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A Review on Fire Impacts on Concrete Structures

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ABSTRACT

Concrete has been used as a construction material due to its versatile behaviour. It exhibits a high degree of fire-resistance. The characteristic ability of concrete structures to combat one of the most devastating catastrophes can be attributed to its constituent materials which make it passive and have relatively poor thermal conductivity. However, concrete structures must be designed for fire outbreaks. The properties of concrete must be balanced against concerns about its fire resistance and susceptibility to spalling at elevated temperatures. In this paper, the causes, effects and some remedies of deterioration in concrete due to fire hazard will be presented. Also, some economical solutions to produce fire-resistant concrete will be discussed.

KEYWORDS: *Concrete, fire, spalling, temperature, compressive strength, density*

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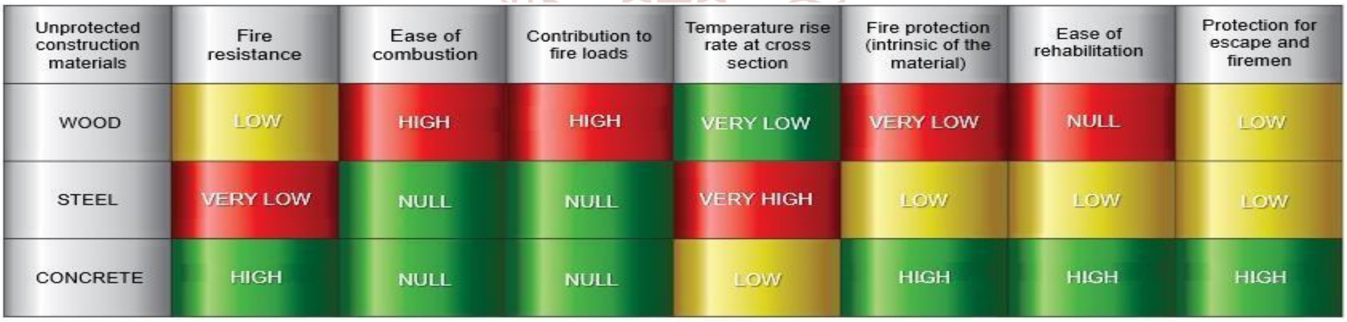
I. INTRODUCTION

Concrete has been utilized as a construction material in one form or another in buildings, bridges, and many other types of structures throughout the world. In addition to being readily obtainable, reinforced concrete has been universally accepted because it can be moulded essentially into any shape or form, is inherently rigid, and is inherently fire-resistant. The summary of the performance of building materials under fire is shown in Fig. 1.

Depending on the proposed use of the structure, building regulations recommend different levels of compartmentation in different types of building to take account of the likely risk of fire in a particular building type [7]. A relatively new method for determining fire exposure used by fire protection engineers is to first calculate the fire load density in a compartment. Then, based on the ventilation conditions and



Unprotected construction materials	Fire resistance	Ease of combustion	Contribution to fire loads	Temperature rise rate at cross section	Fire protection (intrinsic of the material)	Ease of rehabilitation	Protection for escape and firemen
WOOD	LOW	HIGH	HIGH	VERY LOW	VERY LOW	NULL	LOW
STEEL	VERY LOW	NULL	NULL	VERY HIGH	LOW	LOW	LOW
CONCRETE	HIGH	NULL	NULL	LOW	HIGH	HIGH	HIGH

Fig. 1 Summary of the performance of (unprotected) building materials under fire (reproduced from Jacobs, 2007) [1]

The outstanding fire-proof performance of concrete is due to concrete's constituent materials (cement and aggregates) which, when chemically combined within the concrete, form a material that is inert and has relatively poor thermal conductivity [2,3,4]. Fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted [5]. In 1988, the "Construction Products Directive" issued by the Council of the European Communities recognized fire safety as one of the six essential requirements which construction works must satisfy [6].

