HIGH-RISE STEEL STRUCTURES AND THEIR FIRE RESISTANCE PROBLEM A RESEARCH AFTER THE WORLD TRADE CENTER DISASTER

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ABSTRACT

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This study aims to provide information about thermal properties, resistance and behavior of high-rise steel structures under fire conditions, which is the most quoted phenomenon, appeared after the collapse of World Trade Center. Firstly, the definition of fire and fire safety concepts according to the development is clarified. Building regulations, codes and standards of foreign countries and our country is compared, and protection methods for meeting these requirements are listed in order. In the last chapter the reasons for the collapse of the World Trade Center Twin Towers, which meets the highest fire resistance codes in its classification, are discussed.

Keywords: High-Rise Steel Structures, Structural Fire, Fire Safety, Fire Protection Methods, World Trade Center Disaster.

ÖZ

YÜKSEK ÇELİK YAPILAR VE
YANGIN DAYANIMI SORUNU
DÜNYA TİCARET MERKEZİ FACİASI SONRASI BİR ÇALIŞMA

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Bu çalışma Dünya Ticaret Merkezi felaketi sonrası yangına dayanımı tartışılan ve yüksek yapılarda vazgeçilmez bir strüktürel malzeme olan yapısal çeliğin yangındaki dayanımı, özellikleri ve kabiliyetleri araştırılmıştır. Öncelikle strüktürel yangının tanımı yapılmış ve yapısal yangınların gelişimine bağlı olarak yangın güvenliği kavramları belirtilmiştir. Yabancı ülkeler ve ülkemizdeki yangın yönetmelikleri karşılaştırılmış ve ilgili yangın kodlarının sağlanabilmesi için gerekli koruma yöntemleri sıralanmıştır. Son bölümde ise sınıfında dünyanın en yüksek yangın dayanımı sınıfına göre inşa edilmiş Dünya Ticaret Merkezi'nin yıkılma nedenleri tartışılmıştır.

Anahtar Kelimeler: Yüksek Çelik Yapılar, Strüktürel Yangın, Yangın Güvenliği, Yangından Korunma Yöntemleri, Dünya Ticaret Merkezi Faciası.

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SYMBOL

R = actual risk

R accepted = targeted risk

P_o = probability occurrence of a fire

L_x = probable extent of loss

ΔP = pressure difference, Pa (in H_2O)

T_o = absolute temperature of surroundings, °C

T_f = absolute temperature of fire compartment, °C

h = distance above neutral plane, m

K_s = coefficient, = 3460 (7.64)

λ = Thermal conductivity, W/m°C

T = Steel temperature, °C

α = coefficient of thermal expansion

d = Thickness of the insulation material, m

F = Surface area of unit length of the steel member

V = Volume of steel in unit length of the member

m = Moisture content of the insulation, %

ρ = Density of the insulation, kg/m³

t = Fire resistance, minutes

W = unit weight of the steel member, kgf/m

W' = unit weight of the steel member + gypsum board encasement, kgf/m

P = Perimeter of the steel member, mm

CHAPTER 1

INTRODUCTION

1-1- Purpose and Objectives

On the 11th of September 2001, New York City witnessed a tremendous tragedy of the entire history of the world. The 5th and 6th tallest buildings of the world, World Trade Center (WTC), 110 story Twin Towers and more buildings in this complex collapsed by a sudden attack of the terrorists who had used two Boeing 767 commercial airplanes. The planes hijacked just after their departure from Boston to Los Angeles, were full of tons of jet fuels.

The towers were called "a monumental gate to New York and the United States of America." The World Trade Towers, which were visible from any point in the city, were landmarks and symbols of the New York City, and were representations of late 20th century New York Architecture. Thousands of people lost their lives and hundreds were injured in this tragedy. Either the collapse of the towers or the deaths in this tragedy resulted changes for the entire history of the human society.

At the time they were hit, the south tower stood up for 54 minutes, and the north tower stood up for one hour and 44 minutes respectively. Unexpectedly high temperatures overwhelmed the resistance of the buildings to fire by standard fireproofing treatments and the safety of the structures. Even the time difference between the two collapses of the similar constructed twin towers, initiated discussions about the fire protection codes, standards and concepts.

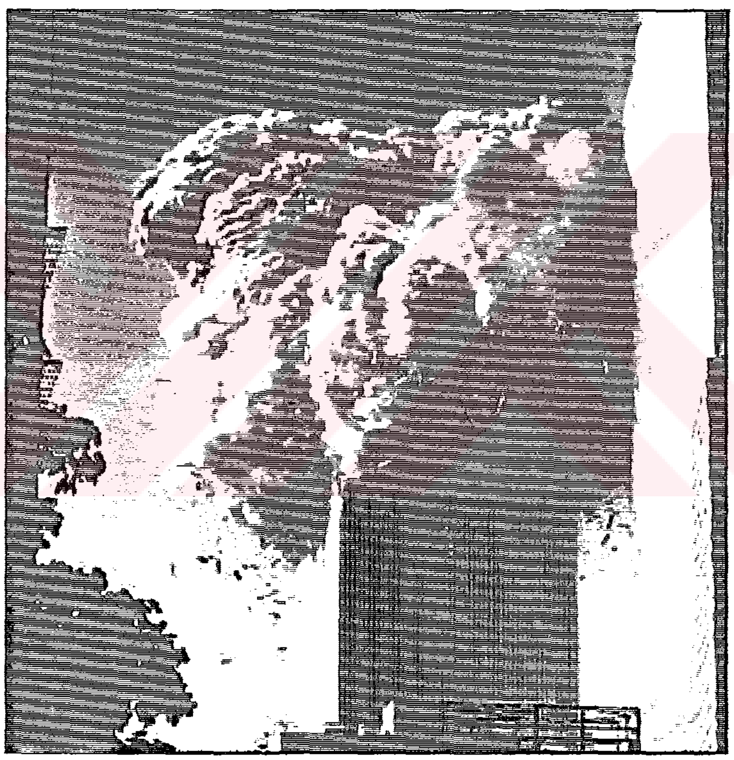


Figure 1.1 Collapse of the North Tower of WTC – 11 September

Millions of people have watched the Twin Towers melting like a candle (Figure 1.1) on their televisions all over the world and the fact that a great amount of the high-rise buildings in the world stood in steel framed structures; these critiques came out with the questions as;

- Is it necessary to use steel in high-rise buildings besides concrete?
- How safe are the high-rise steel structures?
- How can steel structures be protected from fire?

1-2- Designer's Responsibility

The building industry faces many diverse challenges to public safety. Fire safety is but one of these hazards. For decades fire safety of buildings has been greatly emphasized in Western Countries. Fire safety is only one of several considerations that must be incorporated in to a safe structure. Public safety, however, is a major consideration in the training, licensing and practice of architecture. For the architect, public safety means that a project is sanitary, structurally adequate, secure from intrusion, functionally correct, accessible, and has good environmental quality. All this has to be accomplished within a reasonable budget so that the project can be built. As the team leaders in the planning and building process, the architect and the structural engineer are the trained professionals charged with the global overview of the functional, aesthetic, budget, technical and political adequacy of a project. But it is the architect's responsibility to design for the client, coordinate, negotiate, and facilitate the work of numerous, specialists who often promote their cause at the expense of other valid interests in the process. Unfortunately for the architect with responsibility, there is an inherent responsibility that results from his performance if any discipline dominates the team at the expense of another. [1]

The weaknesses in achieving an ideal building design, construction, and maintenance system has been in the inability of our industry to clearly define public expectations for what constitutes public safety. Throughout the years, there have been unofficial regional attempts to prepare a system of codes and standards that try to regulate public safety appropriate with the European Community codes and standards (Eurocodes). Based on the available literature, the present research has been prepared with three objectives:

- To help to provide a better understanding of fire safety of steel structures by supplying a guide for architects, non-professional decision-makers, investors and other concerned people, such as architecture and civil engineering students.
- To help the authorities responsible for the enactment and enforcement of the regulations by providing a summary of fire safety concepts of steel structures with taking into account recent developments.
- To promote communications between architects, designers and fire authorities with regard to fire safety requirements.

1-3- Historical Background of High-Rise Steel Structures

Since the moment of existence, with the need of protection and sheltering of mankind, the term "building" started to be pronounced. Starting with the production of steel, the industrial revolution has started and this caused the building development as vertically. The historical background of the high-rise steel structures can be summarized in two phases.

- Developments in 19th Century
- Developments in 20th Century (Contemporary Developments)

1-3-1- Developments in 19th Century

The use of iron dates back to the prehistoric times, whereas in the 18th century, when new and cheaper processes of production were invented in England and the iron production was industrialized, iron gained a new importance. [2] In 1779 the bridge (Figure 1.2) on Severn River near Coalbrookdale was constructed in iron. With the completion of the iron bridge at Coalbrookdale, Shropshire, there was a rapid development in the use of iron, particularly as cast and wrought iron for bridges and buildings.

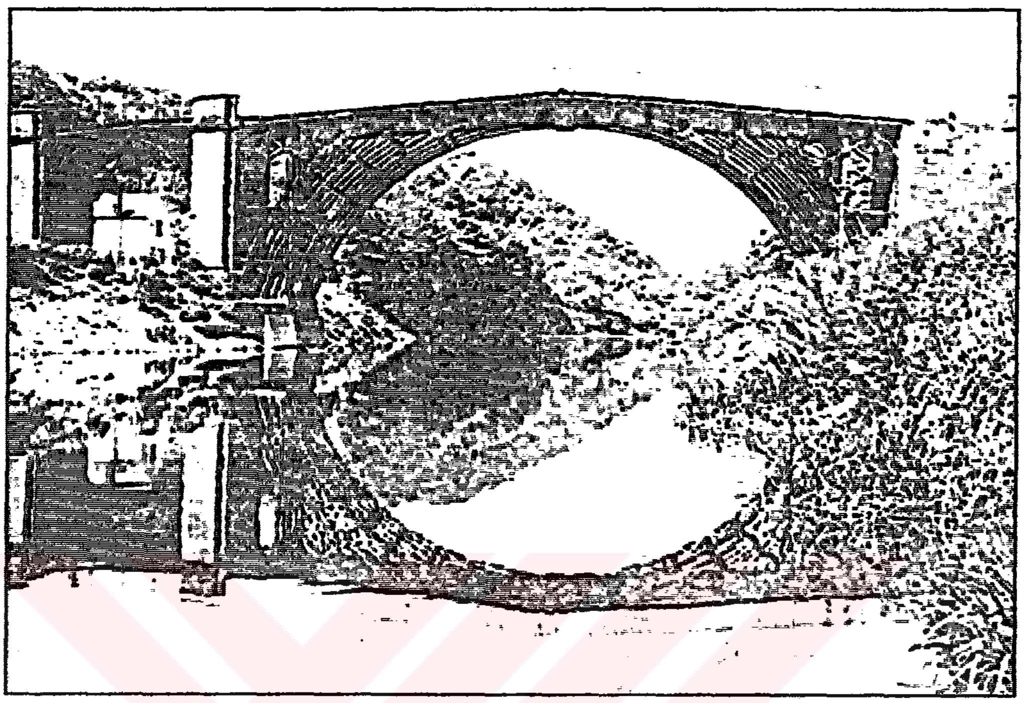


Figure 1.2 Coalbrookdale Bridge - 1779

As the exploitation of glass increased vastly, the sequence in the development of the use of iron reaches a real culmination in the fifties with the construction of the Crystal Palace (Figure 1.3), by Sir Joseph Paxton, was erected in 1851 in London, for the Great International Exposition, using a steel skeleton closed with glass, creating a vast hall of airy lightness. The construction was completed in a period of four months with prefabricated, and mass produced structural elements. After its construction, a considerable number of other Crystal Palaces were erected all over the Western World, edifices of that were almost entirely in iron and glass, particularly the St. Pancras railway terminal is the 78m clear span completed in 1867. [3]

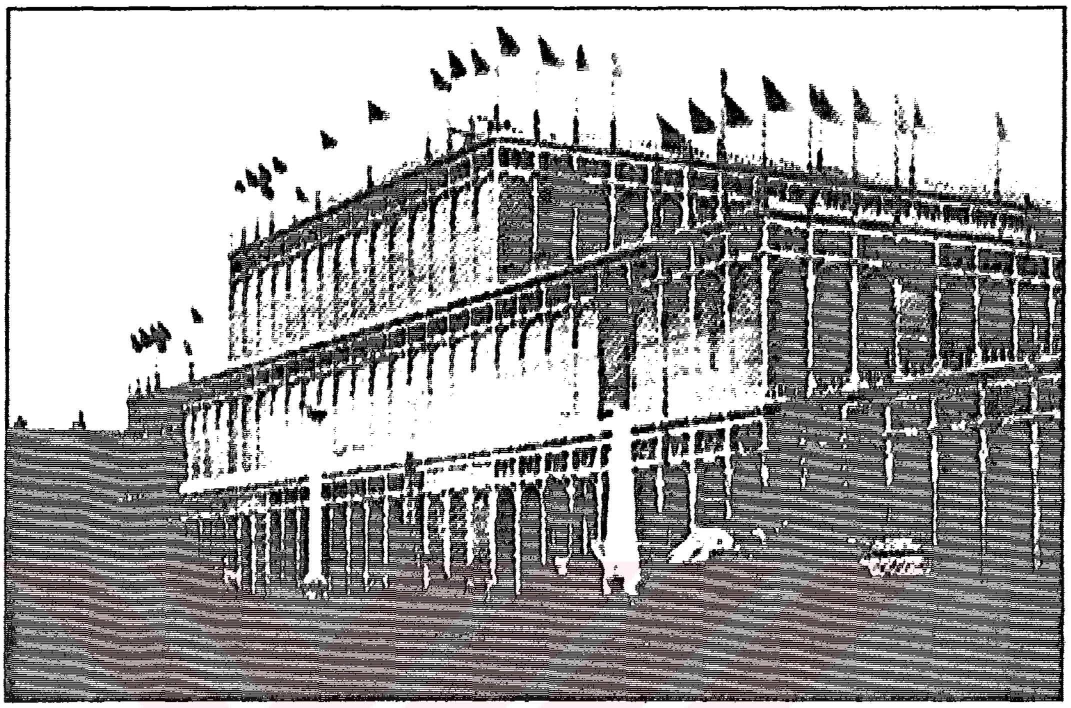


Figure 1.3 Cyrstal Palace - 1851

An important change in the metal structure construction came in 1855. This was the year when Sir Henry Bessemer invented a new method of making steel in sufficient quantity. [3] The Bessemer Converter blew hot air through liquid pig iron, which is called unrefined cast iron, until most of the carbon was burned, and the resulting steel was than cast into molds. This resulted in a great reduction in the price of steel, and became a serious competitor for wrought iron. [2] A short time later, steel took irons place with its strength, elasticity and tensile properties. Opposition in England to the use of steel as a replacement for wrought iron extended until the end of nineteenth century. The situation was different elsewhere; indeed the bridges were at the edge of this architectural development.

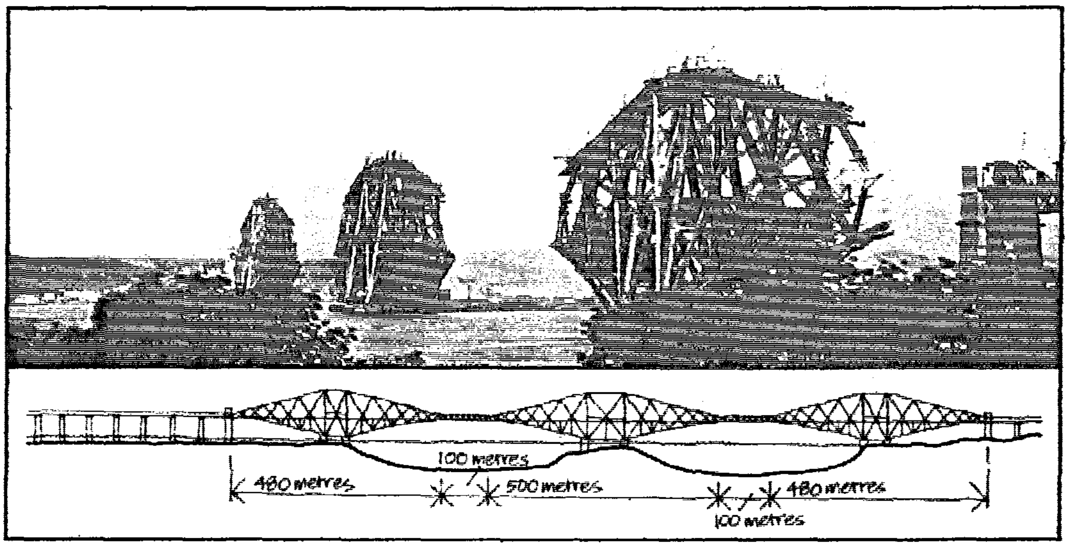


Figure 1.4 Forth Rail Bridge - 1889

The first major steel structure to be built in England was the monumental Forth Rail Bridge (Figure 1.4), completed in 1889. The Ritz Hotel, by the Anglo-French Practice Mewes and Davis completed in 1906, was the first significant structure in London to utilize a steel skeleton to support the full weight of the building. The construction technique followed American practice, where multi-story framed buildings were common. [4]

In America, between 1890 and 1900 a large number of buildings were constructed with riveted steel frameworks and connections designed to resist wind moments, although iron framing had been used in a limited way before that. The first tall building with exterior walls supported on, rather than supporting, the iron and steel framing was the 10 stories (55 m) Home Insurance Company Building (Figure 1.5) erected in 1883 in Chicago, which was designed by William Le

Baron Jenney. Besides its reforming in Architecture, this building is stated as the first skyscraper in the world by "Council on Tall Buildings and Urban Habitat". The buildings main structure was composed of steel beams, which was working between load bearing masonry walls.

