

Thermal behaviour of fire-resistant ceiling boards in a novel cellular beam structure

by

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Declaration

I, PALESA JENNIFER MNANZANA, #####, do hereby declare that this research project, which has been submitted to the Central University of Technology Free State, for the degree: Master of Engineering in Mechanical Engineering, is my independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules, and regulations of the Central University of Technology, Free State. This project has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Abstract

The thermal behaviour of fire-resistant ceiling boards in a novel cellular beam structure is crucial in ensuring the safety and structural integrity of buildings under fire conditions. Recent studies have revealed that there is a lack of comprehensive understanding regarding the thermal behaviour of fire-resistant ceiling boards, particularly ceiling boards with holes, in a novel cellular beam structure. To address this knowledge gap, this dissertation will conduct experimental tests on fire-resistant ceiling boards with service holes, subjected to standard fire temperatures within a furnace. The experimental tests will be followed up with Finite Element Analysis (FEA) modelling of the same samples and a comparison of the results will be carried out. ABAQUS CAE will be used to develop FEA models, applying boundary conditions and thermal properties to accurately create models for the simulations.

Experimental test samples were set up. The samples were prefabricated to 1.2×1.2 m to fit onto the testing furnace opening. These samples were instrumented with type K thermocouples (TCs) to measure temperatures at different positions through the ceiling system. The furnace used during the experimental setup was designed in the work of Fourie (2020).

This work investigated the influence that service holes in ceiling boards will have on the fire resistance of residential and commercial structures. It was found that the presence of service holes in the ceiling boards increases the rate at which heat is transferred through the system. It was also found that the more holes a sample has, the more heat will be transferred through that system and the more rapidly the sample will fail. Another finding was that concealing the holes with fire-resistant material such as ceramic fibre blanket or Calcium Silicate (CaSi) boards delays the rate of heat transfer through the system. Based on the results analysis, the samples, with the dimensions assigned to them in this work and the sizes of the holes, could achieve a 30-minute rating.

Similarities were observed between the FEA-modelled results and the physical test results, wherein the temperature curves followed similar trends for each test. For the four tests, FEA was seen to have underestimated the measured temperatures. The compared temperature curves indicated that for both the physical and simulated tests, the boards behaved similarly and experienced comparable temperature distributions, especially on the unexposed face of the system. The FEA results, therefore, indicate that the FEA model developed predict the heat transfer of such systems and model failure.

Publications

Experimental Testing and Numerical Modelling of Heat Transfer Through a Composite Sandwich Flooring System with Penetrations Exposed to Fire

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Dedication

I dedicate this publication to my God, without whom nothing is possible. His grace was manifested to me throughout this journey. I also dedicate it to my family. My source of support and motivation. My partner, Relebohile Mohale, who stood by me from the very beginning, never complaining, but always encouraging. My children, Maswazi Mnanzana, Kganya and Reatile Mohale, my little angels on earth. They have always been my reason to push through, against ALL ODDS. My siblings, Sylvia Khoboko, Tumi Rakometsi, and Lebohang Mnanzana, have all contributed to my pursuit of this degree. Finally, my late mother, Ida Mnanzana, words fail me, my heart never ceases to be heavy with emotion when I think of all the wonderful things she has missed to witness and experience the joy with me. I do know, however, that joy “comes in the morning” and we will celebrate together in glory. I love you always.

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List of acronyms

2D:	2 dimensional
3D:	3 dimensional
AC:	Air conditioner/conditioning
BCSA:	British Construction Steel Association
BF:	Bottom flange
CaSi:	Calcium Silicate
CBS:	Cellular Beam Structure
CEN:	European Committee for Standardization
EN:	European Standards
FCB:	Fiber Cement Board
FEA:	Finite Element Analysis
FEM:	Finite Element Modelling
FRL:	Fire Resistance Level
FRR:	Fire Resistance Rating
ISO:	International Standardization Organization
LPG:	Liquefied Petroleum Gas
LW:	Lower web
PSSDB:	Profiled Steel Sheet Dry Board
SAISC:	Southern African Institute of Steel Construction
SFC:	Standard Fire Curve
TC:	Thermocouple
TF:	Top flange
THRIP:	Technology and Human Resource for Industry Programme
UW:	Under web
VP:	Void pro

List of symbols

<i>K:</i>	Kelvin
<i>k:</i>	Conductivity
<i>t:</i>	Temperature
<i>T_g:</i>	Gas temperature
<i>l:</i>	Length
<i>α:</i>	Coefficient of linear expansion
<i>Δl:</i>	Change in length
<i>Δt:</i>	Change in temperature
<i>c:</i>	Specific heat
<i>E:</i>	Modulus of elasticity; Integrity
<i>ε:</i>	Strain; Emissivity
<i>σ:</i>	Stress; Stefan-Boltzmann constant
<i>A:</i>	Area
<i>Q:</i>	Heat flow rate
<i>h:</i>	Heat transfer coefficient
<i>t_w:</i>	fluid temperature
<i>R:</i>	Load-bearing capacity
<i>I:</i>	Insulation
<i>%:</i>	percentages
<i>min:</i>	minute/ minutes
<i>W:</i>	Watts
<i>°C:</i>	degree Celsius
<i>mm:</i>	millimeters
<i>m:</i>	meters
<i>J:</i>	Joules

Chapter 1: Introduction

1.1 Background

Steel is a material that is widely preferred for use in construction, particularly in structural frames, for its combination of lightness in weight and high strength, compared to concrete. The use of steel as a construction material can be traced as far back as the 1700s, with its production and properties constantly being improved and enhanced over the years (LLC, 2018). Some of the earliest steel frame constructions include the Brooklyn Bridge in 1883 and the Eiffel Tower in 1889. When a steel member is subjected to heat (for example from a fire), its strength will start to reduce to around 50% of its original value at 550°C and will have lost up to 90% at 800°C (Rayfield, 2018). This reduction in strength will result in the deformation of the steel member under an applied load.

Traditional steel structures are more fire-resistant because of the concrete used to reinforce the structures. Concrete is known to be inherently more fire-resistant than steel. Heat transfer occurs at a slower rate due to the low thermal performance of concrete (Cirpici, et al., 2019). On its own and unprotected, steel may not resist indefinitely the effects of a fire. Hence it is important to protect steel members – individually and within the global structure. This is done to prevent a structure from collapsing while occupants are still inside the building during a fire. Protection is also prioritised to keep a fire contained to a single compartment or as few compartments as possible.

Typical methods used to suppress fire in a structure include active (limiting the fire development and its effects by some action taken by a person or an automatic device) and passive systems (controlling the fire or its effects by systems that are built into the structure or fabric of the building, not requiring specific operation at the time of the fire). One such passive system consists of using fire-resistant boards like Calcium Silicate (CaSi), for ceiling and partitioning applications.

This work focuses on an innovative flooring system and its resistance to fire and the system that uses a profiled steel sheet and has no concrete in-fill. The studies by Marx (2018) and Claasen (2022) showed that a flooring system with no ceiling (protection) will fail sooner and more severely than one with a ceiling. Therefore, a sandwich floor system with a ceiling is required to reduce the effects that a fire will have on a structure. In residential buildings, there is a need for flooring to provide compartmentation (Wright, et al., 1987).

When fire-resistant boards are used as ceiling boards in residential and commercial buildings, it is often necessary to add holes to the board for light fittings, sprinklers, smoke detection systems, and air conditioning ducts. These service holes will influence the fire rating of the boards, which will have a negative influence on the ability of the boards to protect the steel members during a fire thus weakening the steel members. Due to the service holes in the boards, more heat will be transferred through the boards to the steel sections. The determination of the fire rating of a CaSi ceiling board with service holes in it is therefore crucial.

This research project formed part of the Technology and Human Resources for Industry Programme (THRIP) project between the Southern African Institute of Steel Construction (SAISC), Stellenbosch University (SU), and the Central University of Technology (CUT), where the behaviour of the fire-resistant ceiling boards was investigated. The SAISC has developed a novel steel building system, which is cost-effective, easy to build, and suitable for the office and residential market. The system promotes the use of South African structural steelwork and the provision of quality infrastructure for the SA business environment. However, a significant challenge that is faced is the unknown fire resistance of the building system, and this has hindered the commercialization of the structure. Through a series of small-scale tests and FEA simulations, a build-up on previous studies by Marx (2018) and Claasen (2022), this work investigates the impact of penetrations on thermal development.

1.2 Problem statement

Uncontrolled fires can result in the loss of human life and damage to structures, which can have a substantial social and economic influence. Measures commonly used to protect structures in the event of fire include passive and active systems. Passive systems impede the spread of fire or minimise the consequences of a fire and can be included in the structure itself through, for example, specialised coatings and fire-resistant ceilings and/or wall insulations. Active measures include measures to extinguish a fire using water, sprinklers, etc.

Marx (2018) has shown the benefit of using ceiling and/or wall insulation as a fire barrier inside structures. Using a fire-rated board as a ceiling can satisfy the insulation and integrity criteria of various design codes, e.g. EN 1991-1-2 (European Committee for Standardization, 2002). However, in commercial and residential buildings, the fire rating of a ceiling board will be compromised by service holes for lights, sprinklers, and air conditioning ducts. These service holes will negatively influence the fire rating of the board and the complete structure. The extent to which the sudden change in dimensions on the surfaces of the boards and the joints will affect the fire rating is not clear. This research will investigate the influence that service holes will have on the heat transfer properties of a ceiling board and the subsequent protection it will provide to the steel structure during a fire.

1.3 Aim

This research aims to determine the rate at which heat is transferred through the service holes on the exposed face of the CaSi board through to the unexposed face of the Fiber Cement Board (FCB), as the number of the service holes on the CaSi increases and change position. The said rate will impact the Fire Resistance Rating (FRR) of the ceiling system. In conducting FEA model simulations, the results will provide a prediction of the behaviour of the ceiling system in elevated temperatures, with samples exposed to the (ISO 834) Standard fire curve for 60 minutes. Through FEA, the insulation criterion will be studied, with integrity behaviour

being studied through experiments and structural resistance could potentially be determined based upon the temperatures calculated through this study.

1.4 Hypothesis

The presence of service holes in fire-rated ceiling boards significantly reduces their fire resistance, thereby compromising the overall fire protection of the underlying global steel structure. As the size and number of service holes increase, the rate of structural failure of the fire-rated ceiling boards and the steel structure during a fire will increase.

1.5 Objectives

The objectives of this research are as follows:

- Conduct a full literature review to understand fire behaviour and its effects on steel structures, the modes of heat transfer and their roles during a fire, the behaviour of steel at elevated temperatures influenced by their mechanical and thermal properties, the benefits of protecting steel members against the effects of fire, and the thermal behaviour of the ceiling/floor system in a fire. A brief discussion on what FEA is and the benefits of its utilisation instead of conducting physical experiments for fire tests.
- Use a sample with no penetrations on the ceiling board to calibrate the furnace to obtain the Standard Fire Curve (SFC) temperatures.
- Conduct physical experiments to determine the time it will take for each board to fail either one or two of the three FRR criteria.
- Perform FEA simulations using ABAQUS to compare and evaluate the variations between the physical and simulated results to help verify the accuracy of the FEA simulations by comparing them to the physical results.
- Using the forthcoming FEA results as a guideline for accurately predicting the heat transfer through the ceiling system.

1.6 Methodology

The research methodology can be summarised as follows:

The study will primarily investigate the behaviour and the trend which will emanate from the heat that will be transferred through the system.

- This will be done by testing four samples of same outer dimensions and construction under the same fire conditions (ISO 834). The samples will have different hole positions, sizes, and quantities.
- The samples were built as follows – from top to bottom – Fibre Cement Board (FCB), VoidCon steel decking, and CaSi fireboard. The samples were prefabricated.
- The hole positions will depend on the quantity of the holes for each specific sample. The holes will however be placed with equal distribution away from the edges of the samples.
- The samples will each be tested on a 1.2 × 1.2 m furnace. The temperatures will be obtained from a computer that is connected to a data logger, which is in turn connected to thermocouples (TCs) from different positions across the lengths of each sample. The Benchlink 34980A data logger Pro Software was used for the recording of temperature results.
- FEA models will be developed following the physical dimensions of the samples for the comparison between the FEA results and the results of the physical experiments.

1.7 Limitations

The study will not focus on validating the small-scale tests with large-scale tests. There will not be a design of the configuration of the samples as the samples were prefabricated. The study will only focus on the heat transfer aspect and not the intricate structural properties like bending. For these experiments and tests, only the insulation and integrity criteria of the fire resistance rating (FRR) would be tested for this system because the system did not bear any

load, so no structural rigidity would be tested. Due to budget and time constraints, only four samples would be tested.

1.8 Outline of the research

Chapter 1: This chapter will outline the objectives of the study, provide a short background on the literature, outline the problem statement, state the research questions, explain in detail the methodology to be followed to reach the objectives, and state the limitations for the study.

Chapter 2: This chapter will provide a detailed literature review of the study. Heat transfer modes, different types of fire prevention or impedance methods usually used in industry, the benefits of using FEA to simulate tests, as well as the behaviour of steel at elevated temperatures, will be discussed. The Profiled Steel Sheet Dry Board (PSSBD) systems will be briefly discussed wherein the history, and the usefulness of such systems will be the focus. The thermal and mechanical properties of steel will be discussed, which are relevant to this study.

Chapter 3: This chapter will discuss the experimental setup. This is where the methodology will be fully explored. The chapter will explain in detail how the experiments were carried out and how the results would be gathered. An explanation will be provided about how the thermocouples (TCs) were set up on the surfaces of the samples and connected to the data logger. The development of the computer models will also be laid out in this chapter.

Chapter 4: This chapter will discuss and provide an analysis of the results from the experiments that were conducted in the previous chapter. Chapter 4 is where the behaviour and the failure of each sample will be investigated and analysed. The analysis will provide information on how the penetrations affected the heat transfer rate within the system and the performance of the system when subjected to the holes.

Chapter 5: This chapter will take a closer look at the FEA results in comparison to the experimental results. Analyses will be made about the differences in the FCB unexposed face

temperature averages and what could be the cause for these differences, both major and minor differences.

Chapter 6: In this chapter, conclusions will be drawn from the results gathered and discussed in the previous chapter. Furthermore, recommendations will be given for future studies to be conducted stemming from this current study.

1.9 Summary

This chapter gave an overview of the research process. An introduction is made about structural fires and their effects. The problem was identified as well as the methodology to be used towards solving the problem. The aims and objectives of the project were clearly stated, and the limitations were identified. The next chapter will go through the literature that has been reviewed from previous studies addressing heat transfer problems.

Chapter 2: Literature Review

2.1 Introduction

In recent years, there has been a growing concern among designers and builders over the protection of structures from fires, given the increasing intensity, hazards, and frequency associated with such incidents. An early instance of documented significant fires may be traced back to 1871 (LLC, 2018), exemplified by the great Chicago fire, which resulted in a considerable loss of life and rendered numerous individuals without homes (Rayfield, 2018). After the fire, more stringent building regulations were imposed in which less-combustible materials such as brick and stone were utilised for construction (LLC, 2018).

The materials utilised in the construction of contemporary buildings, chosen for their cost-effectiveness during production, can pose a significant risk to the buildings themselves in the event of a fire. This can be their high calorific value, which renders them highly combustible, and their physical properties, especially thermal properties, that would determine how they behave at elevated temperatures.

Fire can manifest in several forms because of the chemical interactions occurring between the flammable substances and the oxygen sourced from the atmosphere. When a fire is appropriately utilised, it offers significant advantages as a means of generating power and heat to fulfil both industrial and residential requirements. However, if uncontrolled, it has the potential to result in extensive structural damage and human suffering (Drysdale, 2011). The implementation of both passive and active fire prevention measures serves the purpose of confining fires and preventing the escalation of small fires into larger ones (Buchanan & Abu, 2017). The occurrence of a series of urban fires with disastrous consequences, particularly in recent times, has generated a growing scholarly interest in the domain of structural fire safety and the safeguarding of buildings from fire hazards (Marx, 2018).

The process of designing a building to mitigate fire hazards necessitates a comprehensive understanding of fire and its inherent attributes, a thorough study of the materials employed in construction and their distinct features, and a comprehensive grasp of the scientific principles governing the many forces at play. This chapter will introduce the concept of fire and delve into the details of heat transfer within the ceiling/floor system used for the protection of the cellular beam structure as designed by the Southern African Institute of Steel Construction (SAISC). The chapter will go on to examine the behaviour of the system's elements in the event of a fire and explore the impact of the ceiling on the system's performance, including the temperatures experienced by the unexposed faces. This chapter will also examine certain details about finite element modelling and its benefits over physical experiments. The inception and evolution of Finite Element Analysis (FEA) in the context of heat transmission, as well as the validity of the results it produces, will be investigated.

2.2 Fire background and classification

Fire is commonly generated through a chemical process involving the interaction of atmospheric oxygen with a combustible substance (Ardiansyah, 2019), such as wood or gasoline. It is important to note that wood and gasoline do not undergo spontaneous combustion solely due to their exposure to oxygen, but for combustion to occur, it is necessary to raise the temperature of the fuel to its ignition point (Harris, 2022). The fire or the flames are just the perceptible manifestations resulting from the chemical reaction known as combustion. **Figure 1** below expresses this phenomenon as the fire triangle.



Figure 1. Fire triangle (Fire Training Company, 2022)

The fire triangle consists of three elements, without which combustion would not occur, the three elements are as discussed below:

- **Fuel:** any combustible material in the form of solid, liquid, or gas.
- **Heat:** energy necessary to increase the temperature of the fuel to a point where sufficient vapours are given off for ignition to occur.
- **Oxygen:** the air we breathe contains about 21% of oxygen, but fire only needs at least 16% to ignite (Marx, 2018). The rate at which heat is released from a fire slows down significantly once the oxygen content of the air decreases (Buchanan & Abu, 2017).

The fuel feeds the fire in the form of a combustible material that reaches ignition temperature due to heating and therefore starts to burn. While oxygen sustains combustion (Harris, 2022), the fire will continue to burn until there is not enough oxygen, heat, or fuel available (Marx, 2018). Fire is one of nature's most catastrophic and destructive forces that leads to great financial losses due to the loss of property, agricultural areas, as well as lives (Marx, 2018). Over the years, the number of structural fire incidents has grown significantly and thus the interest and urgent need to protect buildings against fires has become a great focus for fire engineers and designers. High-rise fire incidents like the Grenfell Tower in West London (in

2017) (**Figure 2a**), and the Sulafa Tower (**Figure 2b**) in Dubai (in 2016) have shifted the experts' focus to the integration of passive and active fire protection measures.

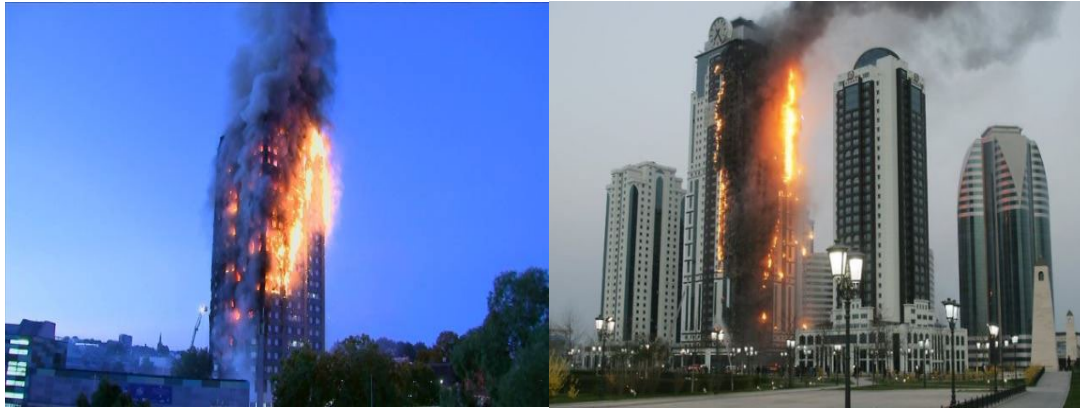


Figure 2(a). The Grenfell Tower in West London in 2017 and **(b)** Sulafa Tower in Dubai in 2016

South Africa is by no means exempt from the occurrence of fires and the negative effects they bear. Every year, there are financial and human losses resulting from both wildfires and structural fires, amounting to an estimated R3 billion in damages (Sgqolana, 2021). Some of the most recent structural fires to devastate South Africa were the National Assembly (parliament building) fire and the fire that destroyed a hijacked apartment block in Johannesburg on 2 January 2022 and 31 August 2023, respectively. The quick propagation of the fire in the parliament necessitated the deployment of 35 firemen and a duration of over 71 hours to effectively combat and suppress it (Parliament, 2022). The damage from that fire alone was projected to reach R2 billion (Felix, 2022). The Johannesburg fire was believed to have lasted for more than 12 hours, leaving more than 70 people dead and approximately 50 people with grave injuries.

The urbanization of people and the structural evolution demanded change and improvement of buildings; thus, engineers began to build larger and higher to allow further increases in urban density and economic growth (Maluk, et al., 2017) and still be cost-effective. The emergence of urban areas has been accompanied by numerous devastating fires, leading to the implementation of fire safety measures. These measures, in the form of regulations

governing building designs, have played a significant role in determining the permissible construction materials and techniques in densely populated cities that continue to rapidly expand (Bisby, et al., 2013). Research has indicated a decline in the occurrence of building collapses during fires, as well as a decrease in fire-related fatalities and injuries in developing countries (Rashbash, et al., 2004). However, it is crucial to underscore the significance of collaboration among building and fire protection experts throughout the entire design and construction process.

Time-temperature curves have been produced to approximate fire behaviour. Examples of such curves included parametric fire curves and standard fire curves. Also, various zonal and computational fluid dynamic models exist for predicting temperature development.

2.2.1 Parametric fire curve

A parametric fire is a natural fire (Alam, et al., 2018) represented as a simplified mathematical time-temperature relationship (Marx, 2018) and considers the compartment size, fuel load, ventilation conditions, and the thermal properties of compartment walls and ceiling.

Modern-day buildings are filled with synthetic materials that increase both the rate of fire growth and the peak heat release rate. This then increases the fire severity above the standard fire curve used to obtain the FRR. Hence the use of certain construction elements may not ensure safe evacuation or offer the required safety for occupants and fire rescuers as stipulated in the technical manuals of building assemblies (William, et al., 2007).

The time at which the maximum gas temperatures ($T_{\max}$) are reached during the heating phase, depends on whether the fire is ventilation or fuel controlled. Larger openings result in more ventilation, thus slowing down the heating rate and reducing the temperatures (Marx, 2018). The fire resistance of the structures is always a crucial factor in fire tests, and these are determined by the temperatures reached as a function of time.

The parametric fire curve is represented by the following equation:

$$T_g = 20 + 1325 (1 - 0.324e^{-0.2t} - 0.204e^{-1.7t} - 0.472e^{-19t})$$

Equation 1

Where:

T_g is the gas temperature (°C)

t is the time in (min)

The equation above allows a more realistic time-temperature curve to be produced for any combination of fuel loads, ventilation openings and wall-lining materials (Buchanan & Abu, 2017).

2.2.2 Standard fire curve

The standard time-temperature curve also referred to as the ISO 834 fire or standard fire (Bahr, 2019) was developed at the end of the 19th century, as a measure to analyse the behaviour of fire within a compartment, and to date, it is still used and regarded as the ultimate rating for the fire performance of structures (Wegrzynski & Turkowski, 2018). The ISO fire curve is widely used in standard fire tests due to its ability to repeat and reproduce the specific thermal action because, in essence, it allows for the heat input to be altered as needed. This enables the standard method for determining the fire resistance of structural and insulation elements (Access Steel, 2010). However, over the years, the curve has proven inaccurate for certain types of fires, because it was developed during a time when wood was the primary fuel load, as opposed to modern buildings where thermoplastic materials, synthetic foams and fabrics are used. The hydrocarbon and parametric fire curves have been developed for materials that are high in calorific values thus increasing both the rate of fire growth and heat release, thus increasing the fire severity beyond the capacity of the standard fire curve (Ariyanayagam & Mahendran, 2013).

The standard fire curve was best suited for this research study because it is a benchmark for assessing material performance. There are noticeable differences between the standard fire curve and the realistic (natural) fire curve, as shown in **Figure 3** below.

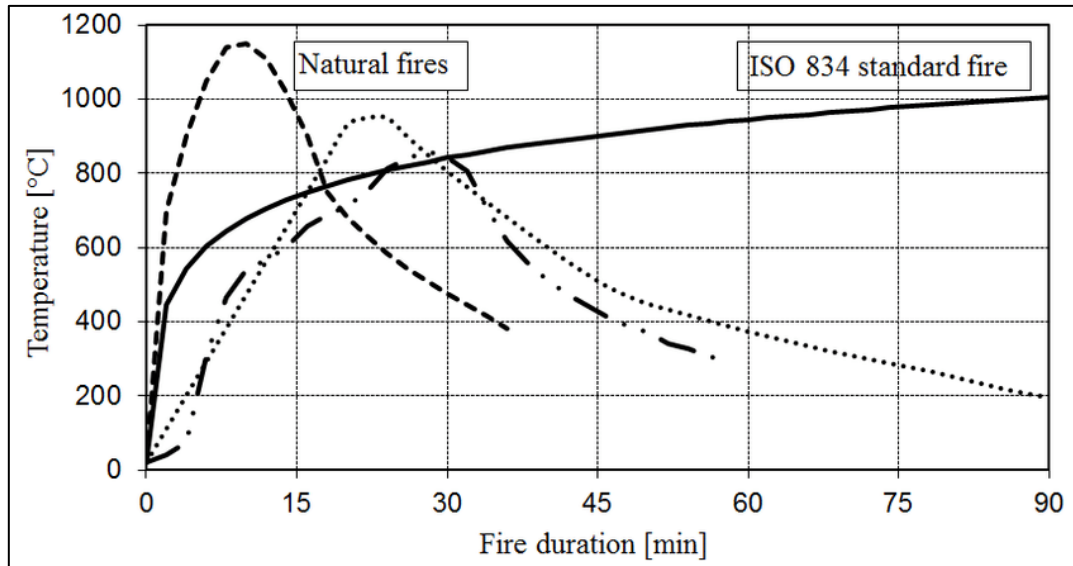


Figure 3. Comparison between the standard fire curve and the realistic (natural) fire curve (Lyzwa & Zehfub, 2017)

The standard fire curve was developed from a steady elevation in temperature that continues to increase with the increase of time and does not have a cooling phase (**Figure 3**). Realistically, for a fire to burn indefinitely, a significant amount of fuel is needed, as well as the correct ventilation conditions that would provide sufficient oxygen. In the case of a real fire, the temperature of the fire drops as fuel and oxygen become depleted. The thermal properties of the building materials will also be a determining factor for the resulting temperature field in the event of a fire (Wegrzynski & Turkowski, 2018).

The problem presented by the standard fire curve is that its development was not based on the response of elements to a real fire (Marx, 2018). The curves are expressed as a uniform gas temperature in terms of time (t).

The testing furnace temperature-time relationship for standard fire testing in a furnace is given by the equation:

$$T_g = 20 + 345 \log(8t + 1)$$

Equation 2

Where:

T_g is the gas temperature in (°C) and t is time (min).

2.3 Behaviour of fire in buildings

Naturally, a fire will ignite, burn, reach flashover (total involvement) point, and then eventually start to decay until it completely subsides. All these stages are characterized by the temperature rise or drop over certain periods, as suggested by the fire curve in **Figure 4**. Some fires will take longer to subside depending on where the fire occurs and its surroundings (the fuel in the fire or the combustible materials around the fire environment). From the fire triangle (**Figure 1**), oxygen is essential for a fire to burn, thus in an enclosed space, in which there is a limited flow of oxygen, a fire will consume all the available oxygen and eventually subside from lack of oxygen in the space, unlike in an open area where an unlimited flow of oxygen is available. It is often crucial for the results of a fire to determine whether the fire is ventilation- or fuel-controlled. A fuel-controlled fire is essentially controlled by the amount of fuel and how the fuel is positioned, while a ventilation-controlled fire is essentially controlled by how much air the fire has access to (Svensson, 2005).

In a structure, a fire will burn in an upward direction because of buoyancy and as the hot gases (plume) reach the ceiling, the fire will start spreading horizontally. The enclosing of the room will increase the pressure of the hot gases resulting from the fire, therefore, there will be a higher pressure on the upper surface and less pressure on the lower surface because any opening of the compartment will act as an entrance point for the cold air and as an exit for the hot gases (Cengel, 2006). At the meeting point of the lower-temperature air and the high-temperature gases, the pressure will be neutral. This point is known as the neutral plane. The neutral plane will lower as the pressure in the hot gases increases. The neutral plane will be

a source to assist fire fighters in determining the location of the fire, the severity thereof, and the heat that is being released, thus the impedance efforts can be enhanced.

2.3.1 Fire development

The development of fire is dependent on a few factors like ventilation conditions, fuel available for the fire, compartmentation, active protective measures, etc. Fire safety objectives are usually met with a combination of active and passive fire protection systems. Fires don't necessarily develop the same way or follow the same pattern, depending on what is prevalent and/or deficient, some fires will subside naturally, and some will not reach flashover. The development of a fire occurs in successive phases as shown in **Figure 4**. These phases are briefly discussed below:

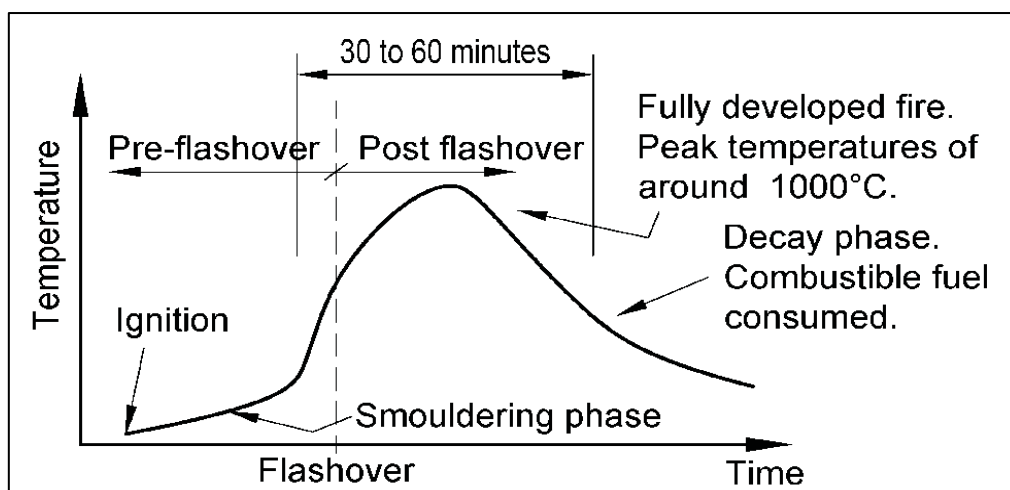


Figure 4. The fire development curve showing the typical behaviour of fire (Kloos, 2017)

2.3.1.1 Inception stage (ignition)

At this stage, the fire largely depends on the characteristics and configuration of the fuel involved. The air in the compartment must contain enough oxygen to continue the development of fire. The overall temperature in the compartment increases, and the radiative heat warms adjacent fuel (combustible materials) and continues the process of pyrolysis (Hartim, 2008).

2.3.1.2 Growth stage

The fire grows as other combustible materials within the compartment ignite. Most fires will spread slowly at first on combustible surfaces, then, more rapidly as the fire grows, at which point there will be radiation feedback from flames and hot gases to other fuel items (Buchanan & Abu, 2017). Convection resulting from plume gasses and subsequent ceiling jet, along with radiant heat from the fire and hot particles in the smoke increases the temperature of the compartment linings and other items within the compartment (Hartim, 2008).

