Concrete and Fire Safety

Guidance on the use of concrete and masonry
for fire resistant and efficient structures

Contents

CONCRETE ENSURES THAT STRUCTURAL INTEGRITY REMAINS, FIRE COMPARTMENTATION IS NOT COMPROMISED AND SHIELDING FROM HEAT CAN BE RELIED UPON.

Cover image:
Hollowcore fire tests, for more information see page 17.

Introduction

In fire, concrete and concrete masonry perform well – both as an engineered structure, and as materials in their own right: this publication explains how. It is a useful reference guide for designers, clients, insurers and government bodies who need a summary of the important aspects of fire safety design, and the role that concrete can play in maintaining the integrity of the structure, thus preventing the spread of fire and protecting lives. Buildings are covered in depth, while reference is made to tunnels and other structures where concrete is also used.

It is important that we create buildings and structures that minimise risk to both people and property as effectively and as efficiently as possible. Because of concrete's inherent material properties, it can be used to minimise fire risk for the lowest initial cost while requiring the least in terms of ongoing maintenance.

In most cases, concrete does not require any additional fire-protection because of its built-in resistance to fire. It is a non-combustible material (i.e. it does not burn), and has a slow rate of heat transfer. Concrete ensures that structural integrity remains, fire compartmentation is not compromised and shielding from heat can be relied upon.

Benefits of using concrete and masonry:

- Concrete and masonry do not burn, and do not add to the fire load.
- Concrete and masonry have high resistance to fire, and can stop fire spreading.
- Concrete and masonry are effective fire shields, providing a safe means of escape for occupants and protection for firefighters.
- Concrete and masonry do not produce any smoke or toxic gases in a fire, so help reduce the risk to occupants.
- Concrete and masonry do not drip molten particles, which can spread the fire.
- Concrete and masonry restrict fire, reducing the risk of environmental pollution.
- Concrete and masonry provide built-in fire protection – there is normally no need for additional measures.
- Concrete and masonry can resist extreme fire conditions, making them ideal for storage premises with a high fire load.
- Concrete's robustness in fire facilitates firefighting and reduces the risk of structural collapse.
- Concrete and masonry are typically easy to repair after a fire, and so help businesses to recover quicker.
- Concrete and masonry is resilient to damage from water used for fire fighting.
- Concrete, when properly designed, can withstand extreme fire conditions encountered in tunnels.

Design principles of fire

The role of fire safety standards

Fire safety standards have played a major role in reducing the number of fires in the UK over the last two decades from 9000 per million people in 1996/7 to 3000 per million in 2016/17.

UK statistics for 2016/17 showed that of the half a million incidents that the fire and rescue services attended 29% were fires in buildings. These resulted in 261 fatalities of which the vast majority (98%) were in dwellings. (These figures do not include the Grenfell Tower disaster.) However, while it is excellent that the numbers of fatalities have reduced, there is still much work to do to reduce injuries and fatalities further. Also, in buildings other than dwellings, the average area affected by a fire has increased to 86m^2 and this is a concern for businesses where the loss of business resulting from fires runs into millions of pounds each year. It is estimated that around half of all businesses affected by a major fire will cease trading due to the losses incurred during the fire.

Much of design for fire safety is concerned with ensuring that people can escape from the building or structure, firefighters are protected and the fire cannot spread to other properties or areas. Current Building Regulations for England and Wales are written with these three aims and there is no requirement for protection of property or to minimise damage. Clients and project teams may choose to go beyond minimum requirements and provide a higher level of protection against the hazards of fire.

Standard testing methods are used to determine the fire performance of materials and building or structural elements. The tests may be either at a small scale (e.g. in a specially built oven/furnace) or at full-scale (i.e. on a part or whole mock-up of a building).

To enable comparison between tests, standard temperature-time curves have been established. These are:

- Standard fire scenarios for buildings (ISO 834 or BS 476)
- Offshore and petrochemical fires (various curves proposed including hydrocarbon curve in EC1) [1]
- Tunnel fires (a number of different curves proposed including RWS, Netherlands and RABT, Germany).

Each option has a different (idealised) temperature-time curve appropriate to the conditions as shown in Figure 1, below. Notice that the idealised temperature in a building fire rises much more slowly and peaks at a lower temperature than, for example, a hydrocarbon fire (for example, from burning vehicles) because there is generally less combustible material present.

These standard fire curves do not include a cooling phase. Other methods of assessing the fire resistance use a parametric curve, see Figure 2, which tries to represent more closely a real fire and uses the presumed fire load in the compartment. The fire load is a function of the total combustible material.

Figure 1: Standard fire curves for three scenarios: tunnels, hydrocarbons and buildings.

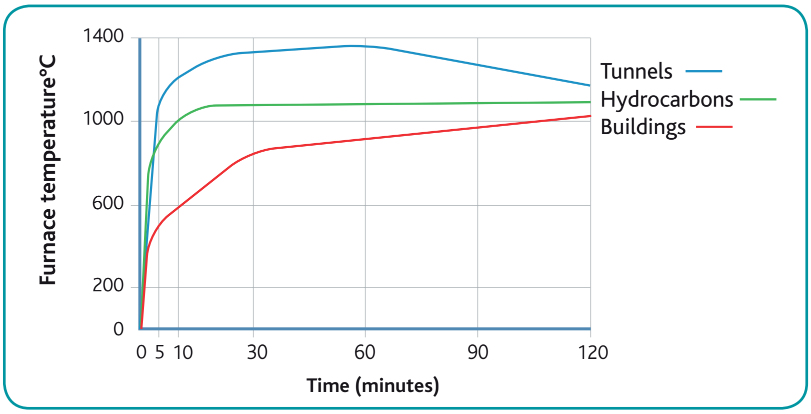
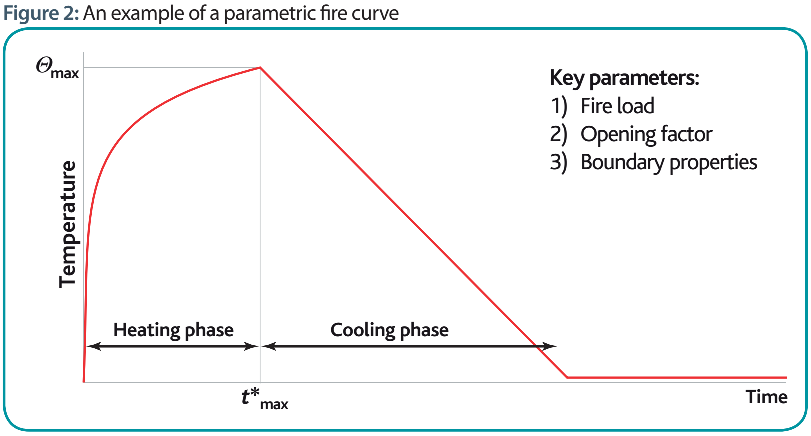


Figure 2: An example of a parametric fire curve



Concrete and fire

Fires require:

- Fuel
- Oxygen
- Heat source

Fires can be caused by accident, energy sources or natural means. The majority of fires in buildings are caused by human error or arson. Once a fire starts and the contents/materials in a building are burning, the fire spreads via radiation, convection or conduction, with flames reaching temperatures of between 600°C and 1,200°C. Harm to occupants is caused by a combination of the effects of smoke and gases, which are emitted from burning materials, and the effects of flames and high air temperatures.

Concrete: the non-combustible material

Concrete does not burn – it cannot be 'set on fire' unlike some other materials in a building and it does not emit any toxic fumes when affected by fire. It will also not produce smoke or drip molten particles, unlike many plastics and metals.

