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Efectis Nederland report

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Investigation of fire in the Lloydstraat car park, Rotterdam

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Contents

1 Introduction

Efectis Nederland BV and the Fire Investigation Team (in formation, in Dutch: Team BrandOnderzoek, or TBO), hereafter FIT of the safety district Rotterdam-Rijnmond (in Dutch: VeiligheidsRegio Rotterdam) have undertaken an investigation into the fire on 1 October 2007 in the parking garage under the residential building “Harbour Edge” on Lloydstraat in Rotterdam.

At 04.16 in the morning the occupants of the residential building Harbour Edge on Lloydstraat reported a fire in the car park under the building. On arrival of the fire brigade flaming was visible out of the façade. Initially the fire brigade focused on the safety of the residents that were still in the building.
During the fire five cars were completely burnt out, one car was 75% burnt and one car underwent charring and melting.

The building structure was severely damaged by the heat of the fire. During and after the fire parts of the floor collapsed. The magnitude and the consequences of the fire were such that the safety district Rotterdam-Rijnmond instigated an investigation into the fire. The investigation was carried out by a research team consisting of Efectis Nederland BV, the FIT, the forensic department of the Rotterdam-Rijnmond police, and on behalf of the insurers, Gorissen & van der Zande Schadeonderzoek (Damage Investigation).

The investigation addressed the following subjects:

- Design of the car park
- Design of the structure
- Course of the fire
- Behaviour of the building during the fire
- Behaviour of the building after the fire
- Preventative and preparative provisions in the building in relation to the mitigating actions of the fire brigade

All of the chapters of this report, with the exception of Section 6.4, have been written by Efectis Nederland BV, under the supervision of the research team. The FIT also under the supervision of the research team, has written Section 6.4 (Preventative and preparative measures) and the accompanying conclusions and recommendations.
As a result of the damage due to the fire TNO Building and Underground carried out numerical studies in order to explain the observed damage to the concrete hollow core slabs. The results of this study are reported separately in TNO report 2007-D-R1236/C –*“Investigation into the structural behaviour during fire of a floor consisting of hollow core slabs as used in Lloydstraat in Rotterdam” (in Dutch).*

2 Design of the car park

2.1 Introduction

The car park consists of seven (half) levels that are positioned with a height difference of ±1.5m to the left and to the right of the heart of the building. The floor area of the car park is ±2100m^2. The car park can easily accommodate sixty vehicles. In this chapter the following questions are answered:

- Which regulations are applicable?
- Which requirements are laid down for the materials and structures?
- What is the expected fire load / rate of heat release according to the regulations and documentation?
- Are the regulations for car parks in agreement with practice?
- Can a car park that fulfils the criteria for an “open space” be evaluated as an open space with regard to the technical aspects of the fire and the accessibility of the fire brigade?
- When and in which type of construction is pre-stressed concrete generally used?
- What is the fire resistance of hollow core slabs?

2.2 Regulations and guidelines for car parks

A car park must fulfil the requirements that are laid out in the Building Regulations for the category ‘other uses’. (In this case the other use is the storage of vehicles). The car park on Lloydstraat is located under a residential building. Due to this it is also necessary to take into account the requirements for residential use when assessing the car park.

The table below summarizes the most relevant requirements of the Building Regulations for car parks and residential use.

Table 1 Summary Building Regulations

	Car park	Residential building
Fire resistance of structure	60 minutes	120 minutes
Floor area fire compartment	1000m^2	1000m^2 + sub fire compartment
Walking distance in the space	40m (B5)	N/a
Walking distance in smoke	60m (B5)	N/a
Presence fire brigade lift	N/a	Floor >20m
Presence dry mains	Floor >20m	Floor >20m
Presence hose reels	N/a	Residential use >500m2
Reaction to fire classification for materials used in fire and smoke free escape routes	Class 2	Class 2
Reaction to fire classification for materials used in smoke free escape routes	Class 4	Class 2
Reaction to fire classification for materials used in other locations	Class 4	Class 4

Relevant requirements for car parks and residential use.

The design of the car park on Lloydstraat fulfils the requirements with respect to safe evacuation. Since the fire compartment of the car park has a usable floor area of ±2100m^2 it does not fulfil the Building Regulations' performance requirements. Based on Article 2.201 of the Building Regulations it is possible, on the basis of an equivalent level of safety, to deviate from the laid down performance requirements relating to the size of the compartment. The requirement that the size of the compartment is limited has the following as its objectives: to control of the fire once it has started, and to prevent people outside the fire compartment from being placed into danger by the fire. It is expected that the fire brigade starts extinguishing the fire within 30 minutes from ignition, after which the fire brigade has a further 30 minutes in which to get the fire under control within the boundaries of the fire compartment.
When setting out a solution on the basis of an equivalent level of safety it is also essential to limit the size of the fire.

For many car parks, in order to determine an equivalent level of safety, the possibility of applying the concept of "open space" is considered. By considering a compartment as an open space (based on Article 2.169 and 2.189 of the Building Regulations) it is assumed that rescue and extinguishing activities can be undertaken during a longer time period. Together with the generally accepted idea that no more that four cars will burn simultaneously in a car park, this forms a basis for allowing an increase in the floor area of the fire compartment.

On the basis of NEN 2443 the conditions for an open car park are:
1 Natural ventilation must be sufficient (according to NEN 1087).
2 At least two walls that stand opposite to each other must be outside walls that are provided with non-lockable openings.
3 The opening in the outside walls must be a minimum of a third of the total wall area of the walls that form the compartment boundaries. (Inside and outside walls calculated together). Or, the openings in the outside walls must be a minimum of 2.5% of the gross floor area of the compartment. These two outside walls must not be separated by more than 54m.
4 The walls with the openings must have a minimum of 5m free space with respect to neighbouring buildings.
5 No part of the lowest floor of the car park can be more than 1.3m below ground level.
6 Walls in the car park can not present any hindrance to the natural ventilation.

The car park on Lloydstraat fulfils the basis conditions for a naturally ventilated car park. The car park also fulfils the requirements of the Building Regulations with the exception of the compartment size.

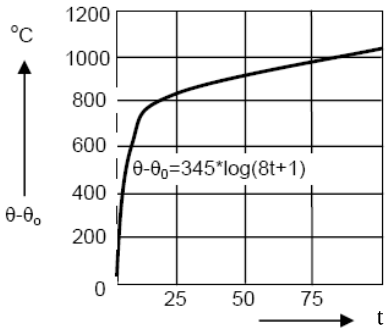
In the "Method for Controlling Fire 2007" (in Dutch: Beheersbaarheid van Brand) a design method for large fire compartments is described that is applicable to car parks. It should be noted that only "Measures 4" (sprinkler) is applicable. During the design of the building on Lloydstraat this document was not yet available. For application of this method a total heat release of 5020 MJ is assumed.

For designing mechanically ventilated car parks use is made of NEN 2443 and the NVBR's draft practical guidelines "Equivalence fire safety requirements of the Building Regulations for mechanically ventilated car parks with a user floor area greater than 1000m^2" (in Dutch).

Also for the design of enclosed car parks the following practical guidelines exist: “Mechanically ventilated car parks with a user floor area greater than 1000m^2” (in Dutch) published on 15 March 2005 by the regional fire brigade Rotterdam-Rijnmond; “Fire safety in car parks” (in Dutch) by the Regional Commission Building and Infrastructure of the district Haaglanden from July 2007; and the publication “Car parks: Fire safety and ventilation” (in Dutch) from SBR.
These guidelines are not applicable to the car park on Lloydstraat.

2.3 Expected fire load and rate of heat release

The (building) regulations do not apply a specific rate of heat release. In the norms (to which the Building Regulations refer) to which the materials and structures must conform, the standard fire curve according to ISO834 is used.



θ = average temperature in deg Celsius
θ_0 = initial temperature (20 deg Celsius)
t = time in minutes

Figure 1: Standard fire curve

The guidelines that are used for the design of mechanically ventilated car parks assume the simultaneous burning of a maximum of four cars, in which fire spread from the first to the second car occurs within 15 minutes. This starting point is taken as a result of tests that were performed in 1998 in a car park in Amsterdam[1]. In the guidelines employed in the Netherlands there is no mention of the fire load and / or rate of heat release in car parks.

Between 1998 and 2001 TNO Centre for Fire Safety (Efectis Nederland), CTICM (Efectis France) and ARBED RECHERCHES (Luxemburg)[2] carried out a European wide investigation on car fires in car parks. During this research various measurements were taken of the heat release rates of different makes and types of car.

For this study different types of cars were separated into the categories given in Table 2.
Table 2

Category 1 6000MJ	Category 2 7500MJ	Category 3 9500MJ	Category 4 12000MJ	Category 5 12000MJ
Opel Corsa Renault Twingo	Ford Escort Opel Astra	Renault Laguna Ford Mondeo	Fiat Croma Ford Scorpio	Peugeot 806 Renault Espace

Categories of vehicle with examples.

[1] *TNO CVB, Leander Noordijk, Tony Lemaire,2005, Modelling of fire spread in car parks.*
[2] *CTICM, ARBED Recherches, TNO, Juli 1998, Demonstration of real fire tests in car parks and high buildings. Daniel Joyeux, Augustus 1997, Natural Fires in closed car parks.*

What is striking from this table is that the total heat release from the lowest category is higher than the value used in the Netherlands (5020MJ), even when the efficiency factor of 0.7 that is referred to in the study is taken into account.

The rate of heat release curve resulting from the tests for one Category 3 car is shown in Figure 2.

In 2001 CTICM was commissioned by the fire brigade of Paris to undertake an inventory of fires in underground car parks in some of the large cities of Europe[3]. According to the statistics, as reported in March 2001, ±97% of the fires in underground car parks were restricted to a maximum of four cars. In car parks located above the ground no cases were recorded where more than three cars were involved. Two fires were recorded in underground car parks where seven cars became involved in the fire.

Statistical research on fires in car parks has also been undertaken in New Zealand[4]. From this research it appears that 93 of 96 fires (97%) occurring in the period from 1995 to and including 2003 remained restricted to one car. An important comment arising from this research is that the cars that were on fire in New Zealand were on average older (14.5 years) than the cars in Europe (8 years). The age of the involved cars can play a significant role in the development of the fire because new cars contain more plastic components and therefore provide a larger heat release rate.

In the Netherlands no statistical research has been undertaken on the size of car park fires. In recent years however various large fires have occurred in car parks. Here follows a short summary:

- Heerlen, 10 cars damaged, danger of collapse.
- Eindhoven, 1 mobility scooter burned, smoke spread in residential building, 80 residents evacuated.
- Hilversum, 2 cars, structural damage, residents evacuated.
- Hilversum, 2 cars and a motorbike, smoke spread in residential building, 60 residents evacuated (over a period of two weeks).
- Leidschendam Voorburg, minibus, 21 occupants evacuated.
- Enschede, 2 cars damaged, minor damage to construction.
- Den Haag, 1 car, residential building evacuated.
- Geleen, Nolenshof, 11 cars burned out, 25 occupants evacuated, severe damage to construction.
- Rotterdam, Lloydstraat 7 cars damaged, 60 residents evacuated.

