In both cases (i.e. at the door and at 1 meter away from the door) the model tends to overpredict the heat flux values (especially at the door). As discussed earlier the sudden drop in heat flux at approximately 4.9 minutes corresponds with the burnout of the timber cladding.

The heat flux curve at the window and at 1m away from the window for the FDS model and the experimental results are depicted in Figure 3.27 and 3.28, respectively.

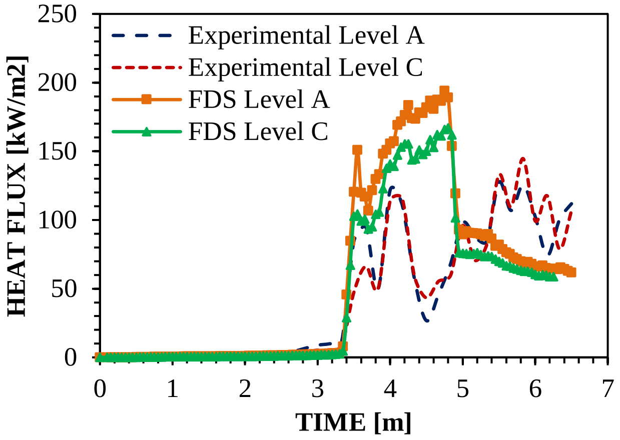

Figure 3.27: Heat fluxes at the window

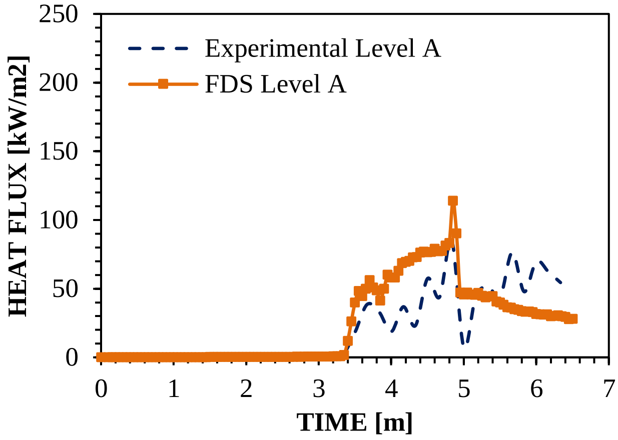

Figure 3.28: Heat fluxes at 1m away from the window

Considering Figure 3.27 closely, it seems that the FDS model is overpredicting the heat fluxes experienced. In the experiment, the timber cladding at the window started to burn away a lot earlier that the prescribed time in FDS. This is because the sudden drop in heat flux in the experimental results, corresponding with the burnout of the cladding, occurred at approximately 4.3 minutes, rather than at 4.9 minutes as modelled in FDS. Additionally, the FDS model overpredicts the peak in heat flux that corresponds with the full ignition of the cardboard. This is mainly due to the following reasons: (a) the assumed combustion efficiency of 1 may be too high (i.e. the heat of combustion of the cardboard could be slightly less), and (b) the way FDS modelled the flame spread across the surface of the cardboard was possibly more rapid than the experiment, meaning more cardboard burned at a particular place in time. This is most likely as a result of the assumed thermal inertia from the literature. Note that a higher thermal inertia will result in a slower surface spread rate. The average heat flux during the fully developed fire stage at the widow of the FDS model is 108 kW/m^2, which is higher than the experimental average heat flux of 88 kW/m^2. Although significant work is required to refine modelling techniques for timber clad informal dwellings, this work does provide a significant step in the right direction in terms of capturing the general behaviour. Challenges with ventilation conditions varying continuously will not easily be overcome by any modelling software due to the complex input parameters required.

The average heat flux during the fully developed fire stage at 1m away from the window of the FDS model is 49 kW/m^2, which compares well to experimental average heat flux of 50 kW/m^2. However, if the heat flux values after 4.9 minutes (i.e. after the timber cladding burned away) are not considered, refer to Figure 3.28, the average heat flux of the FDS model would be higher than the experimental value. Although there are some deviations between the two curves, the FDS model does capture the overall trend relatively well.

3.8. Critical separation distance based on the numerical models

Since the FDS modelling techniques employed suitably replicate the experimental results for the steel clad ISD, the model's predictive capabilities can be used estimate a preliminary critical separation distance between ISDs. In order to do this, it is important to quantify the model uncertainty to produce a probability density function (as depicted in Figure 3.29) in order to calculate the probability that the model value (i.e. the predicted heat flux) will be exceeded. In other words, it is important to define how accurate the prediction is for a given set of input parameters, and what an anticipated error may be.

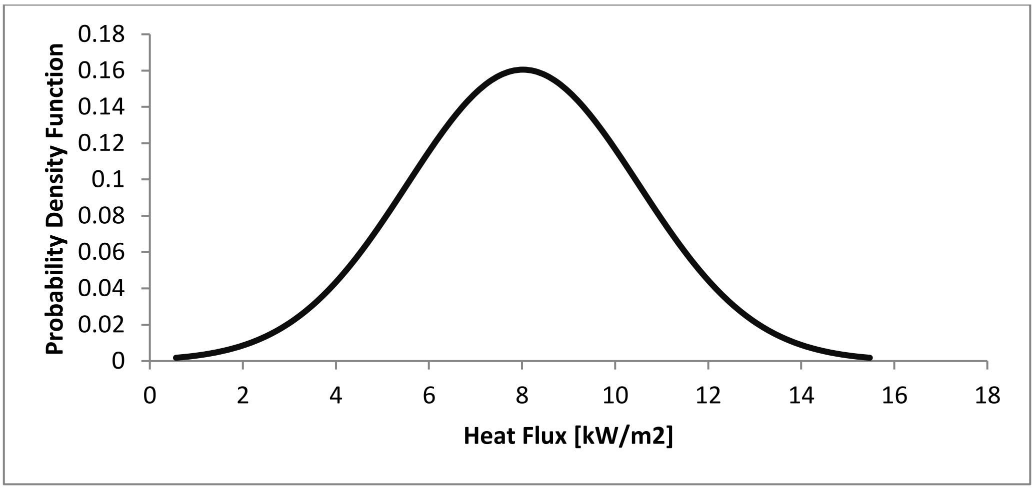

Figure 3.29: Example of a probability density graph (i.e. a Gaussian Distribution also commonly called a bell curve)

To estimate the mean and standard deviation of the distribution the first step is to define $\ln\overline{(M/E)}$ (for a more in depth derivation of the equations that follow, the reader is referred to [51]):

$$\ln\overline{(M/E)} = \frac{1}{n}\sum_{i=0}^{n} \ln\,(M_i/E_i) \tag{3.5}$$

where E_i is a given experimental measurement and it is assumed that E_i is normally distributed about the "true" value and that there is no systematic bias. According to [28] this distribution can be assumed because when experimental uncertainties are reported it is typically expressed as a standard deviation or a confidence interval about the measured value. Thus, there is no systematic bias in a measured value because it can be quantified and adjusted accordingly. M_i is a given model prediction and it is assumed that M_i is normally distributed about the true values multiplied by a bias factor, δ, (the bias factor is a way to express by what percentage the model is over or under predicting on average, for example, a bias factor of 1.13 means the model is over predicting by 13% on average) and n is the sample size. Peacock et al. [52] discussed various possible metrics with a common metric simply comparing the predicted steady state values. In this work, by comparing the steady state heat fluxes (i.e. comparing the experimental heat fluxes to the modelled heat fluxes) at all the TSC positions, $\overline{\ln\,(M/E)} = 0.45$ is obtained. Table 3.5 lists the steady state heat fluxes and TSC positions for both the steel clad dwelling experiment and FDS model along with the procedure used in Equation 3.5.

Table 3.5: Equation 3.5 procedure

TSC Position	Experiment result	Model result	In(M/E)
Door (Level A)	89	105	0.17
Door (Level B)	96	98	0.03
Door (Level C)	114	79	-0.37
1 meter from the door (Level A)	33	34	0.04
1 meter from the door (Level B)	30	25	-0.19
1 meter from the door (Level C)	26	15	-0.58
Window (Level A)	80	84	0.05
Window (Level B)	80	81	0.01
			$\overline{\ln{(M/E)}} = 0.45$

An alternative way of explaining this is by plotting the predicted heat fluxes against the measured heat fluxes, as depicted in Figure 3.30. All the horizontal bar and part of the vertical bar represents the total experimental uncertainty [28]. If the experimental uncertainty can be quantified, then the model uncertainty can be obtained as a result.

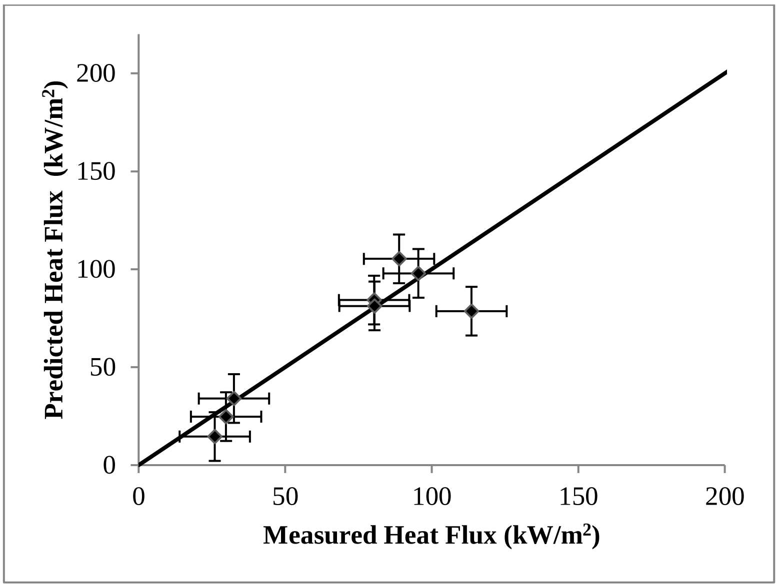

Figure 3.30: Scatter plot of model predictions and experimental measurements for the steel clad dwelling

The least squares estimate of the standard deviation of the combined distribution is defined as:

$$\tilde{\sigma}_M^2 + \tilde{\sigma}_E^2 \approx \frac{1}{n-1} \sum_{i=0}^{n} \left[\ln{(M_i/E_i)} - \ln\overline{(M/E)}\right]^2 \tag{3.6}$$

where $\tilde{\sigma}_E$ is the experimental uncertainty, which is known (for heat flux measurements $\tilde{\sigma}_E$ = 0.11 [28]), $\tilde{\sigma}_M$ is the model uncertainty. Equation 3.6 forces a constrained on $\tilde{\sigma}_E$ that the model uncertainty cannot be less than the experimental uncertainty [28] because it is impossible to demonstrate that the model has less uncertainties that the experiment, thus leading to the following expression:

$$\tilde{\sigma}_E^2 < \frac{1}{2} var(\ln{(M/E)}) \tag{3.7}$$

By substituting the known values into Equation 3.6, $\tilde{\sigma}_M = 0.23$ is obtained. An estimate of δ can be found using the mean of the distribution:

$$\delta \approx \exp\left(\ln\left(M/E\right) + \frac{\tilde{\sigma}_M^2}{2} - \frac{\tilde{\sigma}_E^2}{2}\right) \qquad (3.8)$$

By substituting the known variables into Equation 3.8 a bias factor of 0.92 is obtained, indicating that this model tends to underpredict the heat flux values by 8%. From this a mean and a standard deviation can be calculated and from it a bell curve can be drawn:

$$\mu = \frac{M}{\delta} = \frac{5.5}{0.92} = 6 \;\; ; \;\; \sigma = \tilde{\sigma}_M \frac{M}{\delta} = 0.23\frac{5.5}{0.92} = 1.37 \qquad (3.9)$$

where M = 5.5 kW/m^2 in this case is the average heat flux, during the steady state phase (starting at approximately 13 minutes) at 3 meters away from the door, predicted by the FDS model. The bell curve is depicted in Figure 3.31.

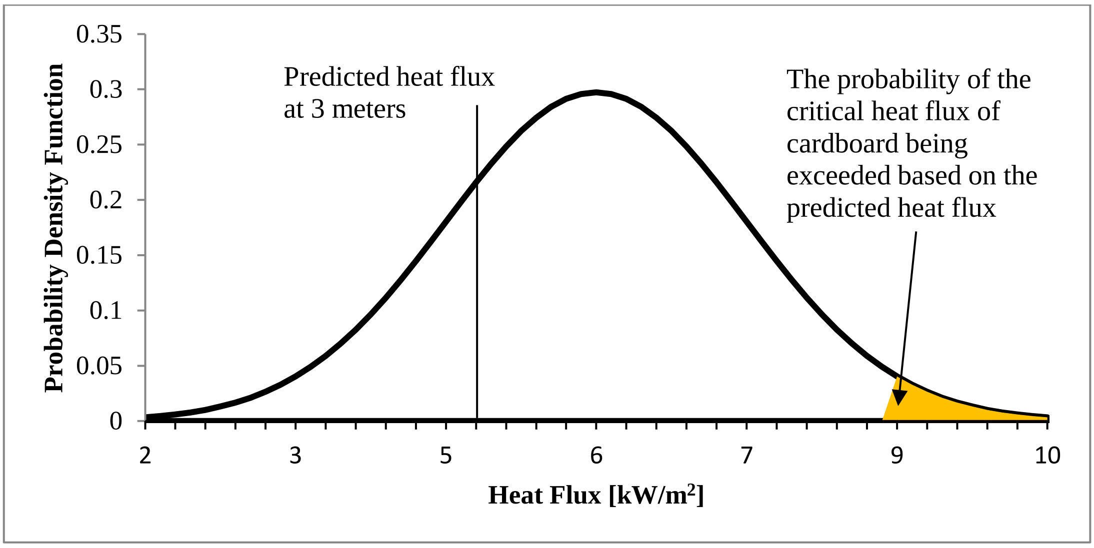

*Figure 3.31: Probability of fire spread occurring at 3 meters spacing, between door opening and the adjacent dwelling. *The critical heat flux where fire spread could occur is assumed to be the critical heat flux of cardboard (i.e. one of the most common lining materials in informal settlements).*

The shaded area beneath the bell curve is the probability that the "true" heat flux can exceed the critical heat flux, and can be expressed via the complimentary error function:

$$P(HF > HF_c) = \frac{1}{2} erfc\left(\frac{HF_c - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2} erfc\left(\frac{8.5 - 5.9}{1.3\sqrt{2}}\right) = 0.033 \qquad (3.10)$$

This indicates that there is a 3.3 % chance that fire spread can occur if the adjacent dwelling is 3 meters away, based on these FDS model predictions. Note that a very conservative CHF value for cardboard (8.5 kW/m^2) was used, if the CHF is changed to 10 kW/m^2 the probability of the predicted heat flux exceeding 10 kW/m^2 is 0.16%. Additionally, if the CHF is exceeded the heat flux must be sustained for a specific amount of time for the cardboard to eventually ignite. Note that the cardboard of an adjacent dwelling is typically exposed to these heat fluxes as a result of poor construction methods, or gaps as a result of the flutes [19]. This finding is similar to [53] but is slightly less conservative than [19] that found that a safe separation distance should be 3.8 m. In [19] the calculations to estimate the safe separation distance was made by using the maximum heat flux values, rather than the steady state values, in Beer's Law. The findings would be very similar should one use the average steady state heat flux values in the equations used by [19].

Since FDS demonstrated its ability to match the experimental results for the timber clad ISD, the model's predictive capabilities can be used estimate a preliminary critical separation distance between timber ISDs. Following the same logic as for the steel clad section, Equation 3.5 gives $\overline{\ln{(M/E)}} = 0.11$. The scatter plot of model predictions and experimental measurements for the timber clad dwelling are depicted in Figure 3.33.

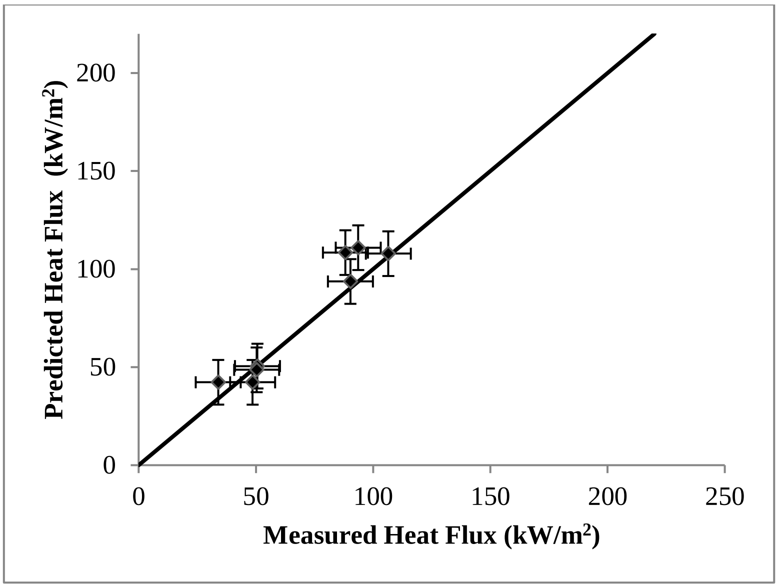

Figure 3.32: *Scatter plot of model predictions and experimental measurements for the timber clad dwelling*

Using $\ln\overline{(M/E)} = 0.11$ in Equation 3.6 and 3.8, gives a model standard deviation of 0.09 and a model bias factor of 1.06, indicating that the model tends to overpredict by 6% on average. Using Equation 3.9, $\mu = 7.45$, $\sigma = 0.68$, assuming a critical heat flux for fire spread to occur as 8.5 kW/m^2 and using a predicted heat flux of M = 7.9 kW/m^2 (i.e. as predicted by the FDS model at 3 meters from the door at Level A), the chance that the CHF of cardboard is exceeded at a distance of 3 meters is 6%, based on these FDS model predictions. This indicates that it is unlikely for fire spread to occur at 3 meters. It should be noted that if the wind conditions become unfavorable this finding will be different.

3.9. Conclusion

This paper has discussed the issues related to, or contributing to, fires in informal settlements and the lack of understanding pertaining to fire dynamics in ISDs and numerical modelling of ISDs. The paper focused on demonstrating numerical models against full scale experiments, and using the models developed to predict a critical separation distance between dwellings. The paper showed that there are challenges to demonstrate the compartment fire behaviour, with FDS, without experimental data (i.e. heat flux and temperatures from the experiments). It shows the complication surrounding compartment fires where leakages are present, and difficulties associated with sudden changes in ventilation conditions (e.g. timber cladding burning), and how these unique phenomena affect the estimation of heat fluxes to the surrounding environment. The predicted two-zone models gas temperatures showed good correlation to the experimental gas temperatures. However, the OZone models were limited and cannot predict heat fluxes, which is crucial when trying to understand fire spread behaviour in informal settlements. Additionally, OZone limits the number of openings per wall to 3, which is not ideal from dwellings with high wall porosity (i.e. like ISDs).

Two full-scale burn experiments have been conducted on ISDs looking at the difference between timber and steel clad dwellings. It was found that temperatures in an ISD can reach 1000-1150°C depending on the total fuel load (i.e. including the structure). The maximum heat fluxes experienced were relatively similar for the steel and timber dwelling, where the steel clad dwelling had an average heat flux at the window (Level A) and the door (Level B) of 80 kW/m^2 and 88 kW/m^2, respectively and the timber clad dwelling had an average heat flux at window (Level A) and door (Level A) of 88 kW/m^2 and 93 kW/m^2, respectively. It is clear that the heat fluxes experienced for both the timber and steel clad dwelling are extremely high and a result a minimum separation distance of 3 meters should be kept between these dwellings. However, this is not always possible because of socio-economic issues.

Based on the given input parameters used in the FDS models in this work, it was found that at a separation distance of 3 meters that there was a 3.3% and a 6% chance that the heat flux would exceed the critical heat flux of cardboard for the steel clad and timber clad dwelling, respectively. It should be noted that this is only applicable for the experiments done in this work and that factors such as wind and different fuel load will affect the critical separation distance.

As a result of the complex nature of ISDs, social particularities and inherently unregulated environments, significant challenges are confronted when developing interventions for informal settlements. Thus, the problems cannot be identified, isolated and solved in a similar manner than commercial buildings or formal dwellings. However, with more than one billion people residing in informal settlements it is a cause for serious concern, and there is a significant need to understand and improve fire safety in informal settlements.

3.10. Acknowledgements

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http://www.sun.ac.za/hpc and the University of Edinburgh's HPC Eddie https://www.ed.ac.uk/information-services/research-support/research-computing/ecdf/high-performance-computing.

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Chapter 4: Experimental study of fire spread between multiple full-scale informal settlement dwellings

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	Extent of contribution (%)
Planning, ordering, preparation and execution of experiments. Writing the manuscript, establishing methodology, data analysis, preparing figures and tables and conducted the interviews.	84%

The following co-authors have contributed to as follows:

Name and e-mails	Nature of contribution	Extent of contribution (%)
Richard Shaun Walls (rwalls@sun.ac.za)	Supervised the work, assisted with experiments and reviewed the manuscript	10%
Charles Kahanji (charles.kahanji@unza.zm)	Assisted with experiments and reviewed the manuscript	6%

Signature of candidate:

Date: 05/06/2019

The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4,
2. no other authors contributed to Chapter 4 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	
	Stellenbosch University	

This chapter is an exact copy of the journal paper referred to above.