Building materials can be classified in terms of their reaction to fire and their resistance to fire, which will determine respectively whether a material can be used and when additional fire protection needs to be applied to it. EN 13501-1 classifies materials into seven grades (A1, A2, B, C, D, E and F). The highest possible designation is A1 (non-combustible materials). The UK also has a National classification system, which has 'non-combustible', 'limited combustibility', Class 0, 1, 2, 3 and 4 (with the lower number indicating lower combustibility, smoke emission or flame droplets). Concrete and masonry are classed as A1 in the European system and 'non-combustible' in the National system, and do not need any further testing, provided there is no more than 1% by weight of organic matter in the concrete. Modern concretes easily meet this requirement.

In the majority of applications, concrete can be described as virtually 'fireproof'. This excellent performance is due in the main to concrete's constituent materials (cement and aggregates) which, when chemically combined within concrete, form a material that is inert and, importantly for fire safety design, has relatively low thermal conductivity.

Performance in fire

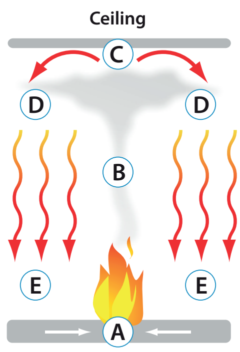
Its relatively low thermal conductivity (heat transfer) enables concrete to act as an effective fire shield not only between adjacent spaces, but also to protect itself from fire damage.

The rate of increase of temperature through the cross section of a concrete element is relatively slow. This means that the internal zones of the concrete do not reach the same high temperatures as a concrete surface exposed to flames. A standard ISO 834/BS 476 fire test on 160mm wide x 300mm deep concrete beams showed that after one hour of exposure on three sides a temperature of 900°C was reached on the surface of the concrete. However, at 16mm from the surface a temperature of 600°C was reached, whilst at 42mm from the surface the temperature had halved to just 300°C. This is a temperature gradient of 300°C in only 26mm of concrete. When the concrete is below 300°C it fully retains its load-bearing capacity.

Even after a prolonged period of fire exposure, the internal temperature of concrete remains relatively low. This quality enables concrete to retain both its structural capacity and fire shielding properties as a separating element. When concrete is exposed to high temperatures in a fire, a number of physical and chemical changes take place. These changes are shown in Table 1, which describes what happens to the material when it is heated to a particular temperature. The temperatures tabled are concrete temperatures, not flame or surface air temperatures.

Spalling is a phenomenon which may occur in particular circumstances in which the surface concrete breaks away at elevated temperatures. In normal buildings under normal fire loads it may not occur at all or is not of significance. However, if, there are concrete strengths above 60MPa, high moisture contents, particular aggregates or the concrete mix contains silica fume, then the likelihood of spalling increases. Designs allow for this in reinforcement detailing and/or the use of polypropylene fibres.

Figure 3: A standard compartment fire



A: Oxygen drawn in to feed fire

B: Smoke plume rising

C: If the flames reach the ceiling they will spread out and increase the heat radiation downward

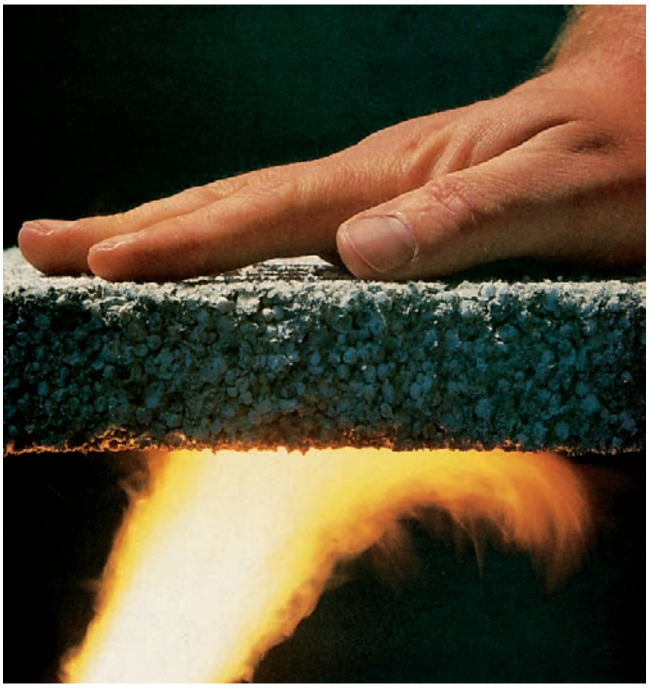
D: Smoke layer forming below ceiling and descending

E: Heat radiated downward onto surface contents

CONCRETE DOES NOT BURN, PRODUCE SMOKE OR EMIT TOXIC VAPOURS

Table 1: Concrete in fire: physiochemical processes

Concrete temperature (°C)	What happens
250-420	Some spalling may take place, with pieces of concrete breaking away from the surface.
300	Strength loss starts, but in reality only the first few centimetres of concrete exposed to a fire will get any hotter than this. Internally the temperature is well below this.
550-600	Concrete experiences considerable creep and loss of load-bearing capacity. However, in reality, only the first few centimeters of concrete exposed to a fire will experience this; internally the temperature is well below this.



Performance after a fire

The majority of concrete structures are not destroyed in a fire. One of the major advantages of using concrete in a structure is that it can usually be easily repaired after a fire, helping to minimise inconvenience and repair costs. The modest floor loads that are actually applied in most building structures, combined with the relatively low temperatures experienced in most building fires, mean that the load-bearing capacity of concrete is largely retained both during and after a fire. For these reasons often all that is required is a simple clean up. Speed of repair and rehabilitation is an important factor in minimising any loss of business after a major fire. These options are clearly preferable to demolition and reinstatement.

Estimates of temperatures reached in the concrete can usually be derived from observations. Often the duration, intensity and extent of a fire can be determined from eye-witness accounts. It may be sufficient to take 'soundings' on the damaged concrete to determine the degree of deterioration. A hammer and chisel can be used to indicate the 'ring' of sound concrete or the 'dull thud' of unsound material. Also, in many concretes the aggregate changes to a pink/red colour at 300°C, the same temperature which indicates strength loss, thus a survey taking small cores can determine the extent of concrete which needs to be removed.

A structural evaluation should follow the material investigation and help determine the method of repair. Repair of concrete exposed to high temperatures is often preferable to demolition and reinstatement for cost reasons. *Assessment, Design and Repair of Fire Damaged Concrete Structures* [2] provides useful detail on this topic.

Case study

Tytherington High School

The impact of a major fire at Tytherington County High School, Cheshire was limited due to the fire resistance of the concrete structure. Rather than taking a year to be demolished and replaced, as was the case with an adjacent lightweight structure, the concrete classrooms were repaired ready for the following term.

Concrete structures

Structural performance in fire

Concrete structures perform well in fire. This is because of the combination of the inherent properties of the concrete itself, together with the appropriate design of the structural elements to give the required fire performance and the design of the overall structure to ensure robustness. Structural frames made of concrete are designed to satisfy this performance demand for overall stability in the event of a fire. Indeed, in many cases concrete structural frames will exceed performance expectations in the event of a fire. The combination of concrete's non-combustibility and low level of temperature rise means that a concrete structure will not burn, and its strength will not be affected significantly in a typical building fire. Furthermore, concrete's inherent fire resistance acts as long-lasting, passive protection. This means that concrete does not have to rely on active firefighting measures such as sprinklers for its fire performance or additional passive fire protection which will be prone to damage during the life of the structure.

Concrete structural elements

Fire performance is the ability of a particular structural element (as opposed to any particular building material) to fulfil its designed function for a period of time in the event of a fire. These criteria appear in UK and European fire safety codes. The three functions of load-bearing capacity (R); flame-arresting separation (E) and heat shielding (I) are detailed in Table 2. Time periods are attributed to each of these to designate the level of fire performance for each function.

