2.1 Fire Resistance

Introduction

Concrete masonry is generally considered to have good fire resistance since it is non-combustible (i.e. it does not burn), absorbs heat only slowly, and does not give off toxic fumes or smoke. As it is a poor conductor of heat and has a high heat capacity, concrete is used to protect other construction materials such as steel and timber from fire. In addition, it is this slow heat absorption which enables concrete to act as an effective fire shield to protect adjacent spaces and contents, as well as itself from internal fire damage.

These inherent properties, combined with the appropriate design of structural elements, ensure concrete performs well in fire.

However, there are some issues surrounding concrete's performance in fire which require careful consideration. This bulletin outlines these issues, while providing general guidance to designers and specifiers on the design of concrete structures against fire.

Principles of Fire Protection

The first and most important objective in fire protection is to safeguard the lives of any people who are in the structure which is on fire, and enable them to exit the building quickly and safely. Secondly, the structure must be designed to allow enough time for fire fighters to safely carry out any search and rescue operations, along with firefighting operations. Thirdly, there are requirements to protect other property under the New Zealand Building Code (NZBC), these include preventing the fire from spreading as well as preventing hazardous materials at the fire site entering waterways.

Concrete masonry is commonly used to provide stable firecells in large industrial or multi-storey buildings as a means to contain a fire and prevent it spreading to the whole building. This is also called fire separation or compartmentation. Concrete walls reduce the spread of fire horizontally and concrete floors vertically. Concrete provides the opportunity to install safe separating structures in a reliable and economical way.

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. The three functions of Stability (R), Integrity (E) and Insulation (I) are universally recognised to define fire protection. Time periods (fire ratings) are attributed to each of these functions to designate the level of fire performance.

The overall Fire Resisting Rating of an element is termed FRR, thus a FRR of 90/90/90 requires a 90 minute rating for each of stability, integrity, and insulation.

Stability

Stability is the load bearing capacity provided by the primary elements within a firecell and includes elements which are part of the structural frame as well as those providing support to other fire rated elements.

The Stability fire rating (R) is based upon the time an element can withstand a standard fire test and retain its loadbearing capacity while allowing for a level of superimposed load.

Integrity

Integrity is the flame arresting separation typically provided by secondary elements, e.g. internal walls, to protect people and goods from flames, harmful smoke and hot gases. Primary elements, along with secondary elements, are also rated for integrity.

The time during which an element's fire separation capability is maintained is determined by the tightness of joints to limit smoke and gas penetration.

Most casualties suffocate in a fire because of the smoke rather than burn in the flames. Concrete does not develop smoke during fire.

Insulation

Insulation is the heat shielding capability provided by either primary or secondary elements. It is applied to fire separations where the transmission of heat may endanger occupants on the non-exposed side or cause fire to spread to other fire compartments. The fire rating is the time defined by a maximum permitted rise of temperature on the non-exposed side.

Active versus Passive Fire Protection

Concrete's and concrete masonry's inherent fire resistance provides a robust passive protection system that usually requires no additional fireproof linings or coatings.

Fire protection for lightweight construction often relies on active protection systems such as sprinklers. However, the robustness of sprinkler systems following an earthquake has been questioned in light of the vulnerability of reservoir water supply and the significant risk of a post-earthquake fire. Many reservoirs are fitted with auto-shut valves for earthquake events.

The integrity of fire linings following an earthquake has also been brought into question by BRANZ research, particularly where dislodged plaster filling at joints, resulting from seismic shaking, compromised the integrity by 40%. In addition, it has also been found that poor workmanship in retrofitting of structures after installation of services through lightweight fire rated elements has compromised subsequent levels of fire protection. Furthermore, fire linings/paint could be damaged by impact e.g. hit by the edge of carried through items or furniture.

It is fashionable to pour scorn on the “old fashioned” approach for fire containment by using a masonry wall between occupancies. Reliance must be placed in "up market active systems" if one is to remain in fashion.

The Great Fire of London, 1666, was one event that led to the use of masonry walls between occupancies. In 1940 the fire-bombing of cities such as London put the “masonry system” to the ultimate test, i.e., containment of fire since for the most part little water was available.