4.1. Abstract

Internationally, informal settlements (also known as slums, favelas, shantytowns, ghettos, etc.) are expanding rapidly which have been associated with numerous large fires (where more than 10,000 people can be left homeless in a single disaster [1]), and an increase in fire related injuries and deaths. As a result of an increase in fire related incidences, various proposed interventions have been funded from governmental or private sources. However, many interventions have been unsuccessful because of technical, political, economic, social or practical issues. It is with the above mentioned in mind that this paper seeks to provide an understanding of fire behavior between multiple informal settlement dwellings (ISDs) as a baseline for future research and experiments. The paper starts by defining informal settlements in terms of construction and continues to look at the potential causes and hazards associated with informal settlement fires. The following two full-scale informal settlement dwelling burn experiments were conducted; (a) three ISDs clad with steel sheeting and (b) three ISDs clad with timber. The heat fluxes and temperatures of both experiments are shown and compared to understand the effect of cladding materials (i.e. timber cladding versus steel cladding, which are mostly used in informal settlements) on fire spread. Some general behavioral observations made during the full-scale experiments are given and discussed (i.e. how fire spreads, collapse mechanisms, etc.). Fire spread times are reported for both experiments, and range between 4 and 9 minutes (i.e. from the start of flashover in the first dwelling to the end of flashover in the last dwelling). These experiments are one of the bigger ISD experiments conducted to date and are the first experiments that measured heat fluxes for ISDs, which is crucial to understand fire spread. An important finding in this paper is that there is a critical separation distance of 3.8 meters needed to prevent fire spread between dwellings.

KEYWORDS: informal settlements, fire spread, fire dynamics, full-scale experiments.

4.2. Introduction

Approximately one billion people reside in informal settlements and the absolute number is expected to increase to 1.2 billion in Africa alone by 2050 [2]. An informal settlement is defined as an area that has not officially been proclaimed as residential and mainly consists of informal dwellings [3]. The typical characteristics of informal settlements such as inadequate structures, lack of basic services and scarcity of water, make these areas extremely vulnerable to fire. Figure 4.1 depicts a typical informal dwelling. As a result of poverty, the inhabitants of informal settlement dwellings (ISDs) are forced to build their dwellings with construction materials available in their immediate surroundings. As a result, these structures are usually poorly constructed and inherently have high wall porosity, as depicted in Figure 4.1. All of these factors add to the vulnerability these dwellings have to fire.

Figure 4.1: Typical informal settlement dwelling

Table 4.1 lists some of the fire incidents that occurred in South Africa during the course of 2017. It is hypothesized that the low number of deaths relative to the number of dwellings affected is due to the fact that people can easily evacuate dwellings once the communities have been made aware of a fire. Discussions with the Western Cape Fire Services indicate that it appears to be the ISD of fire origin where most fatalities occur [4]. Worldwide, there are currently over 300,000 fire-related deaths per year, with over 95% of all burn deaths occurring in low and middle-income countries [5]. Additionally, due to burn-related injuries over 10 million disability adjusted life years are lost each year [5].

Table 4.1: Examples of informal settlement fires in South Africa in 2017 [1,6–10]

Date	Settlement Name	Affected dwellings	Fatalities
14-Nov-17	Foreman Road informal settlement	1000 ISDs, 3000 displaced	2 deaths
27-Oct-17	Skietpoort informal settlement	80 ISDs	1 death
22-Oct-17	Primrose informal settlement	50 ISDs	No deaths
16-Apr-17	Imizamo Yethu	100 ISDs, 300 displaced	1 death
7-Apr-17	Nomzamo	18 displaced	5 deaths
12-Mar-17	Imizamo Yethu	2194 ISDs, ~10000 displaced	3 deaths

Figure 4.2 depicts the causes of most informal settlement fires based on (a) interviews conducted by the authors in 2018 with fire brigades in the Western Cape, South Africa. The interviewed firefighters fought more than 2000 informal settlement fires combined. (b) Feedback gathered in 2017 from informal settlement inhabitants, according to [11] and (c) the South Africa fire loss statistics gathered in 2014 [12]. Note that different metrics were used for each data set and that Figure 4.2 primarily highlights the uncertainty regarding the causes of fires in informal settlements. Additionally, for the South Africa fire loss statistics 32% of the fires had “undetermined” causes. According to firefighters interviewed, it is hypothesized that the inhabitants are often scared their dwelling might be set on fire if they were to confess that a fire started as a result of arson or due to negligence on their part. According to the firefighters the reasons for the discrepancies in the results are as a result of (a) lack of knowledge (i.e. speculation of ignition sources and are not based on any data) and (b) inhabitants potentially not disclosing the actual cause as a result of socio-political reasons as explained above.

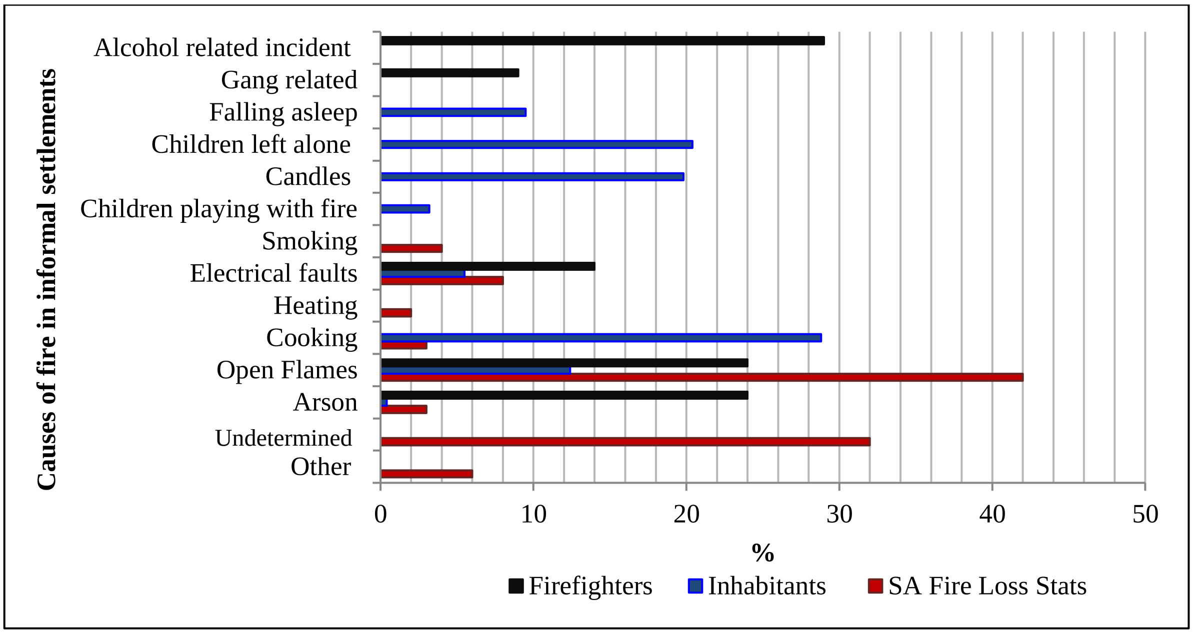

Figure 4.2: Causes of informal settlement fires according to (a) estimates from firefighters, (b) estimates from residents, and (c) South Africa Fire Loss Statistics

Although some solutions to fire spread in informal settlements have been proposed, they usually lack practicality or do not consider social particularities. For example, companies have proposed intervention measures such as: the use of sprinkler networks between informal dwellings, the use of intumescent paint, or even new and improved construction materials [13]. While the proposed ideas were theoretically possible, they were not successful in practice due to socio-economic or socio-political aspects [11] (e.g. theft, vandalism, communities rejecting the proposed solution, the cost implications, etc.). Currently, there is negligible technical basis (with regards to temperatures experienced, rate of spread, heat fluxes, fire behavior, etc.) for comparing and selecting interventions. In spite of various concerted efforts [4] along with some interventions being rolled out in the informal settlements, the fire related injuries and deaths have increased in third world countries. With fire related disasters increasing in informal settlements [12,14,15], it is a cause for serious concern to see how little work has been done in terms of understanding the mechanisms of fire spread in informal settlements. It is with this backdrop that this paper seeks to (a) develop an understanding for fire spread between dwellings based on full-scale experiments, (b) evaluate the impact of different cladding materials (i.e. timber versus steel sheeting) on fire spread between dwellings based on experiments and (c) provide a benchmark to study and compare new interventions against.

4.3. Fire dynamics in informal settlements

This section discusses the basic enclosure fire dynamic principles with regards to ISDs. It is assumed that the reader has a basic understanding of fire dynamics and for further information the reader is referred to various sources in the literature regarding the fire dynamics principles discussed [16–18]. For more specific information regarding the fire development stages as mainly discussed in this section, the reader is referred to [19]. Informal dwellings are typically lined with insulating materials that are highly flammable (e.g. cardboard lining), causing a high initial heat release rate when ignited. The lining material typically has a low critical heat flux value and thus ignites before a significant hot layer has formed. Once the lining material ignites, the flames spread across the entire surface of the lining material causing all the combustible materials to rapidly ignite (i.e. as a result of radiation from the flames of the burning lining material). The burning cardboard lining contributes substantially to the total incident heat flux onto the cribs in the dwellings, and also accelerates the rate of the hot layer growth. In previous unpublished trial experiments it was found that excluding the cardboard lining significantly decreased the rate of fire spread, as discussed above. The hot layer building up at the top of the enclosure and then radiating down towards the combustible materials, will still contribute to the total incident heat flux. In the experiment this behavior of cardboard ignition, surface flame spread, hot layer buildup and subsequent crib ignition was observed in spread between dwellings, as discussed below. The radiation from smoke and convection still contribute towards the dwelling reaching flashover, but in a less substantial way. Once flashover is reached in an ISD, ceiling temperatures ranges between 900°C - 1200°C, based on these experiments and past experiments [20]. A difference between the fire dynamics within ISDs and formal dwellings is that the change from the fully developed phase to the decay phase might be as a result of (a) walls dislodging or (b) walls (i.e. timber clad walls) burning away, changing the ventilation conditions rather than the fuel depleting. In some cases the decay period will never occur for ISDs, but rather structural collapse during the fully developed stage, as depicted in Figure 4.3. This is as a result of poorly constructed structures and the use of timber frames as the main structural support for the dwelling, as depicted in Figure 4.1. Figure 4.3 is a hypothesized fire development curve for informal settlement dwellings based on the experiments conducted in this work, to better describe the phenomena described above in order to easily understand the results presented below. The dashed gray line represents a typical fire development curve for enclosure fires [19], whereas the red and blue lines represent events that differ from traditional fire dynamics theory specifically due to the nature of the structures investigated in this work. Obviously with a change in structural parameters (such as support size, ventilation area, etc.) the hypothesized events will be adjusted, but they do illustrate important factors that influence behavior. It should be noted that ISD fires still follow the same phases as the traditional fire development curve (i.e. growing, flashover, fully developed and decay) and that the purpose of these graphs is to highlight some of the events that occur during the fire development phases that differ from formal enclosure fires.

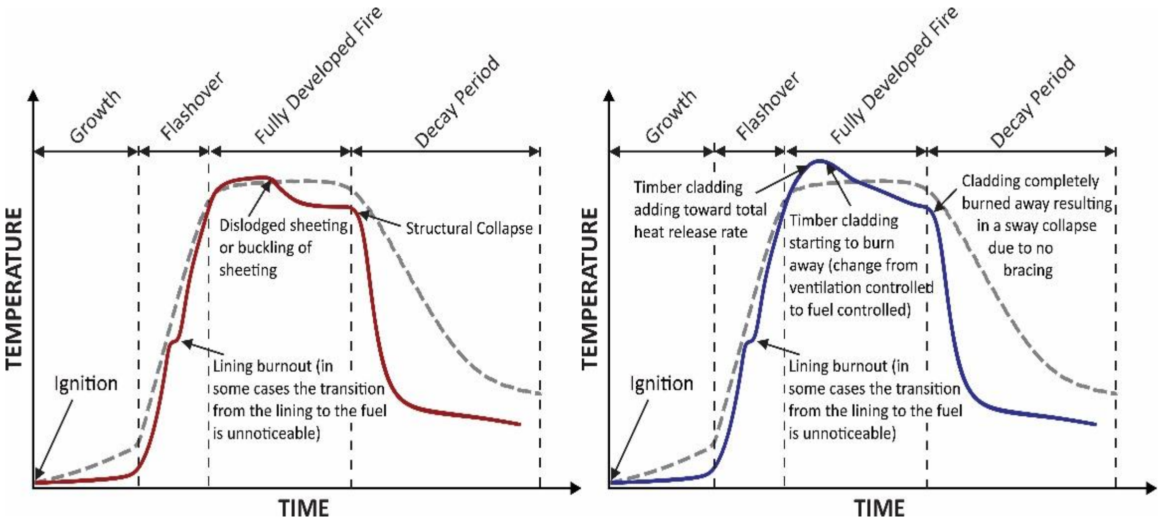

Figure 4.3: Fire development curve of (a) steel sheeting clad dwelling (left graph) and (b) timber clad dwelling (right graph) comparing traditional fire dynamics behavior (dashed grey lines e.g. [19]) to measured temperature showing specific perturbations (which will vary depending on various parameters)

4.4. Experimental setup

In this work a multi-timber clad and a multi-corrugated steel sheeting clad ISD experiment were conducted. Both experiments consisted of three dwellings spaced at 1m apart with the front walls aligned, as depicted in Figure 4.4.

Figure 4.4: Multi-corrugated steel clad dwelling setup (left hand side) and multi-timber clad dwelling setup (right hand side)

The dwellings are numerically numbered from left to right and this convention is adopted for the rest of the paper. Figure 4.5 depicts the details pertaining to the dimensions of the two experiments conducted. The only difference between the two experiments was the cladding material. Figure 4.5 also depicts the positions where the equipment was placed. The thermocouples used were Type K thermocouples and the Thin Skin Calorimeters (TSCs) used were constructed according to [21]. The TSCs have an accuracy of ±10% and a measuring range of approximately 0-200 kW/m^2 [21]. The TSCs were calibrated and validated against a water-cooled heat flux gauge.

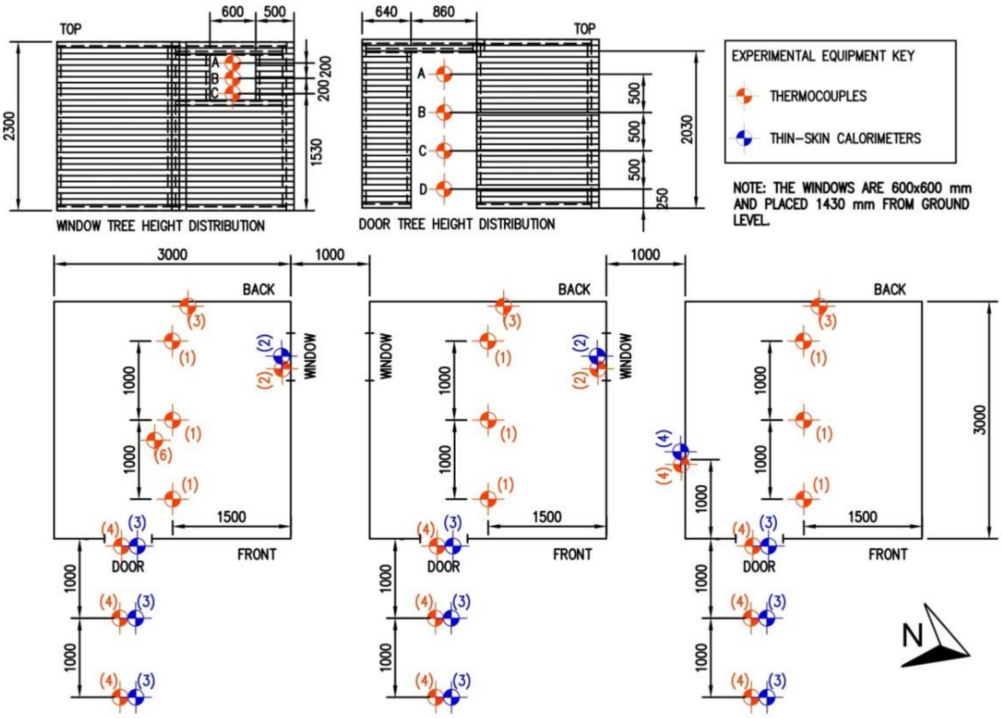

*Figure 4.5: Experimental setup and equipment placing. *The number in brackets indicates the number of instruments in that particular equipment tree. The height distributions of window trees and door trees are depicted by the top left layouts. All trees, not placed*

All the equipment was not present in each experiment, after the first experiment (i.e. the timber clad dwellings experiment) and the analysis of the data; the equipment layout was adjusted based upon the authors' observations and findings. It was decided that an equipment tree at 2 meters away from the door should be added for the steel clad dwellings. This was decided to ensure that more data could be collected at a distance, which is important when considering fire spread.

4.4.1. Experimental fuel load and material properties

It must be acknowledged that the construction materials, contents, ventilation conditions and household areal densities vary massively due to the inherent nature of informal settlements, making it difficult to define a "typical" dwelling. Where possible, available data has been drawn upon to create an experiment that is reproducible, relatively close to reality and through which fire spread mechanisms can be studied. The setup has been arranged such that there would be window-to-window fire spread between dwellings 1 and 2, and then window-to-wall fire spread between dwellings 2 and 3.

The fuel load densities in informal settlements vary substantially and range anything from 370 MJ/m^2 (or lower) to 3000 MJ/m^2, according to [13]. In order to standardize the experiments, a fuel load density of 780 MJ/m^2 was chosen according to EN1991-1-2, being the design fire load density (i.e. the average value) for a residential dwelling [22]. Further research is required to more accurately define the average and range for fuel loads in settlements. However, of equal importance is to understand the nature of the materials and how these materials contribute to fire growth rates, as this also influences spread rates. An equivalent wood load (i.e. pine wood) of 45 kg/m^2 was obtained by dividing the fire load density by the calorific value of wood, initially estimated at 17.5 MJ/kg, as specified in EN-1991-1-2. Additionally, all the walls were lined with cardboard insulation (180 kg/m^3 density and approximately 1.5 mm thick) on the inside to mimic reality. ISDs are typically lined with cardboard to provide thermal insulation for hot summers and cold winters. Based on discussions with researchers who had conducted other large-scale experiments, polystyrene was added to the cribs to enhance fire spread (as timber cribs burn relatively slowly compared to beds, clothes, upholstered furniture, etc. that are typically found in ISDs). However, during the experiments it was observed that the polystyrene had a negligible effect on the fire spread and only melted. Hence, it would not be recommended for future experiments. There were 36 timber pieces (40 x 60 x 900 mm) per crib with nine cribs per dwelling, as depicted in Figure 4.6.

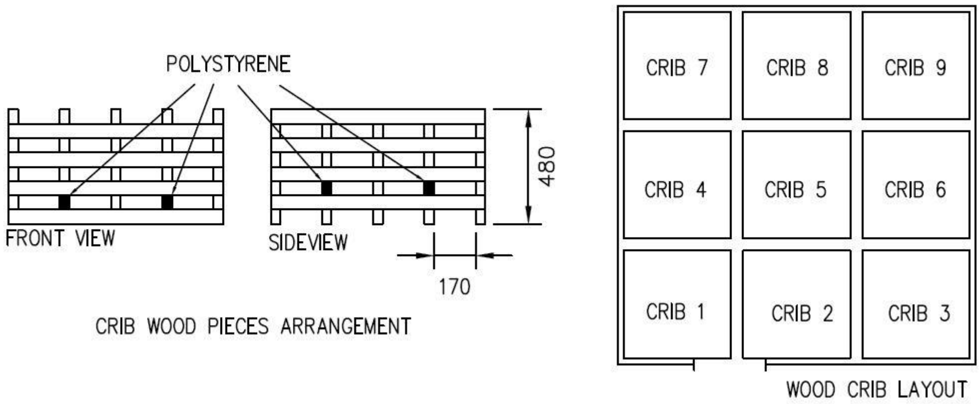

Figure 4.6: Wood crib layout

The timber used in both experiments had a density of 536 kg/m^3. Each crib had 2 polystyrene sticks (40 x 60 x 900 mm) placed at the second and third row of the crib, respectively. The timber clad dwellings were clad with 12 x 100 x 1500 mm timber pieces. The steel sheeting clad dwelling had steel sheeting with a thickness of 0.47 mm. The calorific values were tested and found to be 18.0 MJ/kg and 16.9 MJ/kg (obtained by means of 6 bomb calorimeter tests) for the wood and cardboard, respectively. Due to cladding, the fire load density of a timber dwelling, if the structure and cardboard lining are included, was approximately 1314.3MJ/m^2, whereas for the steel clad dwelling it was 767.7 MJ/m^2. It was assumed that the contents of a home would be independent of the construction material, hence a constant timber crib load was adopted.

4.5. Full-scale ISD fire experimental

In this section, the details and results of (a) the timber clad experiment and (b) the steel clad experiment, are described in more detail.

4.5.1. Multi-ISD timber clad experimental results

The experiment was conducted at the Breede Valley Fire Department in Worcester, South Africa. The ambient temperatures was 29°C and a very light North Westerly breeze (i.e. from the front left to the back right of the experimental setup), with wind speeds fluctuating between being negligible and 2 m/s were observed. Table 4.2 provides a summary of important parameters pertaining to this experiment such as fire spread mechanism, maximum ceiling temperatures, ventilation area, collapse times and maximum heat fluxes, with details being discussed in the sections that follow. It should be noted that some of the heat fluxes listed in Table 4.2 fall outside of the calibration limits (i.e. 200 kW/m^2) of the TSCs, at which point accuracy may be affected and results should be interpreted accordingly.

