

# **Fire and Collapse, Faculty of Architecture Building, Delft University of Technology: Data Collection and Preliminary Analyses**

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## **ABSTRACT**

On the morning of May 13, 2008, a fire that started in a coffee vending machine on the 6<sup>th</sup> floor of the 13-story Faculty of Architecture Building at the Delft University of Technology (TUD), Delft, the Netherlands, quickly developed into an extreme loading event. Although all building occupants evacuated safely, the rapid fire spread severely impacted fire department operations, allowing the fire to burn uncontrolled for several hours, eventually resulting in the structural collapse of a major portion of the building. With the fire continuing to burn after collapse, damage was ultimately significant enough that the building had to be demolished. Collecting and archiving data from this fire is extremely important because structural collapse of high-rise buildings due to fire has historically been quite rare. There are several reasons for this, from the overall infrequency of fire ignition in high-rise buildings, to the combination of structural fire resistance of the frame, fire-rated compartment barriers, automatic fire suppression systems, and fire department suppression activities generally associated with the fire protection strategy for high-rise buildings. This event offers a unique opportunity to study the performance of a code-compliant high-rise building in a major fire wherein the outcome was different than might typically be expected. In order to facilitate analyses of this event, researchers in the United States, under a Small Grant for Exploratory Research (SGER) from the National Science Foundation (NSF award 0840601), teamed up with researchers from TNO and Efectis in the Netherlands, along with Prof. Kees van Weeren of the TUD Faculty of Architecture, to collect data on the fire and collapse. A summary of data collected and outcomes of preliminary analyses are presented.

## **BACKGROUND AND INTRODUCTION**

Fire in high-rise buildings is rare: structural collapse due to fire even more so. When the fire and partial collapse of the Faculty of Architecture Building at TUD occurred, it was recognized that this event provided an opportunity to form a multi-disciplinary, multi-national team to collect data that could be helpful to researchers, engineers and building regulatory officials understand the combination of building and fire characteristics which combined to result in this loss and to develop recommendations aimed at helping to prevent such events in the future. The team was soon formed, consisting largely of the authors, and a plan was developed for collecting and archiving data and information about the building and the event [1].

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## Information and Data Needs

In order to facilitate reconstruction and analysis of a fire event, it is necessary to gather sufficient data and information to (a) develop a time history of the incident, (b) determine the location of fire origin, and (c) establish factors contributing to the fire growth, including successes against the fire and critical failures contributing to its spread [2]. This data subsequently supports failure analysis, which focuses on building performance during the incident, given the building, occupant and fire characteristics. Successful fire reconstruction and analysis therefore requires obtaining pre-fire history and trans-fire information [2,3,4].

Pre-fire data and information establishes the condition of the building, training of the occupants, and emergency response procedures in place prior to the fire event, and includes architectural, structural, mechanical, electrical, plumbing and fire protection features of building as built and at the time of fire, information on the building uses, contents, and facility and emergency management procedures and protocols. Trans-fire events are those events from the point of established burning to extinguishment. Data regarding trans-fire events can be obtained from still photographs and action recordings (digital movies, video, etc) at all stages of the fire, interviews with first responders to determine their response, set up, actions on scene, including fire-fighting and rescue operations, interviews with building occupants, and maps, diagrams, weather data, and other such information helpful to understanding the situation of the day. Collection of these types of data and information are consistent with other major fire investigations, including those with significant structural collapse such as World Trade Center towers 1, 2 and 7 [5,6].

## Data Collection

Over the course of several months, including three team meetings held in the Netherlands, specific data and information needs were identified and agreed, and a significant amount of data and information was gathered. The data and information was collected from a number of sources, including:

- TUD Faculty of Architecture documents, publications, photographs and videos.
- TUD students, faculty and staff.
- Members of the Delft Fire Department and Building Department who were at the fire.
- Reports of investigations carried out by others.
- Photograph and video sharing websites, including general sites such as [www.flickr.com](http://www.flickr.com) and <http://picasa.google.com>, as well as a dedicated site set up at TUD for students and others to post, <http://gallery.tudelft.nl>, and the video posting site [www.youtube.com](http://www.youtube.com).
- Professional photographers and videographers.

The data and information collected was extensive, and included:

- Architectural drawings, including location of fire barriers and fire equipment.
- Complete structural drawings and original structural calculations .
- More than 3000 photographs of the building, pre-, trans- and post fire, with pre-fire photos showing layout, contents of spaces, interior partitions and finishes, trans-fire photographs showing the fire progression, and post-fire photographs showing structural damage.

- From interviews we conducted, eyewitness accounts from: a student who was involved in initial fire extinguishment activity, a Faculty of Architecture staff member who was part of building's emergency response team and who observed the early stages of the fire and activated manual alarm, a facilities management person who was in the building at the time of the fire, four fire service personnel intimately involved in fire extinguishment activity, including first responding fire team, second responding team, and command officers, and members of the inspectional services of the local government, who provided photographs taken during and after the fire, as well as plans and documents associated with the building.
- From interviews we conducted, information from facilities management staff, including descriptions of building construction details, layout, modifications underway, material in vicinity of fire ignition, fire barrier construction, ceiling void arrangement, building systems, and related information specific to the Faculty of Architecture Building.

## **Data Storage**

To archive the data, an internet-based multi-user document storage and retrieval site has been set up using the SharePoint package from Microsoft. The intent of the data archiving is twofold: to provide a central storage area for data to be used by the project team and others in forensic analyses related to the fire and structural response, and to provide a template for a data repository for information about significant fires and collapses world-wide. At present, access to data for analyses by others can be obtained by contacting the authors. In the future, it is envisioned to modify the database such that can be added to as events occur, by those with access to the data, creating a common resource for international research and analyses of such events.