From the list above it appears that relatively small fires can have serious consequences. It also appears from this summary that more than four cars can be involved in fires in car parks.

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[3] *Daniel Joyeux, CTICM, March 2001, Statistics in Car Parks.*
[4] *Yuguang Li, Michael Spearpoint, 2007, Analysis of vehicle statistics in New Zealand parking buildings.*

Rate of heat release several cars
From the curve in Figure 2 it is possible to see how the rate of heat release develops for two or more cars standing next to each other. The development of fire for three cars is shown in the curve of Figure 3. Based on this curve it is possible to deduce the time taken for the fire to develop for several cars.

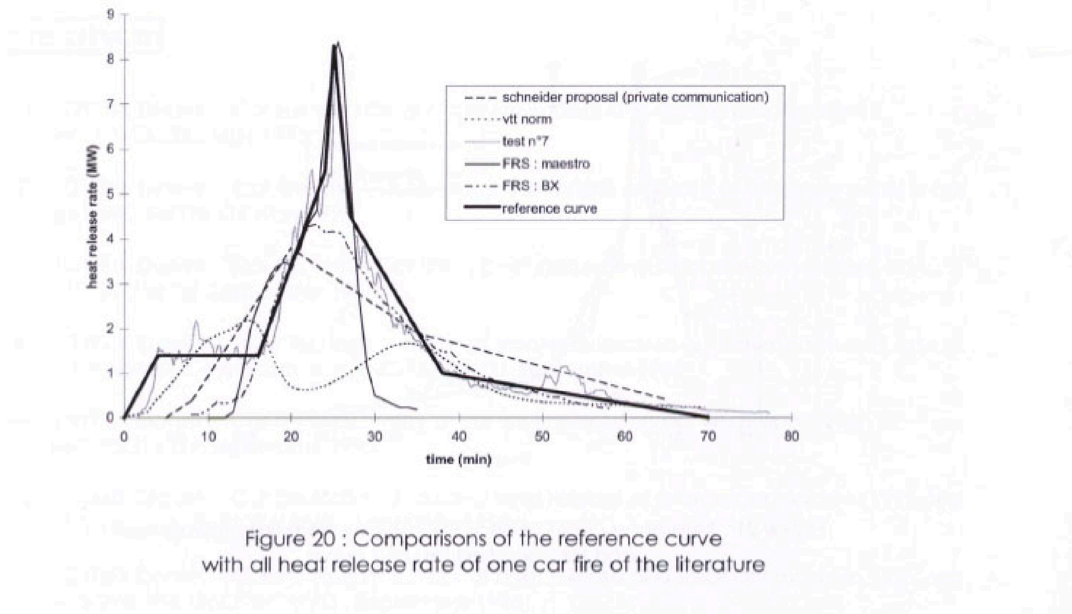


Figure 2: Rate of heat release for a test fire of one car

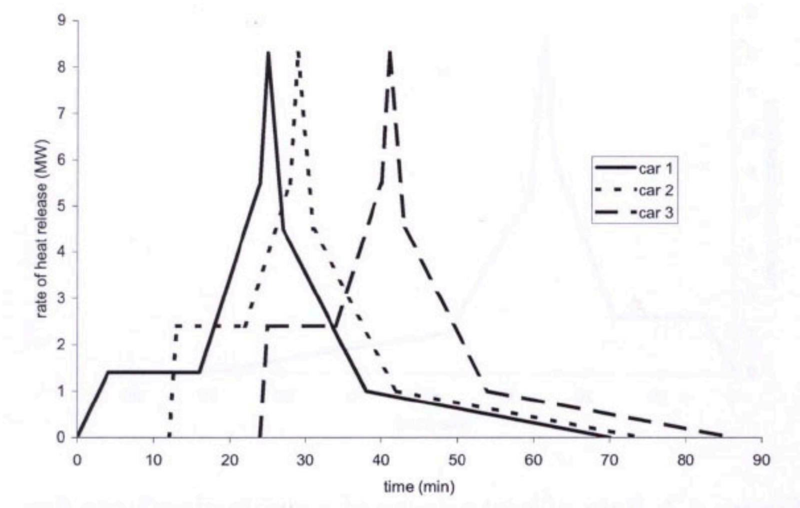


Figure 3: Rate of heat release for three cars

In the various Dutch guidelines and in NEN 6098 (draft) a curve on the basis of three burning cars is employed. It is also assumed that the fire brigade begins to fight the fire after 20 minutes. In addition to this, the presence of a fire alarm system is assumed.

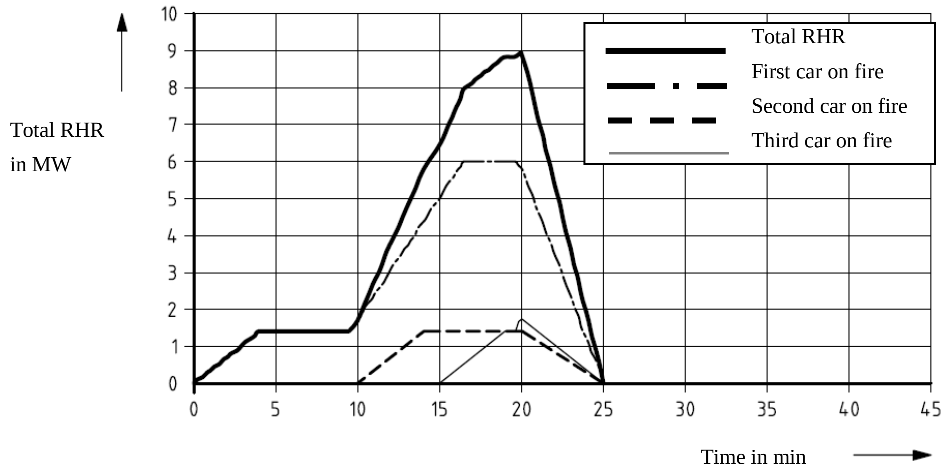


Figure 4: Rate of heat release curve for the design of car parks

For the design of mechanically ventilated car parks larger than 1000m^2 the rate of heat release curve from Figure 4 is applied for CFD simulations of smoke movement. For the car park on Lloydstraat, based on data collected from the research, it can be deduced that, assuming a time of arrival of the fire brigade according to the “standard fire procedure”, at the time of arrival of the fire brigade, at least three cars are fully on fire and two cars have just caught fire. (Note: the standard fire procedure indicates the times at which events such as detection, evacuation and arrival of the fire brigade are expected to take place). Further information about possible fire scenarios is given in Chapter 4 (Fire development).

2.4 Properties of an open car park

In this section consideration is given to the question of whether a car park that is designed according to the regulations for an open or naturally ventilated car park is comparable to an outside situation, with regard to technical aspects of the fire and access by the fire brigade.

As outlined in Section 2.2, an open (naturally ventilated) car park is assessed on the basis of NEN 2443 and NEN 1087. The requirements of these regulations aim to prevent an excessive level of carbon monoxide (CO). A typical car is assumed to produce 0.35m^3/hr CO. A car on fire can produce ±30000m^3/hr smoke over a height of ±2.5m.

A car park that has been designed as ‘open’ is not an ‘outdoor, or outside’ car park and does not comply with the conditions for ‘open spaces’ as defined in Article 2.169 and 2.186 of the Building Regulations. In the explanations accompanying these Articles the conditions for an open space are given as:

1. Radiative flux: <1 kW/m^2

2 Temperature: <45 °C
3 Visibility: >100 m.

Under these conditions it is still safe for the occupants to remain in the space. These conditions are given for smoke free escape routes. For the purposes of fire extinguishing, more severe conditions can be adopted due to the personal protection equipment that the fire brigade uses. The guidelines for closed car parks refer to a visibility of 30m. In studies of the circumstances of fires in tunnels on a European level[5] the fire brigade adopts the following criteria:

1 Radiative flux: <5 kW/m^2
2 Temperature: <100°C
3 Visibility: 7-15m

The fact that circumstances during a fire in an ‘open’ car park are not the same as those for an outside situation can, among other things, be ascribed to the following:

- A ceiling is located above the fire source (±2.4m high for a car park) whereby smoke can spread over a large area (also against the ventilation / wind direction). In the outside air smoke can rise in the form of a plume but will not form a layer.
- Due to the limited climbing height of the smoke the smoke will be only lightly diluted, resulting in limited visibility.
- Due to the limited climbing height of the smoke the smoke will lose little heat due to mixing, whereby the temperature at the ceiling can rise rapidly.
- The hot layer of smoke under the ceiling will emit radiation. This radiation can be great enough to cause secondary fires. In the outside air secondary fires will only exist due to direct flame impingement or direct radiation from the fire source.
- The supply of oxygen is unhindered in the outside air. In an open car park the oxygen supply is dependent on the size and position of the openings. In a car park, at some stage, the fire could become ventilation-controlled, whereupon thicker smoke can be produced than that produced for a fuel-controlled fire.

Based on the above points, it can be concluded that an open or naturally ventilated car park is not comparable to an outdoor or outside situation. The question is whether this is indeed necessary. Also an industrial hall that complies with the compartment size from the Building Regulations doesn’t comply with the outside situation. It is important that the fire brigade can control the fire from a safe position in this sort of building. In open car parks larger than 1000m^2 the fire brigade is not able to act safely without further provisions in the car park.

2.5 Application of pre-stressed concrete and fire resistance of hollow core slabs

Pre-stressed concrete structures are often used. Pre-stressed concrete such as hollow core slabs, solid slab floors and pre-stressed plate floor systems are used in residential as well as in commercial and industrial buildings. Often a compression layer is poured on this type of floor whereby the floor forms a rigid plane that determines the stability of the building. Around the floor tensile ring reinforcement is sometimes applied inside the compression layer. This increases the rigidity of the floor. Such tensile ring reinforcement has also been applied for the building under consideration here.

The building permit for the building on Lloydstraat states that the hollow core slabs must have a fire resistance of 120 minutes. The fire resistance of hollow core slabs is determined numerically. The calculations are provided by the supplier of the floor slabs.

[5] *UPTUN (UPTUN is the acronym for Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels; a European RTD-project funded by the European Commission in FP5.)*

The calculations are undertaken using software (Rekenplan) that includes a statement that the special loading case “fire” is verified by the software. In Chapter 3 the design of the structure and the behaviour of hollow core slabs during fire is considered in greater detail.

2.6 Conclusions

Apart from the Building Regulations there are only a few guidelines available for the design of car parks. These guidelines do not form legal requirements unless they are present in national, provincial or local laws, decrees or acts. No specific requirements are laid down for naturally ventilated car parks.

The regulations do not give any beforehand defined fire loads and / or fire heat release rates for car parks. The guidelines for mechanically ventilated car parks are based on a rate of heat release for three cars and commencement of fire fighting by the fire brigade 20 minutes after ignition.