an assumed source of combustion, the compartment temperature is determined at various times. Another factor considered in the analysis is the effect of active fire protection systems e.g. sprinklers or fire brigades on the growth of the fire [5]. Standard practice for fire-damaged concrete requires that severely fire-affected concrete be stripped from the steel reinforcement and prestressing tendons inserted to a depth of at least one bar diameter. The removed concrete is then replaced with polymer modified cementitious materials or cementitious repair materials. This job is accomplished either by use of a hand trowel or by spraying the materials onto the surface [8]. The thermal properties that influence temperature rise and distribution in a concrete structural member are thermal conductivity, specific heat, thermal diffusivity, and mass loss [9]. The thermal diffusivity of a material is defined as the ratio of thermal conductivity to the volumetric specific heat of the material [9]. It measures the rate of heat transfer from an exposed surface of a material to inner layers. The larger the diffusivity, the faster the temperature rise at a certain depth in the material [10, 11]. Thermal conductivity can be reduced by using lightweight aggregates and glass bubbles in place of normal aggregates [12]. The load-bearing resistance of a concrete structure can be assumed for a specified period [13]. Compressive strength of concrete at an elevated temperature is of primary importance in a fire-resistant design. The strength degradation in high strength concrete is inconsistent and there are significant variations in strength loss, as reported by various authors. Concrete should be made in controlled conditions to minimize the factors that may affect the thermal expansion coefficient, for example, the relative humidity. The mix proportion of the concrete should also be closely regulated, especially the water-cement ratio [14]. Reference [15] elucidated that the addition of steel fibres to high-performance concrete led to a considerable improvement in static and dynamic modulus of elasticity. Pilot-scale experiments on concrete and reinforced concrete structural elements are needed to provide basic validation data for computational modelling [16]. The density of concrete is usually subdivided into two major groups: (1) normal-weight concretes with densities in 2150 to 2450 kg/m^3 range; and (2) lightweight concretes with densities between 1350 and 1850 kg/m^3. When the surrounding temperature rises, concrete starts to lose its moisture. This causes a decrease in the density of concrete. The retention in the mass of concrete at elevated temperatures is highly influenced by the type of aggregate used [17, 18]. Density and workability of the fresh concrete significantly affect its fire resistance. Structural lightweight concrete is more resistant to fire than normal-weight concrete due to a lower reduction in strength at a higher temperature because of inherent stability [19]. It provides more insulation due to improved thermal conductivity.

II. TEMPERATURE DISTRIBUTION INSIDE THE CONCRETE

There are three classic heat transfer mechanisms: conduction, convection, and radiation. In conduction, thermal energy is transferred through interactions between atoms or molecules, although there is no transport of these atoms or molecules, only the displacement of energy. In convection, energy is transported in the form of heat through direct mass transport. In radiation, thermal energy is carried through space in the form of electromagnetic waves moving at the speed of light. In a fire event, there is a combination of these three heat transfer mechanisms, however, within the concrete mass, there is a predominance of conduction heat flux. In this context, the calculation of the development of a temperature field in the cross-section of a structural concrete element exposed to fire involves solving the classical Fourier differential equation (Equation 1):

$$\frac{\partial}{\partial x}\left(\lambda_\theta \frac{\partial \theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_\theta \frac{\partial \theta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_\theta \frac{\partial \theta}{\partial z}\right)+Q=\rho . c_\theta \frac{\partial \theta}{\partial t} \qquad (1)$$

where:
λ_θ: is the thermal conductivity of the material (W/m °C);

ρ.c: is the specific volumetric heat of the material (product of specific mass and absolute specific heat) (J/kg °C);

x y e z: the cartesian coordinates of the three-dimensional system; Q: is the internal heat rate generated on the material;

∂θ: is the temperature gradient in the direction of heat flow; t: time (s).

Internal heat generation Q can be considered 0 (zero) for non-combustible materials (such as concrete). The boundary conditions (on the surface of the element) are expressed in terms of heat flow equations and the thermal properties of the material depend on the type and quantity of materials used in concrete mix design (Leonardo Da Vinci Pilot Project: Handbook 5, 2005)[20]. To exemplify the behaviour of the temperature field evolution as a function of time in a concrete element, the computer simulation study by Ongah, Mendis & Sanjayan (2002) [21] in high strength concrete walls (Fig. 2) with only one side exposed to fire is presented. The graph indicates the significant thermal gradient inside the material (concrete) according to a heat flow model that numerically simulates the fire scenario.