For example R120 indicates that for a period of 120 minutes the element will retain its load-bearing capacity when exposed to a standard fire. In the event of a fire, the structure must perform at least to the level required by Building Regulations. In addition, maintaining the stability of the structure for as long as possible is obviously desirable for survival, escape and firefighting. This performance is particularly important in larger complexes and multi-storey buildings.

Concrete protects against all harmful effects of a fire. As a material it has proved so reliable that it is commonly used to provide stable compartmentation in large industrial and multi-storey buildings. By dividing these large buildings into compartments, the risk of total loss in the event of a fire is virtually removed. Concrete floors and walls reduce the fire area both horizontally (through walls) and vertically (through floors). Concrete thus provides the opportunity to install safe separating structures in an easy and economic manner. Its inherent fire shielding properties do not require any additional fire protection materials or maintenance. The five requirements in Table 3 must be taken into account when designing a structure, and this is the foundation for design methods for structural elements in respect of fire safety in the Eurocodes (e.g. Eurocode 2 1-2 Design of Concrete Structures – structural fire design).

Design of concrete elements in fire

The heat flow generated in concrete elements by fire produces differential temperatures, moisture levels and pore pressures. These changes affect concrete's ability to perform at the three limit states. As a structure must be designed to prevent failure by exceeding the relevant fire limit states, the following must be avoided:

- Loss of bending, shear or compression strength in the concrete and reinforcement.
- Loss of bond strength between the concrete and the reinforcement.

The normal factors of safety in design are not applied in the fire case as it is considered to be an accidental loading. The strength of the full section does reduce in a fire, but should not reduce below the required strength.

Therefore, for any element there are two key design considerations with respect to fire:

1. Overall dimensions, such that the temperature of the concrete in the middle of the section does not reach critical levels.
2. Average concrete cover, so that the temperature of the reinforcement does not reach critical levels. Note that prestressing tendon and strand loses strength at a lower temperature than normal reinforcement.

Accepted values for these dimensions have changed over time as a result of research and development, testing and observation of fire-affected concrete structures, with data for design becoming more accurate by providing additional information on:

- The effects of continuity
- Pre-stressed concrete
- Lightweight concrete
- Choice of aggregate
- Strength of concrete
- Depth of cover

Tabulated values are available in the codes of practice. Alternatively more rigorous calculation methods are available to design elements for required fire resistance performance.

Concrete masonry and fire

Like concrete, concrete blockwork is classified as A1 to BS EN 13501-1 and 'non-combustible' under the National classification. It too is very good at maintaining its structural capacity and heat-shielding properties in fire.

Concrete masonry, or blockwork has excellent fire-resisting capacity and can provide fire resistance of up to six hours with relatively thin walls. Such high levels of performance are rarely required. Generally a standard 100mm-thick masonry wall will be more than sufficient to provide the one hour fire separation between apartments, for example. The exact performance varies between block types and load-bearing conditions, and detailed information is provided by manufacturers for their products. As with all fire detailing, the detail of the joints and junctions of a wall require special attention, but can be simply and effectively constructed. Further information on detailing can be found on the LABC website, combining thermal bridging and fire performance.

There is tabulated data for concrete masonry blocks in BS EN 1996-1-2, [3] but most of the options use bricks and blocks not commonly used in the UK. Table 4 (page 8) gives the fire resistance periods for walls constructed of the most commonly used blocks in the UK. Finishes, such as plaster or fire resisting plasterboard, can be added to the walls to provide longer fire resistance periods.

In this warehouse fire in France, the firefighters were able to shelter behind the concrete wall in order to approach the fire closely enough to extinguish the flames. Courtesy of DMB/Fire Press.

Table 2: The three main fire protection criteria, adapted from Eurocode 1 Part 1-2

Designation	Fire limit state	Criterion
Resistance (R)* Also called: Fire resistance Load-bearing capacity	**Limit of load** The structure should retain its load-bearing capacity.	The load-bearing resistance of the construction must be guaranteed for a specified period of time under a standard fire. The time during which an element's fire resisting load-bearing capability is maintained, which is determined by mechanical strength under load.
Integrity (E)* Also called: Flame arresting separation Tightness	**Limit of integrity** The structure should protect people and goods from flames, harmful smoke and hot gases.	There is no integrity failure, thus preventing the passage of flames and hot gases to the unexposed side. The time during which, in addition to fire resistance, an element's fire separation capability is maintained, which is determined by its tightness to flames and gases.
Isolation (I)* Also called: Fire shielding Heat screening Separation	**Limit of isolation** The structure should shield people and goods from heat.	There is no isolation failure, thus restricting the rise of temperature on the unexposed side. The time during which, in addition to both fire resistance and fire separation, an element's fire shielding capability is maintained, which is defined by a permissible rise in temperature on the non-exposed side.

*Note that the letters R, E, I are derived from French terms; they remain so in the Eurocode in recognition that they were first introduced in France.

Table 3: Concrete structural elements and concrete compartment walls

Objective	Requirement	Use of concrete
1. To reduce the development of a fire.	Walls, floors and ceilings should be made of a non-combustible material.	Concrete as a material is inert and non-combustible (class A1).
2. To ensure stability of the load-bearing construction elements over a specific period of time.	Elements should be made of non-combustible material and have a high fire resistance.	Concrete as a material is inert and non-combustible (class A1). Most of its strength is retained in a typical fire due its low thermal conductivity.
3. To limit the generation and spread of fire and smoke.	Walls and ceilings should be made of non-combustible material; fire separating walls should be non-combustible and have a high fire resistance.	In addition to the above statements monolithic connections are possible which are less vulnerable to fire and make full use of structural continuity.
4. To assist the evacuation of occupants and ensure the safety of rescue teams.	Escape routes should be made of non-combustible material and have a high fire resistance, which can be used without danger for a longer period.	Concrete cores are extremely robust and can provide very high levels of resistance.
5. To facilitate the intervention of the fire and rescue service.	Load-bearing elements should have a high fire resistance to enable effective firefighting; there should be no burning droplets.	In addition to all of the above statements, in most fires, concrete will not produce any molten material.

Table 4: Fire resistance periods provided by separating single-leaf concrete masonry walls (notes 1 & 2)

Dense aggregate blocks – Solid blocks (notes 3,4 & 5)		
Concrete masonry wall thickness (note 8)	**Fire rating**	
	No finishes	**With finishes** (note 9)
75mm non load bearing	**1 hour**	**2 hours**
90mm non load bearing	**2 hours**	**3 hours**
90mm load bearing	**1½ hours**	**2 hours**
100mm non load bearing	**4 hours**	**4 hours**
100mm load bearing	**2 hours**	**4 hours**
140mm load bearing	**3 hours**	**4 hours**
190mm load bearing	**4 hours**	**4 hours**

Lightweight aggregate blocks – Solid blocks (notes 3,4 & 5)		
Concrete masonry wall thickness (note 8)	**Fire rating**	
	No finishes	**With finishes** (note 9)
75mm non load bearing	**2 hours**	**4 hours**
90mm non load bearing	**3 hours**	**4 hours**
90mm load bearing	**1 hour**	**2 hours**
100mm non load bearing	**4 hours**	**4 hours**
100mm load bearing	**2 hours**	**4 hours**
140mm load bearing	**3 hours**	**4 hours**
190mm load bearing	**4 hours**	**4 hours**

Aircrete blocks – Block density > 500kg/m³ (note 6) (For density < 500kg/m³ see note 7)		
Concrete masonry wall thickness (note 8)	**Fire rating**	
	No finishes	**With finishes** (note 9)
75mm non load bearing	**3 hours**	**3 hours**
90mm non load bearing	**3 hours**	**3 hours**
90mm load bearing	**1 hour**	**2 hours**
100mm non load bearing	**4 hours**	**4 hours**
100mm load bearing	**2 hours**	**4 hours**
140mm load bearing	**3 hours**	**4 hours**
190mm load bearing	**4 hours**	**4 hours**

Hollowcore floors with structural topping in fire

Hollowcore floor tests carried out by BRE (see page 17) did not include structural toppings and showed good fire resistance. Hollowcore, with and without topping, was the subject of a European project "Holcofire" conducted by BIBM (European Federation of Precast Concrete Industry) and IPHA (International Prestressed Hollowcore Association). The four-year research project studied the state-of-the-art, performed a meta-analysis on a database of 162 fire tests, and executed fire tests in combination with numerical analysis and calculations. The "Holcofire" study concluded that the proven track record of more than 1000 million square metres of installed hollowcore floors in Europe - plus extensive fire testing in laboratories - confirmed that hollowcore floors meet all regulatory, quality and safety requirements. The study also showed that due to its travelling character, fires in car parks are more severe than standard fires, but even under extreme fire conditions hollowcore slabs perform well.

