STRUCTURAL FIRE ENGINEERING

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Contents

Summary

This chapter presents an overview of “Structural Fire Engineering” as one of the new emerging areas of Fire Safety Engineering. The chapter starts with discussing the concept of structural fire engineering and illustrates the significance of developing high fire safety standards to reduce life loss, injuries and financial damage due to fire. It provides statistics showing life casualties and financial loss caused by fires in some countries of the world. The chapter discusses also the basics of fire and the parameters that cause the start and affect the spread of fire in a room environment. The design of structures in fire is considered by showing the types of loads used in fire design, describing how buildings’ materials (steel, concrete, timber, bricks, and glass) behave under high temperatures and by presenting the methods used for structural analysis in fire situations focusing on the finite element method. Philosophies of fire design including concepts of “Prescriptive” and “Performance-Based” design Codes are also discussed. The chapter zooms on designing main types of structural elements in fire situations including beams, columns, and walls. The effects of axial and rotational restraint, cooling phase of a fire and fire spread are also considered. Methods of measuring fire resistance of structures including time, temperature and strength domains are presented. The chapter discusses in details, active and passive fire protection systems to reduce the fire impact on buildings. These include water sprinklers systems, fire insulation boards, spray-on systems, intumescent painting and timber fire retardants. The chapter concludes by presenting methods of assessment and repairing of buildings after fire. Appendix (A) presents a valuable case study showing the effect of high temperatures on the redistribution of internal forces in a steel frame during fire. Bending moments diagrams, shear forces diagrams and deformations are presented together with tables showing the percentage of the redistribution due to fire effects.

1. Introduction

The fast advances in modern civilization have made the humankind more dependent on using buildings and infrastructure, increasing by that the probability of exposure to various risks and hazards. This has emphasized the importance of maintaining high safety standards in buildings to prevent or reduce casualties, injuries and losses that may occur due to incidents. One of the main threats to human safety is fires. Every year significant life loss and tremendous martial damage occur due to fires happening around the world. A fire can strike at any time in any building including houses, factories, schools, tunnels etc. The most recent 2010 study of the World Fire Statistics Center in Geneva (shown in Table 1) illustrates the significant volume of life and financial losses caused by fire incidents. The increasing need to improve fire safety in buildings has led to the creation of “Structural Fire Engineering” as a new subset to structural engineering. The main objective of Structural Fire Engineering is to improve fire safety standards in buildings’ using experimental and theoretical based research and to provide fire design solutions. This enables to improve the fire safety of buildings by the way of developing buildings fire codes, and fire design standards. Structural Fire Engineering covers all buildings' categories including, steel structures, concrete structures, masonry structures, timber structures, aluminum structures and composite structures. It also covers various aspects of engineering science including: numerical modeling, practical applications, simple calculation models, experimental studies, material behavior at high temperature, case studies, codes of practice and design and analysis of the whole structural behavior.

Country	Deaths per 100,000 persons	Average Percentage of GDP %
Singapore	0.15	0.05
Australia	0.53	0.08
Germany	0.68 (2004-2006)	0.13
United Kingdom	0.82	0.13
Sweden	1.11	0.17
Ireland	1.09	--
France	1.02	0.19
United States	1.23	0.10
Poland	1.57	0.07
Denmark	1.38	0.20
Japan	1.67	0.12
Finland	1.93	0.16

Source: World Fire Statistics, International Association for the Study of Insurance Economics, Bulletin of the World Fire Statistics Centre, No. 26, October 2010, Geneva.

Table 1. Deaths and direct losses caused by fire (2005-2007)

It is known that structures are the places where the majority of human activities take place. The majority of people think that the incident of a fire is something very rare and seems to be far away from their foresight. Yet statistics show that fires can happen everywhere and at any time. Therefore, high fire safety standards in buildings are becoming one of the main priorities in buildings design. The current international orientation is that country's authorities should not permit the construction of buildings without appropriate fire design that complies with the country regulations. In most countries of the developed world, fire design codes have already been developed in the last 2 decades. These fire codes are continuously modified to reflect the latest advances and findings of structural fire engineering research. Fire design codes serve as manuals and guidance for fire designers to produce durable and safe structures in fire. Bad structural fire design can significantly increase the life loss and damage during fire by causing partial or total collapse of the building. This includes the probability of fast fire spreading if one of the structural parts collapsed allowing the fire to spread to other compartments horizontally (within the floor) or verticality (to other floors of the building). Fire resistance is the main objective of Structural Fire Engineering. That is to enable the structure to resist the fire for a certain period of time.