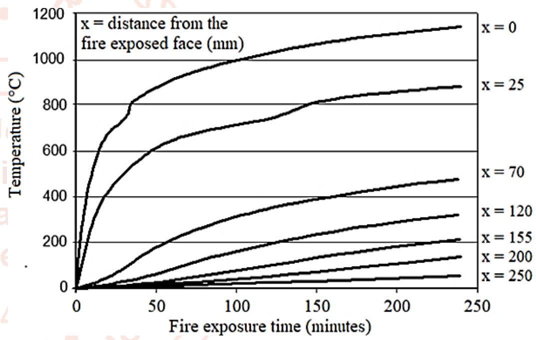


Fig. 2 Temperature field evolution in a high strength concrete wall as a function of fire exposure time (reproduced from Ongah et al. 2002)[21].

Another way to present the temperature evolution inside a concrete element, prescribed by the main international codes, can be seen in Fig. 3. In this case, the instantaneous curves of standardized times as a function of the temperature and depth of the surface exposed to fire are presented, this is a very common model adopted by researchers and in the codes of various countries.

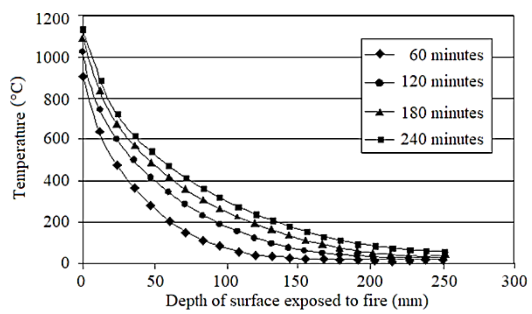


Fig. 3 Calculated temperature distribution as a function of the depth of surface exposed to fire and fire exposure time, by using a numerical model (Ongah et al. 2002) [21].

In general, the physical-chemical process of concrete, involving the interaction between aggregates and cement paste, in a fire situation, can be simplified as shown in Fig. 4.

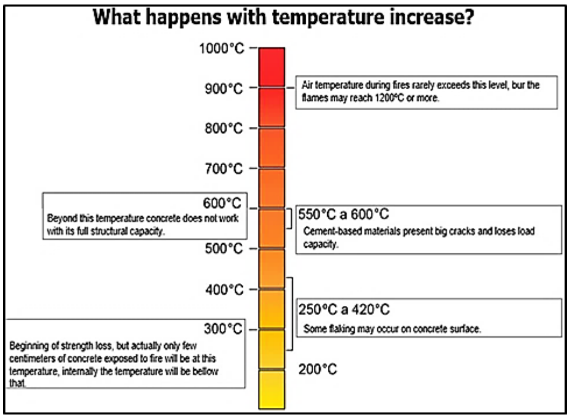


Fig. 4 Physical-chemical process of concrete in a fire situation (adapted from Jacobs, 2007) [1].

III. PERFORMANCE OF STRUCTURAL MEMBERS AT ELEVATED TEMPERATURE

A. Performance of Concrete at Elevated Temperatures

Spalling starts to occur when the concrete reaches an elevated temperature of 250^{0}C. After reaching 300°C, concrete starts to lose its strength. Within 550–600°C, cement-based materials experience creep and lose their load-bearing capacity. At 600°C and higher, concrete loses its ability to function at its full structural capacity. Major damage is usually confined to the surface at the vicinity to the fire origin [22, 23]. A fire-resistance rating typically means the duration for which a passive fire protection system can confine a fire and withstand a standard fire resistance test. Although less amount of strength drop is observed in the case of lightweight concrete when compared to normal weight one, the rate of temperature drop is higher (Fig. 5).