## **Initial Analyses**

Given the large amount of data, it has been possible to undertake some preliminary analyses related to reconstructing the fire event and subsequent structural collapse. This includes piecing together a timeline of the fire from photographs, videos and eyewitness accounts, undertaking a preliminary reconstruction of the first 40 minutes of the fire, estimating fire spread and resulting compartment temperatures, and conducting preliminary structural response to the fire event. The following sections provide an overview of the building, the timeline of the event, the initial fire in the compartment of origin, and preliminary structural response calculations.

## **THE BUILDING**

Completed in 1970, the Faculty of Architecture (FOA) building was a reinforced concrete and steel structure consisting of a combination of six, 3-story structures, which effectively served as a podium, with a 13-story tower located above (see Fig. 1). The 3-story structures included basement, ground floor and 1<sup>st</sup> floor. These structures were characterized by public use space, including an architectural library, an auditorium, exhibition halls, and a cafeteria. The tower served primarily as academic space, featuring lecture halls, offices, and design studios. Floors 2-12 were characterized by a combination of 1- and 2-story interior spaces (see Fig. 2). The 2-story spaces were design studios, characterized by large windows to allow significant natural lighting. Even- and odd-numbered floors were linked in such a way that the studio space carried the floor

designation of the even number (e.g., floors 2 and 3 were linked such that the studio space was designated as floor 2, with the ceiling of that space being the floor 3 ceiling).

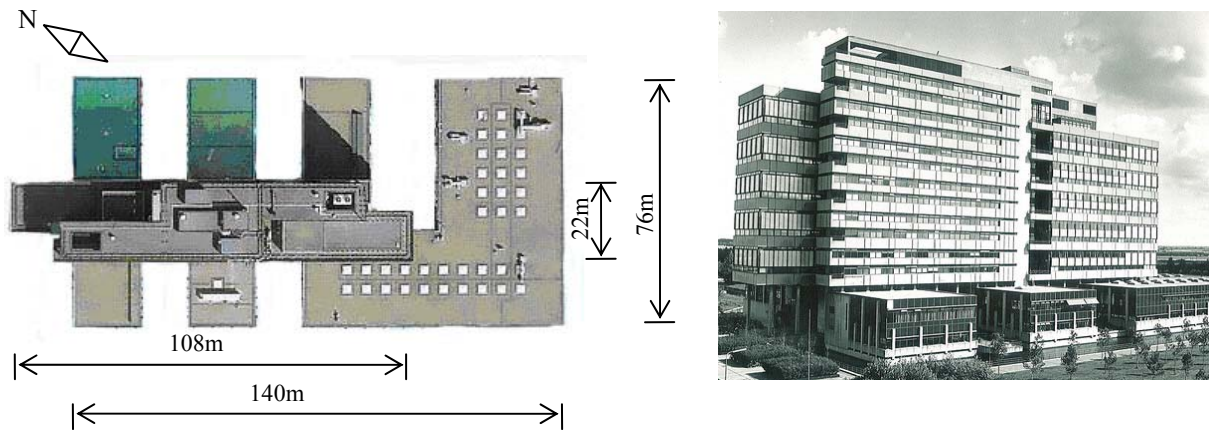


Fig. 1 Satellite top view and bird eye view [7]

Given the nature of the structural design, there was a different floor-slab, joist and beam configuration on even-numbered versus odd-numbered floors. As such, although the ceiling height was nominally 2.7 m for both even and odd floors, spaces above ceilings were approximately 0.3 m and 1m for even floors and odd floors, respectively, excluding approximate slab thickness of 0.15m. This arrangement resulted in 5.85 m ceiling height for the studio spaces.

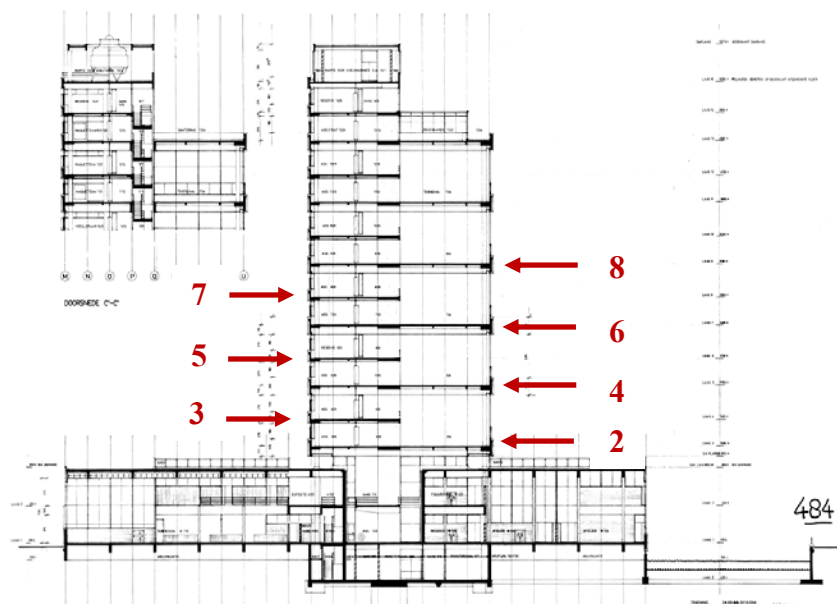


Fig. 2. Faculty of Architecture Building Elevation [8]

The rectangular floor plan of the tower, approximately 108 m long by 22 m wide, could be largely divided into three sections: North, South and Center (or Core). The North and South sections had almost identical floor plans with approximately 5 offices, a glass-enclosed stairwell, and an architectural design studio or lecture hall. The South section also had a glass-enclosed elevator. The North and South sections can be largely divided into two parts: studio area and office area.