Table 4.2: Summary of experimental data obtained from the timber clad experiment

	ISD1	ISD2	ISD3
Fire spread mechanism	Dwelling of origin	Flame impingement on the cardboard and cladding	Flame impingement on the cladding
Maximum ceiling temperature	1104°C	1176°C	1184°C
Ventilation	Door and window	Door and two windows	Door
Time from start of ignition to collapse	13.3 minutes	14.3 minutes	15.3 minutes
Time from start of flashover to collapse	5.1 minutes	5.3 minutes	4.6 minutes
Heat flux (HF) at door	145 kW/m^2	260 kW/m^2	215 kW/m^2
HF 1 meter away from door	150 kW/m^2	273 kW/m^2	No data
HF at window	196 kW/m^2	164 kW/m^2	n/a

The first dwelling (i.e. ISD1) was set on fire by igniting a tin can (100 mm in diameter) filled with paraffin. The tin can was placed in the middle front crib (i.e. crib 2 as depicted if Figure 4.6) and lengths of 125 mm of two timber pieces placed above the can were dipped in paraffin to increase the initial growth phase. Approximately 8.2 minutes after the paraffin source was ignited, the flames had grown high enough to just reach the ceiling. At this point the cardboard on the front wall caught fire and flashover ensued approximately 25 seconds later. The fire in the compartment attained a fully developed state seconds after flashover was reached. The flames could be seen emerging out of the door and the window. Flame impingement occurred through the window of ISD2 that was adjacent to the widow of ISD1, which ignited the cardboard and timber cladding of ISD2 in the process. After flashover in the second dwelling there was flame impingement on the third dwelling causing the timber wall to ignite, as depicted in Figure 4.7. The total time it took for all the dwellings to reach their fully developed phase (i.e. from the start of flashover phase in ISD1 to the end of flashover in ISD3) was approximately four minutes. The intensity of the multi-ISD timber experiment was more significant than expected. Flames of up to 5-6 meters were recorded. It was also observed that branding occurred during this experiment. Branding here refers to small flaming pieces of fuel that were scattered into the air by wind [23]. The fire itself created a fire whirl at around 10-11 minutes, which occurred between ISD1 and ISD2, and this fire whirl initiated the branding. Figure 4.7 depicts the experimental setup and fire intensity of the multi-ISD timber experiment.

Figure 4.7: Multi-ISD timber experimental setup (left hand side) and the fire intensity during the experiment (right hand side)

Figure 4.8 depicts the ceiling temperatures of ISD 1, 2 and 3. The temperatures given for each dwelling are from all three ceiling thermocouples to show the uniformity of temperature throughout the enclosure at ceiling level. Maximum ceiling temperatures are summarized in Table 4.2. Refer to Figure 4.5 for the thermocouple positions.

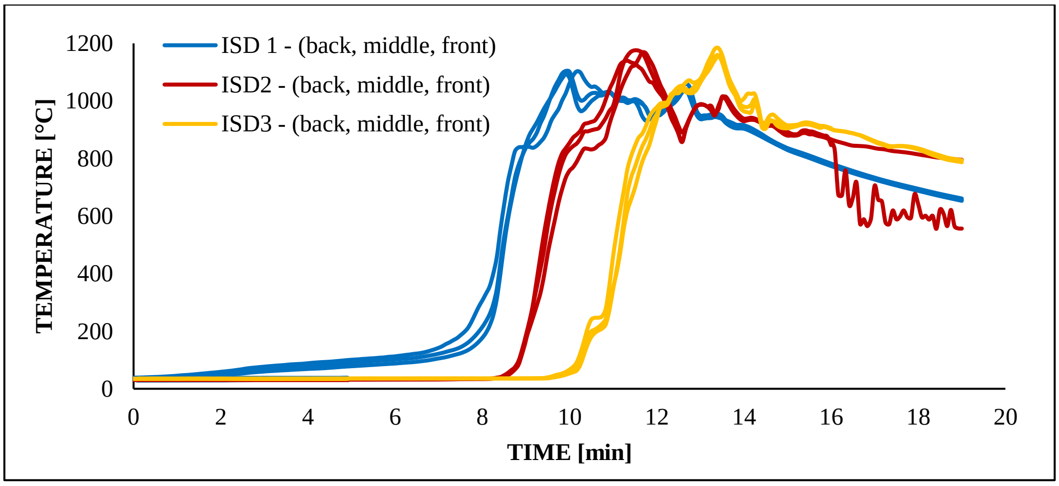

Figure 4.8: Timber dwellings ceiling temperatures

The timber cladding contributed to the total heat release rate of the dwellings (i.e. compared to the steel cladded dwellings), allowing the ceiling temperatures to surpass 1100°C. Once the time-temperature curves, as depicted in Figure 4.8, reach a peak temperature there are no plateaus indicating that these timber dwellings quickly became fuel controlled rather than ventilation controlled, as typically associated with a formal enclosure fire. These dwellings are still fuel controlled during the growth phase and during flashover. After flashover the dwellings become ventilation controlled but the controlling factor rapidly changes to fuel controlled as a result of the timber cladding burning away, creating a significantly larger area of openings for ventilation. The peak temperature coincided with the period of the experiment when the cladding was completely engulfed in flames. This caused the timber cladding to burn away, thereby increasing the ventilation. Once the timber cladding was completely burned away, there were no bracing to prevent the structure from moving laterally, and sway collapse of the structure ensued. It was observed that none of the dwellings collapsed prematurely and that collapse only occurred once the fully developed fire phase was reached, although this would depend on the size of structural members used in real structures.

The heat fluxes at the door positions for dwellings ISD1, ISD2 and ISD3 are presented in Figure 4.9, 4.10 and 4.11 respectively. Figure 4.12 depicts the heat fluxes of the window trees located at ISD1 and ISD2, respectively. To verify the tree placements refer to Figure 4.5. Due to the intensity of the fire and because of structural collapse, a number of the thermocouples and TSCs got damaged during the experiments.

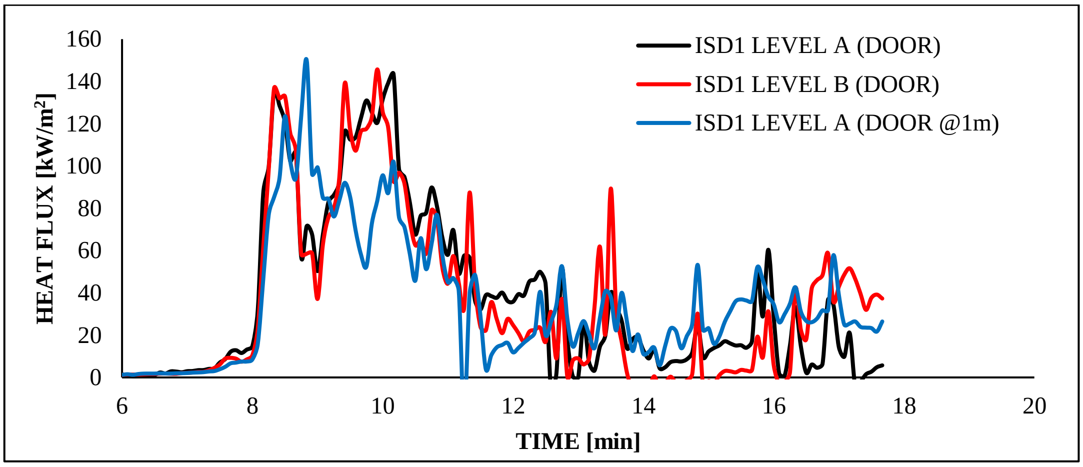

Figure 4.9: Heat fluxes at all door trees for ISD1

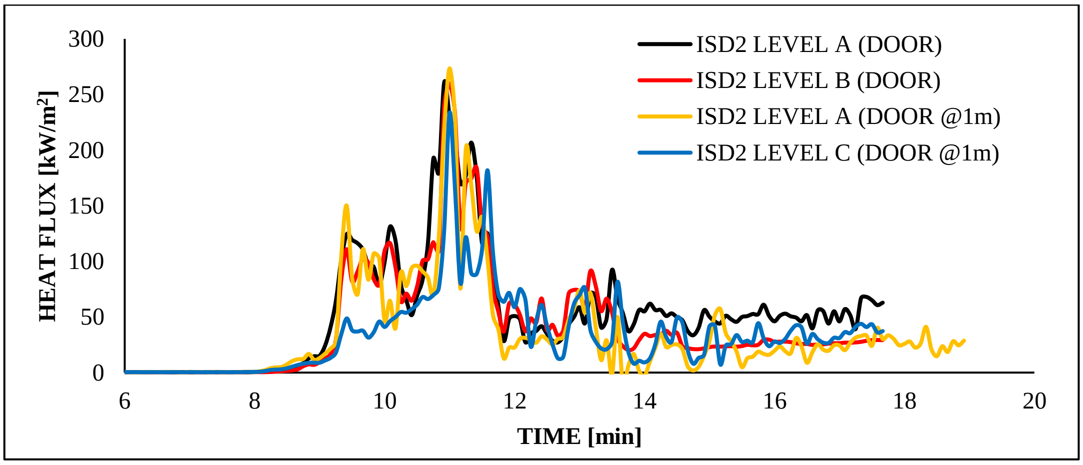

Figure 4.10: Heat fluxes at all door trees for ISD2

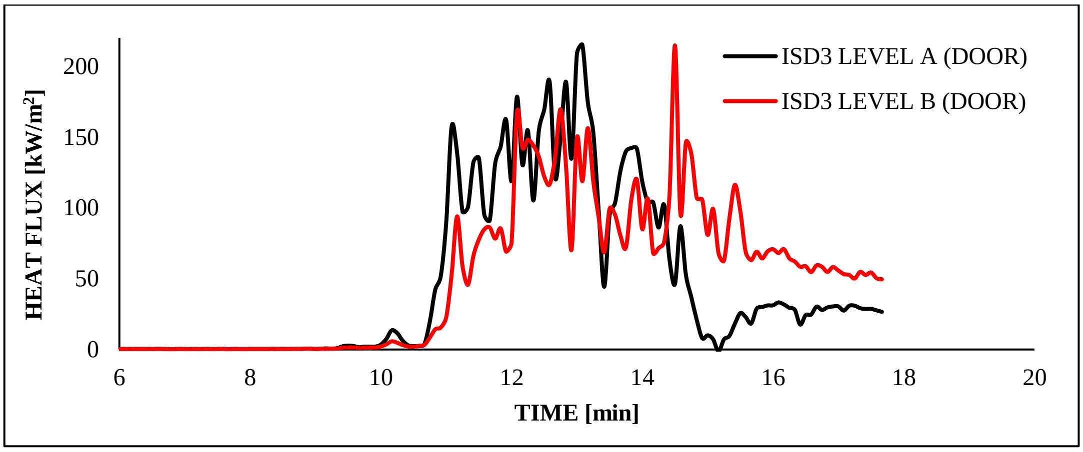

Figure 4.11: Heat fluxes at all door trees for ISD3

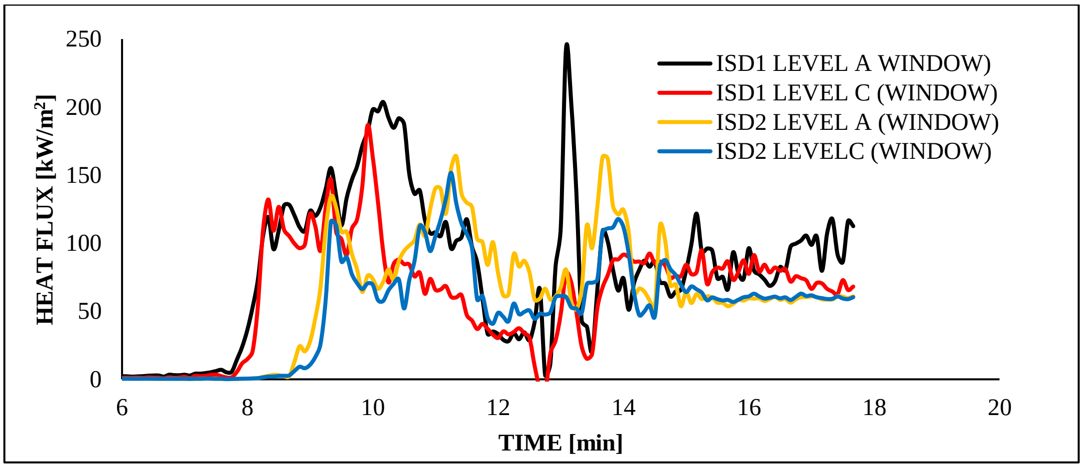

Figure 4.12: Heat fluxes at ISD 1 window and ISD2 window (refer to Figure 4.4)

As a benchmark to compare the results against, the critical heat flux (CHF) for cardboard (typically used as internal lining for insulation in informal dwellings as mentioned earlier) ranges between 8.5 kW/m^2 and 10 kW/m^2 [24,25]. Other common materials found in formal and informal dwellings typically ignite at a CHF of 10–30 kW/m^2 (e.g. timber, wool, nylon, foam, polyester, etc.) [26–29]. The spacing between these dwellings range substantially but based upon authors' visits to informal settlements and [30], the mode typically range between 0–2m in higher density settlements, whereas in more rural areas with less population pressure, dwellings are approximately 5-20m apart.

By considering the maximum heat fluxes listed in Table 4.2 (namely 260 kW/m^2 at the door of ISD2 and 273 kW/m^2 at 1m away from ISD2), it goes against one's intuition that a greater heat flux would be obtained further away from the structure. However, at around 10-11 minutes the entire timber dwelling was engulfed in flames creating a fire whirl. A plausible explanation is that the door tree is unlikely to have been exposed to radiation from the timber walls and as a result the radiation from the walls did not directly fall onto the door TSC, but did onto the TSC placed 1m away from the door, leading to a higher total heat flux. It is clear that the door tree at 1 meter away from the structure was completely engulfed by flames, as depicted in Figure 4.13, indicating that it is possible for such high heat fluxes to occur 1 meter away from the structure.

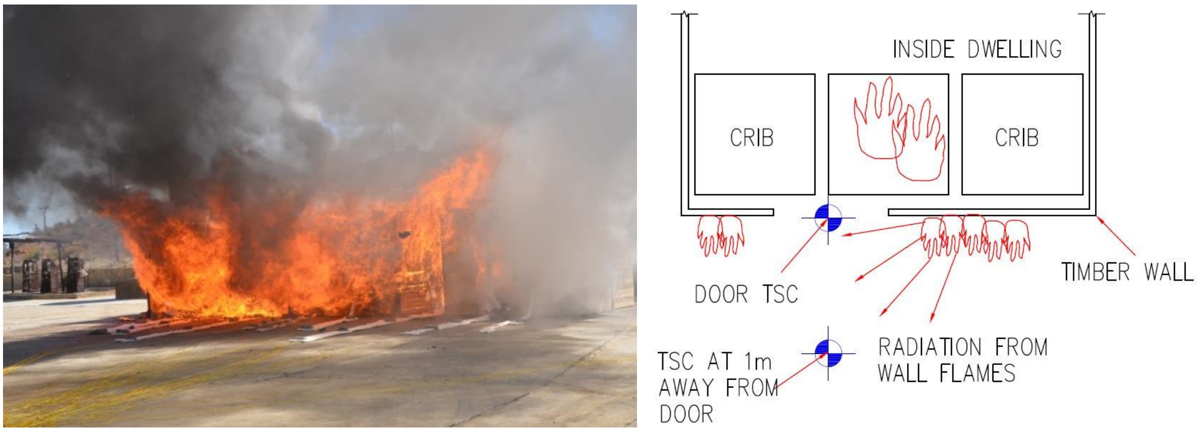

*Figure 4.13: Equipment tree 1 meter away from the structure engulfed by flames (left image) and a visual representation of the theoretical view factor (right image) *TSCs are facing towards the door*

The theoretical view factor calculation also confirms this. Consider the following formula [31]:

$$\dot{Q}_{1\rightarrow 2} = A_1 F_{12} \varepsilon_1 \sigma T_1^4 \tag{4.1}$$

where $\dot{Q}_{1\rightarrow 2}$ is the net energy exchange between object 1 (i.e. the timber wall in this case) and object 2 (i.e. the door TSC in this case), A_1 is the surface of object 1, F_{12} is the fraction of energy leaving surface 1 and reaching surface 2, ε_1 is the emissivity of object 1, σ is the Stefan-Boltzmann constant and T_1 is the temperature of object 1. Because the normal vectors of object 1 and object 2 are facing in opposite directions the angle factor variable, F_{12}, will be zero indicating that the radiation from object 1 does not reach object 2. However, the higher heat fluxes at 1 meter might also be influenced by the 10% tolerance inherent in the TSCs. Both the door TSC and the TSC at 1 meter away from the door falls within the convection zone of the fire, which affects the boundary condition of the TSCs, thus creating additional uncertainties.

Additionally, the peak in heat flux at approximately 13 minutes occurred during the collapse of ISD1 and ISD2 and it is unclear whether the peak should be considered reliable, as depicted in Figure 4.13. As a result it was decided to exclude the peak at 13 minutes from Table 4.2, although such anomalies could occur in a real fire as a collapse results in jets emerging from structures.

The heat fluxes measured 1m away from the door for timber dwellings are extremely high and show that any common materials in an adjacent structure 1m away from the timber dwelling will ignite (based on a CHF of 10-30 kW/m^2) in an informal settlement. It highlights the risk associated with these closely spaced structures. Additionally, it highlights the danger of lining an ISD with a material with a low CHF (e.g. cardboard insulation with an approximate CHF of 10 kW/m^2).

4.5.2. Multi-ISD steel sheeting clad experimental results

This experiment was also conducted at the Breede Valley Fire Department in Worcester, South Africa but on a different date than the multi-ISD timber clad experiment. The ambient temperature on the day of the experiment was 24°C, and there was a slight North Westerly breeze (i.e. from the front left to the back right of the experimental setup) with wind speeds of below 1 m/s. Table 4.3 provides a summary of important parameters pertaining to this experiment such as fire spread mechanism, maximum ceiling temperatures, ventilation area, collapse times and maximum heat fluxes.

Table 4.3. Summary of experimental data obtained from the steel clad experiment

	ISD1	ISD2	ISD3
How did fire spread to it	Dwelling of origin	Flame impingement on the cardboard through a window	Flame impingement on the cardboard through the gaps
Maximum ceiling temperature	1037°C	1070°C	1015°C
Ventilation area	Door and window	Door and two windows	Door
Time from start of ignition to collapse	18 minutes	19 minutes	24 minutes
Time from start of flashover to collapse	8.5 minutes	6.3 minutes	8.4 minutes
Heat flux (HF) at door	156 kW/m^2	153 kW/m^2	133 kW/m^2
HF 1 meter away from door	59 kW/m^2	79 kW/m^2	66 kW/m^2
HF 2 meters away from door	46 kW/m^2	35 kW/m^2	55 kW/m^2
HF at window	160 kW/m^2	200 kW/m^2	n/a

The fire was started in the exact manner as the timber clad experiment. After the paraffin source was ignited at around 9 minutes later the flames had grown high enough to just reach the ceiling. At this point the cardboard on the front wall caught fire and flashover ensued approximately 30 seconds later. Flame impingement occurred through the adjacent window from ISD2 igniting the cardboard lining in the process. The flames burned vertically down the cardboard, as depicted in Figure 4.14, until it reached the timber (at approximately 2 minutes later) and flashover ensued within seconds. After flashover in the second dwelling there was flame impingement on the third dwelling causing the cardboard to ignite (i.e. through the gaps between the wall and roof connection), as depicted in Figure 4.14. The total time it took for all the dwellings to reach their fully developed phase (i.e. from the start of flashover phase in ISD1 to the end of flashover in ISD3) was approximately 8 minutes and 30 seconds. The fire intensity and measured heat fluxes during this second experiment was lower compared to the timber clad dwellings. During this experiment no branding was observed and there were also no signs of fire whirls created by the fire. Flames of up to 4-5 meters were recorded. Figure 4.14 depicts the experimental setup and fire intensity of the multi-ISD steel sheeting clad experiment.

Figure 4.14: Multi-ISD steel sheeting experimental setup (top left), ignition of cardboard in ISD2 (top right), flames traveling vertically downwards (bottom left), and the fire intensity during the experiment (bottom right)

Figure 4.15 depicts the ceiling temperatures of ISD 1, 2 and 3. The temperatures given for each dwelling are from all three ceiling thermocouples to show the uniformity of temperature throughout the enclosure at ceiling level.

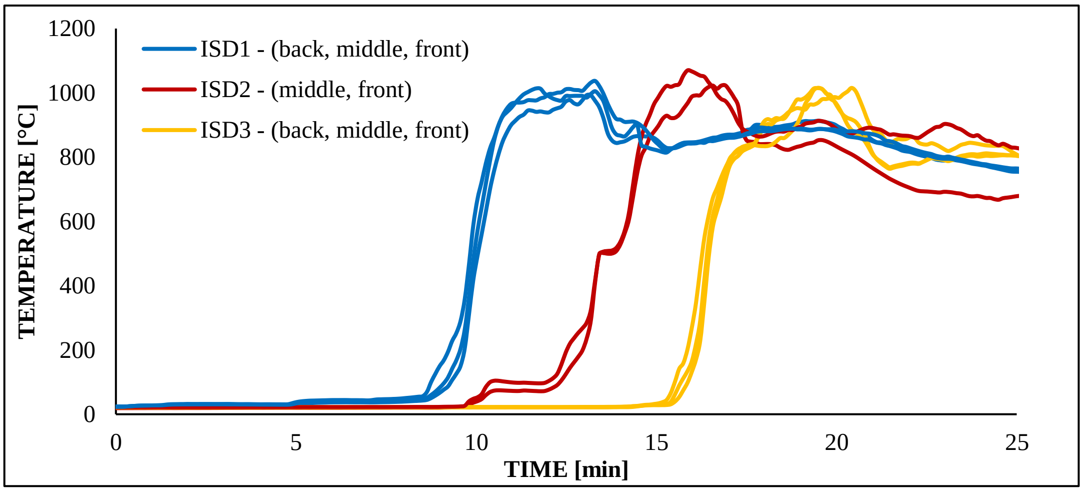

Figure 4.15: Steel dwellings ceiling temperatures

From Figure 4.15, it is clear that the heat release rate in these dwellings was ventilation controlled during the fully developed phase. At approximately 13.2 minutes the sudden change in the rate of temperature increase on the time-temperature curve for ceiling 2 is a transition between the cardboard burning and the ignition of timber cribs, where the perturbation occurs as the cardboard burns out. The mechanism of collapse for the steel sheeting clad dwellings was as a result of the roofs collapsing, as depicted in Figure 4.16.