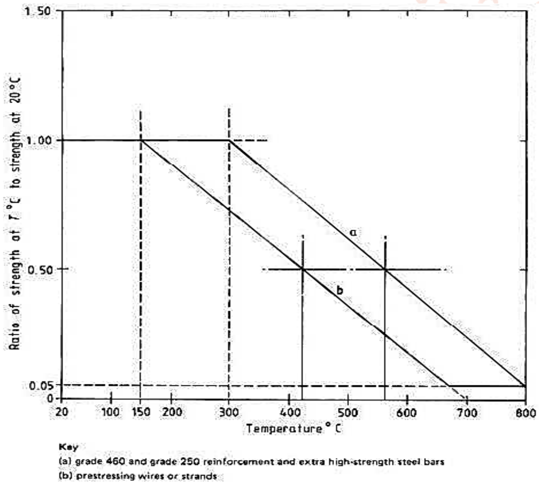


Fig. 5 Variation of concrete strength with temperature [24]

B. Performance of Steel at Elevated Temperatures

Steel reinforcing rebars need to be protected from exposure of temperatures above 200^{0}C to 300^{0}C, This is due to the fact that steels with low carbon content are known to exhibit 'blue brittleness' between 200^{0}C to 300^{0}C. Concrete and steel exhibit similar thermal expansion up to a temperature of 400^{0}C; however, higher temperatures will result in a significant expansion of the steel compared to the concrete and, if temperatures of the order of 700°C are attained, the load-bearing capacity of the steel reinforcement will be reduced to about 20% of its design value [25]. Steel strength also reduces with temperature. The reduction in strength due to an increase in temperature is markedly lesser in high strength steel than a pre-stress wire member (Fig. 6). Steel ratio and strength of concrete have major influences on the fire resistance of the concrete structures under fire [26].

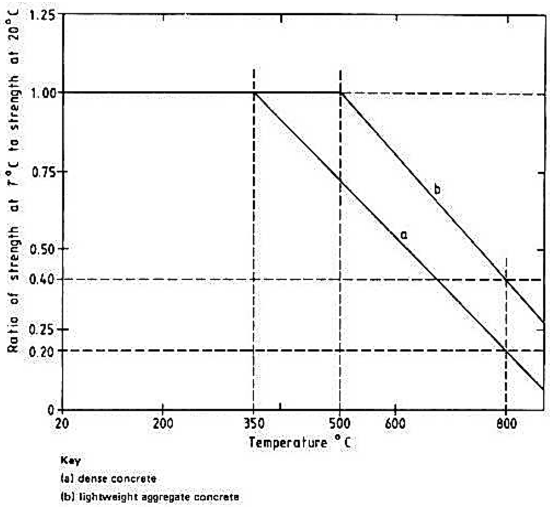


Fig. 6 Variation of steel strength with temperature [24]

IV. FACTORS AFFECTING PROPERTIES OF CONCRETE IN FIRE

Institute for Research in Construction (IRC) shows that the fire performance of high strength concrete (HSC), in general, and spalling, in particular, is influenced by various factor. Original compressive strength of the concrete, moisture content, density, fire intensity, dimensions of members, transverse reinforcement placing, loading, type of aggregate used, fibre reinforcement and water binder ratios are chief factors of concern. Concrete strengths higher than 55 MPa are more susceptible to spalling and may result in lower fire resistance. Higher RH levels lead to greater spalling (when the RH is higher than 80%). The extent of spalling was found to be much greater when lightweight aggregate is used. This is mainly because lightweight aggregate contains more free moisture, which creates higher vapour pressure under fire exposures. The spalling of HSC is much more severe in fires characterized by fast heating rates or high intensities. Thermal spalling increases with specimen size. This is because specimen size is directly related to heat and moisture transport through the structure, as well as the capacity of larger structures to store more energy. Both closer tie spacing and the bending of ties at 135° back into the core of the column enhances fire performance. The provision of cross ties also improves fire resistance. Concrete that is under design load while heated loses less strength than unloaded concrete, the theory being that imposed compressive stresses inhibit the development of cracks that would be free to develop in unrestrained concrete [27]. Of the two commonly used aggregates, carbonate aggregate provides higher fire resistance and better spalling resistance in concrete than the siliceous aggregate. This is mainly because carbonate aggregate has a substantially higher heat capacity. Also, concrete containing limestone and calcareous aggregates performs better at high temperatures than concrete containing siliceous aggregates [28]. For example, quartz-based aggregates increase in volume, due to a mineral transformation, at about 575°C and limestone aggregates will decompose at about 800°C [29]. The addition of polypropylene fibres minimizes spalling in HSC members under fire conditions [30]. Concrete with a higher aggregate-cement ratio suffers less reduction in compressive strength; however, the opposite is true for modulus of elasticity. Loss of elastic modulus, due to a fire, is marginal for concrete with a lower water-cement ratio [27]. For concrete structures, lateral displacement of columns at slab–column joints due to thermal expansion of the slabs might pose additional risk to the global stability of the structure [31].