2.3.1.3 Flashover

Flashover is a sudden and rapid transition to total room involvement of all combustible items in the fire compartment. It means all the combustible materials in the compartment are now engulfed in the fire. The conditions for flashover may be defined in terms of temperature – the ceiling temperatures typically reaches around 500-600 Degrees Celsius or in terms of the amount of the heat flux to the floor of the compartment, which must reach 15-20 kW/m² (Hartim, 2008). The velocity of the burning gases will push out the compartment openings such as windows and doors and the flames will grow after the increase of oxygen because of the open windows and doors.

2.3.1.4 Burning period

During this stage, energy release is at its greatest but is generally limited by ventilation (Hartim, 2008). During the burning period, all exposed surfaces are burning due to a large amount of radiative heat flux within the compartment. It is the burning period that predominantly impacts structural elements and compartment boundaries, such that the elements start to fail, and compartmentation becomes an issue as fires are likely to spread to other compartments (Bengtsson, 2001) if the structure is not adequately insulated.

2.3.1.5 Decay stage

A compartment fire may enter a decay phase as the available fuel is consumed or due to the limited available oxygen (Hartim, 2008). As the fuel burns out, the fully developed fire can no

longer be sustained, thus causing a decrease in room temperature (Marx, 2018) and the decay phase takes effect.

2.4 Fire resistance of buildings and building materials

The purpose of establishing a fire resistance period is to ensure that in the event of a fire within a building, the load-bearing capacity of the building will continue to function until all occupants have escaped (Berret & Byrd, 2013) or been assisted to a safe egress. Fire resistance is defined as the ability of structural elements within a building and the entire building to resist a fire (Marx, 2018) and its effects, and can be quantified as “the ability of structural elements to withstand exposure to a standard fire and associated pressures without loss of its fire-separating (integrity and insulation) or loadbearing function or both for a given time” (SANS 10400, 2002). The requirements of fire resistance are commonly based on the amount of time that the structural element can satisfy a specific criterion while exposed to temperatures occurring during a fire (Li & Wang, 2013).

It is necessary to ensure adequate fire resistance of structural elements that support other members within the building, such as fire-rated ceilings, doors, and other fire-protective barriers (Wald, 2016). This can be achieved by exposing the elements to a standard fire test for the required time and thus determining whether the elements can withstand the fire and its effects. Failure of the latter can lead to fire spread, which could result in global structural collapse (Wald, 2016). Fire resistance is a function of properties of the materials of the walls enclosing the fire, dimensions of the openings, and heat loss to the surroundings, although not considered in building codes (Franssen, et al., 2009).

Figure 5 below is an example of a fire rating of 60/60/60. This means that if a building element is exposed to a 60-minute standard fire test, it would be expected not to fail for 60 minutes for each of the three criteria, namely, insulation, integration, and load-bearing capacity. The fire resistance levels (FRLs) can be many combinations of the three criteria.

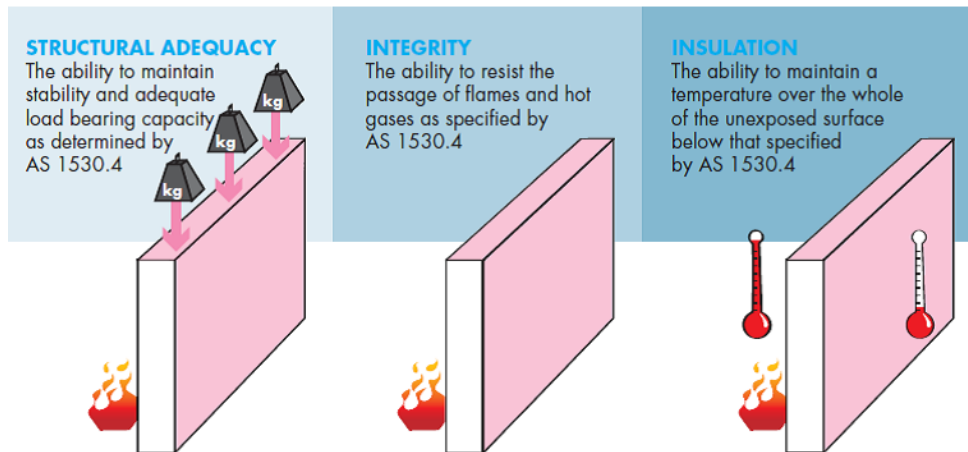


Figure 5. Fire Resistance Rating of 60/60/60 (Macedo, 2020)

It should be noted though that fire resistance is not the length of time that the structure will survive in a real fire, it is simply a standard measure that is used to compare the performance of different designs in a consistent manner (Berret & Byrd, 2013).

Fire resistance has three main criteria (as shown in **Figure 5** above):

Load-bearing capacity (R): The structure should maintain its mechanical resistance and be able to support the main overhead members.

Integrity (E): The ability of the structural members and protection materials to prevent the penetration of flames and hot gases through cracks and gaps caused by separating members (Wald, 2016). Failure of the integrity of members means the fire will spread to the neighbouring compartments, thus compartmentation will fail, leading to possible structural collapse (Marx, 2018).

Insulation (I): This limits temperatures on the unexposed side of the structural and protection members. Failure of this requirement could cause the materials in the next compartment to ignite spontaneously and could lead to compartmentation failure.

2.4.1 The importance of compartmentation

When designing a structure for fire resistance, the scale (small or large) of the fire is not the only aspect to be considered. The spread of the fire is probably the most important aspect to consider because without the appropriate protective measures, small fires can easily become larger fires, and with the adequate implementation of protective materials, large fires can be effectively contained. It is important to prevent a fire from spreading to other compartments, floors, and buildings (Buchanan & Abu, 2017).

In an attempt to contain or suppress fires, there are two methods currently used in the protection of buildings against fires. These two methods are **active fire protection** which will include suppression systems (e.g. automatic sprinklers) or people (e.g. fire brigade), actively working to control or suppress a fire. **Passive fire protection** methods protect structural members through components that form part of the structure such as boards and paints.

It is important to ensure the integrity of different compartments during a fire thereby preventing a fire from spreading. As the fire spreads to other compartments, it becomes difficult, even for a large, well-equipped fire brigade and fire suppression systems to control and extinguish the fire (Marx, 2018).

The absence of active protection measures means that the temperature or ventilation conditions of the fire cannot be controlled or suppressed and therefore a fire will burn for as long as it is fuelled. This example is seen in the Windsor Tower fire that burned for 18-20 hours (Bailey, 2009). The type of cladding material used may also aggravate the spread of the fire – e.g. the Grenfell Tower fire (**Figure 2a**). Compartmentation should be maintained to make sure that the four main scenarios of fire spread are prevented. The scenarios include the spread of fire within the room of origin, the spread of fire to the adjacent room, the spread of fire to the other floors, and worst-case scenario, the spread of fire to adjacent buildings (Marx, 2018).

2.4.2 Passive Fire Protection Methods

Fire protection mechanisms are used in structures to delay the rise in temperature within the structural members when exposed to fire (Gohil, 2016). Current fire protection strategies for buildings often incorporate a combination of passive and active fire protection systems (Franssen, et al., 2009). Passive fire protection systems' purposes are to delay a fire during its early stages and to control the spread of fire and its effects by providing sufficient fire resistance to prevent loss of structural stability within a prescribed period (Franssen, et al., 2009) to which each element and material may be assigned. Passive fire protection materials insulate steel structures from the effects of high temperatures that may be generated by fire. With the right application/installation, they could prevent large damages. However, many of these passive protection materials are usually more costly than the steel that needs protection (Marx, 2018). Passive fire protection materials can be divided into two types, namely, non-reactive (boards, sprays) and reactive (intumescent coatings- which may be thin film or thick film). Fire protection mechanisms commonly used in structures are insulating, absorbing, and intumescent.

➤ **Intumescent coatings**

These are paint-like materials that are inert (chemically inactive) at low temperatures but provide insulation due to a complex chemical reaction that occurs when exposed to higher temperatures. When reaching a critical temperature of typically between 200°C and 250°C, the material starts to expand into a foam-like outer char layer (**Figure 6a**) of low conductivity, protecting the underlying material (McNamee, et al., 2016). Intumescent applications are very costly but provide excellent fire protection results (Gohil, 2016).



Figure 6. (a) Charred intumescent coating, (b) Fire boards as a measure of compartmentation

Intumescent coatings may be divided into two categories

- **Thick film.** Tough and durable. They were originally developed for use with hydrocarbon fires. Usually used where maintenance will be difficult. Expansion ratios are much lower than for thin-film coatings (5:1).
- **Thin film.** Mainly used in buildings where the fire resistance requirements are 30, 60, and 90 minutes. These coatings may be applied on or off-site to the structural members. Typical expansion ratios are about 50:1, i.e., a 1 mm thick coating will expand to about 50 mm when affected by the fire. The off-site application is cheaper than the on-site application in the long run.

➤ **Sprays**

The main advantage of sprays is that they can be used to protect complex-shaped elements and that costs do not increase with the increase of the thickness that needs protection.

➤ **Flexible fibre blankets**

Ceramic fibre blankets are composed of long, flexible, interwoven fibres manufactured by the “blown” and “spun” process yielding a strong, lightweight yet durable fibre blanket for applications in a temperature range between 1260°C and 1600°C (Group, 2024) (Firebird, 2025). Ceramic fibre blankets have high tensile strength (>40kPa)

(Firebird, 2025) for longer life and durability, low heat storage, and low thermal conductivity (0.04 W/mK at 200 °C; 0.08 W/mK at 800 °C; 0.13 W/mK at 1000 °C) (Firebird, 2025), as well as resistance to thermal shock (Group, 2024).

➤ **Boards**

This is one of the most used methods of fire protection, and possibly the most cost-effective. Various fire-resistant boards contain calcium silicate (CaSi) (a group of compounds used as a temperature insulation material). Most of them can provide at least a one-hour fire rating. Their working temperatures are approximately 1050°C and shrinkage only occurs at temperatures of approximately 1000°C (Gohil, 2016). Fire-resistant boards have a low thermal conductivity and are easy to install, in any configuration. CaSi boards contain a certain amount of moisture content, which results in a time delay before the board will heat up and then eventually fail or show signs of failure (due to the time taken for the total evaporation of moisture within the board). The specifications of the boards will differ from board to board and from manufacturer to manufacturer. Installation of boards may be manipulated to comply with the required fire rating criteria for a compartment. The determination of the fixings to be used and the spacing between the fixations of the ceiling board will affect the overall performance of the structure. **Figure 6(b)** depicts the use of fire-resistant boards as a means of compartmentation to comply with the integrity and insulation criteria.

All these above-mentioned methods have been proven to protect steel construction elements during actual fires and fire tests. Builders are in constant search for use of fire-resistant building materials that are all-around good for use, cost-effective, easy to install, easy to maintain, and easily accessible.

From the above literature stating the advantages and disadvantages of all the different passive fire protection methods, it can be concluded that fire-resistant boards are often the preferred method to use for structural fire protection. This is based upon their ease of installation and cost-effectiveness (especially for large structures compared to ceramic fibre blankets where it

will be time-consuming to wrap all structural elements) or too high a cost to coat all elements with intumescent coatings. Installation of the fire-resistant boards is a dry, clean job and the finished product will result in a neatly boxed appearance.

2.5 Profiled steel sheet dry board systems

The profiled steel sheet dry board (PSSDB) flooring systems were first developed and proposed through the early work of Wright, et al. (1989) as an alternative to the traditional timber joist floor system. The system resembles a sandwich, consisting of dry boards on the top and bottom, with a profiled steel sheet decking in the middle. The structure is attached using self-tapping or self-drilling screws that have been proven to increase the stiffness and the strength of the system through composite action (Awang, et al., n.d.). The system has since been extensively studied by several authors, i.e., Wright, et al (1989), Awang, et al (n.d.), Wan Badaruzzaman (2003), Choe, et al (2021), Choe, et al (2022) as both flooring and roofing panels, for structural and thermal performance. The typical layout of the PSSDB systems is shown in **Figure 7** below.

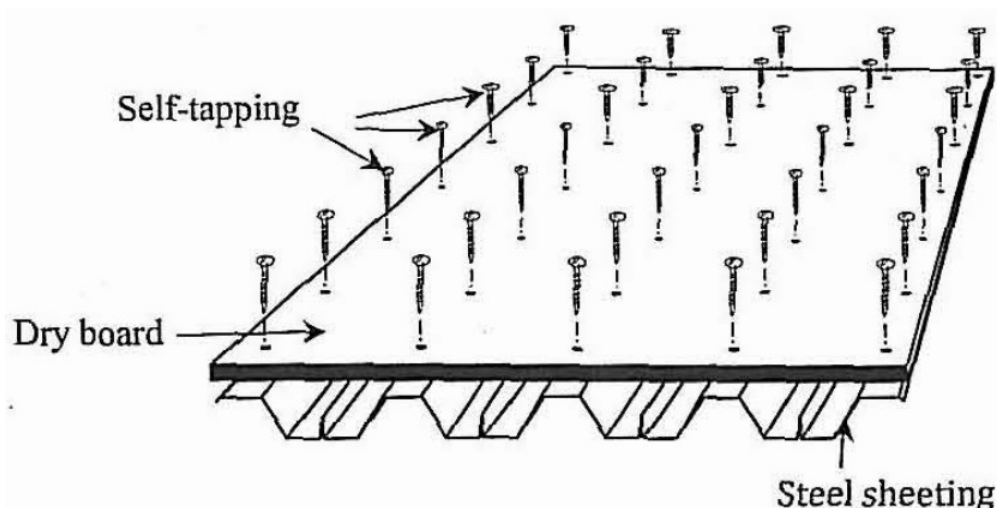


Figure 7. The typical standard layout of the PSSDB systems (Awang, et al., n.d.)

The work of Badaruzzaman, et al (2003) has shown that the PSSDB offers good fire resistance performance with the presence of some different types of concrete infill in the profiled steel, while the work of Claasen (2023) and Claasen (2022) has demonstrated good fire resistance performance of the PSSDB system that has no form of concrete infill. The recent work of Claasen (2023) and the work of Marx (2018) shown that an hour rating for the ceiling with no holes can be achieved, and the rating for a system with holes will be determined in the current work.

2.6 SAISC structure

Figure 8 indicates that steel gained popularity over concrete from the late nineties and has since remained the most used construction material for structures. The popularity and demand for steel usage as a building/framing material has led to the need to find effective and efficient means to protect buildings against fires. Steel is not as inherently fire resistant as concrete, thus there is a need to develop fire protection methods for structures consisting mostly of steel.

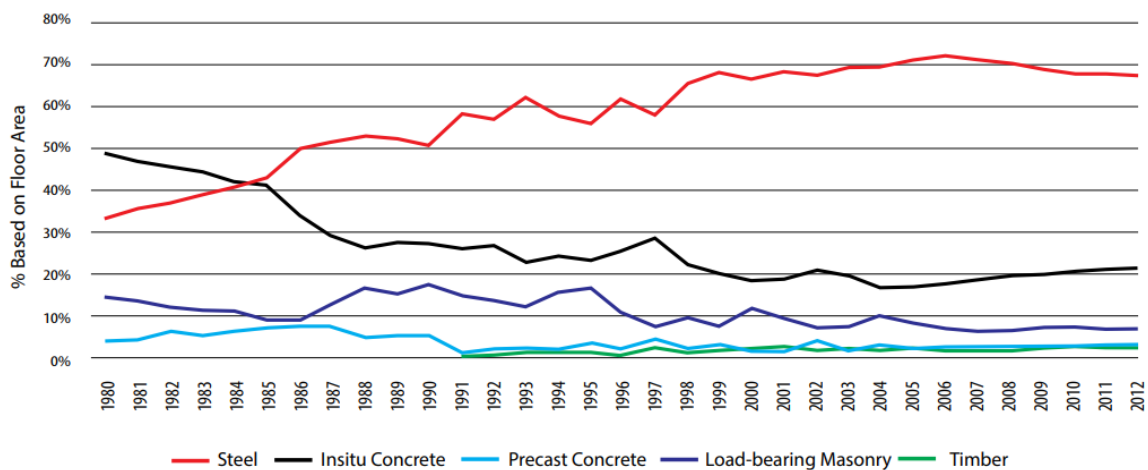


Figure 8. Market share for structural frames in multi-storey buildings (BCSA, 2019)

South Africa is successfully moving towards concrete-free steel structures, following the trend of developed countries in Europe. Using steel as a primary material for construction will lead to significantly reduced construction time and costs. In recent years, there have been several

steel structures erected in South Africa, including the 28-day house (News, 2020) as well as the Barloworld and Caterpillar Head Office and showroom in Johannesburg (Olivotto, 2022). These structures were vetted to have the structural strength required for their classes, and most importantly, cost – and – time – effective. It was also imperative that these structures adhere to the fire safety regulations before being granted permission to be erected. The Southern African Institute of Steel Construction (SAISC) has been pioneering the development of steel structures in South Africa and has overseen the construction and even awarded some of these structures for their robustness and competitiveness in all aspects of world standards. To this end, the SAISC has developed a novel lightweight cellular beam structure (CBS) (**Figure 9**) that makes use of a sandwich flooring system (The sandwich flooring system consists of four layers) as shown in **Figure 10**, made up of fibre-cement board (FCB), fire-resistant boards in the form of CaSi, and metal sheeting.

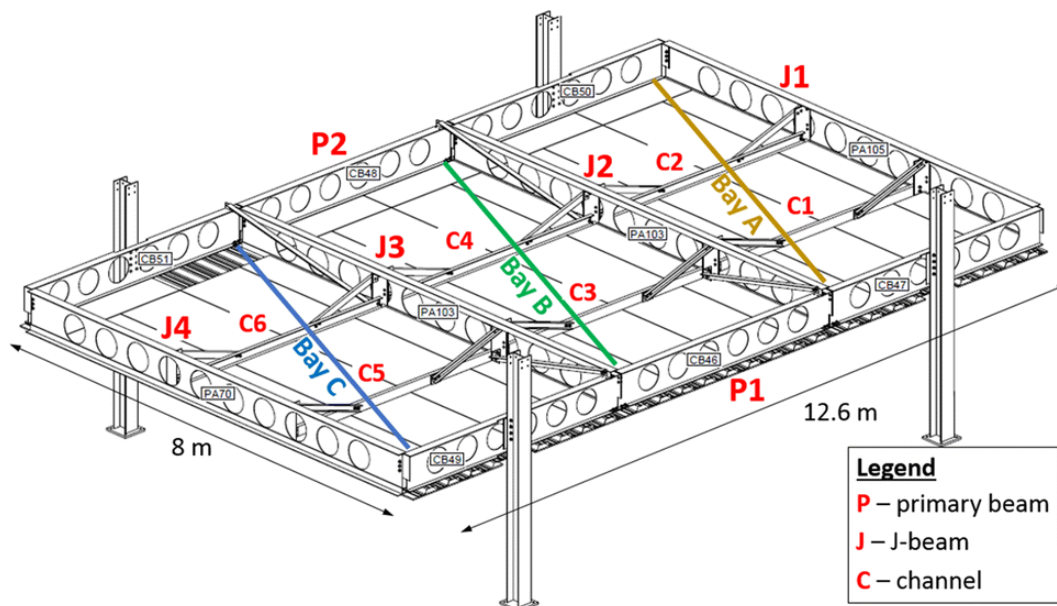


Figure 9. General drawing of three connected CBS modules (SAISC)

The sandwich structure was fitted with CaSi strips to allow an air gap for the reduction of heat flux and the total heat that will be transferred onto the unexposed face of the structure. This structure is intended for multi-storey buildings of between 3-10 floors and it consists of

prefabricated modules comprising of cellular steel beams encased in a multi-layered flooring system and contains no concrete (Marx, 2018). This construction method results in an innovative structure with many benefits, such as reduced construction time (Kloos & Walls, 2019) and labour expertise requirements during their erection (Wright, et al., 1987); (Perera, et al., 2022). The prefabricated steel members are easy to transport to the construction site and can thereon be assembled to form a bigger, yet relatively lightweight structure. This structure also allows for reuse and reconstruction.

The structure will typically consist of two main outer beams, or Primary beams (P-beams) that span 12.6 m each, four (8 m) J-beams at 4.2 m distances along the span of the P-beams, six (4.2 m) channels resting between the J-beams and knee-braces provided between the channels and J-beams. The J-beams are custom-made beams that resemble the letter J, and their particular cross-section is necessary for transportation and assembly reasons (Kloos & Walls, 2019), shown in **Figure 9**.

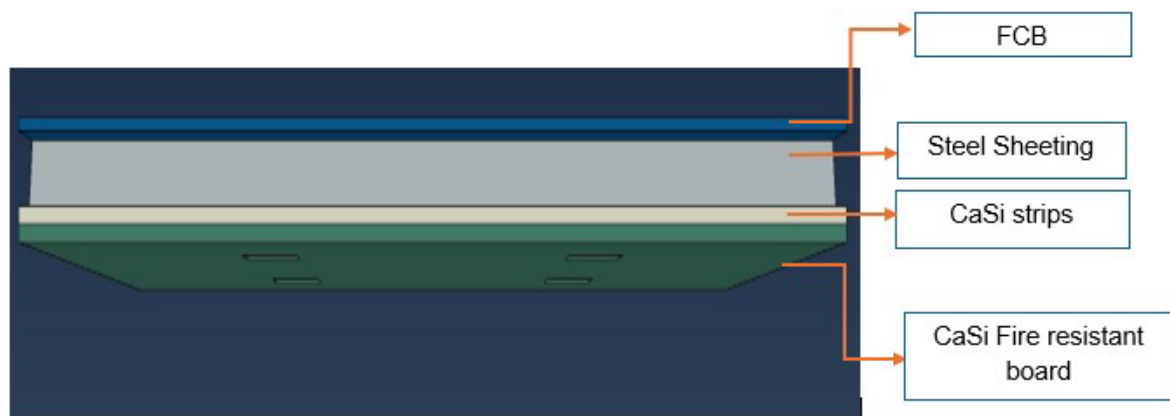


Figure 10. The sandwich flooring system showing all the material layers

The P-beams are specifically designed to accommodate services (lights, air conditioning, sprinklers, etc.) (**Figure 11**) without the need for an extra layer in the flooring system.



Figure 11. Cellular beams with service holes in them

In their article, “Finite Element Modelling of the Structural Behaviour of a Novel Cellular Beam Non-composite Steel Structure in Fire”, Kloos and Walls (2019) ran tests on the structure exposed to a standard fire (with and without ceiling boards) and a parametric fire (with ceiling boards), and they found that generally, the CBS performs especially well, provided that the integrity of the ceiling can be well maintained (Kloos & Walls, 2019). Making analyses for the P-beam and channels at the bottom flange (BF), under web (UW), lower web (LW), and top flange (TF), by dividing the non-uniform temperatures distributions into four uniform temperature distribution segments, they found the maximum temperatures at BF of the beams mentioned above to be lower for the parametric fire and higher for the standard fire test, both with ceiling boards. For all other points of the beams, the maximum temperatures are lower for the standard fire than for the parametric fire.

This has proven that the structure performs at its best when there is a ceiling board as a protective layer. It was proven that a ceiling consisting of fire-resistant boards plays a crucial role in the protection of the structure against fire. What is yet to be investigated is how the ceiling can be allowed to accommodate the predicted inconsistencies that would result from the effects of heat to ensure its integrity during a fire. The sandwich ceiling system should also

allow for services and still satisfy some fire-resistance rating (FRR), like all other structures, individually and within a global structure.

2.7 Typical heat transfer methods during a fire

Heat transfer is a subject of paramount importance in many engineering fields and will form an integral part of the current study of the Cellular Beam Structure (CBS) through the sandwich ceiling system. The effects of a fire on a structure can be understood following the understanding of the principles of heat transfer in the event of a fire. A convenient definition for heat transfer is energy in transition due to temperature differences (Long & Sayma, 2014) or energy in transit between different mediums due to a temperature difference and is governed by the principle of conservation of energy (Patade & Chakrabarti, 2013). The correct application of heat transfer principles is pivotal in protecting the environment (Lewis, et al., 2004) as it can help prevent structural fires, aid in impeding a fire in case of an occurrence and provide economical and efficient solutions for critical fire problems. Heat is transferred in three different modes, namely, conduction, convection, and radiation and these processes can happen separately or together depending on the circumstances (Buchanan & Abu, 2017). The important aspects of solving heat transfer problems are identifying the significant modes and deciding whether the heat transferred by other modes can be neglected" (Lewis, et al., 2004). The three modes of heat transfer are described in the following sections.

2.7.1 Conduction

Conduction occurs in a stationary medium which is most likely to be a solid, but it can also occur in fluids. In materials that are good heat conductors, the heat is transferred by interactions involving free electrons, hence materials that are good electrical conductors are usually good heat conductors (Buchanan & Abu, 2017). Conduction occurs when there is a temperature gradient within the medium or between two free-standing bodies.

Conduction through solid materials is of immediate interest, however, conduction within fluids is also important as it is one of the mechanisms through which heat can be transferred from

the surface of a solid (Hartim, 2008). Conduction is validated and related by Fourier's law stating that the rate of heat flow through a single homogenous solid is directly proportional to the area (A) of the section at the right angle of the direction of heat flow, and to the change of temperature (ΔT) with respect to the length of the path of the heat flow (Eastop & McConkey, 1993), as shown in **Figure 12**.

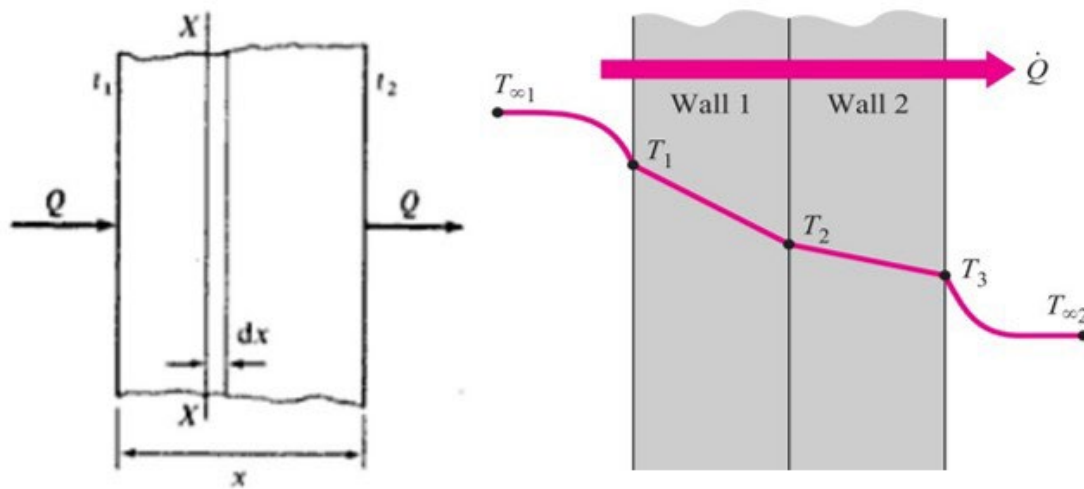


Figure 12. Temperature variation for heat transfer from one fluid to another through a dividing composite wall (Eastop & McConkey, 1993), (Cengel, 2006)

Fourier's law expressed as an equation for one dimension is:

$$q'' = \frac{T_{\infty 1} - T_{\infty 2}}{\frac{1}{h} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h}}$$

Equation 3

Where:

q'' = heat flux (W/m²)

$T_{\infty 1}$ = furnace temperature (°C)

$T_{\infty 2}$ = temperature of air surrounding unexposed FCB (°C)

k_i = Thermal conductivity of materials, $i = 1, 2, 3$

L_i = Thickness of materials, $i = 1, 2, 3$

h = convective coefficient of air

In the relationship above, k is a thermal property measured as the rate at which heat passes through a specified material, allowing a flow-through of energy (Marx, 2018). It is a property of a particular heat-conducting substance (Marx, 2018) and like other properties, depends on the state of the material which is usually specified by its temperature and pressure (Hartim, 2008). Thermal conductivity (k) can also be expressed as the heat transferred per unit of time and unit area divided by the temperature difference.

Heat will always be transferred from the high-temperature face to the low-temperature face as indicated in **Figure 12**. Following this assertion, it can be said that, when two solids are in contact, (in the case of composite structures (**Figure 12**)), there will be transport of heat. The effectiveness of this transition will depend largely on the thermal conductivity of the materials in contact. It is, therefore, brought to attention that low thermal conductivity is a crucial material property to be considered to achieve the desired fire resistance. The thermal resistance of each component in the composite sandwich flooring system are represented by a denominator of the above equation (**Equation 3**). The heat flux from the burner would pass through heated gas before reaching the first solid slab, where the thermal resistance of the gas is expressed by $\frac{1}{h}$. The thermal resistance of the solid slab exposed to the heated air from the burner is given by $\frac{L_1}{k_1}$ and the subsequent resistance of each solid slab of the sandwich flooring system are $\frac{L_i}{k_i}$, where $i = 2, 3$, etc.

2.7.2 Convection

Convection is heat transfer by the movement of fluids, either gasses or liquids (Buchanan & Abu, 2017), by mixing one portion (hotter) of a fluid with another (cooler) (Eastop & McConkey, 1993). Convection can happen in one of two ways, free (natural), where the movement of fluids may be caused by a difference in density resulting in temperature differences, or forced

convection, where the motion may be produced by mechanical means (Eastop & McConkey, 1993) like a fan blowing over a hot surface.

Convection heat transfer is an important factor in the flame spread and in the upward transport of smoke and hot gases to the ceiling or out of a window from a compartment during a fire (Buchanan & Abu, 2017). Whenever there is an appreciable movement of the gas or liquid, the heat transfer by conduction in the gas or liquid becomes negligibly small compared to the transfer by convection. There is always a thin boundary layer of fluid on a surface, and thus the manner in which conductive heat transfer occurs through the thin fluid layer (Eastop & McConkey, 1993).

Convection heat transfer is qualified by Newton's law of cooling, which helps in providing an understanding of the way heat is transferred from a solid to a fluid and vice versa. Newton's law of cooling states that heat transfer from a solid surface of area A , at a temperature of T_w to a fluid of temperature T , is given by:

$$Q = hA(T_w - T)$$

Equation 4

Where h is the heat transfer coefficient, measured in W/m^2K .

This expression, however, does not account for the heat lost to radiation, as in many cases this loss can be negligible when compared to convective and conductive heat transfer. In a fire, especially within a compartment, convection is responsible for the ceiling area reaching flashover temperatures. The hot gasses and plumes rise, effectively and continually lowering the neutral plane.

2.7.3 Radiation

Unlike conduction and convection which need a solid or fluid as a medium to transfer heat, radiation needs no medium (Nellis & Klein, 2008) (Cengel, 2006). Electromagnetic radiation travels most efficiently through a vacuum, though it can pass effectively through many gases,

liquids, and some solids (such as thin layers of glass and transparent plastic materials) (Hartim, 2008). All matter continuously emits electromagnetic radiation unless its temperature is at absolute zero (0 K). It is found that the higher the temperature, the greater the amount of energy radiated (Eastop & McConkey, 1993). Radiation as a wave can be absorbed, transmitted, or reflected.

If two bodies at different temperatures are placed in such a manner that the radiation from each body is intercepted by the other, then the body at the lower temperature will receive more energy than it is radiating and hence its internal energy will increase; similarly, the internal energy of the body at the higher temperature will decrease (Eastop & McConkey, 1993). Radiation is governed by Kirchhoff's law which states that the emissivity of a body that radiates at a temperature T is equal to the absorptivity of the body when receiving energy from a source at the same temperature.