The car park on Lloydstraat complies with the conditions for a naturally ventilated car park. It also complies with the rules from the Building Regulations, with the exception of the compartment size.

The guidelines for mechanically ventilated car parks are not applicable to the building on Lloydstraat.

A naturally ventilated car park cannot be considered as an “open space” according to the definition in the Building Regulations. The fire brigade must take into account the occurrence of more severe conditions in a naturally ventilated car park than in a mechanically ventilated car park.

Building with pre-stressed concrete is a frequently applied construction method. The fire resistance of concrete is established with the help of calculations.

2.7 Recommendations

1. The research team advises the NVBR to inform fire brigades about the risks of fire fighting in a naturally ventilated car park.
2. The research team advises the NVBR and the ministries of BZK (Interior and Kingdom Relations) and VROM (Housing, Spatial Planning and the Environment) to investigate in which ways the safety of fire brigade personnel in a naturally ventilated car park can be improved.

3 Design of the structure

When assessing the design of the structure attempts are made to answer the specific questions that have been posed by the party that is commissioning the work:

a. From a structural point of view is the building properly designed?
b. Did the structure comply with the regulations?
c. Have the correct documents been submitted?
d. Has the structure been assessed in the correct way?
e. What is the main load-bearing structure in this building (for example the steel sections upon which the hollow core slabs lie)?

3.1 Design of the building

At first sight the structural design does not show any shortcomings. The design has only been superficially assessed by Efectis, and Efectis has not checked the calculations. The load-bearing system of the building appears logical, the floor lies (via L-shaped sections) on the load-bearing outer wall and on the load-bearing building core (or in some cases on a THQ (Top Hat Q) beam from the building core to the outer wall). Furthermore the stability of the outer wall is probably obtained by connecting the outer wall to the stiff building core by means of the diaphragm action of the floor slabs.

3.2 Regulation, documentation and testing

These three subjects call for a detailed study and check of the calculations that are present in the dossier. In consultation with the client, this has not been done by Efectis. For this more time would be required and also more insight into the undertaken calculations. Efectis has concentrated on the study of the structural integrity and damage; given the damage that has occurred, notably on the hollow core slabs, a short analysis has been made, see also Chapter 5.

According to the regulations that are currently in force for the calculation of fire resistance of concrete structures (NEN 6071) the bending moment capacity of the floor during fire must be calculated. Furthermore it is assumed that the section warms up (including the steel reinforcement and / or pre-stressing steel) and the strength therefore decreases. The following is not considered:

– cracks such as those in the plane of the pre-stressing strands or directly between two hollow cores,
– spalling behaviour.

When calculating the bending moment capacity the concrete cover on the pre-stressing strands is calculated because this cover forms the insulation layer between the strand and the fire. A thicker cover results in less warming up of the pre-stressing steel, this in turn leads to a larger calculated fire resistance. Such an approach is generally valid when:

– the concrete cover remains intact (therefore no spalling), and
– the critical failure mechanism arises when the bending moment capacity is exceeded.

In the documents from the supplier relating to the calculations, such as those present in the dossier of the Rotterdam Local Building Authorities, and those made available to

Efectis, a fire resistance duration of 120 minutes is stated. The underlying calculations are not provided in these documents and therefore cannot be checked.

On the basis of the informative appendix A of NEN 6071 it is estimated that an “axis distance a” of 50mm is necessary for a fire resistance of 120 minutes. This axis distance consists of the cover + half strand diameter and is, according to the drawings for the floor under consideration, thus 40 +1/2*12.5 = approximately 46mm. This is somewhat too low in comparison to the informative value of 50mm given in NEN 6071.

This deviation however, in the opinion of Efectis, cannot explain the observed forming of cracks in the hollow core slabs. According to the table, an axis distance of 46mm should correspond to a fire resistance w.r.t. failure of 108 minutes (interpolated), assuming that failure occurs due to a reduction of the bending moment capacity when the pre-stressing strands lose their strength. Both the time duration as well as the failure mechanism does not concur with the observations made for the Lloydstraat.

3.3 Load bearing construction under fire conditions

The “load bearing construction under fire conditions” (henceforth referred to as LBC) is defined in NEN 6702:2005. In short, the definition can be summarized by the following: a part of the building construction is a component of the LBC when failure of the part leads to the failure of a building construction that is not located in the same fire compartment.

Based on this definition the LBC includes the load bearing façade and the building core. The floor does not have to be designed as “load bearing construction under fire conditions” if it can be shown that failure of the floors in the parking garage does not lead to failure of structural elements of the residences above.

Such a calculation is not available in the dossier that was provided to Efectis, so it is justifiable to assume that the floors, which provide the connection between the load bearing building core and the load bearing façade, form a part of the LBC. This assumption is supported by the proposition in the dossier that the floor has a fire resistance of 120 minutes. When the floor is considered to form a part of the LBC, also the supports of the floor (i.e. the steel L-shapes and THQ beams) are part of the LBC.

The THQ beams possibly also contribute to the stability of the facade (because they form a connection between the facade and the building core) and they are therefore also in principle a part of the LBC, unless it can be shown that failure of the THQ beam with the floor that it supports has no further consequences.

Given that such evidence is not present in the dossier, the THQ beams are also considered to be part of the LBC.

3.4 Conclusion

The design of the building at first sight is not unusual.
The LBC consists at least of the building core and the load bearing façade. In addition the floors form a part of the LBC because they provide the connection between the façade and the building core. Also the steel elements supporting the floor are part of the LBC.

The verification of the building by the Local Building Authorities has not been checked by Efectis, because it would have been necessary to check the structural fire resistance calculations. With the exception of the conclusions these calculations were not present in the dossier that was provided to Efectis.

4 Fire Development

4.1 Introduction

During the fire seven vehicles were damaged to varying degree. The fire brigade has questioned whether a fire of this magnitude is an exception, or whether this is a phenomenon that should be given due consideration in the future.

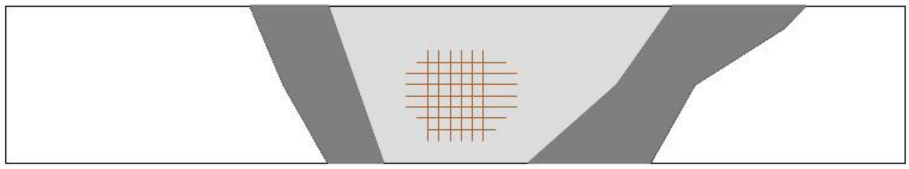
This chapter provides answers to the following questions:

- What was the rate of fire development?
- How did the materials that were present influence the fire development?
- What was the fire load?
- What was the maximum rate of heat release?
- What was the maximum temperature in the compartment and in the structure?
- Was the fire development in agreement with the starting points according to the regulations and guidelines?
- What is the reason that the fire became so severe?
- Could a fire safety installation, such as an alarm system, sprinkler or HVAC, have prevented the fire becoming so severe?

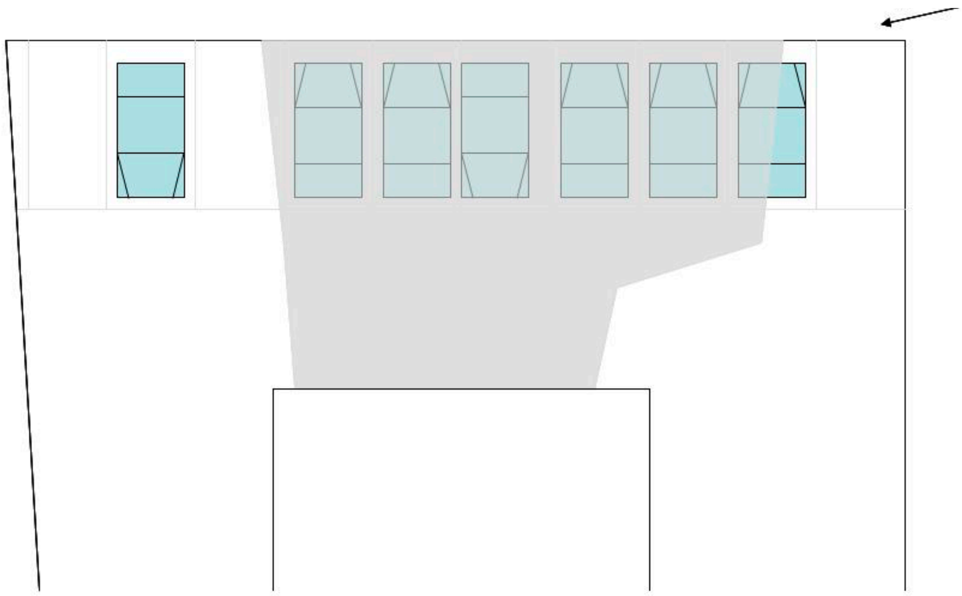
4.2 Fire development and course of fire

The fire development can be determined using theoretical models such as the curve in paragraph 2.3, and on the basis of statements from the bystanders and the fire brigade.
From the damage patterns on the wall and the ceiling of the car park (see Figure 5) and from the damage to the vehicles that were involved in the fire, it can be inferred that the fire began in two cars, namely a Kia Sportage and a Ford Mondeo. On the basis of the fire curve from paragraph 2.3 two scenarios have been formulated for the fire development. These scenarios are given in Figure 6 and Figure 7. Due to the small distance between the Ford and the Kia (<50cm) it is assumed that the fire spread between these vehicles took place sooner than normally would have been expected on the basis of the fire curves, which are based on a separation distance of 70cm.

These rate of heat release curves are theoretical models that are based on the previously named fire tests, and therefore deviate by definition from the actual fire development. It is possible, however, to use the models to sketch a global view of the way in which the fire developed. As mentioned previously in Chapter 2, the curve that has been used is based upon an average car (category 3).



Damage pattern on the wall



Damage pattern on the ceiling (only visible damage on the concrete!)