Figure 4.16: Collapse mechanism: roof falling in (left hand side) and walls collapsing inwards (right hand side).

The heat fluxes at the door positions for dwellings ISD1, ISD2 and ISD3 are presented in Figure 4.17, 4.18 and 4.19 respectively. Figure 4.20 depicts the heat fluxes of the window trees located at ISD1 and ISD2, respectively. To verify the tree placements refer to Figure 4.5.

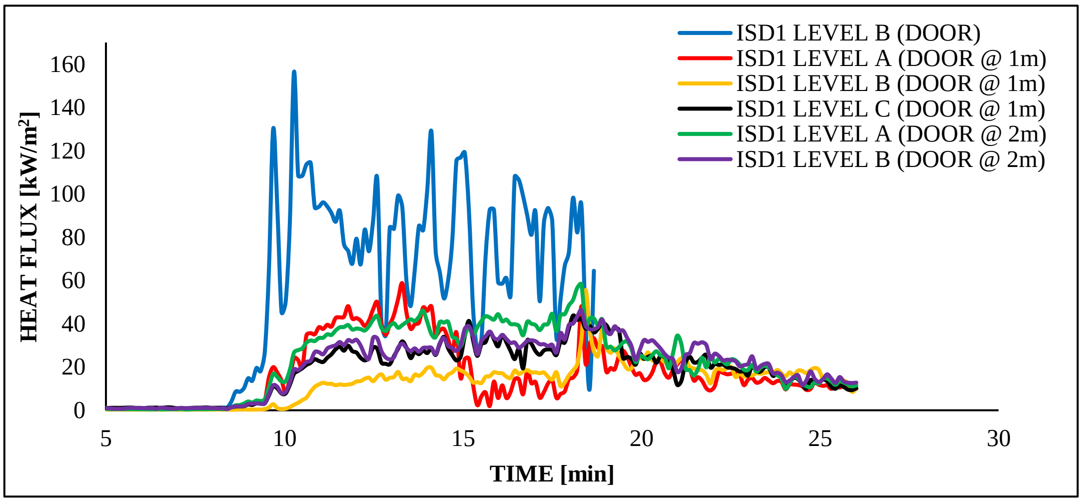

Figure 4.17: Heat fluxes at all door trees for ISD1

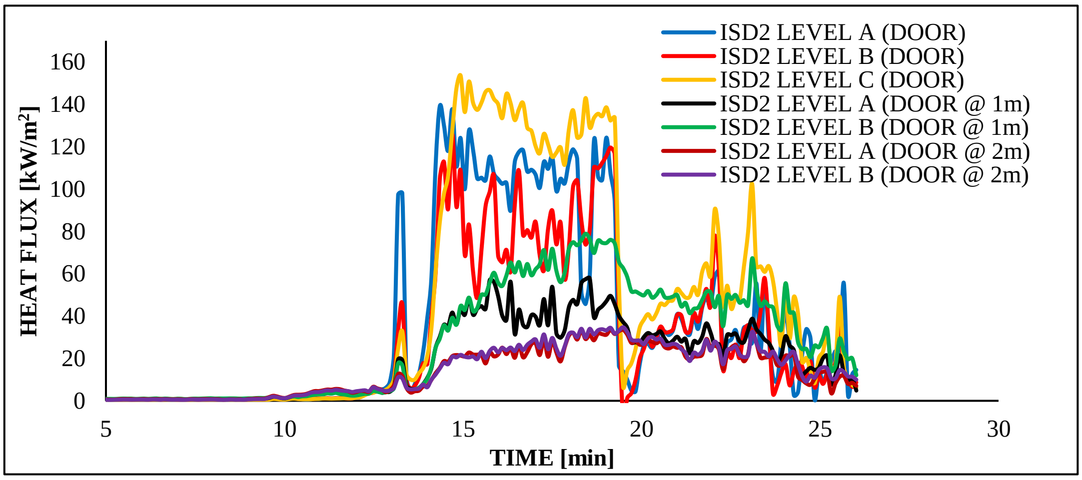

Figure 4.18: Heat fluxes at all door trees for ISD2

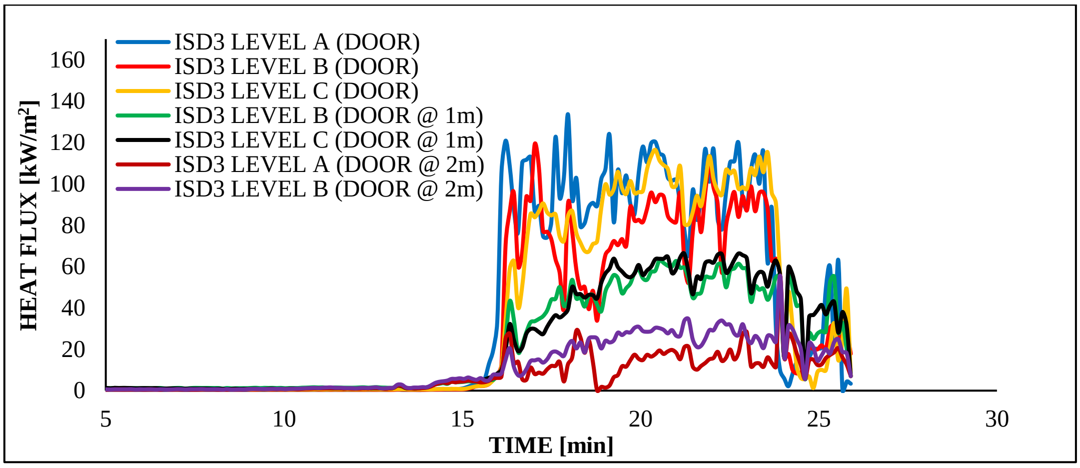

Figure 4.19: Heat fluxes at all door trees for ISD3

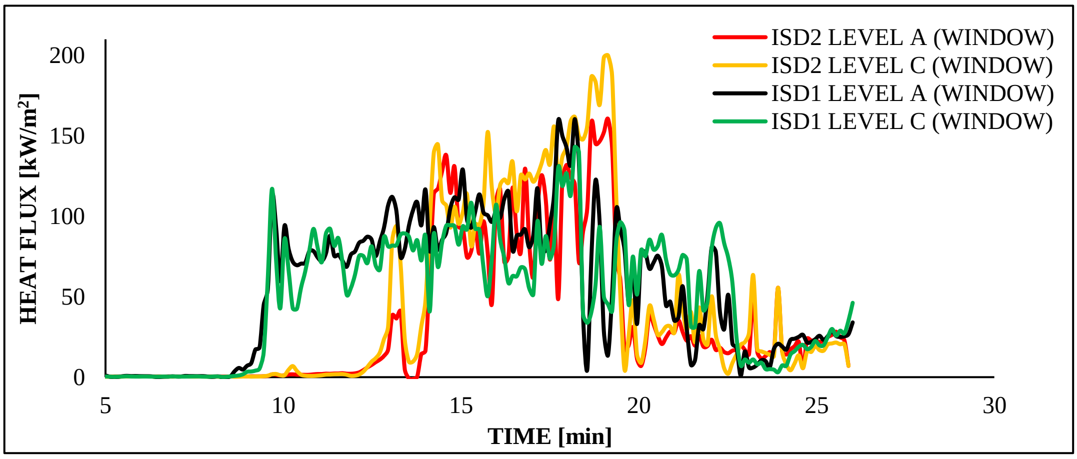

Figure 4.20: Heat fluxes at ISD 1 window and ISD2 window (refer to Figure 4.4)

The peak in heat fluxes seconds before flashover (i.e. at 9.7 minutes, 13.2 minutes and 16.2 minutes as depicted in Figure 4.17, 4.18 and 4.19, respectively), correlates with the burnout of the cardboard and it is also observed, but less clearly, in Figure 4.14 for ceiling 2, as described earlier. However, this peak was sufficient to ignite the cribs and for flashover to occur. In an actual ISD some combustible materials will typically have a lower CHF than wood and will thus ignite simultaneously with (or before) the cardboard.

At 2 meters away from a steel clad ISD this experiment indicates that most materials found in an ISD would be likely to ignite (i.e. the emitted heat fluxes are higher the CHF of most materials). Although, at 2 meter away from ISD2 the maximum heat flux of 35 kW/m^2 might not be enough to conduct through adjacent steel sheeting to ignite the combustible materials on the inside, depending on the structural layouts, configuration factors and wall thicknesses. The heat flux values obtained in the steel clad experiment can be compared to hand calculations using Beer's law, where the radiation at a distance from a flame can be calculated with the following formula [32] [c].

$$\dot{q}'' = I_0 e^{-\kappa L} \tag{4.2}$$

[c] *More information is provided in Appendix C*

where $\dot{q}''$ is the incident radiation (kW/m^2), I_0 is the radiation from the flame and it is assumed to be constant [33–35], κ is the absorption coefficient (m^{-1}) ranging between 2-4 m^{-1} according to [33] and L is the distance from the flame tip (m) to the desired point. The radiation from the flame can be calculated using the following equation [36]:

$$I_0 = (\varepsilon_{flame} + \varepsilon_{gas})\sigma T^4 \quad (4.3)$$

For through draft conditions [22] (i.e. two or more opening in the compartment [36,37]), $\varepsilon_{flame} = 1 - e^{-0.3x_w}$, x_w is given by $x_w = 0.605(u^2/h_d)^{0.22}(h_w + h_d)$, u is the wind speed, h_d is the height of the opening [m] and h_w is the height of the flame tip above the opening [m], $\varepsilon_{gas} = 1$ [36] and T is the flame temperature at the opening (K). Using h_d = 2.03m (i.e. the height of the door), h_w = 2m analyzed from images and video content from the experiment, assuming u = 1 m/s, T = 900°C (i.e. the approximate flame temperature of the flames emerging out of the door for this experiment) and κ as 2 m^{-1} according to [35], the calculated heat flux values at 0 meters, 1 meter and 2 meters are 157 kW/m^2, 21 kW/m^2 and 2.9 kW/m^2, respectively. The calculated heat flux at the door, at 1 meter away from the door and at 2 meters away from the door has an approximate error of 1%, 73% and 92%, respectively (i.e. compared to the experimental values and this will vary from dwelling to dwelling). The values from the top TSC readings were used (and calculated) as they will give the highest heat flux readings. Note by increasing *u* by 100% the maximum heat fluxes will increase by less than 10%. By changing the absorption coefficient to 0.75 to fit the experimental heat fluxes (i.e. similar to what was done in [33,34]), of ISD2 in this case, a maximum error of 6% is obtained, refer to Figure 4.21.

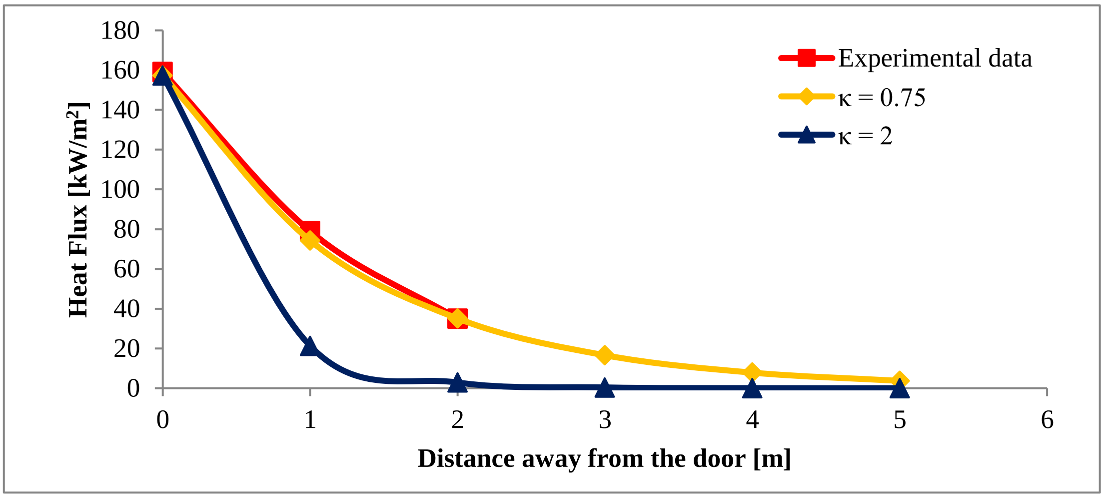

Figure 4.21: Heat fluxes versus calculated heat fluxes with different absorption coefficients

Using Equation 4.2 with κ = 0.75 m^{-1} and q = 8.5 kW/m^2 (i.e. the approximate CHF of cardboard) the minimum separation distance needed for the cardboard not to ignite is approximately 3.8 meters. This is assuming that there will be a gap that exposes the incident heat flux to the adjacent dwellings cardboard, which will not necessarily be the case. This critical separation distance is highly sensitive to the absorption coefficient and the CHF of the adjacent material and the finding should be interpreted accordingly. This is however still an important finding that emphasizes the importance of spacing between the dwellings and that it should ideally range between 3-5 meters, which is similar to the finding in [35]. However, it is not always possible to have a spacing of 3-5 meters between dwellings because the inhabitants will either build a new dwelling in the fire break or will extend their current dwelling into the open space [38].

4.6. Conclusion

This paper has discussed the issues related to, or contributing to, fires in informal settlements and the lack of understanding pertaining to fire dynamics and fire spread in informal settlements. The paper focused on providing a technical basis (i.e. with regards to temperatures experienced, rate of spread, heat fluxes, fire behavior, etc.) for comparing and selecting interventions.

Two full-scale burn experiments have been conducted on ISDs looking at the difference between timber and steel clad dwellings. It was found that temperatures in an ISD can reach 1000-1150°C depending on the total fuel load (i.e. including the structure). It was clear that timber clad dwellings are a higher risk to fire spread with a total spread time of four minutes compared to eight and a half minutes for the steel clad dwellings. The surrounding environment of timber dwellings experienced heat fluxes between 140 kW/m^2 and 270 kW/m^2, indicating that closely built dwellings will ignite as a result. Steel dwellings had lower surrounding heat fluxes ranging between 40 kW/m^2 and 200 kW/m^2, however this doesn’t change the fact that dwellings built at a close proximity will ignite. From these experiments it is clear that dwellings should be spaced at approximately 3-5 meters apart, especially for timber clad dwellings, to reduce the risk of ignition. However, this is not always possible because of socio-economic issues. Although the internal time-temperature behavior of the timber clad dwellings experiment and the steel clad dwellings experiment are similar (refer to Figure 4.3, 4.8 and 4.15 respectively), there is a substantial difference in the maximum heat fluxes recorded. The timber clad dwellings emitted higher heat fluxes at all positions (e.g. 273 kW/m^2 at 1 meter away from ISD2 versus 79 kW/m^2 at 1 meter away from the steel ISD2), as shown in Table 4.2 and 4.3. In addition to higher heat fluxes, the timber clad dwellings experiment had unique phenomena occurring such as branding and fire whirls which will contribute to the risk of fire spread. The cardboard insulation played a substantial role in the spread mechanism for the steel sheeting clad dwellings experiment, as depicted in Figure 4.14. For the timber clad dwellings the cardboard insulation had a reduced effect on fire spread because of the combustibility of the cladding itself. The heat release rate limiting factors are interesting in that for the steel clad dwellings, the dwellings are ventilation controlled during the fully developed stage (as per typical smaller structures) and for the timber clad dwellings the limiting factor becomes fuel availability, during the fully developed stage, as large ventilation openings form through the combustible walls. Overall, the timber clad dwellings are clearly a higher risk to fire spread based on the experimental work done in this paper.

Based on these findings, further work will be conducted by the research team to develop Fire Dynamic Simulator (FDS) models in the near future. The FDS models open the possibility for parametric studies, and interventions could be studied using FDS models rather than expensive experiments each time. However, a priori modeling of such dwellings pose extreme challenges (i.e. the constant change in ventilation conditions and structural collapse), hence has necessitated the study conducted in this paper. The work done in this paper highlighted that the fire spread mechanism (i.e. flame impingement on the cardboard lining) are as a result of wall porosities or openings, meaning some proposed solutions will be less plausible (e.g. intumescent paint) because the flames will still find its way through the small openings. Additionally, this work can be used as a benchmark to compare different interventions by studying the effect on the maximum heat fluxes obtained, time to flashover, maximum temperature, etc.

As a result of the complex nature of ISDs, social particularities and inherently uncontrolled environments, significant challenges are confronted when developing interventions for informal settlements. Thus, the problems cannot be identified, isolated and solved in a similar manner than commercial buildings or formal dwellings. However, with more than one billion people residing in informal settlements it is a cause for serious concern, and there is a significant need to understand and improve fire safety in informal settlements.

4.7. Acknowledgements

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Chapter 5: Towards an engineering approach to model fire spread in informal settlements using fire dynamic simulator

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	**Extent of contribution (%)**
Planning, ordering, preparation and execution of experiments. Writing the manuscript, establishing methodology, data analysis and preparing figures and tables. The modelling work done in the paper and did the data analysis of the modelling results.	92%

The following co-authors have contributed to as follows:

Name and e-mails	**Nature of contribution**	**Extent of contribution (%)**
Richard Shaun Walls (rwalls@sun.ac.za)	Supervised the work, assisted with experiments, advised on the work and reviewed the manuscript	8%

Signature of candidate:

Date: 05/06/2019

The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5,
2. no other authors contributed to Chapter 5 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this dissertation.

Signature	**Institutional affiliation**	**Date**
	Stellenbosch University	

This chapter is an exact copy of the journal paper referred to above, with the exception of Section 5.6.4 that has slightly been modified.

5.1. Abstract

This paper develops a model using Fire Dynamics Simulator (FDS), based upon full-scale experiments, to analyse fire spread in informal settlements (also known as slums, ghettos, shantytowns, etc.). Informal settlements are frequently ravaged by fires, leaving thousands of people homeless,[1] and with more than 1 billion people residing in informal settlements, there is a significant need to understand and improve the fire safety in such areas. This paper focusses on understanding and predicting the fundamental fire phenomena that govern fire spread in settlements, such that in the future, the work can be extended to simulate large-scale fire disasters. Due to high levels of uncertainty inherent with input parameters regarding informal settlements, this work also investigates the sensitivity of fire behaviour to parameters such as ignition temperature, specific heat, conductivity, emissivity of the lining material, emissivity of the compartment boundaries, soot yield and radiative fraction on fire spread between dwellings. It is shown that spread times between two dwellings can vary between one minute and no spread at all, depending on the parameters selected. This paper highlights the importance of such input parameters (especially the material properties of the material that is the first cause of ignition) when trying to model fire spread between dwellings. The aim is that the FDS V6.7 model developed in this work can be simplified and generalised to provide an approximate tool that can consider a wider range of parameters prevalent in settlements, and provide guidance for decision makers addressing aspects such as the width of pathways between dwellings, construction materials utilised, positions of access roads and the potential magnitude of disasters that municipalities may have to respond to.

5.2. Introduction

Informal settlements typically consist of makeshift structures built on land that has not been declared as residential and are characterized by overly dense populations, poorly constructed structures and a lack of basic services (i.e. access roads, water, electricity, etc.).[2] Informal settlement fires epitomize an international problem defined as an "extensive risk" (i.e. "repeated or persistent hazard conditions of low or moderate intensity, often of a highly localized nature, which can lead to debilitating cumulative disaster impacts").[3] Figure 5.1 depicts a typical informal settlement dwelling (ISD) and gives an overview of the fire risks inherent in these dwellings. The data presented in Figure 5.1 is based on the authors' visits to settlements, firefighter interviews conducted by the authors and the literature [4–7].

Population growth and urbanisation is leading to a rapid growth of informal settlements worldwide, meaning that municipalities have to deal with the issue of fire safety in such areas, and sometimes this is done through providing fire safety interventions. However, often the fire safety interventions become practically unsuitable for informal settlements, because the "solution" lacks an engineering basis, or there is not enough data to make an assignation on whether or not the "solution" will work.[4] Some examples of previously proposed interventions are safer electrification of dwellings, safer lighting and heating methods, intumescent paints, suppression systems and smoke alarms.[4,8] However, this work seeks to provide guidance regarding the fire dynamics behaviour experienced in informal settlement dwellings by developing computational models, such that products can be more accurately analysed by understanding the potential fire severity they will be exposed to. Furthermore, by developing a robust and simple model the influence of area layouts on fire spread can be investigated to assist decision-making. With the advances in technology it is possible to develop FDS models, rather than requiring experiments to evaluate different area and housing configurations. FDS modelling is well established in the fire community with a significant amount of work focusing on the validation of small-scale experiments and smoke movement, but with less work focussed on spread between adjacent structures. Furthermore, there is limited literature available on procedures for the numerical modelling of informal dwellings (i.e. structures with thin boundaries, ventilation conditions that change continuously, small openings, structural collapse, wide ranges in fuel loads, high densities in areas, etc.).