From this research came specific guidance for where a thick structural topping is used on top of the hollowcore planks.

A standard hollowcore plank is able to bend toward the fire, but a hollowcore plank with an applied (cold) thick topping makes the upper flange more stiff and in case of fire may prevent the hollowcore from bending towards the fire. Consequently additional bending and shear stresses in the webs may occur due to a curvature and expansion of the bottom flange. Due to these stresses horizontal web cracks can occur.

For this reason, for toppings greater than 25% of the depth of the hollowcore unit, care should be taken as, in a fire situation, horizontal cracks in the webs may subsequently result in the under flange becoming detached. If the bottom flange of a hollowcore slab floor becomes detached due to fire, the (remaining) hollowcore slab with topping can still meet the requirements of the Building Regulations providing that the tying requirements for precast elements required by PD6687-1 are provided [4].

Notes

1. The data is taken from Tables NA.3.1, NA.3.2, NA.4.1 and NA.4.2 in the UK National Annex to BS EN 1996-1-2: 2005 – Eurocode 6: Design of masonry structures.
2. For load-bearing walls the design load has been taken as the design resistance of the wall which is conservative.
3. The density of dense aggregate blocks (1200-2400 kg/m³) and lightweight aggregate blocks (400-1700 kg/m³) is defined in the NA to Eurocode 6.
4. Solid blocks are a Group 1 masonry unit as defined in Eurocode 6.
5. Hollow and cellular blocks are a Group 2 masonry unit and the fire rating is typically less than a solid block.
6. Aircrete blocks in Eurocode 6 are called autoclaved aerated concrete masonry and are a Group 1 masonry unit.
7. For an aircrete block density below 500 kg/m³ a thicker wall may be needed.
8. The thickness referred to is that of the masonry itself excluding any finishes.
9. The minimum thickness of finishes, such as vermiculite gypsum plaster, is 10mm on both faces.

Blade columns

Blade (or fin) columns are columns that are significantly longer than their width. These are frequently used in residential buildings so that the columns fit within a wall, rather than projecting into a room. One of the easiest ways to design such a column for fire resistance is to make it sufficiently long that it can be designed as a wall and the tabulated data for walls can be be used to size the element. Columns can be regarded as walls when the length is four or more times the width. However, there are times when this is impractical and it is necessary to design a blade column as a column. When designed as a wall it is recommended that the blade column is considered as a wall exposed to fire on both sides even when it forms part of a compartment wall.

The tabulated data for columns in BS EN 1992-1-2 (Eurocode 2 part 1-2) [5] are based on square columns and can be used for circular columns. Rectangular columns are assumed to have the same fire resistance as square columns with sides equalling the smaller dimension, so a 300 x 600 column is assumed to have the same fire resistance as a 300 x 300 column. This is conservative, but closer to reality than assuming that the fire resistance is the same as a square column with the same area.

The first method for tabulated data for columns in EC2-1-2 is Method A. There are restrictions on using Method A:

- effective length of the column under fire conditions: $l_{0,fi} \leq 3$ m. This may be assumed to be equal to l_0 at normal temperature in all cases. For braced building structures where the required standard fire exposure is higher than 30 minutes, the effective length $l_{0,fi}$ may be taken as 0.5 l for intermediate floors and $0.5\,l \leq l_{0,fi} \leq 0.7l$ for the upper floor, where l is the actual length of the column (centre to centre).
- first order eccentricity under fire conditions: $e = M_{0Ed,fi} / N_{0Ed,fi} \leq e_{max}$, where e_{max} is 0.15b in the UK.
- amount of reinforcement: $A_s < 0.04\,A_c$
- the tables are based on the degree of utilisation $\mu_{fi} = N_{Ed,fi}/N_{Rd}$.

Provided these restrictions are met, Method A can be used, as can the formula that Method A is based on. This is given in the following equation:

$$R = 120\,((R_{\eta fi} + R_a + R_l + R_b + R_n)/120)^{1.8}$$

Where:

- $R_{\eta fi} = 83(1.0 - \mu_{fi})$ (in the UK)
- $R_a = 1.6\,(a - 30)$, (a is the axis distance and $25mm \leq a \leq 80mm$)
- $R_l = 9.6\,(5 - l_{0,fi})$, ($2m \leq l_{0,fi} \leq 6m$ when using the equation)
- $R_b = 0.09\,b'$, ($b' = 2A_c/(b+h)$ and $b \leq b' \leq 1.2b$; h is the length of the rectangular column and b is the width)
- $R_n = 0$ for n = 4 (corner bars only) or $R_n = 12$ for n > 4 (where n is the number of longitudinal bars in the column)

Table 5 shows the fire resistance of blade columns where h≥1.5b. This data is derived using a method published in The Structural Engineer [6]. If h/b≥4 then the column should be designed as a wall and the tabulated data for walls in Table 5.4 of the Code should be used.

Table 5: Fire resistance data for blade or fin columns.

	μ_{fi}		
b	0.2	0.5	0.7
200	R119/a=30 R149/a=40	R78/a=30 R103/a=40	R55/a=30 R77/a=40
250	R128/a=30 R160/a=40	R86/a=30 R112/a=40	R62/a=30 R85/a=40
300	R139/a=30 R171/a=40 R206/a=50	R95/a=30 R122/a=40 R153/a=50	R69/a=30 R94/a=40 R121/a=50
350	R149/a=30 R182/a=40 R218/a=50	R103/a=30 R132/a=40 R164/a=50	R77/a=30 R102/a=40 R131/a=50

b is the smaller dimension or width of the column
R is the fire resistance in minutes
a is the axis distance - the distance from the centre of the main reinforcement to the face of the concrete.

Interpolation can be used

Fire safety engineering

Normally fire design is based on prescriptive methods and elements are considered separately. Fire safety engineering applies scientific and engineering principles to the design of whole buildings in the case of fire. It is based on the understanding of the effects of fire, the reaction and behaviour of people to fire and how to protect people, property and the environment.

Whole building behaviour

Whilst standard code provisions consider structural elements in isolation, in reality elements interact with one another. The interaction of elements can result in structures being more resilient than assumed in the design.

Where a concrete member, for example a slab, expands under high temperatures to push against the surrounding structure, a mechanical arching effect takes place within the slab. This can provide an alternative load-bearing path for the reinforced concrete structure. This compression action can greatly increase the load capacity of a slab.

Large scale testing has also improved the understanding of a phenomenon known as tensile membrane action. If a slab is highly deformed due to fire, the reinforcement in both the top and bottom of the slab can act in tension as a catenary to transmit the loads back to the supports. The temperature of the top reinforcement tends to be fairly low as the cover from the fire compartment below is large. This means that the tensile strength for this catenary action is at normal levels and not affected by higher temperatures.

On occasions the interaction of elements may be non-beneficial, for example, slender columns being pushed out of position by the expansion of horizontal elements.