New Zealand in common with other countries has embarked on a series of fire protection code changes. By and large, previous codes have been claimed to be ultra conservative and too prescriptive with requirements demanding the use of non-combustible materials such as concrete or concrete masonry.

Associated with changes in fire resistance ratings are changing requirements for using sprinkler systems. While few would question the efficiency of fire control when these active systems work, examples can be quoted of their failure to activate. Indeed, the question of activation after, for example, an earthquake when water pressure may be lost could be critical.

It is these circumstances that PASSIVE control by compartmentisation is paramount using non-combustible materials which have a proven in-service track record. While the passive system does not put the fire out it certainly can prevent spread. It is argued that compartmentisation passive rules should not be relaxed when active systems such as sprinklers are included. Sprinklers may well reduce contents fire loss for the owner and are therefore desirable from an insurance point of view. If they do not work then it is a statistical risk for insurers.

Concrete Performance in Fire

At temperatures of 150°C upwards there is some loss of water from the silicate hydrates in concrete, while temperatures above 300°C result in the loss of bound water, and in turn strength.

While concrete may undergo strength loss at temperatures 300°C and above, the main losses are not apparent until above 500°C. Even though flame temperatures are up to double 500°C, the temperature of the internal concrete remains relatively low as a result of concrete’s slow heat absorption. Therefore, only intense fires of long duration may cause any weakening of concrete structures.

Cement type can have some influence on strength loss. Cements with fly ash and ground granulated blast furnace slag have lower quantities of free calcium hydroxide which can give reduced hydration loss on heating, and consequently lower strength loss.

The fire rating of a concrete is also influenced by the aggregate type. This results partly from the coefficient of thermal expansion between the aggregate and the cement paste being different, particularly at higher temperatures.

The thermal conductivity of concrete depends on the nature of the aggregate, porosity and moisture content. As water is driven from the concrete in a fire, the conductivity of the ‘dry’ concrete is more relevant.

Lightweight aggregate concretes in particular, have very good fire performance in ‘dry’ building fires because they have a thermal expansion closer to cement paste. They also have good aggregate bond and high aggregate temperature stability. Limestone has an additional advantage in that it breaks down at temperatures over 660°C giving off carbon dioxide which provides a blanketing effect against heat penetration.

The effect of aggregate type on fire resistance is demonstrated in the table below. Based on minimum effective slab and wall thicknesses the table shows a range of insulation fire ratings (I) for three different aggregate types.

Fire Resistance Rating (minutes)	Effective Thickness (mm) for Different Aggregate Types		
	Type A Aggregate	Type B Aggregate	Type C Aggregate
30	50	45	40
60	75	70	55
90	95	90	70
120	110	105	80
180	140	135	105
240	165	160	120

Note: Aggregate types:

A - quartz, greywacke, basalt and all others not listed

B - dacite, phonolite, andesite, rhyolite, limestone

C - pumice and selected lightweight aggregates

Source: NZS 4230:2004

The interpretation for masonry walls is as follows:

Fire Resistance Insulated Rating Minutes	Solid or Solid Filled Masonry				
	Wall Thickness (mm)				
	70	90	140	190	240
30	OK	OK	OK	OK	OK
45	OK	OK	OK	OK	OK
60		OK	OK	OK	OK
90		*	OK	OK	OK
120			OK	OK	OK
180			OK	OK	OK
240				OK	OK

* Using a B and/or C Aggregate 90 mm would meet the 90 minute criteria.

Fire Resistance Insulated Rating Minutes	Partial Filled Masonry			
	Wall Thickness*[1]			
	90	140	190	240
30	OK	OK	OK	OK
45	OK	OK	OK	OK
60	OK	OK	OK	OK
90	OK*[2]	OK*[2]	OK*[2]	OK*[2]
120		OK*[2]	OK*[2]	OK*[2]
180			OK*[2]	OK*[2]
240				

*[1] Based on two face shell thicknesses of 35 mm.

*[2] Based on masonry units being light weight.

Equivalent thickness is often quoted:

90 mm	Equivalent thickness	65.8 mm
140 mm	Equivalent thickness	85.0 mm
190 mm	Equivalent thickness	101.8 mm

The concrete cover to reinforcement to ensure protection from fire is shown below.