Stefan-Boltzmann's law of radiation states that the emissive power of a black body is directly proportional to the fourth power of its absolute temperature T , thus:

$$E_B = \sigma T^4$$

Equation 5

For a non-black body

$$E = \varepsilon \sigma T^4$$

Equation 6

Where:

ε : emissivity. Defined as the ratio of the emissive power of the surface to that of a black body at the same temperature (Eastop & McConkey, 1993).

σ : Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$)

Radiation is extremely important during fires because it is the main mechanism for heat transfer from hot flames to fuel surfaces, from hot smoke to building objects, and from a burning building to an adjacent building (Buchanan & Abu, 2017).

2.8 Finite Element Analysis (FEA) models for heat transfer

The Finite Element Method (FEM) is an approximation method that subdivides a complex problem space, or domain, into numerous smaller, simpler pieces (finite elements) whose behaviour can be described with a comparatively simple equation, instead of one large, complex equation (Spatial Team, 2020). It is also regarded as a popular numerical technique to solve many engineering problems of a complex nature including but not limited to heat transfer (Bedruddin & Khan, 2017). “The basic idea of the FEM is to view a given domain as an assemblage of simple geometric shapes, called finite elements, for which it is possible to systematically generate the approximation functions needed in the solution of differential equations by any of the variational and weighted-residual methods” (Reddy & Gartling, 2010). Since its inception in the 1940s (Liu, et al., 2022), FEM has shifted and revolutionised the way complex design solutions are reached and/or determined (Liu, et al., 2022) across a wide range of fields, with heat transfer being one of the subjects for which analysis has been simplified. It represents the most flexible and powerful numerical method for analysing heat transfer problems of general interest (Huang & Usmani, 1994).

FEM has made it possible to solve large, complex engineering problems in a cost-effective and accelerated manner. It has provided means to simulate real-life problems in a way that makes it easy to adjust the initial design parameters to reach the desired target or optimise the design performance. It is important to note though, that the quality of the solution depends upon various factors, including mainly the distribution of meshing throughout the domain, time discretisation for transient problems, proper application of the boundary conditions, and the selection of suitable material properties (Huang & Usmani, 1994). Should the above be carefully exercised, the results yielded are generally particularly reliable and accurate. There

is, however, always room for error, therefore, results need to be critically and carefully examined, especially against those to which they are benchmarked, e.g., experimental if available. FEA has been used as a validation method for as long as it has been in existence, especially for heat transfer problems, and it will be utilised as a validation method in the current work.

Heat transfer problems can be categorised into two states, namely, steady-state and transient. Steady state heat transfer refers to the process during which temperature does not increase or decrease with time, while a transient problem is one during which temperature changes with time. In a real fire, the heat transfer is transient. **Figure 3** and **Figure 4** speak to this fact, albeit that **Figure 4** has a decay phase and **Figure 3** is continuously rising, but the increase and decrease of temperature are happening at a given time. In the current work, samples were modelled in a transient state because the temperature within the furnace was increasing with time.

2.9 Behaviour of the PSSDB elements during a fire

When steel is exposed to elevated temperatures, the temperature of the steel will rise, resulting in a reduction of the strength (load-bearing capacity) and stiffness of the steel elements. This could lead to possible deformation and failure, depending on the applied loads and the support conditions (Buchanan & Abu, 2017). Heated steel will elongate when it is not restrained in any way, such that the expanded members of the steel may cause damage to other parts of the structure (Buchanan & Abu, 2017), however, when it is restrained, the temperature change will be the generation of stress within the element, which could lead to failure such as buckling (Understanding Buckling, 2021). The free-to-expand members will experience less deflection than their restrained counterparts.

Steel has certain physical and thermal properties that make it desirable for use in construction. It is desired for its lightweight when compared to concrete so that it will not experience a large deflection under its weight. Steel possesses high strength in comparison to other construction

metals and has the lowest ratio of weight-to-strength of any material used in construction as an outer frame structure. Steel is ductile; therefore, it will elongate significantly before fracturing. Steel has a higher thermal conductivity than most other materials (Buchanan & Abu, 2017) and a relatively low thermal expansion coefficient. Steel can withstand temperatures of up to approximately 1370°C (Marx, 2018). Structural steel can regain close to 100 % of its pre-heated properties if the temperature does not exceed 720°C (Whitley, 2019). The dimensions of steel members in a structure don't change over the years even when subjected to extreme environmental conditions and can often be reused.

Steel beams and trusses may react differently to severe fire exposure (Mike, et al., 2011) and under different types and magnitudes of loading, depending on the end condition and fabrication. Under these loads, their properties will determine their behaviour and performance. When considering steel in elevated temperatures, the properties that are most looked at are thermal expansion, specific heat, thermal conductivity, modulus of elasticity, etc.

2.9.1 Thermal properties of steel

The material properties of steel vary with the temperature of the steel section. Heat is transferred from the fire in the compartment to the steel member through radiative and convective heat transfer (Marx, 2018) where there are no ceiling boards installed for protection against a fire. Where ceiling boards are installed, conduction also plays a role in transporting the heat to the steel sections. The material properties of structural steel are described in EN 1993-1-2 (European Standards, 2005) by using functions to have an accurate value for each temperature.

2.9.1.1 Thermal expansion

Materials will expand when heated, some more than others, depending on their molecular structure. The basic principle behind the expansion of materials is that when a substance is heated, the kinetic energy of its molecules increases, thus, the molecules begin to vibrate more vigorously and usually maintain a greater average separation. Steel expands when

exposed to elevated temperatures. An increase in temperature will result in more expansion, as expressed by **Equation 7**. When restricted, the effect of temperature change within the steel member will be a generation of stress within the material (Boley & Weiner, 2012). An increase in temperature will increase the compressive stress in the material as will a decrease in temperature increase the tensile stress.

The change in length due to thermal expansion can be calculated with the formula.

$$\Delta l = l\alpha\Delta T$$

Equation 7

Where:

α : is the coefficient of linear expansion measured in $m/m^{\circ}C$

Δl : is the change in length due to heating (m)

ΔT : change in temperature from the ambient conditions to the maximum temperature experienced by the material ($^{\circ}C$)

l : length of the material (m)

An accepted value of the coefficient of linear expansion α for steel is $12 \times 10^{-6}/^{\circ}C$ (Callister, 2007)

The thermal expansion of steel varies almost linearly relative to the temperature, as expressed in **Figure 13**.

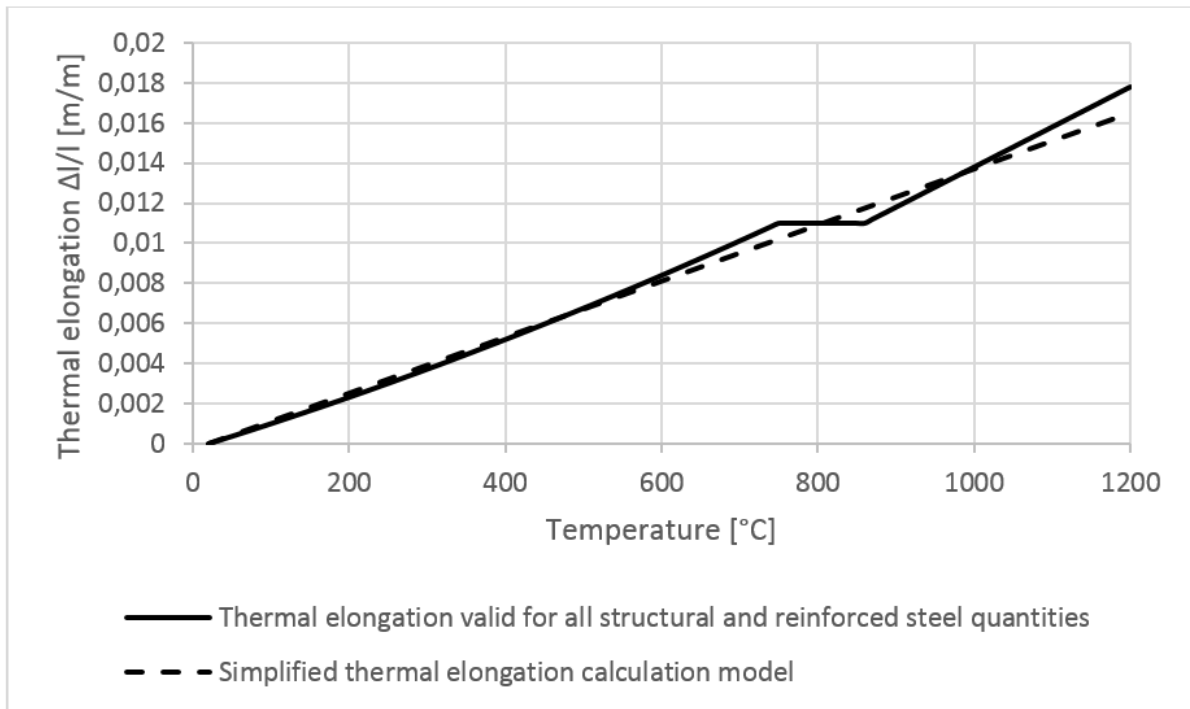


Figure 13. Thermal elongation of steel as a function of temperature (Fourie, 2020)

It is shown in **Figure 13** that when steel reaches the elongation of 0.011 m/m there is no expansion between temperatures of approximately 750°C and 870°C. Expansion begins to take place beyond 900°C again. The period of no expansion is the period of critical temperature for steel and a period during which the rearrangement of the crystal lattice structure occurs, therefore altering the molecular make up (Askeland, et al., 2011). During this period, the coefficient of linear thermal expansion is dormant because α essentially changes with temperature (Askeland, et al., 2011).

2.9.1.2 Specific heat

Specific heat is defined as the amount of energy (Joules) necessary to be gained by a material to cause 1kg of that material to increase by 1°C (Wang, 1995). **Figure 14** shows the variation of the specific heat of (carbon and stainless) steel with temperature.

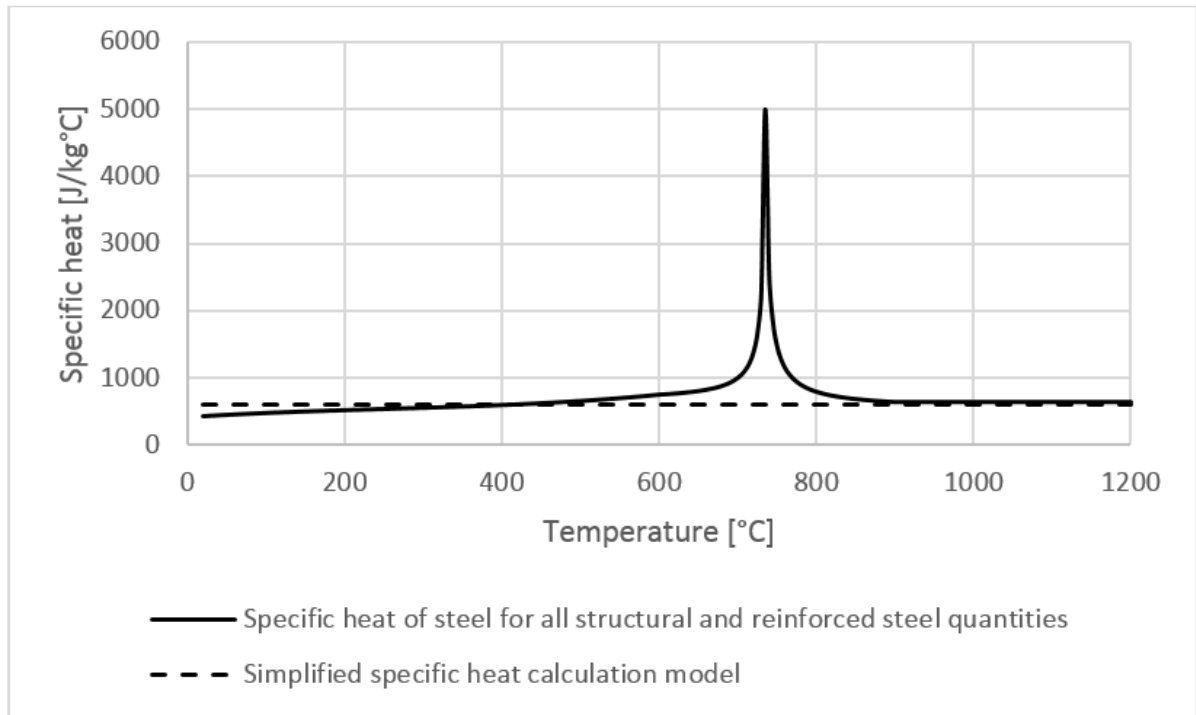


Figure 14. Specific heat of steel as a function of temperature (Fourie, 2020)

Figure 14 also illustrates a steady increase of the specific heat as the temperature increases, until at temperatures approximately between 700 – 800°C, when the specific heat peaks sharply to its maximum of 5000 J/kg°C and then decreases again with the continued increase in temperature. The peak represents the phase change of the crystal structure of steel due to an endothermic process (Wang, et al., 2012). The relationship between specific heat and temperature of the carbon steel is given by the expression(s):

At $20^{\circ}\text{C} \leq \theta_a < 600^{\circ}\text{C}$

$$C_a = 425 + 7.73 \times 10^{-1} \cdot \theta_a - 1.69 \times 10^{-3} \cdot \theta_a^2 + 2.22 \times 10^{-6} \cdot \theta_a^3$$

Equation 8

At $600^{\circ}\text{C} \leq \theta_a < 735^{\circ}\text{C}$

$$C_a = 666 + \frac{13.002}{738 - \theta_a}$$

Equation 9

At $735^{\circ}\text{C} \leq \theta_a < 900^{\circ}\text{C}$

$$C_a = 545 + \frac{17.820}{\theta_a - 731}$$

Equation 10

At $900^\circ\text{C} \leq \theta_a < 1200^\circ\text{C}$

$$C_a = 650$$

Equation 11

Where:

C_a : is the specific heat of steel (kJ/kgK)

θ_a : is the temperature of steel in ($^\circ\text{C}$)

2.9.1.3 Thermal conductivity

Thermal conductivity is a representation of the heat transferred from high to low temperatures. It predicts the heat loss rate through a piece of material and is measured in W/mK. For carbon steel, the thermal conductivity is inversely proportional to the temperature, and that means, the thermal conductivity decreases as the temperature increases (Wang, 1995), as shown in **Figure 15**.

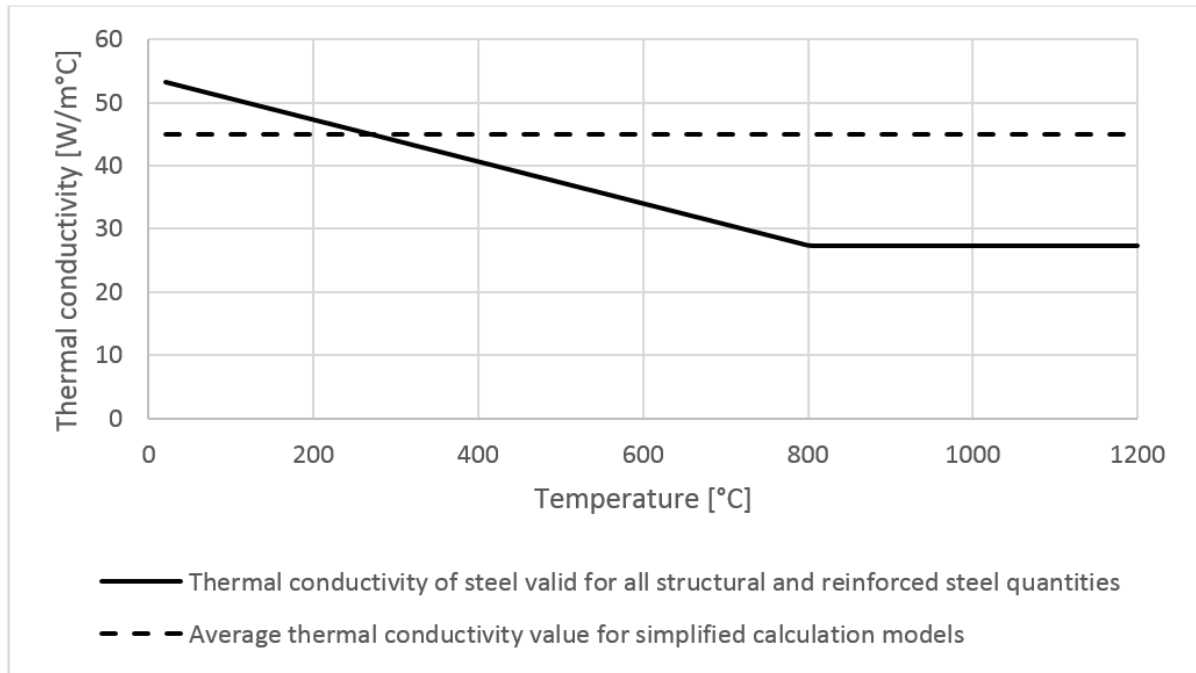


Figure 15. Thermal conductivity of steel against temperature (Fourie, 2020)

Steel has a higher thermal conductivity than most other materials, and the thermal conductivity of steel is generally assumed to be reversible during cooling (Buchanan & Abu, 2017).

The relationship between thermal conduction and temperature of carbon steel as given by the Eurocode is:

$$k_a = 54 - 3.33 \times 10^{-2} \cdot \theta_a$$

Equation 12

At $20^\circ\text{C} \leq \theta_a < 800^\circ\text{C}$

$$k_a = 27.3$$

Equation 13

At $800^\circ\text{C} \leq \theta_a < 1200^\circ\text{C}$

Where: k_a : is the thermal conductivity of carbon steel (W/m°C)

θ_a : is the temperature of the carbon steel °C

2.9.2 Mechanical properties of steel

Certain materials are chosen for specific applications due to their desirable combinations of mechanical characteristics (Karthik, 2019). The mechanical behaviour of a material reflects the relationship between its response and deformation to an applied load or force. Temperature can be thought of as an applied load and will therefore influence the mechanical properties of steel. As the temperature load is increased onto the structure, the properties will tend to be compromised and lead the structure to fail. It is therefore important to know and understand how these properties are affected by elevated temperatures.

Following are the mechanical properties of structural steel that are affected by applied temperature:

2.9.2.1 Tensile strength

Tensile strength refers to the amount of stretching (due to a 'pulling' load applied) that a material can withstand before breaking. The compressive and tensile strength of steel is almost equal (Ardiansyah, 2019). This is the stress at the maximum point (F) of the stress-strain curve in **Figure 16** (Tutorial Tips Civil, 2019) (Callister, 2007). Research has shown that the tensile strength of metals diminishes with an increase in temperature (Gholami, et al., 2020) (Brnic, et al., 2015). The more a metal is heated, the less it can withstand a tensile load.

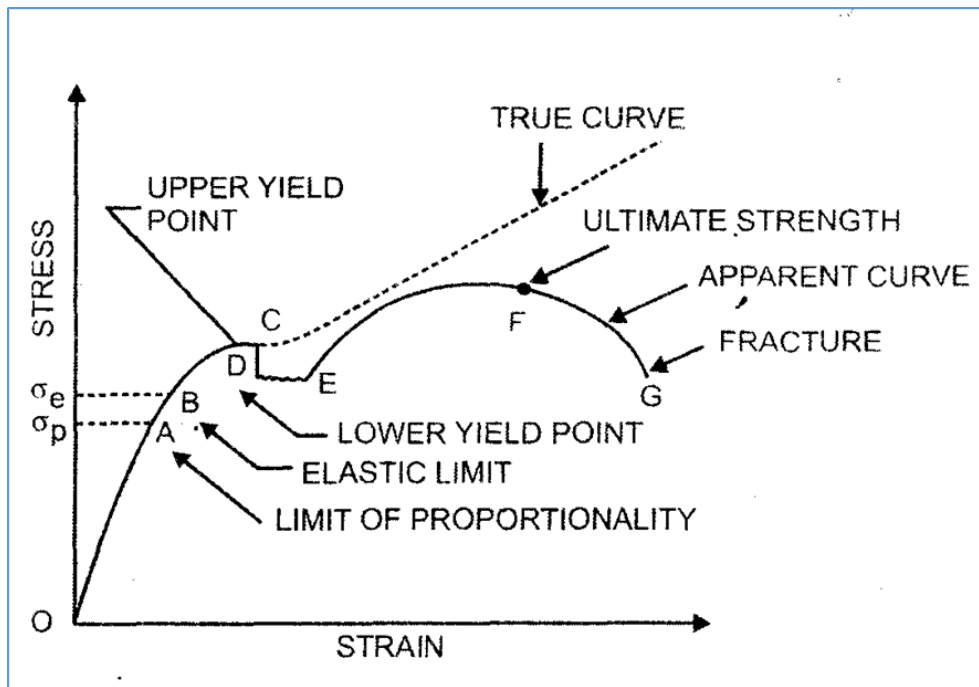


Figure 16. Engineering Stress-Strain curve (Tutorial Tips Civil, 2019)

2.9.2.2 Elastic Modulus

The elastic modulus is a quantity that describes the resistance of an object to being deformed elastically when stress is applied to it. A stiffer material will have a higher value of **E** (Modulus of Elasticity). On the engineering stress-strain curve, point E is the ratio of stress to strain. In **Figure 16**, the region from point 0 to point A, represents the limit of proportionality, where strain is directly proportional to the stress of the material. In this region, a material can be stretched or compressed and will return to its original shape and form once the load is removed. The modulus of elasticity diminishes with an increase in temperature. An increase in temperature, therefore, makes materials susceptible to quicker permanent deformation (Callister, 2007).

2.9.2.3 Hardness

Resistance to deformation, penetration, scratching, machining, and abrasion (Karthik, 2019), especially against localized plastic deformation, is known as hardness. Some materials are harder than others. Hardness is measured by indentation, scratch, and rebound. Hardness is

dependent on ductility, elastic stiffness, plasticity, strain, strength, toughness, and viscosity (Callister, 2007). Since hardness depends on ductility, it can be concluded that an increase in temperature will lead to diminishing hardness of the metal because a metal becomes less ductile as temperature is increased onto the metal.

2.9.2.4 Creep

Creep is the tendency of a solid material to move slowly or to deform permanently under the influence of persistent mechanical stresses. Creep of materials is associated with time-dependent plasticity under fixed stress at elevated temperatures (Higgins, 2014). Creep is more severe in materials that are subjected to heat for long periods and generally increases as they near the melting point.

The temperature range in which creep deformation may occur differs in various materials. The effects of creep generally become noticeable at approximately 35% of the melting point for metals (Callister, 2007).

2.9.2.5 Toughness

Toughness is the ability of a material to absorb energy and deform plastically without fracture. It is directly proportional to temperature change and inversely proportional to the rate of loading (Callister, 2007).

2.9.3. Thermal properties of Calcium Silicate

The use of dry boards was adopted with the development of the PSSDB systems, and along with improved fire resistance performance, they offer an aesthetically pleasing flat finish to the floor that allows for easy convenient attachment of floor coverings that are typically used. The fire-resistant CaSi dry boards have a moisture content of approximately 6%. This means that “heat energy is needed to evaporate the free water and to make the chemical change that releases the water in the crystal structure” (Steau & Mahendran, 2021), thus the moisture content within the board improves the fire resistance performance. Dry boards have thermal

properties that make them resistant to heat and the effects thereof. These properties are also crucial for the FEA model development, especially when the temperature changes with time. Thermal conductivity, specific heat, and density are constant properties at ambient temperature. However, when it comes to fire performance of floor systems, building materials are subjected to temperatures ranging from 20°C to more than 1100°C, (according to the standard fire curve). Hence, the thermal properties are found to vary significantly with the temperature increase, causing dramatic variations in the heat transfer characteristics as well (Perera, et al., 2022). The thermal properties of CaSi boards are discussed below.

2.9.3.1 Thermal conductivity

One of the main purposes served by the CaSi boards is to offer increased fire resistance due to their low thermal conductivity (Tuominen, et al., 2019). CaSi boards are porous (Tuominen, et al., 2019) and are embedded with cementitious material for better performance against fire. These boards are also inherently resistant to the effects of moisture. A study (Steau & Mahendran, 2021) has provided insights into the thermal properties (specific heat, thermal conductivity, thermal diffusivity, and relative density) of the CaSi boards. The study showed that the same boards from various manufacturers could behave differently depending on their chemical composition, although they all offer fire resistance.

Figure 17 presents the proposed values of thermal conductivity and specific heat for the CaSi board, and the author asserts that the particular board was chosen for the standard thermal conductivity equation modelling because it exhibited a combination of high specific heat, low thermal conductivity, reduced mass loss, and low bulk density.

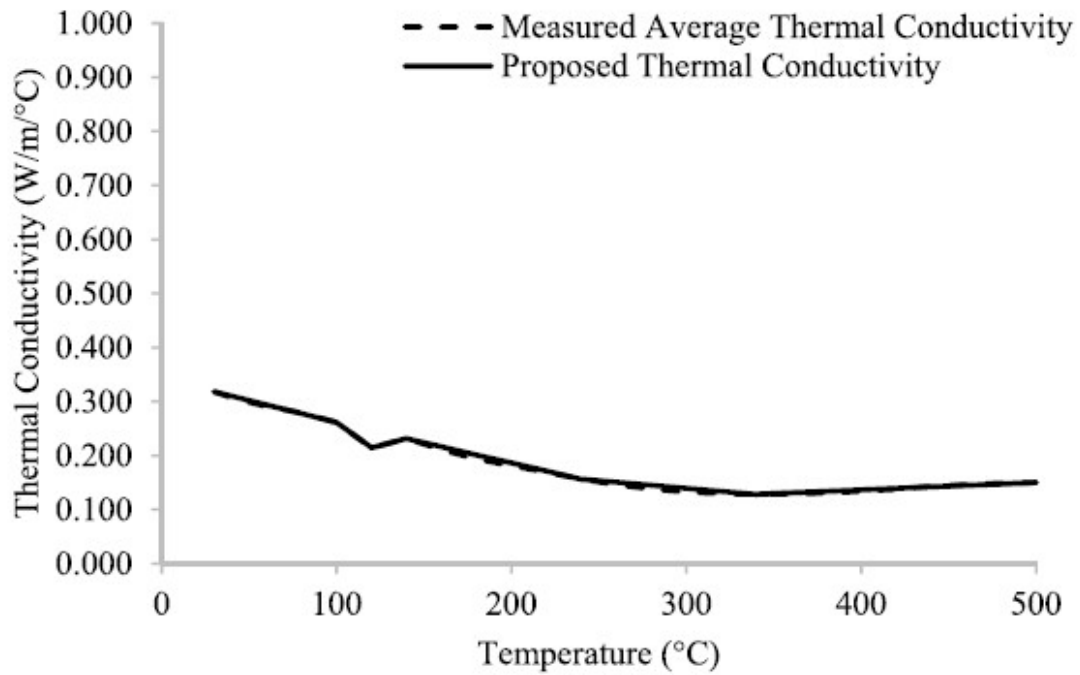


Figure 17. The curve representing the proposed values for Calcium Silicate for modelling (Steau & Mahendran, 2021)

2.9.3.2 Specific heat

The thermal properties of the dry boards as well as the steel are used in the current study as time- and- temperature-dependent parameters. Specific heat of the CaSi board is seen to peak suddenly at approximately 186°C and again at 162°C in the literature, (Steau & Mahendran, 2021), (Dodangoda, et al., 2019) (Perera, et al., 2022). The peak is a result of an endothermic reaction that occurs during the decomposition of calcium sulphate dihydrate (which is in the microstructure of the material).

Figure 18 represents the measured specific heat with an increase in temperature.

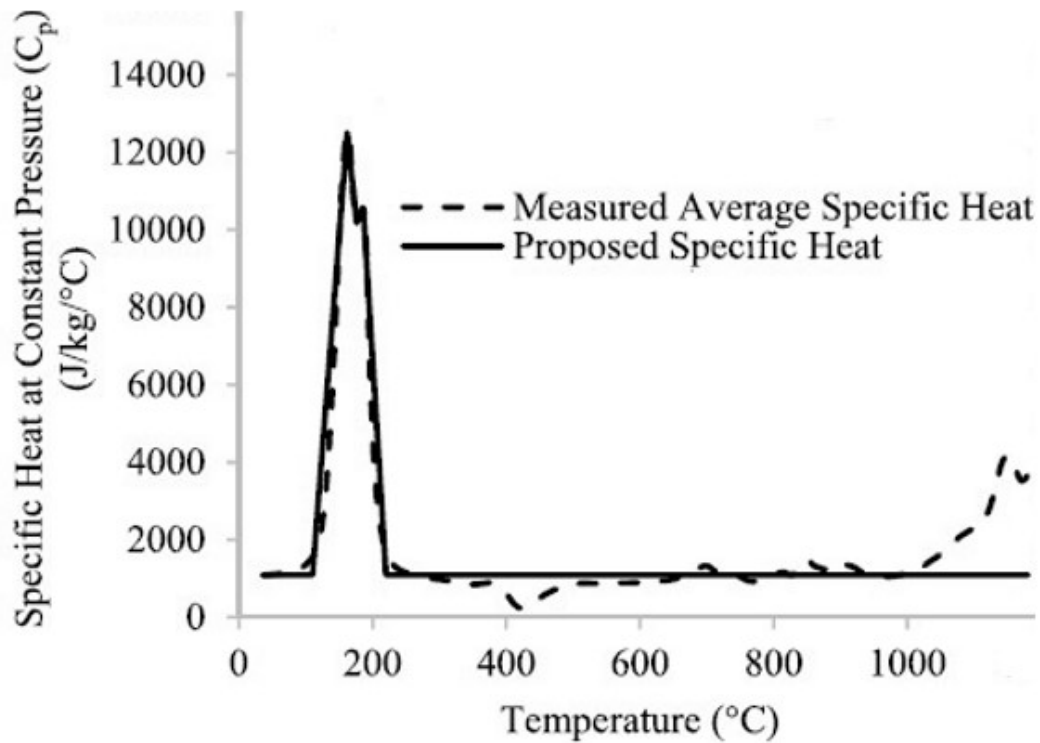


Figure 18. Specific heat for the Calcium Silicate dry board against temperature (Steau & Mahendran, 2021)

2.9.3.3 Density

As a solid material, dry boards inherently have a high density because of their atomic structure. As the atoms of a solid body start to loosen as the material is heated, the density of the material will inevitably decrease. The decline is shown in **Figure 19**, where the decline of temperature occurs between approximately 100°C and 190°C. The decline resulted from the first dehydration and the release of water crystallisation (Rahmanian, 2011) (Perera, et al., 2022) (Mehaffey, et al., 1994). At approximately 190°C, the density now becomes constant with an increase of temperature.