Structural fire engineering

The specialist discipline of structural fire engineering involves the knowledge of fire load, fire behaviour, heat transfer and the structural response of a proposed building structure. The application of structural fire engineering allows a performance based approach to be carried out which can allow more economical, robust, innovative and complex buildings to be constructed than those using the traditional prescriptive rules and guidance approach to fire design.

The growth of structural fire engineering as a discipline is in response to the savings which result from carrying out such structural fire calculations. However, it does have the potential to make future change of use of a building more difficult as there is less redundancy in the design.

The method allows flexibility to increase levels of safety by, for example, protecting the building contents, the superstructure, heritage, business continuity or corporate image. Due to the inherent fire resistance of concrete and masonry structures, they can be used effectively to increase the fire resistance of buildings above that required just for life safety.

Moving from prescriptive to performance-based design

One of the most significant changes in fire safety design for structures has been the move away from prescriptive, tabulated code values for individual elements, which are based on research tests and observations of fire-affected structures. Such data can be inherently conservative when translated into generic tables because it assumes that elements act in isolation and are fully stressed, whereas the elements in any structure act quite differently – as part of a whole.

Individual elements that conform to a particular rating (as tested on a specimen in a 'standard' fire) normally have a better fire performance when acting as part of a structure. In fact, the use of prescriptive, target fire resistance ratings such as those found in the tabulated data in EC2-1-2 have been found to be rather limiting in practice, particularly in fire engineered structures. Elements are classified in strict time periods (e.g. 30, 60, 90 or 120 minutes). The delineation between aggregates is based simply on lightweight or dense concrete, which does not reflect the range of concretes commonly used today.

For these reasons, performance-based structural analysis is becoming more common. Computer modelling techniques are now capable of simulating structural conditions that are very difficult to study even in a full-scale fire test. The development of such software has encompassed thermal analysis (for separating walls), structural analysis (for load-bearing floors) and hydral analysis (to predict moisture movement and spalling). Computer programs capable of performing all three types of analysis (thermohydromechanical analysis) were first developed in the 1970s. They have been refined by researchers in the UK and Italy, particularly in response to tunnel fires and several 3D software tools have been developed for advanced analysis of complex structures.

Since the 1990s, the performance-based approach has permeated into national building codes in countries such as Sweden, Norway, Australia and New Zealand, allowing a cost effective and highly adaptable approach to design. Eurocode 2 is based on such an approach to fire safety design. By considering minimum dimensions in terms of load ratios for individual elements, Eurocode 2 is inherently more flexible and well founded in its methodology than previous design codes.

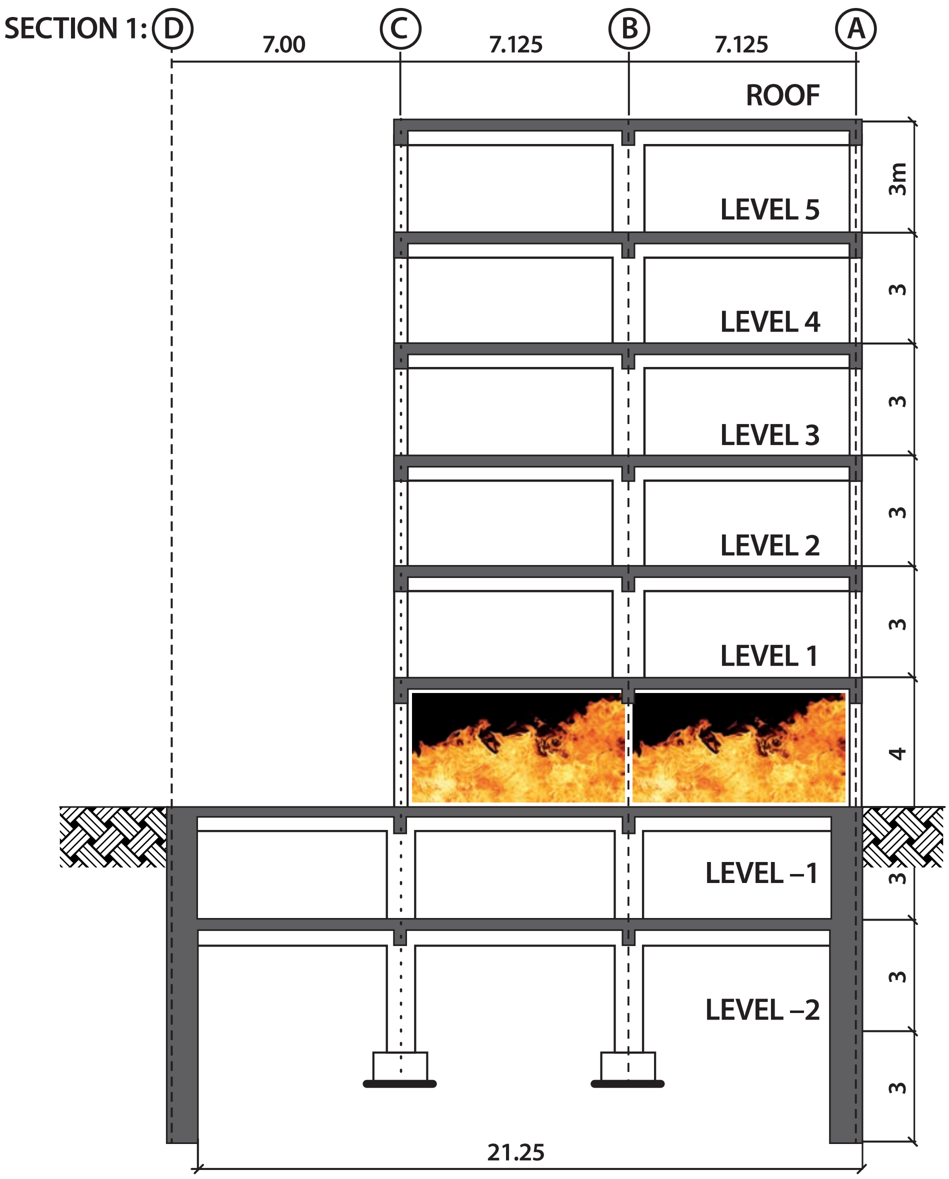
DUE TO THE INHERENT FIRE RESISTANCE OF CONCRETE AND MASONRY STRUCTURES, THEY CAN BE USED EFFECTIVELY TO INCREASE THE FIRE RESISTANCE OF BUILDINGS ABOVE THAT REQUIRED JUST FOR LIFE SAFETY.

Fire safety engineering and concrete

Although fire safety engineering is common for steel framed buildings, it has not been used much for concrete framed buildings. The additional cost of increasing the size of the concrete element or adding a few more millimetres to the cover tends to be insignificant and therefore a leaner approach, which costs more in design, is seldom cost-effective for a client.

A fire safety engineering design has been carried out by CERIB, the French research organisation for concrete, on behalf of the European Concrete Platform following the ISO/TS 24679: 2011 standard "Fire safety engineering, performance of structures in fire". A typical six-storey building was designed using Eurocode 2 Part 1-1. The tabulated data for fire from Part 1-2 were not used for the sizing of the structural elements, but rather these were sized purely for strength and serviceability requirements under the normal temperature (non-fire) conditions.

A fire in the ground floor of the building was modelled using finite element analysis of the temperature gains. Various scenarios were considered, such as no intervention from the fire service, the sprinklers not working, the amount of combustible material being very high or very low, etc. The possibility of the concrete structure failing due to any of these scenarios, or combinations of these scenarios, was shown to be very low with even the worst case of no fire service, no sprinklers and very high fire load only giving a 2.2% possibility of failure. Given that the concrete elements were designed for strength and serviceability only, with no consideration of fire, this research demonstrates the inherent fire resilience of concrete structures.