Fire Resistance Rating Minutes	Cover (mm)
30	20
45	20
60	20
90	35
120	40
180	45
240	50

Most masonry wall reinforcement is in the centre of the wall and hence well exceeds the minimum values quoted. However, care is needed when dealing with columns, pilasters and beams.

Spalling of the surface concrete is a phenomenon which may occur in certain circumstances where the surface concrete breaks away at high temperatures. The problem is not a significant feature for concrete masonry.

Reinforcing steel loses strength at elevated temperatures – there is a 15% loss from 350°C up to 50% at around 600°C, and an 80% loss at 750°C. However, concrete or grout's low thermal conductivity protects reinforcing steel from significant temperature gain provided it has sufficient cover. Thus, the specification of minimum cover to reinforcement has to meet both durability and fire performance requirements.

Basis of Fire Design

Standard test methods are used to determine the fire performance of materials or structural elements. These tests may either be at a small scale with a component of a building in an oven or furnace, or at full scale in a mock-up of a fully assembled building subjected to a fire regime.

Standard fire time temperature curves have evolved to represent typical fires experienced in practice. The curves for fires representing three scenarios for building fires, hydrocarbon fires and tunnel fires are shown in **Figure 1.** These curves are different for the different scenarios. For instance, the temperature of a building fire rises much more slowly and peaks at a lower temperature than a hydrocarbon fire from burning vehicles as there is less combustible material present. Tunnel fires have a significantly higher peak temperature owing to the confinement of the fire. The hydrocarbon load in a tunnel can be considerable, which includes not only vehicles but also the bituminous road surface. As a result, the use of concrete roads in new tunnels is now recommended. **Figure 2** represents a standard furnace time temperature curve for a building fire taken from *AS 1530.4-05 2005 Methods for Fire Tests on Building Materials, Components and Structures (Part 4: Fire-Resistance Tests of Elements of Building Construction).*

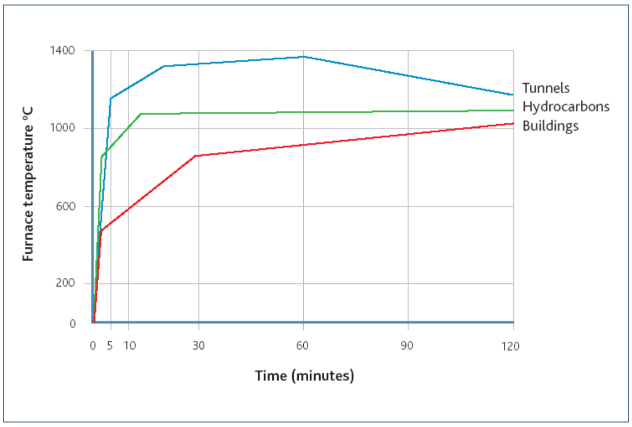

Figure 1: *Standard fire curves for three scenarios – tunnels, hydrocarbons and buildings*

Source: Concrete and fire safety. UK Concrete Centre (2008)

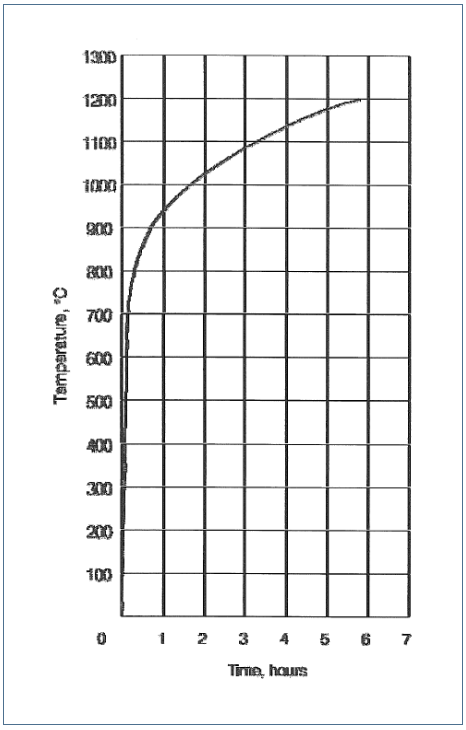

Figure 2: *Standard furnace temperature-time curve*

Source: AS 1530.4-05 2005

The *NZS 3101:2006 Concrete Structures Standard* and the *NZS 4230:2004 Design of Reinforced Concrete Masonry Structures* cite *AS 1530.4-05 2005* as the compliance code for carrying out fire tests on building components or assemblies. This code gives a standard time-temperature curve. This will differ from the time temperature relationship in an actual fire as controlled by a number of factors – fuel, fuel geometry, ventilation and restraint provided on members from adjacent areas of the building which are unaffected by the fire.