Figure 5: Damage patterns

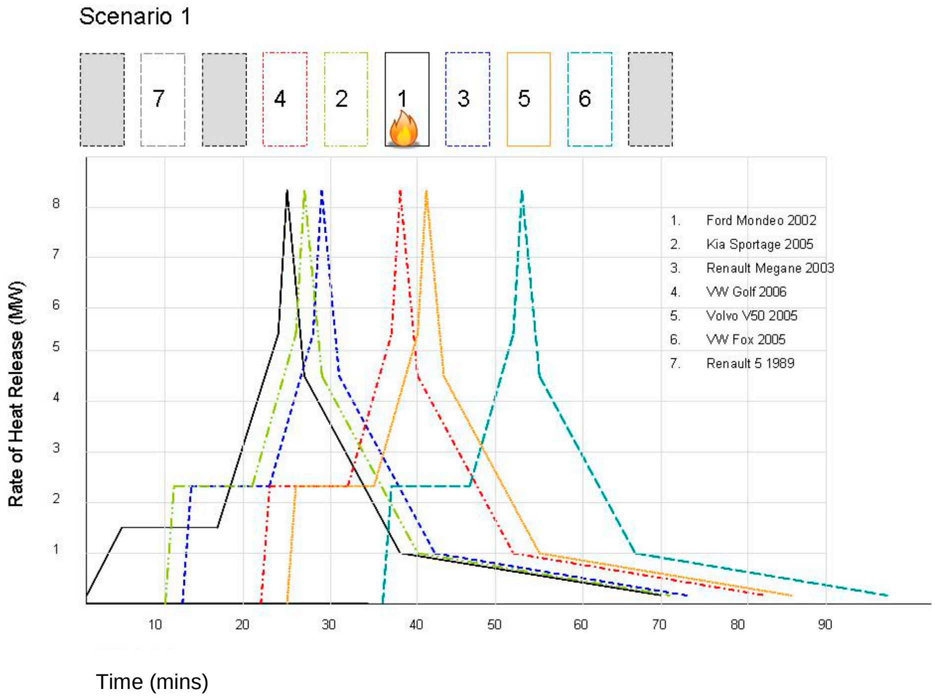


Figure 6: Fire scenario 1

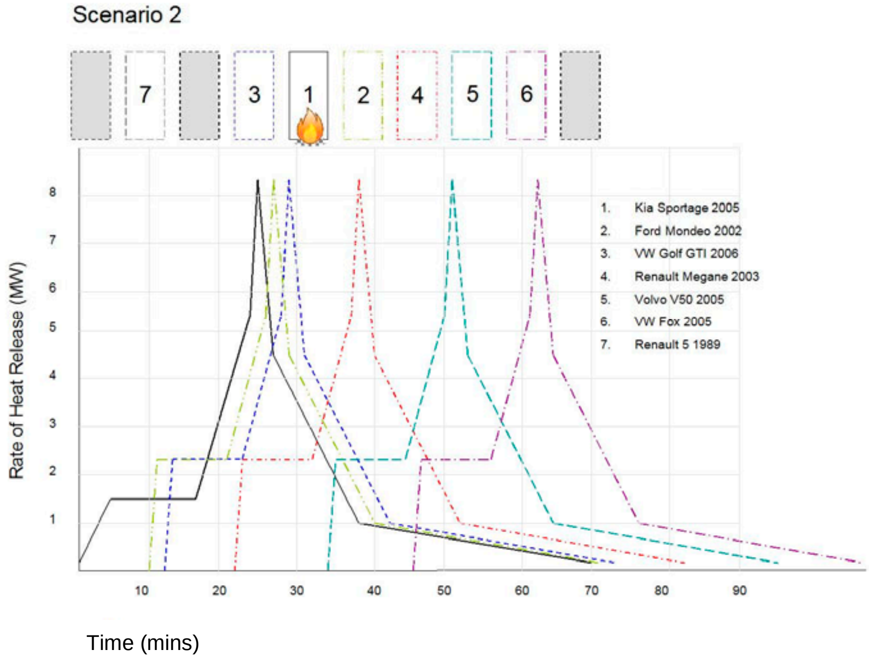


Figure 7: Fire scenario 2

Figure 8 and 9 show the total heat release that can be produced during the fire according to scenario 1 and scenario 2 respectively. The heat is not released in one place, but is spread over the compartment.

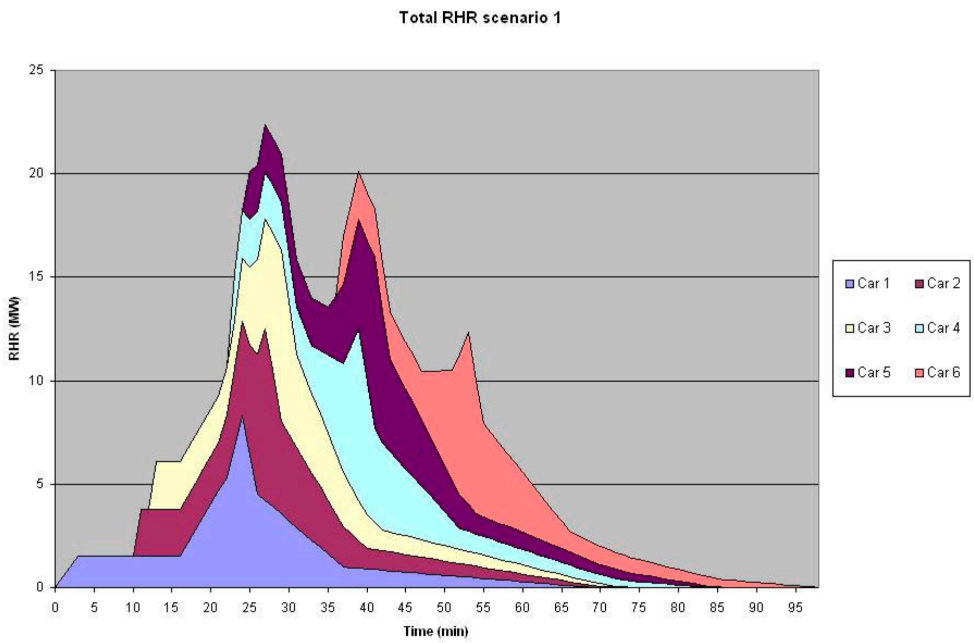


Figure 8:Total rate of heat release scenario 1

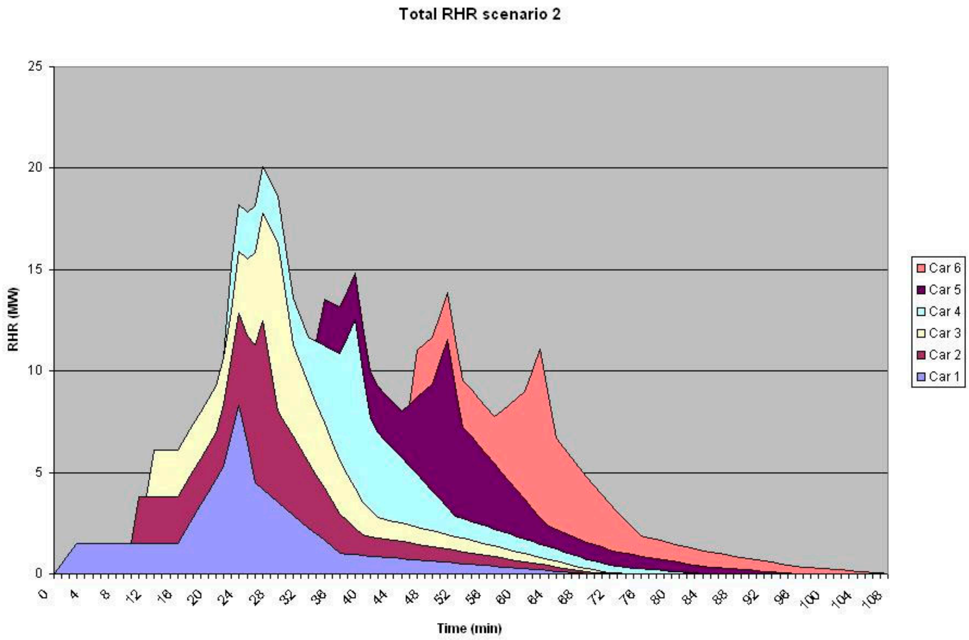


Figure 9: Total rate of heat release scenario 2

The fire development relative to the actions of the fire brigade and the fire development according to the “standard fire procedure” can be envisaged with the help of Table 3 and 4. In these tables the time of detection is coupled to the detection time according to the standard fire procedure fire development. The theoretical fire development is related to the fire development according to the standard fire procedure beginning 13 minutes before the alarm. Note: TS means fire engine truck.

Table 3. Overview of events relative to scenario 1

					Standard fire procedure	
Time (minutes)	Time of incident	**Theoretical fire development (scenario 1)**	Action fire brigade	Evacuation	Action fire brigade	Evacuation
0	04.16-x	Origin fire car 1			time to discovery	time to discovery
10		Origin fire car 2				
12		Origin fire car 3				
13	04.16		1st notification	1st internal alarm	Time to notification	Alarm notification
14	04.17		Alarm for TS 23-1			
15					Time to dispatch	Evacuation time
20	04.22		TS 23-1 On scene			
22	04.24	Origin fire car 4	Middle fire			
23	04.25		Large fire		Fire brigade fully operational	
24		Origin fire car 5				
30	04.32		Start using dry main		Extinguishing period	
36		Origin fire car 6				
40						Evacuation completed
46	04.48		Start extinguishing boat / fire float	Evacuation completed		
59	05.01		Start damping down			
60+X					Damping down, de-scaling	After care

Table 4. Overview of events relative to scenario 2

					Standard fire procedure	
Time (minutes)	Time of incident	**Theoretical fire development (scenario 2)**	Action fire brigade	Evacuation	Action fire brigade	Evacuation
0	04.16-x	Origin fire car 1			time to discovery	time to discovery
10		Origin fire car 2				
12		Origin fire car 3				
13	04.16		1st notification	1st internal alarm	Time to notification	Alarm notification
14	04.17		Alarm for TS 23-1			
15					Time to dispatch	Evacuation time
20	04.22		TS 23-1 On scene			
22	04.24	Origin fire car 4	Middle fire			
23	04.25		Large fire		Fire brigade fully operational	
30	04.32		Start using dry main		Extinguishing period	
34		Origin fire car 5				
40						Evacuation completed
46	04.48	Origin fire car 6	Start extinguishing boat / fire float	Evacuation completed		
59	05.01		Start damping down			
60+X					Damping down, de-scaling	After care

Observations fire brigade.
The commanding officer of the fire brigade reported that external flaming was visible from two openings in the façade at the time of arrival at the premises. Due to the smoke development there was little visibility on the floor where the fire was located. At the time of arrival of the fire brigade it was suspected that two or three cars were on fire.

The 6th car was only partially burned (±75%). This agrees with the fire development according to scenario 1, for which extinguishing by the fire float (fire extinguishing boat) begins at the moment that the fire in car 6 has been burning for approximately 10 minutes. (Note: the building stands on a Rotterdam wharf).

From both scenarios it is noticeable that the development of the actual fire shows strong agreement with the models that have been constructed on the basis of tests.
Also the standard fire procedure shows strong similarities with the actual course of events with respect to the action of the fire brigade and the evacuation of the building.

Worst-case scenario.
Ten parking spaces were present on the fire floor. Of these ten spaces, three were not in use. It is quite conceivable that the fire would have been larger had all the spaces been occupied. In that case it is almost certain that the car next to the Golf GTI would have been involved in the fire, which also would have resulted in involvement of the Renault 5. This means that the worst-case scenario could have been a fire with 8 cars.

4.3 Temperatures

The temperatures that arose during the fire cannot be determined accurately. On the basis of the discolouration of the façade, such as that shown in Figure 10, it can be deduced that the temperature at the façade was probably not higher that 1000^{o}C.