Floors 6 and 7 are illustrated in Fig 3, with the studio area represented by the large open space on the 6<sup>th</sup> floor. The outlined space over the studio on the 7<sup>th</sup> floor reflects the mezzanine area offices. The Center section featured the main stairs, elevators, and restrooms, along with some offices, meeting rooms and storage spaces.

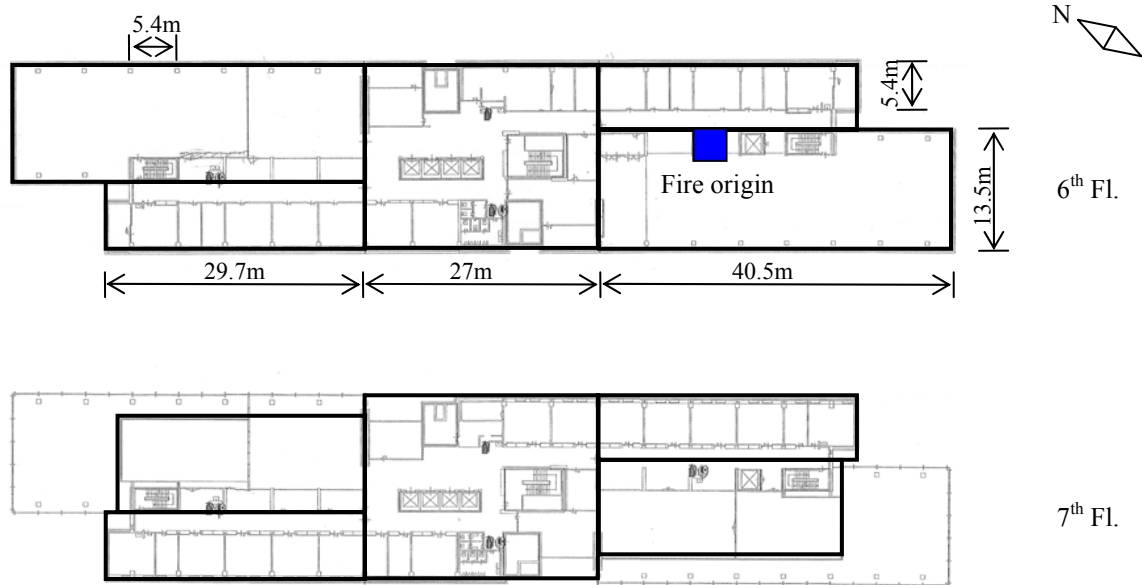


Fig. 3 Floor plans of 6<sup>th</sup> (upper) and 7<sup>th</sup> (lower) floors and their dimensions [8]

As noted above, the North and South sections of even-numbered floors had a larger floor area than did odd-numbered floors. This is a function of the design studios, whose floors were located at even levels, resulting in a mezzanine floor on odd levels, which overlooked the design studios. This is illustrated in Fig. 4. The floor area of the design studios at even floors was approximately 14 m wide and 40 m long, and the space underneath mezzanine or odd floor was largely 14 m wide and 27 m long floor area. The arrangement repeated itself 5 times from floors 2-11 (office areas only on floors 12-13). Note from Fig. 2 that the columns were located slightly inside of the boundary of the exterior walls. This allowed horizontally continuous exterior windows. For the tower section, the height of the exterior window sill was 0.9m and the window heights were 1.8 m for the 1-story ceiling height and 4.95 m for the 2-story ceiling height. In both cases, the top of the exterior windows reached the ceiling of each space. Exterior windows horizontally continued for 40.5 m and 67.5 m for office areas and design studio areas, respectively, which indicates that about 225 m out of 250 m of the tower perimeter was enclosed by windows whose height were either 1.8m or 4.95m. The combination of large open studio spaces and large window openings are of interest with respect to fire spread beyond the compartment of origin (design studio, 6<sup>th</sup> floor, South section) vertically up the South section and horizontally through the Center and to the North, where the collapse occurred.



Fig. 4. Photograph of double-height studio with mezzanine floor, furniture and materials typical of Faculty of Architecture building at time of fire [9].

## EVENT TIMELINE

Using photographs, video and witness statements, a comprehensive timeline was developed. The timeline includes all reported activities starting with a water leak, which was discovered and repaired in the building early in the morning, until the fire was extinguished. The timeline includes data for which times are known or reported, as well as statements for which times are not known but estimated based on collaborating statements and evidence. The excerpt below focuses on the period from just before the fire until initial compartment full involvement. References to sources in the table below include reports (COT [10]), witness statements (Interseco [11] alphabetical references) and photographs.