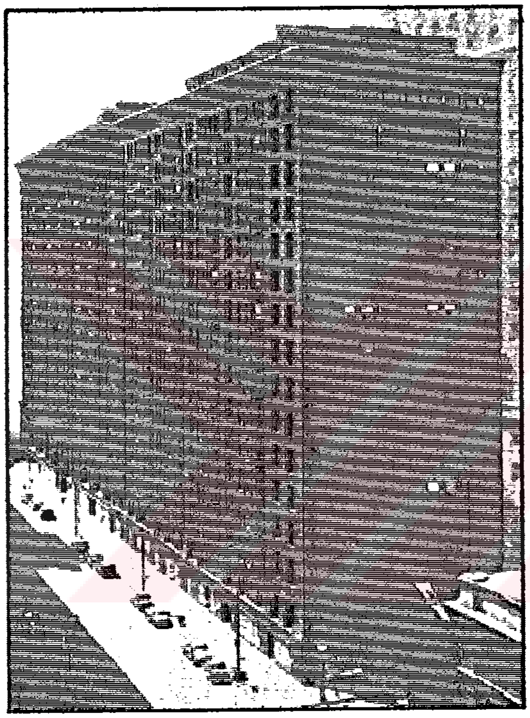


Figure 1.5 Home Insurance Company Building - 1883

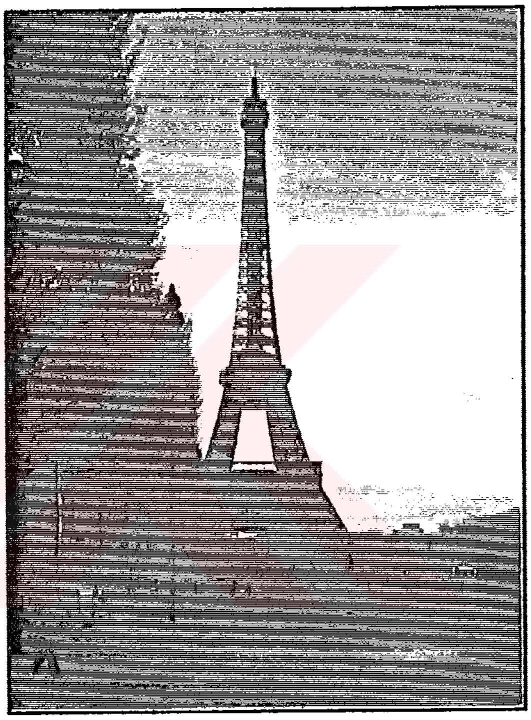


Figure 1.6 Eiffel Tower – 1891

Metal framing alone did not make these achievements possible. The development of the passenger elevator, which was operating in hydraulic systems, responded to taller building structures. Before its invention by Elisha Otis in 1854, buildings could be constructed to a maximum height of six stories. On the other hand, European designers were hardly working on the bare steel framed structures. The Eiffel Tower (Figure 1.6), which was designed by the engineer named Gustave

Eiffel in 1891, represents a typical iron and steel characterization in Paris. Through the use of special techniques and innovative methodologies Mr. Eiffel created the tallest (300 m) structure in the world. It was prefabricated and site riveted. It was described as 'unrealizable, useless and senseless'. One of the eminent French writers, who could not stand the sight of the Eiffel Tower, was dining there everyday in order not see the tower in the Paris scenery [5] But, the tower itself is one of the most remarkable landmarks of the world.

Figure 1.7 Chicago Fire – 1871

People may call Chicago as the birthplace of skyscrapers, however the city was burned out dramatically on 8 October 1871 (Figure 1.7). The results were 18.000 destroyed buildings, 100.000 homeless people, and 300 dead people in just 48 hours. The fireproof construction of the larger commercial and government buildings had proved to be a tragic joke.

An opportunity arose to rebuild most of the central area of the old city. Besides unprotected iron frames and the wood, the rebuilding program was mainly concentrated on using more durable and robust fireproof materials and techniques. With the increase of land prices, it was cheaper to build higher buildings rather than to buy a larger area and this leads the way to the birth of the skyscrapers and the term called "Chicago School". [6] At the turn of the century these unexpected situations attracted ambitious architects and innovative designs.

Four architects dominated this period with the leading company Holabird and Roche: William Le Baron Jenney with the 61 meters Home Insurance Company Building (Figure 1.5); Daniel Burnham with the Reliance Building (Figure 1.8); John Wellborn Root with the Monadnock Building (Figure 1.9); and the most influential of them was Louis Henry Sullivan with the Auditorium Building and Carson Pirie Scott Building were being in success in establishing the influential architectural movement known as the Chicago School. Designed by Burnham and Company, the 15-story Reliance Building (Figure 1.8) was a remarkably advanced structure in these examples. It was the first entirely steel framed building, which causes the exterior to be sheathed in lightweight non-load bearing materials such as glass. Construction was realized in two phases and was constructed amazingly fast, thus only the steel frame for the top 10 stories were erected in 15 days after starting the second phase of the construction. [6]

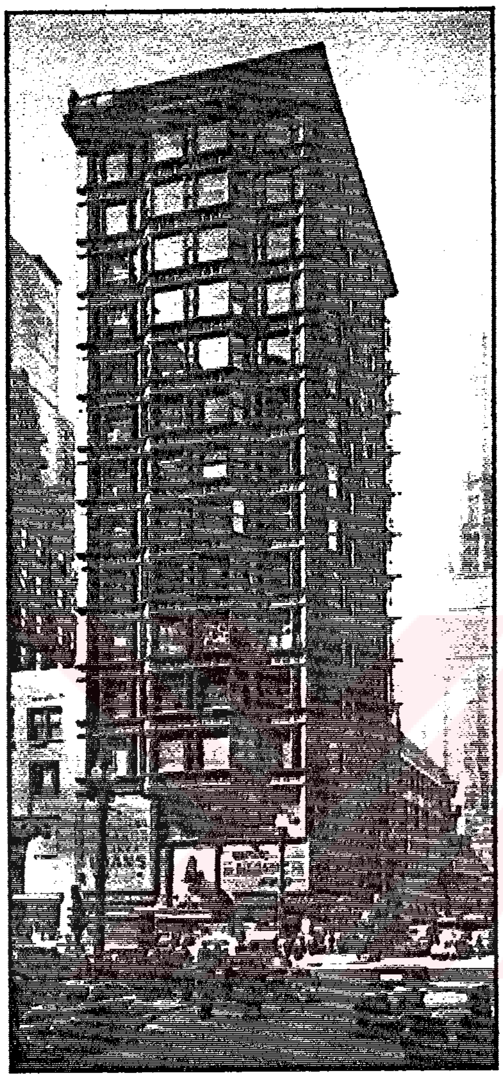


Figure 1.8 Reliance Building – 1895

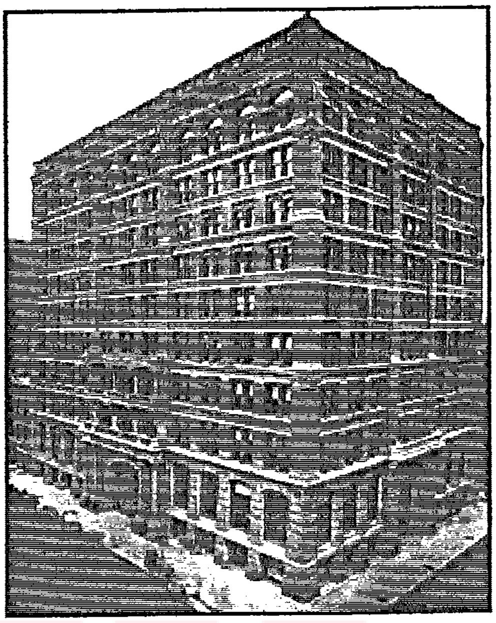


Figure 1.9 Monadnock Building – 1889

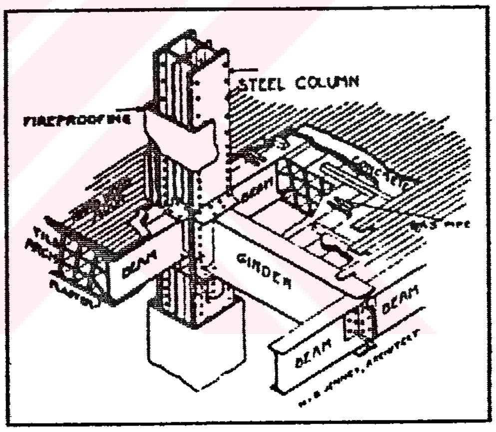


Figure 1.10 Fair Store Building – Fireproof steel-frame detail – 1892

Another first is the William Le Baron Jenney's Fair Store Building in 1892 with the fireproofed steel frame construction (Figure 1.10). In other words, the internal skeleton carrying a protective masonry cladding has firstly used by William Le Baron Jenney. Although these architects have used the first diagonal joints in order to resist the lateral wind forces, thus the concepts called vertical trussed beam and curtain wall existed. [7] As a result in the 19th century, new technical like new construction methods in 1870's, automatic elevators, central heating systems and rational hardware. As the time passed, with the increase of the population and sources, it has become a must to research on the structural problems, comfort technologies, construction methods and fire protection methods.

1-3-2- Developments in 20th Century (Contemporary Developments)

At the beginning of the 20th century with the increase of steel production, newer design techniques have improved for high-rise steel structures. Also the increase of building lot values in the city centers caused building structures to enlarge in the vertical direction. Both materials steel and reinforced concrete were more effective structurally when compared to the already existing materials, such as stone, timber, cast and wrought iron, etc. Below, three periods of time can be summarized, according to the developments in high-rise steel structures.

1-3-2-1- The Period Between 1885 – 1930

The most important facts of this period; invention of automatic elevators and solution of fire safety problems, removed the handicaps through achieving high-rise steel-framed buildings. In the late 19th century New York was moving towards to be the center for new business in the United States. The race was on to outstrip Chicago and make New York the first city of tall buildings. The drop in steel prices, lack of planning regulations, and the legendary ability of the local Mohawk Indian steeplejacks to keep their balance when working at great heights all pushed the race to build taller. The prestige of high-rise buildings, which some of them were far taller than its economical sensibility, were totally insensitive to the environment which they stood. In 1895, the 93 m American Surety Building snatched the title of the world's tallest building from Chicago to New York.

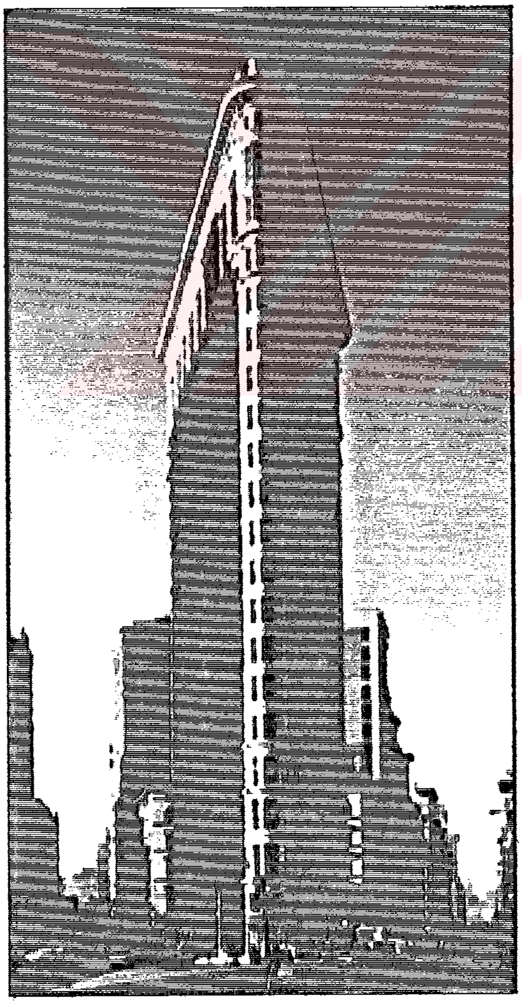


Figure 1.11 Flatiron Building – 1903

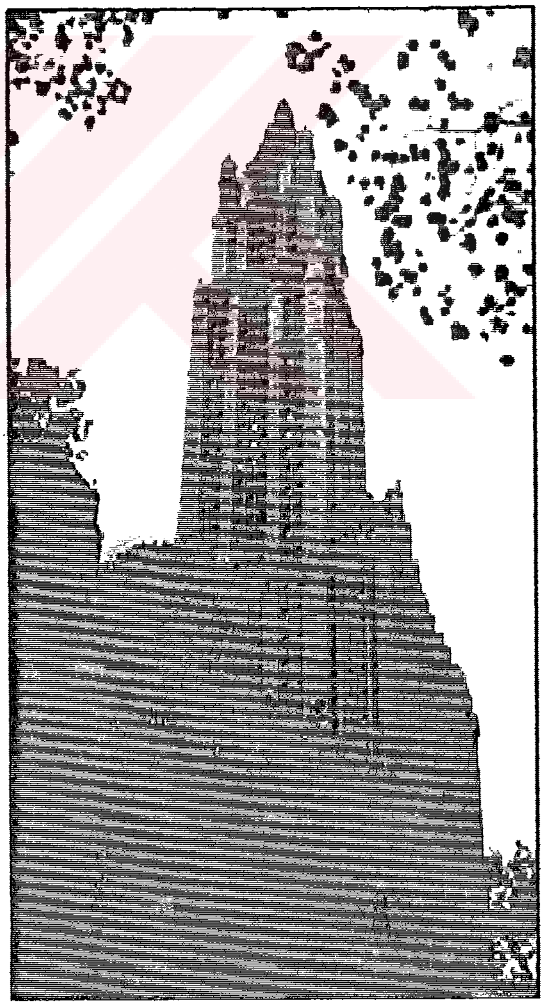


Figure 1.12 Woolworth Building – 1913

However, the term "skyscraper building" entered New York in 1900 and one of the first and the ever-popular Flatiron Building (Figure 1.11) was completed in 1903 on Madison Square, which was designed by Daniel Burnham. But the greatest skyscraper of this period was Cass Gilbert's 52 stories Woolworth Building (Figure 1.12) completed in 1913. It was also the tallest building at that time with 241 meters. [3,7]

1-3-2-2- The Period Between 1930 – 1960

The 2nd World War and the economical crisis after, limited the financial sources thus there was a necessity of the developments in more economical high-rise building methods in this period. Besides their economy, fire detectors and sprinkler systems, heating, ventilating and air conditioning (HVAC) and lightning techniques were improved.

At the beginning of this period, high-rise building technology improved so far that 100 story skyscrapers pronounced. Structural engineers and architects gained a better understanding of the forces acting on a high-rise that, shear-core, shear-truss, and framed-tube structures were all developed. Also higher-grade steel, thicker plate girders, better riveted connections, machine excavated piles and caisson foundations, provide the resistance to all greater forces to be carried. [3,7]

The giant buildings, Chrysler (282 m) (Figure 1.13) by William Van Alen in 1930 and Rockefeller Center (259 m) (Figure 1.14) by Raymond Hood in 1940 were the amazing examples of the high-rise phenomenon, which draws the line of the sky architecture. Nevertheless, the legendary Empire State Building (Figure 1.15) has broken the high-rise record with 381metres in 1931 and holds this record till the completion of the World Trade Center in New York (1971), for 40 years.

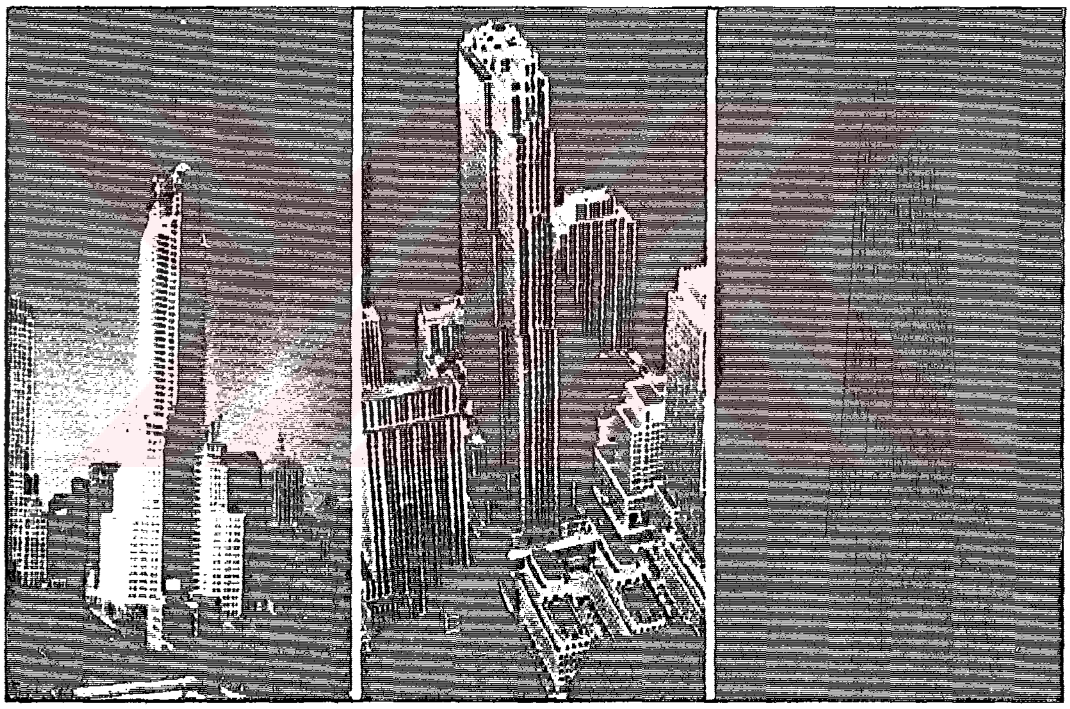


Fig. 1.13 Chrysler Building - 1930 **Fig. 1.14 Rockefeller Center - 1940** **Fig. 1.15 Empire State Building - 1931**

It is an ironic coincidence that on a foggy morning on July 1945, a B-25 bomber airplane crashed into the 79th floor offices of the Catholic War Relief Services (Figure 1.16). When the plane crashed, one of its engines whizzed from the north wall, and through the south wall, ultimately landing on the roof of a nearby building. Debris from the building and plane also severed through elevator cables, and sent two cars and passengers into freefall. Fourteen people had died and the building suffered from the fire damage in short while by the help of the sprinkler systems. [8]

Figure 1.16 Six-meter gash on the Empire State Building – 1945

The concrete encasement of steel frame system of these three buildings was very high resistive against fire but also have a quite loss of material, that is the cause of the bending of the columns and beams resisting to the sheer force applied by the lateral wind forces acting on the lower stories. The value of the buildings was increased by new elevator technology that fewer shafts were needed in a high-rise, leaving more usable floor space. Other improvements such as forced ventilation, fluorescent lightning, and pressurized water systems (sprinklers), all raised the level of comfort and safety within tall buildings. [6,7]

1-3-2-3- 1960 and After (The Supertall Period)

> "During the 1960s, the image of the skyscraper re-emerged as one of economic prowess and might. This return to the individualism of the 1920s can be attributed as much to innovation in the technology of tall buildings as to the growing dissatisfaction with the uniform glass-box look. The development of high-grade steel, fusion-welded sections, and new types of connections offered enormous potential for saving weight and with it construction time and money, especially when combined with some of the new designs for mega-structures." [6]

The term Supertall buildings appeared to be the buildings more than about 70 – 80 stories high is currently receiving increased attention in several places around the world. Improvements in technology made it available to construct the Empire State as the world's tallest building with 381 meters. After 38 years in 1969, the John Hancock Center (Figure 1.17) in Chicago could approach just 37 meters below with (100 stories) 344 meters. The strength needed was achieved extremely economically by placing most of the steel elements on the outside of the structure where it acts as a wind brace. The financial save was just 15 million dollars by using those huge cross braces. But in 1972, the record was broken by New York's World Trade Center (Figure 1.18) at 417 meters, which will soon demolished by terrorist attacks in 11 September 2001. Despite its dullness, architect Minoru Yamasaki applied a number of structural innovations, which will be covered in Chapter 5 of this study. However, two years later, the Sears Tower (Figure 1.19) took this much important title back to Chicago, since it had been in New York 1895. The designer of the building Fazlur Khan, who was working for Skidmore, Owings & Merrill, was the pioneer of the bundled tube structural system, has also designed the John Hancock Tower.

