Fire-Induced Structural Collapse of the TU Delft Faculty of Architecture

Study of Key Columns in the 2008 Faculty of Architecture Collapse

D.T. Dekker



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Study of Key Columns in the 2008 Faculty of Architecture Collapse

by

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to obtain Bachelor degree of Civil Engineering
at the Delft University of Technology,
The thesis will be publicly defended on Tuesday, August 26 at 10:00 AM..

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Project duration: June 30, 2025 – August 26, 2025
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Preface

This thesis has been written as part of the Bachelor's End Project (BEP) in Civil Engineering at Delft University of Technology. The report presents the results of an individual research project focused on the structural fire behaviour of the Faculty of Architecture building, which partially collapsed after a fire in 2008.

The project has been both a technical and personal challenge, requiring the integration of structural engineering, fire dynamics, and thermal analysis. It was particularly demanding because fire engineering was a completely new subject for me. Getting familiar with its concepts (and with specialised software such as SAFIR, DIAMOND and GMSafir) took considerable effort, but also made the project all the more interesting and rewarding. It provided a valuable opportunity to apply theoretical knowledge to a real-life case study and to work independently through each step of the research process.

I would like to express my sincere gratitude to my supervisor, Zhuojun Nan, for her valuable feedback, support, and guidance throughout the project. I also thank Pierre Hoogenboom for his support as second supervisor and examiner, and Roel Schippers for his role as second examiner. I am grateful to the staff of the Civil Engineering faculty for providing the tools and resources necessary to complete this work.

I hope this thesis will be of interest to those studying fire safety engineering and structural behaviour under extreme conditions, as well as anyone interested in the FOA building fire.

D.T. Dekker
Delft, August 2025

Abstract

This thesis presents a focused study on the partial structural collapse of the Faculty of Architecture (FOA) building at Delft University of Technology, which occurred in 2008 following a major fire. Structural failure due to fire is a rare but potentially catastrophic event, especially in reinforced concrete buildings. As architectural designs increasingly favour large open-plan layouts, understanding fire propagation and structural response becomes ever more critical.

The aim of this thesis is to determine how key structural elements, specifically a selected reinforced concrete column on the seventh floor, behave under realistic fire exposure, and how this behaviour compares to the assumptions made in Eurocode-based design. Subsequently, different fire curves were developed: the Standard Fire Curve (SFC), External Fire Curve (EFC), and Parametric Fire Curve (PFC), as defined in the Eurocode, and a Travelling Fire Curve (TFC), constructed using the Extended Travelling Fire Methodology (ETFM) in OpenSees.

A comparative analysis showed that the TFC significantly deviates from both the SFC and EFC, which are often used in design but do not represent realistic temperature developments. The PFC provided a better approximation of the TFC, especially for structural elements located near the fire source. However, only the TFC captured the pre-heating phase caused by radiative exposure before direct flame contact, which is a critical aspect in structural fire performance.

A thermal analysis of the selected column was performed using SAFIR2025, with the Parametric Fire Curve (PFC) as input. The results showed that while the core remained relatively cool, the outer 30 mm of concrete exceeded 500 $^\circ C$, significantly reducing the load-bearing cross-section. The reinforcement, located 52 mm from the surface, reached temperatures up to 450 $^\circ C$, which may contribute to strength loss, bond degradation, and potential spalling.

In conclusion, this study highlights the importance of incorporating realistic fire modelling in the assessment and design of structural elements. The results indicate that reliance on standard fire curves, as currently prescribed in the Eurocode, may underestimate thermal exposure and structural risk in large open compartments. Adoption of advanced fire scenarios such as the Travelling Fire Curve could lead to safer and more resilient building design.

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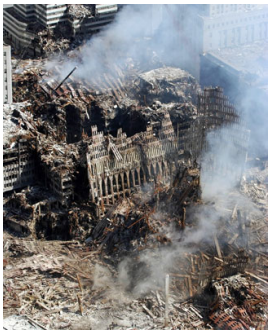
1

Problem analysis

1.1. Context and Relevance

Structural collapse as a result of fire is a rare phenomenon in modern buildings, particularly in reinforced concrete structures. Although most buildings are designed in accordance with contemporary building codes, fire incidents can still lead to partial or total collapse. Such failures may result in fatalities, significant property loss, environmental damage, and major social and economic disruption.
In recent decades, the risk of fire has increased due to the growing presence of electrical equipment and other ignition sources within buildings. At the same time, architectural trends favour large open floor plans, which allow fire and smoke to spread more rapidly and uncontrollably. These developments underscore the growing importance of research into fire propagation and its impact on structural performance.
Despite this increased risk, the design philosophy for fire safety in buildings has changed little over the past years. Structures are still commonly designed using the Eurocode standard fire curve, which assumes a highly simplified and non-realistic fire scenario. However, ongoing research has shown that real fires behave very differently in terms of temperature development within a building. Meanwhile, advancements in computational tools, such as Finite Element Modelling, now allow engineers to simulate realistic fire exposures and structural responses with far greater accuracy. These tools offer the potential to develop more refined and realistic fire curves, leading to improved design strategies.
Although complete structural collapse due to fire remains relatively rare, several high-profile cases demonstrate the potentially catastrophic consequences. The collapse of the World Trade Center towers in New York (2001) remains the most widely known example following prolonged fire exposure. In Europe, the partial collapse of the Faculty of Architecture at Delft University of Technology in 2008 stands out as a well-documented case involving a reinforced concrete structure. Other notable examples include the Windsor Tower fire in Madrid (2005) and the Plasco Building collapse in Tehran (2017). These incidents offer critical insights into the vulnerability of structures to fire and highlight the need for continued investigation into realistic fire scenarios and structural behaviour. (Figure 1.1)



(a) World Trading Center structural collapse (Malakoff, 2002)



(b) Faculty of Architecture Tu Delft structural collapse (Jordana, 2009)



(c) Winsor Tower structural collapse (NSC2, 2006)



(d) Plasco building structural collapse (Macguire, 2017)

Figure 1.1: Examples of four major structural collapses due to fire

This report presents a case study of the structural collapse of the Faculty of Architecture (FOA) at TU Delft, which occurred on May 13, 2008. The fire started in the morning, caused by a short circuit in a coffee machine located on the sixth floor of the south wing. Students were the first to notice the fire and attempted to extinguish it. However, due to malfunctioning firefighting equipment and the rapid growth of the fire, their efforts were unsuccessful. The building was subsequently evacuated.
The fire continued to spread throughout the south wing and quickly reached the upper floors. When the fire department arrived, they initially attempted to fight the fire from inside the building. However, after observing signs of internal structural distress, they withdrew from the building for safety reasons. The fire eventually extended to the north wing. After burning for several hours, the north wing of the building collapsed, as illustrated in Figure 1.1b.
This event raised critical questions regarding fire dynamics, structural robustness, and the adequacy of existing fire safety design methods, particularly those outlined in the Eurocode. Previous investigations have provided valuable insight into the global fire progression and mechanisms of structural failure. This thesis aims to build upon that knowledge by focusing on the local behaviour of a critical reinforced concrete column subjected to realistic fire exposure. The results will be compared to standard Eurocode-based fire scenarios to assess the validity and limitations of current design approaches.

The specific problem addressed in this thesis is the discrepancy between real fire exposure and the standard fire test/parametric fire condition (according to the Eurocode) often assumed in design, and how this affects the structural behaviour of a reinforced concrete column under such conditions, in respect of heat transfer inside the column.

1.2. Objective

Following the collapse of the Faculty of Architecture at TU Delft in 2008, a large-scale investigation was launched to study the causes and contributing factors of the incident. A multidisciplinary team, comprising both Dutch and international institutions including: TNO, Efectis Nederland, TU Delft, Worcester Polytechnic Institute, Michigan State University, and the University Of Texas, examined various aspects such as the fire development, firefighting response, structural performance, and the sequence of events that led to the collapse.
This thesis builds on the findings of those earlier studies by focusing on the local behaviour of a single structural element within the affected part of the building. Specifically, it examines a reinforced concrete column located on the seventh floor of the northwest wing, the area where the structural failure ultimately occurred. The goal of this research is not to determine the exact cause of the collapse, but to give deeper insight into how fire exposure may have influenced the performance of this individual column.
To do so, different fire curves were analysed and compared, including the Standard Fire Curve, the Eurocode-based Parametric Fire Curve, and a realistic Travelling Fire Curve. While a direct thermal analysis was performed only using the Parametric Fire Curve, the comparison between the various fire scenarios provides insight into the effectiveness and limitations of current fire design methods in capturing realistic fire conditions and their potential impact on structural safety.

To gain insight into the role of fire in the collapse of the FOA, the development of the fire is first reconstructed based on available literature, photographs, and reports. Particular attention is given to critical moments in the fire timeline, such as flashover events and the spread of fire near the area of structural failure. This reconstruction supports the selection of a representative column for further analysis, one that was located in the most critically affected zone and may have contributed significantly to the initiation or progression of the collapse.
Following this, the thermal exposure of the selected column is evaluated using various fire scenarios. These include the Eurocode standard fire curve, the Eurocode parametric fire curve, and an estimated realistic fire curve based on observed fire development. The aim is to compare these curves and assess how accurately Eurocode based approaches reflect real fire conditions.
Finally, the temperature distribution within the column is analyzed through heat transfer calculations. Material properties, concrete cover, and reinforcement layout are considered as part of the thermal modelling process.

Through this two-part approach, the thesis aims to answer the following main research question:

Main research question:

- How do the key structural elements (e.g., the selected reinforced concrete column in this study) behave under realistic fire exposure, and how do realistic fires differ from the assumptions in Eurocode-based design?

Sub questions:

- What were the critical events during the TU Delft Faculty of Architecture fire, and how did they influence the progression and effects of the fire?
- What structural element failure of the building caused the collapse?
- How did the thermal conditions evolve in the vicinity of the selected column over time?
- How does the temperature development near the column compare to the standard fire and parametric fire curve used in the Eurocode?
- How did heat transfer through the cross-section of the column influence its thermal response?

1.3. Methodology

To address the research objectives, this thesis is divided into chapters, that eventually give answer to the research questions. Each chapter builds on to the next chapter. Below is a chapter-by-chapter overview of the content to be elaborated.

Chapter 2:
This chapter presents a literature-based study that examines the structural collapse of the Faculty of Architecture (FOA) in 2008. It begins with a reconstruction of the fire development within the building, with particular attention to critical events such as flashover, defined as a sudden and rapid transition from a developing fire to a fully developed fire, during which all combustible materials in an enclosed space ignite simultaneously. Based on this study, a column is identified that is likely to have played a critical role in the collapse. This column, located in the collapsed part of the building, is selected for further analysis.

Chapter 3:
In chapter 3 the different fire curves are discussed. This involves the Standard Fire Curve, External Fire Curve, the Parametric Fire Curve (based on Eurocode), and a realistic fire curve. The Standard, External and Parametric fire curves are described in Eurocode NEN-EN 1991-1-2. The calculation method for the Eurocode-based fire curves will follow the approach outlined in this standard. The realistic fire curve will be represented as a Travelling Fire Curve calculated using the Extended Travelling Fire Methodology. This will take into account the layout of the space surrounding the critical column in order to arrive at a realistic temperature development around the critical column.

Chapter 4:
This chapter focuses on heat transfer within the selected column. The analysis is performed using the Finite Element Software SAFIR. The model includes the geometry of the column, material properties and the reinforcement layout. These parameters are based on available construction documentation and findings from the literature review in Chapter 2.

Chapter 5:
Conclusion

Chapter 6:
Discussion

Chapter 7:
Recommendation for future research

1.4. Scope

This thesis is limited in scope but focused in depth. Its main objective is to evaluate the structural fire behaviour of a single reinforced concrete column located in the northwest wing of the Faculty of Architecture (FOA) building at Delft University of Technology. The research aims to assess how the actual thermal exposure around the column compares to the Standard and Parametric fire curve defined in Eurocode EN 1991-1-2, and to estimate the heat transfer within this column.

The study is based entirely on literature, photographs, and engineering judgment. No new experiments or detailed numerical simulations are performed. Instead, the analysis uses simplified heat transfer concepts and Eurocode-based methods to approximate the column's thermal environment and structural performance under fire conditions. The behaviour of the selected column is evaluated with respect to its reinforcement layout, concrete cover, and material properties.

This thesis does not seek to provide a full explanation of the collapse of the FOA building as a whole, nor to simulate the entire fire event in detail. Rather, it aims to contribute a local, component-level analysis as a case study that may support future research into fire-induced structural collapse

By focusing on a single column within a known collapse zone, this thesis aims to offer specific insights into the applicability and limitations of standard fire design assumptions when confronted with real fire events.