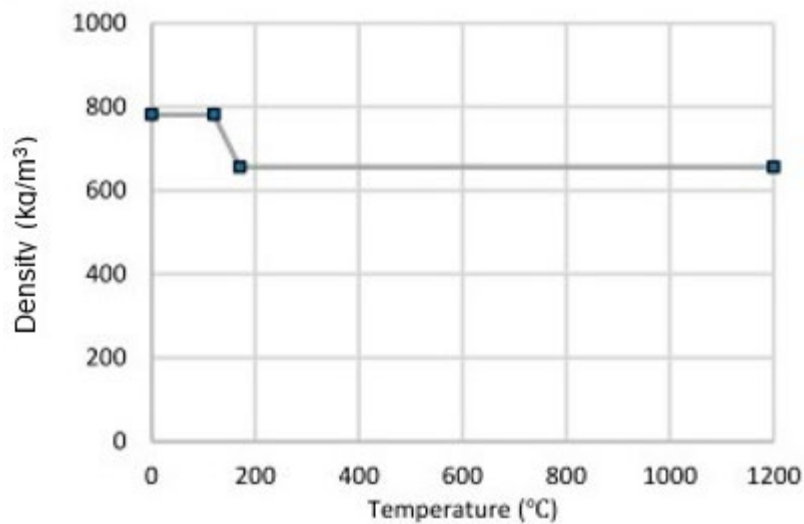


Figure 19. Density of dry board (typically) against temperature (Perera, et al., 2022)

2.10 Conclusion

The chapter provided an overview of the challenges and considerations related to protecting structures from fires. It highlighted the increasing concern among designers and builders regarding the risks posed by combustible building materials and the importance of implementing both passive and active fire prevention measures. The chapter discussed the chemical process of fire, the elements of the fire triangle (fuel, heat, oxygen), and the stages of a fire including ignition, growth, flashover, burning period, and decay. It emphasised the significance of compartmentation in fire design and the impact of fire behaviour on structural elements. A brief discussion on the PSSDB systems was laid out, looking into the thermal properties and mechanical properties (specifically the ones that are affected by temperature increase) of the elements that make up the PSSDB composite structure.

Additionally, the role of finite element modelling in understanding heat transfer and the evolution of fire analysis techniques was explored. Overall, the chapter underscores the urgent need for effective fire protection measures and collaborative efforts to safeguard buildings from fire hazards. Literature was explored to lay a basis for an understanding of fire and

looking at the work by other researchers and authors have done regarding the protection of steel against fire using passive methods in the form of fire-resistant boards.

Chapter 3: Experimental set-up

3.1 Introduction

This chapter details the experimental setup and procedure that was followed when testing the specimens. The experiment was carried out on four small-scale samples that span 1.2×1.2 m² each, one of which (Test Sample 1) was used to calibrate the furnace temperature to reach, as close as possible, the standard fire curve temperatures. The test specimens require a 60-minute fire resistance rating, for the specific criteria of insulation and integrity, according to the (SANS 10400, 2002). The insulation criterion is regulated by the bounds of temperature that the average temperature on the unexposed side of the specimen should not increase by more than 140°C above the ambient or the maximum temperature at any one point on the unexposed surface of the specimen should not increase by more than 180°C or exceed 220°C regardless of the ambient temperature (Tuominen, et al., 2019). The ceiling boards also need to provide integrity, in that, no flames or hot gases should penetrate to the unexposed faces of the systems for a specified period. This chapter will discuss in detail the preparation of the specimens, furnace specifications, set-up, instrumentation, test procedure, and the FEA models' test development.

3.2 Rationale for experiments

Previously, tests have been conducted by various authors on the sandwich floor system, albeit on different scales, where one face of the CaSi board of the system was directly exposed to a standard fire curve, and while insulation and integrity criteria were specifically tested. The experiments include the work by Marx (2018), Claasen (2022), and Claasen, et al (2023) from Stellenbosch University. Both authors have shown that it is beneficial to have a ceiling board (with no holes) attached to the system, such that in both tests the system passed the insulation criteria for an hour's rating (Claasen, 2022), (Marx, 2018).

This research differs from the aforementioned in that the ceiling boards have holes in them of different configurations which simulate lighting holes and/or air condition ducts. The small-scale furnace tests would provide valuable information regarding the temperature distribution through the holes within the sandwich floor system, as well as the behaviour of the specific insulation material used. The experiments focus on whether the size of the samples would affect the overall results in any significant way across the different elements in terms of the total heat transfer.

3.3 Fire test

The objective of the investigation was to assess the potential impact of penetrations, specifically holes, in the sandwich floor/ceiling system on its fire rating. The fire-resistance rating was evaluated by conducting tests on multiple samples that varied only in terms of hole sizes and positions. The fundamental configuration of the samples is depicted in **Figure 10** and **Figure 20**.

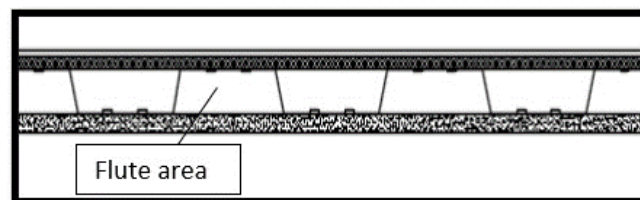


Figure 20. The sandwich system showing the flute area (Marx, 2018)

All the samples were prefabricated and constructed in a similar configuration. They all consisted of fibre cement board (FCB) on the unexposed side, steel sheeting in the middle, and CaSi boards on the fireside, as shown in **Figure 10**.

3.3.1 Preparation of specimens

A set of four samples was subjected to standard fire testing. Each of the samples had outer dimensions of roughly 1.2×1.2 m. The specimens were fabricated utilizing a 20 mm thick

FCB in conjunction with a steel decking measuring 115 mm in depth for the infill area (**Figure 21**).



Figure 21. Side view of the prefabricated sandwich floor/ceiling system with a 20 mm thick FCB, placed on the furnace

The test samples were completely devoid of concrete or any form of traditional reinforcement. The materials were fastened together using special self-tapping screws (**Figure 7**) as would have been assembled in a structure. The fire-resistant (CaSi) ceiling boards were intentionally perforated on the fire-exposed face to replicate service fixtures, such as lights and AC ducts. Different sizes of holes were used to represent the various light fittings commonly used in industry. Consequently, it would be advantageous to examine the impact of larger holes on the rate of heat transfer compared to smaller ones.

All the test samples were initially sized at 1.2×2.4 m each and then cut into sizes of 1.2×1.2 m for the ease of fitting them onto the opening of the furnace (Section 3.3.2). Some of the samples suffered damage during downsizing, and while most of the cracks were too small to have a direct and significant influence on the results, others were too big to ignore (**Figure 22**), and one such damage was concealed with a piece of ceramic blanket (**Figure 23**) to

account for and augment the varying results due to the heat that may be lost. The effects of the damage on the samples will be discussed in Chapter 4.



Figure 22. Broken sample, showing the exposed side



Figure 23. Broken sample with ceramic blanket patch, showing the exposed side

All the holes on all the samples were made directly under the flutes and the distances between the centres of the holes varied slightly for all the samples. In practice, the lights and AC fittings would be simple to have within the flute area, thus the holes were located directly below these flute areas. For experimentation purposes, these locations would represent worst-case scenarios in having the heat from the furnace enter into the open area of the flutes. **Figure 22** and **Figure 23** show the sample that was used for Test 3. The sample had suffered some damage during the down sizing and a ceramic fibre blanket was used to conceal the opening.

The sample descriptions of the test samples used during the experiments are discussed below:

- **Test Sample 1:** The sample had no holes made on the CaSi fire-exposed side. This was the sample used to calibrate the furnace. As indicated in **Table 1**, Test Sample 1 consisted of a 9-12 mm CaSi board, 20 mm thick FCB, and a steel decking with a depth of 115 mm.

Table 1. Summary of the composition of test samples used during actual furnace trials

Test sample	Number of holes	CaSi thickness (mm)	FCB thickness (mm)	Decking depth (mm)
1	0	9-12	20	115
2	2	9-12	20	115
3	2 (1 concealed)	9-12	20	115
4	3	9-12	20	115

- **Test Sample 2:** The sample had two square holes of size 85 × 85 mm each and were both unconcealed, the configuration is shown in **Figure 24**. The sample consisted of a 9-12 mm thick CaSi board, 115 mm deep steel sheet, and 20 mm thick FCB. Each of the holes was made along the length of the flutes. The holes were 258 mm from the one (top) edge and 857 mm from the other (bottom) edge (**Figure 24**).

The sample was mounted onto the furnace in such a way that the burner was on the further side of the two holes (**Figure 46**) and the holes were 600 mm apart, from their centres. The holes of Test Sample 2 were further from the heat source, to investigate if the distance between the holes and the heat source would have any influence on the results.

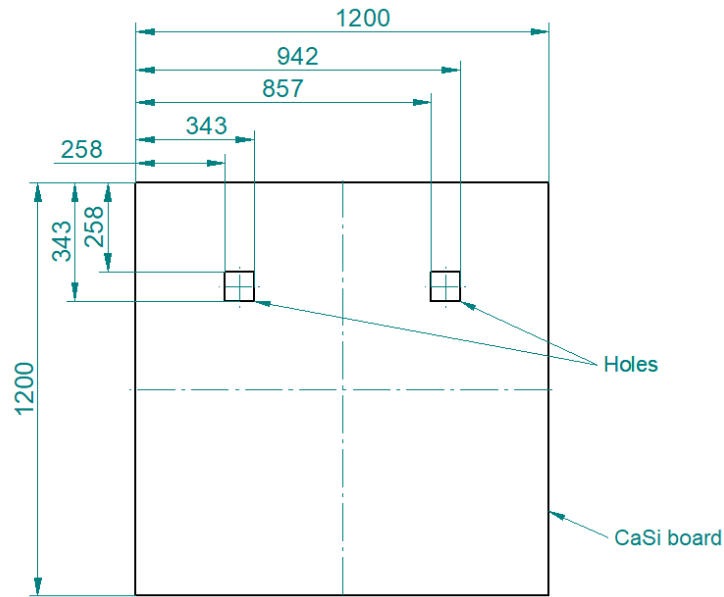


Figure 24. Test Sample 2. CaSi face layout of holes positions and sizes in mm

The sizes of the holes chosen for the light fittings and the AC duct have been assumed based on the size of the small-scale samples. The normal sizes for commercial lights range between 100 mm and 250 mm in diameter, most of which would have square outer casings for which larger openings would be needed. The holes for these experiments were assigned sizes of 85 × 85 mm and 80 × 80 mm. Test Sample 4 had the 80 × 80 mm smaller holes to allow space for the larger hole. Test Sample 3 had 80 × 80 mm size holes to observe the temperature variations compared to Test Sample 2 which had slightly bigger holes of size 85 × 85 mm.

- **Test Sample 3:** This sample had two holes, one below and at the centre of each flute and they were each 80 × 80 mm. The holes on this sample were closer to the heat source and one hole was concealed using the same CaSi material (**Figure 25**), and the other was left open and completely exposed to the fire. For the simple purpose of experimentation, one hole was covered with the same insulation material as the ceiling to observe whether it would be more beneficial to cover (if needed) a hole using any type of insulating material. A void of approximately 100 × 1200 mm was covered with

a ceramic blanket as seen in **Figure 23** due to the damage to the board over that area.

Figure 25 shows the positions and the sizes of the holes in Test Sample 3.

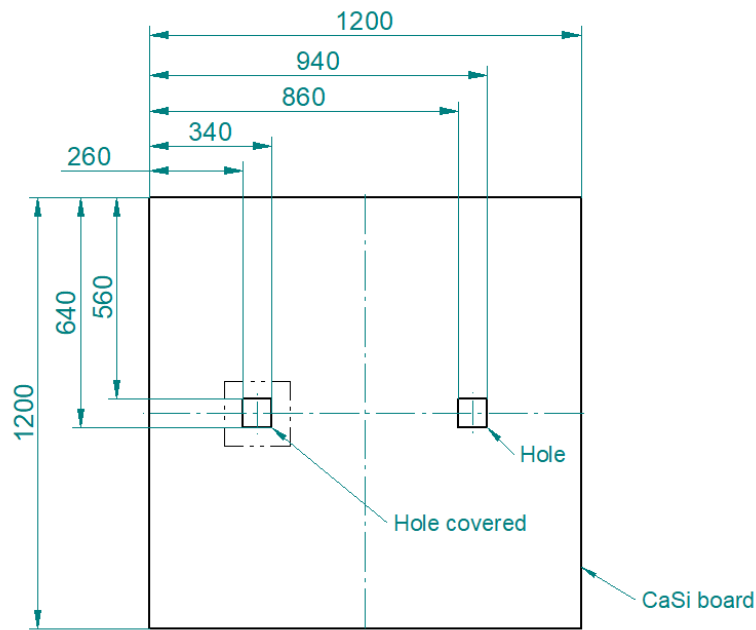


Figure 25. Test Sample 3. CaSi face layout of holes positions and sizes in mm

- Test Sample 4:** This sample had three square holes, with two smaller holes positioned beneath the left flute and the larger one positioned beneath the right flute. The smaller holes had an area of 80×80 mm apiece and were spaced 600 mm apart, measured from centre to centre. The larger hole was 200×200 mm and was at the centre of the flute. **Figure 26** shows the hole positions and sizes as well as the distances between the holes. The larger hole was loosely concealed by a ceramic fibre blanket. The purpose of applying ceramic fibre to the larger hole was to investigate and observe the comparative advantages of utilizing fibre or CaSi for covering holes. The sample was utilized in the context of Test Sample 4.

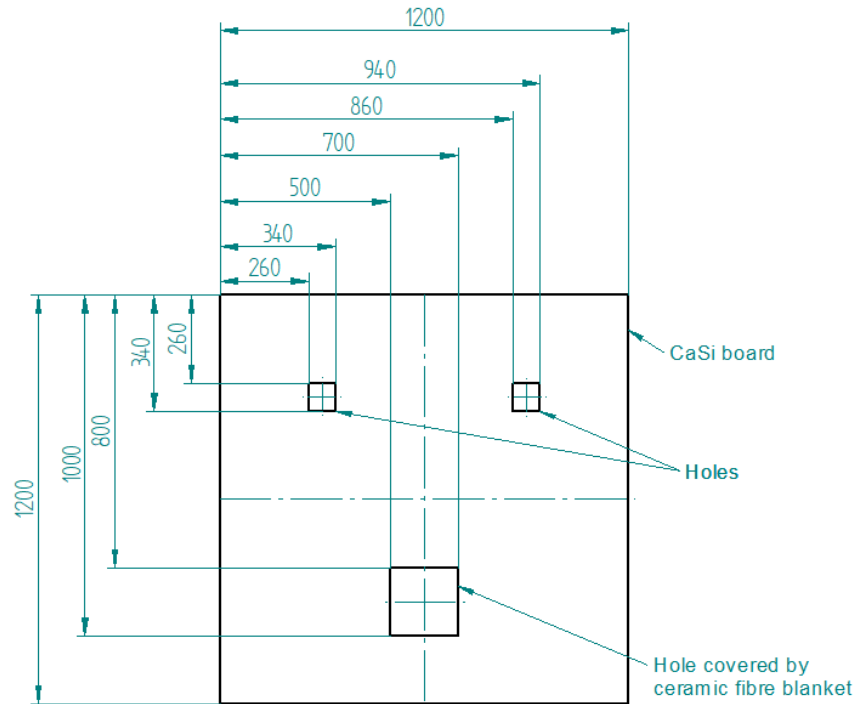


Figure 26. Test Sample 4 CaSi face layout of holes positions and sizes in mm

Chapter 4 will discuss how the results differ per sample, dictated by the size and position of the penetrations, the holes relative to the gas burner, and the thickness of the boards used. The sample with the most penetrations was anticipated to experience more widespread and rapid failure based on the fundamental principles of heat transfer.

3.3.2 Furnace specifications

The steel base, refractory lightweight vermiculite concrete liner, and exterior steel frame comprise the general configuration of the furnace. A gas burner powered the furnace and was secured by a steel latch on one side of the furnace. Depending on the burner's power output, more hand-held burners could be required, (as was the case during the experiments) to obtain the desired heat output. The burners were powered by regular Liquefied Petroleum Gas (LPG). The inside of the furnace was lined with a fibre ceramic blanket (**Figure 27**) to assist with the delay of heat transfer to the outer components of the furnace. Therefore, every

element within the furnace that was directly exposed to the ISO 834 fire was covered with a fibre ceramic blanket (Fourie, 2020).

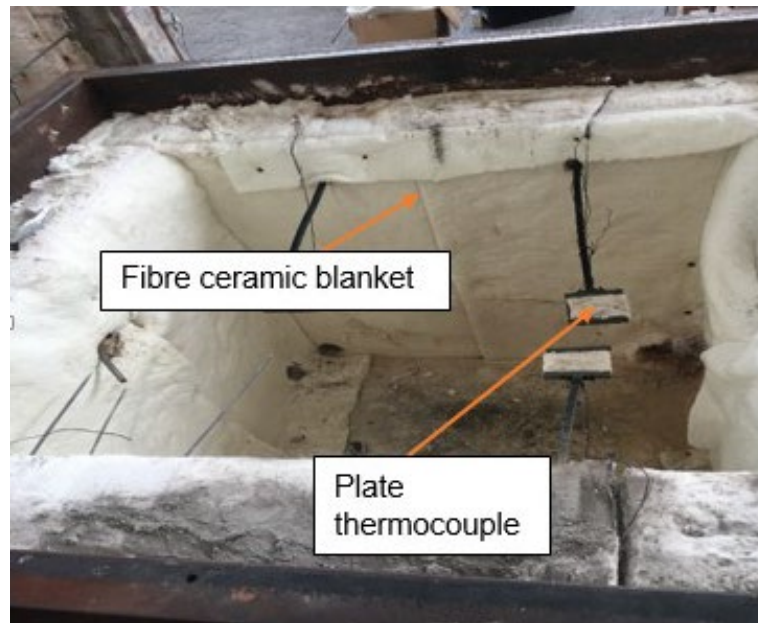


Figure 27. The inside of the furnace is covered in a ceramic fibre blanket

Not only does the fibre ceramic blanket reduce the temperature of the vermiculite lining, resulting in less cracking and spalling of the vermiculite lightweight lining (Fourie, 2020), it also decreases the internal emissivity of the furnace lining, which improves the efficiency and decreases the energy consumption of the furnace (BENKŐ, 1991). This phenomenon, therefore, means there will be diminished losses from the furnace and the temperatures will reach and remain at the desired temperatures throughout the tests.

The area of the furnace opening is $1.2 \text{ m} \times 1.2 \text{ m}$ and the furnace was set up vertically for the conducted experiments to evaluate a floor system in particular. To ensure that the furnace represents the standard ISO 834 fire curve temperatures, one 200 kW power output capacity burner, and two (extra) 40 kW power output capacity burners were used. Since the experiment would be standardized, energy conservation would not be the focus for these experiments, and the furnace's "resulting temperature must be precisely the same as the temperature-time curve" (Wegrzynski & Turkowski, 2018), namely, the ISO 834.



Figure 28. The furnace with one hand-held burner inserted

A chimney opening was used to ensure that there was sufficient airflow for complete combustion inside the furnace. Two of the smaller ventilation openings were used as the hand-held burner positions, as shown in **Figure 28**. Four thermocouples concealed by fibre ceramic blanket inside steel plates were located inside the furnace (**Figure 27**) to constantly read the furnace temperature so that even if one of the TCs may be destroyed during the test, the remaining ones would still provide acceptable and usable results

The furnace was instrumented as shown in **Figure 29** for all the fire tests. The TCs, P1L, and P2R (according to the naming configuration used as described in Section 3.3.3.), were the ones closest to the main burner in all the tests.

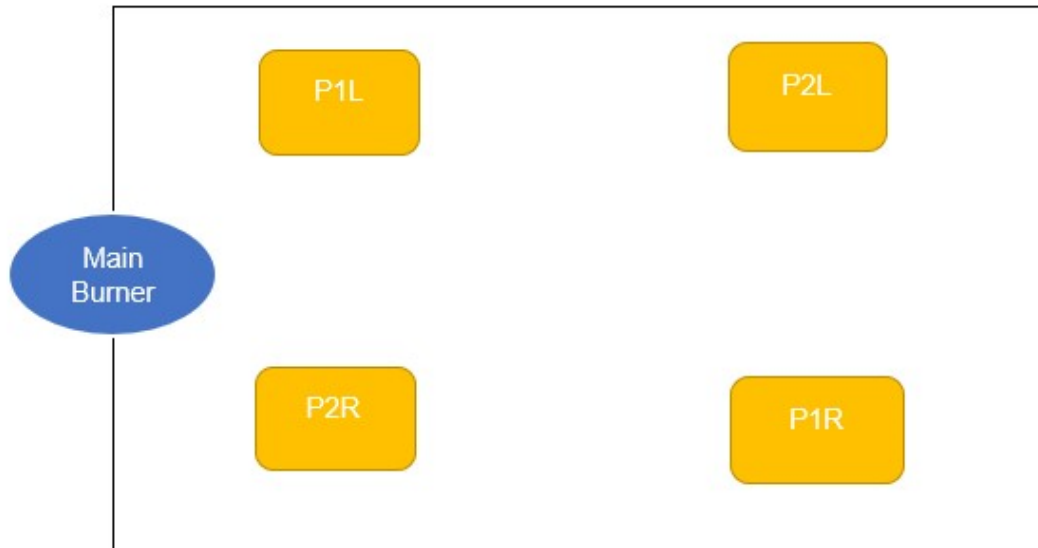


Figure 29. 2D drawing of the position of the TCs inside the furnace

3.3.3 Instrumentation

Due to their affordability and durability (Edgefx.Technologies, 2017), type K thermocouples (TC) were used in the experiments, and because they can read temperatures of up to 1350°C (SwiftHeatandControl, 2017) and the standard ISO 834 fire curve is expected to reach an approximate maximum temperature of 945°C for an hour test. All the TCs that were used on the samples during the tests were thoroughly tested using a TC sensor and multimeter to ensure that they could be utilised for the furnace test.

The general positioning of the TCs was such that there were at least four TCs in each of the vital areas of the system. In this study, the vital areas were considered as the unexposed faces of the FCB because this would be where the insulation criterion was evaluated, and the flutes for the gas temperatures. The exposed faces (CaSi) were instrumented with the TCs to assist with the observation of the temperature decrease from the fireside to the unexposed face. It was important during the experiments to measure the temperatures of the unexposed side (the FCB) of the floor system, the gas temperatures inside the flute areas, and the CaSi exposed face temperatures. The temperature on the unexposed face determines whether or not the system fails the insulation and integrity criterion and the gas temperatures in the flute area were used to determine the heat flow rate.

The TCs were primarily placed inside the flute area of the steel deck, on the exposed face of the system, in between the steel sheet and the FCB, and on the unexposed face of the system. The TCs were attached in such a way that they came through the backboard (FCB) to the exposed face of the CaSi. Since the sandwich floor system was devoid of concrete, it provided easy access for the placement of TCs, and as such, holes were drilled through the FCB, and the TCs were run through the flutes, and then through the holes to the face of the CaSi board. For the simplicity of labelling and reading the measurements, the TCs were placed in three main groups of left, right, and centre and, in the form of straight lines at designated locations as shown in **Figure 30**.

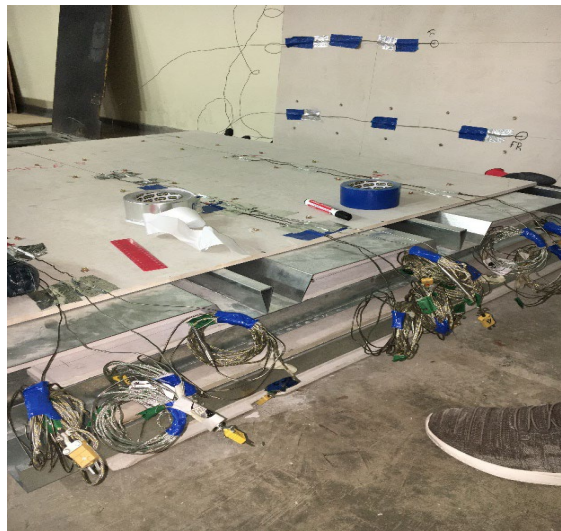


Figure 30. Thermocouple groupings placed on a test sample

The labelling system that was adapted was as seen in **Figure 31**. The symbols were taken and described as follows:

Furnace – P; Exposed – E; Back – B; Flute – F; Centre – C; Right – R; Left – L; Channel (between the steel deck and FCB) – c



Figure 31. An example of the labelling adopted

The TCs were attached in such a way that they always hung down from the sides of the test samples, running down to the data logger that was placed at an approximate distance of 1.8 to 2.2 m from the furnace. To attach the TCs in the flute areas, 2 mm diameter holes were drilled into the FBC and through the steel sheet. The TCs would then be placed in the holes at a depth of 20 to 30 mm. The TCs would then be held down by an adhesive foil tape as shown in **Figure 31**.

3.3.4 Test setup

As discussed in Sections 3.3.1 and 3.3.2, the specimens rested on the open top of the furnace, supported by beams on all four sides of the furnace walls, to expose the bottom side of the floor to the fire (**Figure 32**).

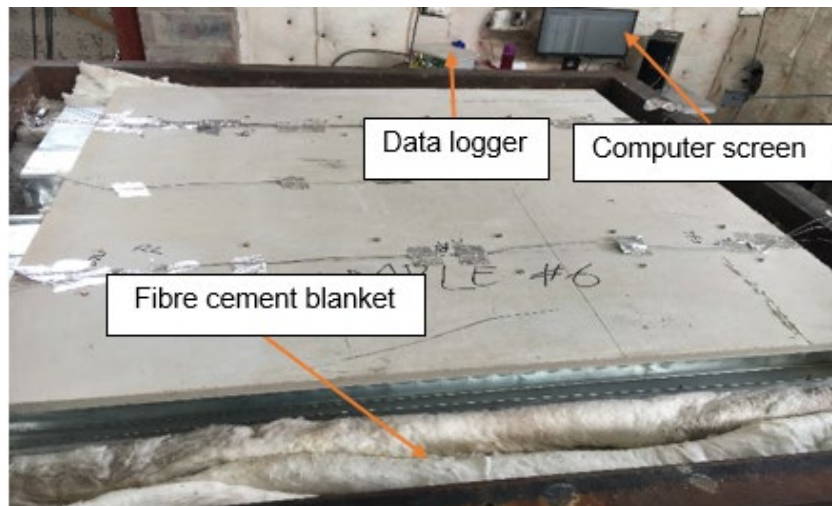


Figure 32. The specimen when rested on the furnace

The sides of the specimens were covered with a fibre ceramic blanket to prevent unnecessary heat losses into the atmosphere at any given time during the tests. The data logger was connected to a computer and the results were generated by the Benchlink 34980A data logger Pro software with the interface shown in **Figure 33**.

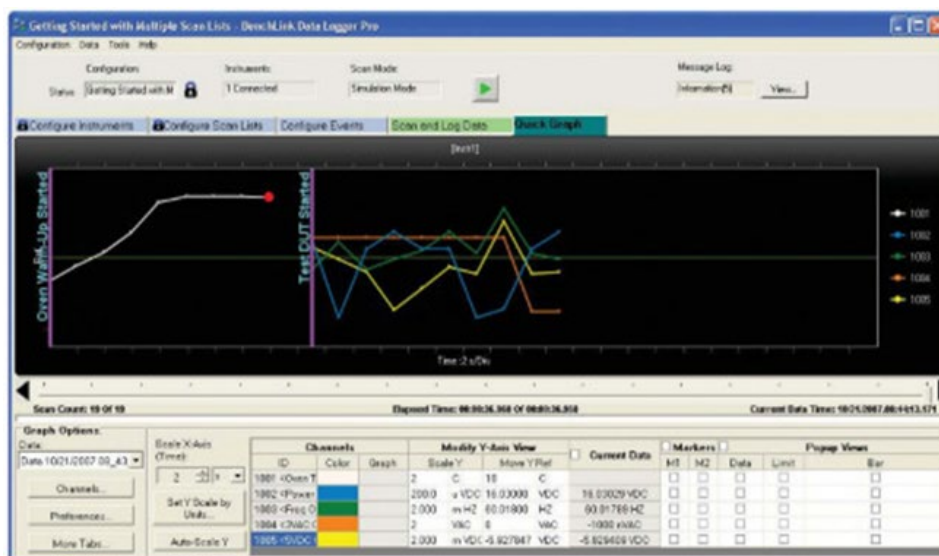


Figure 33. An example of how the software displays data

TCs had to be extended (as shown in **Figure 34** and **Figure 35**) to ensure that they were connected to the logger.



Figure 34. The extensions connected to the thermocouples



Figure 35. Extensions running down to connect to the logger

As the TCs are labelled following the pattern discussed in Section 3.3.3, the extensions needed to be labelled following the same pattern for the logger connection, and input into the logger interface (**Figure 31** and **Figure 35**).

This was done to ensure that the generated results would be obtained at the correct positions. The specimens had between 14 and 21 TCs. The inclusion of additional thermocouples in the instrumentation of these samples would prove advantageous in gathering definitive findings, even in the event of a TC failure during the testing process. The specimens with a lower number of perforations did not inherently require an increased quantity of TCs, particularly within the flutes and on the surfaces not exposed to the external environment.

3.3.5 Test procedure

An initial test run was conducted using Test Sample 1. The reason for that was its simple geometry (it had no holes), therefore, these preliminary results from the test could be easily analysed and understood. During the test, it was seen that the furnace could not operate close to the standard ISO 834 fire curve with the burner that was recommended by '(Fourie, 2020)', therefore, a smaller capacity burner of 200 kW was used together with two hand-held burners of 40 kW each to obtain operating conditions similar to the standard ISO 834 fire curve.

The software connected to the data logger was set to record measurements at 10-second intervals. The software requires the user to identify the measurements required, define limits and actions (such as drawing the temperature curve as the tests are proceeding) to be performed, and then initiate the process. The data was then collated and evaluated. The program compared the standard ISO 843 fire curve with the temperatures that were being measured inside the furnace. This was how the furnace temperatures could be manually altered to reach the desired furnace temperature, by increasing or decreasing the input energy as needed. The hand-held burners were used interchangeably or simultaneously at a time, depending on how the main burner was behaving.

The ambient temperature was taken in the range of 20 to 24°C. However, because more than one test was conducted in a day, tests following the first one would have read ambient temperatures slightly above the initial range. The reason for this was that the ambient

temperatures were read when the specimens were already over the furnace while the furnace was still cooling down from the previous test conducted.

The tests were to be run for one hour ideally, however, some of the tests were suspended before the one-hour mark because they would start showing signs of failure sooner than the one-hour mark was reached. As soon as a test was suspended, the specimen would be offloaded from the furnace using a forklift. The furnace would be allowed some time to cool in the interim while the next specimen was being instrumented for the test. In other instances, a fan was used to aid with the cooling process. Because the furnace heats to temperatures of up to 945°C, it took a considerable amount of time to cool, although it would not cool down to an ideal ambient temperature of 20°C. As a result, the ambient temperature would have to be pre-set to approximately 40°C on the software, depending on the actual initial furnace temperature at the beginning of each test.

3.3.6 FEA model set-up

FEA modelling was deployed to ascertain the experimental results that were obtained from the physical experiments. FEA models created in ABAQUS CAE 2020 were developed for each of the test samples that were physically tested in this work. The parameters that were used for these models were based on the work of Marx (2018) and Claasen (2022) because this work follows on the work that the two authors had already performed. The parts were created as 3D solid homogeneous extruded parts, with the steel sheet as a 3D shell with a thickness of 1 mm, sandwiched in between the CaSi board (on the fire side) and the FCB (on the unexposed side). The different components of the FEA model were assigned temperature-dependent thermal properties. **Table 2** below lists the properties used in the models, obtained from the work of Claasen (2022). The geometries yielded better results when the emissivity values (**Table 2**) were entered as temperature-dependent parameters for the different-sized (large and small), and triangular cavities as indicated in **Figure 38**.