Time	Report - Time Known/Reported	Source
08:15 - 08:30	People recognize smell from coffee vending machine. Plugs are being pulled out of the sockets on the fifth and sixth floor. The coffee machine is not touched. No visible smoke.	COT, F, G, J
8:55	Smoke coming out of the coffee vending machine. Smoke seems to come out of a gap between the top of the machine and the red pantry unit. The smoke is light-grey.	L
9:00	White smoke coming out of a slot above the coffee vending machine. A BHV-employee gets a call about the fire and is asked to take a look at the sixth floor. A gets a message (pager) concerning something like 'brandcentrale'. Starting fire on the sixth floor.	COT, A, H, K, N, Q
9:10	Smoke coming out of the machine 'in a stripe' (from small slot at top front). J describes as 'filthy black smoke'. "Fire balls" (likely burning cups) observed coming out of machine.	COT, H, J, Q
9:15	H and J are extinguishing a starting fire using a hand-extinguisher. Smell of an 'unpleasant' fire stink. Big flames coming out of the coffee machine. F sends H and J away.	F
9:16	The FD gets call for help from a TU Delft project manager. Fire alarm push button activated.	COT
9:18	The Regional Alarm Centre gets an automatic fire alarm from the Faculty of Architecture.	COT
9:27	The first fire brigade arrives at the building and notices smoke on the outside, but no fire. BHV-workers have evacuated the people in the building.	COT
9:32	The second fire officer reports a 'middelbrand' (medium fire). The first fire officer sends four people with 'flatkratjes' to the sixth floor. The people on the sixth floor are trying to extinguish the fire by using the fire hose, there's almost no pressure, so it's useless.	COT
9:33	The second fire officer reports a 'grote brand' (large fire). The heat is intense and a thick layer of smoke fills the space. Soon flames are starting on the ceiling and they retreat. Just before they want to leave through the door, there is a flashover which puts the whole area on fire.	COT
9:50	Conflagration on 6 & 7 South, both sides (E & W) and extending very quickly via the façade.	COT
11:30	Floors 6-11 on fire (South section)	COT
12:15	All fire fighters now outside of the building. Fire spread into Center section.	COT
12:55	Fire spreads to North section (10 <sup>th</sup> floor)	Photos
13:39	Fire observed on North section, Floors 7-11	Photos
16:40	Part of North section collapses	COT

## INITIAL RECONSTRUCTION OF FIRST MATERIALS BURNING

Based on data and information collected, a model of the compartment of origin, the South section of the 6<sup>th</sup> floor, was created using Fire Dynamics Simulator (FDS), a field fire modeling software developed by the U.S. National Institute of Standards and Technology [12]. Since knowledge of the materials involved in the fire is incomplete, and given a large compartment size, it was deemed reasonable to use the prescribed heat release rate (HRR) approach. In this approach, if the surface temperature of a material reaches its ignition surface temperature, the material burns with a prescribed HRR, which is approximated from fire test data. Glass breakage



is an important factor in this simulation. Based on Manzello et al. [13] it is assumed that once exposed glass surface temperature reaches 400°C glass will break. Dimensions of the space were taken from drawings. Contents were arranged based on photographs of the studio space prior to the fire. A representation of the FDS geometry is provided in Fig. 5 and 6.

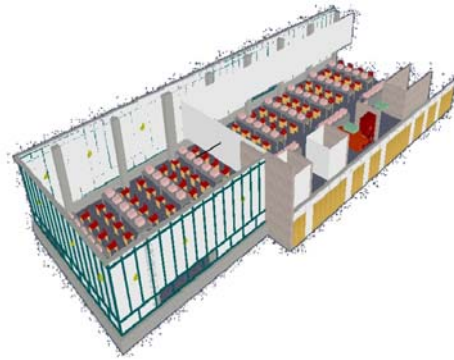
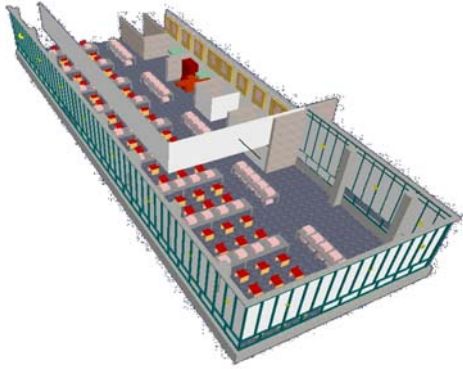


Fig. 5. Geometry showing mezzanine area      Fig. 6. Floor area under mezzanine floor

Building features, materials and material properties were estimated, and HRR curves were developed. Representative material properties and HRR curves are illustrated below.

Table 2. Materials and Properties used in FDS Simulation

Model	Description	Thermal Cond.	Specific heat	Density	Thickness	Ignition Temp.
		W/m-K	kJ/kg-K	Kg/m <sup>3</sup>	m	°C
Coffee Machine Enclosure	5mm thick MDF covered with a polyester material	0.15 [14]	2.8 [14]	640 [14]	0.005	350 [15]
Student study model works	Polystyrene foam	0.03[16]	1.5[16]	20[16]	0.01	350[15]
Tables	10 student work tables, 5 presentation tables, approx. 5.4m(W)*1.2(m)	0.15[14]	2.8 [14]	640 [14]	0.02	350 [15]
Chairs	Polyurethane chair	0.02[16]	1.3[16]	32[16]	0.02	280[16]
Corridor Cabinet	About 8 units in total, 2.1(H)*(1.8~4.5(W))*0.3m(D)	0.15 [14]	2.8 [14]	640 [14]	0.005	350 [15]

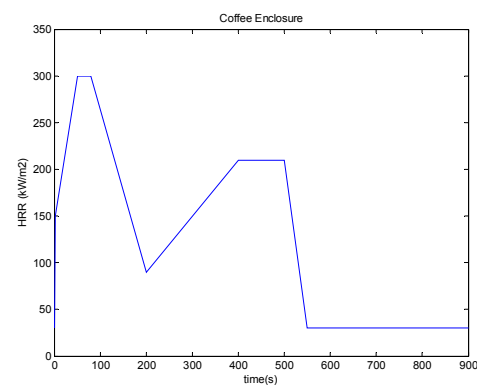
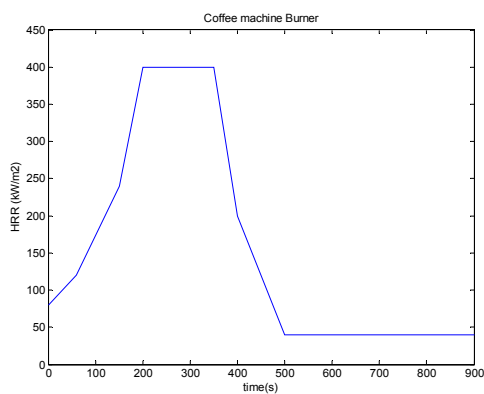