V. REASONS OF STRUCTURAL FAILURE DUE TO FIRE

The methodology by NFIRS system [32] included a review of news sources, technical literature, as well as interviews with a wide range of individuals knowledgeable in structural fire protection. Twenty-two fires were identified that caused either partial or total collapse of a multistory structure. Some reasons of structural failure due to fire are as follows:

A. Stages of Fire Development

Once the material is ignited, fire spreads across fuel objects until it becomes fully developed. Fire spreading rate depends upon fuel composition, orientation, the surface to mass ratio, incident heat and air supply. Fire spreads to other objects by radiation from a flame or smoke layer [33].

B. Physical and Chemical Response to Fire

Most porous concretes contain a certain amount of liquid water [34]. This begins to vaporize if the temperature exceeds 100°C, usually causing a build-up of pressure within the concrete. In practice, the boiling temperature range tends to extend from 100 to about 140°C due to pressure effects. A blend of these physical and chemical changes in concrete results in the reduction of the compressive strength of the material.

C. Spalling

Spalling may significantly reduce or even eliminate the layer of concrete cover on the reinforcement bars, thereby exposing the reinforcement to high temperatures, leading to a reduction in the strength of the steel and hence a deterioration of the mechanical properties of the structure as a whole. The view of concrete spalling after fire damage is shown in Fig. 7.

Fig. 7 Spalling of concrete

D. Cracking

Geogali & Tsakiridis [35] made a case study of cracking in a concrete building subjected to fire, with particular emphasis on the depths to which cracking penetrates the concrete. It was found that the penetration depth is related to the temperature of the fire and that generally, the cracks extended quite deep into the concrete member. Major damage was confined to the surface close to the fire origin, but the nature of cracking and discolouration of the concrete pointed to the concrete around the reinforcement reaching 700°C. Cracks which extended more than 30 mm into the depth of the structure were attributed to a short heating/cooling cycle due to the fire being extinguished. The crack development in concrete structure due to fire is shown in Fig. 8.

Fig 8 Crack development in concrete structure due to fire.

VI. TEST METHODS TO EVALUATE EFFECT OF FIRE ON DAMAGED CONCRETE

The most common test method for determining fire resistance in the United States is the ASTM Standard E 119 Test Methods for Fire Tests of Building Construction and Materials [36, 37]. To help prevent building fires from spreading and protect lives and property, building codes require that walls, partitions, roofs and floor/ceiling assemblies in sensitive locations carry particular fire ratings [38]. In ASTM E-119[36] tests, specimens of tested assemblies are exposed to controlled heat until one of the following occurs: the average temperature measured on the unexposed side of the specimen increases by 250° F; heat, flame or gases escape to the unexposed side; or the specimen collapses under the load. To qualify for fire ratings of 1 hour or more, specimens also must pass a hose stream test to simulate firefighting conditions. There are two options for the hose stream portion of the test—one using a duplicate specimen that has been exposed to heat for only half the required time and one using the specimen that has just passed the entire heat duration. As testing every conceivable combination of unit size, shape and core area is infeasible, the standard industry practice is to calculate the fire resistance of untested concrete by the equivalent thickness method. Using information manufacturers provide on the content and equivalent thickness of particular masonry units, designers can consult standard tables or perform simple calculations to determine a specific assembly's fire rating. Time-temperature curve given by ASTM E 119 [36] is given in Fig. 9.