Table 2. Resultant emissivity values for defined cavities (Claasen, 2022)

Material	Emissivity
CSB	0.8
FCB	0.9
VP 50 (Triangular Cavity)	0.42 at 20 °C 0.8 at 420 °C 0.8 at 800 °C
Material combinations	Resultant emissivity
CBS – VP Decking (Large Cavity)	0.38 at 20 °C 0.67 at 420 °C 0.67 at 800 °C
VP Decking – FCB (small Cavity)	0.4 at 20 °C 0.73 at 420 °C 0.73 at 800 °C

The created parts were assigned sections and assembled as dependent instances. The model steps were created for a total time of 2260 seconds which equates to approximately 37 minutes (which was the time at which the shortest test was terminated). The models were capped at 37 minutes to shorten the modelling time that would be needed for each test. An initial increment size of 0.1 was assigned on the step with a maximum of 10 for a total of 1000 increments. A maximum allowable temperature change of 10°C was imposed. A mesh was then created on parts as they were dependent and could not be meshed on assembly. A linear hexahedral DC3D8 and a linear quadrilateral DS4 elements were created on the mesh with an element size of 0.02 m, allowing for a single element along the thickness of the boards. The geometry of the samples was simple enough not to require a coarse mesh at one area and a finer mesh at another area, thus a consistent mesh of 0.02 m was chosen. The mesh was fine enough to yield suitable results, while the simulation would not be too computationally expensive to run. The TCs were represented by the individual sets that were created on

partitioned parts. These TC sets were created in the same positions in which they were located during the experiments. The TCs are represented in **Figure 36** as red dots.



Figure 36. The unexposed face of the half model with the thermocouple positions as set up in the FEA model for Test Sample 2. The TC labels are as defined in Section 3.3.3

The models' simulations material properties (referred to as “interactions” in Abaqus) of the models were crucial in obtaining comparable results between the experiments and the FEA simulations. **Figure 37** shows how the interactions were imposed onto the model to ensure comparable results between the FEA and the experiments.

The values of $10 \text{ W/m}^2\text{K}$ and $25 \text{ W/m}^2\text{K}$ were used for the outer and inner surfaces, respectively, for the convective coefficient. These are the values as suggested in the work of Claasen (2022), Marx (2018), and Parera, et al (2022).

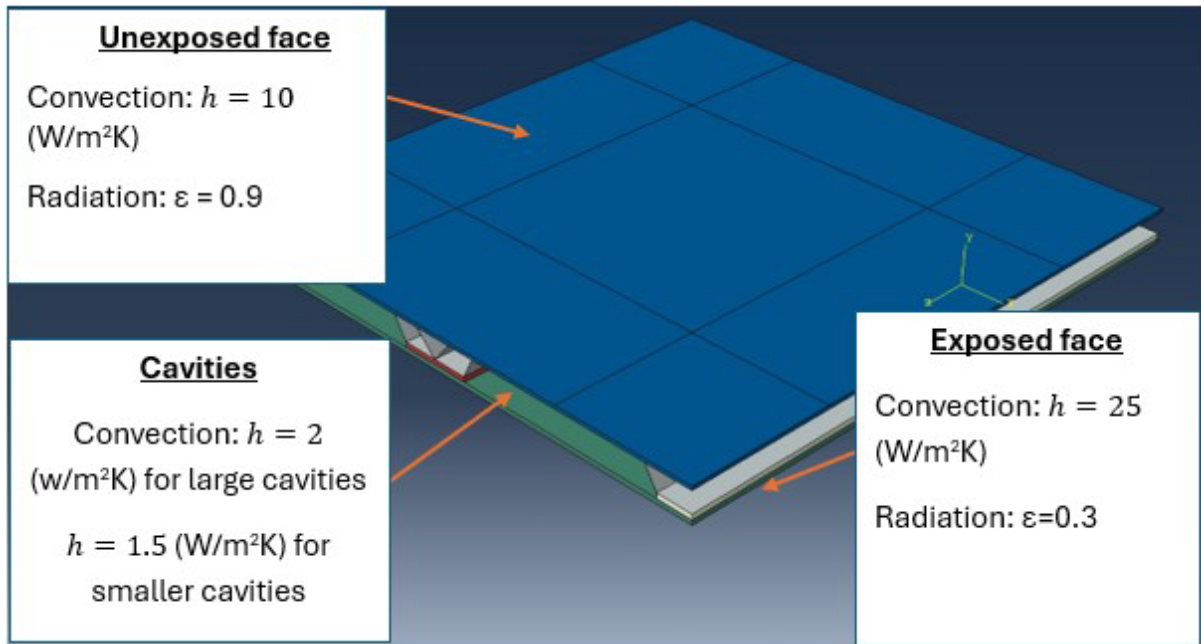


Figure 37. The interactions as imposed on the FEA models

The author Ghojel (2004) asserts that neglecting the presence of thermal contact conductance at the steel-concrete interface can lead to significant differences between computed and measured temperatures. The same contact conductance as the one presented by Mago, Hicks, and Simms (2016) was attributed to the steel-CaSi interface mainly because the system has no concrete, but the gap conductance still needs to be accounted for because, according to the literature, the air gap is responsible for a temperature drop at the interface (Kumar & Reddy, 2016). In this work, the CaSi strips were utilised in these models in place of the concrete moulding that would traditionally be manufactured to withstand the effects of a fire and thus delay the heat transfer through conduction. Radiation and convection are the modes responsible for the major heat transfer that takes place within the voids. The voids or cavities (**Figure 38**) within the ceiling structure have a notable effect on the rate of heat transfer. Radiation had to be modelled within these cavities with the relevant emissivity values assigned to the exact cavity, i.e., small, large, and the triangular cavity.

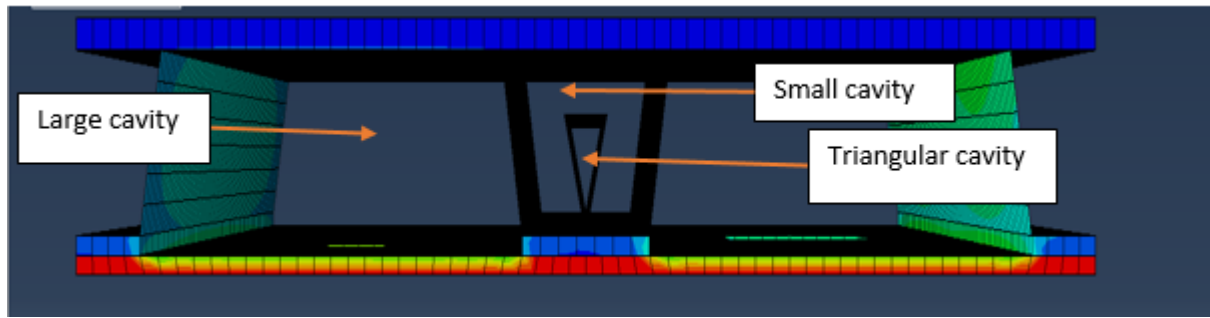


Figure 38. Contour image of Test Sample 4 from ABAQUS, also illustrating the cavities as modelled

The thermal properties of the contour image were obtained from the Eurocode 1993-1-2 (European Standards, 2005), while the material properties of the insulation materials were derived from the work of Claasen (2022) as shown in **Table 3**.

Table 3. Material properties of insulation materials in FE models (Claasen, 2022)

Material name	Density (kg/m ³)	Conductivity (W/mK)	Specific heat (J/kg°C)	Emissivity
Calcium Silicate Board	943 at 0°C 943 at 100°C 818 at 120°C 818 at 800°C	0.236 at 0°C 0.236 at 20°C 0.330 at 89°C 0.323 at 179°C 0.307 at 272°C 0.162 at 367°C 0.339 at 470 °C 0.339 at 800 °C	1727 at 10 °C 1727 at 90 °C 24000 at 100 °C 2600 at 110 °C 906 at 400 °C 906 at 800 °C	0.3
Fibre Cement Board	1250	0.25	2777 at 0 °C 2777 at 90 °C 37000 at 100 °C 4500 at 110 °C 2500 at 400 °C 2500 at 800 °C	0.9

Figure 38 and **Figure 39** both show how heat is transferred from the inside of the furnace to the unexposed faces, through their thickness, for all the test samples (with the colour red indicating the maximum temperature and the colour blue indicating the minimum temperature). The nodal temperatures are shown on average.

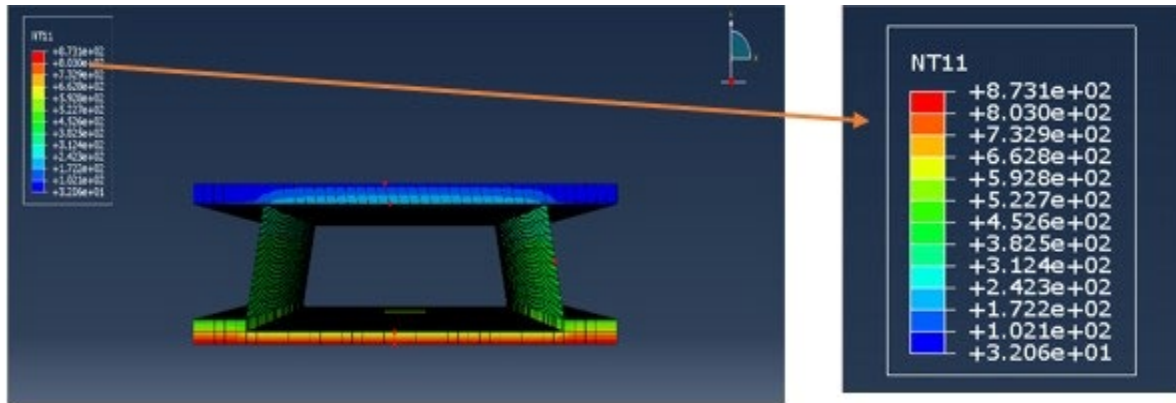


Figure 39. Contour image of Test Sample 2 showing the heat distribution (in Degrees Celsius) from the furnace to the unexposed face

Thermal conductance that is defined in the interactions is crucial to ensure that there is a contact represented in the modelling. The values used for the thermal conductance were derived from the work of Mago, et al (2016) who defined the conductance between steel and concrete as suggested by Ghojel (2004) shown in **Table 4**.

The results (in Chapter 5) showed that using the contact conductance as given by Ghojel (2004) yielded temperatures that coincided with the physical temperature results.

Table 4. The contact conductance of the steel-concrete interface (Mago, et al., 2016)

Conductance [W/m ² K]	Clearance [m]	Temperature [°C]
160.122	0	20 °C
123.272	1e-06	100 °C
108.48	2e-06	200 °C
103.671	3e-06	300 °C
101.449	4e-06	400 °C
100.211	5e-06	500 °C
99.437	6e-06	600 °C
98.9151	7e-06	700 °C
98.5429	8e-06	800 °C
98.2662	9e-06	900 °C
98.0537	1e-05	1000 °C
97.8862	1.1e-05	1100 °C

3.4 Challenges faced during testing

Physical furnace testing is prone to environmental and financial factors that may sometimes delay the testing process. These factors could present disadvantages when the experimental results are compared to simulated results in that there could be discrepancies that are unaccounted for. During the execution of the experiments, some of the challenges that were faced included varying weather conditions. The furnace was situated outdoors, so this meant that on rainy days, no furnace experiments could be conducted. On windy days, the draughts would cause large amounts of oxygen to enter the furnace through the ventilation holes and force heat over to one end of the furnace, while on hot days, the cooling period of the furnace would be lengthy.

Available funds proved to be another major challenge. There had already been some prefabricated samples from a previous project, the samples were only constructed, and they had not undergone any fire testing. These were the same samples that were utilised in the

current experiments, they only had to be cut to the desired sizes (of 1.2×1.2 m). This unfortunately led to some of the samples suffering pre-testing damage. The shortage of funds also demanded that some of the TCs be reused, and this may have been the reason why some of the TCs stopped functioning during a test.

Time constraints were also some of the challenges faced. Four samples were tested in two days, this only presented a challenge when the furnace had to cool down after one test and before the start of the next. That exercise alone would take longer than the actual 60-minute tests, so for cooling purposes, a large fan was used to aid in the cooling process, and that still was not sufficient. Test Sample 4 is an example of a sample that had to be mounted onto the furnace before the furnace was completely cooled. When Test Sample 4 was mounted, the furnace temperature was just over 40°C instead of the ambient 20°C , and at the commencement of the test, the average temperature on the unexposed face was just over 40°C . The FCB unexposed face temperatures were affected by the day's weather conditions.

3.5 Conclusion

A total of four experiments were conducted, all with a span of 1.2×1.2 m. The samples comprised of CaSi boards (exposed face), VoidCon steel sheeting in the middle, and FCB (unexposed). The samples only differed in terms of number and position of holes relative to the gas burner. All four samples had a combination of steel sheeting depth of 112 mm and FCB of 20 mm thickness. They all had the same sized thickness of 9-12 mm for the CaSi. A fibre ceramic blanket was used in each test to seal off the furnace from the heat that would eminently escape. Some of the samples were damaged, and the same fibre ceramic blanket was used to patch the cracks or the voids that were visible before the test.

FEA was conducted to compare the physical test results with the simulated results. The FEA simulations were developed according to the physical likeness of the samples, the properties that govern the samples, as well as the physical surroundings. The reason for that was to

determine whether the FEA simulated results could yield conclusive results and to determine which physical material property parameters should be used in such analyses.

Chapter 4: Results and analyses

4.1 Introduction

Fire represents one of the most severe conditions encountered during the lifetime of a structure, and therefore, the provision of appropriate fire safety measures for structural members is a major safety requirement in building design (Arnedo, 2019). Fire-resistant boards have been used in the experiments as the flame spread preventive measure of choice. The floor/ceiling system tested herein had no concrete as a reinforcing material, therefore, the boards, as the protection for the steel structural members, were dependent upon for thermal protection. The temperature of the unexposed surface of the ceiling/floor system is of particular importance when it is not directly exposed to the fire (Buchanan & Abu, 2017). The temperatures measured on the unexposed (FCB) surface during experimentation will be how the failure of the system is determined.

4.2 Individual test analyses

4.2.1 Test Sample 1: No holes

Test Sample 1 was used to calibrate the furnace. As mentioned in Section 3.3.2, the main burner had a capacity of 200 kW and that was not adequate, hence a second, smaller (hand-held) burner with a 40-kW capacity was added to the furnace. At first, the burner was throttling throughout, and it demanded manual control. This test sample had no holes on the CaSi exposed face. It was the simplest configuration.

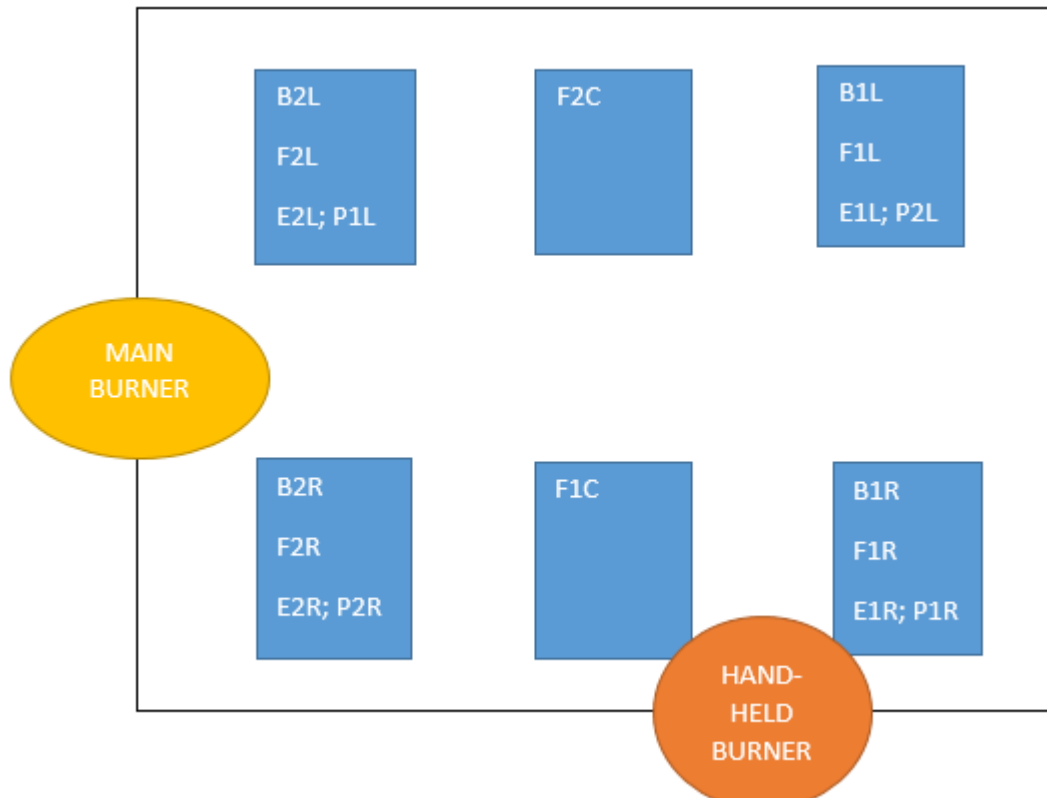


Figure 40. A plan view 2D representation of the TC positions for Test Sample 1

4.2.1.1 Test Sample 1: Furnace temperatures

Figure 41 provides details showing that after the initial 10 minutes the temperatures inside the furnace were following the standard fire curve temperatures (represented by the broken lines) very closely. There were four TCs inside the furnace, as shown in **Figure 27**, but only three of them, namely, P1R, P2R, and P2L recorded readable results. The furnace temperatures were the most important in each of the tests because it was from these temperatures that it was determined whether the tests were conducted according to the SFC.

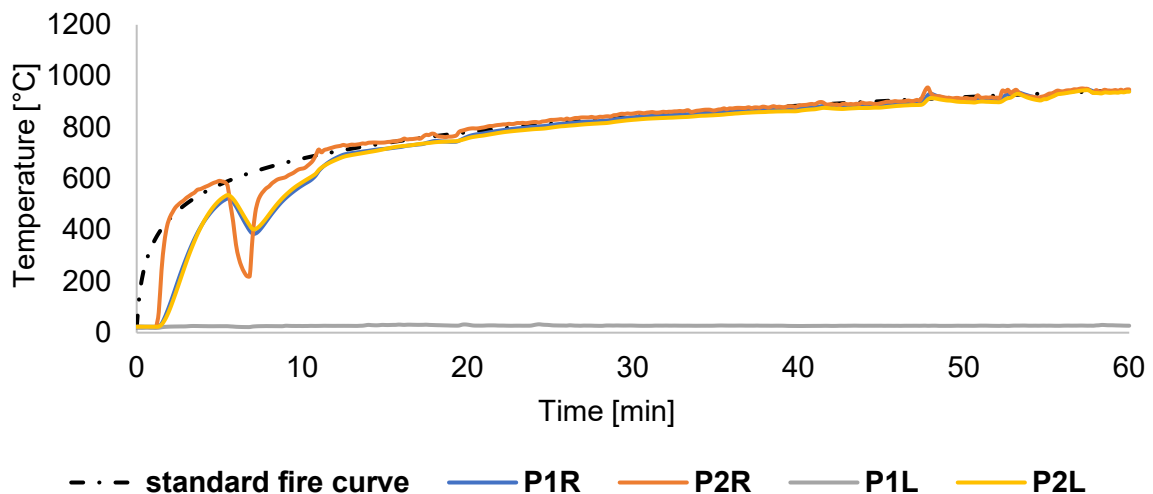


Figure 41. The temperature behaviour of the furnace for Test Sample 1, alongside the SFC

For the first 10 minutes there were fluctuations in the furnace temperatures and the furnace temperatures tended to deviate from the SFC, however, soon after that, at approximately 12.5 minutes, the temperatures were coincident with the SFC. The TC (P2R) started recording a sharp increase (almost straight line) of the temperature for approximately the first two minutes, reading a peak temperature of 536.5°C at 5.5 minutes. The temperature subsequently dropped sharply at 5 minutes, to a temperature of 220.5°C. The fluctuations may have occurred due to the burner unexpectedly losing power (completely shutting down) during the run of the test. However, as mentioned above, the fluctuations did not last long. The disturbance was brief and could not have significantly affected the performance of the global system.

Of the four TCs that were inside the furnace P1L was not accounted for because it malfunctioned during the test. This is indicated by the grey line that is running flat throughout the test (**Figure 41**). The malfunction of the TCs (whenever there was one) did not influence the test results, if the other TCs were functional, the temperature averages on the samples could still be conclusively read and analysed.

4.2.1.2 Test Sample 1: Exposed (CaSi) face temperatures

The temperatures on the CaSi surface were lower than those in the furnace and this may be accounted for by the distance between the centre of the furnace, where the furnace temperatures are measured, and the surface of the CaSi, where the CaSi temperatures are measured. Four TCs were placed on the surface of the CaSi (these are the ones labelled “E” on the schematic), two on each side (left and right) of the board as indicated in **Figure 40**.

Figure 42 is a representation of the temperatures measured on the surface of the CaSi against the SFC as dictated by the current test.

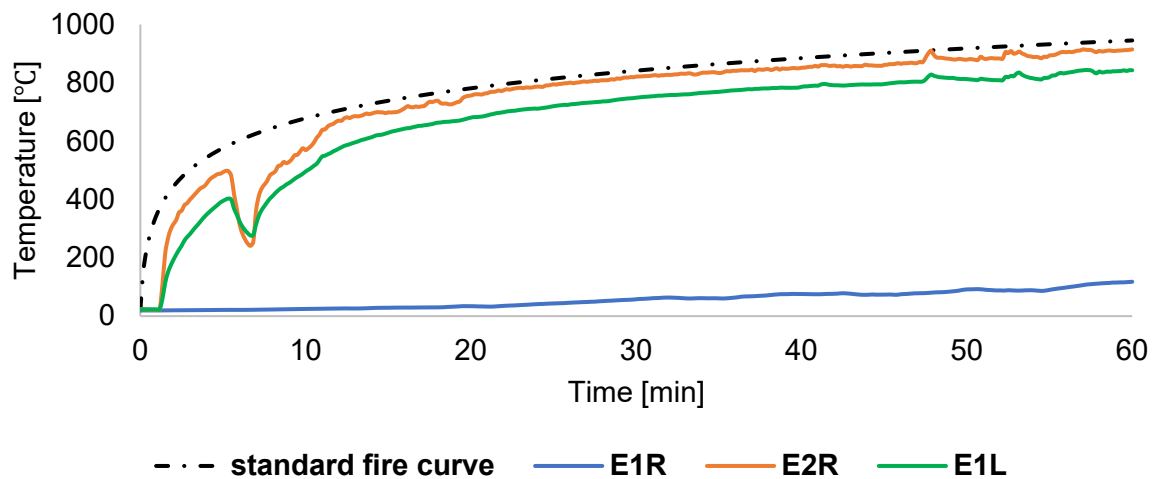


Figure 42. Test Sample 1 temperature curves of the TCs on the CaSi face

In **Figure 42** above, a trend is seen that is similar to the one in **Figure 41**. The temperatures increased and decreased at similar times, although there were appreciable differences in the averages. The temperatures on the exposed face of the CaSi averaged lower than those in the furnace, at 490.0°C as opposed to 579.9°C in the furnace. Of the four TCs that were attached on the surface, one (E2L) did not function, while the other one (E1R) was recording generally lower temperatures and was discounted.

CaSi typically has a moisture content of 6% for the (2440 × 1220 mm) board (Promat, 2012). The moisture in the board will absorb the heat until the moisture evaporates completely and only then will the board start to heat up. This could be one of the factors that account for the surface of the board heating up slower than the inside of the furnace along with the distance factor as mentioned earlier.

4.2.1.3 Test Sample 1: Flute temperatures

At the start of the test, the measurements read in the order, F1L, F2L, F2C, F1R, and F2R, from the hottest to the coolest, as opposed to the end of the test, when the measurements read in the order, F1R, F2R, F2L, F1L, and F2C, from hottest to the coolest. In the beginning, the left side was hotter than the right side, while at the end of the test, the right side was hotter than the left side.

The heat of the gas is what was being measured inside the flutes throughout the tests. Considering the heat transfer through the system layers, the transferred heat decreases from the innermost layer (the furnace) to the outer layer (top of the FCB).

The temperatures in the flute averaged 440.4°C as opposed to the furnace temperatures that averaged 579.5°C and 490°C on the CaSi surface. All the temperatures read from all the TCs remained in the same temperature range throughout the test. **Figure 43** gives an illustration that the hot gases travelled from the front of the system (from the burner side) to the back of the board, on the right side of the board (as per the configuration depicted in **Figure 40**). The figure indicates that at the start of the test, the left side of the sample was the hottest until at approximately the 40th minute when the right side became the hotter side.

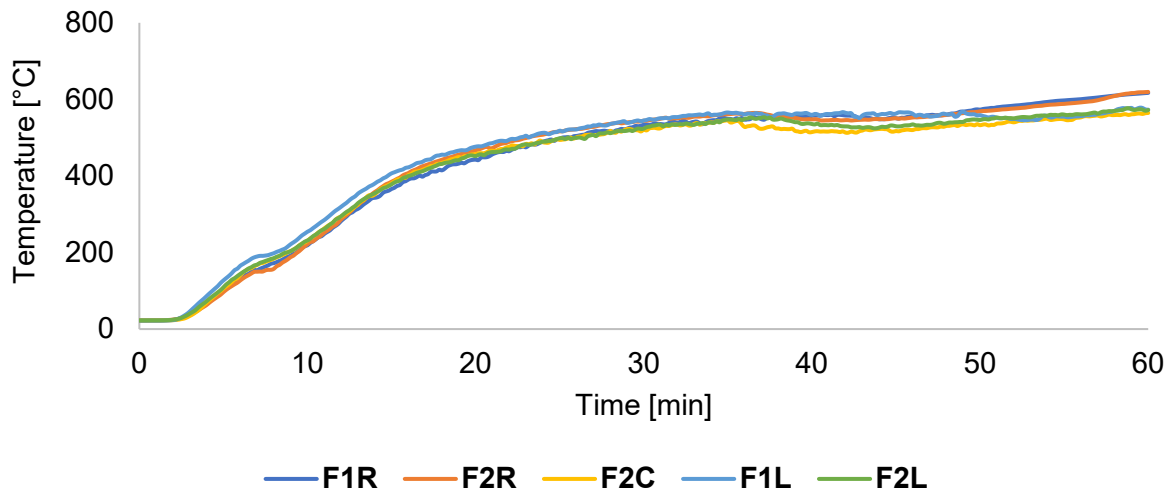


Figure 43. Test Sample 1 Flute area temperature measurement curves

The flute areas were closed off on both ends with a ceramic blanket so that no heat would escape into the atmosphere and compromise the performance, and therefore the results of the system. As in the case of the CaSi surface, there are no specific expected temperatures that should be reached within a specific time frame. The aim of tracking the temperatures within the flute was to see how much more rapidly the hot gases transferred from the flute area to the FCB unexposed side. The flute temperatures from all the TCs well-nigh do not vary from one another, the average difference being negligible.

There were no large variations between the different TC locations within the flute areas. According to the configuration of the TCs in the flutes (**Figure 40**), there were three TCs in each of the two flutes, with one of them not functional during the test.

An additional gas burner was added approximately 36 minutes into the test for reasons mentioned in Section 3.3.2; hence a temperature “switch” is observed in **Figure 43**, the TCs that measured lower temperatures now were measuring higher temperatures and vice versa. The right side (according to the configuration seen in **Figure 40**) became the hottest side because the additional burner was placed 100 mm from the bottom of the furnace on the same (right) side, as shown in **Figure 28**.

4.2.1.4 Test Sample 1: Unexposed (FCB) temperatures

The insulation and integrity criteria are deemed the most important ratings for this ceiling/floor system to pass because the two will determine whether the stability criteria for the global (steel) structure will be satisfied. For the system to comply with the insulation criterion, the average temperature on the unexposed surface must not increase more than 140°C above ambient. Also, the temperature on the unexposed surface must not exceed 180°C for any one point (location) for a 60-minute duration. The Integrity criterion dictates that no flames or hot gases from the fire should physically pass from one side (fireside) to the other side (non-fire side) through holes, gaps, cracks, or any other types of openings. Therefore, should cracks occur at any point during the test (where there had been none before testing), that allow the flames or hot gases to pass through, the element or system will be deemed as non-compliant. The samples that had pre-testing cracks and gaps may therefore be anticipated to fail the integrity criteria sooner.

The unexposed side of the FCB was instrumented with four TCs (**Figure 40**) and they were all in working condition throughout the test. The temperatures on this (unexposed) face had larger average differences between the cooler and the hotter sides (**Figure 44**).

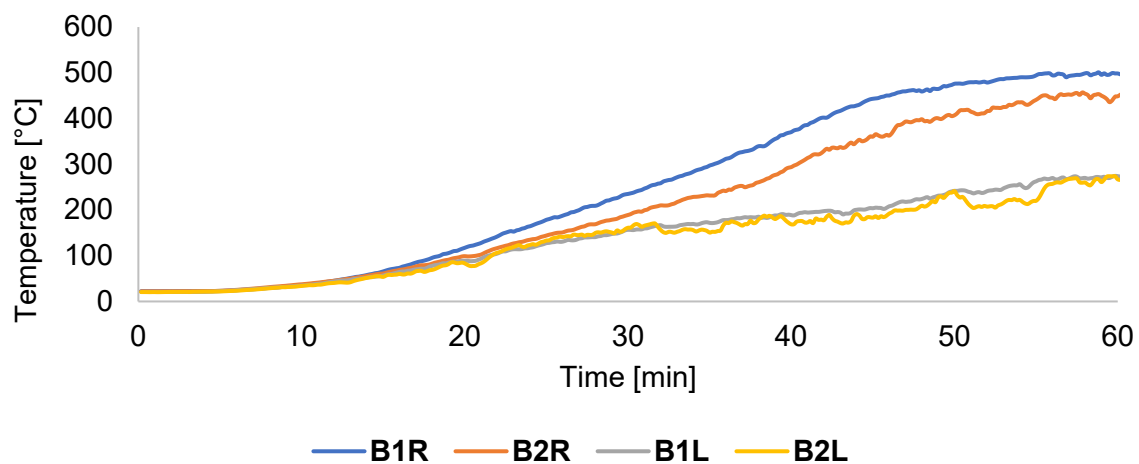


Figure 44. Test Sample 1 Unexposed (FCB) face temperature growth

The average difference between the right-side TCs and the left-side TCs was 92.3°C. Following what is dictated by the insulation resistance rating, at 27.2 minutes of the test, the average temperature was 41.2°C above the average ambient of 21.4°C. The 220°C temperature average was reached at 36 minutes, at which time cracks were starting to be visible on the unexposed (non-fire) surface as shown in **Figure 45**. At the B1R individual position, insulation failed at 27.3 minutes.



Figure 45. Cracks showing on the unexposed FCB at failure

It is important to note that the burner had been running for several minutes before the test commenced, and the temperatures were measured, and this could have compromised the resistance of the system. The reason for the burner to have been running longer than is shown on the results curve (**Figure 44**) is that the furnace was being calibrated to ensure that it operated at temperatures that were congruent with the SFC temperatures. The process lasted for approximately 45 minutes before the actual commencement of the test. The sample was already mounted and set up onto the furnace while it was being calibrated, hence a high-

temperature average was observed on the unexposed face, as compared to the tests that followed (**Table 5**).

Failure may have occurred quicker because of the calibration process that may have, more likely than not, compromised the resistance of the system. The current sample had no holes and may have been expected to have resistance to the end of the test.

Marx and Claasen found that a sandwich flooring system with a ceiling board without holes satisfied an hour rating. Both authors found that at the end of the hour (60 minutes), the average temperatures on the unexposed face of the system was 130°C (Marx, 2018) and approximately 150°C (Claasen, 2022). An assertion is therefore made that had the sample only been exposed to the SFC for given period of one hour (60 minutes) in this experiment, the average temperatures would have lower than the measured values.