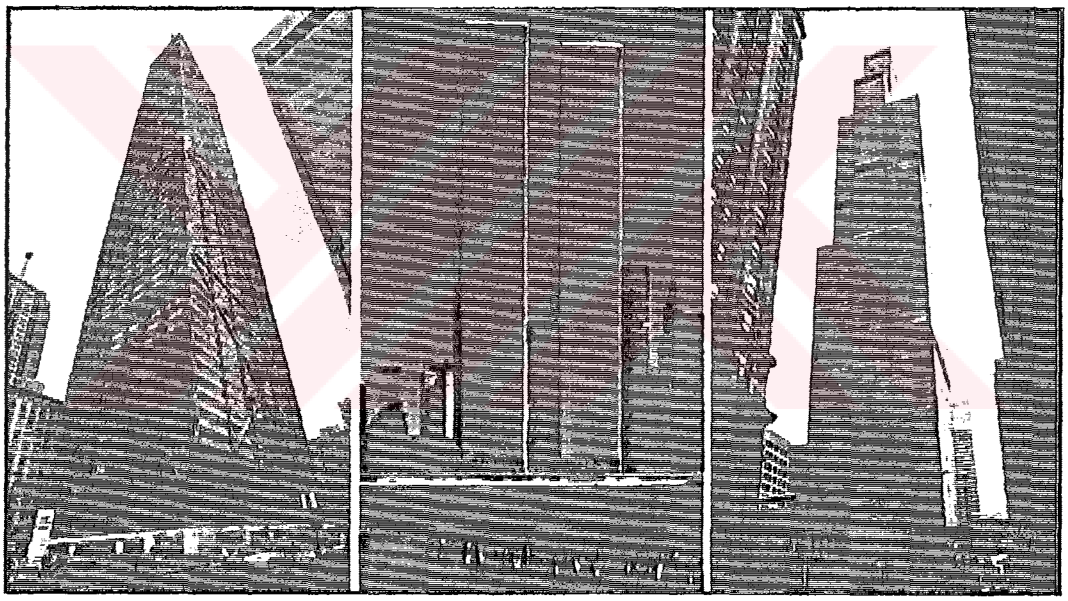


Fig. 1.17 John Hancock Center - 1969 **Fig. 1.18 World Trade Center - 1972** **Fig. 1.19 Sears Towers - 1974**

Opposite to America, Europe was not dealing with the term Supertall Buildings, but on the other side of the world, far-east countries like, Malaysia, Japan, China and Indonesia, were very much-concerned about this term Supertall Steel Structures and studied on the new technologies, engineering standards and architectural expressions with the experience of the western companies in late 1980s. This time these steel buildings represent a branch of industrial technology and the rising value of the far-east economical power. These buildings do look like machines and this machine effect is more than a metaphor; it is a source of technology and imagery that stood up as working monuments and serving for the human beings commercial needs. Both, I. M. Pei's Bank of China (Figure 1.20) and Norman Foster's Hong Kong Bank (Figure1.21) in Hong Kong are the typical examples in this manner. But the Twin Towers of Petronas (Figure 1.22) is the exact answer for the supertall question by the architect Cesar Pelli. These high technological composite structure towers of 450 meters are currently holding the world's highest building record and serving for the traffic of 50.000 people per day as machinery.

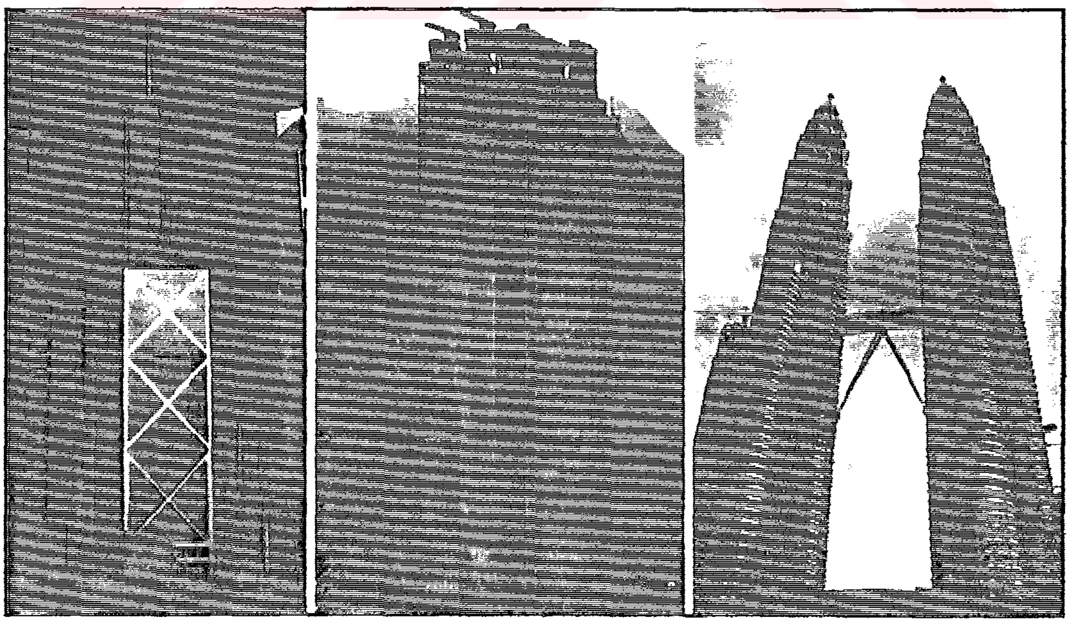


Fig 1.20 Bank of China - 1990 **Fig. 1.21 Hong Kong Bank - 1985** **Fig. 1.22 Petronas Twin Towers - 1997**

1-4- A Short Historical Review of Structural Fire

"Fires in buildings are nearly always man-made, resulting from error or negligence. Primitive man used heat for cooking, warming and lighting his dwelling with the inherent risk that misuse or accident in his control of fuel might precipitate disaster." [10] The principal aim of the fire safety is to protect life and property. As one of the most competent member of a buildings design team, architect was holding all the responsibility of the resident's lives throughout the history. This interesting regulation below, which was stated in B.C. 2250 by the emperor of the Babylon, Hammurabi, shows the responsibility of the architect through the civilization. He stated that:

" If a faulted building collapses by any reason and the building owner dies, the master; if the building owner's son dies, the master's son; will be punished with death." [11]

Since the earliest attempts to implement fire safety, considerable progress has been made in the understanding of structural fire protection. Although many modern approaches have their origins in these early concern. When one can look up to the historical background, fires damaged people's life both as morally and physically and continue to do so. In this historical survey, fire resulted to change the layouts and silhouettes of the cities and give a new shape.

There has been many great fire disasters happened through the history but the most important ones are the Great Fire of London in 1666, Chicago Fire in 1871 and the San Francisco Fire After the Earthquake in 1906. Modern and contemporary references illustrate the progress of fire protection activity after the Great Fire of London in 1666 (Figure 1.23), which took attention to the need for the building control as a means of fire containment. The fire lasts within five days and an area one and a half miles by half a mile lay in ashes (four-fifths of the city of London): 373 acres inside the city wall, 63 acres outside, 87 churches and 13,200 houses. Amazingly, only six people were definitely known to have died, but it would seem probable that many more perished.

Figure 1.23 The Great Fire of London – 1666

In Turkey's known history of fire, 3334 buildings in 1866, 3024 buildings in 1871, 4644 buildings in 1911 and 8480 buildings were damaged in 1918 fires.

According to the historical documents in 1900s each year, about 500 buildings are damaged by fire in Turkey. [16]

The preventions for the people to escape from a burning structure, first began to be investigated in 18th century but considerable advances in materials technology of the 19th century, especially after the 2nd World War, making available substances such as gypsum plaster, concrete with rolled steel, enabled the first fireproof structures to be built. At the end of the 19th century, British Fire Protection Committee (BFPC) provided a scientific approach to research into structural fire resistance by fire tests. This was followed by the publication of a standard (BS 476) defining tests for fire resistance, based on research findings from United States, Germany and Sweden, in 1932.

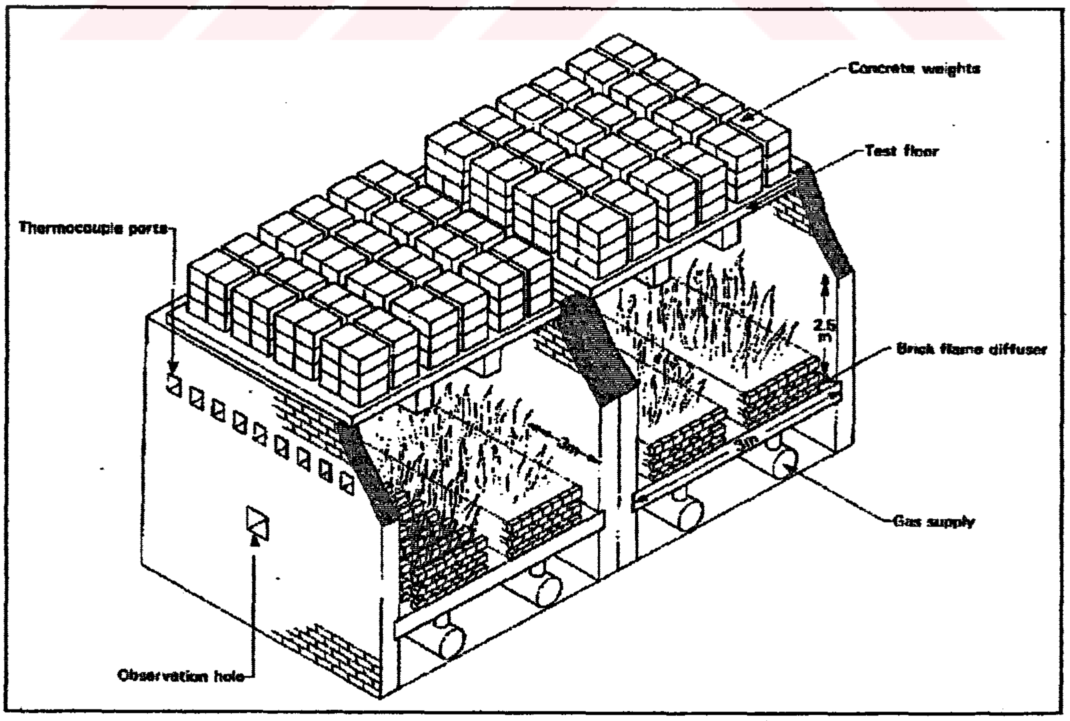


Figure 1.24 British Fire Test Committee fire test – 1901

In United States, the American Society Testing and Materials (ASTM) held had set up a committee to prepare fire test standards in 1917 and issued a standard specification C19 for a standard heating curve (Figure 1.25). It can be observed from the figure that the curves of Britain, Germany and Sweden have very close values to the ASTM C19 curve. [12] However, after the 2nd World War international cooperation organizations like CIB, ISO and likewise, re-considered the fire test methods and conditions, escape roots, diffusion and movement of smoke in buildings and so on. [12]

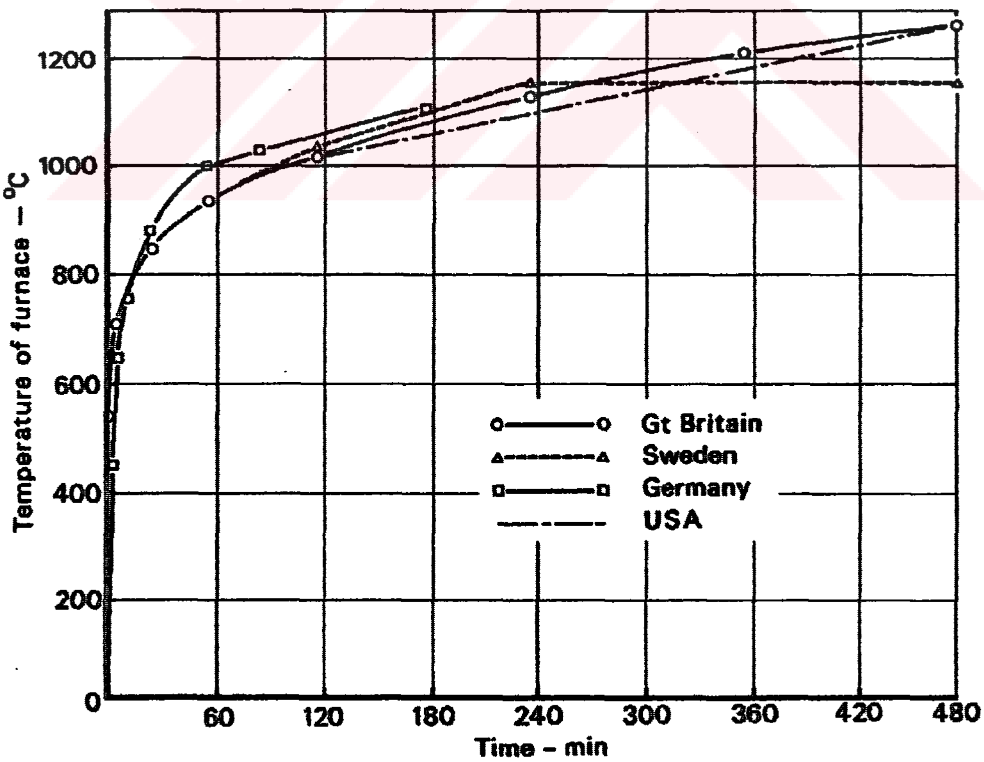


Figure 1.25 Standard Time-Temperature curves of various countries

Construction of large multi-story buildings with non-combustible structural elements, which provides fire resistance, was possible towards the end of the 19th century. However, fires still occurred even in the most advanced buildings of the period. Fire load density was not yet considered as a constraining factor. The storage of combustibles in large quantities was a risk like the use in timber flooring, paneling, partitions and staircases; the fire loading was increasing dramatically.

There were many fireproof buildings destroyed by fire, just because of the structural elements with inadequate degree of fire resistance, chosen by architects. Often the designer's intention, in providing fire-resisting floors for example, was negated because continuous ducts, staircases, lift shafts, etc., were allowed to penetrate the floors without the provision of fire stops. Architects learned the lesson after many buildings were collapsed eventually.

At the beginning of the 20th century, the use of reinforced concrete and steel-frame constructions gained importance. But materials like cast iron and steel, which was known as non-combustible, did not provide fire resistance without adequate protection. The regulations of those years did not require minimum periods of fire resistance; indeed, the term fire resisting was not exactly defined. Little work had been done in attempting to identify the factors regulations, which contributed to fire severity and consequently influenced the nature and quality of protection of buildings. [10]

In this context, there were no scientific research approaches existing till the last 30 years. Nowadays fire safety concepts are researched by the specialists that are known as 'fire engineers', as a real branch of natural sciences. Fire safety is an entirely logical approach for a danger with complicated character and diverts people to necessity of human life and protection of their properties. These necessities are:

- To reduce the probability of fire starts;
- To prevent or to slow down the spread of fire;
- To provide safely, the escape of the people from the fire as quick as possible;
- To ease for the first aid and the fire brigade services;
- To minimize the damages and losses caused by fire. [15]

The important situation is; these objectives stated above should be considered and well understand by the architects and structural engineers.

CHAPTER 2

FIRE

2-1- Definition and Phases of Fire

The American Heritage English Dictionary describes fire as "A rapid, persistent chemical change that releases heat and light and is accompanied by flame, especially the exothermic oxidation of a combustible substance." and the combustion is "a chemical change, especially oxidation, accompanied by the production of heat and light." [13]

As for the Fire Protection Regulations of Municipality of Ankara states that, "Fire is an uncontrolled spread of burning through time and space". [14]

Fire can be useful, but it can also be deadly. It has always fascinated and frightened people. In other words, it is a good servant but a bad master. The civilization would be exactly different or might even non exist, without fire.