Figure 10: Discolouration and spalling of the concrete

Using the numerical model CaPaFi version 2.0 (Car Park Fire) from DIFISEK the temperature development has been determined for the two previously described fire scenarios. Figure 11 shows the temperature development for scenario 1 and Figure 12 gives the temperature development for scenario 2. It is noticeable that the difference in temperature is only a few degrees. In the diagrams the temperature at the ceiling (2.4m high) is given in relation to time and distance from the fire.

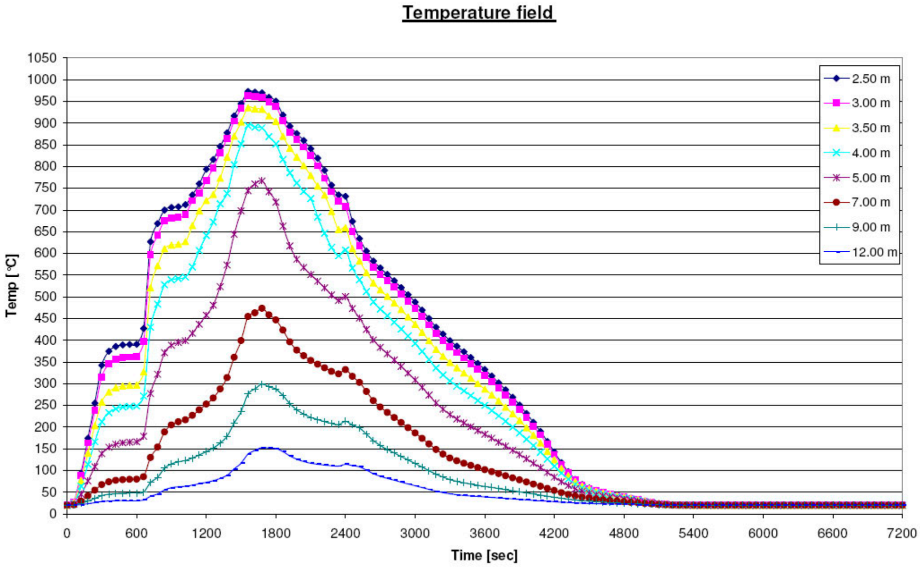


Figure 11: Temperature development scenario 1

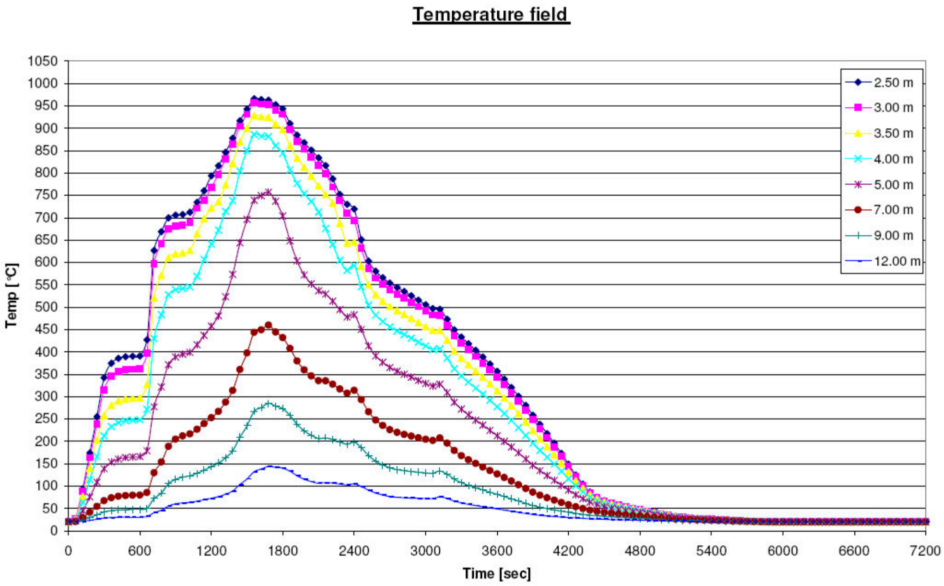


Figure 12: Temperature development scenario 2

The graphs for both scenarios are almost identical to the standard fire curve from 0 to 1000 seconds. From 1000 to 2000 seconds the temperatures are higher. After 2000 seconds the modelled temperatures are lower than the standard fire curve.

4.4 Fire load

Non-permanent fire load.
As mentioned previously (Section 2.2), in order to determine the fire load it is assumed that a car produces 5020MJ. This is based on the list of heat releases from NIFV.
In Table 5 the vehicles that were present in the garage are placed into the categories that have been defined in the research that is referred to in Chapter 2. In order to obtain the actual heat release the values from the table have to be multiplied by an efficiency factor of 0.7. (Not all of the material burns completely. The efficiency factor indicates to which level the combustible material in the car contributes to combustion).

Table 5

Category 1 6000MJ (4200MJ)	Category 2 7500MJ (5250MJ)	Category 3 9500MJ (6650MJ)	Category 4 12000MJ (8400MJ)	Category 5 12000MJ (8400MJ)
VW Fox Renault 5		VW Golf Ford Mondeo	Renault Megane Volvo V50	Kia Sportage

The cars that were present in the garage are placed into the categories of the research.

Table 6

	2100m^2 (whole car park)	310m^2 (floor)	115m^2 (10 parking spaces)
5020MJ / car	7.5 kg pinewood/m^2	6 kg pinewood/m^2	23 kg pinewood/m^2
6650MJ / car	10 kg pinewood/m^2	7.9 kg pinewood/m^2	30.4 kg pinewood/m^2

In Table 6 the variable fire load for the car park on Lloydstraat is given based upon the values from the NIFV's list and from the values from the previously referred to research.

Permanent fire load.
The permanent fire load in the car park is very low. Apart from a few fluorescent light fittings, PE or PP sewage pipes and the façade between the garage and the lift entrance there are few structural elements present that could have contributed to the fire. Until just next to the burned-out vehicles there was no damage to be seen on the thin asphalt layer on the floor. (NB the lines between the parking spaces were still intact). It is assumed that the asphalt layer did not (or hardly) contribute to the rate of heat release.

Conclusion.
Based upon the data of the previously referred to research, it appears that the total heat release of 5020MJ per car from the NIFV's publication is no longer realistic. Using the 2007 car sales figures from Bovag, a global value for the average total heat release for cars sold in the Netherlands is about 6200MJ.
Therefore it is advised to use the average total heat release of a car from category 3 (6650MJ).

4.5 The fire development in relation to regulations and guidelines

From the previous chapters it can be deduced that the actual course of the fire is not in agreement with the starting assumptions for the design of naturally ventilated car parks. The standard fire curve is used as a starting point for the fire resistance and structural integrity of the structural elements. Based on the previous research and the observed damage to the building it can be concluded that the temperature probably increased to just under 1000^{o}C faster than would have been the case according to the standard fire curve.

No special requirements are laid down for evacuation and suppression of fire in naturally ventilated car parks. All of the guidelines refer to fire development for a mechanically ventilated car park. A starting point for this is that automatic fire detection is present in the car park, due to which the fire brigade can intervene in time.

The fire development and the fire brigade’s actions took place practically “according to the book” when looked at relative to the standard fire procedure. Based on the previous research it was expected that a fire in a car park could spread to more than four cars. Based on the fire development in the guidelines, fire spread to more than four vehicles was not to be expected.

4.6 Fire safety installations

The car park in Rotterdam was not provided with special fire safety installations such as automatic fire alarm, sprinklers, or provisions for the venting of smoke and heat (HVAC).
It this section it is considered whether the presence of the aforementioned installations could have had a substantial influence on the development of the fire.

Fire alarm installation
Automatic detection in a building ensures that a fire is detected without the need for human action. It is desirable that fire alarm installations are obligatory in buildings were sleeping people are present. Exceptions to this are family homes and homes in a residential block, where only home smoke detectors are mandatory.

There is no surveillance in a car park under a residential block. A fire can develop unhindered, especially at night. In most cases a fire in this situation is only detected at the moment when the occupants are woken by the noise of bursting tyres and falling structural elements. According to the standard fire development the detection time in this case is 13 minutes. When an automatic fire alarm installation is present the standard fire development assumes that the fire can be detected at least eight minutes sooner. In the case of fire in the Lloydstraat car park (scenario 1) the fire brigade would have been on site at the moment when car 3 started to burn. This would have given the fire brigade a considerably greater chance to get the fire under control even with limited effort (1 fire engine for evacuation, 1 fire engine and ladder truck for fire fighting). Automatic detection is a starting condition for the design of mechanically ventilated car parks as adopted in NEN 6098 (draft). According to the fire scenarios presented in this report the curve in NEN 6098 (draft) appears to give a realistic fire development.

A fire can be detected on the basis of smoke, temperature or flames. In a car park smoke detection can lead to unwanted activation of the alarm. The use of smoke detection is then also unwanted! From the temperature development shown in paragraph 4.3 it can be deduced that the fire can easily be detected within five minutes on the basis of temperature.

Sprinkler installation
A sprinkler installation can control and / or extinguish a fire once it has started. It is to be expected that a sprinkler installation will activate within five minutes. The rate of heat release is limited when the sprinkler is activated within five to ten minutes. It is not plausible to expect that a car fire will be fully extinguished. However it can be expected that the fire will remain under control until the fire brigade arrives. Also the structure will suffer little or no damage due to the fire.

Smoke control
The use of a smoke and heat venting installation in a building can prevent evacuation being impeded by smoke. Also the temperature of the smoke layer will be kept relatively cool, through which the occurrence of secondary fires and failure of structural elements can be postponed or even prevented. Finally an HVAC system has the advantage that it gives the fire brigade the possibility to approach the fire. Since HVAC vents smoke via the roof HVAC is not possible in the car park on Lloydstraat.

In mechanically ventilated garages jet fan ventilation is frequently used and is a form of smoke control. The smoke is pushed into a previously determined direction and is extracted at that point. This gives the fire brigade the chance to approach the fire with “the wind at their backs”.
In order to determine the capacity of the ventilation a visibility through smoke of 30m is used as a starting point.
During the fire in Lloydstraat the distance between the fire brigade personnel and the fire was only ±5m. Even at this distance there was almost no visibility to the fire.
Jet fan ventilation could probably have prevented the smoke spread in the direction of the stairwell. The behaviour of smoke when jet fan ventilation is in use is not easy to predict due to the influence of openings and wind. In this case jet fan ventilation could have negative effects. CFD simulations could be used in order to investigate the possibilities for ventilation in this car park. These simulations do not fall within the scope of this fire investigation.

4.7 Conclusions

The exact time of ignition of the fire cannot be defined. Based on the scenarios that have been presented in this chapter the fire could have had a development time of 13 minutes or more. The development time is dependent on the cause of the fire. As the result of a malfunction, part of the car could have been smouldering for a longer time before the fire developed further. In the case of arson the fire could develop faster than that assumed in the scenarios.