4.2.2 Test Sample 2: Two holes, both open

Test Sample 2 was the sample with two holes. The holes were on the end further from the main burner as shown in **Figure 46**, the holes were both unconcealed and were 85 × 85 mm² each.

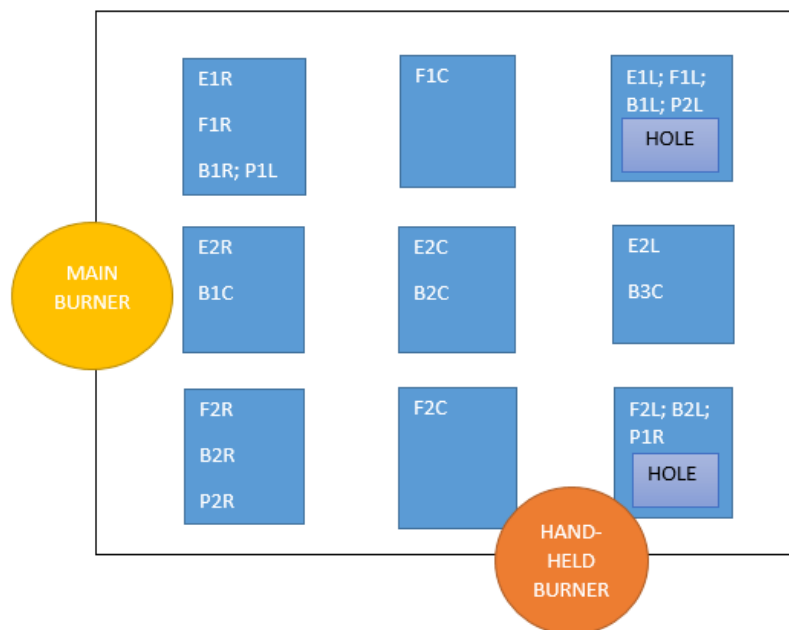


Figure 46. 2D plan view drawing of the TC positions for Test Sample 2

4.2.2.1 Test Sample 2: Furnace temperatures

At the start of Test 2, the two TCs closest to the burner proved that for the first two minutes, the burner was producing just enough heat for the SFC to be followed. It would take a while for the entire furnace to heat up, and even as it heats up, the heating will not be even throughout the furnace area, and thus the temperature readings from the TCs further from the burner would increase slower than the closer two TCs. The two sets of TCs, i.e., the closer (P1L and P2R) and the farther (P1R and P2L) to the burner displayed an identical trend, an increase and decrease of heat at the same instances. This is visible from the graph in **Figure 47**.

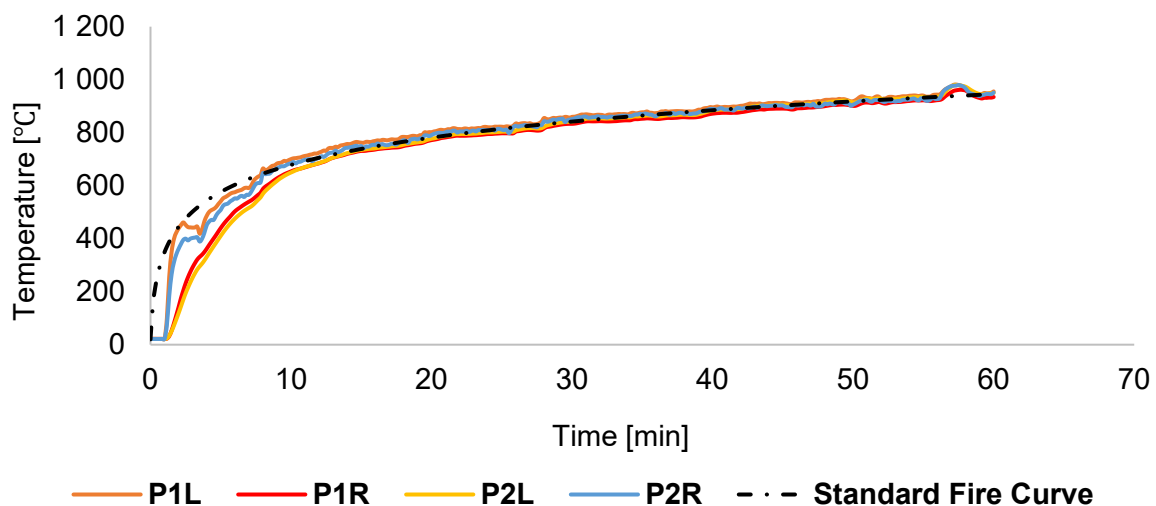


Figure 47. Test Sample 2 furnace and SFC temperatures

Figure 47 shows that at 11 minutes, there was an increase in the energy and thus the heat within the furnace because a hand-held burner was added into the furnace. From this time, the graph indicates that all the furnace TCs were recording temperatures that were within close range to each other. The TCs (P1L and P2R) closer to the main burner show identical fluctuations, though on average, they are 14.1°C apart.

Before the hand-held burner was added to the furnace, TCs closer to the main burner responded instantaneously to the burner's increase and/or decrease of energy and thus heat.

That would explain the trend between 2.50 minutes and 3.38 minutes for TCs closer to the burner. It took approximately five minutes for the TCs to stabilize, from whenceforth they followed the SFC. The average furnace temperatures were aligned with the SFC from just 10 minutes of the test and remained so for the remainder of the test.

4.2.2.2 Test Sample 2: Exposed (CaSi) face temperatures

The hottest point measured by the TCs was 897.9°C. Although the furnace TCs and the exposed face TCs are measuring the temperatures in the same area, the exposed face TCs' temperature increased slower and this would be accounted for by the moisture content in the CaSi, as alluded to in Section 4.2.1.2. During the heating of the furnace, the CaSi would also increase in heat, however, the moisture within the CaSi would have to completely evaporate before the board starts to heat up. The three TCs were in close range at an average of 692.2°C for the duration of the test and 873.1°C by the 60th minute of the test instead of 947.8°C by the same duration for the furnace temperatures.

As with F1R, E2R indicated the same trend, although the drop was not as drastic as it was for the area over F1R. There was still a loss of heat for approximately one minute. The temperature increased once again and then started to fluctuate, as illustrated in **Figure 48** and **Figure 49**.

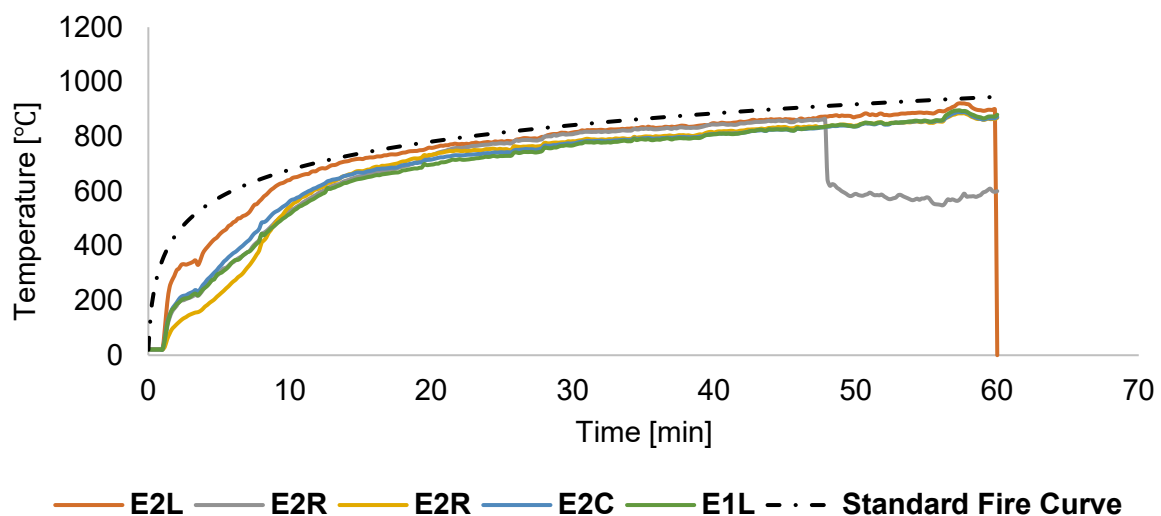


Figure 48. Exposed (CaSi) face and SFC temperatures for Test Sample 2

Apart from the E2L being slightly out of range with the rest of the TCs for the first 22 minutes of the test, all the other TCs were grouped within the acceptable range of the standard fire curve. The curves in **Figure 48** also indicates that exposed face temperatures were slightly below the SFC. The exposed face temperatures were measured at a distance slightly higher than the distance where the furnace temperatures were measured. The reason for the plummet at TC E2L position could be that it ceased to function completely, hence the rapid plummet to zero.

4.2.2.3 Test Sample 2: Flute temperatures

The subsequent increase in temperatures from the rest of the TCs was due to the addition of the hand-held burner at 11 minutes into the test. In **Figure 49**, F2L progressed from reading the lowest temperature to the third highest, alluding to the former statement. Had F2C been functional, it would have also measured higher temperatures, especially as it was directly above the added hand-held burner.

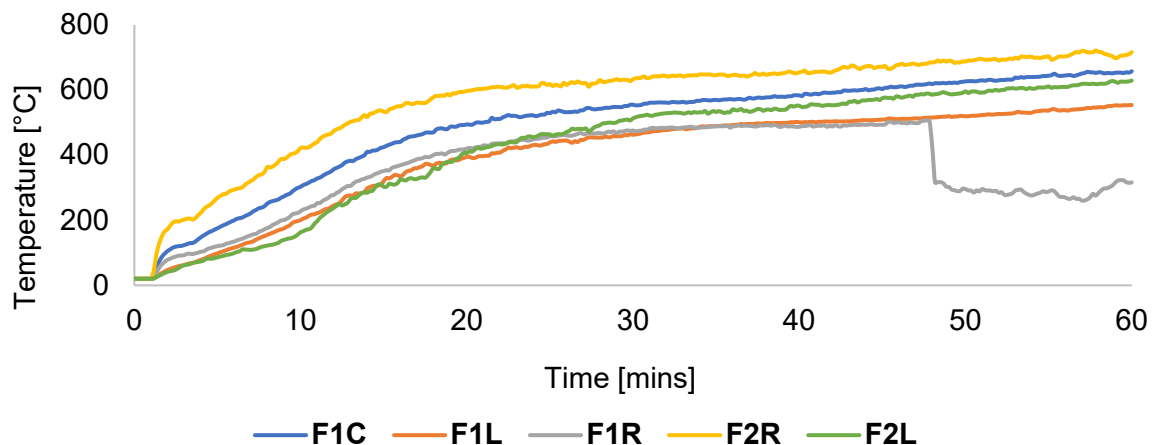


Figure 49. Curves showing temperature growth in the flute areas for Test Sample 2

The TCs in the flutes were essentially measuring the gas temperatures in the flutes. There was a convective heat transfer from the CaSi into the flute and from the flute to the surface of the steel sheet. However, since there were openings in the CaSi, most of the heat within the flutes was coming directly from the furnace in the form of radiation.

At 11 minutes when the hand-held burner was added, the temperatures at the back of the furnace started to rise, and this is evident by observing the F2L curve on the graph (**Figure 49**). The three lower reading TCs, due to their position in relation to the holes and burners (**Figure 46**), prove that without the holes, all the TCs would have measured temperatures within the same range. According to the trend of the curve, F1R indicates that heat was lost drastically for one minute (**Figure 49**) and then started to fluctuate nonlinearly until the end of the test. Heat could have been escaping from the openings on the sides that were closed off with the ceramic fibre blanket to prevent such an occurrence. F1C and F2R recorded the highest temperatures, although they were 79.9°C apart on average. Between the two, F2R was closer to the burner, directly above the open hole and in line with the hand-held burner, while F1C was only in line with the opening (along the length of the flute), shown in **Figure 46**. At 18 minutes, it can be seen in **Figure 49** that F1L and F2L interchange their trends. F2L started to increase above F1L, and this could be because the temperatures at the back of the furnace, where F2L was positioned, started to increase as a result of the additional hand-held burner.

The highest temperatures were measured at positions closest to the main burner, namely, F2R, F1C, and F1R, from the hottest to the coolest respectively as shown in **Figure 49**.

4.2.2.4 Test Sample 2: Unexposed (FCB) temperatures

At certain instances during the test, the temperatures would tend to be constant for approximately 10 minutes at a time as indicated in **Figure 50**. The constant temperature could have been rationalised by the fact that the main burner had not been reinforced by the additional hand-held burners. The smaller hand-held burners were added at approximately 11 minutes into the test. Up to approximately 100°C, the main burner had reached its maximum energy release. The same phenomenon is also observed for Test Sample 3.

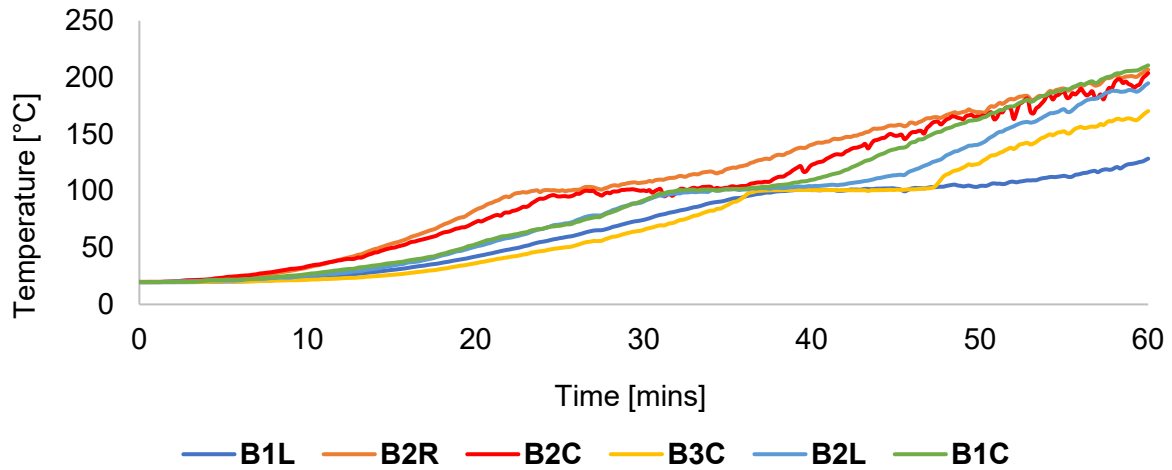


Figure 50. Curves showing the temperature rise on the unexposed face

The highest temperature reached was 209.6°C in the 60 minutes. The FCB temperatures were generally lower around the centre of the board (B3C). B2C and B2R were in the direct exposure of the main burner (**Figure 46**), thus they measured higher than B3C and B1C for which the average distance to the holes is shorter than it is to the left side of the board.

By the end of the test, TC B1C measured the highest temperature. This could be because of the hand-held burner that was introduced to the furnace as well as its close proximity to the main burner. At the start of the test, the position of B1C recorded the third-highest temperature, and throughout the test, the temperature at that same position increased steadier than the others, whose reading was somewhat constant for 10 minutes on average before rising again. The failure occurred at 58 minutes for the hottest single position. At 58 minutes, at the position of TC B2R, the temperature was 201.0 °C which was 181.2 °C above the ambient temperature of 19.8 °C. The overall failure was reached at 53.67 minutes where the temperature was 161.1 °C on average and 141.4 °C above the average ambient. Cracks started to be visible directly above the holes (**Figure 51**) at approximately 50 minutes. The areas above the holes were directly and constantly exposed to the heat and that could have shortened the time to failure.

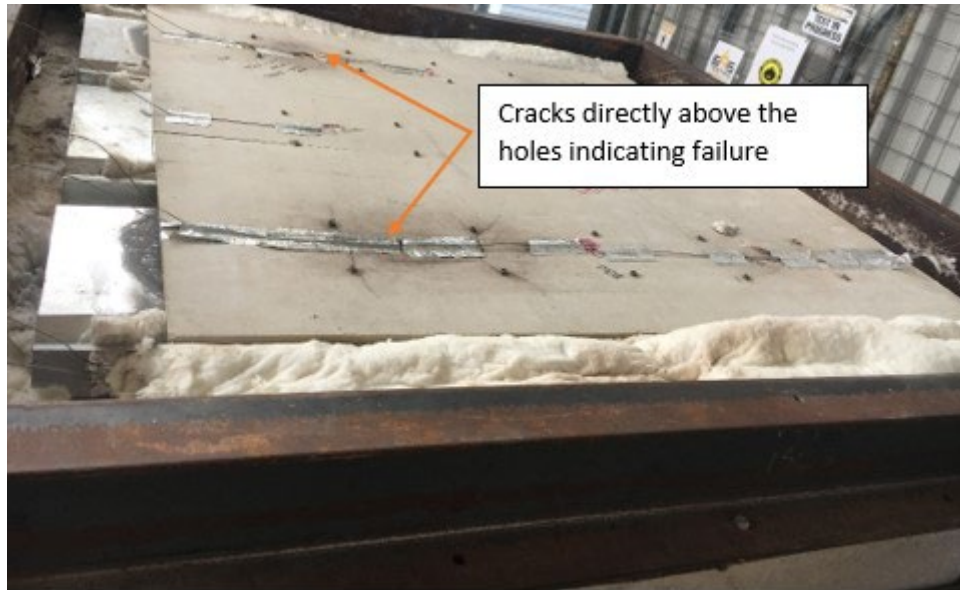


Figure 51. Test Sample 2 at failure

4.2.3 Test Sample 3: Two holes, one concealed

Test Sample 3 had two holes that had their centres at the centre of the CaSi exposed face. The holes were 80 × 80 mm with a centre distance of 600 mm apart. One of the holes was concealed with the same CaSi material as the face on which the holes were.

Figure 52 Shows the placement of the TCs and the positions of the holes for Test Sample 3.

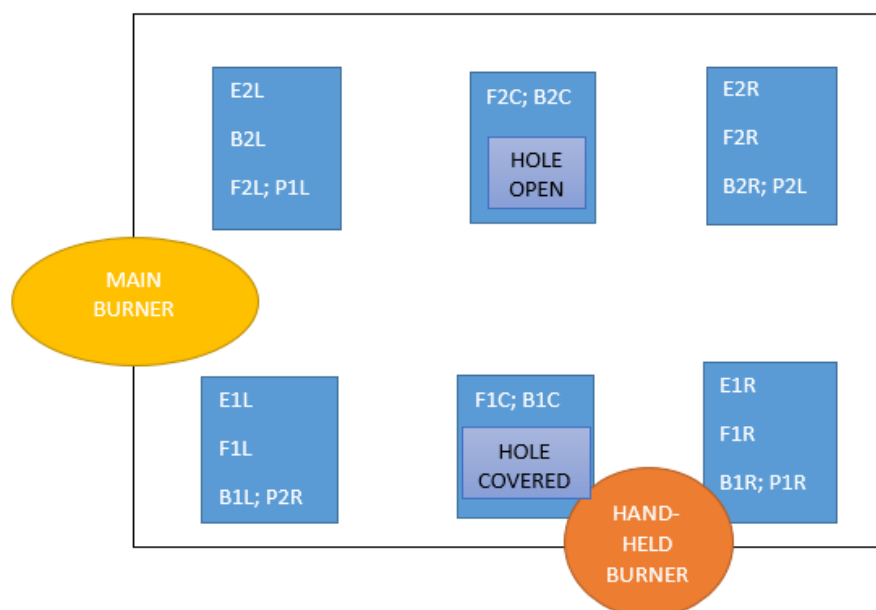


Figure 52. 2D drawing of the TC positions for Test Sample 3

4.2.3.1 Test Sample 3: Furnace temperatures

At 11 minutes, the temperatures were eventually coincident with the SFC temperatures, as seen in **Figure 53**. The starting temperature was 42.0 °C on average.

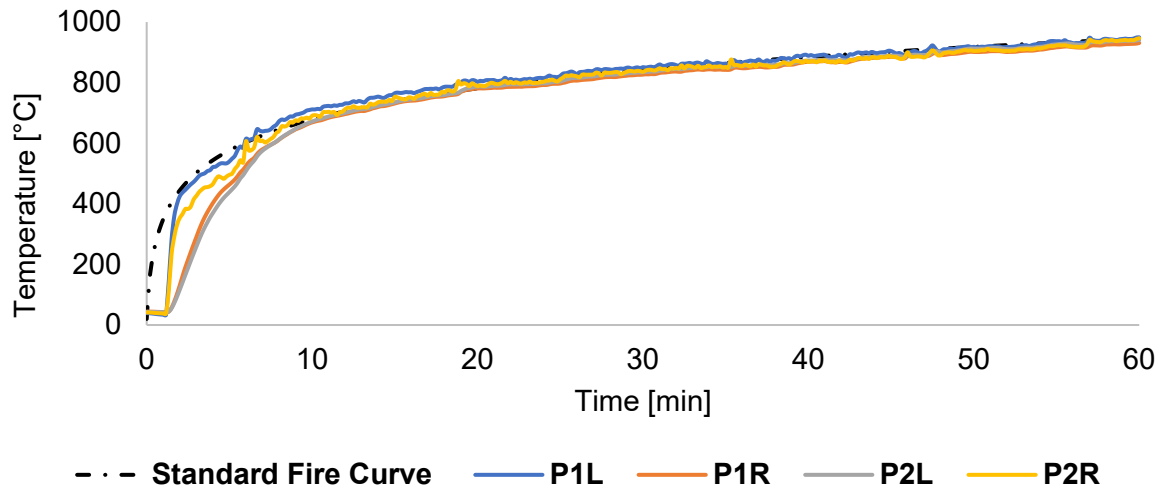


Figure 53. Furnace and SFC temperature growths for Test Sample 3

Figure 53 shows curves of the furnace temperatures relative to the SFC. From the curves, it is read that the average of the furnace at 60 minutes of the test was 942 °C while that of the SFC was 945.3°C. From what can be seen from the curves in **Figure 53**, the furnace was operating at the desired temperatures (SFC temperatures), and therefore, the results from this test could be used with no reservation. All TCs were working for the full duration of this test. The TC positions in the furnace were the same for all the tests, as shown in Section 3.3.2, (**Figure 29**), and as has been the trend, the TCs closest to the main burner were the ones measuring the highest temperatures.

4.2.3.2 Test Sample 3: Exposed (CaSi) face temperatures

The exposed face TCs measured temperatures that were exceptionally close to the furnace temperatures. The exposed face temperatures on average for the duration of the test were 708.1 °C while those of the furnace were 775.9°C. The exposed face temperatures were running slightly lower than the SFC, as shown in **Figure 54**.

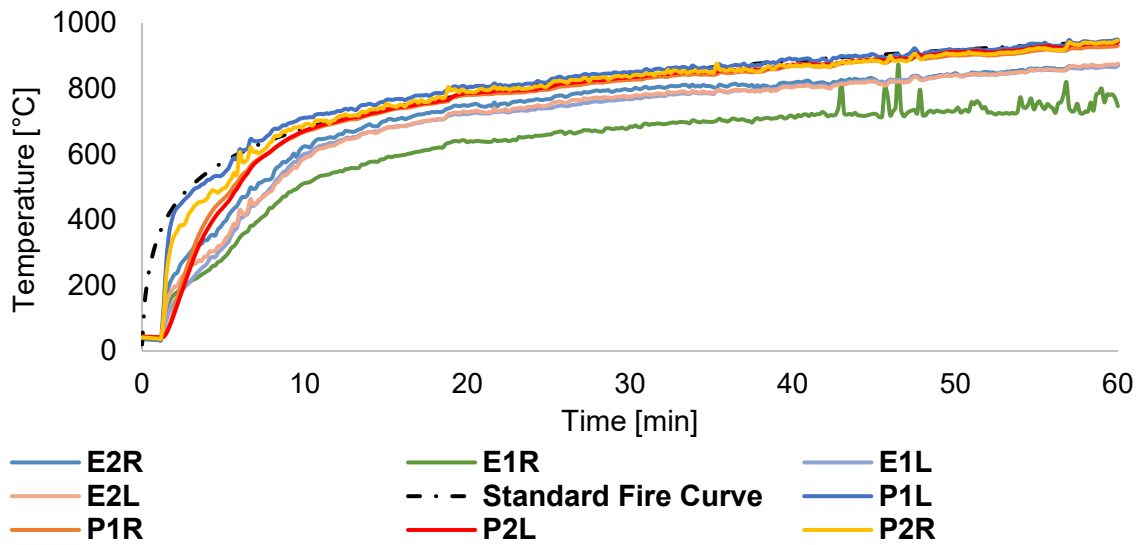


Figure 54. Test Sample 3 furnace, exposed face, and SFC temperature growth patterns

The three TCs, namely E2R, E1L, and E2L were recording a similar trend as the furnace TCs at the same positions, especially as of the 21st minute. The measurements were only similar in trend and not in magnitude. One TC (E1R) started to malfunction at approximately 42 minutes, however, it did not stop functioning completely. The trend for the exposed face temperatures was similar to the SFC and could have very well been expected because the exposed CaSi face and the furnace were essentially in the same area. The phenomenon was observed for all the tests conducted.

Figure 54 shows curves of the furnace temperatures, and the exposed face temperatures alongside the SFC using **Equation 2**. The difference between the furnace average and exposed CaSi face at 60 minutes was 100.5°C. The TC E1R was recording the lowest temperature.

The temperatures on the left (as indicated by the TC positions in **Figure 52**) of the sample, were the hottest temperatures with an average of 701.6°C, while the average on the right side was 669.5°C.

4.2.3.3 Test Sample 3: Flute temperatures

Of the five TCs that were attached to the sample to record temperatures in the flute area, only four were working for the full duration of the test. F2C was situated right above the open hole (**Figure 52**), and this was the reason why it recorded the highest temperatures throughout the test. The hottest positions were the ones around the open hole, then the ones closest to the main burner, respectively. The attachment of a ceramic fibre concealment on the exposed side of a section of the sample resulted in reduced temperatures within the flutes located on the right side (as depicted in **Figure 55**) of the sample, where the ceramic blanket was attached. The average temperature within the flutes throughout the test was 573.0°C. This was lower than the exposed CaSi face average which was 708.1°C.

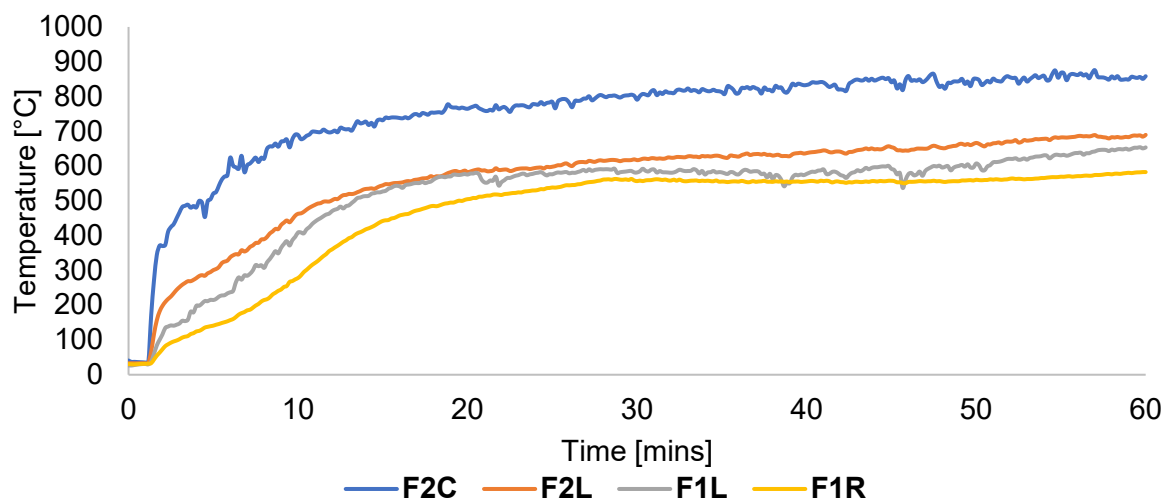


Figure 55. Flute temperature growth for Test Sample 3

The average flute temperature of Test Sample 2 (both holes open) was lower at 446.9°C than that of Test Sample 3 (one hole concealed) at 573.0°C. The positions of the holes for the two samples mentioned above were not the same. For Test Sample 2, the holes were further from the main burner, i.e., 257.5 mm from the edge furthest from the main burner, which means the inner edges of the holes were 857 mm from the main burner (**Figure 24**), while for Test Sample 3, the holes were only approximately 560 mm from the main burner as they were in the centre

of the sample (**Figure 25**). The distances were measured from the centres of the holes. The one hole on the CaSi exposed face was concealed with a CaSi board, and the holes for Test Sample 3 were slightly smaller than those of Test Sample 2, and it was for this reason that the flute average temperatures could not increase as rapidly as those for Test Sample 3. It should be noted that in the flute area of Test Sample 2, five TCs were recording temperatures, while for Test Sample 3, there was one less TC recording temperatures.

As indicated in **Figure 55**, the flute temperature curves were increasing in the same manner as the SFC. The left side, which in this case was the side closest to the main burner, is the side measuring the highest temperatures, even though the single TC, F2C was recording the highest because it was directly above the open hole. F1R was reading the lowest temperatures. It was furthest from the main burner and the open holes collectively (**Figure 52**).

4.2.3.4 Test Sample 3: Unexposed (FCB) temperatures

Six TCs were attached to the unexposed face of the FCB, but only five were functional during the test. TC B2R was not recording any readings. The hottest position on the FCB was at the TC B2C location because this TC was directly over the open hole (**Figure 52**). **Figure 56** shows a trend that is very similar to the one in Test Sample 2 (**Figure 50**).

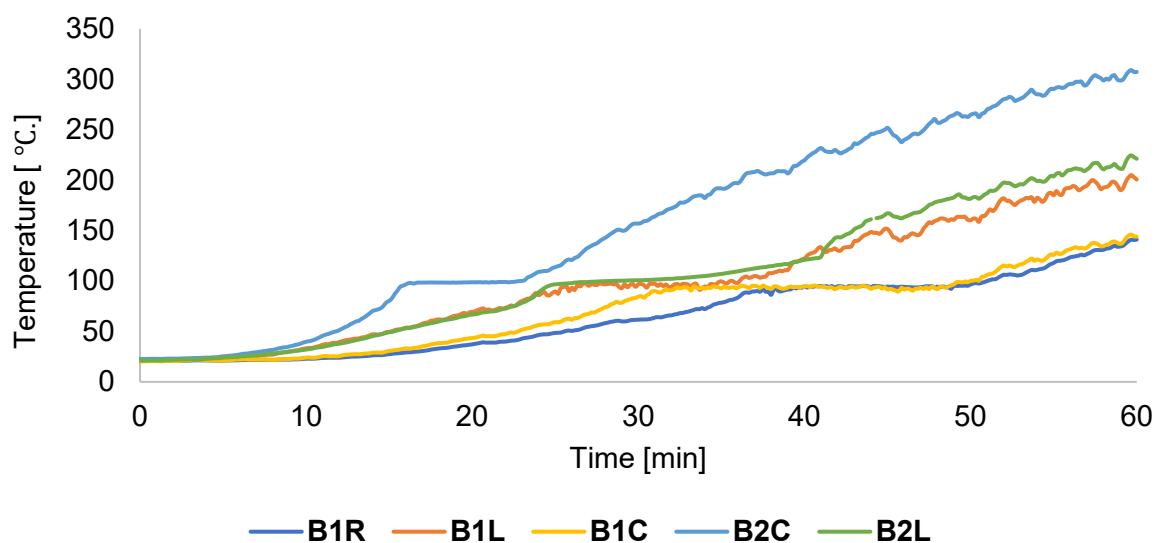


Figure 56. Unexposed (FCB) temperatures for Test Sample 3

The curves are generally increasing exponentially, and that was a different trend from what has been observed through these experiments. When examining the unexposed side of the sample, it was observed that the average temperature was comparatively higher on the left side, due to the section on the right that was covered with ceramic fibre. Furthermore, it should be noted that the prominently hot area in Test Sample 3 was the B2C area.