Cross section through the model under investigation

Specialist design guidance

Some types of structure require more rigorous analysis or consideration in the case of fire. This tends to be where the risks are higher, such as in tall or complex buildings which are more difficult to evacuate from, or the fire load is greater, such as tunnels or liquid fuel storage. When designing these types of structure it is worth considering seeking specialist guidance.

Tall buildings

Tall buildings require higher degrees of fire resistance as they normally have more occupants and it is more difficult to fight fires in tall buildings. Standard firefighting appliances can reach up to 18m high, but specialist equipment is required for heights that are greater. Tall buildings should be designed to allow the occupants to leave the building through smoke-free staircases. Lifts cannot normally be used during a fire so safe spaces should be provided for anyone unable to use stairs. Smoke-free staircases and dedicated lifts should provide access for fire-fighters.

Concrete is able to provide a safe egress route to safety and safe spaces for anyone unable to use those routes. Because concrete typically provides greater than the minimum fire resistance period, the structure can remain intact even during a major fire such as that which engulfed the Grenfell Tower in London in June 2017.

Liquid fuel storage

Concrete storage tanks for oil and other flammable liquids can be seen all over the world. Due to concrete's excellent fire resistance compared with some other materials, concrete liquid fuel storage tanks can be built nearer to one another with the reassurance that a fire local to one tank is less likely to spread to adjacent tanks.

Tunnels

Tunnel fires can reach higher temperatures than experienced by buildings, particularly when burning fuel, asphalt and vehicles are part of the incident. Temperatures have reportedly reached up to 1,350°C, but more usually reach around 1,000 - 1,200°C. Peak temperatures in a tunnel fire are reached more quickly than in buildings mainly because of the calorific potential of hydrocarbons contained in petrol and diesel fuel.

Major incidents, such as the fires in the Channel Tunnel (1996), Mont Blanc Tunnel (1999) and St Gotthard Tunnel (2001), highlighted the devastating consequences of tunnel fires.

The use of concrete for road surfaces in tunnels is helpful. It can provide part of the structural design of the tunnel and just as important, because concrete does not burn, it does not add to the fire load within the tunnel. Since 2001, all new road tunnels in Austria over one kilometre in length have been required to use a concrete pavement.

Concrete is often used as a tunnel lining on its own or with a thermal barrier. Much research has gone into developing concrete lining materials to minimise the effects of spalling from lining surfaces when exposed to severe fires.

Protective structures

Concrete is probably the most versatile material in the world with which to build protective structures for defence, research or commercial purposes. It can be moulded into almost any shape and designed to withstand predicted imposed dynamic or static stress. Where radiation shields are necessary, normal weight concrete is considered to be an excellent material for construction because it attenuates both gamma and neutron radiation. Concrete is used in pressure and containment vessels for nuclear reactors and for particle accelerators such as cyclotrons. The addition of heavier aggregates such as magnatite makes concrete even more effective at preventing gamma ray penetration. This performance characteristic of concrete applies not only to protective shields but also to the storage of radioactive waste and structures in which isotopes are handled.

Blast protection

Structures that are specifically meant to afford protection against blasts include missile silos, explosive stores, facilities where explosives are handled and tested, factories where explosive conditions can arise, and military and civil defence shelters. Concrete is well suited for such structures, whether for underground use or located within a normal building.

In addition, there is growing awareness of the vulnerability of buildings to external attack. Precast concrete cladding panels used on the MI6 Headquarters in London prevented the building suffering significant damage after a rocket attack in September 2000.

Spalling

Use of fibres to prevent spalling

Spalling may sometimes be a part of concrete's response to the high temperatures experienced in a fire. For normal buildings and normal fires (e.g. offices, schools, hospitals, residential), design codes already include the effect of spalling for these applications. For example, research on the experimental results used as the basis for developing the UK structural concrete design code BS 8110 found that these results supported the assumed periods of fire resistance and in many cases were very conservative [9].

Figure 4 shows a comparison between floor slab performance in fire tests and their assumed performance within the design codes. Many of the specimens experienced spalling during the fire tests, so the fact that most slabs exceed assumed levels of performance is clear evidence that spalling is accounted for in design codes. The fire test carried out at Cardington in 2001 on a seven storey concrete frame (see the section on fire tests on page 17) showed that, although significant spalling occurred during the test, the slab was able to withstand the imposed load throughout the test and for many months following.

High performance concretes, which are often used for tunnels and bridges, can be vulnerable to spalling because they are very dense. High performance concretes are characterised by low permeability, which can mean that very high pore pressures can build up during a fire. One option is to cover the surface of the structural concrete with a thermal barrier. However, a more efficient solution is to incorporate polypropylene fibres within the concrete mix. Researchers believe that by melting at 160°C, these fibres and any micro cracks adjacent to them provide channels for moisture movement within the concrete, thus increasing permeability and reducing the risk of spalling.

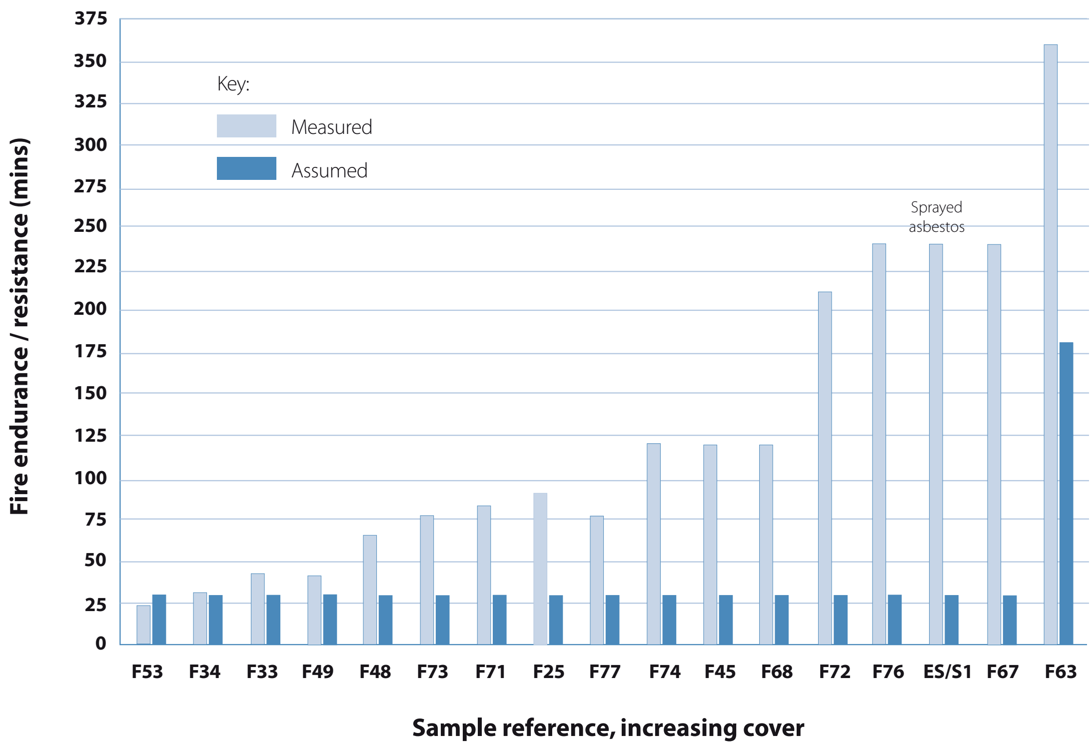
The use of fibres in high performance concrete to prevent or limit spalling is a proven technique. Research is continuing to optimise performance.

Currently Eurocode 2-1-2 allows four methods of designing a high strength concrete against spalling. These are:

1. A reinforcement mesh.
2. Using a type of concrete that has been shown to resist spalling.
3. Using protective layers.
4. Using 2kg/m^3 monofilament polypropylene fibres in the concrete mix.