2

Case study

This chapter presents a case study of the 2008 fire in the Faculty of Architecture (FOA) building. It focuses solely on the timeline of the fire development within the building itself. Based on the fire timeline, the structural elements that played a significant role in the collapse of the northwest wing of the building are identified. A detailed description is provided for these structural elements.

2.1. Development of the fire

Below is a summary of the fire development in the FOA building, highlighting only the key moments along with time indications. Appendix A provides schematic representations of the fire spread, offering a clear and visual understanding of the incident. This reconstruction is based on visual material, previous reports, and eyewitness accounts (Zannoni M. et al., 2008).

At 8:15 AM on May 13, 2008, smoke began to emerge from a coffee machine located on the sixth floor of the southwest wing of the FOA building. A short circuit inside the machine had caused a fire to ignite. Students who noticed the fire attempted to extinguish it, but their efforts were unsuccessful. By 9:10 AM, smoke and flames had intensified significantly. Fireballs, most likely burning plastic cups, were seen erupting from the coffee machine. Students who were still near the machine tried to extinguish the fireballs on the ground using a fire extinguisher. They hesitated to use the fire extinguisher directly on the machine, as they feared this might worsen the electrical short circuit. When an in-house emergency responder (BHV'er) arrived at the scene, they instructed everyone to evacuate the floor. At this point, students and staff left the building and waited for the fire department to arrive.
By 9:45 AM, the fire had fully spread out over the entire south wing. The flames had grown so intense that even the fire brigade was forced to retreat. Initially, the fire was contained within the south wing, as the north and south wing were separated by two firewalls. However, the south wing featured large open spaces and vertical voids between floors, where the floor separations consisted of non-fire-resistant glass. These design features allowed the fire to spread rapidly upwards.
By 10:30 AM, the fire had consumed the sixth through eighth floors of the south wing. By 11:30 AM, it had reached the eleventh floor. Around this time, a small fire was also observed in the central hall between the north and south wings, on the sixth floor.
At 2:30 PM, the fire had fully breached into the north wing. A small fire was burning on the sixth floor, while the entire eleventh floor of the north wing was in flames. Meanwhile, the fire in the south wing had nearly burned itself out. By 3:30 PM, the fire had spread to the seventh through eleventh floors of the north wing. At 4:00 PM, flames reached the sixth floor of the north wing as the fire on the eleventh floor began to burn out.
By 4:30 PM, everything above the seventh floor had been completely burned out, with only a few small fires remaining. At 4:40 PM, the entire north wing of the building collapsed.
A few months later, the entire structure, including the cellars, was demolished and recycled. All that remained was a flat grass-covered field.

A more detailed timeline, illustrated with figures, can be found in Appendix A.

2.2. Failing structural element

The spread of the fire through the FOA building has been described above. As mentioned, at 4:40 PM, part of the north wing of the building collapsed. This section of the report investigates which structural element(s) failed first and contributed to the collapse. This analysis is based on visual material.

A photograph that clearly illustrates the condition of the building shortly before its collapse is shown in Figure 2.1. In this image, the northwest wing of the FOA building is prominently visible. The fire appears to have largely burned out on all floors. However, dense black smoke is still emerging from the seventh floor, particularly from the areas near the façade-side columns (circled in white in the figure). The location of the columns at the facade can be seen in Figure 2.2. It is important to note that, although no visible flames remain at this point, some degree of combustion may still be occurring. This means that heat is still being generated, and the temperature inside the compartment may continue to rise even in the absence of visible flames.
A notable observation is that the smoke seems to originate specifically from the locations of these columns. One possible explanation is that the black smoke is not solely the result of ongoing combustion, but may also contain dust or fine debris released as the columns begin to fail. Another striking feature is the pronounced sagging of the roof above the north wing. This deformation may be attributed to column failure, either through inward or outward buckling, or possibly to the collapse of supporting beams.

In this report, it is assumed that the columns on the seventh floor along the northwest façade were the first to fail and played a critical role in the collapse of this section of the building. As a result, the analysis focuses exclusively on these columns.



Figure 2.1: Photograph of the northwest wing of the FOA building just before collapse (Rob Jastrebski, 2008)

2.2.1. Critical column

Surrounding column:

From this point onward, this report focuses exclusively on the columns located on the seventh floor along the northwest façade, the part of the building that ultimately collapsed. In Figure 2.2, these columns are highlighted with red circles.

The FOA building consisted of a low-rise section and a high-rise tower. The high-rise portion, referred to as the tower, had 15 floors and was divided into a north wing and a south wing, connected by a central hall. The layout of the tower was mirrored across this central hall, making the floor plans of the north and south wings nearly identical (refer to Figure 2.2).
The red hatched area in Figure 2.2 indicates the section of the building that ultimately collapsed. This part of the building consisted of office spaces on almost every floor. These offices were separated by timber-framed partition walls covered with gypsum boards and insulated with Rockwool. All offices were connected by a central corridor.

A floor plan zoomed in on the red hatched area from Figure 2.2 is presented in Figure 2.3. The corresponding dimensions are also indicated. Each office measured 4.9 by 5.4 meters, with a floor to ceiling height of 2.7 meters. The hallway in front of the offices was 2.7 meters wide. Each office typically contained two desks, filing cabinets, small cupboards, and various accessories such as binders, reports, scale models, drawings and computers. The façade-side columns were embedded in the walls but remained visible. Each office had one door providing access to the corridor. On the façade side, every office had four large windows, each measuring 1.1 meters in width and 1.8 meters in height. The window sills were positioned 0.9 meters above floor level.

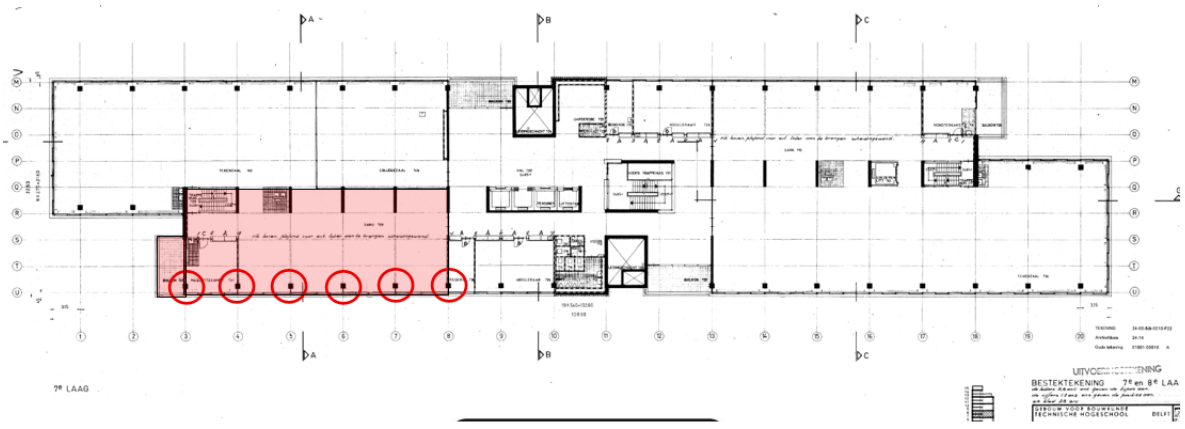


Figure 2.2: Floor plan of the seventh floor with the columns of the northwest wing encircled with red and the collapsed zone highlighted in red

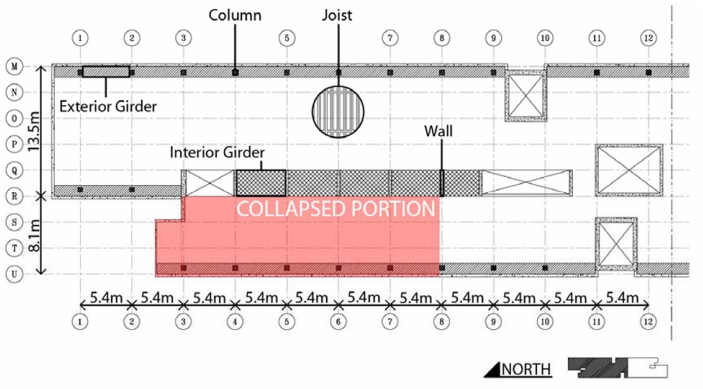


Figure 2.3: Floor plan of the seventh floor zoomed in on the collapsed area, including dimensions. (Engelhardt et al., 2013)

Properties column:
The structure of the FOA building consisted primarily of cast in place concrete elements. The main load bearing system was composed of reinforced concrete columns, beams, and slabs. The columns in the tower section of the building had cross sectional dimensions of 500 × 500 mm. Column height varied depending on their location within the structure. On the northwest side, within the area that ultimately collapsed, columns measured 3.15 m on even numbered floors and 3.85 m on odd numbered floors. On the northeast side, where large open spaces spanned two stories in height, columns reached up to 7.00 m. This thesis focuses specifically on the columns located on the seventh floor, which were 3.85 m tall.The required fire resistance of the columns in the FOA building was R120 (fire resistance of 120 minutes), in accordance with Eurocode 1992-1-2 (NEN, 2021). This requirement applies to buildings classified as educational facilities, such as schools.

The façade-side columns, circled in Figure 2.2, also measured 500 × 500 mm. Each column contained 12 longitudinal reinforcement bars, with bar diameter decreasing at higher elevations in the structure. On the seventh floor, the longitudinal bars had a diameter of 32 mm. The stirrups consisted of 8 mm bars, spaced at 250 mm intervals. The concrete cover, the distance from the column surface to the outer edge of the reinforcement, depended on the diameter of the longitudinal bars. On the seventh floor, this cover measured 28 mm. A detailed drawing of a cross-section of one of these columns is shown in Figure 2.4.
It should be noted that the corner columns of the building featured a slightly different reinforcement layout. However, this difference is considered minor and does not warrant separate analysis within the scope of this study.

The concrete used for the columns had a compressive strength of 34.32 MPa (equivalent to 350 kg/cm^2). The cement type was Type A blast furnace cement, with a density of 375 kg/m^3 of concrete. The concrete mix included a plasticizer at a concentration of 0.2%.
The specific type of aggregate used in the columns is unknown. However, one report suggests that the most likely aggregate was river gravel or siliceous aggregate.
Structural design documents for the FOA building indicate that the maximum allowable stress in the reinforcement was 207 MPa. The exact steel grade used could not be confirmed in the available literature. Therefore, it is assumed that the reinforcement bars were of steel grade S275, with a yield strength of 275 MPa.
Although not all details of the concrete mix and its exact proportions were available, the known values for concrete strength and reinforcement grade are considered sufficient for the purposes of the calculations performed in this thesis.

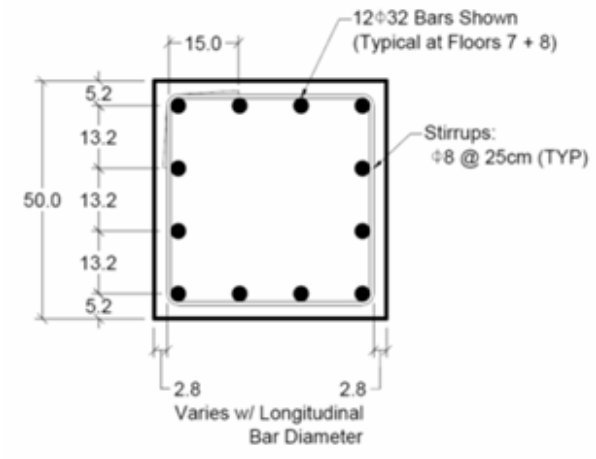


Figure 2.4: Cross section of a column in the tower at 7th floor (Engelhardt et al., 2013)

3

Fire curves

In this chapter, various fire curves are developed. Fire curves are time–temperature relationships used to simulate the thermal exposure of building components during a fire. Several methods exist for generating such curves, and this chapter presents four different approaches.
The first is the Standard Fire Curve (SFC), as defined in the Eurocode. This curve represents a simplified temperature-time relationship and is commonly used as a basis for testing the fire resistance of construction materials and structural elements. It assumes a uniform and fully developed fire with continuous temperature increase over time.
The second approach is the External Fire Curve (EFC). This fire curve is similar in shape to the standard fire curve but is adjusted for structural elements located at the exterior of a compartment, such as façade-side columns, that are only exposed to fire on one side.
The third approach is the Parametric Fire Curve (PFC), also defined in the Eurocode. Unlike the standard fire curve, the parametric curve accounts for the specific characteristics of a given compartment, such as geometry, ventilation, and thermal properties of enclosure materials. This allows for a more realistic simulation of both the heating and decay phases of a fire.
Finally, a Travelling Fire Curve (TFC) is applied, representing the most realistic fire scenario considered in this study. This approach simulates the movement of a fire front across a floor plate, leading to spatially and temporally varying thermal exposure. The TFC is generated using the Extended Travelling Fire Methodology (ETFM), based on the layout and material configuration of the studied area.