All types of fire, or its wider context combustion need, three ingredients. These are: Combustible Material (fuel), Oxygen and Heat, which are known as the parts of the Fire Triangle. (Figure 2.1)

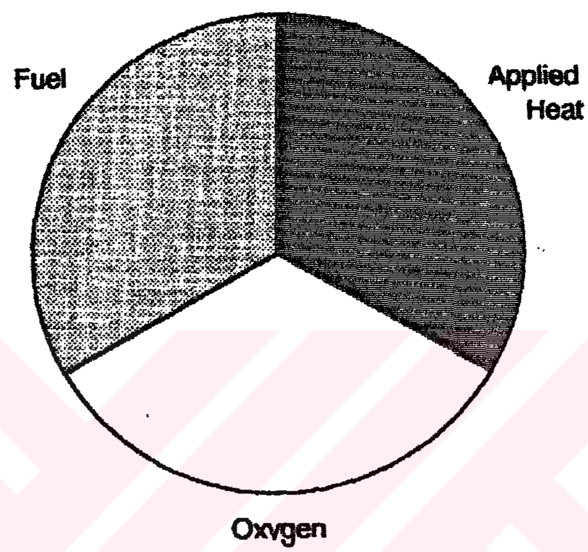


Figure 2.1 The Fire Triangle

The minimum heat needed for the combustion is directly deals with the type, shape and surface of the combustible material. However, the speed of combustion depends on to the renewable amount of the oxygen in that burning space. If it is examined carefully from the Figure 2.2, a standard fire curve with θ value of temperature at t time, has three phases:

I. Growth and development

II. Effective combustion

III. Decay

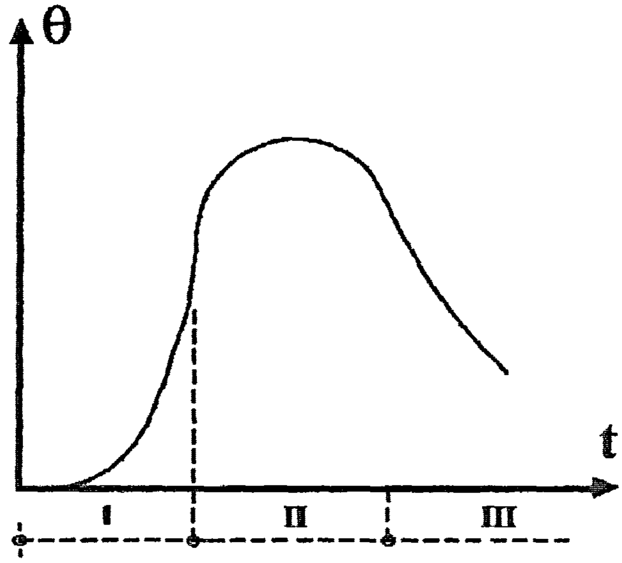


Figure 2.2 Phases of Fire

As most of the fires occur, the transition between first phase; 'growth and development' and the second phase; 'effective combustion' is called the 'ignition' and continues for a very short time as it can be observed from the graphic above. In simple words, ignition is "the initiation of combustion" and has relation with the fire load of that material. During the first phase, the temperature of heat remains low and does not effect to the structural elements. But in the second phase heat produce and temperature of fire increases and the structural elements will be affected rapidly. This phase is taken into consideration in fire protection analysis of buildings conscientiously. Finally in the third phase; 'decay', the temperature start to decrease but the destroying effect continues. Besides if the fire brigade or automatic sprinkler system interferes before the 'effective combustion', which is the moment of 'ignition', the structural system will not be damaged or collapse. [15]

2-2- Physical Properties of Fire

There are three clearly defined physical properties of fire that, heat can travel from one region to another. These are: Conduction, Radiation and Convection. 'Conduction' is a process in which thermal energy can transfer through a solid or liquid of heat by contact. In most building materials it is a molecular process that the thermal energy can travel to the cooler parts. However, in metallic materials electron movement through the solid material causes this energy transfer. In metal structures, a good conductor, like steel, can carry thermal energy from the fire zone to a combustible material in another zone. (Figure 2.3) [10]

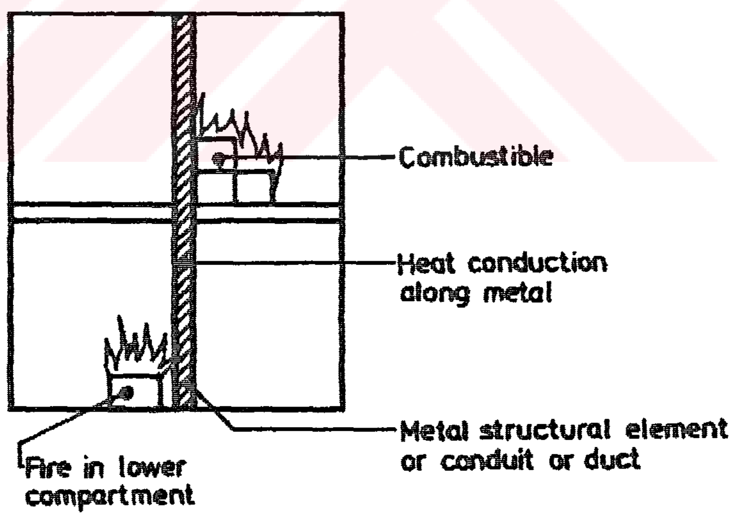


Figure 2.3 Thermal conduction of a metal building structure

'Radiation' is the transfer of energy by electromagnetic waves, which can travel through a vacuum, or through a transparent solid or liquid. Radiation is extremely important in fires because it is the main mechanism for heat transfer from flames to fuel surfaces, from hot smoke to building objects and from a burning building to a building next to.

Between 76 – 80 percent of energy released from a fire is cause of the 'Convection' process that plays a very important role in the spread of fire. In simple terms when a heat source is introduced to a fluid as shown in Figure 2.4, the fluid layer closest to the hot surface warms up and becomes more buoyant compared to the rest of the fluid. This fluid takes away some of the thermal energy from this region and is replaced by cooler, denser fluid. [10]

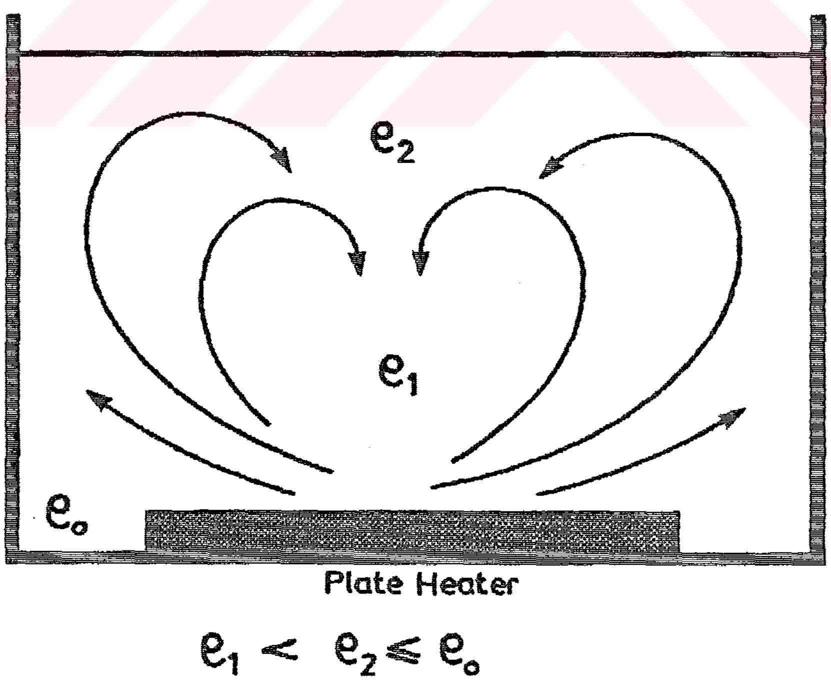


Figure 2.4 Buoyancy effect of convection process

In this effect, with the axial movement of the clean air from bottom to top, provides a fluid layer at the ceiling. The heat of this layer increases rapidly and prepares the condition for the ignition directly or with the help of the radiation from the reflecting surfaces of materials.

2-3- Fire Load

The fire load of a building is the combustible material of its construction together with its combustible contents. The concept of fire loading has its origins from the studies before 2nd World War. The term 'fire load' is used to describe the heat energy that could be released per square meter of floor area of a compartment or story by the combustion of the contents of the building and any combustible parts of the superstructure itself. [10] Many European references express 'fire load' as energy density per square meter of total bounding surfaces of the room. Actually because of the historical reasons, this load deals with the determined 'equivalent wood load' in kg/m^2 unit and states the amount of wood that has the equal heating energy. Besides the fire load of wood is 40000 kcal/kg approximately. The fire load of any building will vary from time to time owing to changes in operation and relocation, additions to, or removal of its combustible materials. Below, typical values for fire loads of different functional buildings in various countries illustrated for consideration.

Table 2.1 Typical Fire Loads

Building type	Typical fire load density	
Small residential buildings	25	kg/m^2
Institutional buildings	25	kg/m^2
Other residential buildings	25	kg/m^2
Office buildings	25 - 50	kg/m^2
Shops	up to 250	kg/m^2
Industrial buildings	up to 150	kg/m^2
Places of assembly	25 – 50	kg/m^2
Storage and general	up to 500	kg/m^2

2-4- Building Codes and Standards

Building codes and standards have similar but different functions. A building code specifies minimum requirements for design and construction of buildings and structures, whereas standards are a set of conditions or requirements to be met by a material, product, process or procedure.

There are two types of building codes. The first type of codes, which are specification codes, spell out in detail what materials can be used, the restrictions of the size of a building, and how components should be assembled. The second type of codes is the performance code that details the objective to be met and establish criteria for determining whether the objective has been achieved.

The scope in the use of standards is their adoption into the building code by reference, therefore there is a strong consistency between building codes, as a result of the reliance of codes on nationally recognized standards. Standards may also describe a method of testing to determine physical, functional, or performance characteristics of materials or products. As an example, testing standards deals with the methods and procedures to establish levels of quality or performance of materials. Their contents can be, procedures for measuring such characteristics like structural strength and stability, durability, combustibility or flammability, and fire resistance. [17] Following are major test standards for the structural fire resistance of various countries:

Table 2.2 Test standards for structural fire resistance

United Kingdom	: BS 476 – Part 8, 1972
United States of America	: ANSI/ASTM E119
Federal German Republic	: DIN 4102 – Parts 2,3,5,6
France	: Arrete of 5.1.1959
Belgium	: NBN 713 – 020
Denmark	: DS 1051
Italy	: Circular 91. (1961)
Netherlands	: NEN 3884
Turkey	: TS 1263 / Sept. 1983
ISO	: ISO 834, 3008, 3009

Building codes and standards are important factors in design decision-making. However, codes and standards alone are insufficient to provide achievable fire safety levels in the buildings constructed today. To achieve this, the building designers must play a more active role in the fire safety design of the building.

2-5- Fire Resistance

Structural elements like columns, beams, walls or floors should be measured by a test according to its resistance for a certain time. According to Buchanan 'fire resistance' is simply a measure of the ability of a building element to resist a fire, which is quantified as the time for which the element can meet certain criteria during exposure to a standard fire resistance test. [18] There are three criterions (Figure 2.5) for fire resistance testing, these are:

- **Stability:** Resistance against deformation or collapse.
- **Integrity:** Resistance against the passage of flame to an adjoining compartment.
- **Insulation:** Resistance against the passage of heat by conduction, [5] which might cause ignition in an adjoining compartment.

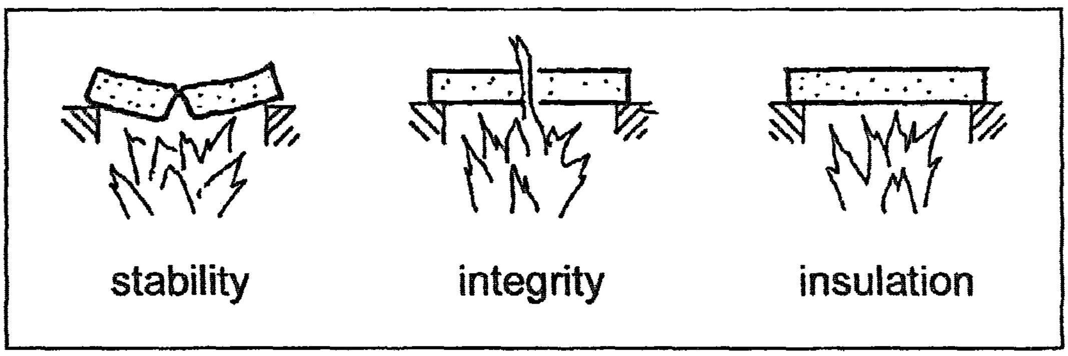


Figure 2.5 Failure criterions for structural fire resistance testing

In order to achieve the 'stability' criteria the structural element must perform its load-bearing function and carry the applied loads for the duration of the test, without collapse. The 'integrity' and 'insulation' criterions aimed to test the ability of preventing fire spread from the room of origin, whereas to achieve the integrity criteria (Figure 2.6) the test sample must not develop any cracks or split that allows smoke or hot gas to pass through to an adjoining compartment.

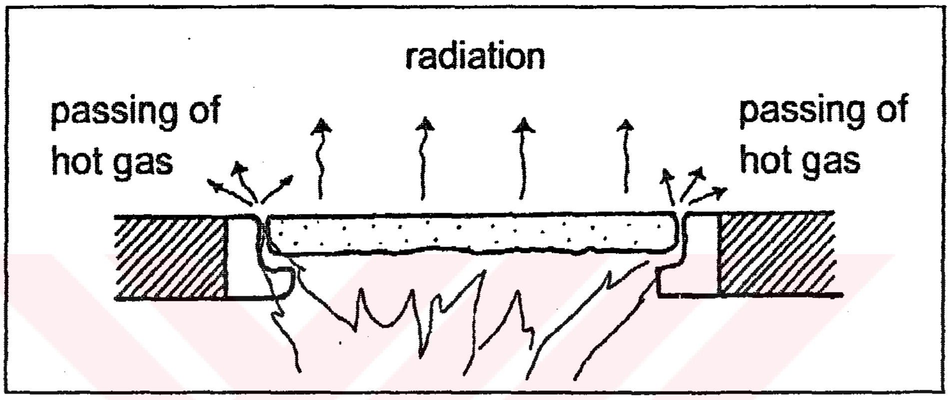


Figure 2.6 Integrity criteria

All fire-rated construction elements must meet one or more of the three criterions according to their function in the fire resistance tests as shown in Table 2.3. Some countries use the terms 'fire rating', 'fire endurance rating' or 'fire resistance level', which are interchangeable. Fire resistance ratings are most often defined in whole numbers of hours or parts of hours. For example a column that should have a fire resistance of 75 minutes, which has been shown by a test, will usually be defined a fire resistance rating for one hour. These tests are not intended to simulate real fires. Their purpose is to allow a standard method of comparison between the fire performances of structural elements. [18]

Table 2.3 Failure criterions for major construction elements

Construction element	Stability	Integrity	Insulation
Column	X		
Beam	X		
Floor / Ceiling	X	X	X
Load-bearing wall	X	X	X
Partition		X	X
Door		X	X
Fire-resistant glazing		X	

For the steel structural members there is normally little problem in achieving the requirements of integrity and insulation, which are criteria in evaluation of fire spread. According to the Turkish Standards of Fire Resistance Classes and Fire Resistance Test Methods for the Elements of Building Construction TS 1263, which is based on the Standards of Federal German Republic DIN 4102 in March 1984, divides fire resistance ability of structural elements into five main groups in Table 2.4.

Table 2.4 Fire Resistance Classifications

Fire Resistance Classes	Minimum Periods of Resistance (minute)
F 30 - Fire Preventive	≥ 30
F 60 - Very Fire Preventive	≥ 60
F 90 - Fire Resistant	≥ 90
F 120 - Very Fire Resistant	≥ 120
F 180 - Extremely Fire Resistant	≥ 180

A fire may take two minutes, two hours, or two days to develop to flashover depending on whether the igniting source could be a smoldering cigarette, or an arsonist at work. The only thing that has certainty is that the fire development will accelerate rapidly as flashover is approached. The standard time-temperature curves of the fire resistance tests are not intended to represent the growth of fires, they are more a reflection of the time constants of the test furnaces, which are carrying out such tests.

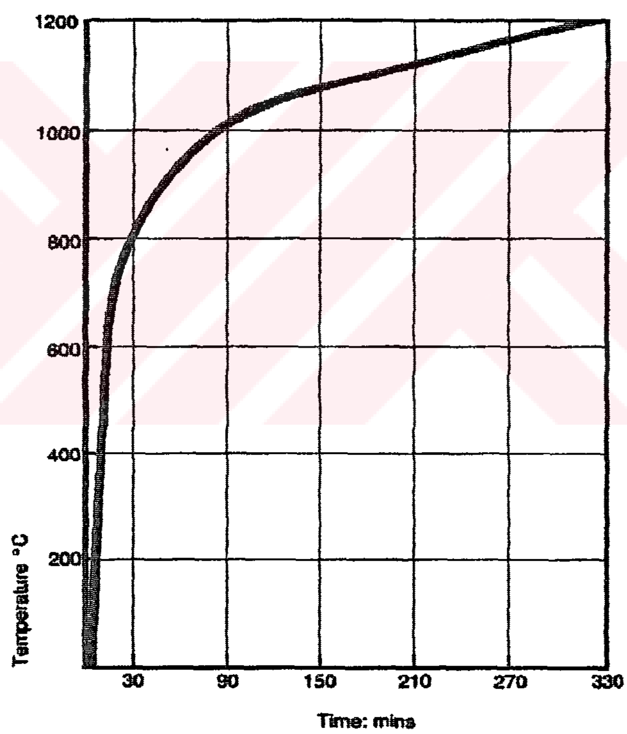


Figure 2.7 Standard time – temperature curve in Fire Test

The curve in Figure 2.7 shows the correlation between time and temperature in a standard fire test. The numerical expression of this curve according to TS 1263 Turkish Standards versus various countries standards as follows.

Table 2.5 Turkish Standards versus various countries standard time – temp. curves

Time (minutes)	TS 1263 Temperature (°C)	DIN 4102 Temperature (°C)	ASTM E119 Temperature (°C)	ISO 834 Temperature (°C)
0	N/A	0	20	20
5	556	556	538	576
10	659	658	704	678
15	718	719	N/A	N/A
30	821	822	843	842
60	925	925	927	945
90	986	986	N/A	N/A
120	1029	1029	1010	1049
180	1090	1090	N/A	N/A
240	1133	1133	1093	1153
360	1193	1194	N/A	N/A
480	N/A	N/A	1260	1257

All building materials experience a certain degree of degradation in the performance when exposed to fires. The elevated temperatures affect the material's strength and rigidity and as a result its structural performance at some point. For the most commonly used structural materials steel and concrete, which are non-combustible, are affected in this case as shown in Figure 2.8. Properties of steel material that affect the behavior of structural members exposed to fire are discussed in more detail in Chapter 3. Some of the material properties can be expressed by equations but for several of the properties, the dependence on temperature can only be shown in graphics.