The materials present in the building did not have a significant effect on the fire development. The fire load was formed by the cars that were present.

The models used in this report assume a maximum rate of heat release of 8.3MW per car. In total the maximum rate of heat release is ±20-23MW. This heat release was spread out over the compartment.

A fire curve has been constructed using the models for car fires in car parks. For a fire such as that in the car park in Rotterdam it appears that the temperature in the beginning of the fire can increase faster than that indicated by the standard fire curve. The duration of the thermal load on the structure is shorter than the duration of the load according to the standard fire curve.

The fire development does not agree with the starting points for the regulations and guidelines. In particular the starting points concerning the fire load of the car and the applicability of the standard fire curve are debatable.
On the basis of the regulations and guidelines a fire of this severity was not to be expected.

The severity and course of the actual fire strongly agrees with the theoretical scenario 1, in which the fire begins in the Ford Mondeo. More research into actual fires in car parks is necessary in order to validate the model used here.

The regulations for ventilation in naturally ventilated car parks are not based upon the conditions during a fire such as those occurring in the Lloydstraat fire.

The presence of a fire alarm system would have contributed to the faster arrival of the fire brigade. Through this the fire severity would have been limited and the structure would have undergone less damage, whereby the consequential damage for the residents would have been limited.

4.8 Recommendations

3 The research team advises the NIFV to modify the total heat release of the cars to the average value (6650MJ) from the research of CTICM and TNO.

4 The research team advises the NVBR to inform the fire brigade about the possible course of the fire and the severity of a fire in a car park.

5 The research team advises the relevant Ministries (Housing and Internal Affairs) to undertake research into actual fires in car parks, and to revise the regulations and guidelines where necessary.

6 The research team advises the relevant Ministries to investigate whether the implementation of fire detection in car parks under (residential) buildings should be made mandatory.

7 The research team advises the issuer of permits to accept “equivalent solutions” for car parks larger than 1000m^2 only on the basis of the presence of a fire alarm system or an automatic extinguishing system.

8 The research team advises the investigation of whether other possibilities exist for the prevention of fire spread, such as fire/smoke screens on the ceiling between parking spaces, raised borders between parking spaces (prevention of spread of motor fuel spills and suchlike).

5 Structural damage

The damage is described separately for beams, elements of the façade and floor slabs.

5.1 Façade elements

The interior of the load bearing prefab façade elements has undergone spalling to a depth beyond the steel reinforcement. Because of this an eccentric load exists whereby the façade is inclined to buckle towards the outside. The buckling to the outside is held back by the floor (as far as the floor is still present). If the façade were to buckle global collapse of the floors above is likely.

Figure 13: View of the spalled concrete surface of the façade.

5.2 Steel beams

The hollow core slabs are partially supported on steel THQ-265x6-190x15-500x15 (according to the drawing, this has not been measured on site) beams and partially placed on steel L-shapes that are attached to the façade and the building core.

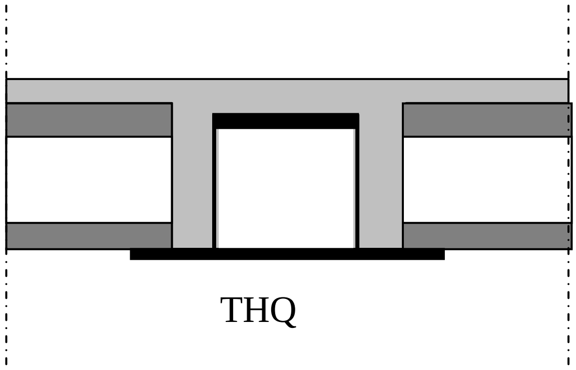


Figure 14: Schematic cross-section THQ beam. This is a rectangular hollow section with a plate that juts out from both sides. The hollow core slab is laid on the protruding plate, the gap between the end of the hollow core slab and the side of the THQ beam is filled with concrete.

The bottom flanges of the THQ beams and the L-shapes were protected from fire by fire resistant boards. During the inspection of the fire damage this protection was to the greater part still intact. Probably the temperature of the steel remained limited due to the fire protection. Had the steel temperature become too high then the bottom flange could have deformed, possibly causing the hollow core slabs to slide off their supports.

In the past a calculation method was developed for allowing the bottom flange to remain unprotected[6]. It is expected that this calculation method would have shown that fire protection of the bottom flange was necessary. Within the scope of this work this has not been investigated further.

Figure 15: Steel L-shape is still intact, and the fire protection is partially present after cooling down.

[6] TNO-report 2002-CVB-R06136: Fire resistance of Integrated Beams (A.J. Breunese en J.H.H. Fellinger, 2002) (in Dutch)

5.3 Hollow core slabs

The floor consists of concrete hollow core slabs with a slab height of 260mm and five hollow cores. Inside the bottom part of the slab there are 10 pre-stressing strands with diameter 12.5mm and a concrete cover of 40mm, with a total steel cross-section of 930mm^2 per slab. Inside the upper part of the slab there are no pre-stressing strands. This information comes from the “assembly plan calculations” that are present in the file from the Rotterdam Local Building Authorities.

Large cracks occurred in the slabs, in many cases causing large parts of the slabs to fall down. The figure below schematically shows the shape of the cracks.

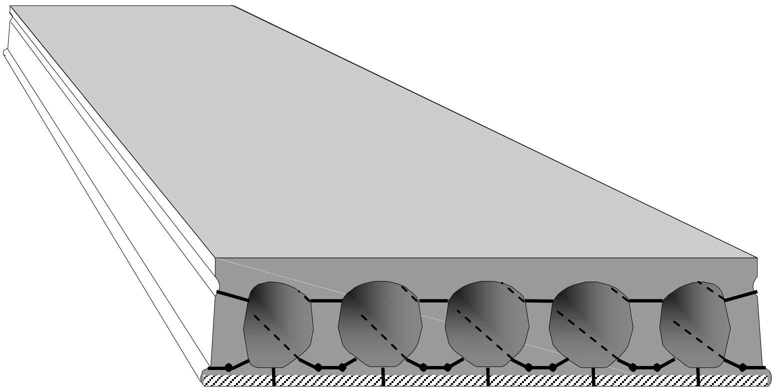


Figure 16: Schematic cross-section of the damage in one of the hollow core slabs. The black lines represent cracks and the hatched area is the spalled concrete.

Figure 17: Spalled underside of the hollow core slab (slightly further away from the fire). The picture shows that the spalling reaches the hollow cores in many places.

Figure 18: Some strands were completely twisted apart from each other because they were forced out of the concrete during the collapse of the bottom part of the floor. Most of the strands were not twisted apart from each other because the concrete cracked around the strand.

Figure 19: The crack is at a distance of approximately 14cm from what was the underside of the slab.

Figure 20: The upper side of the strand lay at about 5cm from what was the underside of the floor slab, so the concrete cover was about 4cm.

Figure 21: Concrete spalled to the depth of the hollow cores, but the pre-stressing strands are still covered. (picture: Rotterdam Local Building Authorities)

Figure 22: Crack in the plane of the pre-stressing strands, picture taken close to the support.

Figure 23: The crack causes the strands to be released. In some cases the strands are fully extracted from the concrete, causing the bottom half of the slab to fall down on a car.

Figure 24: Fallen bottom half of the floor slab on the other end of the span. In the right hand side top corner of the picture, the strands are still connected to the concrete above the support.

Figure 25: In some cases the bottom half of the slab remained hanging because both ends of the pre-stressing strands still were fixed in the concrete above the supports.

5.4 Summary

The damage that is most striking is the excessive crack formation in the hollow core slabs. This includes both horizontal cracks between the individual hollow cores and vertical cracks from the hollow cores extending to the bottom surface of the slab. Over a large area of the damaged slabs, the bottom half of the slab has fallen down. Also some pre-stressing strands detached from the construction and fell down.

At a slightly larger distance from the fire the hollow core slabs are damaged by spalling of concrete up to a depth of a few centimetres. Also the façade elements are damaged to a spalling depth of a few centimetres. On the hollow core slabs the spalling damage in many cases is up to the depth of the hollow cores. On the façade elements, the outer reinforcement has become exposed over a large part of the surface.

The steel THQ beams, and the L-shapes that supported the floor slabs, were protected on the underside by fire resistant boards. The steel parts have not suffered any visible damage.

6 Behaviour of the building during the fire

This chapter describes the structural damage that occurred during the fire and an attempt is made to explain the observed damage. Concrete questions are:

- Did the structure of the building behave as expected after a fire, and does this conform to the regulations?
- Which failure mechanism of the structure could have occurred during the fire?
- What caused the breakdown of the fire brigade lift (lift that is required to be functional during a fire for use by the fire brigade)?
- Was the supply point of the dry mains easily within reach and accessible?

6.1 Behaviour of the building during fire with respect to regulations

During the fire the structure did not completely behave as expected with respect to the regulations. This is elucidated in the paragraphs below. The clarification is limited to structural behaviour. The development of the fire, and the accompanying temperatures in the compartment, has not been taken into account. It can be stated however that the temperatures that occurred during the fire probably deviate from the standard fire curve, see Chapter 4 for more information. The temperature development calculated in that chapter deviates somewhat from the standard fire curve in terms of the rate of heating and the fire duration. An important additional fact is that half an hour after the fire a water canon located on the fire float (in the nearby harbour) started to extinguish the fire, reducing the fire duration and resulting in rapid cooling.

6.1.1 Spalling damage

The concrete of the façade as well as the hollow core slabs suffered spalling. The depth of spalling varies. A large part of the steel reinforcement in the façade was completely exposed. Also the spalling damage on the hollow core slabs is substantial, in some cases until the depth of the hollow cores.

In general, concrete structures are not checked for loss of cover on reinforcement due to concrete spalling. Also, in the available documentation no information is found that indicates that this should be taken into consideration in the design of the building. It can therefore be presumed that the design is based upon the (possibly implicit) assumption that spalling would not occur. In the norm that is relevant to this situation, NEN 6071, the possibility of concrete spalling is described with the following comment:

> COMMENT (article 6.1.2)
>
> A moisture content greater than 7% (by volume) is also unfavourable with respect to the possibility of spalling. It is deemed that in buildings a stable moisture content is normally present and is equal to 7% (by volume).

The background to this comment is that an interior climate is usually present in buildings such that the concrete structure is maintained at about 20^{o}C and therefore will dry out to a stable moisture content. Concrete with a high stable moisture content is in general more susceptible to spalling than dryer concrete.

It is presumed by NEN 6071 that spalling will not occur in concrete that is within a building (interior) climate. This assumption is based upon possibly out-of-date information. From fire tests and investigations of real fires Efectis has the experience that concrete spalling occurs in many situations where according to NEN 6071 this should not happen. In the opinion of Efectis, the chance of spalling must be supposed to be greater than the chance that is expected on the basis of NEN 6071.