3.1. Standard Fire Curve

The Standard Fire Curve (SFC) is a widely adopted time–temperature relationship used in the design and assessment of structural components exposed to fire. The SFC was also applied in the design of the FOA building to evaluate the fire resistance of its structural elements. It is formally defined in Eurocode: NEN-EN 1991-1-2, which adopts the curve from ISO 834 (NEN, 2025). The SFC provides a simplified representation of how temperature in an enclosed space increases as a function of time. The curve is described by the following formula:

$$T_g = 20 + 345 * log_{10}(8t + 1) \tag{3.1}$$

- T_g = gas temperature in fire compartment ($^{\circ}C$)
- t = time (minutes)

As can be seen in the formula above, time is the sole variable in this expression. The graph of the SFC is shown in Figure 3.1, which illustrates a fire scenario with a duration of two hours. This duration was chosen as it matches the required fire resistance rating of the columns (R120), as mentioned earlier. Moreover, in the actual fire event, the fire burned for approximately two hours from the moment it reached the seventh floor until the collapse occurred. A key observation is the logarithmic increase in temperature, there are no drops or fluctuations. During the early phase (first 20 minutes), the temperature rises steeply, after which the rate of increase gradually slows. By the 120-minute mark, the temperature exceeds 1000 $^{\circ}C$.

The SFC offers a highly simplified representation of fire development in an enclosed compartment. Since it considers only time as an input parameter, it does not reflect the influence of factors such as ventilation conditions, compartment geometry, or fuel load. Moreover, the SFC does not include a cooling phase, making it not really suited for performanced based structural design.

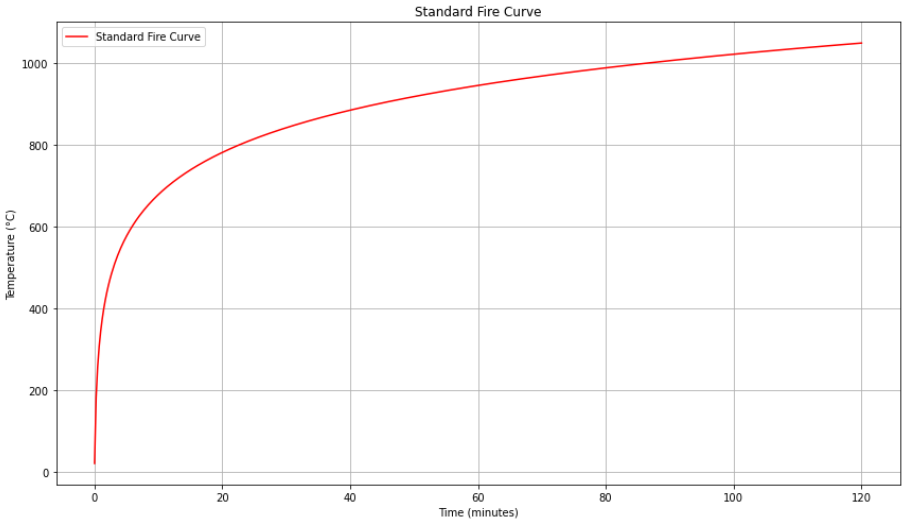


Figure 3.1: Standard Fire Curve according to NEN-EN-1991-1-2

3.2. External Fire Curve

The External Fire Curve (EFC) is a time-temperature fire curve given by:

$$T_g = 20 + 660(1 - 0.686e^{-0.32t} - 0.313e^{-3.8t}) \tag{3.2}$$

- T_g = gas temperature in fire compartment ($^{\circ}C$)
- t = time (minutes)

The EFC is a time-temperature relationship, that is representative of the reduced exposure experienced by elements on the facade of the building. This curve could be more representative for the columns analyzed in this thesis. (H. Buchanan & K. Abu, 2017)

The time-temperature curve of the External Fire Curve can be seen in Figure 3.2. What is particularly notable about the EFC is that it closely follows the Standard Fire Curve during the first 10 minutes. After this point, however, the EFC levels off significantly, stabilizing at a temperature of approximately 680 $^{\circ}C$. This is substantially lower than the SFC, which reaches around 1000 $^{\circ}C$ at 120 minutes.
This considerable difference can be attributed to the limited thermal exposure on the exterior side of the façade columns. Because the fire in this area is not enclosed by walls, a significant amount of heat is lost through radiation and convection to the surrounding environment. An additional contributing factor is the reduced likelihood or delay of flashover due to excessive ventilation, which allows hot gases to escape continuously. At the same time, this high level of ventilation supplies additional oxygen to the fire, which can support combustion and may accelerate fire growth during the early stages.

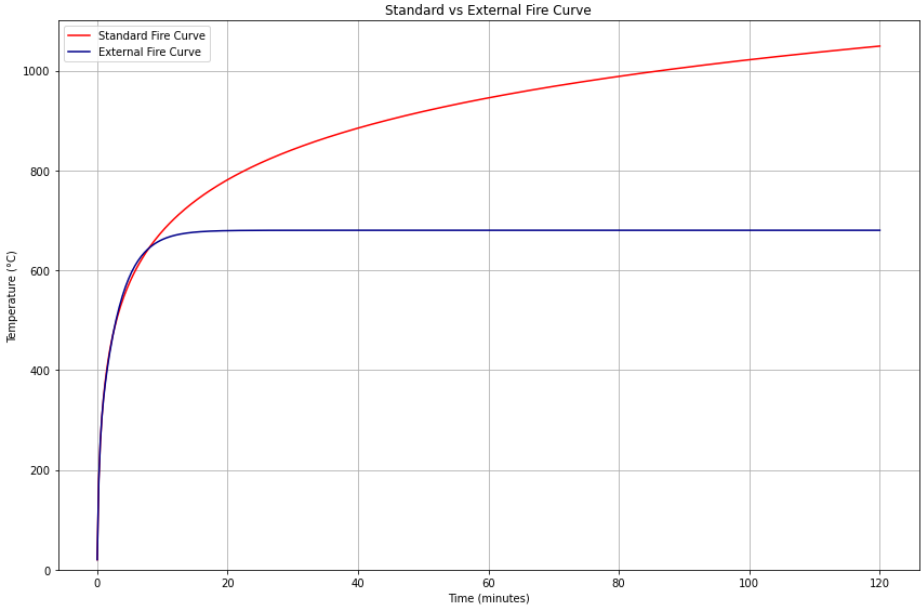


Figure 3.2: Standard Fire curve and External Fire Curve according to NEN-EN-1991-1-2

3.3. Parametric Fire Curve

Annex A of Eurocode NEN-EN 1991-1-2 provides an equation for modelling parametric fires. This approach takes into account factors such as the fuel load, the size of ventilation openings, and the thermal properties of wall and ceiling linings. As a result, it produces a more realistic time–temperature curve compared to the Standard Fire Curve. The equation for the Eurocode Parametric Fire Curve (PFC) is presented below:

$$T_g = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \tag{3.3}$$

- T_g = gas temperature in fire compartment ($°C$)
- t^* = fictitious time (minutes). Given by: $t^* = \Gamma t$
- Γ = gamma. Given by: $\Gamma = \frac{(F_v/F_{ref})^2}{(b/b_{ref})^2}$
- F_v = opening factor ($m^{0.5}$). Given by: $F_v = \frac{A_v H_v}{A_t}$
- F_{ref} = 0.04 ($m^{0.5}$)) (Eurocode (NEN, 2025))
- b = $\sqrt{\text{thermal inertia}}$ = $\sqrt{k\rho c_p}$ = 1900 ($Ws^{0.5}/m^2K$) (Eurocode (NEN, 2025))
- b_{ref} = 1160 ($Ws^{0.5}/m^2K$)
- A_v = total area of vertical openings on all walls (m^2)
- H_v = weighted average of window heights on all walls (m)
- A_t = total area of enclosure (walls, ceiling and floor, including openings). (m^2)

The maximum temperature T_{max} in the heating phase happens for t^* = t^*_{max}

$$t^*_{max} = t_{max} * \Gamma \tag{3.4}$$

- t_{max} = $max[(0.2 * 10^{-3} q_{d,t}/F_v); t_{lim}]$
- $q_{d,t}$ = design value of the fire load density (MJ/m^2) related to the total area A_t of the enclosure. Given by: $q_{d,t}$ = $q_{d,fi} * A_f/A_t$
- $q_{d,fi}$ = 744 (MJ/m^2) for a densely loaded office, design value of the fire load density related to the floor area A_f taken from Annex E Eurocode (NEN, 2025)
- t_{lim} = 20 (minutes) (NEN, 2025)

Using the equations provided above and the guidelines outlined in the Eurocode Annex A, the Parametric Fire Curve (PFC) was constructed. This was achieved by implementing the equations in Python and plotting the resulting temperature–time relationship. The parameters used in the calculation are described and explained below. The resulting PFC graph is presented in Figure 3.3. In this graph, three different Parametric Fire Curves are plotted for the same room. The only difference is the design value of the fire load density related to the floor area. These values are taken from NEN-EN 1991-1-2 Annex A and explained below.

- Total area of vertical openings on all walls:
  All offices in the northwest wing were equipped with four windows each, measuring 1.1 meters in width and 1.8 meters in height, with the window sills positioned at a height of 0.9 meters (refer to subchapter 2.2.1 for layout of the office). Based on this information, the ventilation opening area A_v can be calculated.
  $$A_v = 4 * (1.1 * 1.8) = 7.92m^2 \tag{3.5}$$
- Weighted average of window heights on all walls:
  All the windows in the office had the same height of 1.8 meters. Therefore:
  $$H_v = 1.8m \tag{3.6}$$

- Total area of enclosure:
  The total enclosure surface area of the office is calculated as the sum of the surface areas of all walls, the floor, and the ceiling, including any openings. The office had a width of 4.9 meters, a length of 5.4 meters, and a floor to ceiling height of 2.7 meters. This results in a total enclosure surface area of:
  $$A_t = 2(4.9 * 2.7 + 5.4 * 2.7 + 4.9 * 5.4) = 108.54m^2 \tag{3.7}$$
- Opening factor:
  $$F_v = \frac{A_v H_v}{A_t} = \frac{7.92 * 1.8}{108.54} = 0.0979 \tag{3.8}$$
- b_{ref} = 1160 ($Ws^{0.5}/m^2K$) (Value for normal weight concrete (NEN, 2025))
- Gamma:
  $$\Gamma = \frac{(F_v/F_{ref})^2}{(b/b_{ref})^2} = \frac{(0.0979/0.04)^2}{(1900/1160)^2} = 2.233 \tag{3.9}$$
- Design value of the fire load density related to the floor area A_f:
  The design value of the fire load density related to the floor area is determined using NEN-EN 1991-1-2 Annex E, which includes a table listing values for $q_{d,fi}$ for various types of occupancies (This table can be seen in Appendix B). In Figure 3.3, three different curves are plotted, each based on a different value of $q_{d,fi}$. The lowest curve corresponds to a $q_{d,fi}$ value of $420\ MJ/m^2$, representing a standard office. The middle curve uses a value of $744\ MJ/m^2$, which corresponds to a densely loaded office, defined in the Eurocode as an office with at least 20 % of its floor area occupied by archive storage. This value is considered highly plausible, as the FOA offices contained many filing cabinets and stored documents. Finally, a third curve is based on $q_{d,fi} = 1000\ MJ/m^2$, to account for the additional presence of architectural models, technical drawings, and reports that were likely present in the offices at the time of the fire. These materials would have significantly contributed to the total fire load within the space.
- Other parameters:
  The other parameters, as previously described, were calculated in the Python script.