Fig. 7. Coffee Machine Burner HRRPUA [17]      Fig. 8. Coffee Machine Enclosure (wood) [17]

Several simulations were run, and as appropriate, modifications were made to correspond with witness observations. Key assumptions and modifications include:

- To provide initial ventilation, three windows are opened.
- At about 240s (09:34AM) the corridor cabinet is ignited. The ceiling of mezzanine floor is ignited and flame spreads on the ceiling to the studio area.
- At about 300s (09:35AM) the corridor is fully involved. About half of the ceiling under the mezzanine catches on fire. Some student models (polystyrene foam) are ignited.
- At about 360s (09:36AM) fire reaches steady state due to lack of oxygen.
- At about 830s (09:44AM) a window is broken on the east side.

The HRR history of the simulation is shown in Fig. 9. Fig. 10 provides a snapshot of the FDS at 360 s into the simulation. Based on the level of data and information available, it is concluded that it possible to simulate the initial fire conditions with a reasonable degree of confidence.

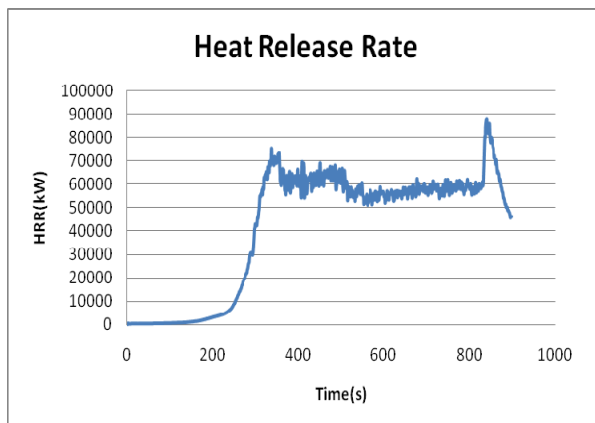


Fig 9. HRR History for Initial Fire

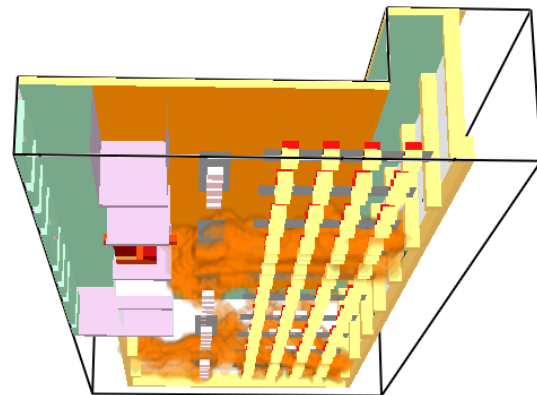


Fig 10. FDS Snapshot at 360 s

## PRELIMINARY ANALYSIS AND OBSERVATIONS OF STRUCTURAL RESPONSE

Collapse of a major reinforced concrete structure in fire, as occurred with this building, is a rare event. Consequently, it is important to understand the factors that led to the collapse, and the implications these factors have on our understanding and practices for assessing the structural fire resistance of reinforced concrete structures. As a first step, it was necessary to obtain a clear description and understanding of the structural system of the building. Fortunately, excellent records were kept from the original design and construction, and a nearly complete set of structural design drawings and calculations were available. Based on the available information, following is a brief description of the structural system for the tower portion of the building.

The FOA Building was a reinforced concrete structure that used mild (non-prestressed) steel reinforcement. The specified cube compressive strength of the concrete was  $300 \text{ kg/cm}^2$ . For the tower, some basic elements of the structural system can be seen in Fig 3. A more detailed drawing of the north portion of a typical floor in the tower is shown in Fig. 11, which was re-drafted from the original design drawings. The layout of structural members at the south end of the floor is essentially identical to the north, reversed in the east-west direction. Square columns ran along the outer perimeter of the tower, spaced at 540 cm in the north-south direction.



The columns were 50cm x 50cm over the full height of the building, with the amount of reinforcement decreasing with height. Within the middle portion of the tower were a series of walls, also spaced at 540 cm in the north-south direction. Girders running in the north-south direction connected the columns. Girders also connected the walls in the north-south direction. Both sets of girders were wide and shallow sections.