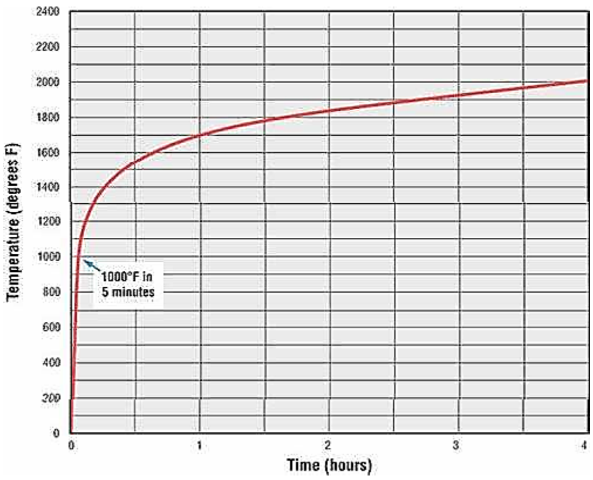


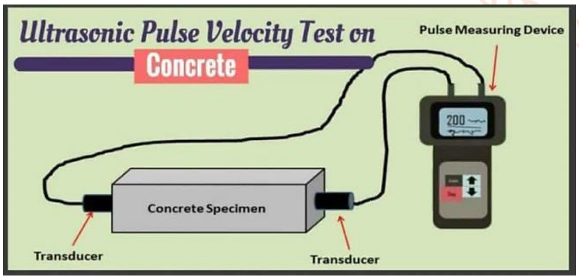
Fig. 9 Time-temperature curve [36]

A. Visual Inspection

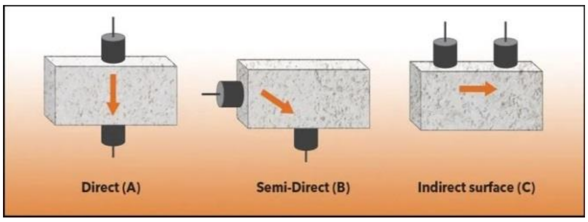
The visual inspection of the fire-affected structure and the status of some of the components of the structure such as aluminium, glass panes, etc. after the fire suggest the approximate temperature to which the structure was subjected [39].

B. Ultrasonic Scanning

The UPV (Ultrasonic Pulse Velocity) measurement (Fig.10) is one of the various non-destructive test methods used to evaluate concrete integrity and – more generally – the level of damage in the material. In particular, the velocity of sound in concrete is a high-quality thermal-damage indicator, due to its sensitivity to any change of Young's modulus. When concrete is exposed to fire, the increase of temperature in the deeper layers of the material is rather slow and progressive. Because of this (due to the rather low thermal diffusivity of concrete), this process produces significant temperature gradients between the outer and inner layers of any given concrete structure (i.e. between the surface and the core). UPV technique may also be applied to determine the reduced quality of concrete employing indirect or direct techniques on cores [40, 41].



(a)



(b)

Fig. 10(a, b) UPV testing of concrete member

C. Core Sampling and Testing

Tests on core samples give direct evidence on residual compressive strength and temperature to which the concrete member is subjected to during fire. The pulse velocity values of these core samples can be compared to confirm the estimated temperature and the accuracy of estimation of the depth of damaged concrete. Studies on core samples reveal that their density and compressive strength bear a relation which helps to confirm the estimated temperature.

D. Residual Strength of Steel

To assess the residual properties of the reinforcement, samples from different locations are to be collected and tested for yield and ultimate strength, percentage elongation and modulus of elasticity. The reduction in the strength and modulus of elasticity will give an approximation of the temperature to which the member has been subjected to during fire.

VII. EFFECTS OF FIRE ON CONCRETE (CASE STUDY)

The Windsor Tower or Torre Windsor (officially known as Edificio Windsor) was a 32-storey concrete building with a reinforced concrete central core [42,43]. A typical floor was two- way spanning, 280mm deep waffle slab supported by the concrete core, internal RC columns with additional 360mm deep steel I-beams and steel perimeter columns. Originally, the perimeter columns and internal steel beams were left unprotected in accordance with the Spanish building code at the time of construction. The Windsor Tower was completely gutted by the fire on 12 February 2005. A large portion of the floor slabs above the 17th floor progressively collapsed during the fire when the unprotected steel perimeter columns on the upper levels buckled and collapsed.