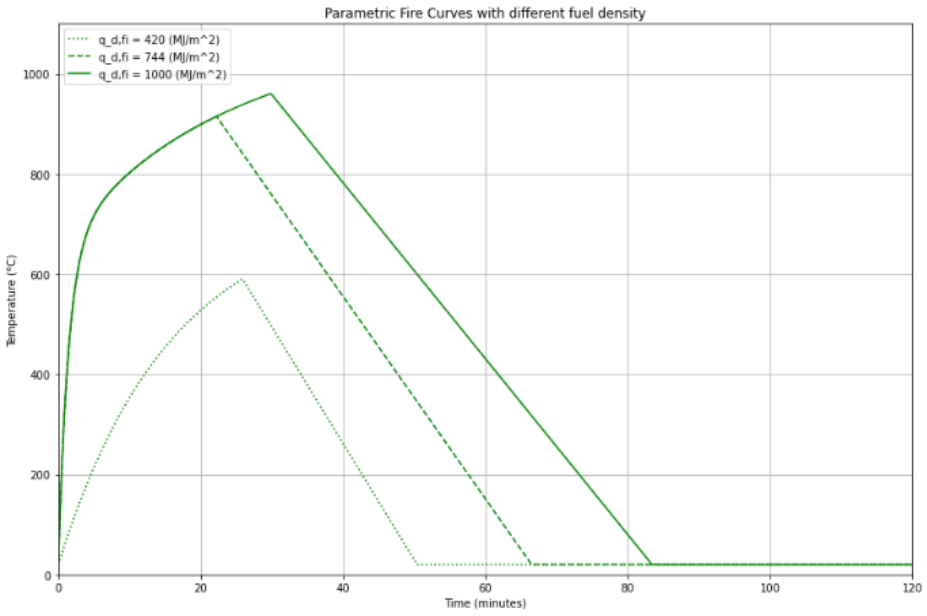


Figure 3.3: Parametric Fire Curves, with different values for the design value of the fire load related to the floor area. According to NEN-EN-1991-1-2

What stands out in Figure 3.3 is that the time–temperature curve rises as the fuel load density increases. This is logical: the more combustible material present in the office, the higher the temperatures that can be reached. At a $q_{k,fi}$ value of 420 MJ/m^2, both the peak temperature and the overall shape of the curve are significantly lower than at 744 and 1000 MJ/m^2. The temperature in this case also returns to the ambient level of 20 $°C$ much sooner when the fuel load is lower. An important distinction is that with a $q_{k,fi}$ of 420 MJ/m^2, the fire is fuel-controlled, whereas at $q_{k,fi}$ values of 744 and 1000 MJ/m^2, the fire becomes ventilation-controlled (if t_{max} is given by $(0.2 * 10^{-3} q_{d,t}/F_v)$, the fire is ventilation controlled). The curves for 744 MJ/m^2 and 1000 MJ/m^2 are nearly identical during the first 20 minutes. The curve corresponding to $q_{k,fi} = 1000\ MJ/m^2$ continues to rise slightly longer and also takes more time to return to the initial temperature of 20 $°C$. The curve with a fire load density of 744 MJ/m^2 reaches a maximum temperature of 915 $°C$ at 22.2 minutes. The curve with a fire load density of 1000 MJ/m^2 reaches a maximum temperature of 960 $°C$ at 29.9 minutes
A shared feature of all these curves, and a key characteristic of the Parametric Fire Curve, is the inclusion of a cooling phase. This distinguishes it from the Standard and External Fire Curves, and more accurately reflects the realistic time–temperature behaviour of a fire in a compartment.

Finally, all the fire curves discussed so far are combined and presented in Figure 3.4 for comparison.

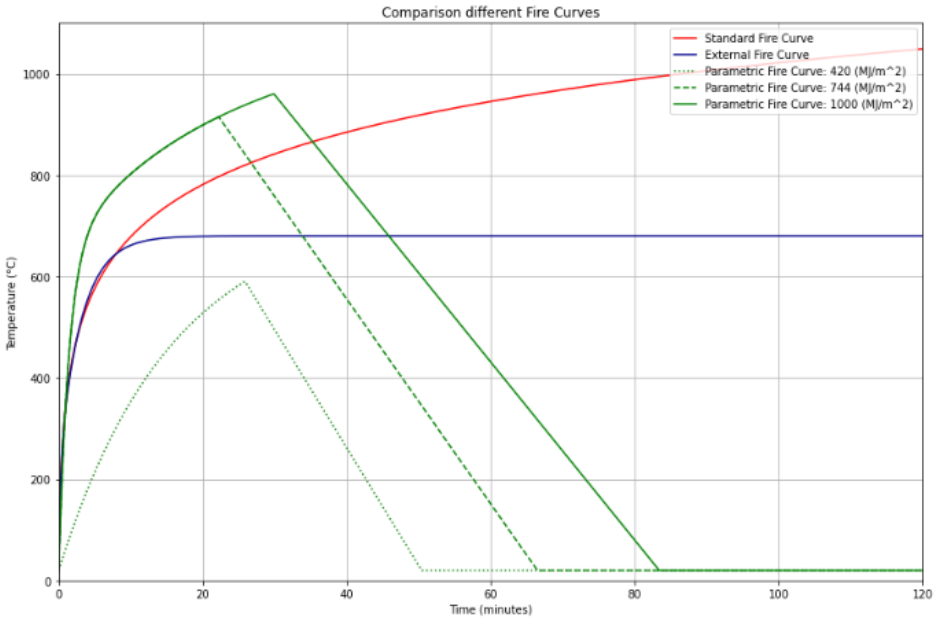


Figure 3.4: Graph of the Standard, External and Parametric fire curves.

3.4. Travelling Fire Curve

A significant challenge in structural fire engineering is representing fire exposure in a way that is both realistic and accessible to practitioners. In recent years, this issue has been addressed through the development of travelling fire methodologies. This concept models fires that ignite locally and spread gradually by "travelling" across large floor plates over time, particularly in large open compartments. With this method we can estimate a more realistic time-temperature curve.

3.4.1. Introduction Extended Travelling Fire Method

There are several representations of travelling fires available in the literature. In this thesis, the Extended Travelling Fire Methodology (ETFM) is adopted as the framework for modelling the fire scenario. The ETFM was developed by mobilizing Hasemi's localized fire model for the near-field fire plume, and combining it with a zone model (ie, the FIRM zone model) to account for the hot smoke layer in the far field (Dai et al., 2020).

This approach allows the ETFM to consider both energy and mass conservation, enabling more realistic fire design in large open compartments. While earlier travelling fire models already accounted for location-specific heating and cooling phases, the ETFM improves upon these methods by also incorporating the effects of the smoke layer and ensuring a consistent energy balance throughout the compartment.

A key characteristic of this fire scenario is the interaction between the near-field flame and the far-field smoke layer, which leads to pre-heating of structural elements before they are exposed to direct flames, a condition that more accurately reflects fire progression in large open-plan buildings.

3.4.2. Model input

To model the travelling fire, several parameters must be defined. These include the compartment dimensions, opening conditions, and fuel load conditions. Each of these parameters is described in detail below.

- Compartment dimensions:
  In this thesis, the travelling fire is examined in only one specific area of the FOA building, namely the space that ultimately collapsed, located in the northwest wing on the seventh floor. In the previously discussed fire curve analyses, a single office within this wing was considered. However, for the Travelling Fire Curve (TFC), the entire portion of the wing that collapsed is treated as an open-plan space (see Figure 3.5). The walls separating the corridor from the offices were constructed from timber frames and plasterboard. It is a reasonable assumption that these walls already failed during the fire. As such, the shaded area shown in the figure can be considered one open compartment for the purposes of the fire modelling. The dimensions of this compartment are also indicated in the figure: the space has a length of 27 meters and a width of 8.1 meters. The columns are positioned along the outer façade of the building, spaced at 5.4-meter intervals (measured center to center). The average height of the red-shaded compartment is 2.7 meters.

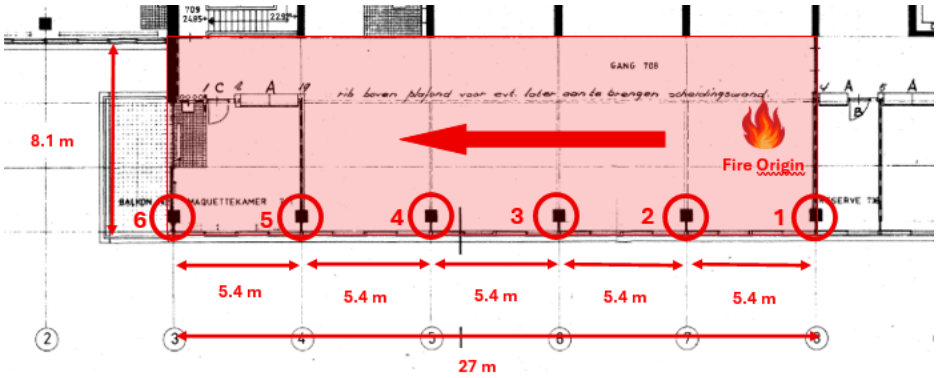


Figure 3.5: Compartment dimensions for Travelling Fire analysis

- **Opening conditions:**
  To model the Travelling Fire, the opening conditions must also be taken into account. These include all vertical openings within the compartment that contribute to ventilation. In this case, the large windows along the exterior façade of the building are considered, as they contribute the most to the total ventilation area of the compartment. The two doors leading to the hallway and staircase contribute minimally to the total opening surface and can therefore be neglected. Additionally, it is possible that these doors were fire-resistant and remained closed during the fire, in which case they would function as part of an enclosed compartment. However, no definitive information is available to confirm this assumption.

  It should be noted that, due to limitations in the ETFM implementation within OpenSees, openings were considered on both sides of the compartment, rather than only along the exterior façade as in the real situation. As a result, the total ventilation area may have been overestimated. However, this assumption is considered acceptable, since it is possible that internal walls had already failed during the fire, effectively opening up both sides of the compartment. Moreover, in both the one-sided and two-sided opening configurations, the fire would remain ventilation-controlled. Therefore, the overall fire development and temperature profiles are not expected to differ significantly.

  Each window along the building façade measured 1.1 meters in width and 1.8 meters in height, and each office contained four windows. As shown in the Figure 3.5, the entire façade featured 20 windows in total, resulting in a combined opening area of $39.6\ m^2$. Because OpenSees does not allow for modelling each window individually, the window openings are simplified into a single continuous opening along the exterior wall of the compartment. To do this, the total window area is divided by the length of the compartment, yielding an equivalent opening height of $\frac{39.6}{27} = 1.47$ meters and a opening length of 27 meters. The height of the window sill was 0.9 meters, meaning that the soffit height is located at $0.9 + 1.47 = 2.37$ meters.

- **Fuel load conditions:**
  For the fuel load conditions, the fire spread rate, fuel load density, and heat release rate per area must be defined. These values are based on assumptions and reference data provided in the Eurocode. A fire spread rate of 6.50 mm/s is assumed, which according to the literature, reasonably reflects real world conditions. This value represents a fast moving fire. For the fuel load density, a value of 744 MJ/m^2 is used. This same value was previously applied in the Parametric Fire Curve and represents the average fuel load density of a densely loaded office, as specified in NEN-EN 1991-1-2 Table E.5. The Heat Release Rate (HRR) per unit area is also taken from the Eurocode (NEN-EN 1991-1-2 Table E.6). For a densely loaded office with a medium fire growth rate, this value is 250 kW/m^2. The initial fire size is thereby 13.2 MW. This is a relatively high value for a compartment fire, but it is still considered realistic given the fire load and layout of the affected area.

Using these parameters, a model can be developed ,using the software package OpenSees (“openSees”, n.d.), to simulate the temperature development within the specified compartment. Since the scenario involves a travelling fire, the temperature varies depending on the location within the compartment. Therefore, six different columns are analyzed. These columns are encircled and numbered in Figure 3.5. Column one is on the right side of the compartment in the corner where the fire starts and column six is located at the far left side corner of the open compartment.

3.4.3. Model output

The results obtained from OpenSees using the parameters described above are shown in Figure 3.6. In this figure, six curves are plotted, each representing the gas temperature evolution around a column within the compartment. The first curve corresponds to the corner column located at the ignition point of the fire. As expected, this column heats up first.

It is noteworthy that both the first and sixth columns reach a lower peak temperature compared to the other columns. This can be explained by their position at the corners of the open compartment as the edge structural elements, where boundary conditions differ from those in the interior.

The curves also clearly show that the further a column is located from the fire origin, the longer it takes to reach its peak temperature. As the fire front approaches, the surrounding gas temperature of each column increases, followed by a cooling phase once the fire has passed. This pre-heating phase, before direct fire exposure, is also clearly visible in the curves, especially good visible for column 5.

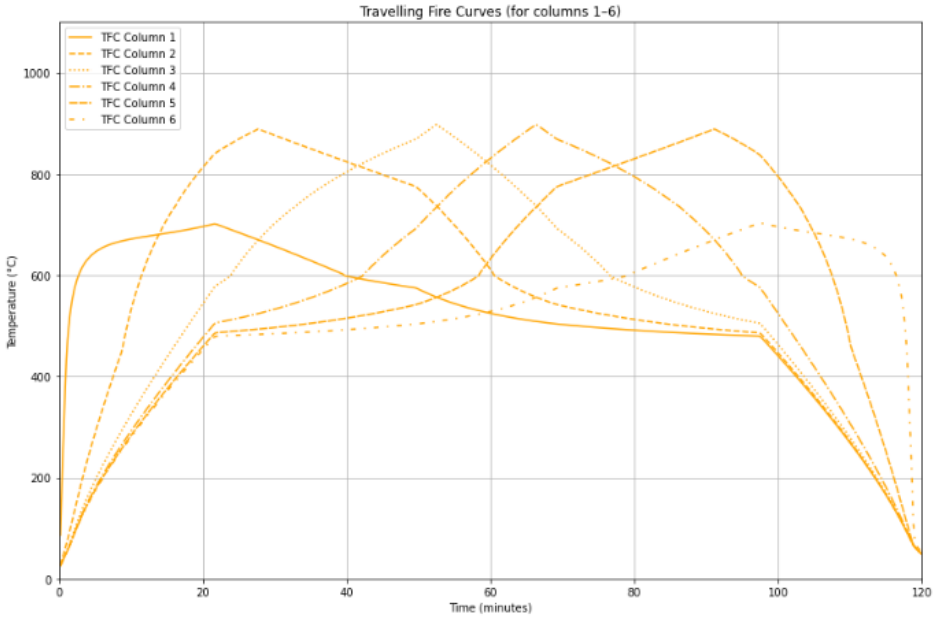


Figure 3.6: Travelling fire curves for the six columns in the compartment. Developed using the ETFM in OpenSees (“openSees”, n.d.)