The sample started to fail over the open hole and nearest to the screws. The screws were self-tapping to minimise the drilling of holes, which minimised the risk of drilling larger holes than were required for the screws and thus minimise the need for robust sealing of the accidental openings. The screws still created holes through which they would fit. The areas close to the screws allowed crack initiation and propagation as a result of elevated temperatures.

The critical temperature when insulation failed, was reached at 31 minutes for the position at B2C. At 50 minutes, cracks started to propagate over the entire surface of the board. After 60 minutes, the overall average temperature had not reached 220°C. The sample failed the integrity criteria because the hot gases and the smoke were escaping through the cracks. Insulation failed at a single point at 31 minutes while overall failure was well beyond the 60 minutes. The different points reached critical temperatures at different times because they were exposed to heat at different rates.

4.2.4 Test Sample 4: Three holes

As mentioned in Section 3.3.1, the sample had three holes, two smaller ones which were 80 × 80 mm, and the larger one was 200 × 200 mm². The smaller holes were both made over a single flute length. The larger hole was made with its centre exactly halfway through the board. Some amount of heat was escaping through the holes and thus, no unwanted heat was residual on the exposed face of the CaSi. This could explain the lower averaging temperatures of the CaSi exposed surface. Having two holes on the one side of the sample and technically

no hole on the other side (because it was concealed) would mean a higher temperature increase on the side of the open holes and less on the side of the concealed hole.

Figure 57 shows a layout of the holes and the TC positions on the CaSi exposed face for Test Sample 4.

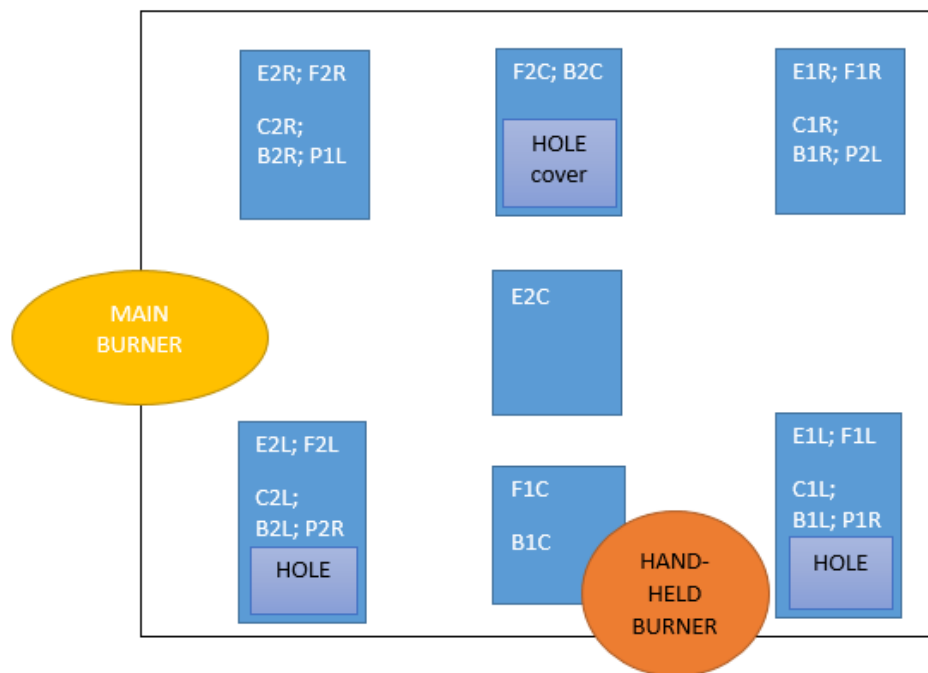


Figure 57. 2D drawing of the TC positions for Test Sample 4

4.2.4.1 Test Sample 4: Furnace temperatures

Of the four TCs that were placed in the furnace, one was not working, namely, P1L. In **Figure 58**, it is observed from the working TCs that the furnace temperatures are slightly above the SFC.

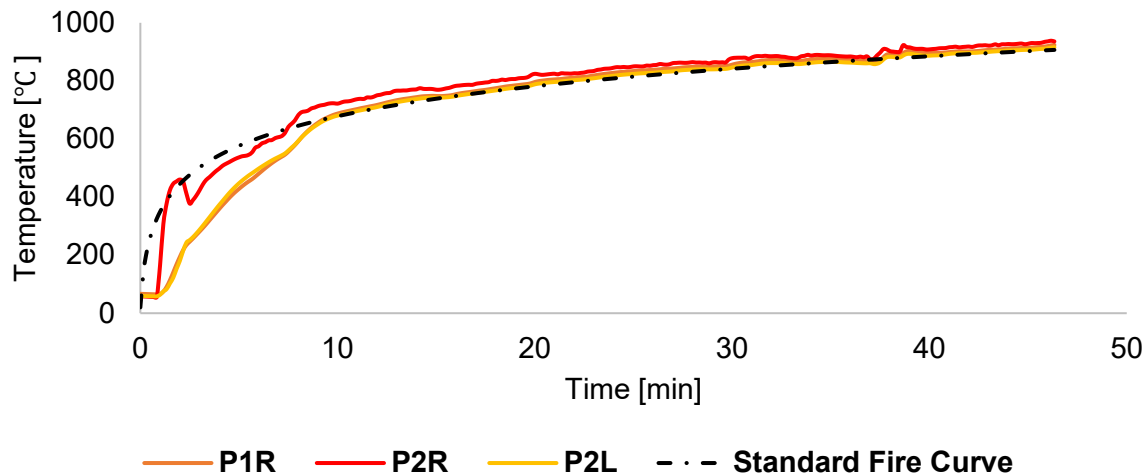


Figure 58. Test Sample 4 furnace and SFC temperatures

The average difference between the furnace temperatures and the SFC was 18.2°C. The TC setup for this test was the same as for all the other tests. The test was allowed to run for just over 46 minutes as it failed rapidly. The test was running on both the main burner and the hand-held burner from the onset.

The average temperature at the start of the test was 61.7°C, although the ambient temperature was set at 20°C on the program. This meant that the average at the end of the test would be approximately 40°C higher than it would have been had the test started at a 20°C ambient. When the test was stopped at 46 minutes, the average temperature inside the furnace was 925.2°C.

The furnace temperatures could have been higher than the SFC since the starting average temperatures were already approximately 40°C, which was 20°C above the usual average temperature. **Figure 58** shows the curves of the furnace temperatures alongside the SFC. As mentioned earlier, the test was stopped just after 46 minutes due to rapid failure.

4.2.4.2 Test Sample 4: Exposed (CaSi) face temperatures

Comparing the furnace and the exposed face temperatures relative to the SFC, the exposed (CaSi) face temperatures were lower (on average) than those inside the furnace (**Figure 59**).

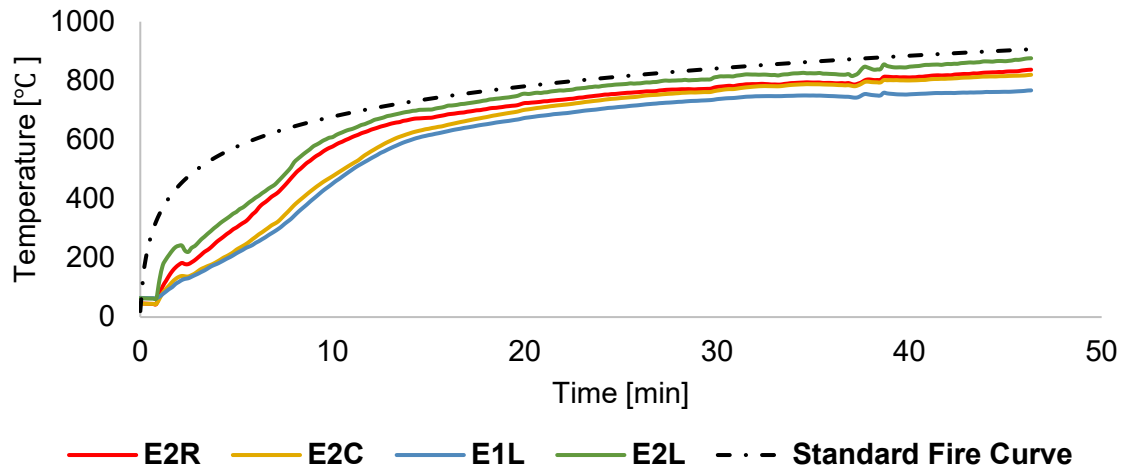


Figure 59. Exposed face and SFC temperatures for Test Sample 4

The CaSi exposed face averaged 526.9°C for the duration of the test, while the furnace averaged 748.8°C, the difference was therefore 221.8°C. Five TCs were placed on the CaSi (exposed) face and only four were working for the duration of the test.

E2L and E2R recorded the highest amongst the four working TCs. The said TCs were situated closest to the main burner, as shown in **Figure 57**.

4.2.4.3 Test Sample 4: Channel temperatures

The channels were labelled as the spaces between the edges of the steel sheet troughs and the FCB. The steel sheet troughs lay directly on the inside of the FCB and the TCs were placed between the two surfaces to measure temperatures in the said spaces. The recorded temperatures were similar to those on the exposed CaSi face. C2L and C2R recorded the highest temperatures as with the TC's E2L and E2R on the CaSi face. As shown in **Figure 57**, the said TCs were placed in the same positions, thus it was easy to explain their behaving in similar trends. **Figure 60** is a representation of the exposed face temperatures and the channel temperatures alongside the SFC.

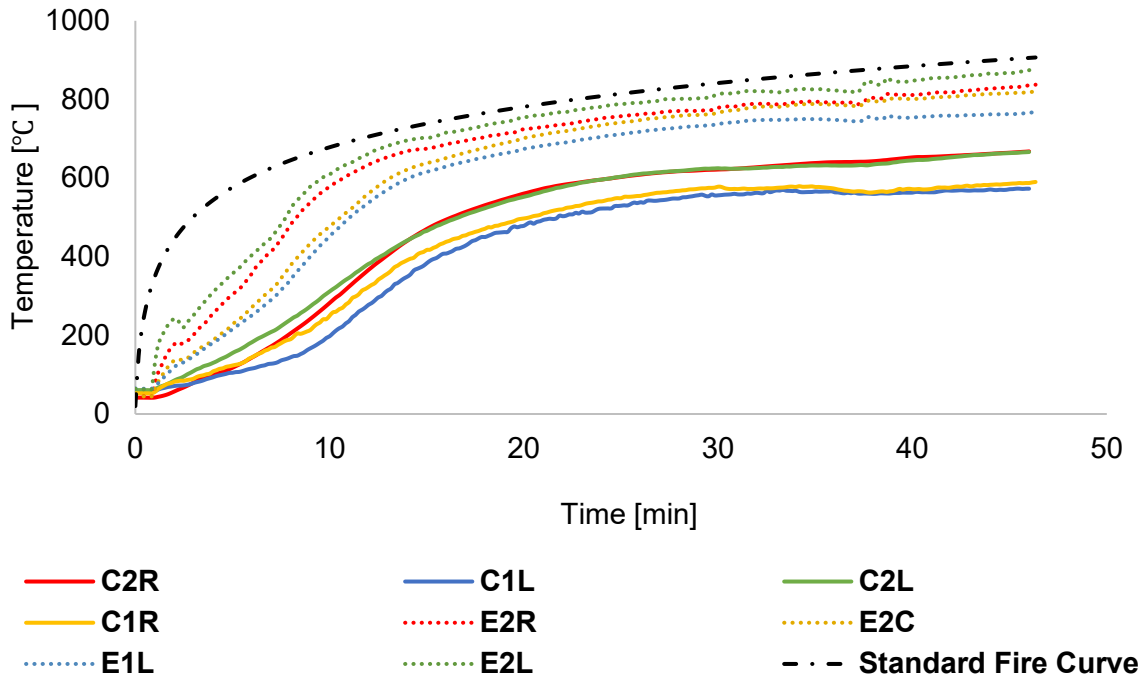


Figure 60. Curves showing the temperature growth on the exposed face, the channel, and the SFC for Test Sample 4

Figure 60 shows that the temperatures were similar, although the channel temperatures were lower on average. The starting average was 52.9°C. The average test temperature for the channel was 455.1°C as opposed to the CaSi test average of 642.8°C, measured from the four working TCs. **Figure 57** and **Figure 60** also (visually) highlight that the further away from the furnace the surface is, the cooler the temperatures get.

4.2.4.4 Test Sample 4: Flute temperatures

As with all the temperature recordings before this one, **Figure 61** illustrates that the hottest positions were at F2L and F2R, which, according to **Figure 57** were the positions closest to the main burner. All the TCs in these areas were working for the duration of the test. The test temperature average in the flute areas was 498.9°C. The temperatures recorded on all six TCs, show that the flute temperatures were generally lower than the SFC and the exposed face. The difference between the highest recorded temperatures and the lower ones within the flutes was 131.6°C.

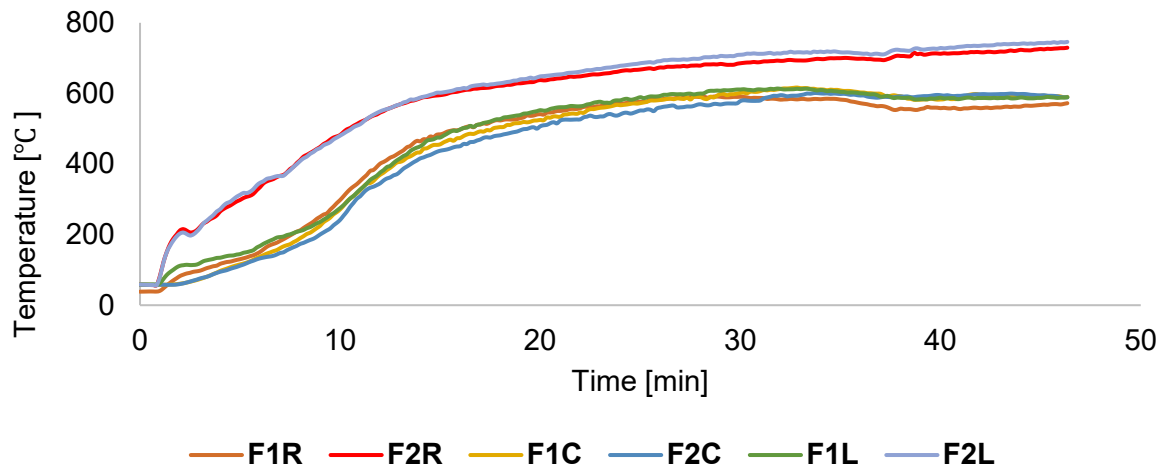


Figure 61. Flute temperature growth for Test Sample 4

For Test Samples 1,2 and 4, the flute temperatures were behaving the same. The explanation for the rapid heating up of the flute areas, in the case of Test Sample 4, could have been the holes. Heat rapidly escaped through these holes, into the surfaces or areas above them, even though one of the holes was loosely covered. In the areas further from the burners, it was cooler because the heat had to travel further and longer to reach these areas. Smoke and flames could easily escape through these passages through the system aided by these holes. The one hole was loosely concealed, and therefore, due to the material used to conceal the hole, i.e., ceramic fibre, which has a low thermal conductivity, not as much heat escaped through this hole as it would have if all the holes were directly exposed to the heat from the furnace.

4.2.4.5 Test Sample 4: Unexposed (FCB) temperatures

As has been the trend for Test Sample 4, the hottest positions are the ones closest to the main burner, namely, B2L and B2R with the single hottest being B2L, indicated by the curves in **Figure 62**. This proves true since not only was this position closest to the main burner, but it was also directly above an uncovered hole (**Figure 57**). The temperature increase was slow until approximately 17 minutes at which time the average unexposed FCB temperatures were 68.1 °C and for the remainder of the test, the average temperature was 192.5°C.

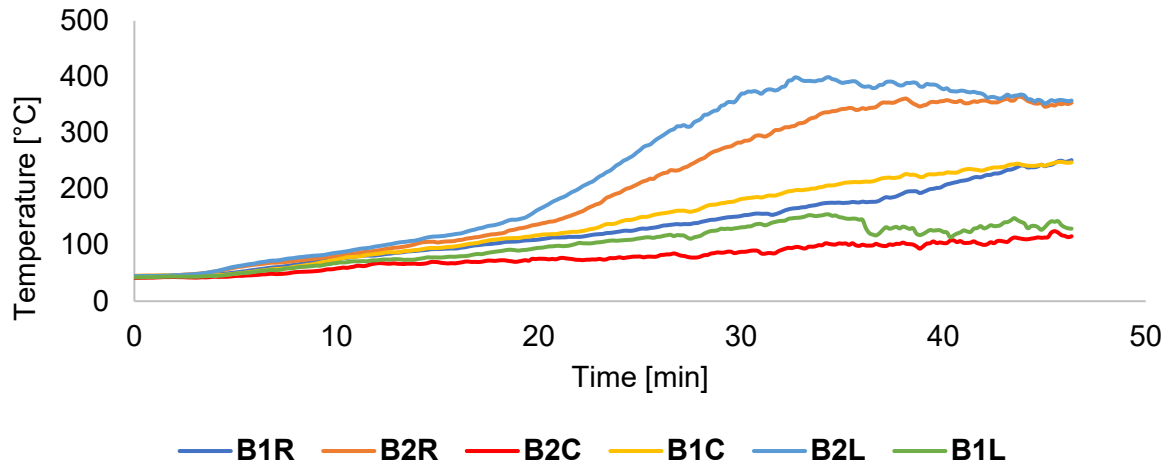


Figure 62. The unexposed FCB temperatures for Test Sample 4

The side to the left of the main burner (**Figure 57**) was the hottest side on average, at 157.0°C as opposed to the right side which was at 136.1°C. The heat difference was justified by the additional hand-held burner that was placed on the left of the furnace as seen in **Figure 28**. The other reason for the heat difference between the two sides was that the large hole, which was on the right of the sample, was covered with a ceramic fibre blanket. At approximately 40 minutes, the FCB was seen to be hogging (i.e. deflecting upwards) although no other common signs of failure were visible yet. The average temperature at this point was 131.9°C. The test was suspended at 46 minutes when integrity failed. The smoke was seen at this point coming out from the cracks that initiated directly above the two smaller holes. At the end of the test, the average FCB temperature was 146.6°C, and this was 110.2°C above the 36.4°C ambient. The cracks initiated above the left side, where the two smaller, uncovered holes were located, and then slowly progressed over the rest of the board.

The B2C thermocouple was positioned directly above the larger, covered hole, resulting in its measurement of the lowest temperature on the unexposed face. The utilization of a ceramic blanket to enclose one of the holes yielded advantageous outcomes for the board's functionality, thereby enhancing the overall performance of the system. The thermal conductivity of a ceramic fibre blanket is rather low, and it exhibits black body behaviour,

hence preventing the transmission of heat by radiation (Fourie, 2020). Consequently, the right side (according to the TC configuration in **Figure 57**) of the sample had lower temperature averages.

4.3 Discussion

The biggest interest in these experiments was whether the samples would acquire the insulation and integrity criteria as described in Section 3.1. For most samples, cracks would begin to initiate at a single point and then propagate along a wider span of the unexposed face. Smoke would then pass through these cracks, and thus the sample would be deemed to have failed the integrity criterion. The insulation criterion was tracked by closely observing the temperature rise on the unexposed face of the samples, thus it was easy to track once the temperatures on the unexposed face exceeded the allowable temperature ranges that satisfy the insulation rating. The samples were also seen to be sagging, following the crack propagation.

Table 5 gives a clearer indication of the differences in the averages on different surface layers for the different tests. The values in the table were taken using the 35-minute cut-off time, as this was the shortest duration of all the tests run.

Table 5. Temperature averages of the test samples on different surfaces after 35 minutes

	Furnace temp. avg. (°C)	CaSi temp. avg. (°C)	Flute temp. avg. (°C)	FCB back temp. avg. (°C)
Test 1	513.7	427.1	367.2	101.5
Test 2	694.4	618.2	377.8	54.9
Test 3	698.5	608.5	423.7	61.9
Test 4	709.7	493.2	466.0	123.9

For each of the surfaces in each test, only the functioning TCs were considered for the temperature averages and as such, the averages were not taken from the same number of TCs, although from the same surfaces. Having fewer or more TCs on a surface would cause the average to be higher or lower. The sample with no holes (Test Sample 1) had the lowest averages on all the surfaces except on the back of the FCB. However, when assessing the temperature averages for that single Test Sample 1, the FCB average is the lowest temperature of all the layers of the said sample. Test Sample 1 had the longest lifespan of all the other samples as it only failed at 47 minutes despite having been used for calibration.

In addition to the concealment of one hole in Test Sample 3, a notable distinction between Test Samples 2 and 3 lies in the spatial arrangement of the holes relative to the burner. The distances between the holes of Test Sample 2 and the main burner were much greater, resulting in lower average values compared to Test Sample 3 across all layers, except for the CaSi face. The heat distribution in Test Sample 2 exhibited less uniformity and slower propagation compared to Test Sample 3. This variation can be attributed to the positioning of holes in Test Sample 3, which were located at the central points along the length of the flutes, representing the central region of the system.

Test Sample 4 presented evidence supporting the notion that centralized holes facilitated a more efficient transfer of heat to the unexposed side. Rapid failure could have been anticipated because of the larger hole that was at the centre of the length of the flute. The hole would have made it easier for the heat to travel through the sample had it not been covered at all. Thus, failure for Test Sample 4 was delayed solely because one of the holes (the larger hole) was loosely covered with a ceramic fibre blanket.

Tests 1 to 3 had a heat exposure going beyond 60 minutes and none of the tests failed the insulation criterion by the 60-minute mark. Average FCB temperatures were still notably below the temperatures specified for insulation criterion failure, as represented in **Table 6**.

Table 6. FCB temperature averages at the actual time when the tests were suspended

	Suspend Time (min)	FCB Temp. Average (°C)
Test Sample 1	60	183.82
Test Sample 2	60	88.33
Test Sample 3	60	99.64
Test Sample 4	42	136.842

Test 4 was suspended at 46 minutes because integrity failure had been reached. Smoke was observed coming from the cracks that had initiated and propagated directly above the two smaller holes.

For Test Samples 1 to 4, a consistent decline in temperature averages was observed when comparing the fireside to the unexposed faces (**Figure 63**).

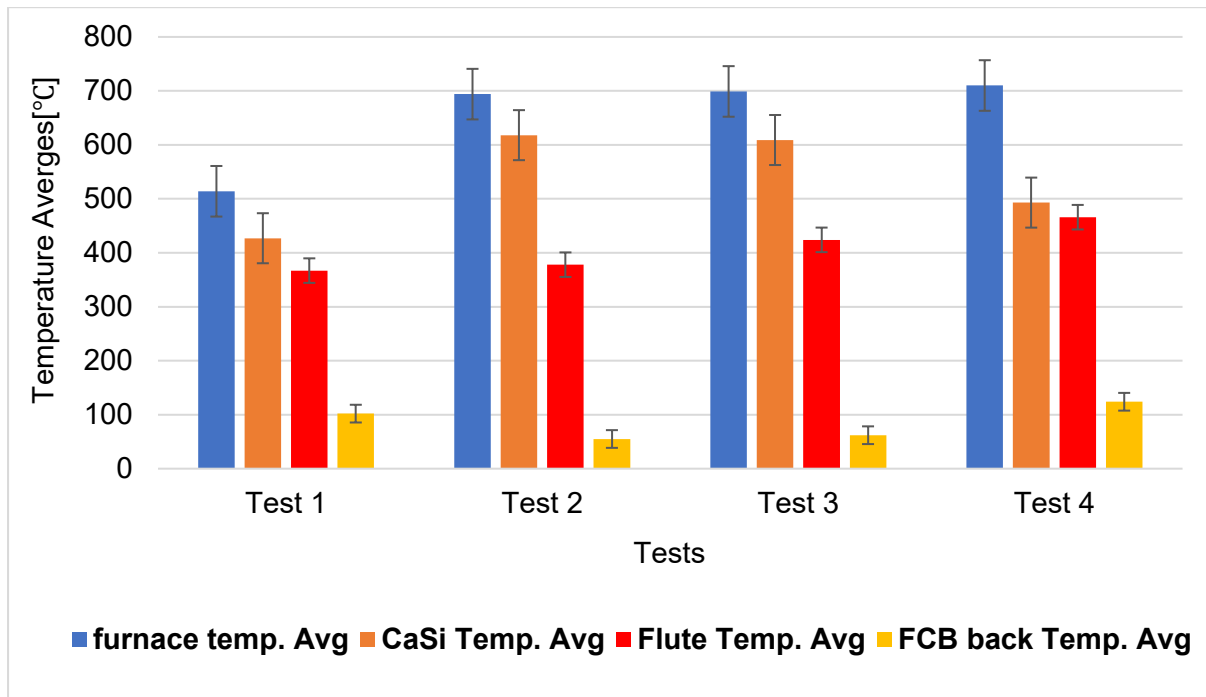


Figure 63. Temperature variations by layer for each Test Sample

The occurrence described can be anticipated within the context of conductive heat transport in composite systems, as depicted in **Figure 12** and governed by **Equation 3**. **Figure 63**

provides a visual account of the small observable variations in furnace temperature averages between all the samples, with the largest difference between any two consecutive tests at 180.7°C between Test Sample 2 and Test Sample 1.

4.4 Conclusion

All the tested samples were of different hole configurations and sizes. The objective of this study was to assess the impact of holes of varying sizes and positions on the outcomes, in comparison to a system without any holes. All the samples behaved differently under identical fire conditions, contingent upon factors such as the number of holes, the locations of these holes on the boards, and the placement of the holes relative to the burner attached to the furnace. For all the tests, it was observed that moving from the inner to the outer layers of the system, i.e., the CaSi exposed face to the FCB unexposed face, the average temperatures decreased (**Table 5**).

Moreover, the more holes a test sample has, the more rapidly it fails. Data supports the notion that implementing a form of coverage for system holes (such as for Test Samples 3 and 4) is advantageous, as such coverage effectively prolongs the system's resistance in instances when the ceiling board has penetrations. While the results present no evidence of a correlation between the size of the holes and heat transfer rate, an increased number of holes on the ceiling surface corresponds to a heightened damage rate. The placement of the holes relative to the heat source significantly influences the system's performance. Ensuring the furnace is heated to the prescribed temperatures according to the standard fire curve is essential to obtain reliable findings that align with a universally accepted testing methodology.

Chapter 5: FEA result analysis and comparison

5.1 Introduction

This chapter will undertake an analysis of the FEA results and a comparison with the experimental data. As indicated in Chapter 3, Section 3.3.6, the test samples were simulated using ABAQUS software to assess the precision and overall characteristics of heat transfer relative to the experimental findings. After conducting various experiments and simulations, it will be feasible to ascertain the reliability of computer simulations in predicting heat transfer mechanisms and observing the overall behaviour of the sandwich floor system subjected to a standard fire, without the need for physical experimentation. Variations in temperature averages can be anticipated between the experimental and FEA results. These variations can be attributed to several factors, such as the ideal and controlled conditions under which the simulations were conducted, as well as the input of the correct material property parameters such as conductivity, convection, size of the sample, etc.

5.2 Samples

A total of four samples were tested experimentally and computer models were designed and set up to accurately replicate the physical samples and they were simulated and analysed through FEA using ABAQUS. The anticipation was for FEA to yield results that were similar and even close to the experimental results in how the heat transitions from the heat source (furnace) to the unexposed face of the FCB, although there may be slight variations in averages because of the conditions under which the computer simulations were conducted in contrast to the physical experiments. FEA was purely governed by the application of the boundary conditions and the accurate input of the heat transfer parameters such as

conductivity, emissivity, etc. as listed in Tables 2 to 4. The FEA models were set up as described in Section 3.4.

5.3 Results discussion and comparison between experimental and FEA results

Temperature curves obtained from FEA simulations generally follow similar trends as the experimental results curves, increasing and decreasing alike. What is clearly observed is that the FEA temperature curves are smoother than those of the experimental temperature curves. Generally, for Test Samples 1 to 3 the FEA temperatures are lower than the experimentally recorded temperatures. For Test Sample 4, the experimental temperatures are displayed higher than the FEA temperatures. The sample on which the Test Sample 4 experiment was performed, had three holes of which one was covered with a ceramic blanket, which could explain why the FEA temperatures were higher because the sample was simulated without the ceramic blanket covering.

Test Sample 1 was essentially used to calibrate the furnace and to benchmark for the other three Test Samples. The furnace had been heating up for a short period before the temperatures were recorded, resulting in the physical temperatures being much higher than the FEA temperatures at the start of the said test sample. The temperature increase trend is the same for both sets of results (**Figure 64**), albeit the FEA temperatures are visibly lower than the experimental temperatures. FEA results display an increasing trend that replicates the experimental results. For Test Sample 1, the FEA temperatures did not vary, therefore the results of B2L(FEM), B2R(FEM), B1L(FEM) and B1R(FEM) are shown as a single line in **Figure 64**. A comparison between the two sets of results indicates that FEA may be used to predict the behaviour of such a system (a system with no holes) subjected to a standard ISO 834 fire.

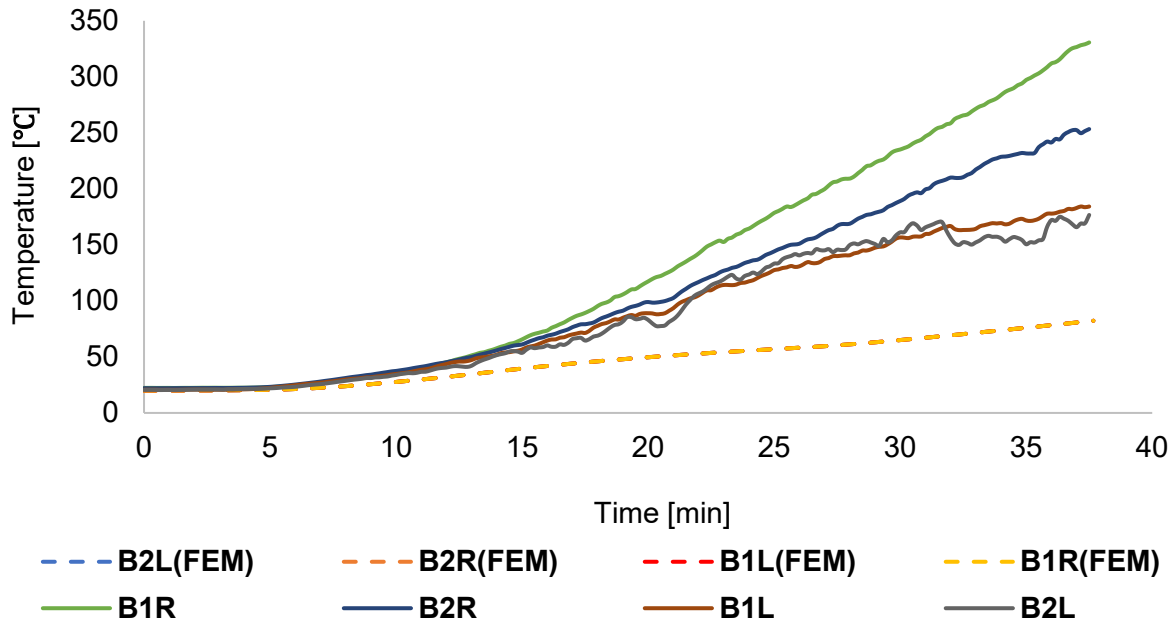


Figure 64. A comparison of the unexposed FCB temperatures between the FEA and the experimental results for Test Sample 1

Figure 65 illustrates the individual TC temperatures in an enlarged view of how they vary from hottest to coolest, with temperature ($^{\circ}\text{C}$) values on the y-axis and the time (sec) on the x-axis.