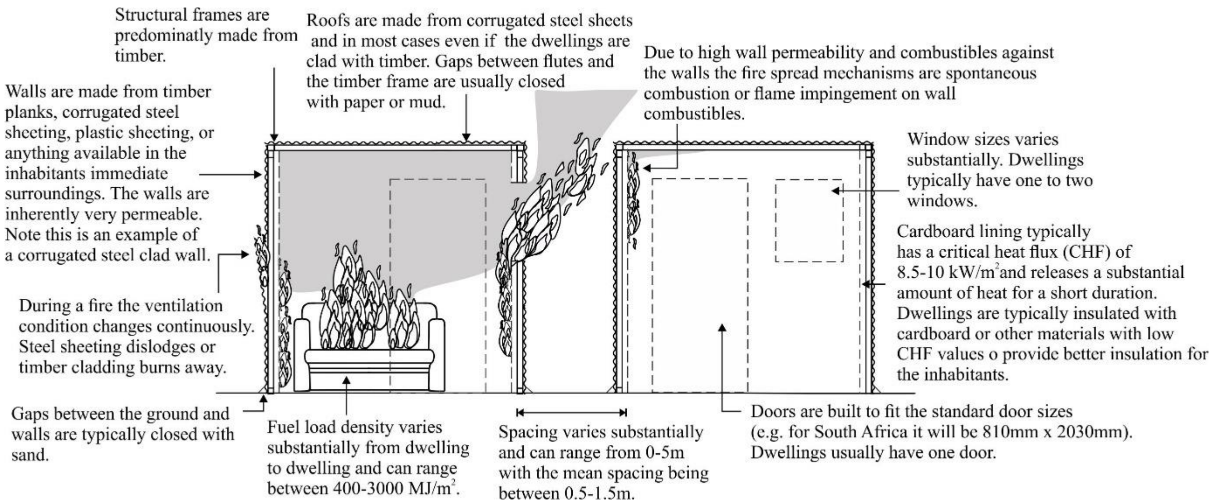

Figure 5.1: A typical informal settlement dwelling

Although current computer technologies are dramatically advancing, running an accurate model containing multiple ISDs would require millions of cells and would require significant computational effort. Furthermore, for the purpose of running parametric studies and testing interventions using FDS, it is not practical to have such a computationally heavy model. Hottel[9] noted that “a case can be made for fire being, next to the life processes, the most complex of phenomena to understand” and the same can be said for predicting fire spread. The difficulties relating to predicting fire spread in informal settlements revolve around three principle issues:[10] firstly, there are a significant number of fire and fire spread scenarios to consider as a result of the accidental nature of fire. Secondly, the computer power and the actual knowledge required to perform all the calculations needed for a particular fire scenario are limited (relative to the highly complex environments considered). Each fire scenario must at least consider, heat transfer, radiative transport, turbulent mixing, multi-phase flow, bluff-body aerodynamics and combustion, all of which are active studies of their own. Lastly, due to the inherent nature of informal settlements, the data needed to describe the fuel and configuration of the informal settlement will typically not be accurately available (and is one of the main focusses of this work). It is actually questionable the extent to which a highly accurate model would even be useful in an area defined by such high variability.

In order to make any progress in predicting fire spread in informal settlements the questions asked should be significantly simplified. At this point in time, instead of developing a methodology that can be applied to all fire spread scenarios (a longer term aim) this paper seeks to provide a method that can predict fire spread for two experiments where the parameters are well known, with the hope that the method developed can be generalized over time in order to analyse more complex problems in the future. These experiments are (1) a triple steel sheeting clad dwelling experiment, and (2) a triple timber plank clad dwelling experiment. The details of these experiments are discussed in detail by Cicione et al.[5]* The important outputs of the models developed are the calculation of spread time and heat fluxes at a distance from dwellings as compared to measured experimental data, such that with further research the work can also be extended to settlement level spread modelling. It is with this backdrop that the paper aims to (a) develop a simplified FDS models (i.e. reduced computational effort needed, and minimal material data needed) to analyse fire spread between multiple dwellings and (b) study the influence of mesh independent parameters on fire spread between dwellings to identify key parameters for characterising fire spread. Simplifications made to the models include the modelling of combustion through simple burners, a methodology for modelling linings on walls (a key factor in spread), and considerations regarding leakages.

5.3. Setup of the full-scale experiments and FDS models

Two full-scale ISD experiments were carried out at the Breede Valley Fire Department in Worcester, South Africa, as part of a series of experiments to understand fire dynamics in informal settlements. Figure 5.2, and the discussion that follow, give the dimensions and details of the full-scale experiments, from which the geometries in the FDS models have been created. Figure 5.3 visually depicts the experiments conducted. A summary of results from the experiments are presented in Table 5.1.

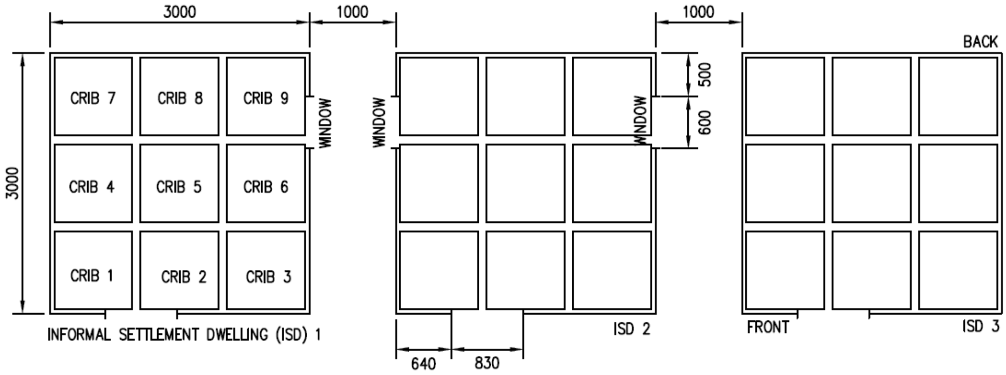

Figure 5.2: Experimental details showing timber crib layouts, ISD spacing and ventilation details

*Refers to Chapter 4 of this dissertation

Figure 5.3: Images of experiments conducted for the steel and timber clad fire experiments showing fire behaviour when the second and third dwellings had ignited [5]

Table 5.1: Summary of details from the steel (Experiment 1) and timber (Experiment 2) clad triple ISD experiments [5]

		ISD 1	**ISD 2**	**ISD 3**
Exp. 1: Steel	Spread mechanism	Dwelling of origin	Flame impingement on the cardboard through window	Flame impingement on the cardboard through gaps
	Ventilation	Door and window	Door and two windows	Door
	Max. roof temp	1037°C	1070°C	1015°C
	Time from flashover to collapse	8.5 minutes	6.3 minutes	8.4 minutes
	Heat flux 1m from door	59 kW/m^2	79 kW/m^2	66 kW/m^2
Exp. 2: Timber	Spread mechanism	Dwelling of origin	Flame impingement on the cardboard and cladding	Flame impingement on the cladding
	Ventilation	Door and window	Door and two windows	Door
	Max. roof temp	1104°C	1176°C	1184°C
	Time from flashover to collapse	5.1 minutes	5.3 minutes	4.6 minutes
	Heat flux 1m from door	150 kW/m^2	273 kW/m^2	No data

The height of the dwellings, door openings and window openings were 2.3 m, 2.03 m (2 m was used in FDS) and 0.6 m, respectively. The windows were placed 1.43 m from ground level (1.4 m was used in FDS). The walls of the dwellings for Experiment 1 and Experiment 2 were clad with corrugated steel sheeting and timber planks (12×100×1500 mm), respectively. The roofs for both experiments were made from corrugated steel sheeting and all frames were constructed from 50×50mm timber sections. All dwellings were lined with corrugated cardboard (1.5 mm thick) on the inside of the walls and the floor of the dwellings. As a result of the timber frames around the windows, the cardboard lining did not run up to the edge of the window, but rather to the inside of the timber frame (i.e. stopped 50mm away from the edge of the window in the inside). This was accounted for in the FDS models by leaving a one cell gap between the cardboard and window opening. The density of the wood and the cardboard was 536 kg/m^3 and 180 kg/m^3, respectively. The fire was started in crib 2 of ISD 1 for both experiments. ISD1 refers to the first dwelling from the left, followed by ISD2 in the middle and then ISD3 on the right as depicted in Figure 5.2. This convention is adopted for the rest of the paper. The procedure for modelling these experiments will now be discussed.

5.3.1. Heat release rate, grid size and computational domain

Unfortunately, heat release rate (HRR) could not be measured during these experiments due to the size of the experiments conducted. The model developed was simplified by assigning a total HRR per unit area

(HRRUA) to a burner within the dwellings. The burners in ISD2 and ISD3 were set to start burning once the gas temperature exceeded the ignition temperature of the timber cribs (i.e. 350 °C as shown in Table 5.2) at the crib height. In order to estimate a HRRUA for the timber cribs the SFPE timber crib calculations by Babrauskas[11] was used. The HRR of the free burning cribs can be prescribed by the following very well-known HRR formula:

$$\dot{Q} = \dot{m}\Delta H_{eff} \tag{5.1}$$

where $\dot{m}$ is the mass loss rate measured in kg/s and ΔH_{eff} is the effective heat of combustion measured in kJ/kg. The mass loss rate (i.e. of the free burning cribs) is taken as the lesser of the porosity-controlled mass loss rate:

$$\dot{m} = 4.4 \times 10^{-4} \left(\frac{S}{h_c}\right)\left(\frac{m_0}{D}\right) \tag{5.2}$$

and surface-controlled mass loss rate:

$$\dot{m} = \frac{4}{D} m_0 v_p \left(1 - \frac{2 v_p t}{D}\right) \tag{5.3}$$

where the stick thickness is D = 0.04 m, the clear spacing is S = 0.17 m, the crib height is h_c = 0.48 m, the number of sticks per row is n = 15 (i.e. assuming one big crib in the dwelling), the initial crib mass was m_0 = 375.11 kg (i.e. 41.68 kg × 9 cribs), giving $v_p = 2.2\times10^{-6} D^{-0.6}$ according to Babrauskas[11] and the heat of combustion of the timber is ΔH_{eff} = 18 MJ/kg (as measured by a bomb calorimeter test and assuming a combustion efficiency of 1). This was also the heat of combustion used on the reaction line with a soot yield of 0.03 as assumed for ventilation controlled compartment fires.[12] This gave a surface-controlled mass loss rate with a limiting HRR of 10250 kW. The model used a 2.8×2.8 m burner in the middle of the dwelling, thus a HRRUA of 1314 kW/m^2 was prescribed. An unpublished work by the authors has developed a detailed FDS model that includes individual timber elements to validate the procedures employed above and has been shown to provide consistent results**.

A significant amount of work in the fire community has been done in terms of analysing cell size sensitivity for plume fires. According to [13] the minimum cell size should be *0.1D** where *D** is calculated as follow:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty T_\infty c_p \sqrt{g}}\right)^{2/5} \tag{5.4}$$

where D* is the characteristic fire diameter [m], $\dot{Q}$ is the heat release rate [kW], ρ_∞ is the ambient air density [kg/m^3], T_∞ is ambient the temperature [K], c_p is the specific heat [kJ/(kg·K)], and g is the gravitational acceleration [m/s^2]. For a HRR of 10250 kW a characteristic fire diameter of D* = 2.4 m is obtained, meaning a minimum cell size of 0.1D* = 0.24 m is required. In this case a cell size of 0.1 m^3 was used. The computational domain was 12×4.6×3 m (length × width × height).

***Refers to Chapter 3 of this dissertation*

As a result of the cell size, the thickness of the cardboard had to be adjusted to be one cell size thick (this is to have full functionality in FDS according to [14]). The HRRUA of the cardboard was obtained by means of a Fire Propagation Apparatus (FPA) test and the curve is depicted in

Figure 5.4. The heat flux used in the FPA test was 50 kW/m^2 (the FPA tests were conducted at the University of Edinburgh).

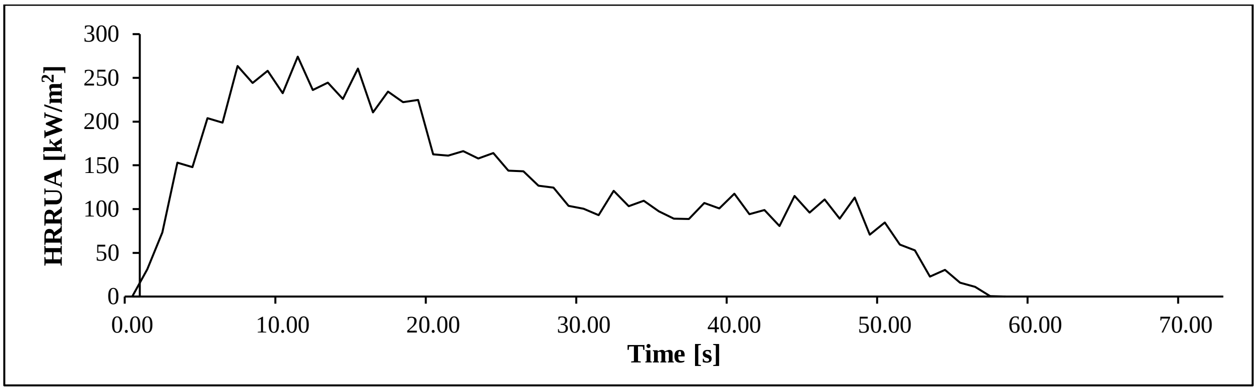

Figure 5.4: HRRUA curve of the corrugated cardboard

5.3.2. Material properties, obstruction specifications and leakage

The three materials used in the experiments and being modelled in this work were steel, timber and cardboard. The thermal properties of timber and cardboard vary substantially in the literature. The range in value of each property, as found in the literature, are tabulated in Table 5.2. For the "original" model, the values depicted in **Bold (**Table 5.2) have been used. Note that the densities of the cardboard and wood were adjusted to account for the change in volume of the obstruction, as mentioned earlier. Table 5.3 gives the details pertaining to the obstructions created in the FDS models. The effective heat of combustion of the cardboard was 10.985 MJ/kg (assuming a combustion efficiency of 65% [15]).

Table 5.2: Material properties from the literature for combustible materials, with bold values indicating values selected

Properties	Steel	Corrugated cardboard	Wood
Density [kg/m^3]	7850 [16]	180 **(Used in FDS - 2.7*)**	536 **(Used in FDS – 64.32*)**
Specific Heat [kJ/(kg·K)]	0.6 [16]	1.52 - **2.7** [17,18]	1.24 - 2.8 [19–21] **(1.3** [20]**)**
Conductivity [W/(m·K)]	45 [16]	0.064 - **0.42** [18,19,22,23]	0.11 - 0.15 [19,21,24] **(0.14** [24]**)**
Emissivity	0.42 [25]	0.7 - **0.9** [22,23,26]	0.75 - 0.91 [25] **(0.9)**
Ignition temperature [°C]	n/a	**263** - 323 [26]	300 - **350** [21,24]

**As mentioned earlier, the densities were adjusted to account for the change in volume of the obstruction.*

Table 5.3: Details pertaining to the FDS model obstructions

OBSTRUCTION	Actual thickness	Model obstruction thickness	Surface thickness	Backing condition	Bulk and surface density
Steel wall	0.47mm	100mm	0.25mm	Exposed	Not specified
Cardboard lining	1.5mm	100mm	50mm	Void	2.7 kg/m^3

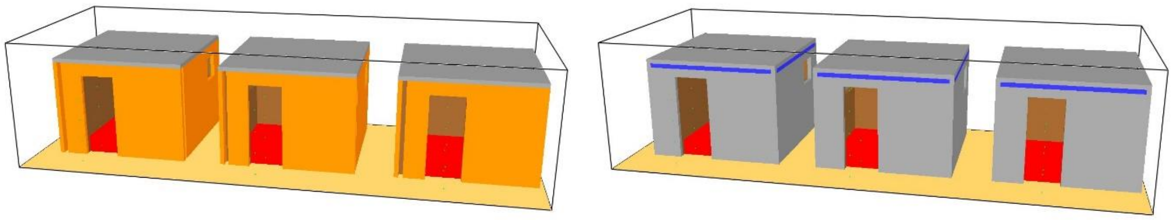

Figure 5.5: Smokeview of the timber clad (left) and steel clad (right) FDS models

As a result of the flutes of the corrugated sheeting and the gaps between timber cladding, both experiments experienced a large amount of leakage, which is typical of informal dwellings, but difficult to model. For the steel clad model, the wall-roof connection leaks (i.e. as a result of the corrugated flutes) were modelled by making use the leak functionality of a HVAC systems. The leak area and flow loss were specified as 0.0255 m² and 0.1, respectively. These leakages were also the main fire spread mechanism between ISD2 and ISD3 in the experiments. For the timber clad dwelling, the small leaks between timber cladding pieces were modelled by creating a gap of one cell size on the side of each wall, as depicted in Figure 5.5.

5.4. FDS results of the steel clad dwelling – Experiment 1

An initial cell sensitivity study was done for ISD1 by refining the cell size with a factor of 2, and the temperature results are depicted if Figure 5.6. As seen in Figure 5.6, the cell size had a negligible effect on the gas temperature within the enclosure, as well as on the heat fluxes at a distance of 1 meter away from the door. Only ISD1 was considered in order to reduce the computational effort needed to run the model. It is assumed that if the fire behaviour is not affected by the cell size for ISD1, it will generally also not affect the behaviour of ISD2 or ISD3.

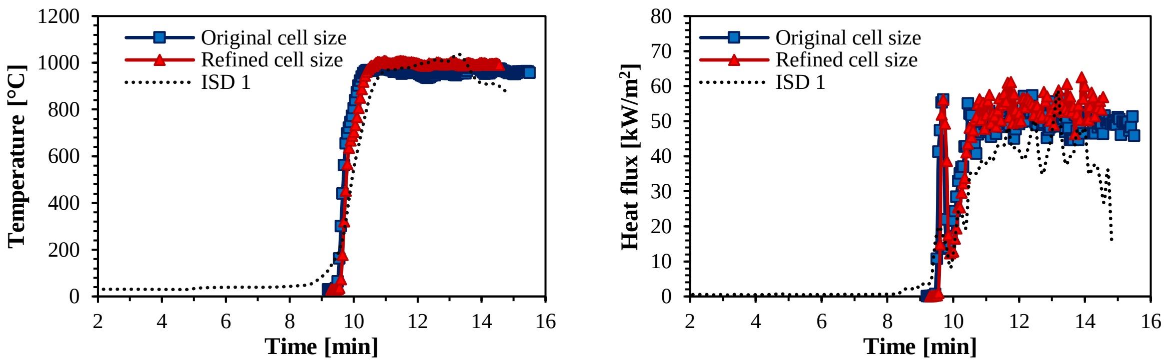

Figure 5.6: The effect of cell size on ceiling temperatures (left graph) and the effect of cell size on heat fluxes (right graph), in comparison to experimental results (ISD 1)

The “original” model shows good enclosure correlation (i.e. the gas temperatures and fire development behaviour within the enclosure) and a good correlation in the fire spread rate between ISD1 and ISD2, as depicted in Figure 5.7 (a). However, fire spread between ISD2 and ISD3 did not occur. It is difficult to define the fire spread time and for simplicity it was decided to define the fire spread time between dwellings as the time between flashover phases, where the ceiling temperature is equal to 500 °C (where flashover is defined as the phase between the growth stage and the fully developed stage). Thus, an increase in the spread rate indicates a shorter time between flashover phases. Although, the spread time between dwellings could have been defined in many other ways, this method provided the most consistent numerical manner to quantify spread time with less uncertainties (e.g. when did ignition occur, when did flashover start or end, etc.). In order to study the influence of mesh independent parameters on the fire spread rate between dwellings, it is important to pick a "baseline" model to compare the model variations against. It is important that spread occurs between all three dwellings for the baseline model and thus it was decided to lower the ignition temperature of the cardboard to allow fire spread to occur. The results of T_{ig} = 263 °C to T_{ig} = 220 °C are depicted in Figure 5.7 (a) to (g). The dotted lines are the experimental results and the solid lines are the FDS model predicted results. ISD1 is the first dwelling to reach flashover for both the model and the experiment, followed by ISD2 and then ISD3. The temperature readings in Figure 5.5.7 (a) to (g) were taking at 150 mm from ceiling level.

From Figure 5.7 (a) to (g), it is clear that the ignition temperature (of the lining material) has a substantial effect on the rate of fire spread from one dwelling to another. It is interesting to note that although the ignition temperature has a large effect on the fire spread rate, it has a negligible effect on the maximum and steady state ceiling temperatures, as depicted in Figure 5.7 (a) to (g), and on the heat fluxes experienced, as depicted in Figure 5.8 (a) and (b). Figure 5.8 (a) and (b) are the heat flux (HF) curves at the door (1750 mm from ground level) and at 1 meter away from the door (1750 mm from ground level) of ISD2. The heat flux curve with the higher values are the readings at the door and the lower heat flux values are the readings at 1 meter away from the door. The heat flux curves times of the FDS models were offset to match the flashover phase of the experimental curves. ISD2 collapsed at approximately 19 minutes and no data is considered after structural collapse. The dotted lines are the experimental results and the solid lines, ISD 1 (blue), ISD 2 (red) and ISD 3 (orange), are the model results.