3.5. Comparison

In this subchapter, all relevant fire curves designed earlier in this chapter are compared in a single figure (refer to Figure 3.7). This figure presents the Standard Fire Curve (SFC), the Parametric Fire Curve (PFC), and the Travelling Fire Curve (TFC).

For the PFC, only the curve corresponding to a fire load density of 744 MJ/m^2 is used. This value was selected because it is assumed to best represent the actual conditions in the FOA building. Additionally, PFCs based on different fire load densities do not differ significantly in shape or peak temperature (refer to Figure 3.4).

For the TFCs, only the curves for columns 2 through 5 are plotted. These columns are not located in the compartment corners and are therefore considered representative, as they reach higher peak temperatures compared to corner columns.

The External Fire Curve (EFC) is not included in this figure, as it reaches significantly lower temperatures than the other curves and is therefore considered less relevant for this comparison (refer to Figure 3.4).

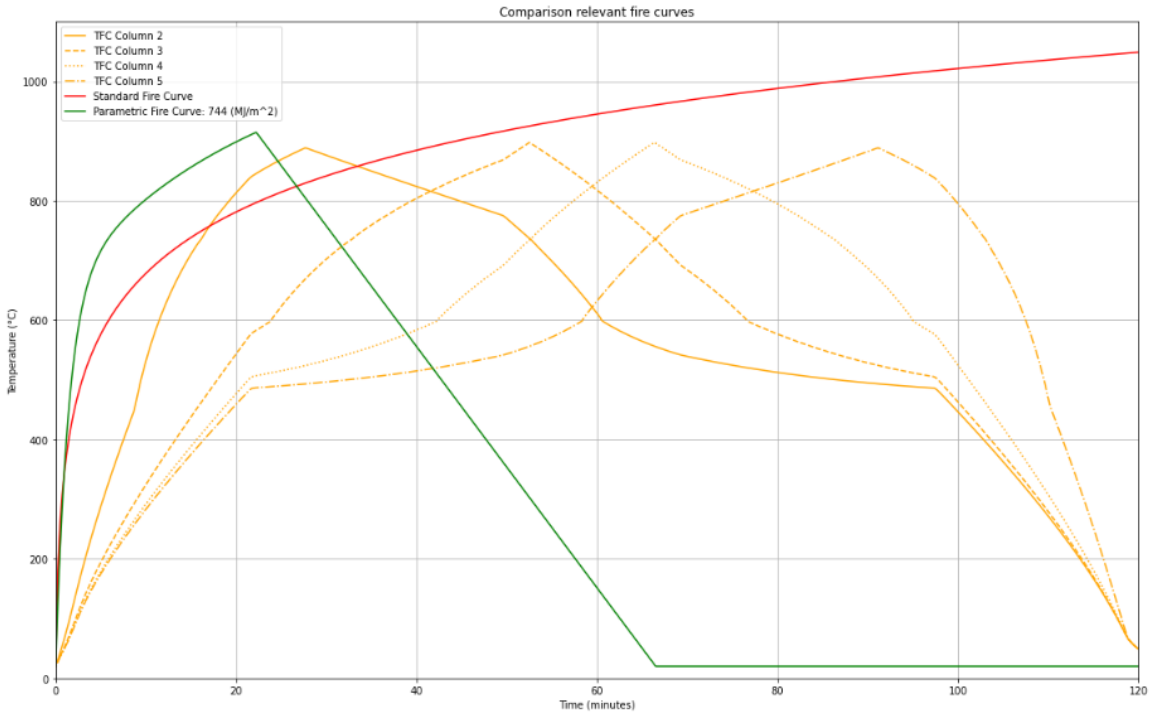


Figure 3.7: Comparison of all the relevant fire curves

Below, key comparisons between the different fire curves are described point by point:

- Initial temperature rise: It is evident that the Parametric Fire Curve (PFC) shows the fastest initial temperature increase. This curve has the steepest slope at the beginning of the graph. The Standard Fire Curve (SFC) shows a similar early trend, but begins to level off after approximately 2 minutes. In contrast, the Travelling Fire Curves (TFCs) exhibit a delayed temperature rise. This is explained by the nature of the Extended Travelling Fire Methodology (ETFM), which assumes that the fire travels across the compartment, causing the temperature at a given location to increase only as the fire front approaches.

- Peak temperatures: The maximum temperatures reached by the different fire curves are relatively similar. The SFC does not have a defined peak, as the temperature continues to rise over time. In this case, it reaches approximately 1050 °C at 120 minutes. The PFC reaches a peak temperature

of 915 °C at 22.2 minutes. The TFCs produces different peak temperatures depending on the location of each column; however, all reach approximately 900 °C, at different times.

- Presence of cooling phase: A notable distinction is that the SFC does not include a cooling phase, the temperature keeps increasing throughout the duration. In contrast, both the PFC and TFC incorporate a cooling phase, which more accurately reflects real fire behaviour in compartments.
- Homogeneous vs. spatial temperature distribution: The TFC is the only method that considers spatial temperature variation within the compartment. It accounts for differences in thermal exposure depending on the location of the column and the position of the fire. The SFC and PFC, on the other hand, assume a uniform temperature throughout the entire compartment. As a result, four different TFCs are plotted, each representing a different column within the space.
- Comparison between PFC and TFC for column 2: An important observation is the strong similarity between the TFC for column 2 and the PFC. This is logically explained by the fact that column 2 is located close to the initial fire source at the start of the simulation (meaning at $t = 0s$ in the graph). It heats up immediately, which causes its temperature curve to closely resemble that of the PFC.
- Progression of temperature in TFCs: As previously mentioned, the TFC does not assume a single homogeneous temperature, but rather models multiple temperature profiles depending on fire spread and spatial location. This results in four distinct temperature curves. The gas temperature around the column closest to the fire origin (column 2) reaches its peak temperature first. After the fire passes, this column begins to cool, and the next column reaches its maximum. The last to be reached by the fire is column 5, which therefore reaches its peak temperature last. A notable characteristic of the TFC is the visible pre-heating phase: even before the fire directly reaches a column, its temperature begins to rise due to exposure to radiative heat (from both smoke and fire). This behaviour is not captured by the SFC or PFC, and represents a key distinguishing feature of the TFC approach.

4

Heat transfer analysis

In this chapter, the heat transfer analysis is carried out for the column previously identified and discussed in this thesis. This concerns the column located on the seventh floor, along the exterior façade of the FOA building's northwest wing (refer to Chapter 2.2.1).

The heat transfer analysis is performed using the computer software SAFIR, a tool used to analyze both the thermal and mechanical response of structures and structural elements exposed to fire. Although the detailed procedures of the program lie outside the scope of this thesis, in essence, SAFIR calculates heat transfer from the fire-exposed environment to the structural element, based on a given time–temperature curve. This enables the simulation of temperature development within a cross-section over time.

The time–temperature curves used in this analysis are those established in the previous chapter. Only the Parametric Fire Curve is considered in this analysis.

In this thesis, a two-dimensional heat transfer analysis is conducted over the cross-section of the column. A three-dimensional analysis, which would account for temperature variation along the height of the column, is not performed. It is assumed that the temperature remains uniform over the full height of the space, which allows for a simplified yet representative analysis inside the scope of this thesis.

4.1. SAFIR

In this thesis, SAFIR 2025 ("SAFIR", n.d.) is used for the thermal analysis. SAFIR 2025 is a finite element computer program capable of performing both heat transfer and structural analyses (including torsion and other effects). However, in this thesis, only a thermal analysis is performed for the critical column.
To carry out a heat transfer analysis in SAFIR 2025, a text-based input file is required. This file contains the geometry and material properties of the column, as well as the applied time–temperature curve. The input file is not generated directly within SAFIR 2025 but is created using a pre-processor called GMSafir. The input for SAFIR 2025, prepared using GMSafir, is described below.

4.2. SAFIR input

In this thesis, the input file was created using the pre-processor GMSafir ("GMSafire", n.d.). Within this interface, the column geometry, material properties, and the time–temperature curve were defined. These properties are described below.

Column:
The column modeled in GMSafir corresponds to the same column discussed earlier in this report (refer to Figure 2.4). This column has dimensions of 500×500 mm and contains 12 longitudinal reinforcement bars with a diameter of 32 mm. In GMSafir, the column was modeled as a square cross-section of 0.5×0.5 m (units are in meters). Both the longitudinal and transverse reinforcement were omitted in

the model, as the difference in thermal properties between steel and concrete has a negligible effect on the overall heat transfer within the column.

The material properties of the concrete used in the column were already described in Subchapter 2.2.1. The specific input values assigned in GMSafir are listed below:

- Specific mass: 2500 kg/m^3
- Moisture content: 34.5 kg/m^3 (standard)
- Convection coefficient (hot side): 25 W/m^{2}K (standard)
- Convection coefficient (cold side): 4 W/m^{2}K (standard)
- Relative emissivity: 0.7

These are the concrete material properties required for performing the thermal analysis in GMSafir.

Time-temperature curve:
The time–temperature curve used in the heat transfer analysis is the Parametric Fire Curve corresponding to a fire load density of 744 MJ/m^2 (refer to Figure 3.3). This curve was selected because it is easier to implement in GMSafir compared to the Travelling Fire Curves (TFCs). Moreover, the PFC shows reasonable agreement with the TFC, particularly for columns located near the fire origin. The PFC was entered into GMSafir using the pre-processor UT Fire. In the GMSafir model, all four sides of the column were exposed to the fire.

Timeline:
Finally, in GMSafir, the total duration of the simulation must be specified. In this case, the analysis was carried out over a period of 2 hours. The first thermal calculation was performed at 60 seconds (usually 10 s is used), followed by time steps of 60 seconds until the full 2 hour duration was reached.

Figure 4.1 shows the representation of the column as modeled in GMSafir. It is clearly visible that the reinforcement has not been included in this analysis. The column is divided into smaller elements, known as the mesh. The mesh defines the accuracy of the thermal analysis: a finer mesh results in a smoother and more detailed temperature distribution, but also increases the computational effort required.

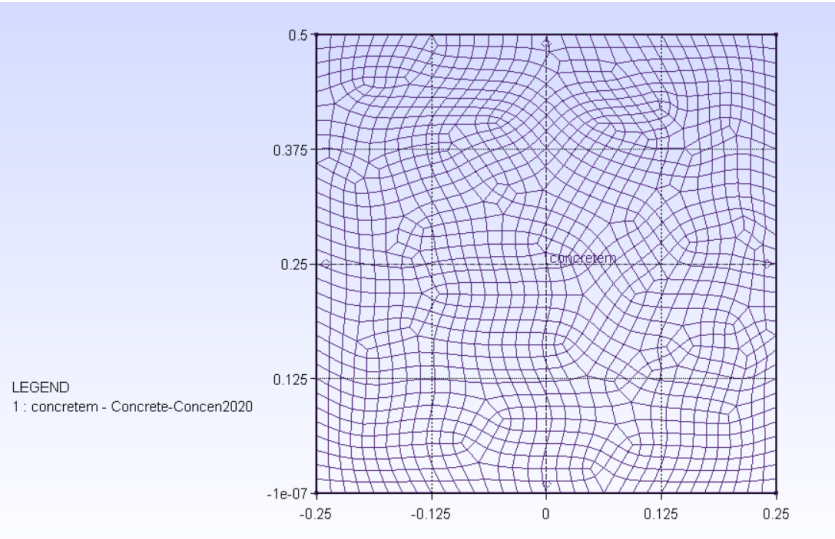


Figure 4.1: Column modeled in GMSafire

4.3. SAFIR results

The output generated by SAFIR consists of three different files: two text documents and one .XML file. The .XML file can be processed using the post-processor DIAMOND (“DIAMOND”, n.d.), which converts the data into a visual representation of the heat transfer within the column. Figure 4.2 shows a visualization of the temperature distribution in the column at a time of $t = 1800$ s. This corresponds to the moment shortly after the peak temperature of the Parametric Fire Curve.