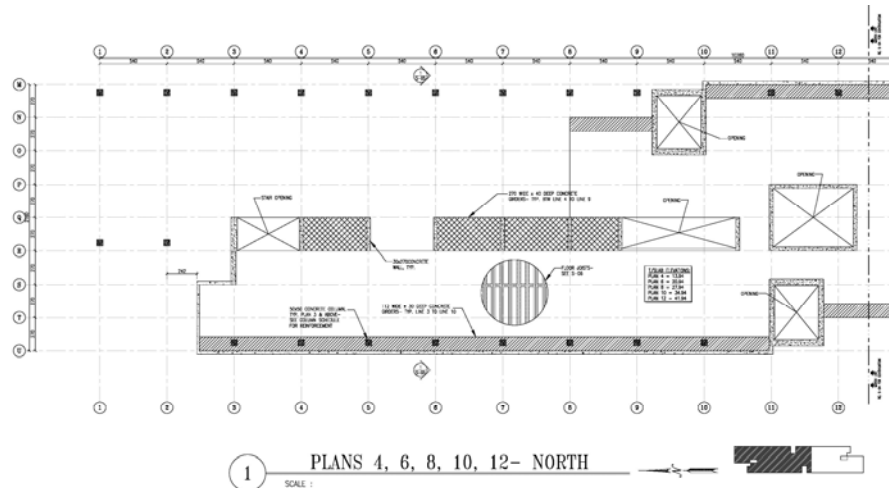


Fig. 11. Structural Elements, Tower, North End, Typical Floor

The floor system consisted of a series of reinforced concrete joists running in the east-west direction between girders. Typical details are shown in Fig. 12. Depending on their location, the joists were either 25 cm or 40 cm in depth. The joist floor system consisted of a series of precast inverted U-shaped sections as shown in Fig. 12. The remaining portions of the floor slab between precast elements were cast-in-place. These cast-in-place portions of the floor were formed with timber. These timber forms were reportedly left in-place after construction was completed, as they were hidden behind a drop ceiling system. One item of particular interest in examining the joist details was the concrete cover, which varied from 15 to 20 mm; somewhat smaller than

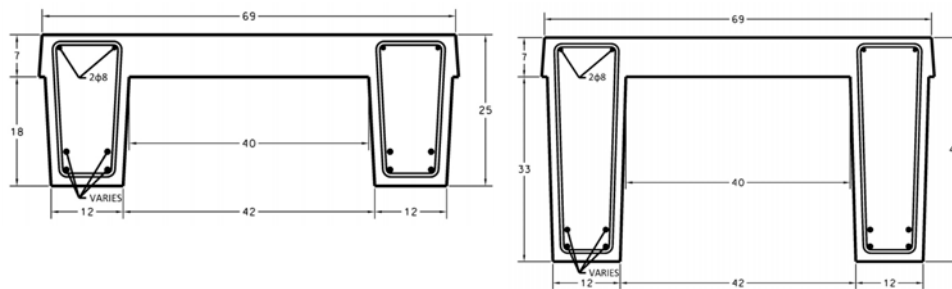


Fig. 12. Typical Floor Joist Details (dimensions in cm)

might be expected based on current code requirements. As described earlier, some portions of the double height floors had mezzanine levels that were hung from the floors above (Fig. 4). These mezzanines were constructed with a structural steel floor system, and were hung from the reinforced concrete joists using steel rods.

In evaluating possible causes of collapse, several contributing factors must be examined. These include the effects of thermally induced forces and deformations of the structural system, the effects of material strength and member capacity degradation at elevated temperature, and the effects of spalling. At this stage of the investigation, several preliminary analyses have been conducted to gain insight into the impact of the fire on the capacity of key structural members. This includes a simplified compartment fire analysis, heat transfer analysis for selected structural members, and cross-section capacity calculations for the heated members.

To estimate temperatures to which the structural members were exposed, simplified compartment fire analyses were conducted for a typical office in the northwest portion of the building. A single-zone approximation was used to characterize post-flashover conditions. A series of analyses were conducted using the computer programs OZone [18] and BRANZFIRE [19]. Published compartment time-temperature curves were also evaluated [20]. Parametric studies were conducted to consider a reasonable range of fire loads, ventilation conditions, and compartment boundary thermal properties. A typical result of such an analysis obtained from OZone is plotted in Fig. 13. Also shown for comparison is the ASTM E119 [21] time-temperature curve. Although the parametric study showed a range of time-temperature curves, the curve plotted in Fig. 13 was representative of the general trends of predicted peak temperatures and duration, and was used for subsequent heat transfer and structural analysis. The predicted peak temperature was on the order of  $950^{\circ}\text{C}$ , and the predicted duration of high temperatures, say greater than about  $300^{\circ}\text{C}$ , was on the order of 30 to 45 minutes. The time frame for which severe burning was observed in any given location on the northwest wing from photo and video evidence seems to suggest these predicted durations are reasonable.

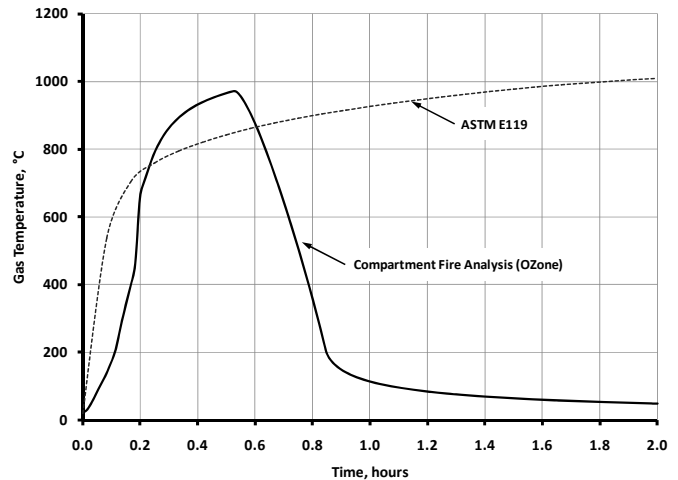


Fig. 13. Typical Result of Compartment Fire Analysis

Results of the compartment fire analysis were then used to conduct two-dimensional heat transfer analyses for selected column, girder and joist cross-sections. The heat transfer analyses provided data on the temperatures throughout the cross-sections as a function of time. The heat transfer analyses were conducted using the computer program SAFIR2007 [22] together with the preprocessor UTFIRE [23]. Thermal material properties were taken from Eurocode 2 [24]. Finally, using the cross-section temperature distributions predicted from the heat transfer analysis, member cross-section flexural and axial capacities were computed as a function of time. Elevated temperature mechanical properties for concrete and reinforcing steel were also based on Eurocode 2. Member cross-section capacities were computed using a computer program that was custom developed for this project.