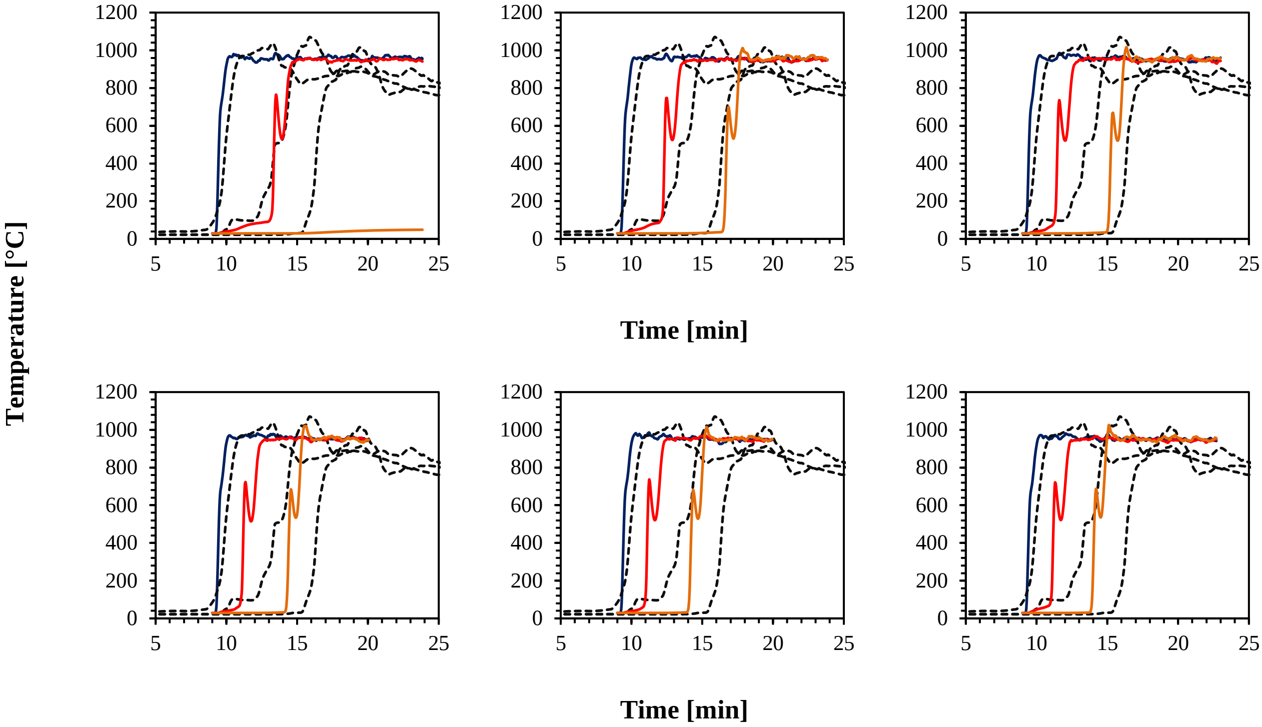

Figure 5.7: FDS ceiling temperatures showing ISD 1 (blue), ISD 2 (red) and ISD 3 (orange) relative to experimental results (black). (a) T_{ig} = 263°C of the cardboard (top left) – (g) T_{ig} = 220°C of the cardboard (bottom right)

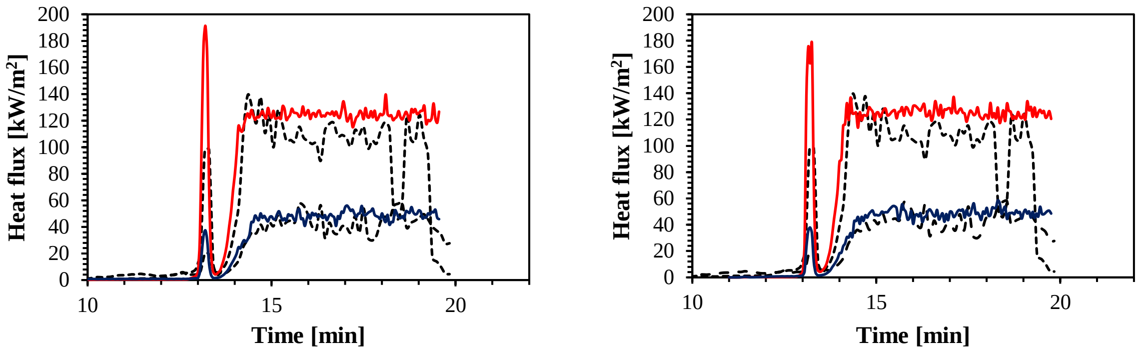

Figure 5.8: FDS HF curves at the door (red) and at 1 meter away from the door (blue) relative to experimental results (black). (a) HF (ISD2) when the T_{ig} of the cardboard is 263 °C and (b) HF (ISD2) when the T_{ig} of the cardboard is 220 °C

The only slight difference in the two HF graphs is the peak heat flux that occurs at 13.1 minutes (this peak corresponds with the full ignition of the cardboard). For the case where T_{ig} = *220 °C*, the peak is 7% lower. The FDS model over-predicts the heat flux generated by the cardboard, compared to the experimental heat flux. This is likely as a result of how the fire spread across the surface of the cardboard. In the model, the fire tends to spread more rapidly across the surface of the cardboard, thus generating a higher HRR, i.e. because more cardboard is burning at a specific place in time compared to the experiment, where the fire spread rate across the surface of the cardboard is slower and thus allowing some of the cardboard to burn away before all the cardboard is in engulfed in flames. This is likely also the reason for the quicker response (during the flashover phase for the FDS models) in the time-temperature curves at ceiling level.

It was decided to use the FDS model, with the ignition temperature of cardboard equal to 255 °C as the "baseline" model, because it gave the best correlation for the fire spread rate between dwellings, compared to the experimental results. Figure 5.9-5.5.12 are the heat flux curves in front of the window of ISD1 and door of ISD1-ISD3. The symbols used in Figure 5.9-5.5.12 indicates the following: E – Experiment, M – Model, HF – Heat Flux, D – at the Door, @1D – At 1 meter away from the Door, W – at the Window and B – Level B (if not indicted, Level A can be assumed). Level A is 1750 mm from ground level and Level B is 1250 mm from Ground level.

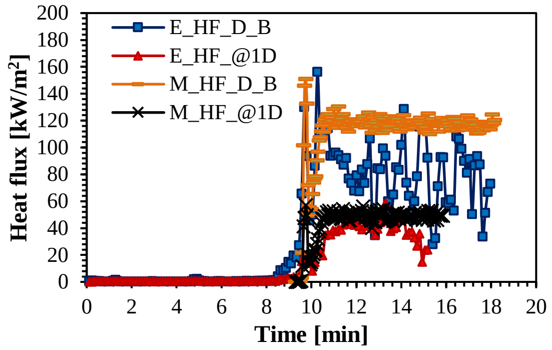

Figure 5.9: ISD1 - Heat flux curves in front of the door

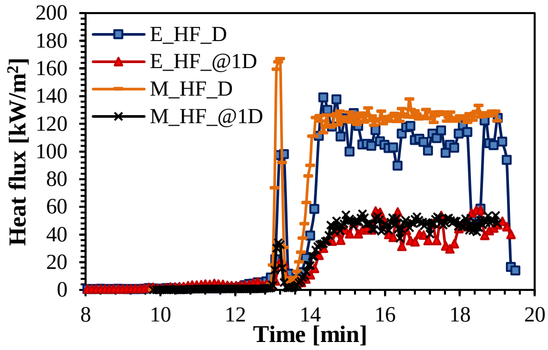

Figure 5.10: ISD2 - Heat flux curves in front of the door

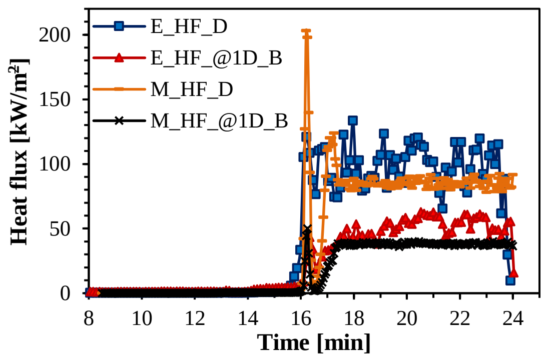

Figure 5.11: ISD3 - Heat flux curves in front of the door

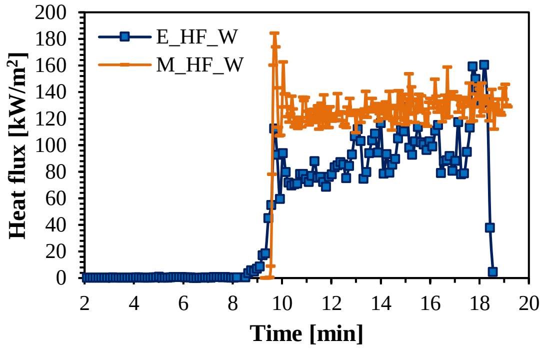

Figure 5.12: ISD1 - Heat flux curves in front of the window

Considering Figure 5.9-5.12, the FDS model results capture the behaviour of the experiment relatively well. The model tends to overpredict the peak value that correspond with the full ignition of the cardboard lining, as depicted to Figure 5.10-5.12. As explained above, this is likely as a result of how the fire spread across the surface of the cardboard and as a result the amount of cardboard that burns at a particular time. The model captures the steady state heat fluxes very well, with the exception of the heat fluxes at the door of ISD1, as depicted in Figure 5.9, and the heat fluxes at the window of ISD1 Figure 5.12. For the heat fluxes at the door of ISD1 the average steady state value of the model is 106 kW/m^2 which is 37% higher than the average steady state value of the experiment of 77 kW/m^2. The experimental heat fluxes vary substantially for ISD1 compared to the other dwellings and could be linked to the performance of the thin-skin calorimeter used in the experiment, or if it had been damaged. For the heat fluxes at the window of ISD1 the average steady state value of the model is 129 kW/m^2 which is 29% higher than the average steady state value of the experiment of 100 kW/m^2. However, overall trends show good correlation and the general physics of the experiment have been predicted.

5.5. FDS results of the timber clad dwelling – Experiment 2

The timber clad dwellings experiment was modelled in the same manner as that of the steel clad structures, except with a different wall material. It was decided to use T_{ig} = *255 °C* for the cardboard lining for the timber clad dwellings as well in order to best represent the results. All other properties and parameters are in accordance with Table 5.2 and 5.3. Figure 5.13 is a comparison between the ceiling temperatures of the model and experimental results. Figure 5.14-5.17 are the heat flux curves of the FDS model and experimental results in front of the window (ISD1) and the door of ISD1-ISD3. The timber clad models had more uncertainties in terms of how the timber cladding could be modelled, because of the constant change in ventilation condition as a result of the timber cladding burning away in the experiments. ISD1, ISD2 and ISD3 collapsed at approximately 13.3 minutes, 14.3 minutes and 15.3 minutes, respectively. The cladding started to burn away minutes earlier. The graphs below are only plotted up to the point where the cladding started to burn away (i.e. when the ventilation starts to change substantially). The cladding provided stability to the structure so once it was burnt through collapse ensued shortly thereafter. Additionally, due to imperfections in timber planks used, the cladding had small gaps in between each timber piece, creating more uncertainties that cannot be captured in FDS (i.e. especially with a relatively coarse mesh). However, once again such leakages are a reality in poorly built informal structures.

In general, the model of the timber clad dwelling provided good results, considering the complexity of the experiment's ventilation conditions. The fire spread rate and the enclosure gas temperatures are depicted in Figure 5.13. Considering Figure 5.14 and Figure 5.15, FDS tends to overpredict the heat fluxes experienced at the door and tends to underpredict the earlier heat fluxes experienced at 1 meter away from the door. The model heat fluxes at 1 meter away from the door seem to increase and stabilise, at the same value as the experiment, after a minute and up to the point where the cladding timber starts to burn on the exterior. Overall, the FDS model seems to perform poorly when looking at the door heat fluxes of ISD1 and ISD2. It should be noted that a number of assumptions where made to simplify the model (especially the cladding) and that this will have affected the results. Based on Figure 5.14 and Figure 5.15 there is further research needed in order to develop a simplified and practical way to model informal settlement timber dwellings where ventilation is highly variable.

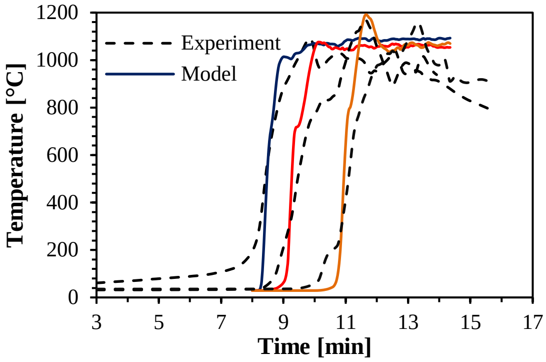

Figure 5.13: FDS versus experimental ceiling temperatures showing ISD 1 (blue), ISD 2 (red) and ISD 3 (orange) relative to experimental results

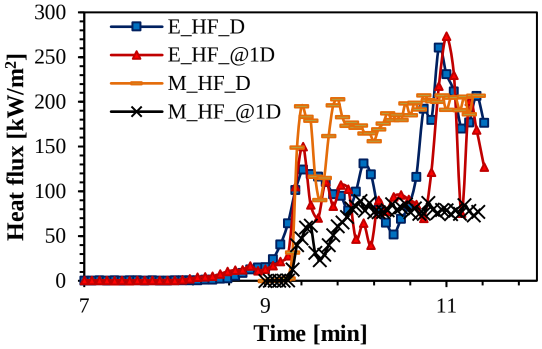

Figure 5.14: ISD1 - Heat flux curves in front of the door

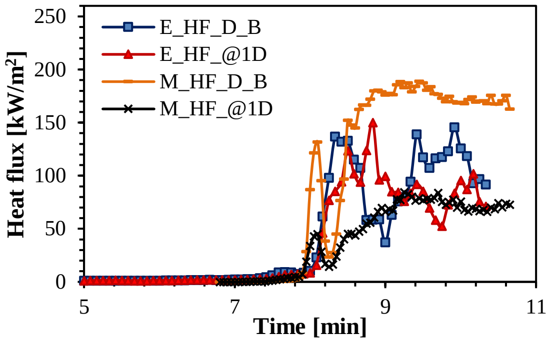

Figure 5.15: ISD2 - Heat flux curves in front of the door

Figure 5.16 and Figure 5.17 present HF values at the door of ISD 3 and the window of ISD1, and these provide a better correlation, although the FDS model still overpredicts the initial heat fluxes, but it seems that the curves may have reached the same steady state values. Steady state in this case lasted for a very short period as a result of the burning of the timber cladding and structural collapse.

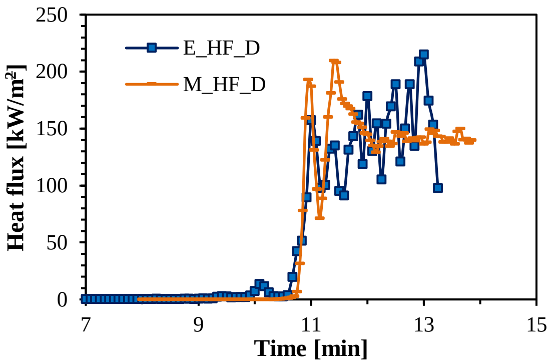

Figure 5.16: ISD3 - Heat flux curves in front of the door

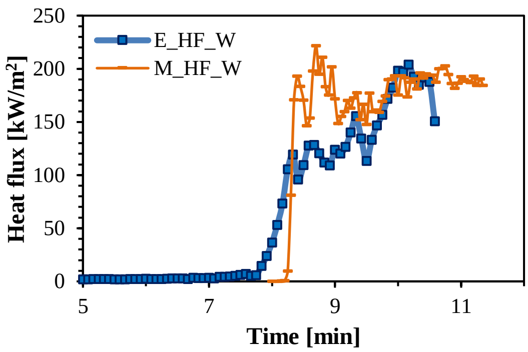

Figure 5.17: ISD1 - Heat flux curves in front of the window

5.6. Influence of mesh independent parameters on fire spread

The purpose of this section is to highlight the importance of the input parameters and how they affect the fire spread behaviour between dwellings. Parameters such as specific heat, conductivity, emissivity of the lining material, the emissivity of the compartment boundaries, soot yield and radiative fraction are considered. For simplicity, and space limitations, only the steel clad dwelling was used for the sensitivity analysis, as its behaviour can be more accurately captured. The effect of the various parameters is studied by considering the spread rate between dwellings and the heat fluxes experienced. Heat fluxes at 1 meter away from the door (1750 mm from ground level) of ISD2, and internal ceiling temperatures, are used as a comparison between models, although multiple values could have been considered. Note that the model heat flux curves times were offset in order for the flashover phase to match with the flashover phase of the experiment.

5.6.1. Specific heat

The specific heat of the cardboard has a negligible effect on the heat fluxes experienced and on the steady state ceiling temperatures. It does however have an effect on the fire spread rate. Considering Figure 5.18 closely, it seems that the spread rate between ISD2 and ISD3 remained approximately the same, but that the spread rate between ISD1-ISD2 increased rapidly for C_p = 1.5 kJ/(kg·K) (the spread rate did increase slightly for C_p = 1.5 between ISD2-ISD3 as a result of a decrease in thermal inertia). An increase in spread rate indicates a shorter time between flashover phases, as mentioned earlier. Lowering the specific heat below a certain value enables the cardboard (in ISD2) to heat up fast enough to ignite with the initial heat flux peak that corresponds with the full ignition of the cardboard rather with the heat flux generated by the timber cribs (i.e. the burner in the case of the FDS model).

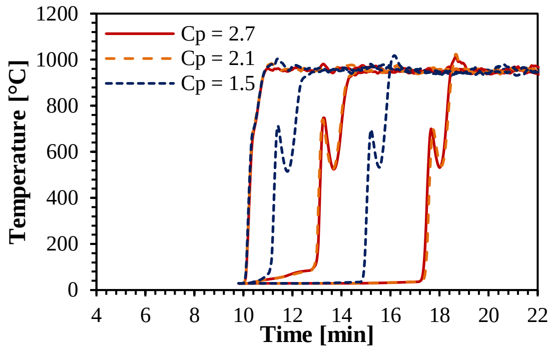

Figure 5.18: Ceiling temperatures - Variation in the specific heat of the cardboard

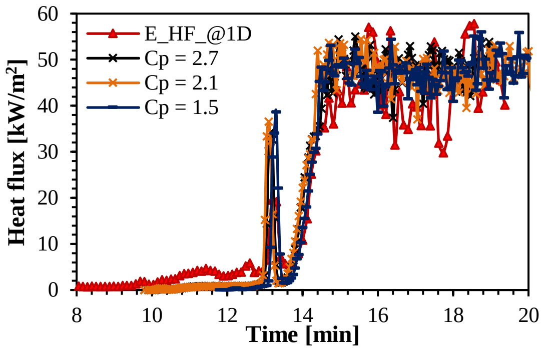

Figure 5.19: Heat fluxes at 1 meter away from the door – Variation in the specific heat of the cardboard

5.6.2. Conductivity

In this case the fire spread rate between dwellings increases as the conductivity of the cardboard decreases, meaning a shorter time to ignition for the cardboard of the adjacent dwelling. This follows the well-known argument that for thermally thick solids (i.e. a solid with a thickness greater than 15 mm [27]), the thermal inertia governs the ignition and surface flame spread.[24] The thermal inertia (that consists of the conductivity) determines the rate of rise in surface temperature and consequently the time to ignition. Thus, by increasing the conductivity, the rate of rise in surface temperature is decreased and as a result the time to ignition is increased.

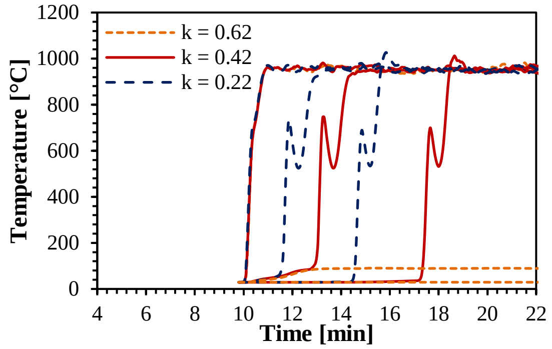

Figure 5.20: Ceiling temperatures - Variation in the conductivity of the cardboard

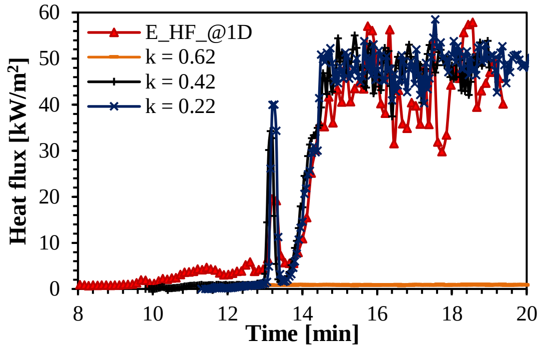

Figure 5.21: Heat fluxes at 1 meter away from the door - Variation in the conductivity of the cardboard

5.6.3. Emissivity of lining material

The emissivity of the cardboard has a negligible effect of the heat fluxes experienced, as depicted in Figure 5.23. However, Figure 5.22 indicates that as the emissivity decreases the fire spread rate between dwellings decrease. This is similar to a finding in [28] and it follows Kirchhoff's law that states that a fraction of the total radiative power that the surface of the cardboard emits and absorb is represented by the emissivity, meaning that the absorption component dominates for relatively cold surfaces heated by a nearby flame. By establishing the fraction re-radiated back into the gas phase and the fraction of incident radiation absorbed, this parameter has a large effect on the surface temperature.[28]

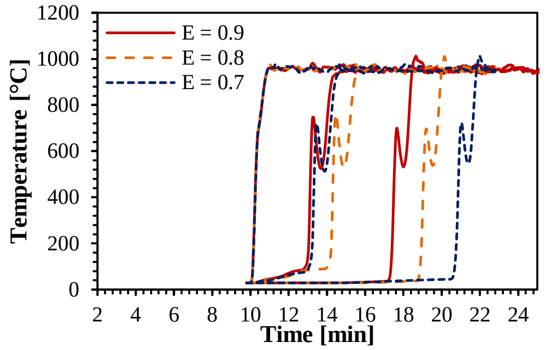

Figure 5.22: Ceiling temperatures - Variation in the emissivity of the cardboard

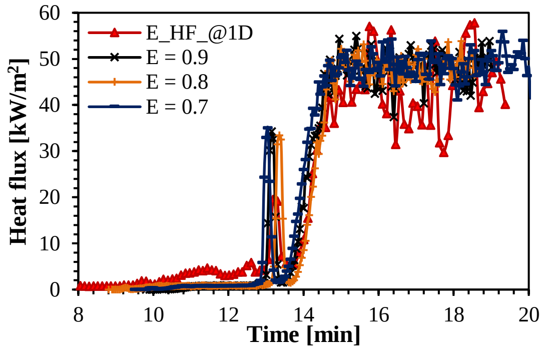

Figure 5.23: Heat fluxes at 1 meter away from the door - Variation in the emissivity of the cardboard

5.6.4. Emissivity of compartment boundaries (i.e. the corrugated steel cladding)

Figure 5.24 and Figure 5.25 show the influence of the corrugated steel emissivity, and it is clear that the emissivity of the steel has a substantial effect on the gas temperature in the compartment. As the emissivity increases the compartment gas temperature decreases, and as a result the heat fluxes decrease. It seems counterintuitive that as the gas temperature and radiation decrease the fire spread rate between dwellings increase. A possible explanation for this could be that as the emissivity increases the steel becomes a better absorber and emitter of heat, allowing the cardboard of the adjacent dwelling to heat up at a faster rate.