VIII. SOME ENGINEERING SOLUTIONS TO IMPROVE FIRE SAFETY

Fire safety engineering is the application of science and engineering principles to protect people and their environments from the destructive effects of fire and smoke. Main principles of fire engineering are as: continuity of operations; property protection and life safety. Fire protection is the lessons and practice of extenuating the unnecessary effects of fires. Several methods are used to protect concrete from fire. Insulating board systems through gypsum board and calcium silicate board are used generally. Besides, man-made mineral fibre systems are used in some cases. Firewalls, fire separation or barrier walls or penetration protection may also be utilized.

A. Fire Wall and Barrier Wall

A firewall is a passive fire protection system that has protected openings. This wall (Fig. 11 (a, b, c, d)) extends continuously from the foundation to or through the roof. Generally, it is located following the locally applicable building code. Purpose of firewall is to subdivide a building into separate fire areas so that it restricts the spread of fire from one side to other. A barrier wall is designed to limit the spread of fire and smoke from a controlled fire (Fig. 11 (e)).

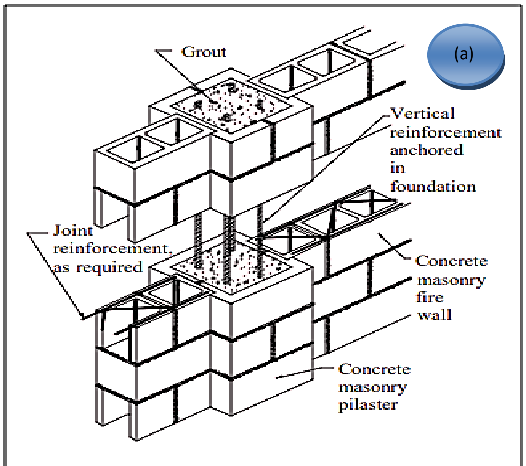


Figure 1—Freestanding or Cantilevered Fire Wall with Pilaster

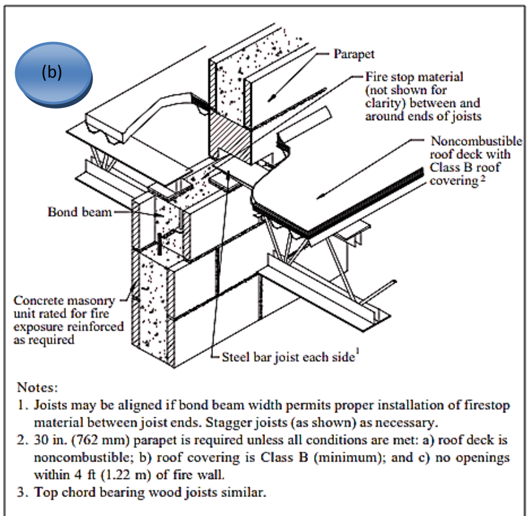


Figure 2—Laterally Supported Loadbearing Fire Wall

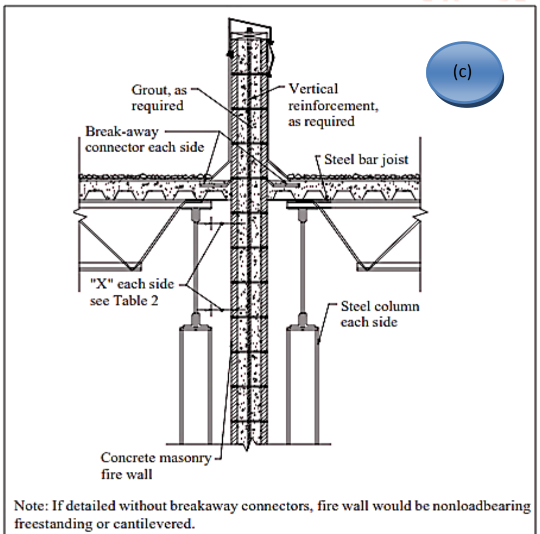


Figure 3—Laterally Supported Nonloadbearing Fire Wall

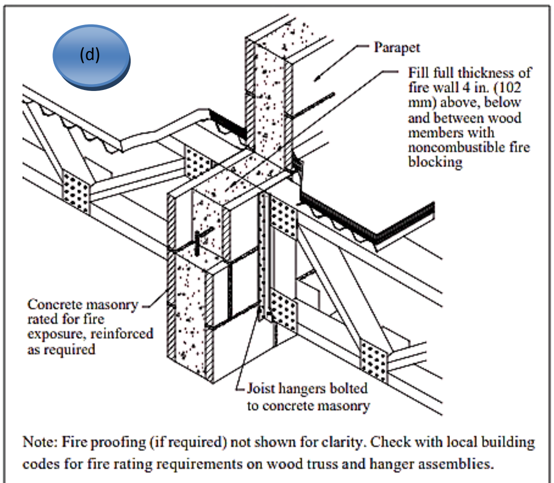


Figure 4—Laterally Supported Loadbearing Fire Wall: Wood Framing

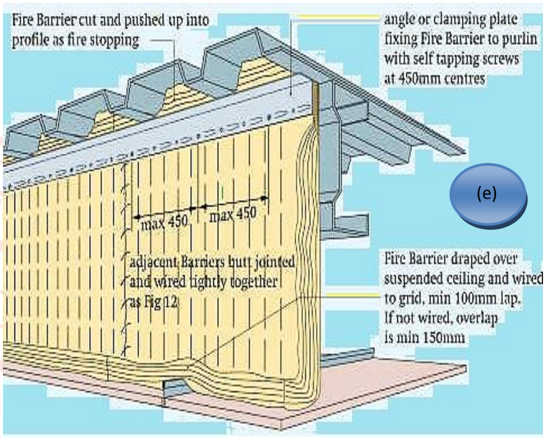


Fig. 11 Fire wall and Barrier wall

B. Door

A "fire door" is the door that is tested and listed to stop fire only. Smoke may pass around the sides of the door (Fig. 12).

(a) (b)

Fig. 12 Fire Door (a) Vertical ("Roll-Up") Fire Doors (b) Horizontal ("Sliding") Fire Door

C. Penetration Protection

Penetrating items are steel, ferrous or copper pipes, tubes or conduits. Annular space between the item and the fire-resistance-rated wall must be filled to maintain the fire-resistance rating with filling material - concrete, grout, or mortar (Fig. 13). Separation in buildings by structural elements prevent horizontal and vertical spread of fire [44].