The increasing sophistication of computer modelling techniques has enabled data from standard fire tests on building components to be interpolated into the predicted fire behaviour of building assemblies and whole buildings. This has had the effect of reducing the need for comprehensive whole assembly fire tests of buildings.

NZBC Fire Safety Requirements

NZBC Compliance Document Clause C Protection from Fire is structured into seven acceptable solutions, C/AS1 to C/AS7 plus two verification methods. The acceptable solutions (AS) represent seven different risk groups for buildings with a maximum number of storeys of 20. All AS are 'deemed to comply' solutions, other specific design solutions can be submitted but require verification.

Each AS consists of seven parts, these are:

- Part 1: General - Scope, occupant load, etc.
- Part 2: Firecells, fire safety systems and fire resistance ratings.
- Part 3: Means of escape - Safeguard people from illness or injury whilst escaping and facilitate fire rescue operations.
- Part 4: Control of internal fire and smoke spread.
- Part 5: Control of external fire spread.
- Part 6: Fire-fighting.
- Part 7: Prevention of fire occurring.

There are two categories of fire ratings: Life rating and property rating:

1. Life rating applies to fire rating requirements in Part 3: Means of escape and Part 4: Control of internal fire and smoke spread.
2. Property rating applies to fire rating requirements in Part 5: Control of external fire spread.

The Fire resistance rating of each AS or risk group may vary and is described in Part 2.3.

The most common rating is 60 minutes. With automatic fire sprinklers and smoke detectors fitted, the rating can be halved in some cases. However, as mentioned earlier, sprinklers may not be fed when water is most needed in an earthquake event as auto-shut valves stop the water flow from the reservoirs.

Further fire safety systems are shown with table 2.1 in Part 2 of each AS.

Most fire rated boundary walls utilise concrete for its superior toughness, good fire rating and being structurally sound, as well as having good Spread of Flame Index (SFI) and Smoke Developed Index (SDI) properties according to AS/NZS 1530.3, which are satisfactory for the worst case scenario.

High-rise apartments are generally concrete structures and the fire escapes (deemed safe places) are concrete enclosed, usually bare, to comply with the need to have no combustibles within the space.

In the design of a multi-level building, each level is a separate firecell. Hence penetrations through the floor must be protected against the passage of fire by the installation of a suitable fire stopping mechanism. The most common need for floor penetrations is to distribute services up the building. Services on each level do not require any further fire protection unless there is a special case to warrant it. Another alternative is to provide a fire rated shaft running up the building with all services in it. This requires the services taken from the shaft onto each level to be protected with a suitable fire stopping mechanism.

Structural Fire Design

Chapter 5 of NZS 4230:2004 sets out the design requirements for fire resistance of structural concrete masonry.

In the scope which sets out this chapter, it is noted that the basis of the design relates to AS 3600 which has been adapted to reflect the properties of New Zealand masonry. The reason for basing on AS 3600 relates to the fact that all structural masonry is reinforced and hence fits more closely to reinforced concrete than unreinforced masonry documents.

The background for AS 3600 relates to the Australian fire document AS 1530, Part 4. The chapter deals with the following design:

- Clause 5.4: Fire resistance of walls

  In particular axial load is interrelated to the slenderness ratio of the wall and its end fixity arrangements.

- Cause 5.5: Fire resistance for beams
- Clause 5.6: Fire resistance for columns

  In particular, columns can be exposed to fire on all sides or be partially exposed as sides become protected by a wall for example.

Fire resistance rating can also be calculated by reference to Clause 5.7 and using fire test information generated by AS 1530, Part 4 or BS 474, Parts 20-22.

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 the use of a performance based approach using advanced calculation methods which lead to more economical, robust and innovative concrete buildings.