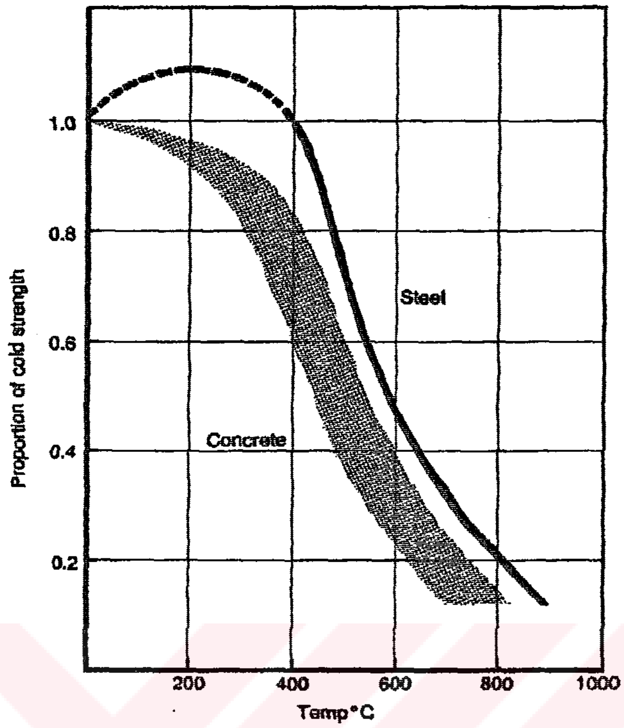


Figure 2.8 Strength reduction at high temperatures

2-5-1- Fire Resistance Requirements

The overall performance of a building must provide firstly means to isolate a fire within a compartment and secondly prevent local failure leading to collapse of the whole structural system. In order to meet the first objective, the structural components surrounding the fire compartment should be designed to prevent fire spread. The second objective needs a proper arrangement of structural system, taking into account the possibilities of load redistribution in case of local failure.

Regulations and supporting documents specify the minimum periods of fire resistance necessary in defined situations, according to the fire load occupancy of the building and to its height or cubic capacity. The fire resistance requirements in the building codes are usually a function of these factors. However the severity of a fire and thus the required fire resistance is a function of additional factors. These factors include the properties of material of the walls enclosing the fire, and the dimensions of the openings (windows) in the walls through that air can be supplied to the fire. [17] Figure 2.8 illustrates the relationship of these factors for fire severity.

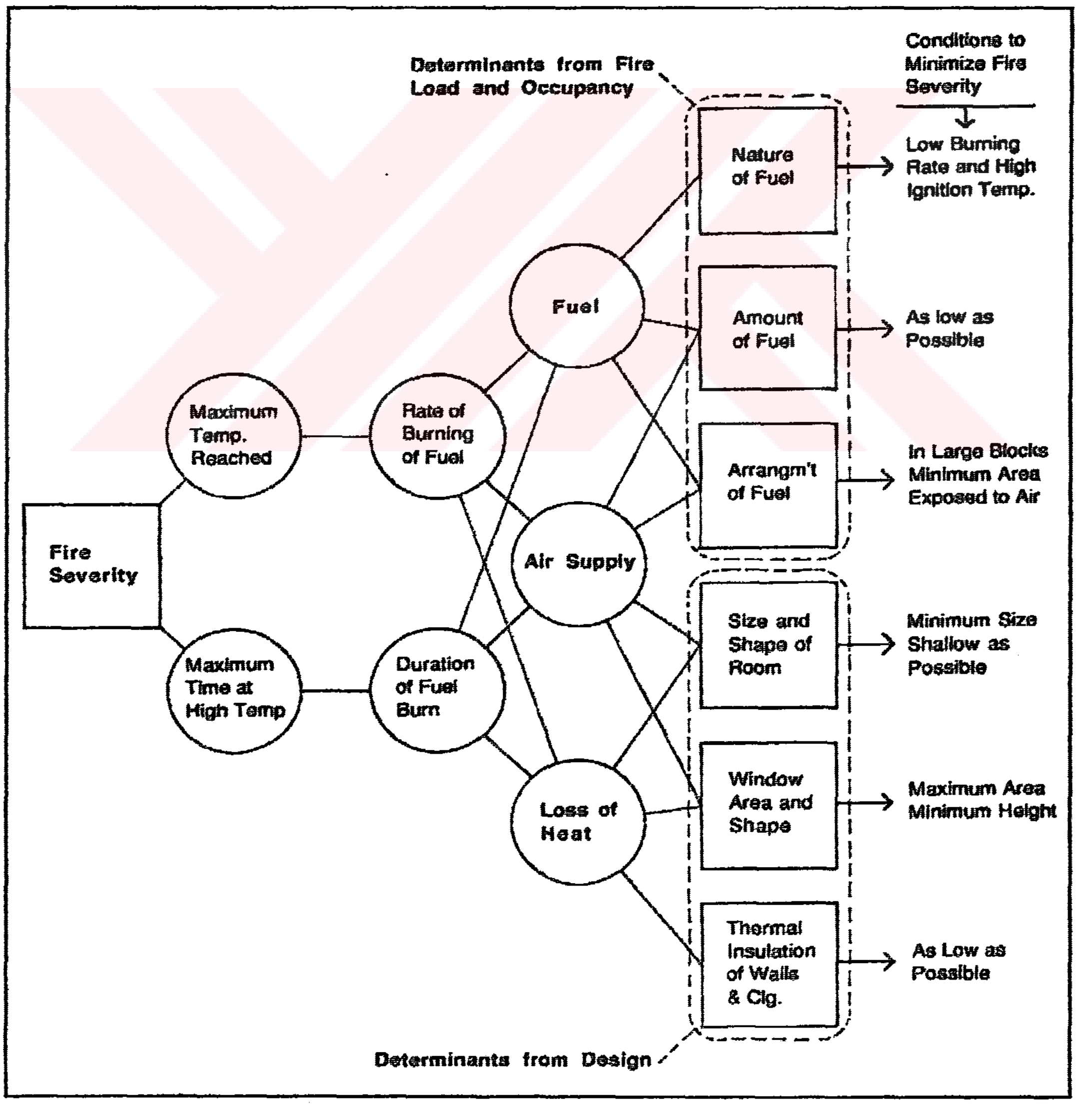


Figure 2.9 Factors for fire severity

The degree of fire resistance required of a structural member is related to the building function. For instance an office building and a factory or a shopping mall cannot meet at the same values of fire load, user density or volume of compartment. Table 2.6 is a sample of building regulation requirements for fire resistance for multi-story shops in United Kingdom.

Table 2.6 UK Building Regulation requirements of fire resistance for multi-story shops (1991)

Maximum height	Maximum floor area (m²)	Maximum cubic capacity (m³)	Fire Resistance (Ground - upper story)	Fire Resistance (Basement)
3	150	No limit	30'	60'
7	500	No limit	30'	60'
15	No limit	3500	60'	60'
28	1000	7000	60'	120'
No limit	2000	7000	120'	240'

If we speak of current fire resistance requirements we always mean the values determined by national codes. These fire resistance classes like 15/30/60/90... minutes, which represent the time that an isolated element will resist the action of a standard fire curve. If we try to give an overview of European requirements as a function of the number of stories, we find the following data. [19]

Table 2.7 European requirements as a function of the number of stories (ISO 834 - 1990)

Type of building	Requirements	Resistance Class
one story	no low requirements	possibly up to F30
2 to 3 stories	no or low requirements	possibly up to F60
more than 3 stories	medium requirements	F60 to F120
tall buildings	high requirements	F90 and more

In Switzerland and the Netherlands for example the fire resistance requirements have been simplified as; Fire duration in minutes = fire load density in kg/m^2 wood equivalent. This is normally given in steps of 30 minutes. For fire loads more than 15 kg/m^2 and less than 30 kg/m^2 wood equivalent, the requirement therefore will be 30 minutes. In addition for normal risks most countries limit requirements to a maximum of 60 or 90 minutes, knowing the quick response and quality of action of their fire brigade organizations.

2-5-2- How to achieve Fire Resistance Requirements

The fire resistance level of a building required or missed by regulations can be achieved by both fulfilling the requirements and by suitable alternative methods. There are several major options available for the designer to achieve the fire resistance requirements in order to protect the building or reduce the life loss and financial loss. The major options include, active and passive protection methods. Some of these methods are widely discussed for steel structures in Chapter 4.

- **Choice of material**

Materials for both the structure and the fittings and furniture should be non-flammable to reduce the risk of ignition, fire spread and heat and should generate a minimum amount of smoke to retain visibility for escape of occupants and to reduce the risk of asphyxiation.

• **Passive protections**

The most commonly used option normally only applied to steel and timber frameworks but sometimes to concrete structures. The structure is designed in normal manner and the steel-frame then covered with materials like gypsum or spray on materials, so that the temperature remains low in the event of a fire. For most buildings insulation of the structural frame to prevent collapse is the least effective way of reducing casualties or financial loss. If the temperature in a burning compartment reaches a level at which the structure is in danger of collapse the costs, both in terms of lives and contents loss, will have already occurred.

• **Structural design**

The fire resistant design approach uses calculation methods to predict the performance and survival time of the steel work based upon its high temperature material properties. An important level of fire resistance can be achieved in steel framed structures even without passive protection. Researches are showing that the designer can influence fire resistance by his choice of member stresses, connections, interaction between members, interaction between members and other elements of construction and location of members inside or outside the structure.

- **Boundary wall conditions**

The boundary walls or façades facing other buildings should be designed with sufficient stability, integrity and insulation and with suitable attention to the size of windows and separation distance to reduce the risk of ignition from fires in neighboring property.

- **Compartmentation**

Division of building interiors by fire and smoke retaining barriers is well recognized as a mean of limiting the consequences of fire. Compartmentation is a feature of all national building regulations.

- **Ventilation**

Releasing smoke and heat to the atmosphere is preferable to retaining them inside the building where they can endanger the occupants and hinder fire brigade action

- **Fire detection systems**

Fire alarms provide early warning to building occupants and make longer escape time. Detection systems are being developed having greater reliability and with reduced risk of false alarms than has been possible in the past. They insure a rapid intervention of fire brigade and by this strongly reduce the probability of flashover and important losses.

- **Sprinkler systems**

The sprinkler systems does not only help to extinguish fires and limit fire spread but they also reduce smoke, thus enhancing life safety and reduce temperatures, thus limiting destruction of contents, structural damage and consequential losses.

- **Escape roots**

The ability of people to escape rapidly from burning buildings is well recognized as the most effective means of minimizing casualties. Escape provisions, to ensure safe exits, feature in all national building regulations. If casualties are to be reduced from their present levels other aspects of building evacuation need to be considered. In particular, since most casualties occur in domestic buildings at night when occupants are likely to be asleep, consideration could be given by legislators to provision of fire detectors to increase escape time.

- **Fire engineering**

Quantitative methods of assessing the temperatures that will be generated in natural fires are now available. These techniques make it possible to determine fire resistance requirements more precisely than by traditional methods based on the standard fire. In particular it allows the designer to determine with greater accuracy the amount of passive protection required, to ensure structural stability.

2-6- Building Regulations

Building regulations are statutory instruments, which set down minimum requirements for the design and construction of buildings. Minimum requirements are established to safeguard the health and safety of society and generally represent a compromise between optimum safety and economic feasibility. [10] In Turkey building developers establish their own requirements, which may exceed the minimum requirements of building legislation. But very often fire safety requirements are omitted or thought after the design process is completed. This naturally causes serious problems.

In this research, the aim is to provide a better understanding of fire safety of steel structures by supplying information about; the properties of materials that make up fire insulation, and the methods of their application. In this context, much research has been carried out in other countries. In most of the developed countries, the concept of fire safety is of prime importance and various types of calculation and protection methods have been developed. Naturally the building regulations reflect and include these developments.

In 21st Century the designed environment is changing and developing according to the needs of the humans life. Even single functioned simple buildings like houses or shops have changed and improved to terms of apartments and shopping malls or centers. Nowadays multi-function buildings like skyscrapers contain functions like, shops, schools, residences, hotels, sport centers, offices and etc. together in the same structure, which needs different levels of HVAC, lightening (electrical wiring) or plumbing and naturally fire protection measures.

Building regulations assume that if certain components of fire safety can be identified and suitable standards are applied to particular building types, a satisfactory level of fire safety will be achieved. Generally most of the building fire regulations follow the outline shown below. But certain specific conditions may cause changes in the regulations and their pattern.

1. Classification of buildings by type
2. Compartmentation of buildings
3. Prescription of fire resistance requirements for elements of structure
4. Limitation of unprotected areas of external walls
5. Prescription of constructional requirement for separating walls, compartment walls and floors
6. Prescription of constructional requirement for protected shafts
7. Specification of the type and constructional requirement for fire resisting doors
8. Controlling of the penetration of fire barriers by services

9. Specification of non-combustibility requirements for stairways in prescribed situations
10. Description of requirements for cavity barriers and fire stops
11. Controlling of the spread of flame over walls and ceilings
12. Relation of the sitting of buildings with roof constructional requirements. [10]

As for Turkey, there are no official publications related with fire resistance calculations or regulations, which match the European Community Standards (Eurocode). Most developed countries have included fire resistance classes of various structural materials and building types in their official regulations and laws of public works but unfortunately the fire resistance classes specified in TS 1263 are still not covered in any laws in Turkey. [20] There are quite a few unofficial, regional publications released with the efforts of the local fire brigade organizations in the last decade. These point out the need for the regulations of fire safety in buildings. These regulations will be mentioned in this part of the study.

2-6-1- Fire Precautions in Developed Countries

In developed countries, a great deal of standards and regulations exits for fire safety of residential and public buildings that guides to the constructors and inspectors. Supervision of the structural precautions starts at the very beginning of the design stage and continues periodically. This is the responsibility of fire brigade organizations.

Fire brigade organizations in developed countries are composed of two divisions; these are fire extinguishment and fire prevention. The prevention divisions, which correspond to Fire Brigade Chief Commandership in Turkey, are responsible from the following basic services.

a) Examination of the new structural project from fire protection point of view, and consulting the architects, engineers or contractors if necessary.

b) Checking the use of existing buildings according to its function and fire prevention facilities (extinguishing systems, plumbing, etc.) and also forcing to complete the missing deficiencies according to the building regulations.

c) Educating people about protection from fire and its effects.

Nevertheless in these countries, the sprinkler system, which is the most effective extinguishing technique, is an obligation for most of the buildings. Buildings like; movie theatres, congress halls, restaurants, nightclubs, warehouses, hotels, hospitals and buildings taller than 10 stories must be equipped by automatic sprinkler systems. [21]

One of these developed countries, in United States; building regulations for fire safety are the most strict and comprehensive codes. The NFPA (National Fire Protection Association) code is such a code. The construction types presently identified in NFPA 220 as well as in the three model building codes, UBC (Uniform Building Code), B/NBC (Basic / National Building Code) and SBC (Standard Building Code), classify buildings into at least five groups. These are:

I. Fire Resistive
II. Non Combustible
III. Exterior Protected Combustible
IV. Heavy Timber
V. Wood Frame

Two are identified as non-combustible and three as combustible construction types of construction. Table 2.8 gives the fire resistance requirements for the structural frame, interior bearing walls, floor construction and roof construction of the five basic types of construction. The term "structural frame" as used in the table refers to the columns and the girders, beams, trusses and spandrels having direct connections to the columns and all other members, which are essential to the stability of the building as a whole. A national system is used to identify the fire resistance required for the three basic elements of the building. These elements are (1) the exterior wall, (2) the primary structural frame, and (3) the floor construction. A three-digit notation was developed as follows:

- 1st Digit – Hourly requirement for exterior bearing wall fronting on a street or lot line.
- 2nd Digit – Hourly requirement for structural frame or columns and girders supporting loads from more than one floor.
- 3rd Digit – Hourly requirement for floor construction.
- For heavy timber construction, the notation "H" and not a digit is used for the structural frame and floor construction designations.

Therefore, for example, a "332" building would have 3 hour exterior bearing walls, a 3 hour structural frame, and 2 hour floor construction and would correspond to the NFPA 220. Besides the general NFPA codes in America there are local regulations and classifications for buildings. For the concept of fire safety, one of the strictest codes is the New York City Building Code. NY City Building Code divides the construction types into two main groups; noncombustible and combustible. Each of these in turn is divided into five types. The fire resistance required for the interior structural members and for the exterior walls distinguishes these subdivisions. A similar classification is used in London, England, which also has major risk zones. This code divided, the city according to the population density of the region. [22]

Table 2.8 NFPA 220, Standard on Types of Building Construction

	Type I		Type II			Type III		Type IV	Type V	
	443	332	222	111	000	211	200	2HH	111	000
EXTERIOR BEARING WALLS ---										
Supporting more than one floor, columns or other bearing walls	4	3	2	1	0*	2	2	2	1	0*
Supporting one floor only	4	3	2	1	0*	2	2	2	1	0*
Supporting a roof only	4	3	1	1	0*	2	2	2	1	0*
INTERIOR BEARING WALLS ---										
Supporting more than one floor, columns or other bearing walls	4	3	2	1	0	1	0	2	1	0
Supporting one floor only	3	2	2	1	0	1	0	1	1	0
Supporting a roof only	3	2	1	1	0	1	0	1	1	0
COLUMNS ---										
Supporting more than one floor, bearing walls or other columns	4	3	2	1	0	1	0	H**	1	0
Supporting one floor only	3	2	2	1	0	1	0	H**	1	0
Supporting a roof only	3	2	1	1	0	1	0	H**	1	0
BEAMS, GIRDERS, TRUSSES & ARCHES --								H**		
Supporting more than one floor, bearing walls or columns	4	3	2	1	0	1	0	H**	1	0
Supporting one floor only	3	2	2	1	0	1	0	H**	1	0
Supporting a roof only	3	2	1	1	0	1	0	H**	1	0
FLOOR CONSTRUCTION	3	2	2	1	0	1	0	H**	1	0
ROOF CONSTRUCTION	2	1 1/2	1	1	0	1	0	H**	1	0
EXTERIOR NONBEARING WALLS	0*	0*	0*	0*	0*	0*	0*	0*	0*	0*

Those members listed that are permitted to be of approved combustible material

*** Requirements for fire resistance of exterior walls, the provision of spandrel wall sections, and the limitationor protection of wall openings are not related to construction type. They need to be specified in other standards and codes, where appropriate, and may be required in addition to the requirements of this Standard for the construction type**

**** "H" indicates heavy timber members.**

2-6-2- Fire Precautions in Turkey

In Turkey, precautions and legislations for fire safety and extinguishing methods are dispersed in various types of laws, and are arrange under different headings. Few fire regulations exits but unfortunately in most of them there are no further details other than the provision of bucket pickax and shovel. Following are the list of the laws and regulations that are being in force:

- Regulation on Protection of the Public Buildings Against Fire (1966)
- Regulations on Flammable, Explosive, Dangerous and Harmful Substances (1973)
- Law Nr: 3030 on Management of the Municipalities of Greater Cities (1984)
- Regulations on Principles of the Formation, Mission, Education and Supervision of Fire Brigade Organization (1985)
- İstanbul Greater City Municipality - Fire Protection Regulations (1992)
- İzmir Greater City Municipality - High-Rise Building Regulations (1993)
- Ankara Greater City Municipality, Fire Brigade Directorate - Fire Protection Regulations (1993)
- General Directorate of Civil Defense - Regulations on Protection of Buildings Against Fire (2001)

General Directorate of Civil Defense – Regulations on Protection of Buildings Against Fire (2001)

The most comprehensive and updated Regulations prepared by the General Directorate of Civil Defense released on June 7th 2001, has no obligation as a law in Turkey yet. This Regulation shall come in to force when it will be published in the Turkish Official Gazette in the year 2002. When we take a look on this new Regulation, in the 1st part 3rd section, the buildings are classified into ten different types according to their functions. These are the following:

a) Buildings for Meeting (sports halls, movie theatres, night clubs, etc.)

b) Buildings for Education (kindergartens, schools, universities, etc.)

c) Buildings for Health Service (hospitals, clinics, retirement homes, etc.)

d) Jails, Prisons and Reformatories

e) Buildings for Accommodation (hotels, apartments, dormitories, etc.)

f) Buildings for Trading (shopping centers, gross markets, restaurants, etc.)

g) Office Buildings (banks, municipalities, public service buildings, etc.)

h) Industrial Buildings (factories, hangars, refineries, power plants, etc.)

i) Buildings for Storing (warehouses, car parks, silos, barns, etc.)

j) Multi-use Buildings

In the 2nd part 1st section, the buildings are classified into three major types according to their degree of danger. These are:

- **Low Danger Buildings:** made of low combustible materials.
- **Medium Danger Buildings:** made of medium combustible materials and producing an important amount of smoke and gas.
- **High Danger Buildings:** made of high combustible materials and having probability of blast.