The easiest method is the use of method 4, polypropylene fibres. These can also be used in lower strength concretes if the risk of spalling needs to be reduced.

Figure 4: Comparison between measured (light blue) and assumed (dark blue) fire resistance based on depth of cover [9].



Experience of fires

Lessons can be learnt from the performance of buildings in real fires. A large number and range of fire damaged concrete structures in the UK have been investigated. Information was collected on the performance, assessment and repair of over 100 structures including dwellings, offices, warehouses, factories and car parks of both single and multi-storey construction. The forms of construction examined included flat, trough and waffle floors, plus associated beams and columns, and examples of in-situ and precast concrete construction in both reinforced and prestressed concrete.

Examination of this information showed that:

- Most of the structures were repaired. Of those that were not, many could have been repaired but were instead demolished for reasons other than the damage sustained.
- Almost without exception, the structures performed well during and after the fire.

Lower insurance premiums with concrete

Every fire causes an economic loss. In most cases, insurers have to pay for the damage caused. For this reason, insurance companies maintain comprehensive and accurate databases on the performance of all construction materials in fire. This knowledge is often reflected in reduced insurance premiums.

Insurance premiums for concrete buildings across mainland Europe tend to be less than for buildings constructed from other materials which are more often affected badly or even destroyed by fire. In most cases, concrete buildings are classified in the most favourable category for fire insurance due to their proven fire protection and resistance. Of course, every insurance company will have its own individual prescriptions and premium lists, which will differ between countries. The fact remains, however, that because of concrete's good performance, most insurers will offer benefits to the owners of concrete buildings. When calculating a policy premium, insurers will take the following factors into account:

- Material of construction
- Type of roof material
- Type of activity/building use
- Distance to neighbouring buildings
- Nature of construction elements
- Type of heating system
- Electric installation(s)
- Protection and anticipation (preparedness)

For example, insurance premiums for warehouses in France are reduced if concrete is chosen [7]. Selecting a concrete frame and walls for a single storey warehouse presents a possible 20 per cent reduction on the 'standard'/average premium paid. In deciding the final premium, the insurers also take into account security equipment, fire prevention and suppression measures, which include compartmentation – a fire prevention option which concrete construction options excel at.

Independent fire damage assessment

An independent investigation of the cost of fire damage in relation to the building material which houses are constructed from was based on statistics from the insurance association in Sweden (Forsakringsforbundet). The study was on large fires in multi-family buildings in which the value of the structure insured exceeded €150k. The sample set was 125 fires which occurred between 1995 and 2004. The results showed that:

- The average insurance payout per fire and per apartment in concrete/masonry houses is around one fifth that of fires built from other materials (approx €10,000 compared with €50,000)
- A major fire is less than one tenth as likely to develop in a concrete/masonry house than one built in other materials
- Of the concrete houses that burned only nine per cent needed to be demolished whereas 50 per cent of houses built from other materials had to be demolished.

Case study

Windsor Tower Fire, Madrid, 2005

The protection provided by concrete is clearly shown by the behaviour of the Windsor Tower, Madrid during a catastrophic fire in February 2005. The concrete column and cores prevented the 29-storey building from total collapse, while the strong concrete transfer beams above the 16th floor contained the fire above that level for seven hours.

The fire caused €122 million of damage during the refurbishment of a major multi-storey office building in Madrid's financial district and provides an excellent example of how traditional concrete frames perform in fire.

Built between 1974 and 1978, the Windsor Tower included 29 office storeys, five basement levels and two 'technical floors' above the 3rd and 16th floors. The 'technical' or strong floors, each with eight super-deep concrete beams (measuring 3.75m in depth – the floor to ceiling height elsewhere), were designed to act as massive transfer beams. The plan shape of the building was essentially rectangular, measuring 40m x 26m from the third floor and above. Normal strength concrete was used for the structural frame's central internal core, columns and waffle slab floors with the floors also supported by tubular steel column props on the facade.

At the time of the structure's original design, water sprinklers were not required in Spanish building codes. With subsequent amendments to legislation, the tower was being refurbished to bring it into line with current regulations. The scope of the refurbishment work included fireproofing every steel perimeter column, adding a new facade and external escape stairs, and upgrading alarm and detection systems, as well as the addition of two further storeys.

The fire broke out late at night on the 21st floor, almost two years after the start of the refurbishment programme, and at a time when the building was unoccupied. Once started, the fire spread quickly upwards through openings made during the refurbishment between perimeter columns and the steel/glass facade. It also spread downwards as burning facade debris entered windows below. The height, extent and intensity of the blaze meant firefighters could only try to contain it and protect adjacent properties while the fire burned for 26 hours, engulfing almost all the floors in the building.

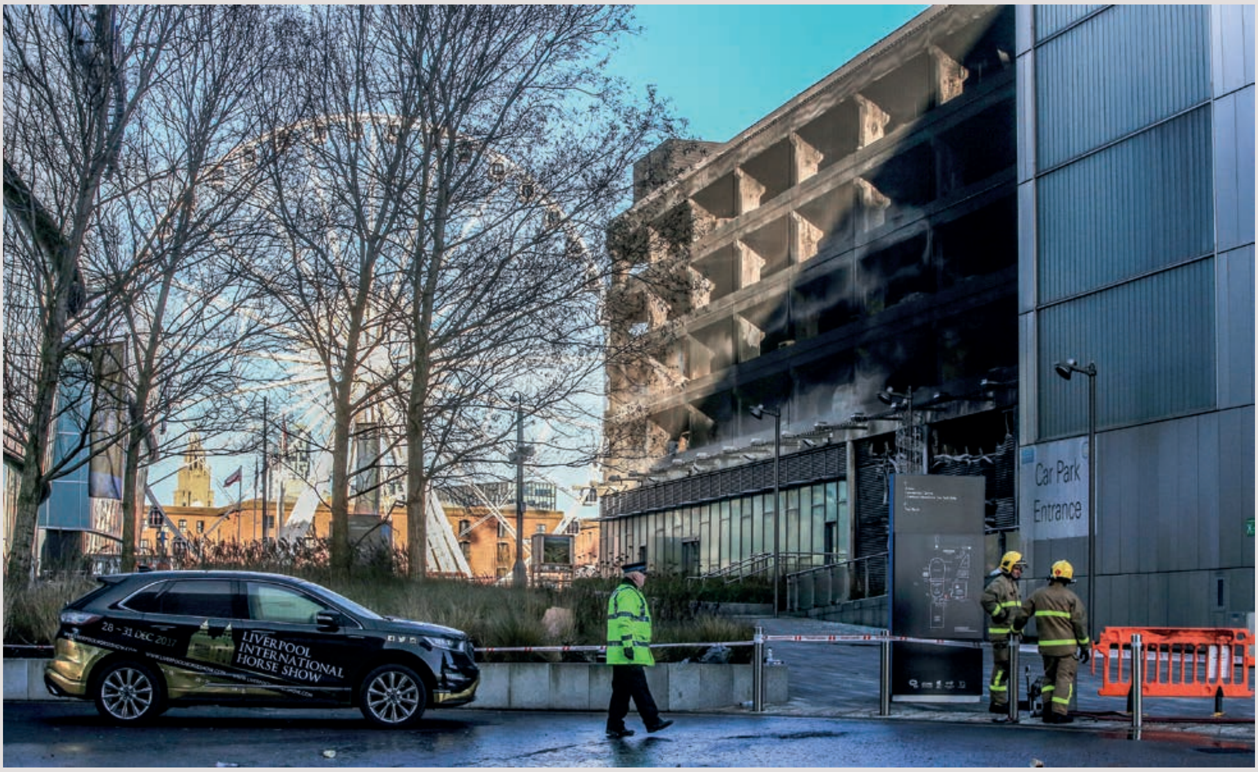
When the fire was finally extinguished, the building was completely burnt out above the fifth floor. With most of the facade destroyed, there were fears that the tower would collapse. However, throughout the fire and until eventual demolition, the structure remained standing.