Fig. 13 Fire penetration protection system

Fire following the earthquake (FFE) is a serious threat to structures that are partially damaged in a prior earthquake potentially leading to a quick collapse of the structure [45,46]. Test results confirmed the need for the incorporation of FFE into the process of analysis and design [45].

IX. CONCLUSION AND RECOMMENDATIONS

In this paper, several reasons of structural failure and degradation of concrete due to fire have been summarized. Moreover, the effects of fire and different technology to improve fire resistance capacity of reinforced concrete have been described. Improve structural design methodology, testing for fire protection materials, technology and systems, changing building operations and maintenance functions while sustainingthe modern technology and materials that constitute elements of the fire protection system must be introduced to reduce fire threat. Detailed studies of the performance of concrete structures in real fire incidents can also assist greatly in advancing knowledge of real-time behaviour. Some recommendations that can be developed through this study are as follows:

1. Thermal diffusivity of a concrete member can be reduced by using lightweight aggregate and styrofoam in concrete.
2. Density can be reduced by replacing of normal weight aggregate with a lightweight aggregate as lightweight concrete is less vulnerable to fire.
3. Elastic modulus and tensile strength of concrete can be increased through the introduction of steel fibres to perform better during afire.
4. The repair measures such as cement grouting for improving the core concrete and using weld mesh for spalled areas are to be adopted as retrofitting measures.
5. Closer transverse reinforcement spacing and utilization of carbonate aggregate instead of silicious aggregate must be considered during design.
6. Spalling in HSC members can be minimized through the addition of polypropylene fibres.

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