As it is stated in the 2nd part 2nd section, the stability of load bearing system and elements must be calculated and dimensioned according to provide the stability of the building for the while of the evacuation of people or extinguishing of fire. These calculated elements must provide the demanded periods of fire resistance and the correlation between time and temperature and classification of construction materials in TS 1263 will be used. Extra calculations will be required for the special structures.

The classification of the building materials for the normal buildings and the classification of fire resistance requirements for structural elements are shown in Table 2.9 and Table 2.10 respectively.

For the purpose of fire safety, B3 class of easy flammable building materials cannot be used in the constructions. Such materials can be changed into B2 class of normal flammable building materials by using them in composite construction or by using preventive measures. In the buildings higher than two stories, the load

Table 2.9 Combustion classification of building materials

Class Of Combustion	Name Of The Classification	Behaviors Observed During Fire	Classified Materials Without The Need Of Testing
A	Non Combustible		Sand, Gravel, Adobe, Clay, Natural Structural stones
A1	Never Combustible	Non Flammable Non Combustible No Sparkling No Coalification	Minerals, Soil, Lava, Cement, Lime, Plaster, Anhydrite Clinker, Dilated Clay, Schist, Glass, Pearlit, Vermiculite Mortar, Concrete, Reinforced Concrete, Pre-stressed Concrete, Mineral Filled Stones Brick, Tile, Glass, Ceramic Asbestos Cement & Mineral Fibers Metals & Alloy Metals (Iron, Steel, etc.)
A2	Low Combustible	Partially combusts if a flame source exits No Sparkling Partially damages No conductivity Non additive for Fire Load	Note: In order to classify, material must be tested
B			
B1	Low Flammable	Continues combustion after the decade of the source Special Features: - Combustion heat - Flame Temperature	Light plates made of Wood Shavings Gypsum Boards Asbestos Cardboard & Paper Hard PVC Pipe d ≥ 3,2 mm PVC Floor Coverings, Wooden Parquet
B2	Normal Flammable	- Combustion temperature - Smoke Production - Toxic Gas Production	Wood $\delta \geq 400\ kg/dm^3$ d>2 mm $\delta \geq 230\ kg/dm^3$ d>5 mm Artificial Wooden Plate Hard PVC Plate PP, PE, ABS, ASA Pipes PMMA plates d ≥ 2 mm Polyester d ≥ 1.3 mm Polyethylene $\delta \geq 940\ kg/dm^3$ d > 2 mm Asphalt & Bituminous Roofing
B3	Easy Flammable	Materials not included by the classes above Note: B3 Class cannot be used in structures.	Wood < 2mm Paper, Rush, Straw, Wood Shavings, Cotton, Cellulose Fibers

Table 2.10 Fire resistance classification of structural elements

Fire Resistance Period (Minute)	Combustion Classification Of Material Used Main Compartments[1]	 Other Compartments	Naming Of The Structural Elements [2]	Representation
≥ 30	B	B	Fire Preventive	F30 - B
	A	B	Fire Preventive & Main Compartments made of Non-Combustible Material	F30 - AB
	A	A	Fire Preventive & made of Non-Combustible Material	F30 - A
≥ 60	B	B	Very Fire Preventive	F60 - B
	A	B	Very Fire Preventive & Main Compartments made of Non-Combustible Material	F60 - AB
	A	A	Very Fire Preventive & made of Non-Combustible Material	F60 - A
≥ 90	B	B	Fire Resistant	F90 - B
	A	B	Fire Resistant & Main Compartments made of Non-Combustible Material	F90 - A
	A	A	Fire Resistant & made of Non-Combustible Material	F90 - A
≥ 120	B	B	Very Fire Resistant	F120- B
	A	B	Very Fire Resistant & Main Compartments made of Non-Combustible Material	F120 - AB
	A	A	Very Fire Resistant & made of Non-Combustible Material	F120 - B
≥ 180	B	B	Extremely Fire Resistant	F180 - B
	A	B	Extremely Fire Resistant & Main Compartments made of Non-Combustible Material	F180 - AB
	A	A	Extremely Fire Resistant & made of Non-Combustible Material	F180 - A

1) The meaning of the Main Compartment is every kind of load bearing part providing stiffness.

2) Only from the point of fire resistance.

bearing walls, footings and columns must be constructed in at least F90-A class. As for the walls, interior coatings and heat insulation must made of minimum B2 class of normal flammable building materials. For the high-rise buildings B1 class low flammable materials are required. However, for the buildings lower than two stories, the exterior cladding material must be at least B2 class whereas cladding for higher buildings must made of A class non-combustible building materials. [23] More information about coating materials for steel structures is given in Chapter 4.

2-7- Fire Risk

In order to reduce the loss of lives firstly the risks to life must be reduced. Fire is one of the most effective risks to life. The usual way to measure the risk of fire for a given type of building is expressed by the formula;

$$\boldsymbol{R = P_o \times L_x \leq R \text{ accepted}} \qquad 2.1$$

where:

R = actual risk

R accepted = targeted risk

P_o = probability occurrence of a fire

L_x = probable extent of loss

The risk R can never be zero and we have to accept a certain level of risk for every type of building. This level will depend on the number of persons, their ability to escape and the value of contents exposed to fire. The probability of fires getting out of control is completely related to the type of active measures available, as indicated in Table 2.11. [19]

Table 2.11 Probability of fires getting out of control

Type of active measures	Probability of fires getting out of control
Public fire brigade	100 / 1000
Sprinkler System	20 / 1000
High standard residential fire brigade combined with alarm system	≥ 10/1000 / 1/1000
Both Sprinkler system and residential fire brigade	≥ 1 / 10.000

The actual risk can also depend on the kind of use and type of occupancy as on the type of the building. The kind of use will determine the fire load density. For example a library has a higher fire load density than a metal fabricating facility. The occupancy gives some important indications for the probability of fatal casualties. This may be explained by an example. In the industrial field most buildings have only one story. Normally there are active healthy people inside the building, who are familiar with the building layout. In case of fire they will escape quickly and fire protection of the structure is normally unnecessary. In residential buildings or hospitals, which may be multi-story, occupants may be asleep or incapacitated when fire occurs and thus unable to escape quickly. In such cases improved fire safety provisions are necessary. It is well known that the risk of fire occurrence is relatively small. But in assessing fire precautions the potential severity of a fire and the probable loss amount should be considered.

2-8- Fire in High-Rise Buildings

Fire safety in high-rise buildings is a different, and much more complex problem than for low buildings. Many common factors exist when fire threats in high-rise buildings are considered. This is due to two major, specific facts. First, above a certain height, fire fighting and rescue actions can only be undertaken from the inside of the building. This involves necessarily special means and techniques, and leads to considerable additional requirements upon the design and the technical equipment of the building, in order to meet the risks and dangers specifically resulting from its tallness. Secondly, total emergency evacuation of a tall building is impracticable within a reasonably short time. Among other things, it should be noted that certain particular characteristics of the building, or of its use, could lead to reinforcement of the requirements for safety. This applies for instance to buildings with some special occupancies (physical or mental disability of occupants, expensiveness or vital importance of some equipments, etc.)

Due to impracticability of total evacuation, there are two main objectives to be attained for the safety of people: (1) evacuation from the compartment in fire to safe refuge areas, and (2) non-involvement of the other compartments of the building. The major aspect to take into account hereby is the fact that by far most of the casualties in high-rise building fires is due to the effects of smoke and toxic gases.

2-8-1- Smoke Movements During Fire

The term smoke is defined in accordance with the American Society for Testing and Materials (ASTM) and the National Fire Protection Association (NFPA), which state that smoke consists of airborne solid and liquid particulates and gases that evolve when a material undergoes combustion. Smoke is recognized as the major killer in all fire situations in high-rise buildings. A smoke control system must be designed so that the driving forces that cause smoke movement do not over power it. Some of the major driving forces causing smoke movement are stack effect, buoyancy, expansion, wind and the HVAC system. [24]

There is usually an upward movement of air within building shafts (stairwells, elevator shafts, mechanical shafts, etc.) when it is cold outside. This normal air movement is called 'stack effect'. As a simple physical law, the air in the building has a buoyant force, which causes air to rise in the building shafts, because it is warmer and less dense. And of course as the opposite condition, when the outside air is warm, the airflow exists in the opposite direction, which is called the reverse stack effect (Figure 2.10). Also the high temperature smoke in a fire has a buoyancy force due to its reduced density that makes pressure difference between a fire compartment and its surroundings.

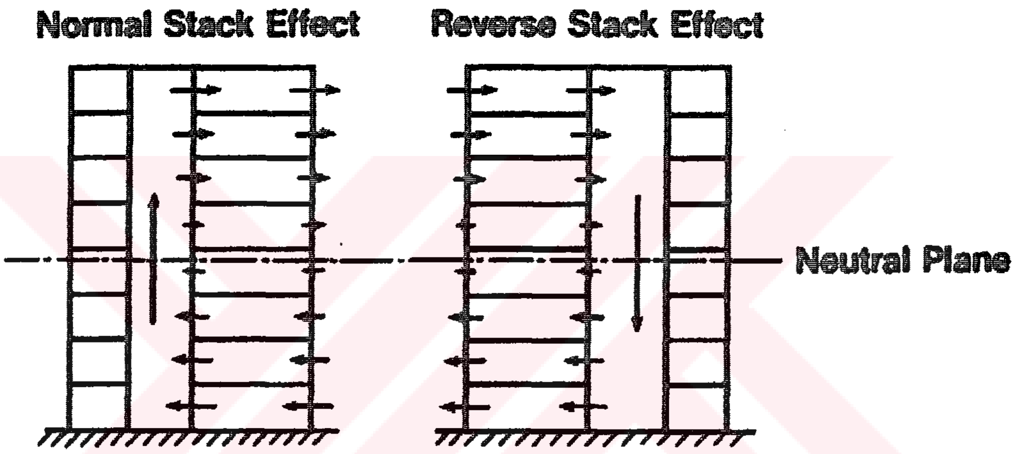


Figure 2.10 Air movement due to normal and reverse stack effects

The pressure difference can be expressed by and equation of:

$$\Delta P = K_s \left(1 / T_o - 1 / T_f \right) h \qquad 2.2$$

where:

ΔP = pressure difference, Pa (in H_2O)

T_o = absolute temperature of surroundings, °C

T_f = absolute temperature of fire compartment, °C

h = distance above neutral plane, m

K_s = coefficient, = 3460 (7.64)

Naturally, for tall compartments where the distance ***h*** from the neutral plane can be larger, much larger pressure difference is possible. This buoyancy-induced pressure causes smoke movement to the floor above the fire floor with the leakage paths in the ceiling. [24]

2-8-2- Compartmentation

Compartmentation is a process of designing barriers in to a building that will prevent the spread of fire. Similar objectives apply to the subdivision of individual buildings into two or more fire compartments either horizontally or vertically. Regardless of how well a barrier element is designed, constructed and installed, prevention of fire and smoke spread can only be effective if the building itself behaves in a predictable manner. Barriers thus are known as firewalls and have rated values based on laboratory tests. Before a building is accepted as the satisfying the compartmentation requirements an analysis is made of the behavior of the building as a whole. The effectiveness of a barrier is determined by the: [25]

- Inherent fire resistance of its materials
- Details of its construction and its internal construction and the method by which it adjoins other building elements
- Penetrations, such as fire resisting doors and shutter assemblies, fire resisting windows, cavity barriers, ducts, electrical raceways and others.

Compartment floors are the most important elements of high-rise buildings in restricting the vertical spread of fire between two occupancies. Most floors have an inherent level of fire resistance due to the need to carry the load imposed by the contents but may also be compromised if any penetration, edge junction or duct is not sealed to resist fire and smoke. There are three types of compartment floors (Figure 2.11) [26]:

1. Floors designed to separate different occupancy types,
2. Floors in the same occupancy type but carries different occupants,
3. Floors of type 2 in compartments containing high hazards or plant.

The location and design of the barriers forming a compartmentation scheme must be able to protect the structural ability of the building. The collapse of structural elements of the building is a more serious threat to firefighters than to occupants, since the time required for a structural collapse is usually sufficient for occupancy evacuation. It is readily apparent, however, that no effective firefighting method is possible if major sections of the building collapse, endangering lives and permitting new sources of oxygen to feed the fire.

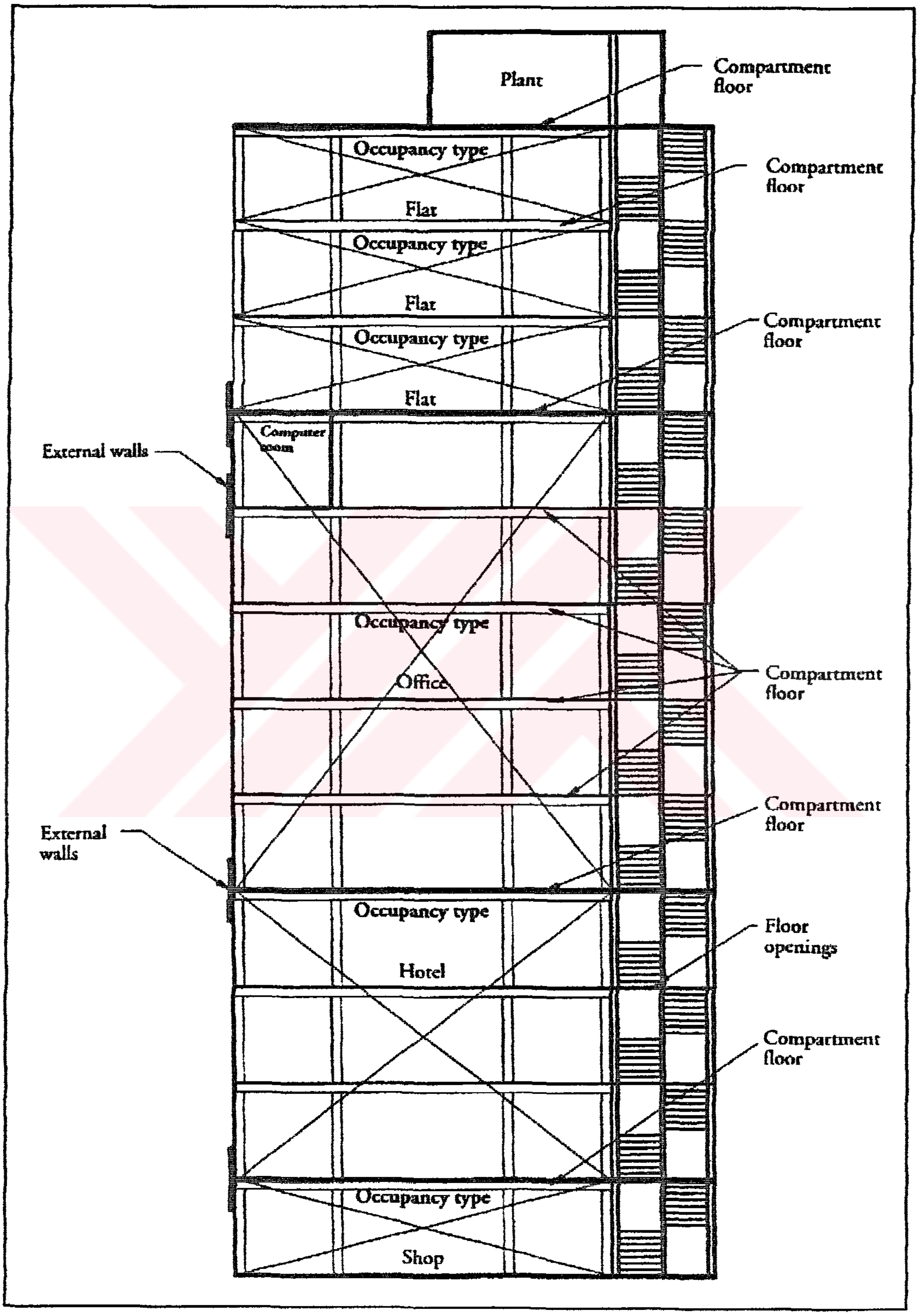


Figure 2.11 Compartmentation of a multi-story building containing different occupancies

2-8-3- Fire Safety Concepts

High-rise buildings should provide its structural stability for the time of the evacuation and fire department operations. On the static design of a high-rise building, the structural safety against several loads can be checked carefully by engineering methods using an electronic computer and by personal experience. On the contrary, the safety of human life and the structural stability against fire are directly related to the conformation with the articles of building codes. Figure 2.12 shows the design systems for the safety of human life and the structural stability against fire, commonly applied in many countries nowadays. When the details of construction are decided on the basis of specification only, the intention to use scientific methods for the determination of construction is neglected.