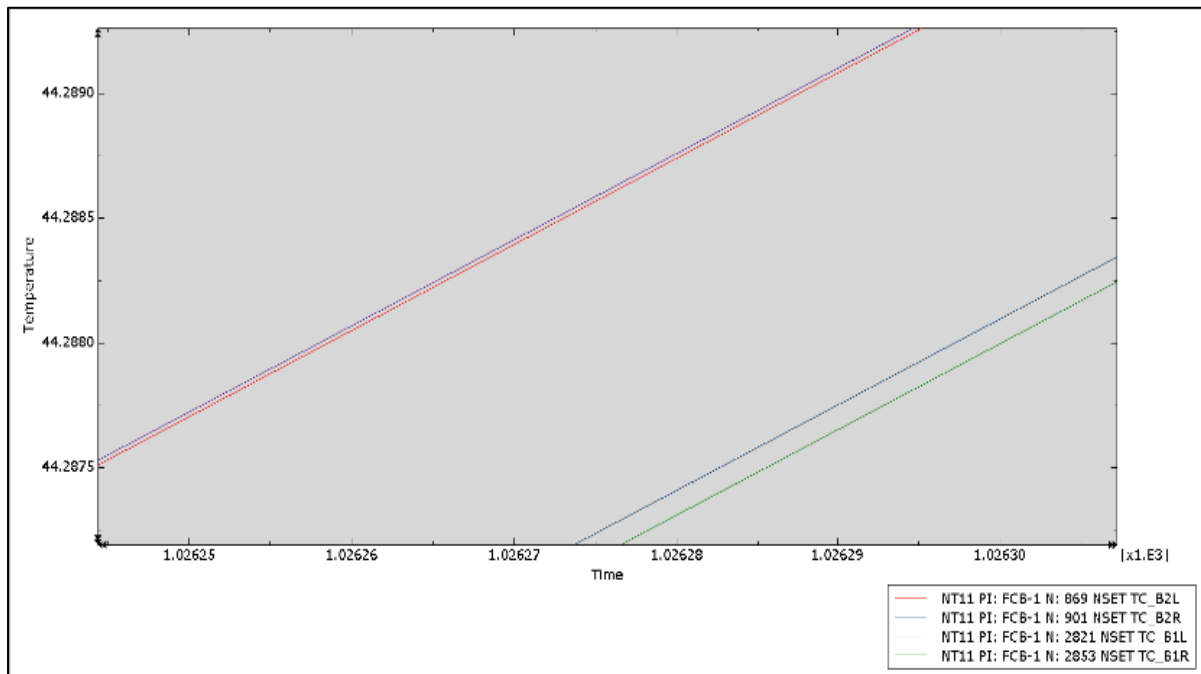


Figure 65. An enlarged portion from the ABAQUS-generated Temperature-Time graph for Test Sample 1

The variations are insignificantly minute when looked at on a bigger scale in **Figure 65** (specifically for the FEA temperatures) and **Figure 66**

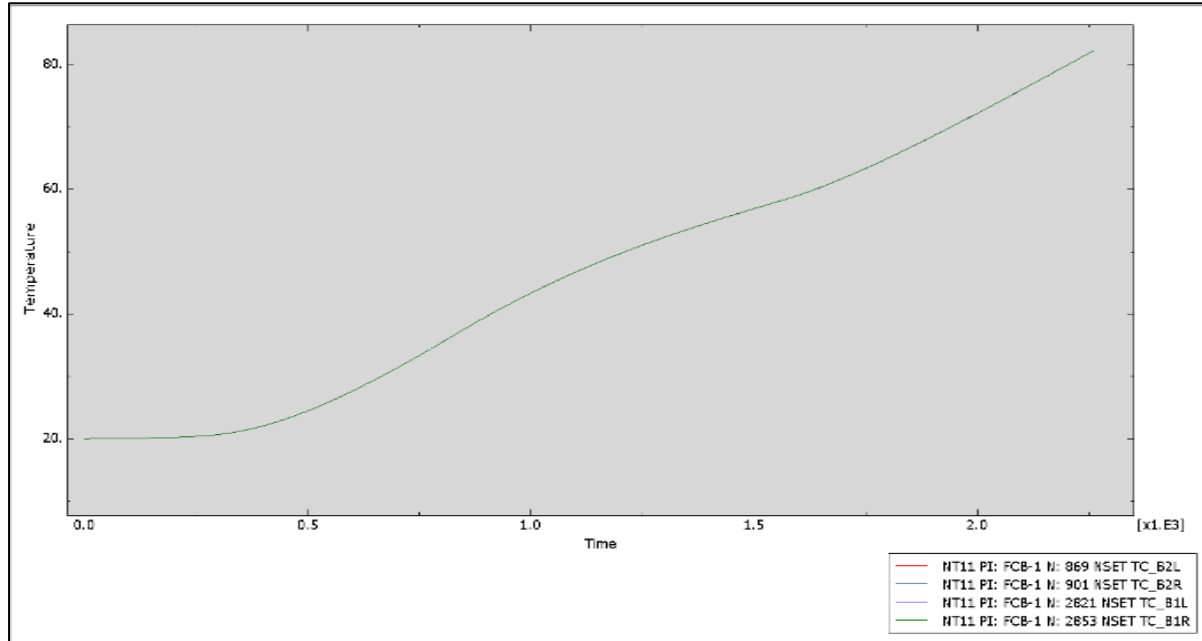


Figure 66. ABAQUS-generated Temperature-Time graph for Test Sample 1

Figure 67 and **Figure 68** show the variations between the resulting temperature measurements from the physical experiments and the computer simulations for Tests 2 and 4 respectively. For Test Sample 2 (**Figure 67**), the temperatures were generally lower for the FEA than for the physical experiment for all layers of the sample.

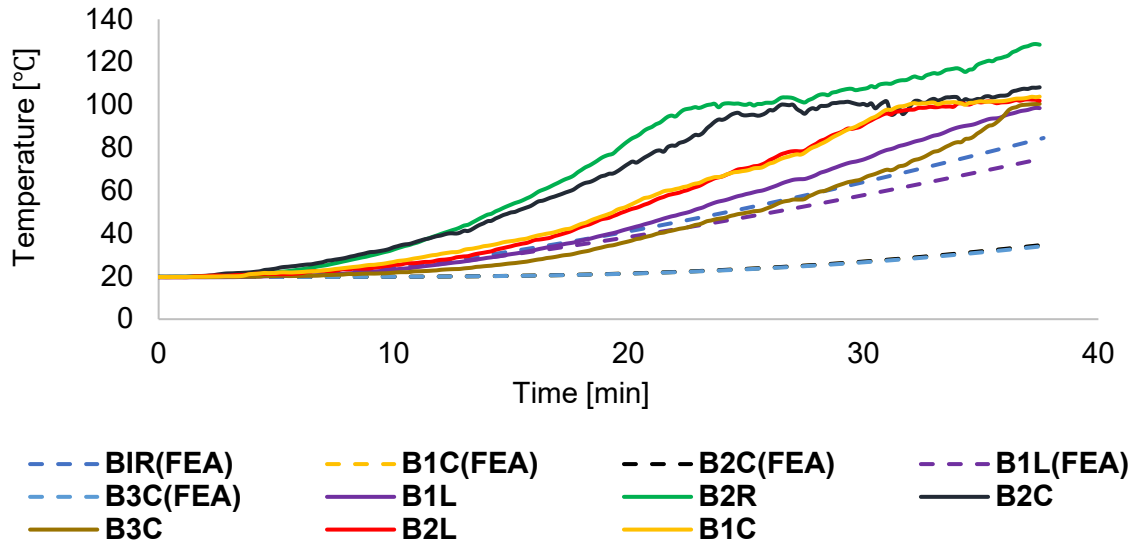


Figure 67. A comparison of the unexposed FCB temperatures between the FEA and the experimental results for Test Sample 2

The trend is similar for both sets (experiments and simulation) of results, although, from the experimental results, the temperatures stabilise (remain constant) for several minutes at different instances (times) as of 20 minutes, while there is only a constant, steady rise for the FEA results. Only half of Test Sample 2 was modelled because the sample was symmetrical, and thus the modelling process was simplified and shortened. There is no evidence in the literature to prove the inconsistency of temperature results from the symmetrical modelling approach. It is important to note that valid results can be obtained using this approach if appropriate boundary conditions are implemented and accurate properties are assigned to the model.

Tests 2 and 3 similarly had two holes on the exposed CaSi face. The differences between the samples were that Test Sample 3 had one of its holes concealed using the same CaSi material as on the exposed face of the sample, while both holes of Test Sample 2 remained unconcealed. The other difference was that Test Sample 2 had its holes at a distance of 600 mm from the burner end, and Test Sample 3 had the holes at the centre of the sample (approximately 300 mm from the burner end). **Figure 68** illustrates that the comparing TCs

(B2L) that lie on the side of the unconcealed hole (**Figure 52**), recorded higher temperatures for both the FEA and physical test. The FEA results replicated the physical tests in that all the comparing TCs, respectively follow the trend, from the hottest to the coolest points on the FCB, showing once again the reliability of FEA in predicting the behaviour of the sandwich flooring/ceiling system.

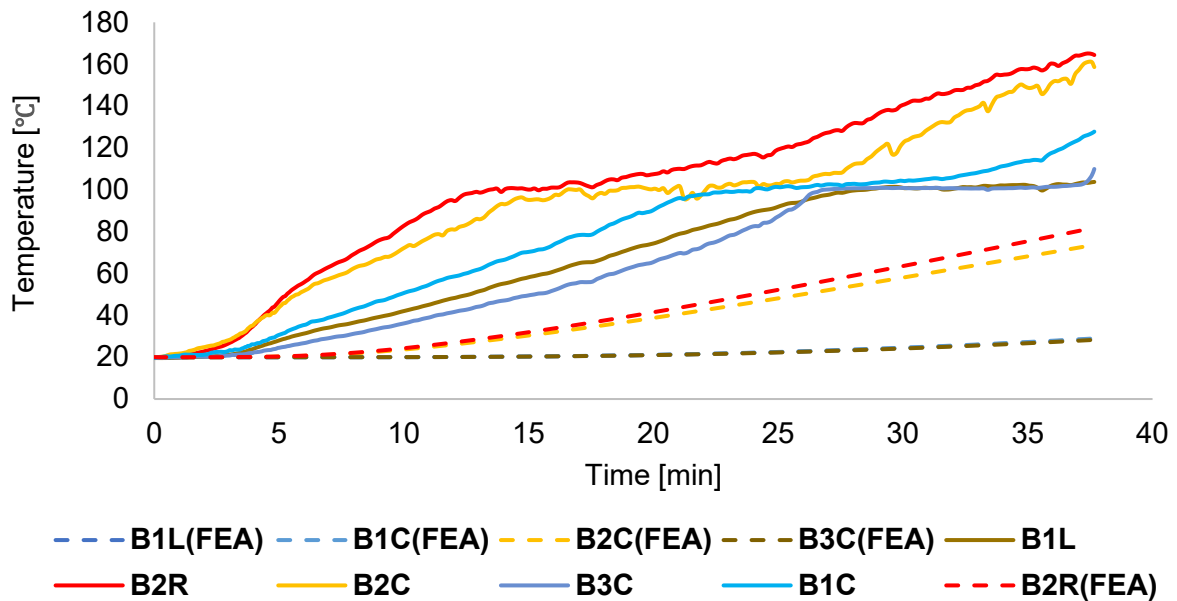


Figure 68. A comparison of the unexposed face temperature curves between the physical experiments and the FEA models for Test Sample 3

Figure 69 is an illustration of the Test Sample 4 results. The main difference between FEA and experimental results is that there is a delay in the rise of temperatures of the experimental test.

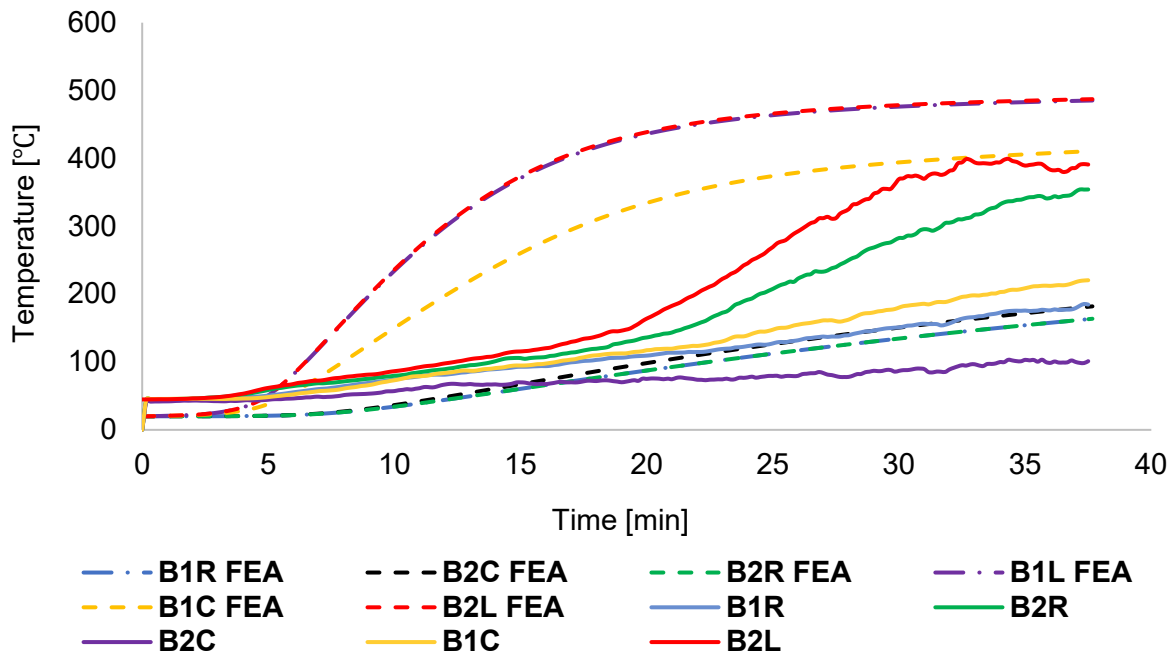


Figure 69. A comparison of the unexposed FCB temperatures between the FEA and the experimental results for Test Sample 4

The sharp, distinct temperature increase only occurs at approximately 17 minutes during the physical experiment (Section 4.2.4.5), while it occurs at approximately 5 minutes during the simulation. The comparing TCs between FEA and the physical experiments, namely, B2L, recorded the hottest temperatures alike. Test Sample 4 had its larger hole covered with a ceramic blanket during the physical experiment, a phenomenon which could not be accurately simulated and, therefore, was not modelled. The results, however, represent a similarity between the general temperature increase, albeit the FEA model averaged higher temperatures. FEA also proves the left side of the sample to be the hottest because of the large hole that was on the right side of the sample and was physically covered with a ceramic blanket, while the two smaller holes that were not covered were on the left side of the sample.

The samples that had covered holes, i.e., Test Samples 3 and 4, had an advantage of cooler temperatures on the FCB unexposed face depending on the location of the holes, as shown in **Table 5** and **Figure 63**.

Observing the results in **Figure 70**, FEA temperatures are notably lower than the experimental test temperatures for all the test samples except Test Sample 4. As mentioned earlier, Test Sample 4 had its larger hole covered with a ceramic blanket, an exercise that ensured lower experimental temperatures and not for the comparing FEA model. Also, to be considered is the fact that there was no additional heat source in modelling and thus could be the reason for lower FEA temperatures.

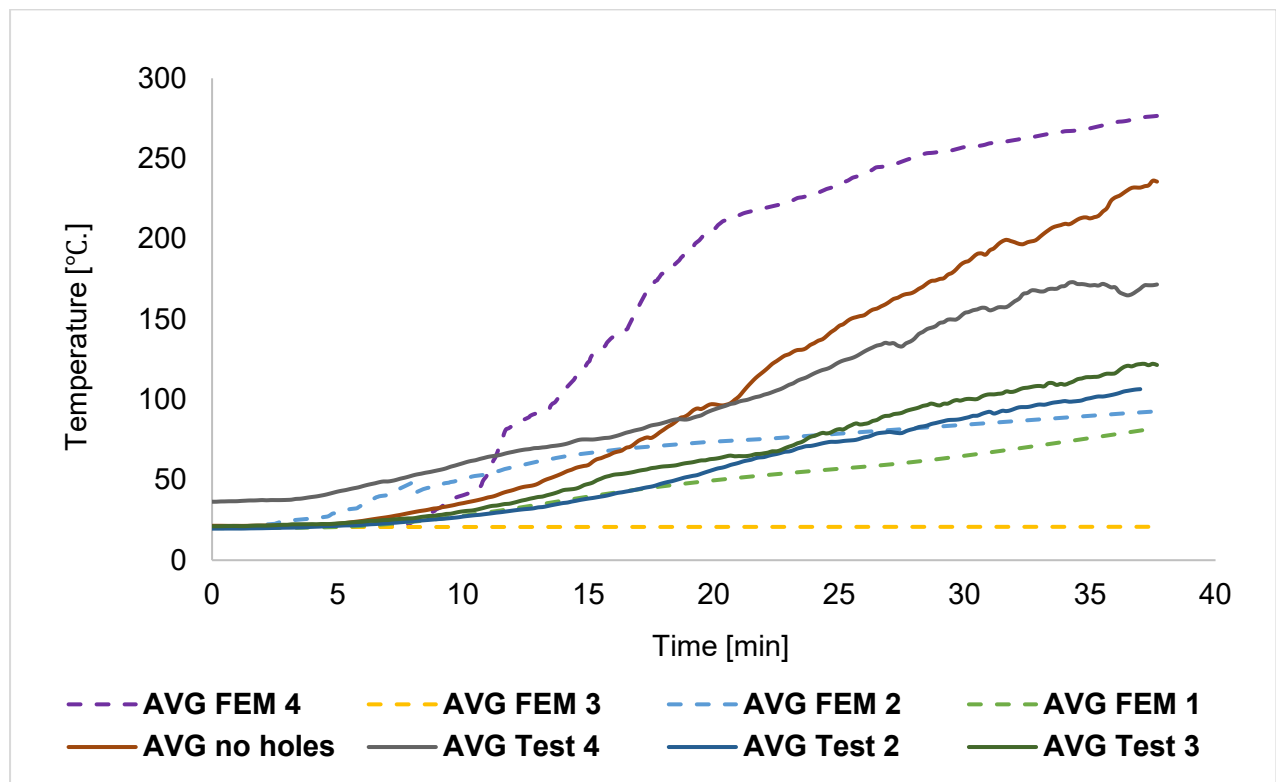


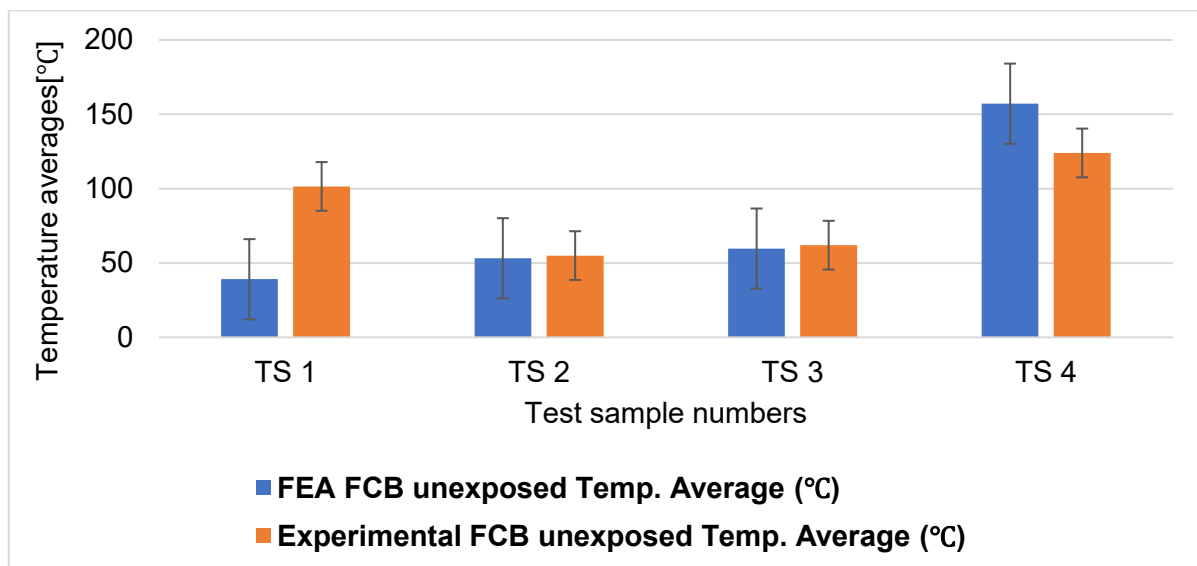
Figure 70. A comparison graph of unexposed FCB temperature averages between physical Tests and FEA models

Table 7 indicates that the comparing results between Test Samples 2 and 3 do not vary significantly in terms of their averages. What is indicated by the FEA results for Test Sample 1 is what could have naturally been the FCB unexposed temperatures for the experiment had the sample not been utilized to calibrate the furnace.

Table 7. Comparison of the FCB unexposed temperatures between the FEA models and experiments

Test Sample	FEA FCB unexposed Temp. Average (°C)	Experimental FCB unexposed Temp. Average (°C)	Temperature differences (°C)	Temperature differences (%)
1	39.2	101.5	62,3	61.4
2	53.2	54.9	1,8	3.2
3	59.7	61.9	2,3	3.6
4	157.1	123.9	33.2	21.1

Figure 71 illustrates the variations seen in the average temperatures between FEA and the experimental measurements on the unexposed surface of the FCB for all the samples. The bars illustrate that the experimental values for Tests 1 to 3 exhibit higher values, whereas Test 4 demonstrates lower values. Tests 2 and 3 exhibit notably diminished fluctuations, indicating a strong correlation between the models and the experimental results.



**TS denoting Test Sample*

Figure 71. Variations between the experimental and FEA FCB temperature averages

During Test 4, the simulation was conducted without including the covering on the larger hole. Consequently, the temperatures obtained by FEA were observed to be higher compared to the experimental temperatures. Based on the comparative accuracy between the FEA results and the actual results, it is plausible to infer that the elevated temperatures observed in the model are a consequence of the absence of a cover for the larger hole.

5.4 Conclusion

For this study, the aim of conducting FEA model simulations was to ascertain that FEA could be used as an adequate method to predict the behaviour of the ceiling system exposed to elevated temperatures. The results obtained from the experiments and FEA models could provide a means to observe similarities and variations; consequently, a conclusion could be drawn regarding whether FEA can accurately predict different scenarios before validating physical experiments.

The findings of this study indicate that complete reliance on either modelling or experimentation in isolation may not be a suitable approach, particularly in the context of fire testing when a minimal margin of error is desirable. Results from Test Samples 2 to 4 provide proof that FEA may be used to predict the unexposed face temperatures of a sandwich floor system subjected to a standard fire and therefore model its behaviour. The highest percentage difference between the three aforementioned tests is 21.1% from the Test Sample 4. Test Sample 4 was experimentally tested with one of its holes (the larger hole) covered with ceramic fibre blanket. Physical experiments are considered to yield more realistic outcomes due to their ability to replicate realistic settings, such as ambient temperature, in addition to being done under controlled circumstances guided by the standard fire curve. Consequently, these experiments are more likely to produce results that closely resemble real-world scenarios. In contrast to modelling, wherein conditions were only reliant on accurate parameter inputs rather than external factors that may fluctuate throughout the test.

As mentioned in Section 4.2.1.4, Test Sample 1 had the longest exposure to the SFC on the furnace, hence the large variation between the FEA and the experimental results for Test Sample 1. The FEA temperature averages were lower than the experimental test temperature averages. The percentage difference between the FEA and the physical test results may have been much smaller had the sample not had as much exposure to the elevated temperature as it did.

Chapter 6: Conclusions

6.1 Project Overview

The main objective of the study was to determine how rapidly heat would be transferred to the unexposed face of the FCB within the flooring/ceiling system when the CaSi ceiling board on the exposed face has holes that will mimic service holes for lights and AC ducts. For the system to pass the fire resistance rating, the most important of the ratings to be considered in this work were integrity and insulation. The system was not carrying any load; therefore, stability was not the focus in this study. The objectives as discussed in Chapter 1, Section 1.5, were met and discussed.

A full literature review was conducted in Chapter 2. The fire phenomenon was discussed, where the definition of fire and the science behind it were described. The history behind the PSSBD was stated and how these systems behave at elevated temperatures (standard ISO 834 fire). The chapter also discussed the details of heat transfer and the three mechanisms that govern it, as well as the properties of the PSSBD materials that would be affected by elevated temperatures. The SAISC modular steel cellular beam structure was discussed, as well as fire prevention methods and their application and relevance to this study.

Chapter 3 discussed the setup of the physical experiments, from the downsizing of the samples, the placing of the thermocouples, the calibration of the furnace, and the reading of the results from the Benchlink 34980A data logger Pro Software. The location of the service holes and the determination of the number of thermocouples on each sample were part of this process. The methodology was fully explored in this chapter. The design and setup of the FEA models were also detailed and discussed in Chapter 3. All the properties used were stipulated along with all the parameters.

A total of four samples were tested, in a furnace, subjected to a standard (ISO 834) fire. The results of these tests were thoroughly analysed and discussed in Chapter 4. The results of the

test samples were presented graphically – of each level/layer of the sandwich floor/ceiling system. Finally, the unexposed face temperatures of all the samples were presented in a table for observation to determine which sample heated up more rapidly, especially on the unexposed FCB face. The results were then discussed in detail, looking at the failure trends, the behaviour of the boards, and how failure was characterised and identified.

Chapter 5 explored the FEA results, and a graphical comparison was made between FEA and experimental results. The most important temperature face to be monitored was the FCB unexposed, as such, the comparison in this chapter was between the unexposed faces of the FCB of both the FEA models and physical experiments.

An overview and summary of the project were presented in Chapter 6. The findings from the study were presented in this chapter, thus providing a clear understanding of the performance of the sandwich ceiling system as tested physically and modelled. Finally, recommendations and suggestions were given for future work that stems from the current work and previous, but most recent work.

6.2 Project findings and conclusions

All of the four tested samples yielded results that were comparable to the theory of heat transfer through composite systems, as denoted by **Equation 3**. It could be observed in Chapter 4 that the temperatures were decreasing at every layer – from the innermost (CaSi exposed face) to the outermost (FCB unexposed face) – as governed by Newton's law of cooling and heat transfer by conduction for composite structures. The phenomenon was observed for each of the four samples. The shortest test lasted for approximately 42 minutes, as such, all the samples may be assigned a 30-minute rating for both integrity and insulation.

All four of the samples were modelled with ABAQUS CAE 2020, and in comparison, to the physical results, the curves (yielding from the FEA results) are similar concerning the temperature increase and/or decrease. Although the FEA tended to either over – or – underestimate the actual physical temperatures (not following any pattern), the trends were

similar for all samples. Considering that the shortest experiment had only 42 minutes of elevated temperature exposure, all the other test results were rounded down to the same duration. Tests 1 to 3 had exposure beyond 60 while Test 4 was suspended at 42 minutes due to integrity failure. Smoke was perceived through the cracks that initiated above the two smaller holes. The FEA models were conducted for a maximum of 35 minutes, and for that duration, there was no predicted insulation failure for any of the samples.

The study aimed to determine the rating that could generally be assigned to samples with service holes. According to the behaviour and performance of the samples and the temperatures recorded on the unexposed FCB faces of all the samples, a 30-minute rating can be assigned to the systems with holes in them, while integrity would still have to be accounted for. This rating is for worst-case scenarios, where the sample areas are smaller in comparison to the areas of the systems used in construction. Beyond 30 minutes, but prior to the 60-minute mark, all the samples had failed insulation and integrity. Furthermore, it is presented that the benefit of FEA lies in providing the ability to conduct simulations for different scenarios at a low cost and possibly shortened time before any physical experimentation can be conducted based on the FEA results that present a more suitable solution. The physical experiments can then validate what would have already been predicted by FEA for more specific scenarios.

It is important to note that these tests represent the worst-case scenarios for the floor/ceiling system that was being investigated. The holes were close in proximity to one another due to the fire-exposed area being small-scale (1.2 m × 1.2 m), and there was limited height between the fire source (burner) to the exposed surface of the CaSi because of the small size of the furnace. The largest distance between the holes for any of the samples was up to 600 mm. The system was only reliant on passive fire protection methods (fire-resistant ceiling boards and ceramic fibre blanket) to impede the fire, delay the rate at which the heat is transferred, and curb the effects thereof. No active methods were employed. The tests were conducted under controlled conditions that don't necessarily represent real-time or real-world fire

conditions. The holes represent the lights and AC fittings, and during experimentation, the lights and the AC were not fitted, thus leaving the holes completely exposed to the heat from the furnace, and consequently, the next surface, i.e., the flutes.

It was observed from the analyses of Test Samples 3 and 4 that having the open holes covered with some insulation material lowered the rate at which heat is transferred to the unexposed face. To this end, the author asserts that as an additional protective measure, lights and AC systems be lined with ceramic blankets to aid the delay of heating of the surfaces beyond the holes. Additionally, water sprinkler systems, together with the insulation method, may increase the fire rating of the floor/ceiling system.

6.3 Recommendations for future work

The end goal for the entire project was to determine whether the SAISC steel modular structure could ultimately be commercialised. To be commercialised, it must satisfy all the FRR criteria. Reaching conclusive results will aid industry contractors in planning for fire safety in structures. Results have shown that having a great number of holes in a small area will lead to rapid insulation and integrity failure, however, having the holes sealed off with ceramic fibre and perhaps other forms of sealants in the gaps will help delay failure or to increase the rating.

This study was limited to small-scale test samples, therefore, smaller holes and fewer holes, and the samples only had square holes. What can be looked at for future work is large-scale tests of the same sample with holes and variable sizes and shapes to see whether the size of the samples and holes have a bearing on the overall performance of the PSBBD flooring/ceiling system tested in the same conditions of testing, i.e., standard fire testing within a specially designed furnace. This study may also investigate the stability of the ceiling system and the structure wholly.

Building Information Modelling (BIM) can be used as a technology in collaboration with ABAQUS for better prediction of the behaviour and strength of the system and consequentially, the entire steel structure. The study of the progressive collapse of a 3 to 10

storey residential or commercial SAISC modular steel structure can be modelled specifically with the 30-minute rating as determined by this current work. Following previous and current work, a foundation has been laid for fire Codes and Standards to be developed for South Africa. This could also include investigating whether the 30-minute rating would allow enough time for egress within the specific tested steel structure.

The parameters used for the FEA models yielded results that were comparable to the experimental results. The parameters may, therefore, be utilised as standard parameters for FEA modelling for similar floor/ceiling systems.

Through this study, it was shown by the temperature results that samples with holes fail more rapidly than those without any holes. The more holes they have, the more rapid the failure in terms of Fire Resistance Rating (FRR). This knowledge will help designers keep cognizant of the fact that the impact of “service” holes on the heat transferred through the system will need to be considered from the early stages of design, and thus how to prevent excessive damage.

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