Analytical computer based modelling of whole buildings utilise the interaction between building elements which can result in structures being safer than calculated in design based on individual structural elements. For example, when a concrete slab expands under high temperatures to push outwards against its supports, a mechanical arching effect takes place in the slab. The compression generated in the bottom of the slab can greatly increase the load capacity.

External Walls

Section 4.8 of NZS 3101: 2006 gives particular requirements to prevent collapsing external walls outwards in a fire. The loadings code requires free standing external walls to be designed to resist a face load of 0.5 kPa in the after fire condition. When a fire occurs inside a building, the interior face of the wall heats up and expands while the exterior face remains relatively cool. Coincidentally the eccentricity of axial load on the wall causes additional deflections due to the P-delta.

The wall has the potential to collapse when the actions on the wall due to thermal bowing and P-delta effect can lead to the wall's capacity being exceeded effect – see **Figure 3**. Such a collapse into adjoining property risks placing fire crews or neighbours in danger. A base-cantilever-resisting mechanism is usually required to prevent collapse.

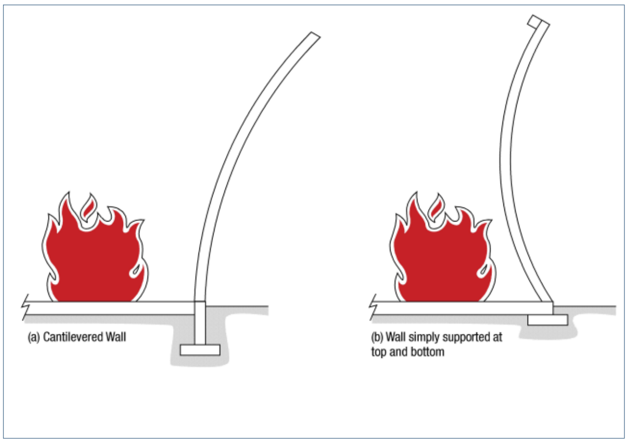

Figure 3: *Deformation profile caused by heating one side of the wall*

A wall connected to a very weak or flexible roof structure will need to be designed with a cantilever base connection. The design of the unprotected mild steel connections needs to be based on 30% of the yield strength of the exposed steel in ambient conditions.

Components made from other types of steel shall use mechanical properties of the steel at 680^{o}C. Details for FRR ratings and fixing of proprietary inserts are given in the standard. Adhesive (glued) anchors are have been found to behave poorly at elevated temperatures and need to be protected from fire.

Recent research has been carried out on slender panels by BRANZ and the University of Auckland owing to a concern of the high slenderness ratios of on-site and off-site precast panels being used in practice. A range of slenderness ratios from 30 to 75 were investigated. NZS 3101:2006 places a slenderness ratio limit of 75. Other maximum slenderness ratios have been proposed. By comparison NS 4230 sets a slenderness ratio of 50.

Insurance and Fire Damage

A recent, independent European investigation on the cost of fire damage in relation to the building material from which houses are constructed used statistics from the Insurance Association in Sweden (Forsakrings Forbundet). The study was on large fires in multi-storey 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 pay-out per fire and per apartment in concrete/masonry houses is around one fifth that of fires involving other materials (approximately €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

The time taken to repair a building after a fire is important in terms of downtime for commercial businesses. Concrete and concrete masonry buildings are generally easier and quicker to repair.

In buildings subject to arson attack such as schools, the loss of contents and repair time is also critical. These losses can be significantly less in concrete and concrete masonry buildings.

In the UK there have been a disproportionate number of fires in timber structures under construction. The fire load of a timber building being constructed is significant, and cannot be contained effectively until compartmentation is completed. In a concrete and concrete masonry structure the fire load during construction is significantly less.

Conclusions

The excellent performance of concrete and concrete masonry structures in fire is widely accepted. The role of concrete in providing passive fire protection gives a significant advantage over steel and timber structures and provides a more robust solution to fire protection. The behaviour of concrete in fire is well understood, and is substantiated by a wealth of fire testing research data.

Concrete design standards have historically been based on prescriptive data generated from fire tests. Eurocode 2 outlines an alternative approach based on computer simulation and performance based fire-safety engineering. This allows a greater degree of flexibility in terms of sizing concrete elements for fire safety and will lead to the more efficient design of concrete and concrete masonry structures.

Sources and Further Reading

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