Representative results of member cross-section capacity analyses are shown in Fig. 14. This figure plots cross-section capacity as a function of time for three cases: joist flexural capacity for positive bending (tension on bottom), joist flexural capacity for negative bending, and column axial capacity. The gas temperature versus time curve that was used for this analysis is the OZone generated curve shown in Fig. 13. Note that the gas temperature-time curve is also plotted in Fig. 14. In Fig. 14, all quantities are normalized to their peak values. Gas temperatures are normalized to the peak gas temperature, which occurs approximately 30 minutes into the analysis. Member cross-section capacities are normalized to the capacities at  $20^{\circ}\text{C}$ . Thus, for example, a normalized capacity of 0.80 indicates that the cross-section retains 80-percent of its capacity at normal temperature.

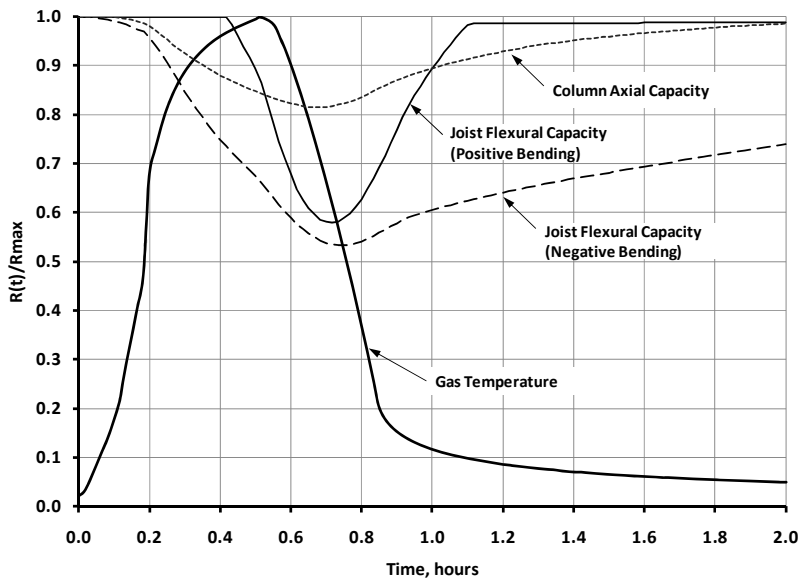


Fig. 14. Normalized Cross-Section Capacities of Joist and Column

the members are at their weakest condition well into the cooling phase of the fire. This plot also shows that the most significant loss of capacity occurs for flexure in the joists. This significant loss of flexural capacity may be the result, in part, to the rather small concrete cover in these members. Note that the loss of axial capacity in the columns is rather small. The columns always retained more than 80-percent of their normal axial capacity throughout the analysis.

The analyses described above are continuing by the investigators. Considerable additional analysis will be needed before potential triggers for the structural collapse can be hypothesized with some reasonable degree of confidence. The member capacity analyses described above all assume that the member cross-section remains intact during the fire. That is, these analyses assume that no significant fire induced spalling has occurred in the reinforced concrete members. The occurrence of such spalling can rapidly and dramatically reduce member capacities, and is also being considered by the investigators as a key cause of the collapse.

Spalling is defined as the breaking-off of chunks of concrete from the surface of a concrete member when exposed to high and rapidly rising temperature. The spalling in concrete is primarily dependant on the rate of temperature rise (fire scenario), permeability (typically related to strength and presence of silica fume) and exposure (relative humidity) and other conditions (geometry, aggregate type). Though spalling is often an issue in higher strength concretes, it can occur in other concrete types under the above specified conditions. Spalling occurs when the pore pressure in a concrete member, generated due to evaporation of moisture, exceeds the tensile strength of concrete. At present, there is very limited information on ways to incorporate spalling into fire resistance calculations. This is mainly due to lack of calculations methodologies and reliable high-temperature material properties for predicting spalling in concrete.

Recently a spalling model has been developed at Michigan State University [25] for evaluating fire-induced spalling in concrete structures. This spalling sub-model has been incorporated into a fire resistance model for evaluating fire response of concrete structures [26]. The spalling

The member capacity plots in Fig. 14 show that as gas temperature increases, member capacity decreases. Similarly, as the gas temperature decreases, the members begin to regain capacity. The analysis predicts that the members reach their minimum capacity about 45 minutes into the analysis. At this point, the gas temperature is well past its peak (which occurs at 30 minutes) and has already cooled substantially. Thus,

analysis utilizes principles of mechanics and thermodynamics, including the conservation of mass of liquid water and water vapor, to compute pore pressure in the concrete resulting from fire exposure. The computed pore pressure is checked against the temperature dependent tensile strength to determine if spalling has occurred. The spalling and fire resistance models have been validated by comparing predictions with test data for temperature, pore pressure, extent of spalling, strength, deflections and fire resistance [25,26].