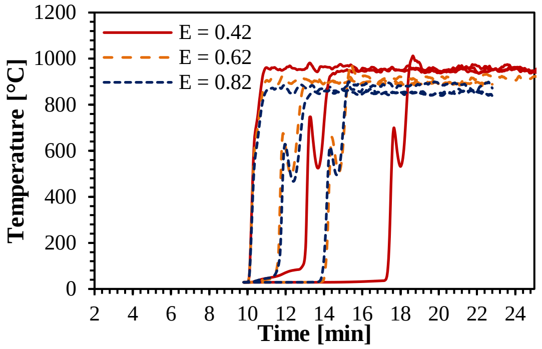

Figure 5.24: Ceiling temperatures – Variation in the emissivity of the corrugated sheeting

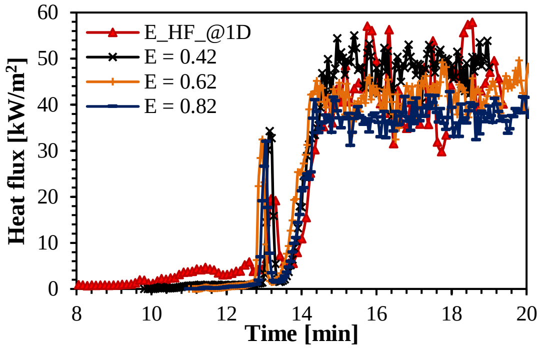

Figure 5.25: Heat fluxes at 1 meter away from the door – Variation in the emissivity of the corrugated sheeting

5.6.5. Soot Yield

The soot yield has almost no effect on the heat fluxes experienced, as depicted in Figure 5.27. The soot yield does however affect the gas temperature in the compartment and from Figure 5.26 it is clear that the higher the soot yield, the higher the gas temperature. Increasing the soot yield from 0.03 to 0.045 increases the spread rate. On the other hand, decreasing the soot yield to 0.015 did decrease the spread rate between ISD2-ISD3, but not between ISD1-ISD2 which appears to be counter-intuitive. It might be that the change in soot yield changed the local turbulent behaviour between the dwellings and as a result an extended flame caused earlier spread.

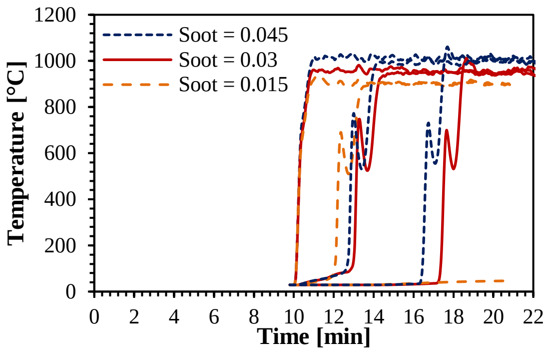

Figure 5.26: Ceiling temperatures – Variation in the soot yield

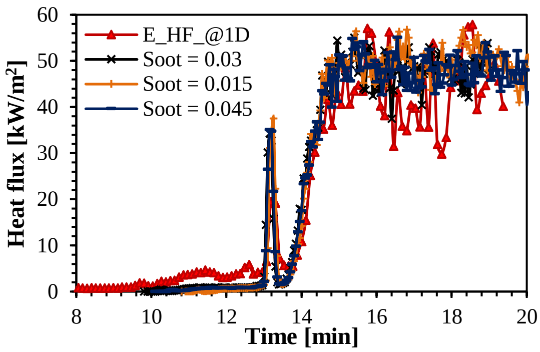

Figure 5.27: Heat fluxes at 1 meter away from the door Variation in the soot yield

5.6.6. Radiative fraction

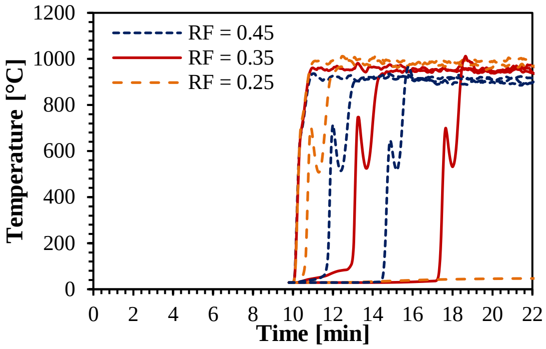

Figure 5.28: Ceiling temperatures – Variation in the radiative fraction

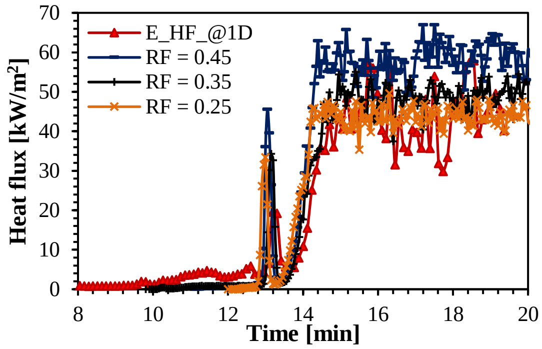

Figure 5.29: Heat fluxes at 1 meter away from the door – Variation in the radiative fraction

Changes in the radiative fraction specified affects the heat fluxes experienced, as depicted in Figure 5.29. As the radiative fraction increase, the heat fluxes increase. The radiative fraction has an opposite effect on the gas temperature in the compartment, because as the radiative fraction increases the gas temperature decreases. From Figure 5.28 it indicates that as the heat flux increases (i.e. as a result of the increase in radiative fraction) the spread rate increases. However, for the radiative fraction equal to 0.25 the spread rate increased between ISD1-ISD2 but decreased between ISD2-ISD3. This indicates that the spread rate between ISD1-ISD2 is likely more susceptible to gas temperature.

5.7. Conclusion

This work has developed models in FDS to predict and analyse fire spread in informal settlements. The steel clad model developed shows good correlation with the experimental results, but the fire spread rate is extremely sensitive to the input parameters. There is still a significant work needed to develop an engineering approach (i.e. a simplified and practical method) to model large-scale fire spread in informal settlements, especially where combustible side claddings are present leading to continuously changing ventilation conditions.

This work highlighted the importance of input parameters and the substantial effect it has on the rate of fire spread between dwellings. For the lining material used, an increased specific heat, an increased conductivity and a decreased emissivity lead to a decrease in spread rates. Predicted spread rates between dwellings can range between 1 minute and 4 minutes (relative to the experimental value of approximately 3 minutes) for ISD 1-2, and between 3 and 7 minutes to no spread (relative to the experimental value of approximately 2 minutes) for ISD 2-3. When modelling spread between dwellings in large settlements the time of fire spread from dwelling to dwelling is an important factor, but this work has shown how it is difficult to define due to the inherent variability of materials used in informal settlements. However, with further research the model could be extended, especially through the use of statistical procedures, to be suitable for considering such variability in informal settlements. By considering the variety of materials used in settlements, variations in distances in dwellings, changes in ventilation conditions and construction materials used, a Monte Carlo-type analysis could be used to provide a distribution of expected spread times between dwellings, and then applied to capture large-scale fire spread. Such spread models would be useful for understanding, and potentially predicting, the large fire disasters that regularly occur in countries such as South Africa. Finally, as a result of the sensitivity of input parameters, results from FDS should be interpreted carefully and should be validated or verified where possible.

5.8. Acknowledgements

The authors would like to acknowledge the financial support of the Cape Higher Education Consortium & Western Cape Government (CHEC-WCG) partnership, the Ove Arup Foundation (TOAF), and the Global Challenges Research Fund (GCRF of the EPSRC) under unique grant number EP/P029582/1. Computations were performed using the University of Stellenbosch Central Analytical Facilities, HPC1: http://www.sun.ac.za/hpc

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Chapter 6: Conclusion

This work has developed novel understanding of (a) the enclosure fire dynamics in ISDs, (b) the heat fluxes emitted by ISDs, (c) the effect of different cladding materials on (a) and (b), and has presented novel work investigating (d) the use of numerical models to predict the behaviour of ISD fires. Figure 6.1 summarises the development of the research in this work, as presented in Chapter 1. Each chapter has presented detailed conclusions regarding the aspects addressed. However, details below present some overarching conclusions stemming from this research.

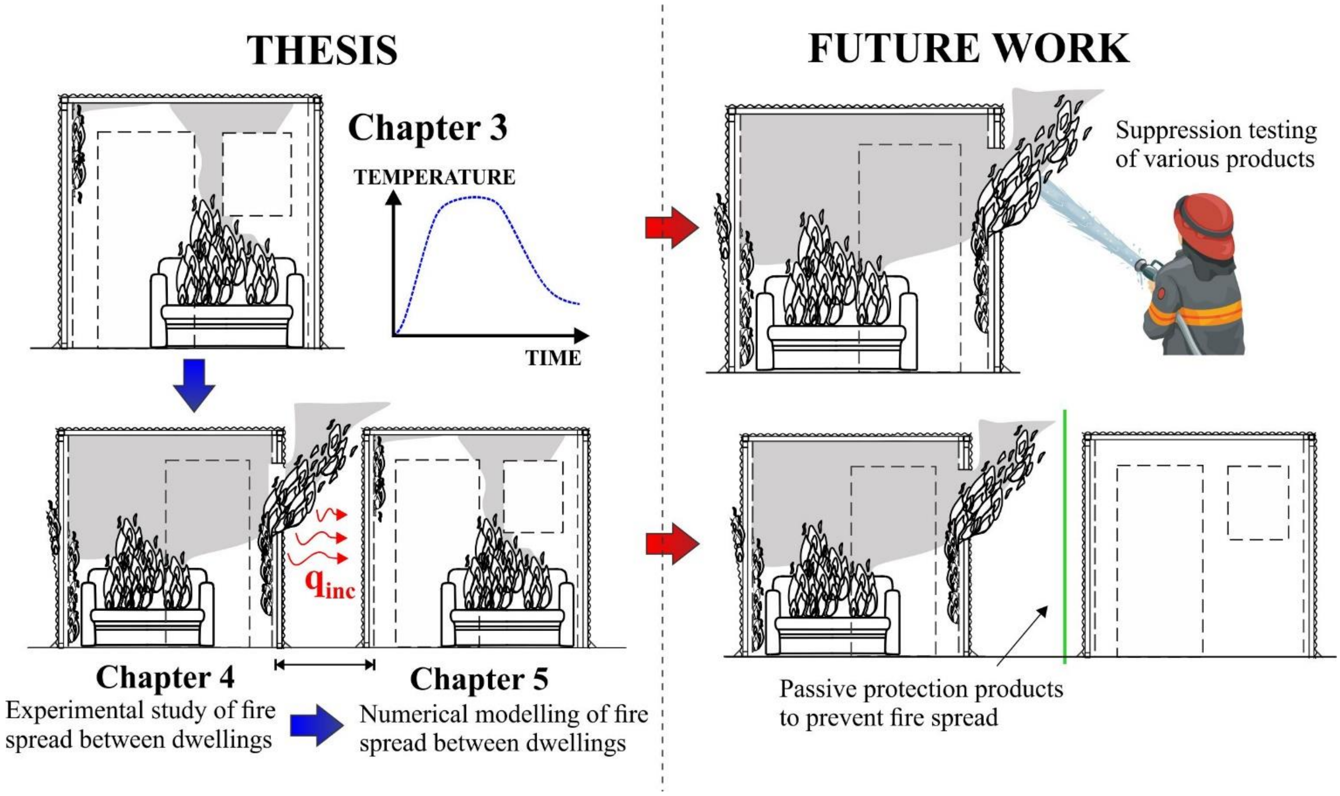

Figure 6.1: Dissertation structure with guidance for future work

It is clear that informal settlement fires are a global problem and that the knowledge regarding these fires is in its infancy. The work shows that ISDs behave very similar to formal dwellings (Chapter 3-4) i.e. the fire has an ignition, a growth stage, flashover stage, a full developed fire stage and a decay stage (collapse in this case). It was found that the timber dwellings are more prone to fire spread as a result of higher heat fluxes and faster spread rate between dwellings (Chapter 4). It is clear that with heat fluxes surpassing 150-200 kW/m^2 at 1 meter away from the door that any common material will be ignited within seconds. This highlights the risk associated with these closely spaced structures. The work found that an approximate primary safe separation distance of 3 m (i.e. based on the average heat fluxes emitted during the single dwelling experiments) would be sufficient for fire spread not to occur, although further work is required to consider factors such as wind and ember attack. It should be acknowledged that a separation distance of 3 m is not always possible because of socio-economic-political issues, and although the research results may inform good practice, due to the lack of code enforcement in settlements may not necessarily be easy to implement. Further research may also highlight that when wind and ember attack are included, even though a 3m separation distance does reduce the probability of large fires occurring, it might still not be sufficient to completely avoid fire spread between dwellings.

The dissertation also touched on the subject of fire spread interventions and the lack thereof. It was seen that the proposed "solutions" typically lack a technical basis or did not consider the socio-economic-political issues inherent in informal settlements (for more information refer to Appendix A.1). The hope is that the experiments conducted in this work will be used as a benchmark to tests and compared future interventions and that the experiments will for a basis for future research.

The research continued by developing detailed FDS models (i.e. to the level of modelling the timber crib behaviour) and came to the conclusion that FDS captures enclosure fire dynamics in ISDs and heat fluxes emitted by ISDs well. However, it is worth noting that there are a significant number of assumptions made to model these experiments and that the results should be interpreted accordingly, and that the findings might differ for other ISDs. Additionally, the FDS models also showed less agreement to the timber clad experiments and this was mainly as a result of how the timber cladding was modelled and how the cladding behaved in the experiments (i.e. the enclosure had continually changing ventilation conditions as a result of the cladding burning away). Since the "detailed" FDS models showed relatively good correlation to the experiments, the research continued by attempting to simplify the FDS models (i.e. by increasing the cell size and by modelling the cribs with burners). The basis for the simplified model was to create a model that was computationally less time consuming, making modelling of multiple dwellings more practical. The "simplified" FDS models developed showed good correlation with the steel clad dwellings, but as a result of further assumptions (i.e. compared to the detailed FDS models), the simplified models did not show very good correlation, in terms of heat fluxes emitted, with the timber clad dwellings. However, it should be noted that the FDS models still captured the overall trends of the timber clad experiment and also showed good spread rate correlation compared to the timber clad experiment.

Chapter 5 concluded by conducting a sensitivity study of mesh independent parameters, where it was found that the models are extremely sensitive to the material properties of the cardboard (i.e. the inner wall lining materials). The sensitivity study further revealed that certain parameters have a substantial effect on fire spread and should be further investigated to determine if material parameters can be used to improve fire safety in these areas. Based on the simplified FDS models it is clear that the emissivity of the compartment boundaries played a substantial role in the heat fluxes emitted, where an increase in emissivity led to a decrease in heat fluxes emitted. Furthermore, although obvious, properties effecting the thermal inertia of the lining material had a large effect on the spread rate, where an increase in thermal inertia led to an increase in the time to ignition of adjacent structures (i.e. a material takes longer to ignite when exposed to a constant heat flux). The challenge in real dwellings is that homes are lined with a very wide variety of materials, making definitive assertions regarding individual fire behaviour difficult. However, on a global scale through the use of statistical procedures coupled with a knowledge of generally used materials, it may be possible to capture general behaviour observed in large settlements (as discussed in Section 6.1 below).

It is clear that the solution to this complex problem is not simple, and as a result of the complex nature of informal settlements, the solution cannot be obtained by isolating and simplifying the problem as typically done for formal areas, but it must rather be addressed though a holistic approach. It is clear that the solution will be a combination of components, across multiple sectors including engineering design, education, firefighter interventions, early warning systems, risk reduction measures and much more. However, with one billion people residing in informal settlements, it is necessary that greater effort be placed on improving fire safety in these communities.

6.1. Future research stemming from this work

Throughout this dissertation, and above, mention has been made of the next steps that can be taken to address many questions regarding fire safety for informal settlements, as shown in Figure 6.1. Many of these steps are now being addressed through the work of other co-researchers, based on the results of this dissertation, namely:

- Study on the use of suppression products for informal settlements, and the development of a benchmark test for evaluation suppression systems (Loffel, 2019).
- Forensic investigations to understand fire disasters and to more accurately analyse fire spread mechanisms, along with human movement during incidents (Flores Quiroz, 2021).
- Development of benchmark tests for assessing passive protection products applied to informal settlements homes, that provides a representative fire exposure environment (Narayanan, 2021).
- Computational modelling of large-scale fire spread (De Koker et al., 2019).
- Various other tests looking at scaled models for analyzing fire spread.
- Developments of informal settlement risk maps.

It is envisaged that the various other topics for future research in this dissertation will be progressively addressed by researchers in the coming years, both locally and internationally. This research has not solved the problem of informal settlement fire safety, but has provided a foundation from which further research, such as listed above, can start making inroads into the municipal, fire brigade, household and governmental response to this problem.

An obvious next step to this research would be to develop a statistical fire spread model where the inputs to the physics base model would be generated based on a Monte Carlo analysis. In such a model, spread time can be defined as:

$$t_s = t_f + t_{ig} \tag{6.1}$$

where t_f is the time it takes the dwelling to reach its fully developed fire stage, once ignited (at which point it starts radiating heat onto the adjacent dwelling, i+1) and t_{ig} is the time it takes the dwelling (i.e. dwelling i) to ignite the adjacent dwelling (i.e. dwelling i+1). A simple procedure is depicted in Figure 6.2.

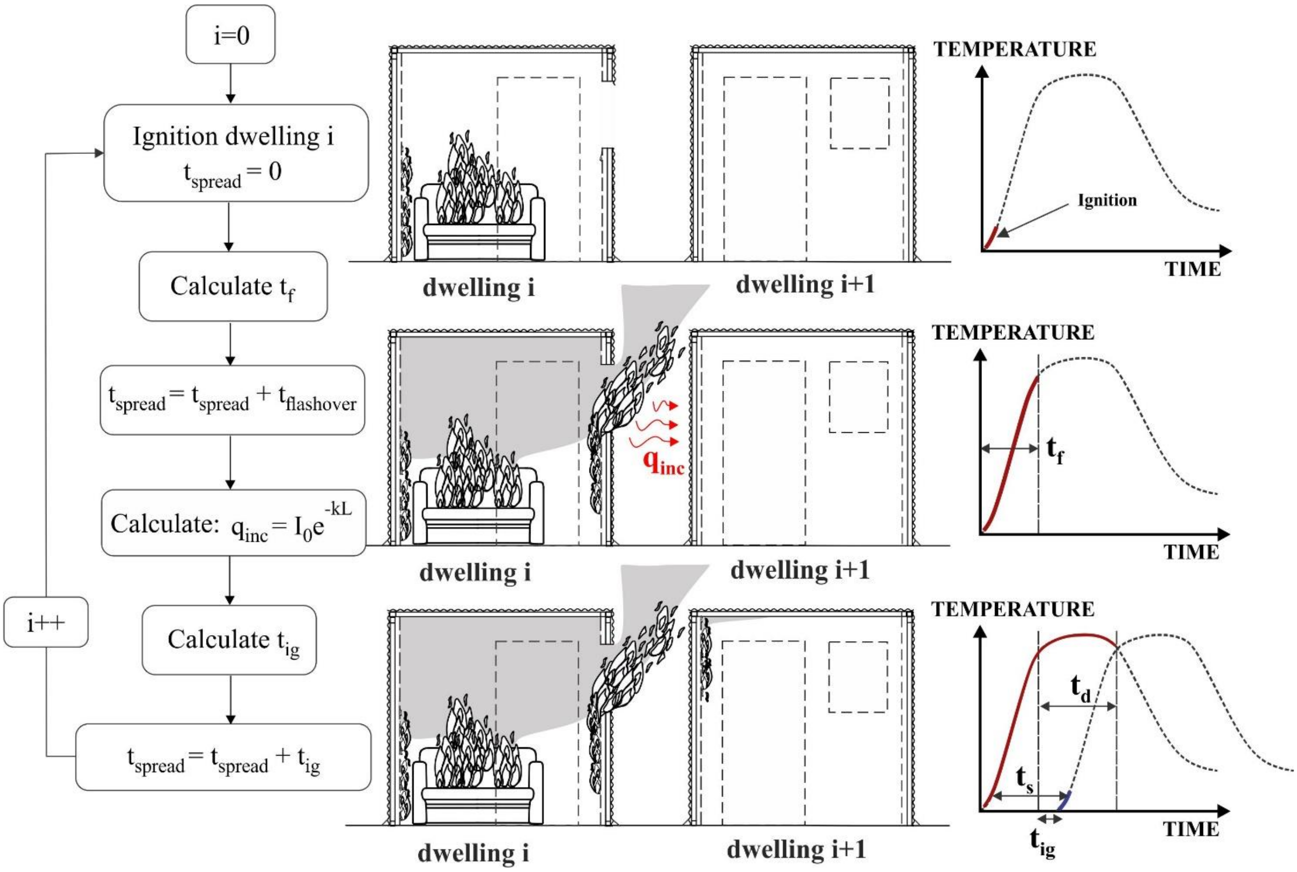

Figure 6.2: Fire spread methodology

Where the inputs needed to calculate t_f (Equation 2.9), q_{inc} (Equation 4.2.) and t_{ig} (Equation 2.1 and 2.2) will be generated based on a Monte Carlo analysis. The maximum period that radiation can be emitted from a dwelling's openings is up to the point of structural collapse (a method to estimate the time to structural collapse is given in Appendix A.2) or up to the point of fuel depletion. By supplying data regarding distributions in fuel load, distance between dwellings, ventilation conditions, material types and similar factors it may be possible to simulate large fires to provide predictive capabilities in identifying high risk areas, or to quantify the magnitude of disaster municipalities may need to respond to.