2. Principles of Fire

There are three elements required for a fire to start: fuel, oxygen and ignition. The materials that form the building's contents are the fuel of the fire. These materials can be either part of the building structure including wood frames, doors, windows, lining materials, service materials etc. It can also be the materials of the furniture which is considered as the main fuel particularly in the early stages of the fire. An ignition occurs when a combustible material is heated to a certain temperature that is sufficient to trigger the exothermic reaction of combustion. Conventional ignition sources in buildings are mainly human made including cigarettes, candles, gas heaters, matches, etc. Ignition can also be triggered by machines, electricity or radiation from heaters and other hot objects. The second phase after ignition is the spread of the fire (see Figure 1). Factors that affect the speed and the rate of fire spread are the flammability and thermal properties of the fuel, the location and the size of the flame within the compartment. When the fire starts the generated heat is transferred in all directions by three ways, conduction, radiation and convection. Conduction is the heat transfer in solid materials which happens between molecules when a thermal gradient is present. For example; steel is a better conductor than concrete. Thermal conductivity and thermal inertia are the main two parameters that measure the heat conductivity of any material. In radiation, the heat is transmitted by emission from the material surface in the form of electromagnetic waves that travel through space and other media. Radiation is an effective mechanism of fire spread as the heat transfers directly from the flame to other potential fuels in the surrounding area. Radiation also depends on the emissivity of the emitting surface and the properties of the receiving surface and the distance between them. However, convection is considered as one of the major modes of heat transfer as the heat is transferred by movement of molecules in fluids. The main fluids for heat transfer by convection are hot gases including smoke. However, heat can also be transferred through liquids. The convection happens usually upwards against gravity and depends on many factors including ventilation of the room and velocity of the hot gases. The main parameter to measure convection is the convective heat transfer coefficient.

2.1. Room Fire

When a fire starts in a room it spreads and grows. The rate of fire spread depends on many factors including the geometry of the room, the combustible objects and the ventilation openings in the room. Fire spread in a room is a complicated process and mainly uses the three mentioned methods of heat transfer. The growth of a fire also depends on the properties of the materials forming the floor, ceiling and walls. At a certain moment of time when the heat fluxes reach a critical degree all combustible items in the room start to burn causing a significant and fast increase in heat release temperature’s causing what is known as “flashover” as shown in Figure 1. The flashover is considered as the start of the “master seen” of the fire episode known as the “post-flashover” phase (see Figure 1). The post flashover is the peak of the fire as the highest rates of heat fluxes and temperatures are released and all the combustible materials pyrolyze. This creates a turbulent movement of hot air and gases in the room. The post flashover stage is the phase of the fire that has the highest impact on structural elements and on the integrity of the compartment. Therefore, improving the performance of structural elements during the post-flashover is the main target of

Structural Fire Engineering. After the post-flashover the fire starts to decay and the objects and the gases cool down as shown in Figure 1.

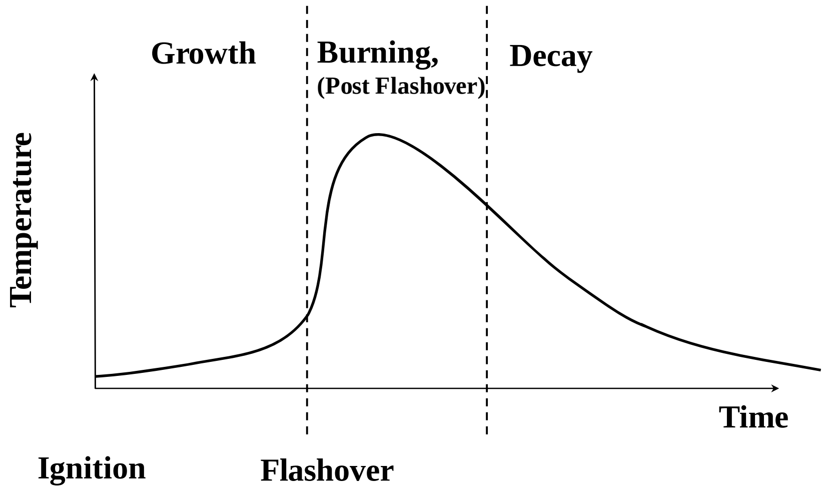

Figure 1. Development of a room fire

2.2. Standard Fire Curves

In Structural Fire Engineering there are several standard fire curves used for analysis, design and fire testing purposes. The trend of these fires is different from the natural fire (shown Figure 1) as they do not have a decay (cooling) phase. There are several standard fire curves adopted in Structural Fire Engineering, including the ISO 834 curve, the Hydrocarbon curve, the RWS curve, the RABT curve, and the ASTM E119 curve. In this chapter the first three fire curves are presented.