For an unheated construction (in particular one that is exposed to the outside) such as the building considered here, it is also questionable whether the condition referred to in the comment is satisfied. After all during the lifetime of the concrete it will be exposed to a climate that is on average wetter, through which the pores of the concrete will contain more water. No samples from the undamaged parts of the structure of the building considered here were taken in order to determine the moisture content.

6.1.2 Cracking and breaking off of parts of the slab

The large extent of cracking of the hollow core slabs is not anticipated in the norm. A calculation according to NEN 6071 is in essence a calculation of the (non-spalled) section with respect to the bending moment. The cracks on the hollow core slabs can be however most likely attributed to internal stresses as a result of the large temperature differences between the directly heated surface of the concrete and the cold concrete lying behind this, and because the heated concrete cannot expand freely to the sides. Such effects are not taken into account in the calculation according to NEN 6071.

6.1.3 Literature relating to fire resistance of hollow core slabs

For a possibly more detailed explanation of how the cracking occurred, other relevant documentation has been consulted in addition to the prevailing regulations.
The observed failure mechanisms are often not described in sufficient detail in existing investigation reports. In many cases testing is only done until the required fire resistance and not until the moment of collapse. Furthermore, in current fire tests single structural elements only are investigated. Possible impediment of thermal expansion due to surrounding elements (adjacent slabs, compression layer) is therefore not taken into account.

The most relevant is the recently internationally published work of Dr. J.H.H. Fellinger. In his doctoral research[7] he investigated the collapse of hollow core slabs on shear and on anchorage of the strands. Crack formation comparable to the damage observed in the building on Lloydstraat has also been theoretically determined by him for a similar type of floor. However, this was not a main goal of the research. He attributes this cracking to laterally restrained deformation. At the end of his thesis he writes: “further research is recommended into (..) the effects of transverse restraint on the horizontal cracks at mid depth in the (..) slab.”

[7] Fellinger, J.H.H., 2004, Shear and Anchorage behaviour of Fire Exposed Hollow Core Slabs

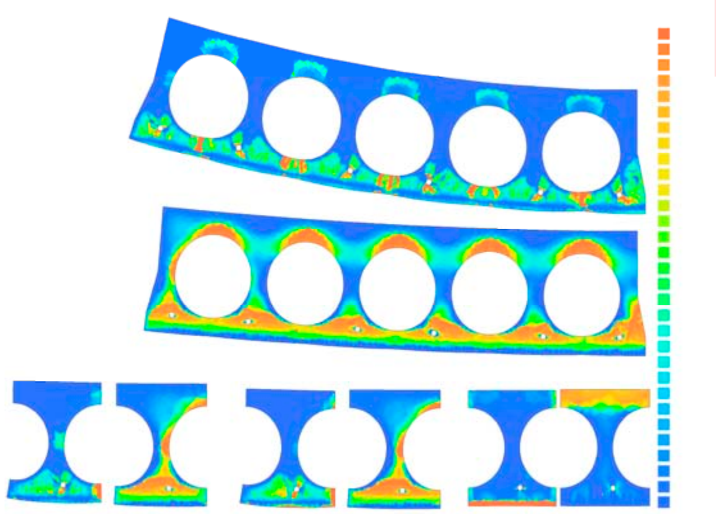


Figure 26: Calculation of cracking in the cross-section of a comparable hollow core slab (source: Fellinger 2004)

As a result of the observed fire damage and the aforementioned recommendation from Dr. J.H.H. Fellinger, TNO Building and Underground carried out a numerical study in order to explain the observed damage to the concrete hollow core slabs. The results of the study are reported separately in TNO-report 2007-D-R1236/C – "*Investigation into the structural behaviour during fire of a hollow core slab as used in Lloydstraat in Rotterdam". (in Dutch)*

6.1.4 Steel elements

The steel elements (L-shape and THQ beams) upon which the hollow core slabs were placed, were protected with fire resistant boards of thickness 12 to 15mm. Efectis did not check whether this thickness is sufficient for the required fire resistance.
The fire resistant boards did in any case ensure that the steel elements were not severely deformed. Because of this the hollow core slabs did not fall from their supports. Without the fire resistant boarding it is quite conceivable that this would have occurred.

Figure 27: Collapse of the floor due to deformation of the bottom flange of the L-shape (not observed in the investigation under consideration here).

6.2 Possible failure mechanisms during fire

During the fire the structure could have collapsed due to the hollow core slabs breaking or slipping from their supports. This could have possibly led to a sudden impulse on the floors underneath resulting in progressive collapse. This, however, is unverifiable since the current knowledge of collapse of structures is insufficient to give clear answers.
Collapse of one or more floors could indicate that the outside façade had too little support from the sides, allowing the façade to buckle outwards. Consequently the upper floors (parking and residential levels) would also have collapsed.

6.3 Functioning of the fire brigade lift

The performance of the fire brigade lift has not been investigated by Efectis. By the time Efectis had received questions regarding the functioning of the fire brigade lift the lift had already been repaired and cleaned.
The fire brigade stated that the lift did not function any more during the incident. The lift was fitted out as a fire brigade lift according to the information on the building permit.

Efectis contacted the manufacturer of the lift (Schindler). According to them the electronic apparatus is fitted in the pit underneath the lift shaft at about 0.3m from the floor. The lift will stop functioning as soon as this apparatus becomes immersed in water and short-circuits. After the fire the supplier confirmed that the lift pit was filled with water up to the ground floor. It is plausible that this was the reason for failure of the lift. NEN-EN81-72 (requirements for fire brigade lifts) states that apparatus that is located less than 1 metre above the floor of the lift well should be watertight.

6.4 Preventative and preparative measures

During the mitigating actions in the car park of Harbour Edge it was observed that one of the staircases, which was part of a so-called “dual-spiral staircase” was no longer usable for evacuation during the emergency evacuation of the premises. The reason was due to the fact that the low pressure hoses were connected to the dry main in the staircase to the floor on which the fire occurred. Due to the presence of the hoses, the smoke resistance and fire resistance of the staircase was compromised, after which this escape route was blocked by smoke.

It became apparent for those attempting to evacuate through the staircase, having to change staircases was illogical and confusing. It was necessary for the fire brigade to remove the hoses temporarily from the staircase and to delay any action on the fire floor until the residents from the premises had passed the fire floor.

This gives reason to re-open the discussion regarding the use of dual-spiral staircases for buildings with the upper floor more than 20m above ground level. In the current Building Decree the use of vestibules in front of a staircase is obligatory only above 50m.
When using the vestibules above 20m the dry mains can be placed in the vestibules referring
For vestibules above 20m the required dry main(s) can be placed in the vestibule on the basis of Article 2.191 (Building Decree) (linking NEN 1594), and evacuation is not hindered by the actions of the fire brigade and the use of the dry mains.

6.5 Conclusions

The occurrence of concrete spalling is observed in many fires in practice, also in situations where spalling according to NEN 6071 would not be considered an issue. Furthermore it appears from the comment in NEN 6071, that the stable moisture content in buildings is deemed to be so low that the chance of spalling is limited, in practice can be very widely interpreted. Also unheated spaces or those exposed to outside climates (such as car parks) are assumed to be “buildings” for which spalling therefore does not occur.

This deserves at least the recommendation that whether the concrete indeed is located in a heated building should be determined. For an unheated or outside space it should be substantiated that the structure does not spall. For a heated space the chance of spalling is smaller, but for such spaces it is also not possible to rule out damage from spalling.

Thermal cracking takes place in all concrete structures that are exposed to fire. In most cases the concrete is reinforced (upper- and lower rebars and stirrups) and due to this the cracking does not lead to severe damage or collapse. Also this cracking occurs internally and is hardly discernable on the surface of the concrete. For concrete structures that are for the most part un-reinforced (such as elements that are pre-stressed in the longitudinal direction only) it should be shown that thermal cracking does not lead to collapse. Consideration should be given to the connection of structural elements; the thermal stresses are strongly influenced by possible obstruction due to the presence of adjacent elements, or for example a compression layer.

It is reasonable to ascribe the failure of the lift to the amount of extinguishing water that flowed into the building. In the case of the fire in Lloydstraat a large amount of water entered the building due to the action of the fire float. In any case, a water level of 0.3m in a lift well is also to be expected for “normal” actions of the fire brigade.

Due to the absence of a vestibule in front of the staircase a situation existed where smoke directly entered the staircase, thereby hindering the escape of the residents.

6.6 Recommendations

9 The research team advises the standardisation committees w.r.t. NEN 6071 to specify in article 6.1.2. that for structural elements that are unheated and that are exposed to an outside climate it should no longer be taken for granted that spalling does not occur. The commission is advised to state the measures that can be taken and to provide the argumentation that accompanies these measures.

10 The research team advises the standardisation committees w.r.t. NEN 6071 to carry out studies into the consequences of crack formation resulting from thermal gradients in un-reinforced and lightly reinforced concrete structures during fire, also under the influence of loading and restrained deformation.

11 The research team advises the standardisation committees w.r.t. NEN-EN81-72 to investigate whether it is necessary to increase the limit of 1m, as given in the norm.

12 The research team advises the NVBR to inform fire brigades about the risks of the use of a fire brigade lift.

13 The research team advises the relevant Ministries, in consultation with the NVBR, to investigate whether it is necessary to modify the Building Regulations w.r.t. the presence of porches in front of staircases that extend over a height of more than 20m.

7 Behaviour of the building after the fire

In this chapter the behaviour of the structure during the cooling period and after the fire is briefly examined. The following questions were posed:
- did the extinguishing action contribute to the collapse of the hollow core slabs?
- do the regulations take into account effects after the fire?
- did the building structure behave as expected after the fire?
- which failure/collapse mechanisms of the structure could occur after the fire?
- is it possible to determine how unstable the building was after the fire?

7.1 Effect of extinguishing action on building damage

It is unknown to which extent extinguishing with water can cause damage to concrete. While some experts believe that spalling damage can occur during extinguishing, this has never been experimentally investigated under controlled circumstances.
From the report of the Rotterdam fire brigade it is apparent that their (second) attempt at fighting the fire was stopped because banging and cracking noises could be heard coming from the structure. Only after this was the fire float brought into use. Therefore the spalling and cracking (banging and cracking noises) had already started before the fire float was used.
This indicates that the structural damage in any case also already occurred before extinguishing began.

7.2 Cooling period in the regulations

The regulations do not take into account effects during the cooling period. During the cooling period structural elements begin to contract (since usually they have expanded during heating) and this contraction can lead to tensile stresses, which can lead to damage occurring particularly in connections. This last point is a greater concern for steel structures rather than concrete structures and appears not to have yielded problems in the building on Lloydstraat. From the pattern of smoke on the hollow core slabs it could be seen that these did not partly slide off their supports due to contraction.

Even so, it appears that the process of crack formation in the hollow core slabs continued during the cooling phase, since certain parts of the floor slabs only fell down a few hours after extinguishing, see figures 28 and 29. This could be due to the fact that the heat further penetrated the structure. While the surface of the structure is already beginning to cool some of the heat that is already present in the structure will conduct further into the structure.