6.2. Recommendations for future experimental work

Future research can focus on many different aspects, ranging from refining technical parameters to improve modelling, to developing guidelines to improve fire safety. For future experiments, it is recommended that the heat release rate and mass loss rate during the experiments be measured. The heat release rate data of the cribs and cardboard will add a lot of value towards the development of the simplified FDS models proposed in this dissertation. It is also recommended that a study on the effect of leakage and thin boundaries (i.e. by doing a heat balance of the compartment) on the heat fluxes emitted by the dwellings be conducted.

Furthermore, in order to get a better understanding of how certain variables effect the emitted heat fluxes, an experimental parametric study testing different variables such as dwelling sizes (e.g. double storey dwellings, dwellings with larger floor areas, irregular shape dwellings), fuel loads (e.g. furniture, fuel with high calorific values), ventilation conditions (e.g. adding glass and doors to the opening, changing the size of the openings), dwelling geometries, lining materials (e.g. timber, curtains), etc. will be advantageous.

Moving away from pure engineering research, the development of guidelines to inform fire safety in informal settlements is a natural next step in this overall research field. This would be of significant use to municipalities, governmental agencies and NGOs. The challenge is that it is difficult, from an engineering perspective, to define and implement performance requirements in the manner done for formal dwellings. However, through the insight gained in this work fire engineers can apply the knowledge to ascertain which products, suppression systems, area layouts and fire brigade responses may, or may not, be effective. Much of this work is already underway as part of the larger project, although in many instances may have to be qualitative. It is envisaged that such work may lead to, for example, municipalities and organisations discouraging the usage of certain lining systems, and preventing community relief work projects from supplying materials meeting certain requirements. Furthermore, through the application of the work it may be possible to identify more critical areas, in terms of fire spread, in a settlement and this could guide where effort should be placed in terms of the role-out of interventions.

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Appendix A

In the development of this dissertation a variety of research papers focusing on informal settlement fire safety have been completed in conjunction with other researchers. The abstracts of papers included in this Appendix address issues closely aligned with the work in this dissertation but have not been included in the body of the work as they do not focus on the central theme of understanding fire dynamics. The reader is referred to them for:

- the application of this work in understanding what interventions may or may not work in settlements (A.1);
- an approximate method for predicting collapse times of dwellings (A.2);
- an example of a large fire where thousands were left homeless (A.3), which could be used to calibrate the spread model proposed in Chapter 6; and
- lessons learnt in experimental testing of informal settlement dwellings (A.4).

A.1. Appraisal of fire safety interventions and strategies for informal settlements in South Africa

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Published in: *Disaster Prevention and Management: An International Journal* (*https://doi.org/10.1108/DPM-10 2018-0350*)

This abstract is an exact copy of the abstract of the paper referred to above

A.1.1. Abstract

Purpose – Informal settlements are inherently unstructured in nature, lack adequate services, regularly have high population densities and can experience social problems. Thus, fires can easily propagate rapidly through such areas, leaving thousands homeless in a single fire. The purpose of this paper is to present an appraisal of various interventions and strategies to improve fire safety in informal settlements in South Africa (globally, similar settlements are known as slums, ghettos, favelas, shantytowns, etc.), considering aspects of both technical suitability and social suitability.

Design/methodology/approach – This paper focusses on three specific aspects: ignition risk management, active fire protection interventions and passive fire protection interventions. These are presented within a framework to outline how they may mitigate the impact of fires.

Findings – Often "solutions" proposed to improve fire safety either lack a sound engineering basis, thus becoming technically inefficient, or do not consider social circumstances and community responses in settlements, thereby becoming practically, socially or economically unsuitable. It must be understood that there is no "quick fix" to this significant problem, but rather a combination of interventions can improve fire safety in general. A broad understanding of the various options available is essential when addressing this problem, which this paper seeks to provide.

Practical implications – This paper seeks to provide an overview to guide policymakers and organisations by illustrating both the advantages/benefits and disadvantages/challenges of the interventions and strategies currently being rolled out, as well as potential alternatives.

Originality/value – A broad but succinct appraisal is provided that gives insight and direction for improving fire safety in informal settlements. It is hoped that the challenges associated with the fire safety interventions discussed can be addressed and improved over time.

A.2. Estimating time to structural collapse of informal settlement dwellings based on structural fire engineering principles

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Stellenbosch University, Department of Civil Engineering, Stellenbosch, South Africa

Published in: *The Seventh International Conference on Structural Engineering, Mechanics and Computation (SEMC 2019)*

This abstract is an exact copy of the abstract of the paper referred to above

A.2.1. Abstract

To model the spread of fire through informal settlements (also known as slums, favelas, shanty-towns, etc.) it is important to be able to approximate the time at which structural collapse of the dwellings (sometimes referred to as "shacks") occur. Fire spread models can be an important tool for analyzing how to improve the fire safety of settlements through layout reconfiguration, or for analyzing the influence of different construction types. This paper provides input to fire spread models by developing a methodology for determining the time to the structural collapse of informal dwellings based upon experimental data and methods in the literature. The paper compares theoretical collapse times (based on the effective cross-section method) to experimental collapse times to evaluate whether structural fire engineering principles can be applied to in-formal structures, which are areas where there is untreated timber, eccentric members, out-of-straight elements, etc. Data from four full-scale experiments consisting of 8 dwellings has been utilized, and this data consists of both timber clad and corrugated steel clad dwellings. The timber clad dwellings experience a sway collapse (i.e. as a result of the cladding burning away) whilst the steel clad dwellings experience roof collapse as a result of the simply supported ceiling beam failing in bending. All timber clad dwellings collapsed ap-proximately 5 minutes after flashover and the steel dwellings collapse approximately 6-8 minutes after flash-over. The effective cross section method indicates that for both the timber clad and steel clad dwellings the theoretical time to collapse falls within the range of the experimental collapse times. Even though there are significant uncertainties inherent in analyzing informal settlements this work provides novel insight with regards to how structural fire engineering principles can be applied within sub-models of systems analyzing fire risk and spread, such that the safety of the 1 billion people living in informal settlements can be improved.

A.3. Fire spread analysis for the 2017 Imizamo Yethu informal settlement conflagration in South Africa

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Stellenbosch University, Department of Civil Engineering, Stellenbosch, South Africa

Published in: *International Journal of Disaster Risk Reduction, 2019 (DOI: 10.1016/j.ijdrr.2019.101146)*

This abstract is an exact copy of the abstract of the paper referred to above

A.3.1. Abstract

On 11 March 2017, a large fire ravaged through the Imizamo Yethu informal settlement in Cape Town, South Africa, killing four people. A total of 2194 informal dwellings were destroyed, and over 9700 people were displaced. This paper presents an analysis of the spread of the fire and factors that contributed to the conflagration. This work is based on interviews with the firefighters that responded to the incident, the disaster management incident log of the day, photographic evidence from various sources, reports in the public domain and site visits. Over 170 firefighters drawn from across the City of Cape Town's Fire and Rescue Services battled for over 13.5 h to put out one of the largest fires to have happened in a South African settlement in recent times. The efforts by firefighters to tackle the fire were hampered by several factors among them, inaccessible or narrow driveways, the absence of sufficient water supply in the area, and certain community interactions. This work is novel as in the literature there is negligible data regarding fire spread analyses in informal settlements. This has hampered the development of evidence-based responses and fire safety interventions being developed, as it is sometimes unclear how to reduce fire spread. The rate of spread during the fire is approximately calculated. By understanding fire spread rates, community interactions and suppression challenges firefighting strategies, engineering designs and municipal responses to this problem can be enhanced.

A.4. Fire dynamics in informal settlement "shacks": Lessons learnt and appraisal of fire behaviour based on full-scale testing

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This abstract is an exact copy of the abstract of the paper referred to above

A.4.1. Abstract

This paper presents discussions regarding informal settlement (also known as slums, shantytowns, favelas, etc.) fire dynamics and lessons learnt from full-scale tests on dwellings, typically referred to as "shacks" in South Africa. Smoldering and flaming fire setups are considered, and both timber and representative household contents are used as fuel sources. It is shown that due to the small size of shacks flashover can be obtained within minutes. Maximum temperatures recorded are typically around, or in excess of, 1000°C, depending on the fuel and structural configurations. Due to the poor construction methods used for such structures they can collapse, or walls can open up, meaning that ventilation conditions continuously change and are difficult to accurately define. The presence of flammable wall finishes or drapes has a significant effect on the rate of fire spread and fire behaviour, and such flammable finishes are often present in dwellings. Computational fluid dynamic (CFD) software (Fire Dynamics Simulator (FDS)) is utilized to analyze certain tests, which generally shows good correlation. However, due to significant variations in fuel contents, ventilation conditions, structural configurations and wall finishes there is a high degree of uncertainty inherent in developing models for such environments. From the work a greater understanding of fire dynamics in low income, temporary structures (comparable with some refugee camps) can be obtained through which better solutions and interventions can be developed. Recommendations are provided for how to simulate shack fire scenarios in experimental testing more effectively.

Appendix B

This Appendix provides additional information with regards to the experiments conducted in this dissertation that was not addressed in the body of the dissertation. As mentioned in the body, the timber and steel clad dwellings were identical with the only difference being the cladding material of the walls. All dwellings used in this dissertation were constructed by simply assembling the panels depicted in Figures B.1-B.5 in a specific manner. The corrugated steel sheets left and right roof panel were used to construct the roof of all the dwellings used in the dissertation. The dotted lines indicate the 50×50 mm timber sections.

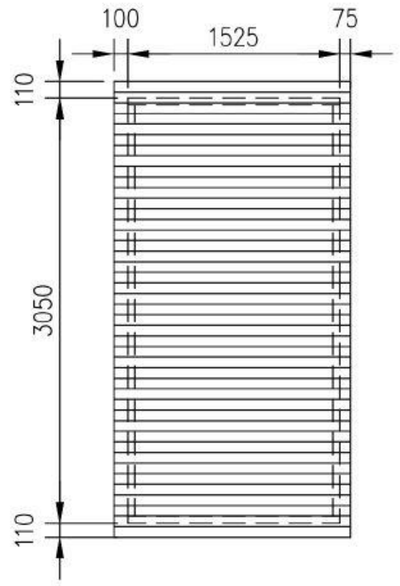

Figure B.1: Left roof panel

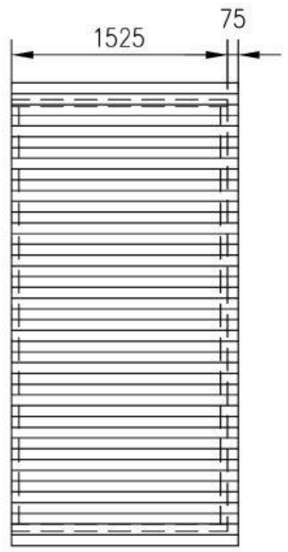

Figure B.2: Right roof panel

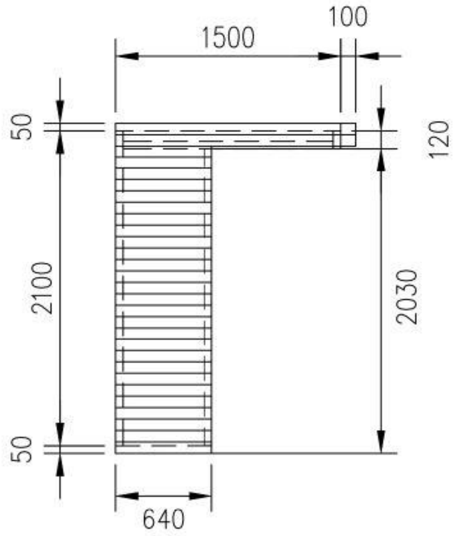

Figure B.3: Door panel

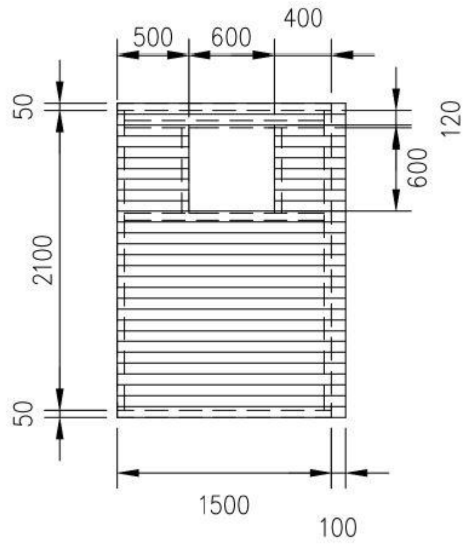

Figure B.4: Window panel

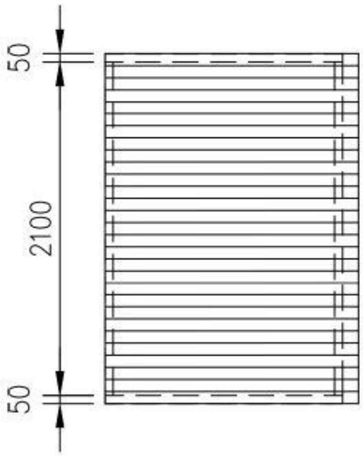

Figure B.5: Side panel

Appendix C. Clarification on specific topics discussed in the body of this dissertation

The purpose of this section is to elaborate on certain topics discussed in this dissertation, and to rectify one issue in Chapter 4. Since the dissertation was done by publication, some discussions in Chapter 3 to 5 were shorted due to space constraints in journal publications. Throughout this dissertation superscripts have been added to indicate further discussion at a later stage, as provided below. The elaboration is addressed in a bullet manner below, where the letter refers to the corresponding superscript in the body of the dissertation.

a. Section 3.5.2: The leakage area of 0.0255 m^2 is the approximate leakage area of the gaps created by the flutes of the corrugated steel sheets. The flute height was 17 mm, meaning an average opening height of 8.5 mm. Multiplying the opening height by the length of the dwelling (3 m) gives an approximate leakage area of 0.0255 m^2 per wall.

b. Section 3.5.2: Although the position of the gaps in the timber clad dwelling (representing leakage between timber planks) were placed arbitrarily, a sensitivity study was done to determine the effect of the position of the gaps on the FDS results, compared to the experimental results. Moving the gap closer to the ceiling level resulted in slightly lower temperature readings. The placement of the gaps had a negligible effect on the heat fluxes obtained, which was also the critical output parameter in this case.

c. Section 4.5.2: It should be noted that Equations 4.2 is an incorrect application of Beer's law, and that the equation used should rather be seen as fitting an inverse exponential function, that is a function of the distance between dwellings (L), to the experimental results. Thus, the coefficient κ should be seen as a correlation factor, as opposed to the absorption coefficient, where κ = 0.75 gives the best fit to the experimental data. The correct method to calculate the radiation at a distance is to consider (i) the radiation emitted from the hot compartment (comp), plus (ii) the radiation emitted from the flames ejecting from the opening (flame), plus (iii) the radiation emitted from the galvanised steel sheets (sheet). The radiation emitted then reduces as the target (the receiver) moves further away from the emitters, i.e. as a result of the configuration factor. The equation describing the three items above is as follows:

$$\dot{q}'' = \sigma \varepsilon_{flame} \emptyset_{flame} T_{flame}^4 + \sigma \varepsilon_{comp} \emptyset_{\mathrm{comp}} T_{comp}^4 + \sigma \varepsilon_{sheet} \emptyset_{sheet} T_{sheet}^4 \qquad \text{(C.1)}$$

where $\emptyset$ is the configuration factor for each source. Assuming that the emitters and receiver are parallel to each other, the configuration can be described with the following equation:

$$\emptyset = \frac{2}{\pi}\left[\frac{x}{\sqrt{1+x^2}} tan^{-1}\left(\frac{y}{\sqrt{1+x^2}}\right) + \frac{y}{\sqrt{1+y^2}} tan^{-1}\left(\frac{x}{\sqrt{1+x^2}}\right)\right] \qquad \text{(C.2)}$$

where $x = H/2L$ (H being the height of the emitter), $y = W/2L$ (W being the width of the emitter) and L is the distance between the emitter and the receiver in meters. $\varepsilon_{flame} = 0.465$ (as calculated in

Section 4.5.2), $\varepsilon_{comp} = 1$ (Section 4.5.2), $\varepsilon_{sheet} = 0.42$ (Section 3.5.2), $T_{flame} = 900$°C and $T_{comp} = 1030$°C. Since the temperature of the galvanized sheets was not measured, a range of $T_{sheet} = 600$°C $-$ 900°C is considered (where $T_{sheet} = 600$°C is used in the lower bound heat flux curve and where $T_{sheet} = 900$°C is used the upper bound, as depicted in Figure C.1). For the hot compartment gases, the configuration factor is calculated using Equation C.2, where the emitter height and width are considered to be the height and width of the door (H = 2.03 m and W = 0.86 m). For the steel sheets, the configuration factor is calculated using Equation C.2, where the emitter height and width are considered to be the height and width of the front face of the dwelling (H = 2.3 m and W = 3 m) minus the configuration factor of the door. Lastly, the configuration factor for the flame at the door is also calculated using Equation C.2, where the emitter height (H) is considered as a range between 2 - 4 m (where H = 2 m is used in the lower bound heat flux curve and where H = 4 m is used in the upper bound, as depicted in Figure C.1) and the width is considered as the width of the door opening (0.86 m). Furthermore, at L = 0 m the door flame does not contribute to the radiation since the combustion is happening behind L = 0. In this case it is assumed the percentage of q_{flame} is zero at L = 0 and that the percentage received increases approximately linear between L = 0 m and L = 1 m, according to the measured heat fluxes. Based on the details above the graph in Figure C.1 is obtained, with an upper bound and lower bound being plotted, based on varying the temperature of the sheeting and flame height. Due to the corrugations of the steel sheeting, difficulty in accurately defining the size of the flame, the inclination of the flame, and similar issues, the proposed methodology is approximate, but nevertheless suitable for obtaining an estimate of heat flux at a distance from the dwelling.

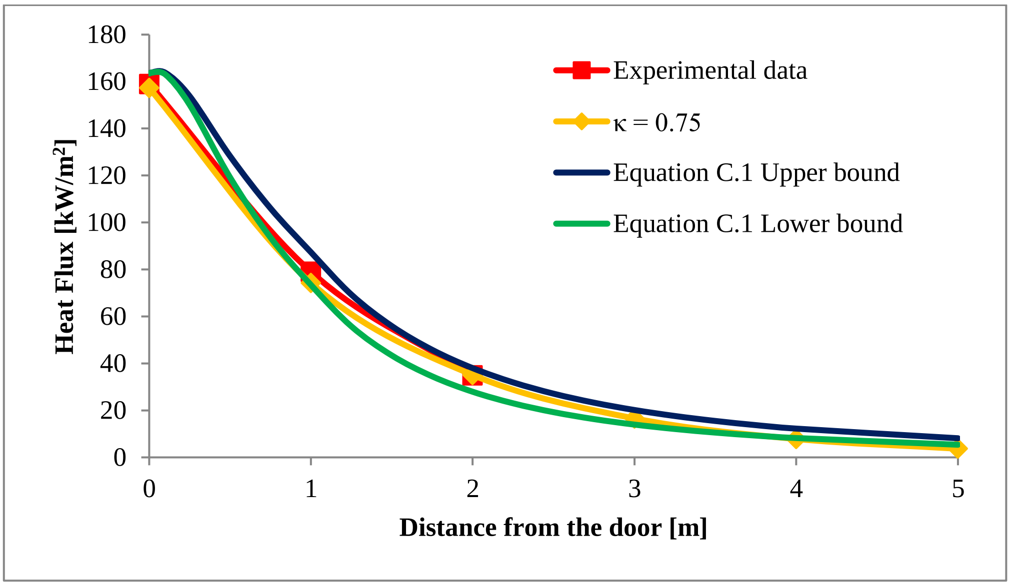

Figure C.1: Radiation at a distance away from the door of ISD2

From Figure C.1, assuming a CHF of 8.5 kW/m^2, the exponential fitted curve ($\kappa = 0.75$) gives a minimum separation distance of 3.8 m, whereas the lower and upper bound curves produced based on Equation C.1 give a minimum separation distance of 3.9 m - 4.8 m. It should still be noted that a

CHF of 8.5 kW/m^2 is a lower bound value for cardboard and that the assumptions of (a) the emitters and receiver being parallel to each other and (b) that the cardboard is directly exposed to the radiations are conservative. Thus, the separation distance of 3.9 m – 4.8 m is conservative in wind still conditions.