The ISO 834 fire curve is a relatively mild curve and defines the temperature T in Centigrade using the relationship:

$$T = 345\log_{10}\left(8t+1\right)+T_0 \qquad (1)$$

where, t = the time in minutes and T_0 = the ambient temperature in (°C). The ISO834 fire curve is shown in Figure 2.

The Hydrocarbon fire curve is more severe than the ISO 834 (see Figure 2) and it is intended for use with structural elements exposed to large fires. The temperatures T (in Centigrade) of Hydrocarbon fire curve are determined by the formula:

$$T = 1080\left(1-0.325e^{-0.167t}-0.675e^{-2.5t}\right)+T_0 \qquad (2)$$

The most severe fire curve which is mainly used for industrial and tunnels' fires is the RWS fire curve. This fire curve was introduced by the "Rijkswaterstaat" the Dutch <u>Ministry of Transport, Public Works and Water Management</u>. The RWS fire curve is defined by the data shown in Table 2 and presented in Figure 2.

Time (minutes)	Temperature (°C)
0	20
3	890
5	1140
10	1200
30	1300
60	1350
90	1300
120	1200
180	1200

Table 2. The RWS fire curve

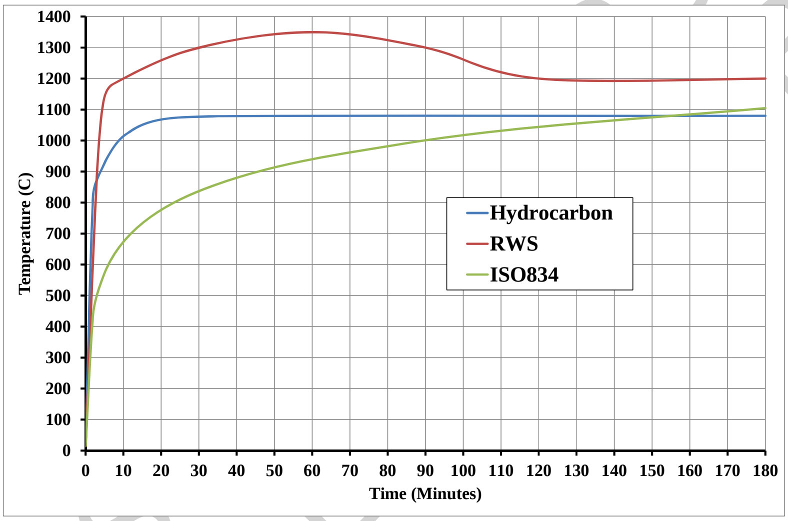

Figure 2. Standard fire curves.

3. Structures Exposed to Fire

In structural design under normal temperatures, the designer should ensure that the bearing capacity of the structural elements including columns, beams, walls, and slabs, (and also the building as a one unit) is higher than the applied loads. Any failure of any element may cause partial or total collapse of the building. Conventional loads in buildings are either dead load which includes all stationary objects including linings, flooring, plastering, service accessories etc. These also include the self-weight of the structural elements. The other type of loads is the live load which presents any moving objects including people, mobile furniture, vehicles, airplanes etc. An additional type of loads which is the fire load has to be considered when designing buildings for fire. The high temperatures released during fire can significantly reduce the bearing capacity of the structural elements and accelerate the failure of the element or the building as a whole (if compared with the case of normal temperatures). Apart from the deterioration of the material properties during fire, the designer must also consider the effect of the interaction between the structural members and other parts of the building. This is known as the effect of axial and rotational restraint. The designer should also consider other effects of fire on materials including concrete spalling, wood charring and local buckling that may significantly influence the element bearing capacity under fire. In general, the designer should ensure that the following design relationship is satisfied during the period of the fire:

$$S_{\text{fire}} \geq L_{\text{fire}} \tag{3}$$

where S_{fire} = the strength of the element subjected to fire and L_{fire} = the applied loads during the fire period.

3.1. Loads in Fire Design

The applied loads considered in fire design are governed by relationships that combine the dead and the live load. For example the Eurocode 1 adopts the following relationship for domestic and residential buildings:

$$L_{\text{fire}} = 1G_{\text{k}} + 0.5Q_{\text{k}} + 0.3Q_{\text{sk}} \tag{4}$$

where G_{k} = the characteristic dead load and Q_{k} = the characteristic permanent live load; Q_{sk} = the semi-permanent live. The value of parameters 1, 0.5 and 0.3 may vary in Codes of other countries. For normal conditions the designer should leave a factor of safety to accommodate any severe incidents including fire, Earthquake etc. Usually the strength of the buildings is designed to be 50-60% higher the maximum applied loads.