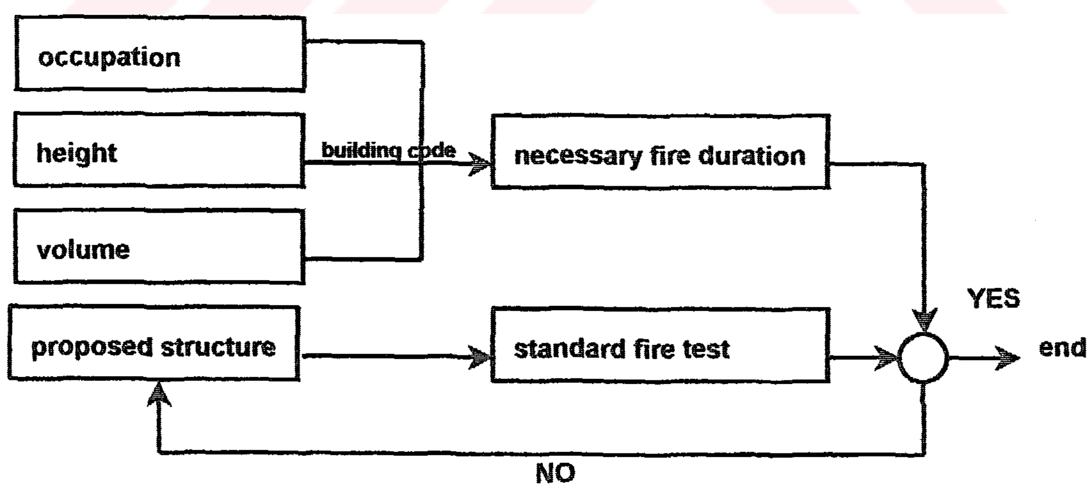


Figure 2.12 Design systems for the structural stability

As the building code had a strong force, the standard fire test and the combustibility test have seemed the most important subjects in the fire research field. These test results are directly important for building regulation, but not directly important for scientific research on fire.

For example, the probability of fire occurrence in a high-rise building involving 5.000 people is 1.000 times of the probability in an individual house involving 5 people if the fire occurrence per head is the same. Thus the threat of human life against fire in a tall building is much greater than one in a small building if the construction is similar. For the reduction of this threat, the building code requires a lot of extra facilities in the high-rise building. But the construction and the service systems become too complex to regulate them by simple specification type articles in a building code for fire safety in a high-rise building. It is desired to establish some checking system, putting to use some engineering method suitably to ensure fire safety in each building like static design.

The start of design is a proposal of an idea to meet a purpose. The external forces or the environmental forces and the targets are assumed, and each external force is inputted in a checking system to obtain a response value. If the response value does not satisfied the target value, the proposed idea is modified and again the response value is obtained. This procedure should be continued until a satisfactory value for the response is obtained. (Figure 2.13) [9,27]

Assumption of external forces and targets, and selection of checking system to be used are the most important problem in this design procedure. The concept of these assumption and selection should be dependent on the philosophy of the designer (including engineer) supported by the building code. The building code, I think, should be intended to point out the concept of assumption of external force and target. An engineer should do the selection of the checking system.

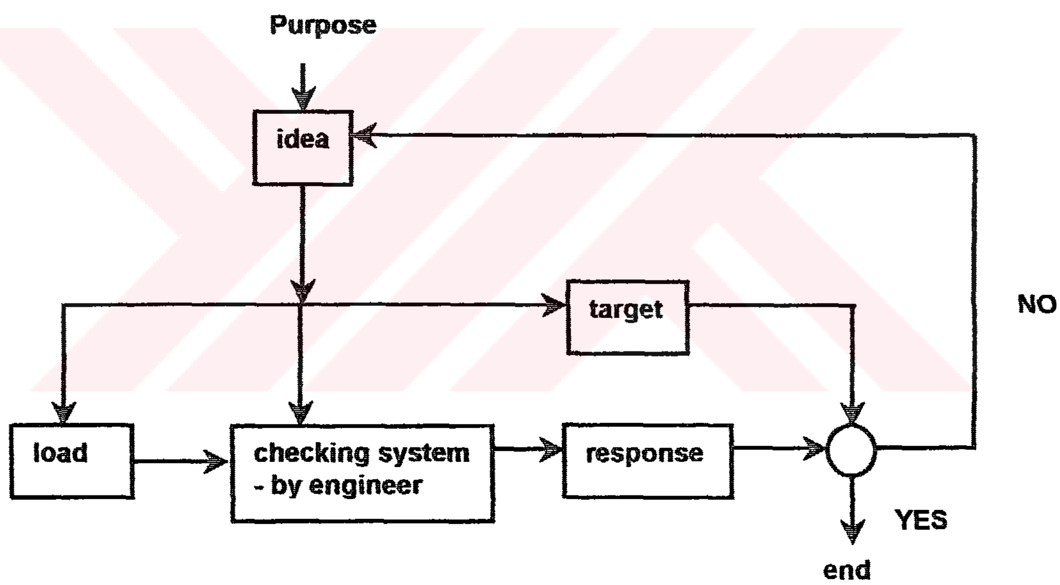


Figure 2.13 Engineers response in the design system

In order to develop possible fire safety concepts it is essential to examine the usual development of an uncontrolled fire as shown in Figure 2.14. The influence of fire precautions may be visualized by this reference also.

A fire safety concept should be defined as an optimal package of integrated structural, technical, and organizational fire precaution measures, which allows well-defined objectives, agreed by the owners, the fire authorities and the designers to be fulfilled.

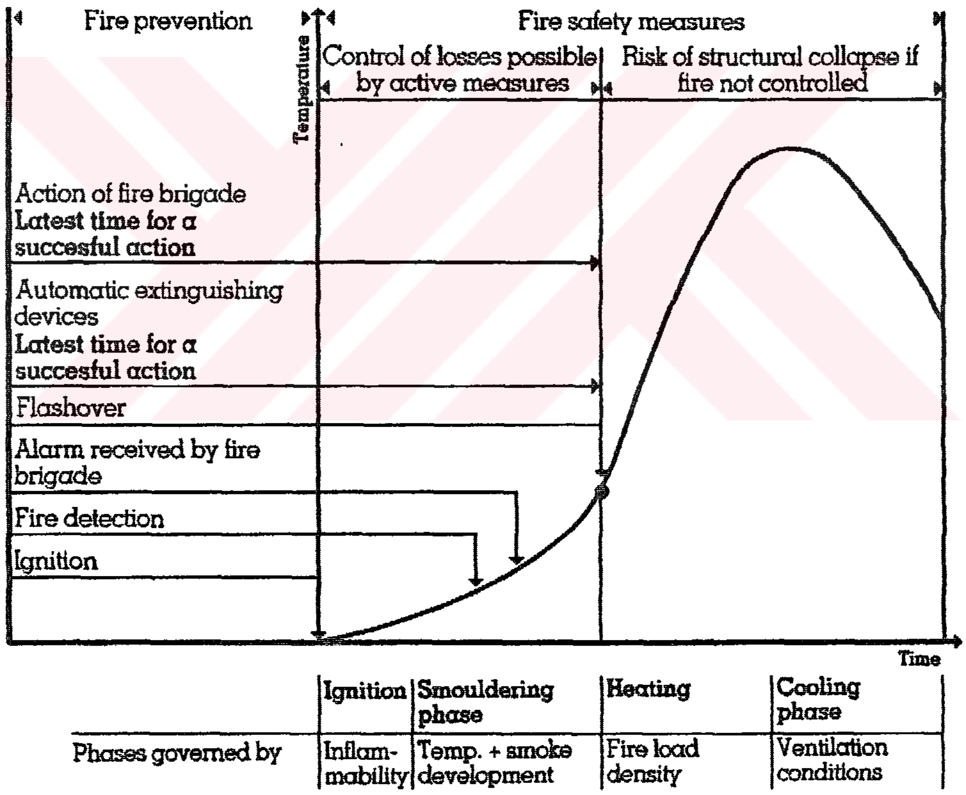


Figure 2.14 Influence of fire precaution measures in uncontrolled fire

Three major approaches to fire safety can be stated as, (1) the structural concept, (2) the monitoring concept and (3) the extinguishing concept.

The **structural concept** comprises compartmentation combined with and adequate fire resistant structure. It may also be the best choice as long as the normal use of the building allows compartmentation by fire resistant floors and walls. The necessary time of fire resistance should be determined by the condition that the fire should not spread outside the fire compartment. For this reason the separating and load bearing function of the relevant building components should be maintained during the predicted duration of the fire. However it is often more cost effective and surely preferable for investors to use alternative concepts that is based on the avoidance of flashover by means of non-structural active fire measures because the passive protection concepts does not guarantee about reserviceability and reparability of compartments involved in the fire. Wider discussions about structural protection of steel structures are held in Chapter 4.

The **monitoring concept** is based on observation of building against fire by the use of automatic detection devices and automatic transmission to a fire brigade. The major aim of this concept is to prevent the flashover (Figure 2.14) by automatic alarms and early invention by fire fighting services. The automatic alarm systems are activated by smoke, heat or flames, which work mechanically or by electronic systems. This concept is most applicable for occupancies with reduced fire load densities, for medium-rise buildings in which fires may be expected to develop slowly and where an effective and quick responding fire brigade is available. Compartmentation and fire resistance requirements may be reduced.

The **extinguishing concept** is based on automatic extinguishing devices such as sprinklers, CO_2 or Halon Systems with automatic alarm transmission to an adequate fire brigade. The application with structural resistance may be the ideal choice for high-rise buildings for designers. It is mostly used for occupancies with medium or high fire load densities and fast developing fires. Building owners are usually afraid of the damage, which these systems may cause by the water poured on the documents or stored material. In fact sprinklers open their valves only at the spot where temperature reaches a critical limit to 70°C to 140°C. It can be noted as 75% of all fires in contact with sprinkler devices are controlled by 1 to maximum 4 sprinkler heads. (Figure 2.15) This represents, about 50 m^2 watered by opened sprinkler heads. It is important to know that both automatic detection and extinguishing systems have to be maintained once or twice a year by specialists. Below Table 2.12 gives data about fire extinguishing systems, working methods and application. [19]

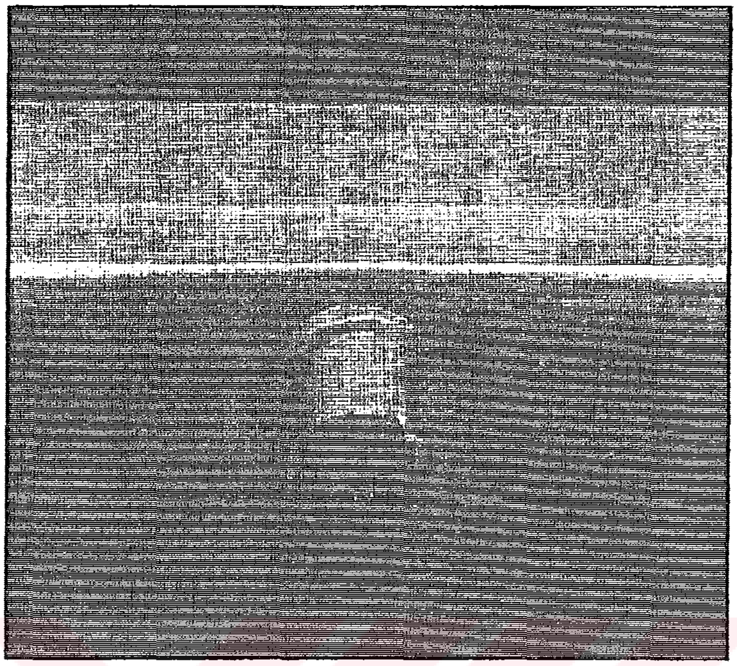


Figure 2.15 Sprinkler head

Table 2.12 Fire extinguishing systems, working methods and application

System	Measures and working method	Application
Sprinklers	Water, cooling	Office and public buildings, stores, warehouses, factories
Water deluge systems	Sprayed water, cooling	Theatres, petrochemicals
Fire extinguishing by foam	Foam of water and chemicals, cooling and stifling	Storage tanks, chemical industry, petrochemicals
CO_2 systems	Displacing CO_2 and stifling	Computer systems
Halon systems	Halogenated hydrocarbon, prevention of chemical reactions between burning material and oxygen	Inflammable liguids, computers.

2-8-3-1- Costs of Fire Safety Concepts

The type of occupancy and the choice of the structural design are the main variables governing the amount of fire protection measures necessary and thus the cost of total Fire Safety Concept. According to studies of the Steel Promotion Committee of Eurofer, which brings together the Steel Information Centers from Belgium, Luxemburg, France, Germany, Great Britain, Italy, the Netherlands, Switzerland and Austria, the following costs for investment and maintenance of fire safety determined.

Structural concepts like coating or spraying systems has an approximate cost of wide range starting from **13** to **96 € / m^2** floor. Using multi-functional systems such as specially designed fire resistant suspended ceiling can significantly reduce this value. Also, the use of composite load bearing systems allows significant reductions in fire resistance costs. Almost there is no cost needed for maintaining this system.

Monitoring concepts which includes automatic alarm transmission devices to an adequate fire brigade costs between **7-11 € / m^2** floor for a modern high-rise building to be built. Its cost increases up to **11-15 € / m^2** floor for application in an existing building. Also 2 - 4 % of this investment will be spending for maintenance, including yearly mandatory control costs. The annual fees for the automatic connection to the fire brigade organizations must be added.

Extinguishing concepts which also includes automatic alarm transmission devices to an adequate fire brigade costs between **10-15 € / m²** floor for a new modern high-rise building to be built. And also its cost increases up to **15-20 € / m²** floor for application in an existing building. The connection to the municipal water supply network or the installation of a reservoir and sprinkler pumps includes variable costs, which must be determined from case to case. The maintenance costs including the twice a year mandatory control is about 0,5 % of the investment costs.

It should also be mentioned that the fire safety level of the investment has an opposite balance with the insurance premiums for the building.

Throughout the Chapter 2 the natural chemical event of fire and its effects on structural environment has tried to be described. In the next chapter some information about steel – fire relation is discussed in order to understand the need of fire protection methods of steel in the chapter afterwards.

CHAPTER 3

STEEL STRUCTURES

3-1- Why Steel Structures

Steel is the most important metal used in building construction. Without it we would be confined to massive all masonry buildings with arched floors, or masonry wall-bearing buildings with wooden floors. In many parts of the world, structural steel is the first choice of architects and engineers for the framework of multi-story buildings. Steel construction offers many advantages such as fast erection; wide clear spans, light foundations and the cost can be compared very favorably with other methods of construction but besides its cost for Turkey its inadequate fire resistance ability is a handicap for the decision makers. Lets take a simple look at the main advantages and disadvantages of steel comparing to other structural materials such as wood and concrete in a few topics.

- In practical manner, steel is a homogeneous and also isotropic material, which gives an opportunity of a smaller safety factor comparing to other structural materials to the structural engineers for dimensioning calculations of structural members.

- By the cause of its high strength, the total weight of the load bearing steel portion in the gross weight of the entire building is very less which provides tall and long spanned structures, light foundations and structures resisting to earthquake loads.
- The load bearing ability of a steel column is much more stronger compared to a reinforced concrete in the same section size.
- The lesser load carried by foundations, provides construction even on the least stable topographies.
- Its modulus of elasticity is very high ($E = 2.100.000$ kg/cm^2) when compared to wood ($E = 100.000$ kg/cm^2) that means few and thinner element needs in order to prevent the structural system from various types loads, deformation and vibration.
- Steel framed constructions are completing in a shorter period of time with prefabricated, and mass produced structural elements by computers which also stops the human faults in construction sector.
- Steel structures can be demounted and constructed elsewhere in the same quality or can be repaired if partially damaged. It is mostly done after partial fires in steel buildings.
- Any additions and modifications can be done to the main frame of steel structures at anywhere or anytime needed.

- The most important disadvantage of steel structures is its resistance against fire. It looses its strength at elevated temperatures. For this reason it must be protected if there is a possibility of temperatures above 500°C.
- Another important fact is the corrosion problem. Structures that unprotected against corrosion cannot keep its structural properties for a long time.
- Its mostly known higher cost compared to reinforced concrete is equalized by the erection time that shortens the construction site activities.

3-2- Behavior of Steel Structures in Fire

The mechanical properties of all common building materials decrease with elevation of temperature. Although steel is an uncombustible material without any release of smoke or toxic gases, it also a good heat conductor and thin sections follow very closely the elevation of temperature in the fire compartment.