Figure 28: Photo taken at 06.46 (source: Safety district Rotterdam-Rijnmond)

Figure 29 Photo taken at 09.01 (source: Safety district Rotterdam-Rijnmond)

In no way at all are effects during the cooling phase taken into account in the regulations. Firstly, the formation of thermal cracks is not taken into consideration (neither during heating nor during cooling). Secondly, the fire resistance is determined using the theoretical temperature development according to the standard fire curve. This fire curve describes a continually increasing temperature, due to which at any moment the exposed structure can collapse. If collapse has not (yet) taken place after a period of 30, 60, 90 or 120 minutes, “fire resistance” is referred to. The phase after the attainment of this theoretical fire resistance time is not considered, whereby effects such as further heating through the construction or, on the other hand, cooling of the structure remain out of the picture.

7.3 Stability after fire

It is especially difficult to provide general rules for the assessment of the stability of a building after fire. In fact this depends completely on the structure, the nature of the fire and the damage that has occurred.
In the building considered here it is particularly important to know whether the load bearing façade was still sufficiently strong and was supported sufficiently from the sides. The façade was spalled as far as the reinforcement but because the façade elements are relatively thick this does not have to lead directly to collapse. From the hollow core slabs it can be argued that the floor was very unstable after the fire, and that it was a sensible choice to support this (even though this is a dangerous task).

7.4 Conclusions

Important effects can occur in the structure during the cooling phase. Contraction of structural elements (that have expanded during heating) can lead to large stresses in the structure that can, in theory, lead to collapse. In addition, in structures with a large heat capacity and low heat conduction (such as concrete structures) heat can penetrate deeper into the structure during the cooling phase. This can affect the thermal stress distribution. This presumably leads to extra cracking and collapse of the structural elements.
The effect of accelerated cooling (extinguishing) on such processes is largely unknown.
Application of the “natural fire safety concept” (NFSC) allows a more realistic treatment of fire, with a developing phase, fully developed fire and finally a cooling phase. The design of a structure with the help of the NFSC can, if applied properly, lead to insight into the structural effects during cooling. In addition, it is important that the fire in the compartment is modelled correctly (fire load, growth rate etc) and that the structure is not considered as separate parts but rather as a connected whole, since the connections between structural elements can also cause large internal stresses during cooling.

The stability after fire can only be assessed if there is knowledge of the load bearing characteristics of the building. This knowledge is difficult to obtain from the documents that are typically available. Furthermore, in general it is important that this information is available quickly so that measures should be taken as soon as possible after the fire in order to support the structure if necessary. The structural engineer should undertake calculations with additional scenarios including collapsed or weakened structural elements, in order to better prepare for the “damaged situation”.

7.5 Recommendation

14 The research team advises the fire brigade that when extinguishing the fire and executing other activities in a concrete building within a few hours after the fire, consideration should be given to the possibility that stresses could develop in the structure also during the cooling phase and that deformation or movement could occur.

8 Conclusions and Recommendations

The conclusions and recommendations from the various chapters are summarised in this chapter.

8.1 Conclusions w.r.t. the design of the car park

Apart from the Building Regulations there are only a few guidelines available for the design of car parks. These guidelines are not legal requirements unless they are present in national, provincial or local laws, decrees or acts. No specific requirements are laid down for naturally ventilated car parks.

The regulations do not give any beforehand defined fire loads and / or fire heat release rates for car parks. The guidelines for mechanically ventilated car parks are based on a rate of heat release for three cars and action of the fire brigade 20 minutes after ignition.

The car park on Lloydstraat complies with the conditions for a naturally ventilated car park. It also complies with the prescriptions from the Building Regulations, with the exception of the compartment size.

The guidelines for mechanically ventilated car parks are not applicable to the building on Lloydstraat.

A naturally ventilated car park cannot be considered as an ‘open space’ according to the definition in the Building Regulations. The fire brigade must take into account more severe conditions in a naturally ventilated car park than in a mechanically ventilated car park.

Pre-stressed concrete is frequently applied. The fire resistance of concrete is established with the help of calculations.

8.2 Conclusions w.r.t. the design of the structure

The design of the building at first sight is not unusual.
The LBC consists at least of the building core and the load bearing façade. In addition the floors form a part of the LBC because they provide the connection between the façade and the building core. Also the steel elements supporting the floor are part of the LBC.

The verification of the building by the Local Building Authorities has not been checked by Efectis, because it would have been necessary to check the structural fire resistance calculations. With the exception of the conclusions these calculations were not present in the dossier that was provided to Efectis.

8.3 Conclusions w.r.t. the fire development

The exact time of ignition of the fire cannot be defined. Based on the scenarios that have been presented in this chapter the fire could have had a development time of 13 minutes or more. The development time is dependent on the cause of the fire. As the result of a malfunction, part of the car could have been smouldering for a longer time before the fire developed further. In the case of arson the fire could develop faster than that assumed in the scenarios.

The materials present in the building did not have a significant effect on the fire development. The fire load was formed by the cars that were present.

The models used in this report assume a maximum rate of heat release of 8.3MW per car. In total the maximum rate of heat release is ±20-23MW. This heat release was spread out over the compartment.

A fire curve has been constructed using the models for car fires in car parks. For a fire such as that in the car park in Rotterdam it appears that the temperature in the beginning of the fire can increase faster than that indicated by the standard fire curve. The duration of the thermal load on the structure is shorter than the duration of the load according to the standard fire curve.

The fire development does not agree with the starting points for the regulations and guidelines. In particular the starting points concerning the fire load of the car and the applicability of the standard fire curve are debatable.
On the basis of the regulations and guidelines a fire of this severity was not to be expected.

The severity and course of the actual fire strongly agrees with the theoretical scenario 1, in which the fire begins in the Ford Mondeo. More research into actual fires in car parks is necessary in order to validate the model used here.

The regulations for ventilation in naturally ventilated car parks are not based upon the conditions during a fire such as those occurring in the Lloydstraat fire.

The presence of a fire alarm system would have contributed to the faster arrival of the fire brigade. Through this the fire severity would have been limited and the structure would have undergone less damage, whereby the consequential damage for the residents would have been limited.

8.4 Conclusions w.r.t. the damage to the structure

The damage that is most striking is the excessive crack formation in the hollow core slabs. This includes both horizontal cracks between the individual hollow cores and vertical cracks from the hollow cores extending to the bottom surface of the slab. Over a large area of the damaged slabs, the bottom half of the slab has fallen down. Also some pre-stressing strands detached from the construction and fell down.

At a slightly larger distance from the fire the hollow core slabs are damaged by spalling of concrete up to a depth of a few centimetres. Also the façade elements are damaged to a spalling depth of a few centimetres. On the hollow core slabs the spalling damage in many cases is up to the depth of the hollow cores. On the façade elements, the outer reinforcement has become exposed over a large part of the surface.

The steel THQ beams, and the L-shapes that supported the floor slabs, were protected on the underside by fire resistant boards. The steel parts have not suffered any visible damage.

8.5 Conclusions w.r.t. the behaviour of the building during the fire

The occurrence of concrete spalling is observed in many fires in practice, also in situations where spalling according to NEN 6071 would not be considered an issue. Furthermore it appears from the comment in NEN 6071, that the stable moisture content in buildings is deemed to be so low that the chance of spalling is limited, in practice can be very widely interpreted. Also unheated spaces or those exposed to outside climates (such as car parks) are assumed to be "buildings" for which spalling therefore does not occur.

This deserves at least the recommendation that whether the concrete indeed is located in a heated building should be determined. For an unheated or outside space it should be substantiated that the structure does not spall. For a heated space the chance of spalling is smaller, but for such spaces it is also not possible to rule out damage from spalling.

The research team advises the standardisation committees w.r.t. NEN 6071 to specify in article 6.1.2. that for structural elements that are unheated and that are exposed to an outside climate it should no longer be taken for granted that spalling does not occur. The commission is advised to state the measures that can be taken and to provide the argumentation that accompanies these measures.

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8.6 Conclusions w.r.t. the behaviour of the building after the fire

Important effects can occur in the structure during the cooling phase. Contraction of structural elements (that have expanded during heating) can lead to large stresses in the structure that can, in theory, lead to collapse. In addition, in structures with a large heat capacity and low heat conduction (such as concrete structures) heat can penetrate deeper into the structure during the cooling phase. This can affect the thermal stress distribution. This presumably leads to extra cracking and collapse of the structural elements.
The effect of accelerated cooling (extinguishing) on such processes is largely unknown.
Application of the "natural fire safety concept" (NFSC) allows a more realistic treatment of fire, with a developing phase, fully developed fire and finally a cooling

phase. The design of a structure with the help of the NFSC can, if applied properly, lead to insight into the structural effects during cooling. In addition, it is important that the fire in the compartment is modelled correctly (fire load, growth rate etc) and that the structure is not considered as separate parts but rather as a connected whole, since the connections between structural elements can also cause large internal stresses during cooling.

The stability after fire can only be assessed if there is knowledge of the load bearing characteristics of the building. This knowledge is difficult to obtain from the documents that are typically available. Furthermore, in general it is important that this information is available quickly so that measures should be taken as soon as possible after the fire in order to support the structure if necessary. The structural engineer should undertake calculations with additional scenarios including collapsed or weakened structural elements, in order to better prepare for the “damaged situation”.

8.7 Recommendations

1 The research team advises the NVBR to inform fire brigades about the risks of fire fighting in a naturally ventilated car park.

2 The research team advises the NVBR and the ministries of BZK (Interior and Kingdom Relations) and VROM (Housing, Spatial Planning and the Environment) to investigate in which ways the safety of fire brigade personnel in a naturally ventilated car park can be improved.

3 The research team advises the NIFV to modify the total heat release of the cars to the average value (6650MJ) from the research of CTICM and TNO.

4 The research team advises the NVBR to inform the fire brigade about the possible course of the fire and the severity of a fire in a car park.

5 The research team advises the relevant Ministries (Housing and Internal Affairs) to undertake research into actual fires in car parks, and to revise the regulations and guidelines where necessary.

6 The research team advises the relevant Ministries to investigate whether the implementation of fire detection in car parks under (residential) buildings should be made mandatory.

7 The research team advises the issuer of permits to accept “equivalent solutions” for car parks larger than 1000m^2 only on the basis of the presence of a fire alarm system or an automatic extinguishing system.

8 The research team advises the investigation of whether other possibilities exist for the prevention of fire spread, such as fire/smoke screens on the ceiling between parking spaces, raised borders between parking spaces (prevention of spread of motor fuel spills and suchlike).

9 The research team advises the standardisation committees w.r.t. NEN 6071 to specify in article 6.1.2. that for structural elements that are unheated and that are exposed to an outside climate it should no longer be taken for granted that spalling

does not occur. The commission is advised to state the measures that can be taken and to provide the argumentation that accompanies these measures.

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