3.2. Thermal Stresses

3.2.1. Thermal Stresses in Bars

When a bar is exposed to a uniform temperature, a thermal expansion occurs as shown in Figure 3-a. The value of thermal expansion depends on the value of the temperature increase and on the material's coefficient of thermal expansion. If the bar is allowed to expand freely, the total change in the length can be calculated using the equation:

$$\delta = \alpha \cdot L \cdot T \tag{5}$$

Where α = coefficient of thermal expansion of the material, L = original bar length, T = the increase in the temperature. The free expansion of the bar allows thermal strain (elongation) to occur, however the value of the thermal stresses = 0 (see Figure 3-a). If the thermal elongation of the bar is restricted by imposing a restraint against the bar's expansion, thermal stresses will be created. The value of the thermal stresses σ_x depends on the degree of the imposed restraint. If assuming complete restraint is applied against the bar expansion the thermal stress σ_x can be calculated using the following formula:

$$\sigma_x = E \cdot \alpha \cdot T \tag{6}$$

where E = the Young Modulus of the bar's material (see Section 3.4). If the bar is partially restrained against thermal expansion then the stress value is:

$$0 \le \sigma_x \le E\alpha T$$

3.2.2. Thermal Stresses in Beams

If a beam with dimensions $b \times h$ as shown in Figure 3-b is subjected to temperature increase (T_1 on the top surface and temperature T_2 on the bottom surface) and is fully restrained against thermal expansion (as shown in Figure 3-b) the thermal stresses are:

$$\sigma_{\downarrow} x = E\left(T\, y/0.5h\right) \qquad (7)$$

where $T = \left(T_2 - T_1\right)/2$, y = the distance for the center of the beam to the level where the stresses are calculated (see Figure 3-b). If the beam is allowed for free expansion and free bending the value of thermal stresses is calculated using the relationship:

$$\sigma_x = E\alpha T\left(y\right) + \int_{-0.5h}^{0.5h} E\alpha T\left(y\right) y dy \qquad (8)$$

It can be seen from Eqs. (7) and (8) that the value of the thermal stresses varies according to the distance from the center of the section and reach the maximum value at the external fiber of the section.

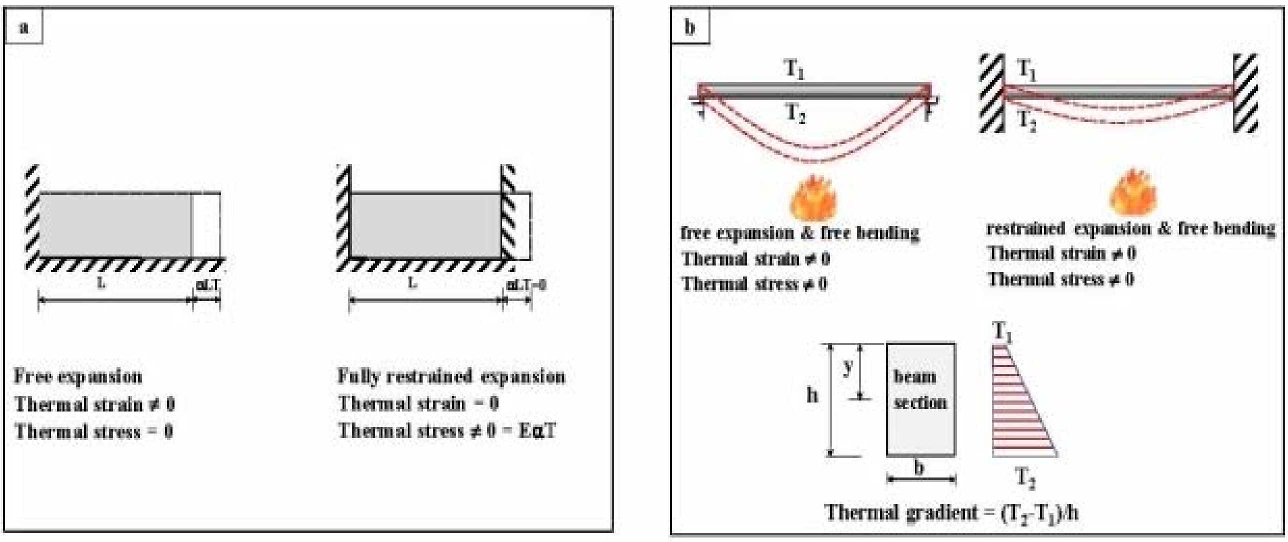

Figure 3. a- Thermal stresses in bars, b-Thermal stresses in beams

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Biographical Sketch

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