A review of post-fire photographs of the FOA building indicates loss of cross-sections in certain parts of the buildings. This was postulated to be due to fire induced spalling. As a preliminary analysis, the above MSU model was applied to analyze a typical reinforced concrete (RC) column from the TUD building to predict the extent of spalling and fire resistance. The selected column is of 500 mm square cross-section and of 3 m length. The RC column was assumed to have a reinforcement comprising of 4-32 mm bars. The column was assumed to carry a load of 400 KN (40% of its load carrying capacity at room temperature) at the time of fire incident. The column was made of concrete of cube strength of 300 kg/cm<sup>2</sup> (cylinder strength of 25 MPa) and the reinforcement having a yield strength of 400 MPa. Also, the column is said to have bent ties (135° bent to the concrete core). The compartment fire shown in Fig. 13 was used as the fire scenario in the analysis. Since the permeability of concrete in the column is not known, fire resistance analysis was carried out by assuming three different orders of permeability ( $10^{-17}$ ,  $10^{-18}$ ,  $10^{-19}$ ).

Results from the analysis indicate that when a permeability of  $10^{-17}$  is assumed, no spalling occurs and the RC column survives burn-out condition. When the permeability is changed to  $10^{-18}$  spalling is predicted to start in the 22<sup>nd</sup> minute of fire exposure and stops at about 40 minutes into the fire. At this time most of the cover concrete is lost, but the column in this case also did not fail. About 28.5% of the column cross-section was predicted to have spalled off. The survival of the column can be

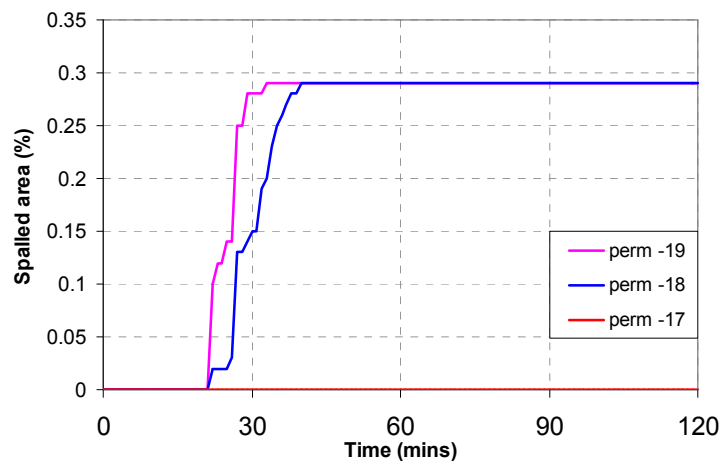


Fig. 15 Progression of spalling

attributed to the fact that by the time the column lost enough mass due to spalling and lost strength due to degradation of material properties, the fire was in the decay phase and the column could regain its strength. This column could be said to have just marginally survived the fire. With a permeability of  $10^{-19}$  spalling starts a bit early at 21 minutes in the fire exposure and stops in 35 minutes. This column fails in 43 minutes into fire exposure. As stated, spalling progressed faster in this column and thus when the cover of concrete was lost the fire temperature were at its peak and thus the column could not sustain the applied load. Figure 15 shows the progression of spalling for the three permeability values. Figure 16 shows the area of cross-section lost in the column at 30 minutes (temperature peak) of exposure and 50 minutes (burnout) of exposure.

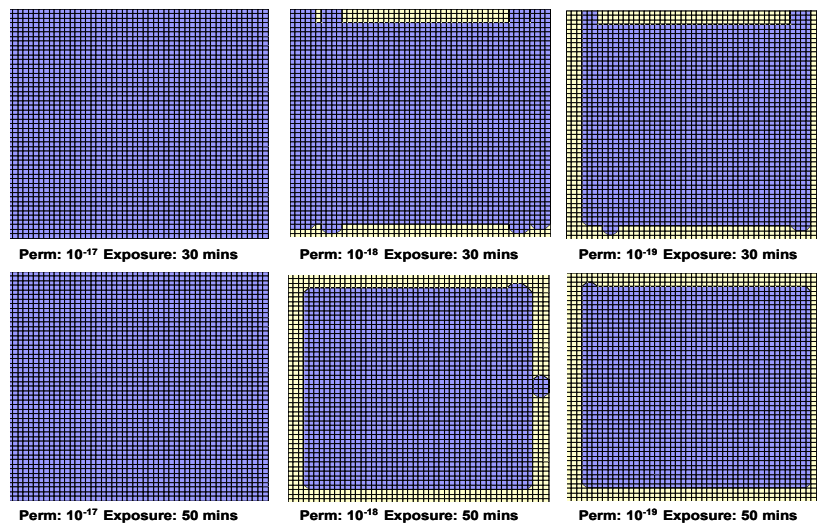


Fig. 16 Loss of cross-section due to fire induced spalling

The above analysis illustrates the possibility of fire induced spalling in RC columns leading to structural collapse. However, it should be noted that fire response modeling of concrete structures, as well as prediction of spalling, is very complex and is highly dependent on the input parameters (high temperature properties, fire temperatures etc). For this a detailed analysis is required and efforts in that direction are currently underway by the authors.

## SUMMARY AND CONCLUSIONS

A large amount of data and information has been collected regarding the fire and partial structural collapse of the Faculty of Architecture Building at the Delft University of Technology. The ability to collect this data was facilitated by an international cooperative effort aimed not only at understanding this event, but at establishing a mechanism for data collection and archiving for future fires of significance. Using the data collected, preliminary analyses of the initial fire situation and of the fire impact on the structure have been undertaken, with the results showing promise for helping to understand the specifics of the fire and building design which led to the collapse. Going forward, attention will be given to fire spread beyond the compartment of origin, including building features that contributed to the spread (e.g., window breakage, barrier performance), development of time-temperature histories, and analysis of the structure under the fire conditions, including assessment of the impact of fire induced spalling of the columns.

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