It is notable that the outer surfaces of the column experience a significant temperature increase, while the inner core remains largely unaffected. This indicates that heat penetration into the column is relatively limited during the fire exposure. Additionally, the temperature at the outer edge of the column closely follows the surrounding gas temperature. Although this is not directly visible in the figure, it is confirmed by the numerical output provided in the SAFIR text file.

In Appendix C, the same figure as shown below is presented, but with the longitudinal reinforcement bars included. This visualization illustrates the temperature distribution in the vicinity of the reinforcement. The rebars are mainly located within the green-shaded area, indicating that the temperature around them ranges approximately between 200 °C and 450 °C.

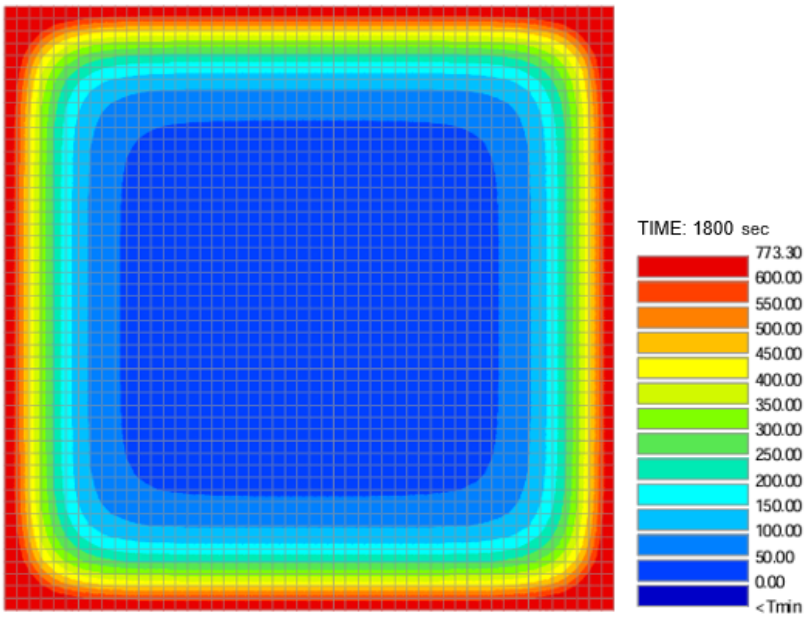


Figure 4.2: Output of the heat transfer analysis at time $t = 1800$ s. visualized with DIAMOND

4.4. Column capacity loss due to heat transfer

The heat transfer analysis presented in this chapter shows that the core of the column remains relatively cool, while the outer layer experiences significant heating. According to Eurocode EN 1992-1-2 (NEN, 2021), concrete begins to lose strength significantly at temperatures above 300 $^{\circ}C$, and its compressive strength is considered negligible beyond 500 $^{\circ}C$.

As shown in the SAFIR output (Figure 4.2), the outer edges of the column reached temperatures exceeding 500 °C. The concrete layer with temperatures above this critical threshold extends approximately 30 mm inward from the surface. This implies that around the entire perimeter of the column, a 30 mm thick shell can no longer be considered structurally effective. As a result, the effective cross-section of the column is reduced from 500 × 500 mm to approximately 470 × 470 mm.

It is also important to note that the longitudinal reinforcement lies within the heated outer zone of the column (see Appendix C). Because steel expands more than concrete when exposed to elevated temperatures, differential thermal expansion can lead to internal stresses within the concrete. This may

result in spalling, a phenomenon in which the heated concrete cover bursts or flakes off. As a consequence, the reinforcement may become exposed and lose its bond with the surrounding concrete core. This further reduces the structural integrity and load-bearing capacity of the column.

In summary, the fire exposure caused a loss of structural capacity in the outer shell of the column, while the inner core retained partial strength. This non-uniform degradation may result in reduced stiffness, uneven stress distribution, and increased susceptibility to buckling. Although the full structural analysis lies outside the scope of this thesis, these results suggest that the column likely experienced a significant reduction in axial load-bearing capacity due to fire exposure.

5

Conclusion

This thesis set out to investigate how key structural elements behave under realistic fire exposure, and how this behaviour contributes to progressive structural collapse when compared to assumptions made in Eurocode-based design.

Based on the case study presented in Chapter 2, it is likely that the columns on the seventh floor of the northwest wing were among the first structural elements to fail and initiated the collapse of that part of the building. Although it cannot be stated with absolute certainty that these columns were solely responsible, they were selected as representative elements for further analysis in this thesis.

In Chapter 3, four fire curves were studied: the Standard Fire Curve (SFC), External Fire Curve (EFC), Parametric Fire Curve (PFC), and Travelling Fire Curve (TFC). Of these, the SFC, EFC, and PFC are prescribed by the Eurocode. The TFC, developed using the Extended Travelling Fire Methodology (ETFM), is considered to represent the realistic fire scenario in the case of the FOA building.

A key finding is that the TFC differs significantly from the SFC and especially the EFC. These conventional curves do not account for realistic spatial and temporal variations in fire exposure. In particular, the EFC significantly underestimates temperatures compared to the TFC and appears unsuitable for assessing fire behaviour in open compartments. The PFC, on the other hand, shows the closest agreement with the TFC, particularly in cases where a structural element is located near the fire source or in a relatively small compartment. However, it still assumes a uniform compartment temperature, which limits its accuracy in large open-plan spaces such as the FOA building.

The TFC accounts for both the movement of the fire and spatial variation in thermal exposure, including a pre-heating phase caused by the fire and smoke layer. This effect, which is not captured in any of the Eurocode-based curves, results in staggered peak temperatures across columns, depending on their location relative to the fire front.

The heat transfer analysis in Chapter 4, conducted using SAFIR2025 with the Parametric Fire Curve as input, showed that the core of the column remained cool, while the outer 30 mm reached temperatures above 500 $^{\circ}C$. This effectively reduced the load-bearing cross-section to 470 × 470 mm. The reinforcement, located 52 mm from the surface, reached up to 450 °C and was within the heated zone. Spalling likely occurred due to thermal stresses and pore pressure build-up in the concrete, which exposed the reinforcement to direct heating. In combination with bond loss, this further compromised the structural capacity of the column.

In conclusion, this study highlights the limitations of Eurocode-based fire curves, particularly the SFC and EFC, in representing realistic fire exposure for large compartments. While the PFC provides a more reliable approximation, it is only accurate under specific conditions. The TFC, as developed through ETFM, captures the full complexity of fire development and offers a more realistic foundation for performance-based fire design. For critical structural elements, especially in large open buildings,

fire safety assessments should increasingly rely on such realistic modelling approaches to avoid underestimating the risks of progressive collapse.

6

Discussion

While this thesis provides valuable insights into the thermal behaviour of structural elements under fire exposure, several assumptions and limitations should be acknowledged, as they may influence the validity and reliability of the results.

Selection of the critical structural element:
A key assumption made in this study concerns the identification of the structural element most likely responsible for initiating the partial collapse of the FOA building. This selection was based on the analysis of photographic and video material, as well as eyewitness reports. However, no official report definitively confirms which structural element failed first or was underdesigned. As such, the column investigated in this thesis is a well-motivated, yet unverified, choice that introduces uncertainty to the foundation of the analysis.

Isolated element analysis:
In reality, the investigated column on the seventh floor is part of a larger structural system that includes beams, slabs, and connections to surrounding elements. In this thesis, the column was studied in isolation, without considering the interaction with the rest of the structural frame. Although this simplification was necessary to keep the analysis manageable, it limits the extent to which the results can be used to describe the behaviour of the entire building during fire exposure. Effects like load redistribution or support from connected parts of the structure were not included, which could influence how accurate the conclusions are about the collapse.

Assumptions in fire curve construction:
The fire curves used in this thesis were developed using both Eurocode-based methods and a travelling fire simulation. While the Standard Fire Curve, External Fire Curve, and Parametric Fire Curve were constructed according to the guidelines in NEN-EN 1991-1-2, several input parameters, especially for the PFC, had to be estimated using tabulated values or assumptions. These estimations were based on characteristics and Eurocode recommendations but are not suited to the exact contents or layout of the FOA building.

The Travelling Fire Curve (TFC), generated using a computational model based on the Extended Travelling Fire Methodology (ETFM), also involved simplifications. For example, the geometry of the compartment was idealised, and uniform material and ventilation conditions were assumed. These modelling choices affect the precision of the fire exposure simulation. Therefore, while the comparison between the PFC and TFC yielded valuable observations, it should be noted that the comparison is not entirely exact due to differences in modelling approaches and input assumptions.

Limitations in the thermal analysis:
The heat transfer analysis was performed using SAFIR2025, with the Parametric Fire Curve (PFC) as the only thermal input. Although it is technically possible to implement the Travelling Fire Curve (TFC) in SAFIR, this was not achieved within the scope of this thesis due to time constraints and the com-

plexity of the modelling process. Ideally, thermal analyses would have been performed using multiple fire curve inputs ,including the TFC and potentially time–temperature curves based on specific column locations, to better reflect the range of thermal exposure scenarios. Additionally, several simplifications were made in the thermal model itself: material properties were assumed based on literature, and the reinforcement was not included, as it was expected to have only a minor effect on the overall temperature distribution within the column.

7

Recommendation for future research

This thesis presents a focused study on the 2008 fire in the Faculty of Architecture (FOA) building at TU Delft and its effect on a single structural element. As fire engineering remains a developing field, real-life incidents such as this one are rare and therefore highly valuable for research. It is important that the available data (photos, videos, and eyewitness reports) continue to be used to gain deeper insight into fire dynamics and the behaviour of structures under fire exposure. Below, several suggestions for future research are proposed:

- Development of more advanced time–temperature curves:
  In this thesis, various fire curves were developed, including a Travelling Fire Curve (TFC) based on the Extended Travelling Fire Methodology (ETFM). For future studies, it would be valuable to explore more advanced or realistic fire curve models. This could be achieved using alternative methodologies or by applying Computational Fluid Dynamics (CFD) simulations. Such approaches can offer improved accuracy in representing fire behaviour and temperature development, potentially leading to more reliable methods for designing fire-resistant structures and structural components.

- Analysis of structural systems instead of isolated elements:
  This thesis focused on a single column, analysed in isolation. However, in real structures such as the FOA building, structural elements are interconnected and influence each other's behaviour. Future research could investigate a system of structural components (e.g. beams, slabs, and columns) under fire exposure. For example, thermal-induced bending of beams may alter the loading on adjacent columns, leading to more critical and complex structural responses. Understanding these system interactions could improve the assessment of collapse mechanisms and enhance fire safety design.

- Structural capacity analysis under fire exposure:
  Another important direction for future research would be to investigate the mechanical performance of structural elements in the FOA building under elevated temperatures. A structural analysis could be conducted to assess how fire exposure affects load-bearing capacity, deformation, and failure modes. Particular attention should also be given to spalling, the explosive breaking away of concrete cover due to thermal stress and moisture, as this phenomenon can expose reinforcement bars and further reduce the structural integrity of elements. This type of study would contribute valuable knowledge to the design of more robust structures capable of withstanding fire-induced conditions.

Such research directions can help close knowledge gaps and improve the future of performance-based fire design.

A

Development of the fire

This appendix contains a detailed description of the fire spread throughout the FOA building. The progression is illustrated using schematic drawings taken from the report: Fire at the Faculty of Architecture TU Delft (Scheffer & van de Werfhorst, 2010). The view of the FOA building is from the west wing. The left side of the image is the north wing.

The timeline begins at the southwest wing around 9:15 a.m., which corresponds to the reported start of the fire according to eyewitness accounts. As shown in the image, the fire is initially confined to the sixth floor and is concentrated around the coffee machine. At this stage, the fire remains under control.

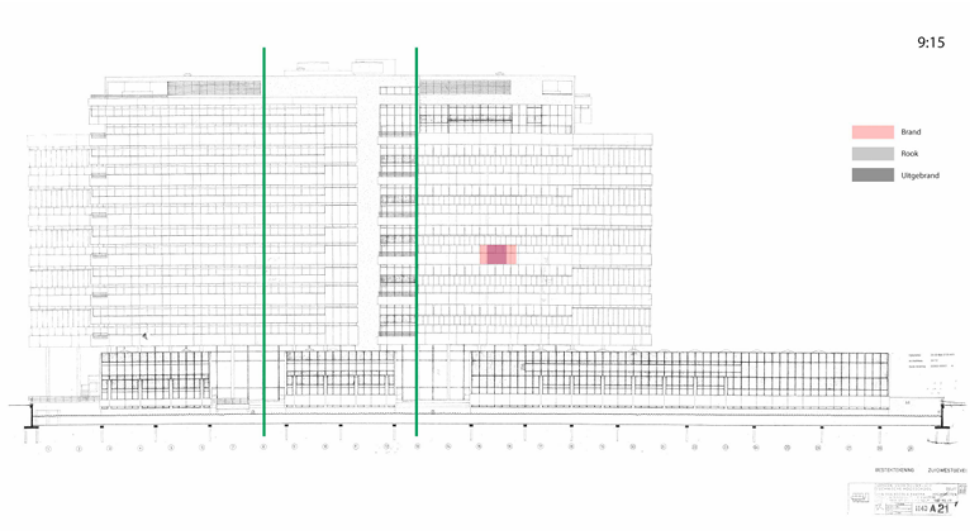


Figure A.1: Fire at 9:15 AM (Scheffer & van de Werfhorst, 2010)

By 9:45 AM, the fire had already spread throughout the entire southern section of the sixth floor. At 9:30 AM, the fire brigade entered the fire compartment but was caught off guard by the rapid development. Due to a malfunctioning fire hose reel, they decided to retreat. At that moment, a flashover occurred, resulting in the entire sixth floor being engulfed in flames. Firefighters observed that smoke was not being contained by the compartment walls. Notably, smoke was visible on the sixth-floor balcony, but even more remarkably, smoke could also be seen emerging from the upper levels of the building.