Only the facade and floors above the upper concrete 'technical floor' suffered collapse. The perimeter steel columns above the upper technical floor had yet to be fire-proofed during the refurbishment works. These failed and the slabs which they supported collapsed. Some internal concrete columns also subsequently failed due to increased loading from slabs that had lost their perimeter support or the impact of falling slabs. The passive resistance of the concrete columns and core helped prevent total collapse, but the role of the two concrete 'technical floors' was critical, particularly the one above the 16th storey, which contained the fire for more than seven hours. It was only then, after a major collapse, that falling debris caused fire to spread to the floors 15 and below. But even then, damage was limited to the storeys above the lower 'technical floor' at the third level.

This presents powerful evidence of the inherent passive fire resistance of concrete and also that strong concrete floors placed at regular intervals in a structure can minimise the risk of progressive collapse and prevent the spread of fire. The forensic report on the fire performance of the Windsor Tower was carried out by Spanish researchers from the Instituto Tecnico de Materiales y Constucciones (Intemac). The independent investigation focused on the fire resistance and residual bearing capacity of the structure after the fire. Amongst Intemac's findings, the report states that: *"The Windsor Tower concrete structure performed extraordinarily well in a severe fire…The need for due fireproofing of the steel members to guarantee their performance in the event of a fire was reconfirmed. Given the performance of these members on the storeys that had been fireproofed, it is highly plausible, although it can obviously not be asserted with absolute certainty, that if the fire had broken out after the structure on the upper storeys had been fireproofed, they would not have collapsed and the accident would very likely [have] wreaked substantially less destruction".*

Case study

Car Park Fire, Liverpool, 2017



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A major fire broke out at the Liverpool Echo Arena multi-storey car park on 31 December 2017. It was unprecedented because the fire spread rapidly from one car to others on that level and on to other levels. The seven-storey building was gutted and 1,400 cars were destroyed. Luckily, no-one lost their life as people in the car park at the time of the fire were able to escape down the concrete stair cores. The building had a substantial reinforced concrete frame which withstood the fire although some of the thin concrete slabs suffered significant damage.

The fire

The car park was adjacent to two apartment blocks, which were occupied during the fire. The car park was almost full when fire broke out in a vehicle on the third floor. Merseyside Fire and Rescue Services arrived within a few minutes by which time the fire had spread to several adjacent cars. Some cars were abandoned on the ramps and the occupants left through the protected staircase towers. Firefighters attacked the blaze from within the third floor but were unable to stop its spread. The fire was prevented from spreading to adjacent buildings and was put out after several hours. There were no casualties, and no complete collapse so the event is classed as a near-miss in both life-safety and structural terms.

The building

The car park was built in 2006 and the overall size was approximately 70m x 60m with columns at about 7m centres in the shorter direction. There were four spans of beams in the longer direction and four concrete stair and service cores with fire doors onto the parking floors. Precast ribbed slabs spanned 7m between the beams, and these were badly damaged by the fire. The stair cores were relatively undamaged, aside from some structural cracking.

As an open car park, this would only have needed a fire rating of 15 minutes in accordance with Approved Document (AD) Part B [8]. The SCOSS (Standing Committee on Structural Safety) Alert on the car park fire stated, "Given that it withstood a hydro-carbon type fire for several hours with limited damage is a testament to the inherent robustness and fire-resistant nature of the structure."

Fire tests

During a fire, concrete performs well, both in terms of its material properties and as a structural element. However, driven by a culture of continual improvement, the concrete industry continues to undertake research into the inherent characteristics of the material that allow it to perform well in the event of fire.

Systematic research into the effects of fire on concrete buildings dates back to the early 1900s, when researchers began looking into both the behaviour of concrete as a material and the integrity of concrete structures. François Hennebique, one of the pioneers of reinforced concrete, carried out a full scale test in Paris as early as 1920 at a firefighter's congress. From 1936 to 1946 a series of tests was carried out at the Fire Research Station in Borehamwood, in the UK. These tests formed the basis of modern design codes for concrete structures such as CP 110, the code which later became BS 8110. Further information on major changes to fire design codes in the UK can be found in the comprehensive Building Research Establishment (BRE) study Fire safety of concrete structures: Background to BS 8110 fire design [9]. This report explains how research and development has informed code development and how newer, performance-based approaches are better equipped to facilitate the efficient design of robust concrete structures.

A full scale fire test was carried out on an in-situ flat slab in the concrete test building at BRE Cardington in September 2001. The building was designed as part of a research project into the process of construction, for which the fire test was not a primary objective. The high-strength concrete with high moisture levels was therefore not typical of buildings and designers would have taken additional efforts to minimise spalling if it was a real building. As a result, extensive spalling occurred, but despite this, the slabs supported the loads throughout the test and afterwards. The results from the test were summarised in the BRE publication Constructing the Future issue 16 as "The test demonstrated excellent performance by a building designed to the limits of Eurocode 2". The report stated "The building satisfied the performance criteria of load bearing, insulation and integrity when subjected to a natural fire and imposed loads. The floor has continued to support the loads without any post fire remedial action being carried out." [10]

Two full scale tests were carried out in March 2006 on precast hollowcore floors supported on fire protected steel frames at the BRE fire test facility at Middlesbrough. Each fire test was carried out on a three-bay frame with 200mm deep hollowcore units, without any structural topping, spanning seven metres resulting in a total floor plate area of 125m^2. The two tests were identical with the exception of the second test having a more robust detail to tie the units and the supporting steel beams together. Both floor plates, which were subjected to very severe fire conditions, performed extremely well supporting the imposed loads during both the heating and cooling phases of the fire. The results of the tests demonstrated that a beneficial load path was created by lateral thermal restraint to the floor units and that full scale testing replicated the experience gained from real fires where precast hollowcore floor slabs have been proven to have excellent overall inherent fire resistance [11].

Fire safety of concrete structures: Background to BS 8110 fire design [9] published by BRE provides a summary of fire tests that underpin the development of concrete design codes.

BRE's full-scale tests in 2006 demonstrated extremely good performance of the 200m deep hollowcore floor plate.

BRE used masonry walls to provide the fire containment for its full-scale hollowcore floor fire tests because of masonry's fire performance credentials.

Summary

Fire safety is a key consideration in the design and use of buildings and structures. Extensive legislation and design codes are in place to protect people and property from the hazards of fire. The continuous development of these codes has ensured that ongoing research and development work is incorporated in current practices during design, construction and occupancy.

Extensive research into the performance of concrete in fire means that there is an excellent understanding of the behaviour of concrete both in a structure and as a material in its own right. This basic science will provide the essential information to support the move from prescribed tabulated values for fire resistance to computer simulation and performance-based fire safety engineering.

While prescriptive data will continue to have a role to play, standards such as Eurocode 2 incorporate greater degrees of flexibility on the sizing of concrete elements for fire safety. This means designers will have scope for more efficient design of concrete structures that meet everyone's needs.

Concrete also provides a mechanism for designers to provide a level of protection in excess of regulations. Clients may choose this so as to increase property safety rather than only provide minimum life safety protection.

EXTENSIVE RESEARCH INTO THE PERFORMANCE OF CONCRETE IN FIRE MEANS THAT THERE IS AN EXCELLENT UNDERSTANDING OF THE BEHAVIOUR OF CONCRETE BOTH IN A STRUCTURE AND AS A MATERIAL IN ITS OWN RIGHT.

Using concrete and masonry construction limits the risk of devastating fires during construction.

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