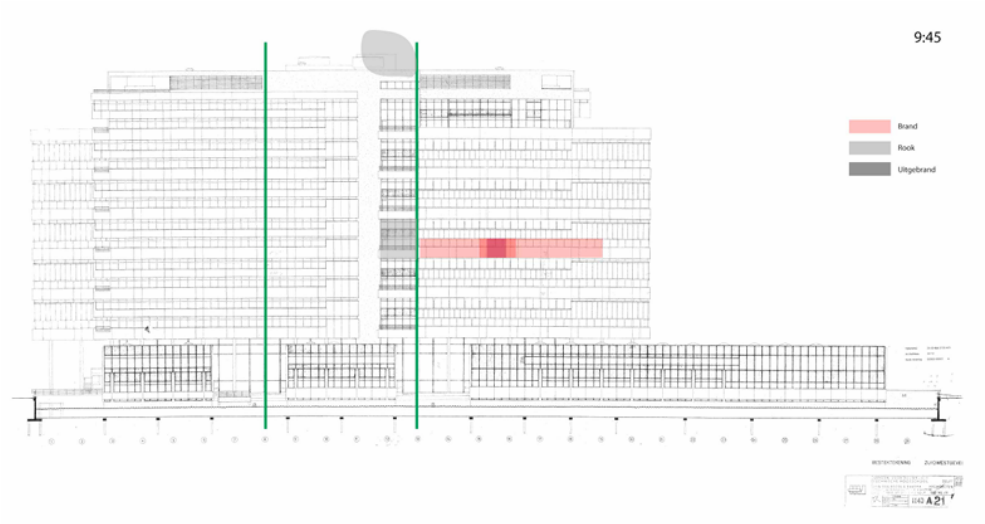


Figure A.2: Fire at 9:45 AM (Scheffer & van de Werfhorst, 2010)

At 10:00 AM, the fire had further spread across the sixth floor. The fire had now advanced within the compartment. It may appear that the fire on the right side of the building had also reached the seventh floor. However, there is no suspended floor at this location; instead, the compartment here spans a height of two stories. Smoke is still visible on the upper side of the building.

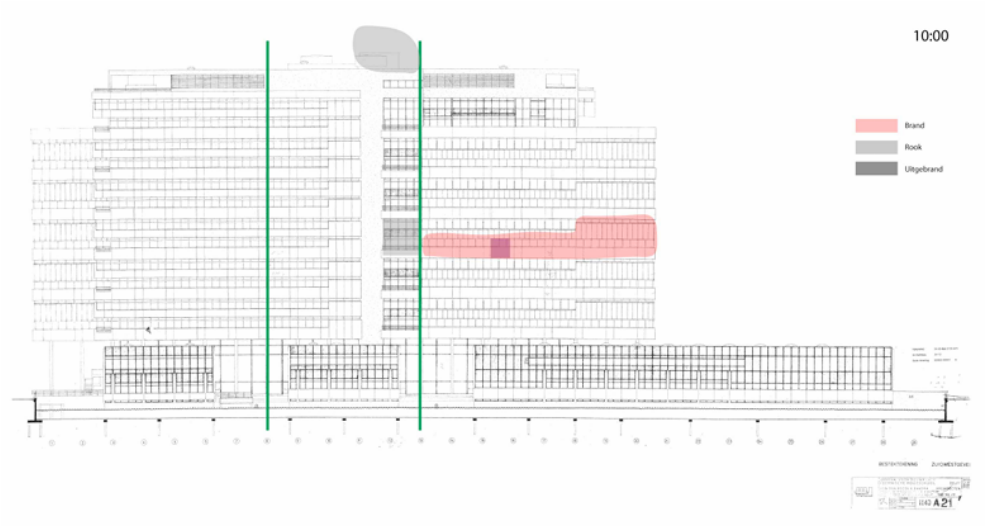


Figure A.3: Fire at 10:00 AM (Scheffer & van de Werfhorst, 2010)

By 10:30 AM, the fire had intensified significantly. The compartments on both the sixth and seventh floors were fully engulfed in flames. The fire had also spread to the compartment above, affecting the eighth and ninth floors, which were now completely involved. Smoke was now visibly emerging from balconies adjacent to the compartments on these two floors.

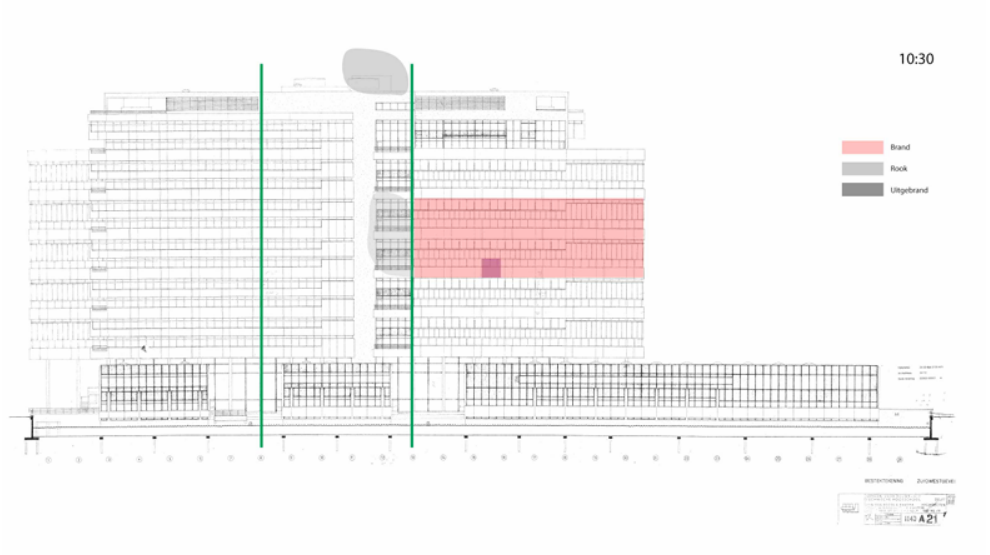


Figure A.4: Fire at 10:30 AM (Scheffer & van de Werfhorst, 2010)

By 11:00 AM, the fire had continued its upward progression, eventually engulfing the tenth and eleventh floors. Additionally, flames had reached the central hall on the sixth floor, where firefighting efforts were actively underway. It was noted that the interior steel beams had become severely distorted, and that the floors on the west side were visibly higher than those on the east side.

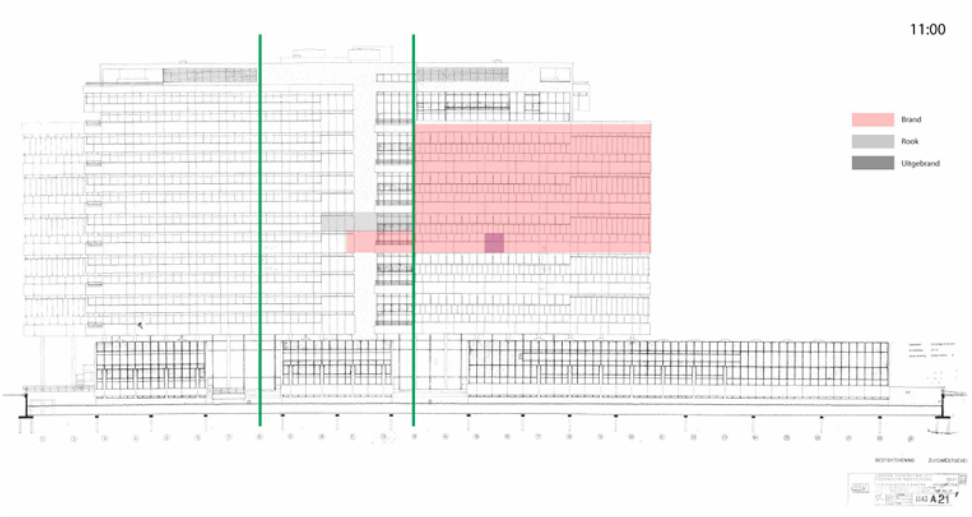


Figure A.5: Fire at 11:00 AM (Scheffer & van de Werfhorst, 2010)

By approximately 11:30 AM, the southern wing was almost entirely burned out. Due to the risk of structural collapse and uneven floor levels, it was decided to evacuate the building. All firefighting personnel were withdrawn.

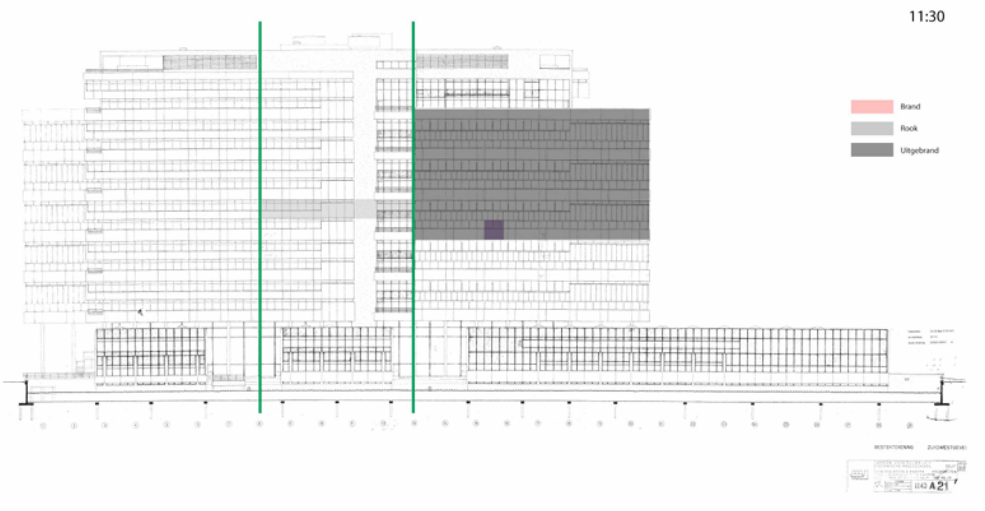


Figure A.6: Fire at 11:30 AM (Scheffer & van de Werfhorst, 2010)

By 2:00 PM, the fire had definitively spread into the adjacent compartment. Active flames were now visible on the seventh and tenth floors. In the compartments immediately surrounding the fire, smoke had also become apparent. By 2:30 PM, the fire on the seventh floor had breached the compartment boundary and extended into the northern compartment. Flames had also reached the eleventh floor above the central hall. Within half an hour, the compartment surrounding the central staircase was almost entirely burned out.

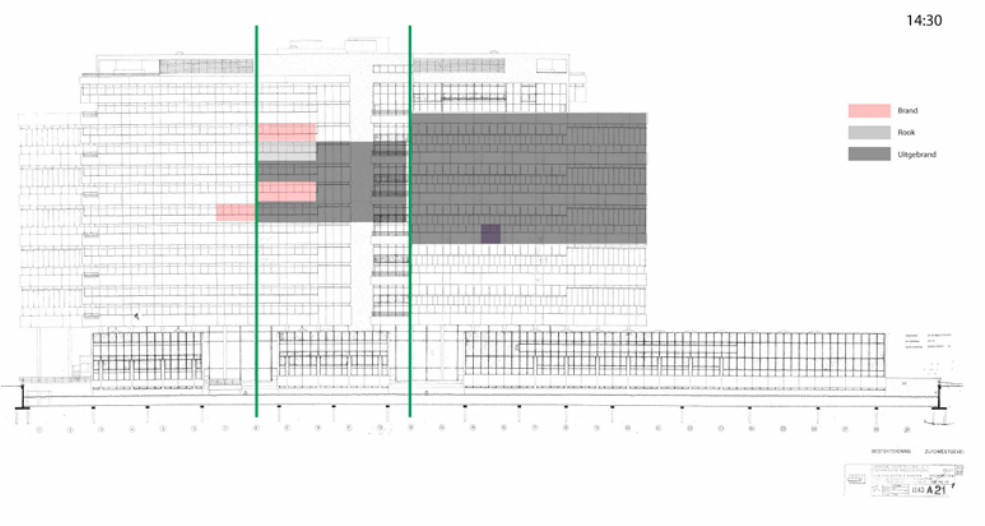


Figure A.7: Fire at 2:30 PM (Scheffer & van de Werfhorst, 2010)

At 3:00 PM, it became clearly visible from the outside that the seventh to eleventh floors in the northern compartment were completely filled with smoke. The fire on the seventh floor had slightly intensified, and a new fire source had emerged on the eleventh floor.

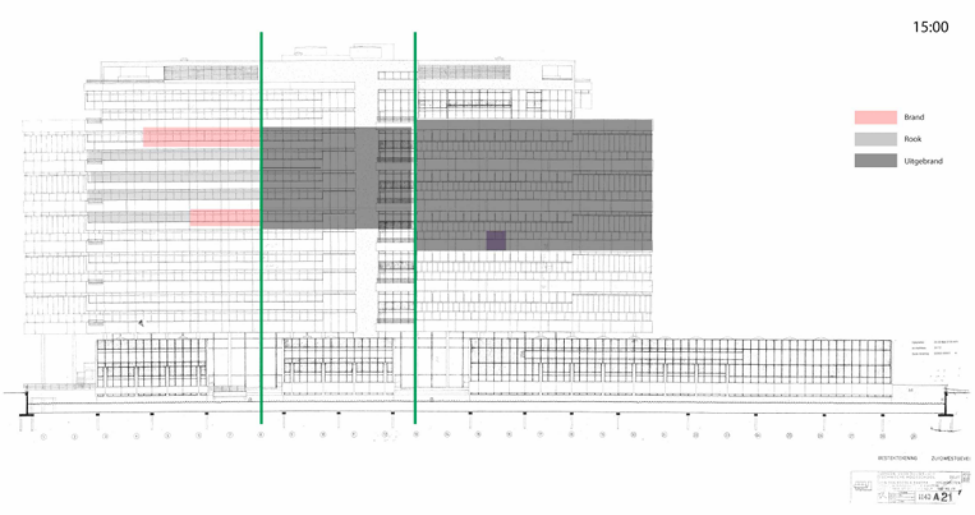


Figure A.8: Fire at 3:00 PM (Scheffer & van de Werfhorst, 2010)

By around 3:30 PM, the fire on the uppermost floors had developed significantly, with those floors now almost entirely engulfed in flames. On the seventh floor, the fire had somewhat subsided, although it was still burning.

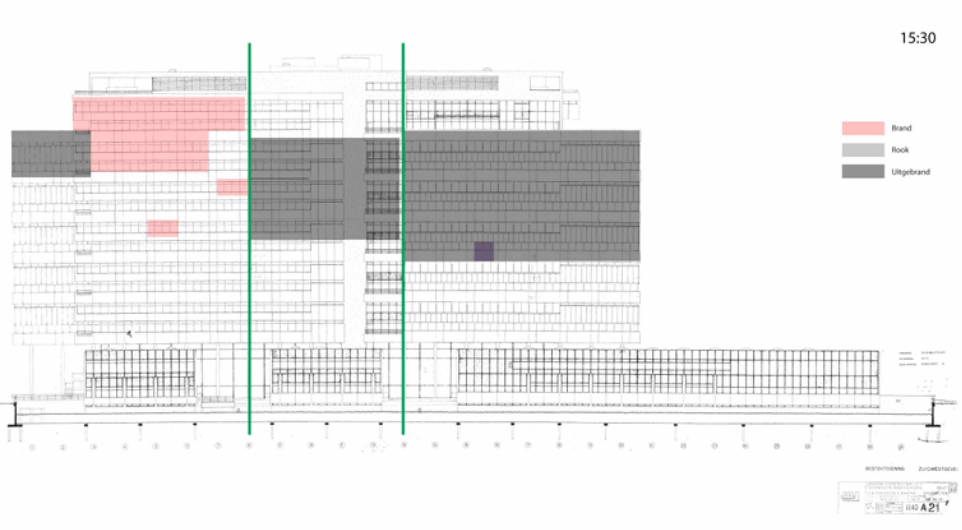


Figure A.9: Fire at 3:30 PM (Scheffer & van de Werfhorst, 2010)

At 4:00 PM, the fire suddenly flared up again (for unknown reason) on the south side of the building. Meanwhile, on the north side, the flames on the upper floors had nearly reached their peak and began spreading downward.

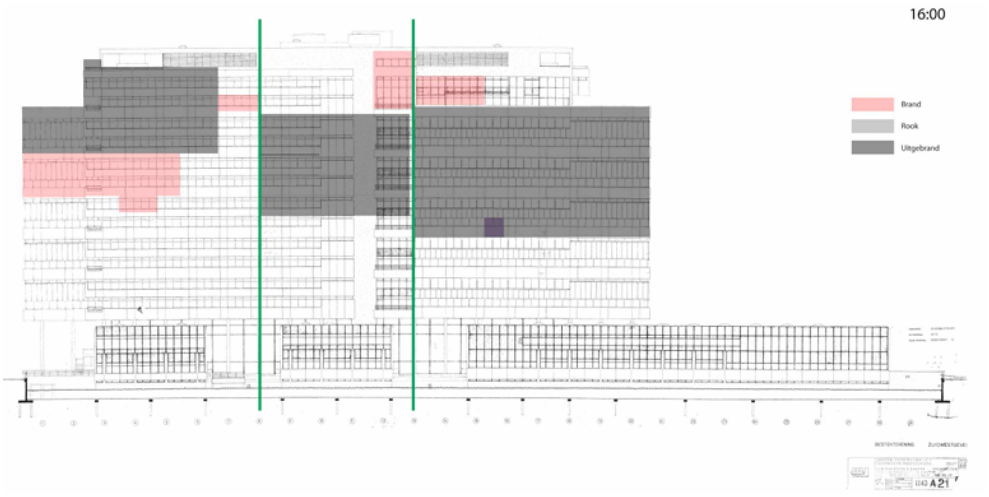


Figure A.10: Fire at 4:00 PM (Scheffer & van de Werfhorst, 2010)

By 4:30 PM, everything above the seventh floor was almost completely burned out. Only a small fire remained active on the seventh floor, which means the seventh floor burnt for a while.

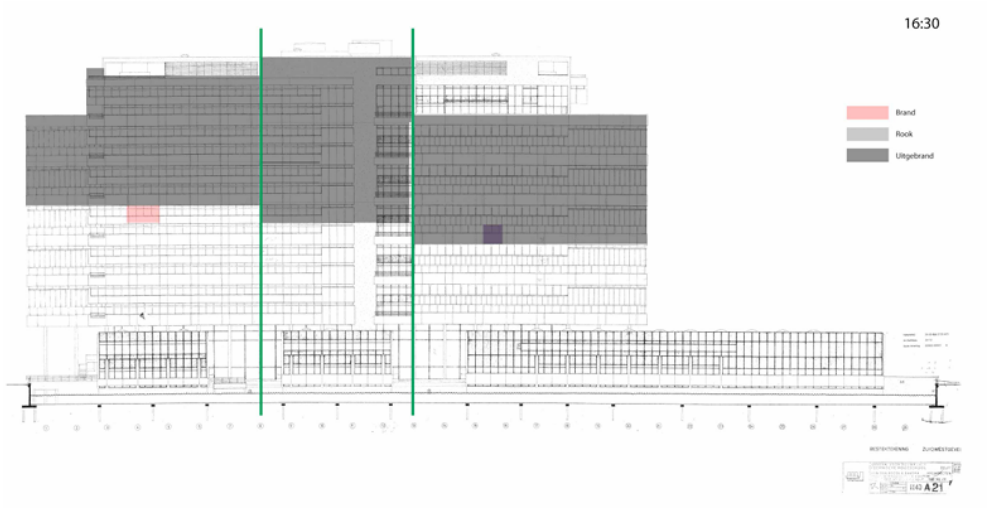


Figure A.11: Fire at 4:30 PM (Scheffer & van de Werfhorst, 2010)

At 4:40 PM, the north wing of the building collapsed. After this, the fire in the building flared up again. Since this development falls outside the scope of our research, it has not been included in the timeline.

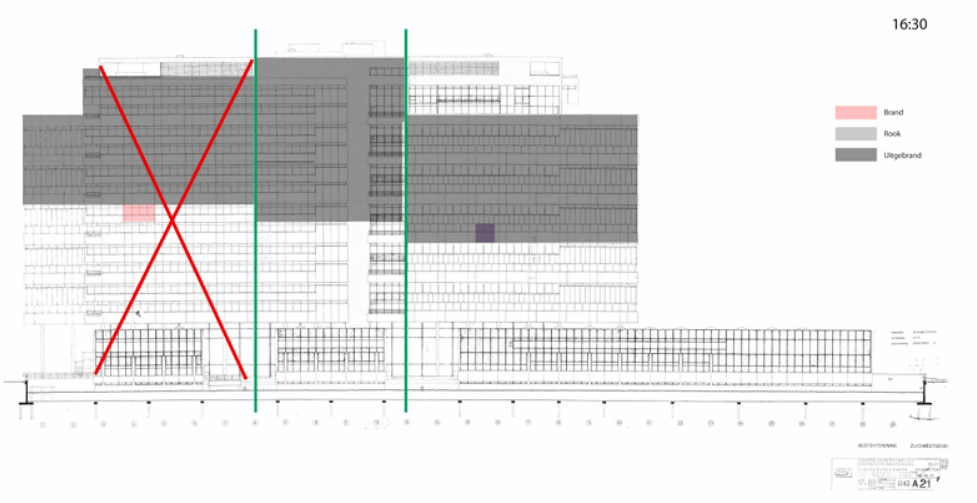


Figure A.12: Fire at 4:40 PM (Scheffer & van de Werfhorst, 2010)

B

Fire load classification of occupancies

(1) The fire load densities should be classified according to occupancy, be related to the floor area, and be used as characteristic fire load densities $q_{k,fi}$ [MJ/m²], as given in Table E.5.

Table E.5 — Fire load densities $q_{k,fi}$ [MJ/m²] for different occupancies

Occupancy	Average	80 % Fractile
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library, Archives	1 500	1824
Densely loaded office (office including minimum 20 % archive's surface)	744	905
Office	420	511
Sparsely loaded office (open space office with limited combustible furniture, paperless office without archives)	206	250
Classroom of a school	285	347
Commercial area	600	730
Theatre (cinema)	300	365
Public space: Circulation areas, walkways	100	122
NOTE Gumbel distribution is assumed.		

(2) The values of the fire load density $q_{k,fi}$ given in Table E.5 are valid in case of a factor δ_{q2} equal to 1,0 (see Table E.1).

(3) The fire loads in Table E.5 are valid for ordinary compartments in connection with the here given occupancies. Special rooms are considered according to E.4.2.

Figure B.1: Fire load densities $q_{k,fi}$ (MJ/m^2) for different occupancies

C

Thermal analysis of column including rebar

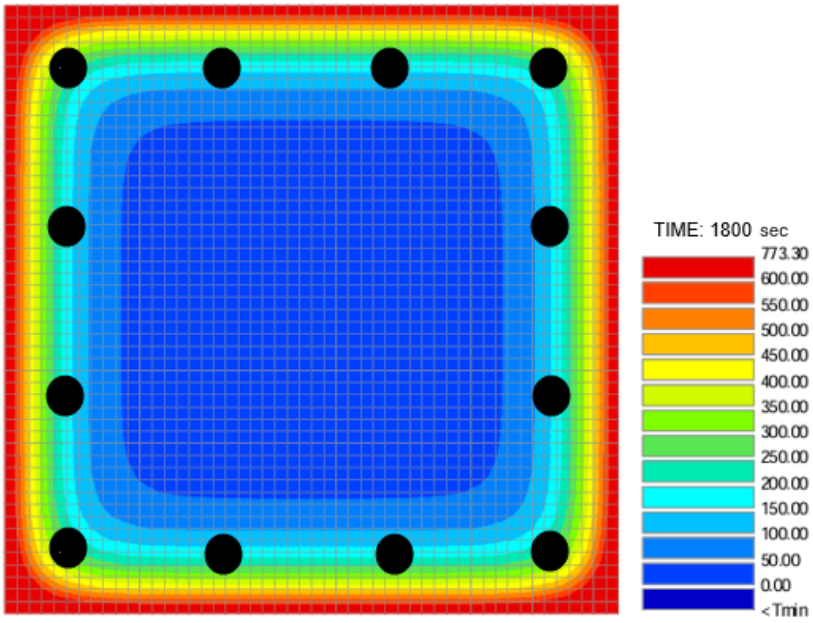


Figure C.1: Output of the heat transfer analysis at time $t = 1800s$ including the longitudinal reinforcement bars

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