When a steel structure is exposed to a fire, the steel temperatures increase and the strength and stiffness of the steel are reduced, leading to possible deformation and failure, depending on the applied loads and the support conditions (Figure 3.1). Beyond approximately 250°C the mechanical strength of steel decreases rapidly and when the temperature reaches values above 450°C, may lead to collapse. The 'collapse temperature' is also known as the 'critical temperature' and varies according to the protection methods and methods of design. The increase in structural steel temperatures depends on the severity of the fire, the area of steel exposed to the fire and the amount of applied fire protection. There are many methods of protecting steel members from the effects of fire, so that structural steel buildings with applied fire protection can be designed to have excellent fire resistance. These protection methods are discussed in Chapter 4. The main factors affecting the behavior of steel structures in fire are as follows:

- the elevated temperatures in the steel members,
- the applied loads on the structure,
- the mechanical properties of the steel, and
- the geometry and design of the structure. [18]

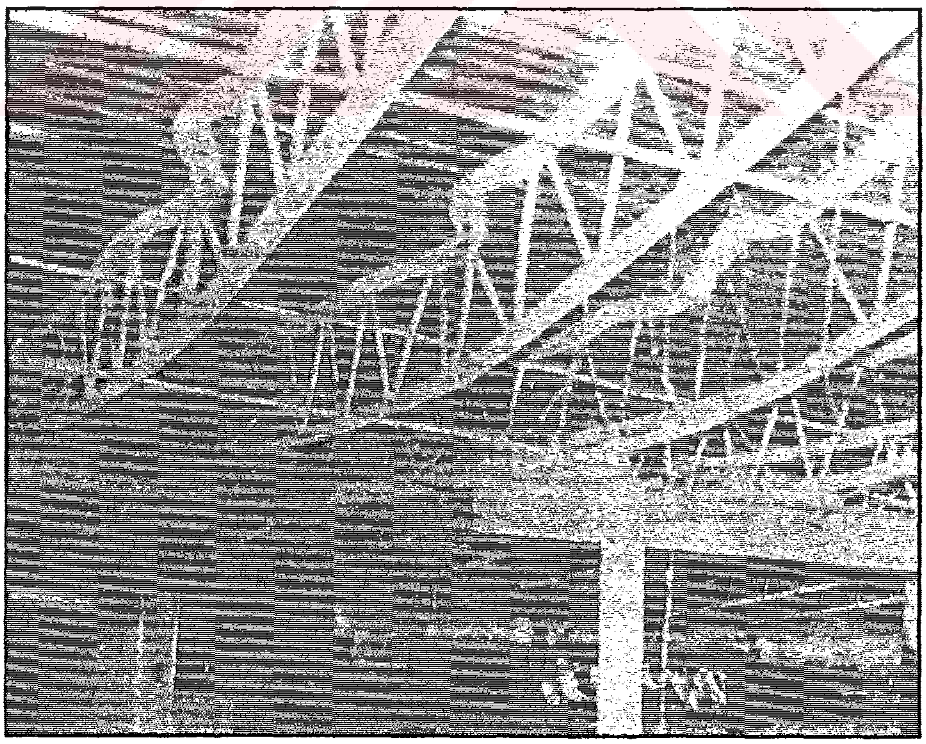


Figure 3.1 Typical fire damage to unprotected steel trusses in restrained conditions

Unprotected steel structures tend to perform poorly in fires compared with reinforced concrete or heavy timber structures, because the steel members are usually much thinner. Steel also has a higher thermal conductivity than most other materials. Unprotected steel structures can survive some fires if the severity is low and the steel does not get too hot. Full-scale tests and some real fires in large steel buildings have shown that well designed structures can resist severe fires in without collapse, even if some of the main load bearing members are unprotected. Before discussing the protection of structural steel against fire lets take a look at its properties.

3-3- Chemical Properties of Structural Steel

Steel is essentially an alloy of iron and carbon but, despite this apparent simplicity, it is one of the more complex and interesting of all materials. The American Heritage English Dictionary describes steel as "A generally hard, strong, durable, malleable alloy of iron and carbon, usually containing between 0.2 and 1.5 % carbon, often with other constituents such as manganese, chromium, nickel, molybdenum, copper, tungsten, cobalt, or silicon, depending on the desired alloy properties, and widely used as a structural material." [13]

These are complex chemical compounds but, for simplicity, it can be assumed that the basic source material is iron oxide (FeO) but the pure iron itself cannot be used as a structural material because of its specifications. The main difference of the structural steel from iron is the carbon (C), which increases the strength and stiffness of steel. But carbon also reduces elasticity and tensile properties of steel. For this reason the 5 % amount of carbon in the steel is being reduced to 1-2 % while producing from its ore. Following are the major alloys used in steel production:

Chromium (Cr) : Increases the strength and resistance against corrosion and friction.

Copper (Cu) : Increases the elasticity and resistance against corrosion.

Manganese (Mn) : Increases the elasticity in low temperatures and load bearing ability. Also absorbs the oxygen inside the melted steel.

Silisium (Si) : Increases the load bearing ability and resistance against corrosion. Also absorbs the oxygen inside the melted steel.

Molybdenum (Mo) : Increases the strength of steel in high temperatures and resistance against corrosion. [27]

3-4- Thermal Properties of Structural Steel

The fire resistance of a structural system or an element is related with its thermal and mechanical properties. The weakness in resistance of steel at high temperatures is the most important handicap of this material. The temperature rise in a steel member as a result of a heat flow is a function of the 'thermal conductivity' (k) of the material. In Eurocode it has shown by **λ** symbol. The value of this property varies according to the chemical composition at room temperature. This variation can be expressed approximately by the following equations (Eurocode 3,1995):

$\boldsymbol{\lambda = 54 - 0.0333T}$	for $20°C \leq T \leq 800°C$	3.1
$\boldsymbol{\lambda = 27.3}$	for $800°C \leq T \leq 1200°C$	3.2

where:

λ = Thermal conductivity, W/m°C

T = Steel temperature, °C

The thermal conductivity of steel is higher in comparison with the materials used for protection of steel: at room temperature it is about 54 W/m°C whereas for dense concrete it is below 2 W/m°C. It is commonly assumed that the conductivity of steel is high enough for normal size sections to have a uniform temperature throughout, but temperature differences exist in large sections as well as in sections that may be able to lose heat, the top flange of a beam in contact with a concrete slab for example. Figure 3.2 shows the thermal conductivity of steel decreases with increasing temperature and depends upon the composition of the material. [12, 17]

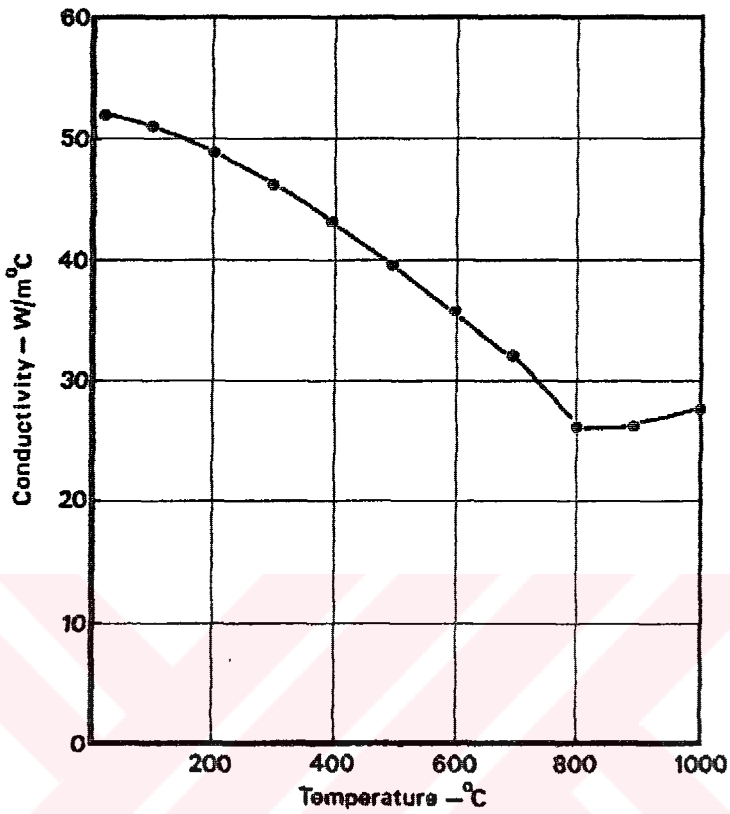


Figure 3.2 Thermal conductivity of steel

The second property, which affects the temperature rise and distribution in a structural steel section, is the 'specific heat' (c_p). It is the characteristic that describes the amount of heat input required to raise a unit mass of material a unit of temperature. Its unit is (kJ/kg°C). Measurements of specific heat under constant volume and constant pressure conditions, solid materials do not show any difference. If the specific heat diagram of steel examined, it will be observed that the increase continues progressively up to 700°C where there is a sharp peak before it starts to decrease (Figure 3.3). [12]

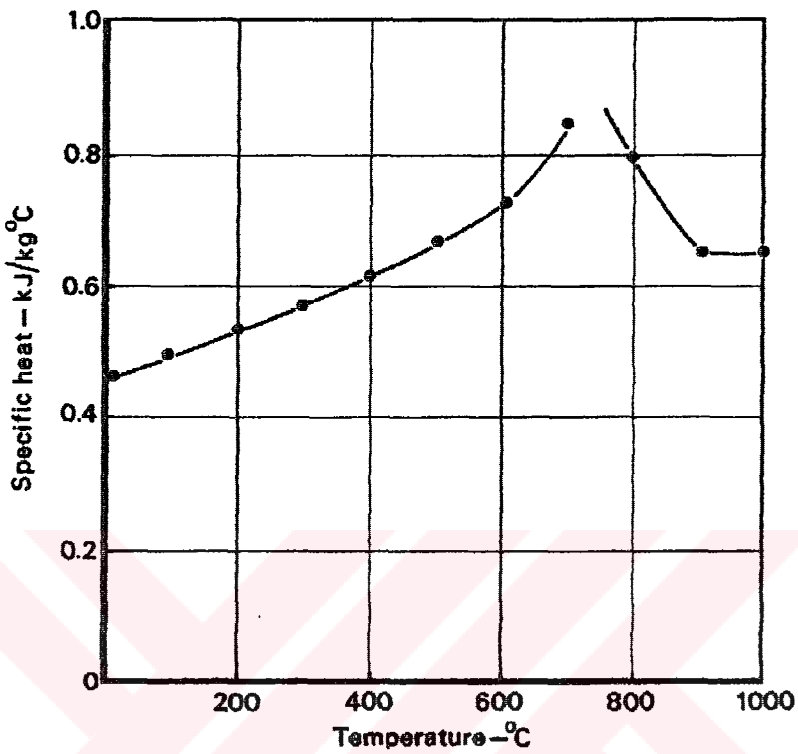


Figure 3.3 Specific heat of steel

Another property is the 'thermal diffusivity' (a), which is a measure of how effectively the heat is dissipated through the material. In simple words, it is the ratio of the thermal conductivity to the volumetric specific heat of the material. The value of thermal diffusivity varies according to the variations in thermal conductivity and specific heat. As the value of thermal diffusivity increases, the heat moves faster away from the heated surface area. One of the most conductive materials, steel has a high thermal diffusivity that uniform temperatures can exist across a cross section, whereas with low diffusivity materials a steep gradient can be expected (Figure 3.4).

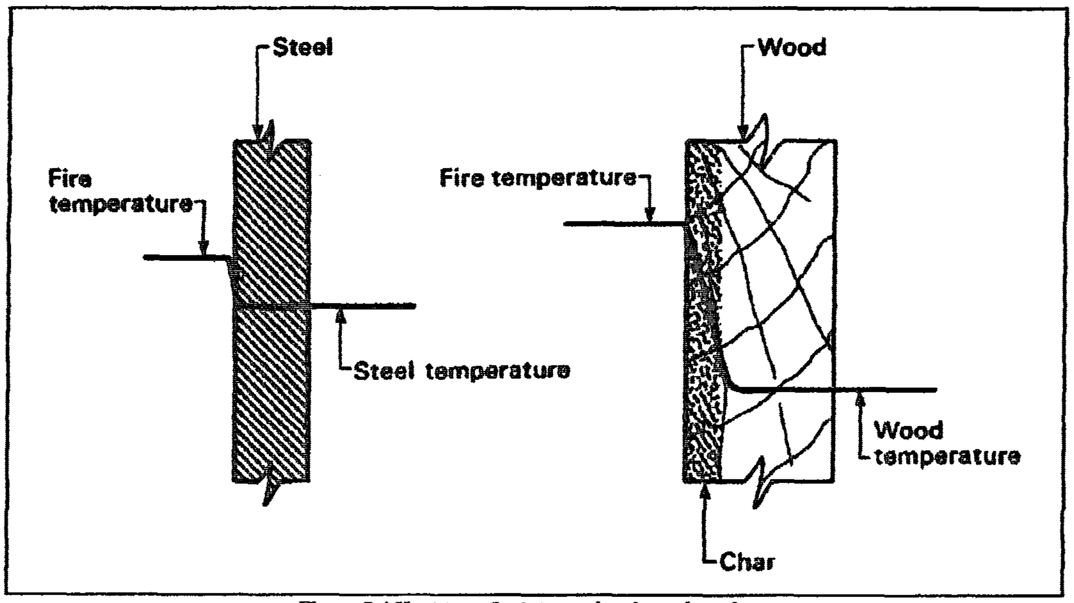


Figure 3.4 Heat transfer into steel and wood sections

The relation between thermal diffusivity and temperature has shown in Figure 3.5, which the structural steel has a value of 0.84 m^2/h at 20°C and decreases linearly to 0.28 at 700°C.

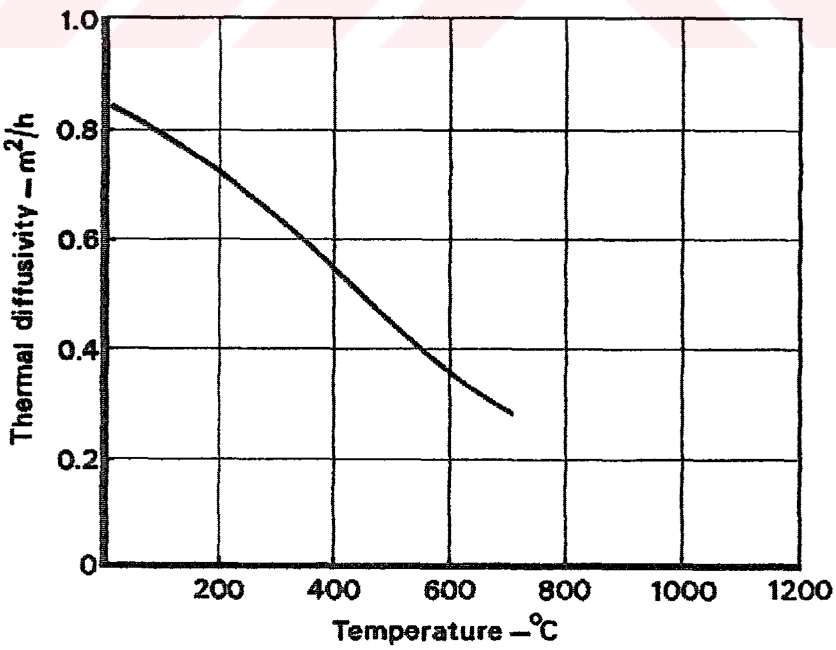


Figure 3.5 Thermal diffusivity of steel

3-5- Mechanical Properties of Structural Steel

As it is mentioned before, steel is a homogeneous and also isotropic material that has a crystallized structure, which means that its mechanical properties remain constant in every location and position. For this reason it is the ideal material for design engineers in their calculations as a matter of fact. There are two different ways that steel is used in building construction. It is used either as a structural material or as reinforcement elements in concrete. In the first case the steel sections are hot-rolled into various shapes and connected to steel or concrete elements. For the reinforcement, the material is in the shape of bars, wires or tendons and also has ribs to improve bond.

The effect of temperature on the mechanical properties of steel such as, 'modulus of elasticity' and 'yield strength', which are the primary effects on its strength, beginning from 100°C is conspicuous. These are commonly defined in terms of the relationship between stress (σ) and strain (ε). The modulus of elasticity of structural steel decreases with increasing temperature, as shown in Figure 3.6. [12]

There are two values that typically characterize the strength of hot-rolled structural steel which are yield and tensile strengths. The typical stress – strain curves for steel at various temperatures are illustrated in Figure 3.7.

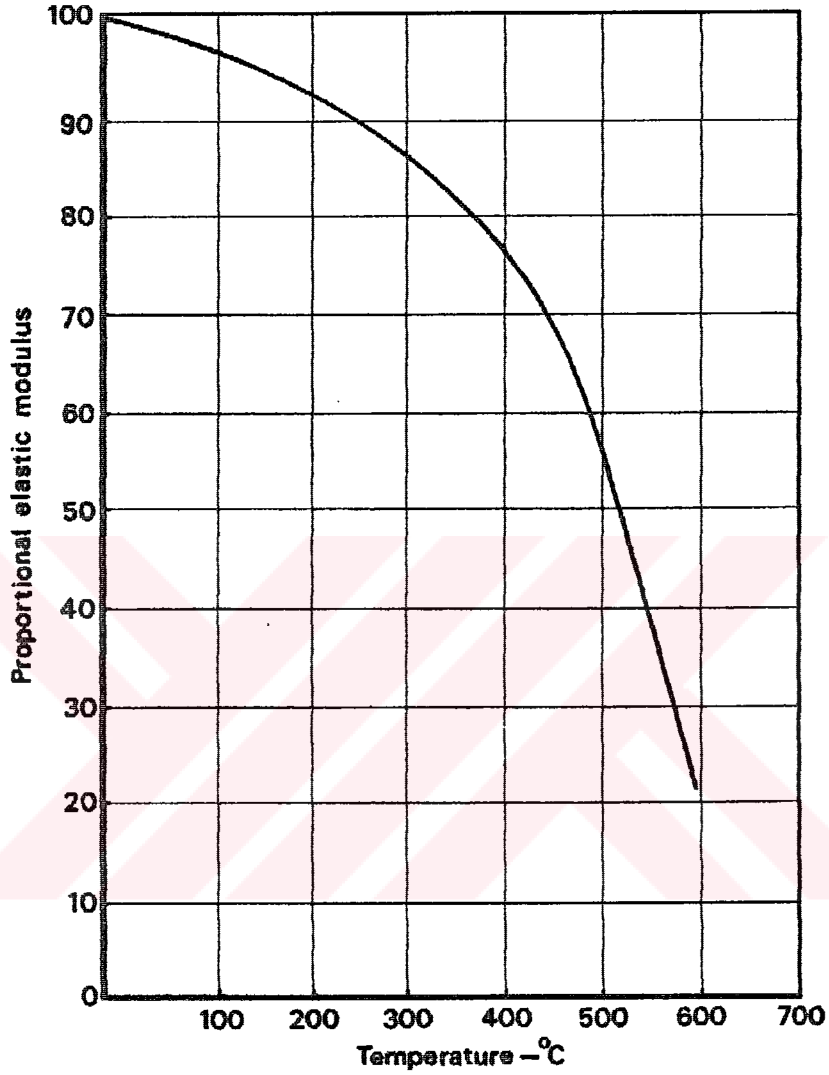


Figure 3.6 Modulus of elasticity – temperature relation of structural steel

This type of stress - strain curves allow two important parameters to be determined. The point that strain occurs without any increase in stress, which first yielding of the section is observed and the ultimate strength when rupture of the section takes place.

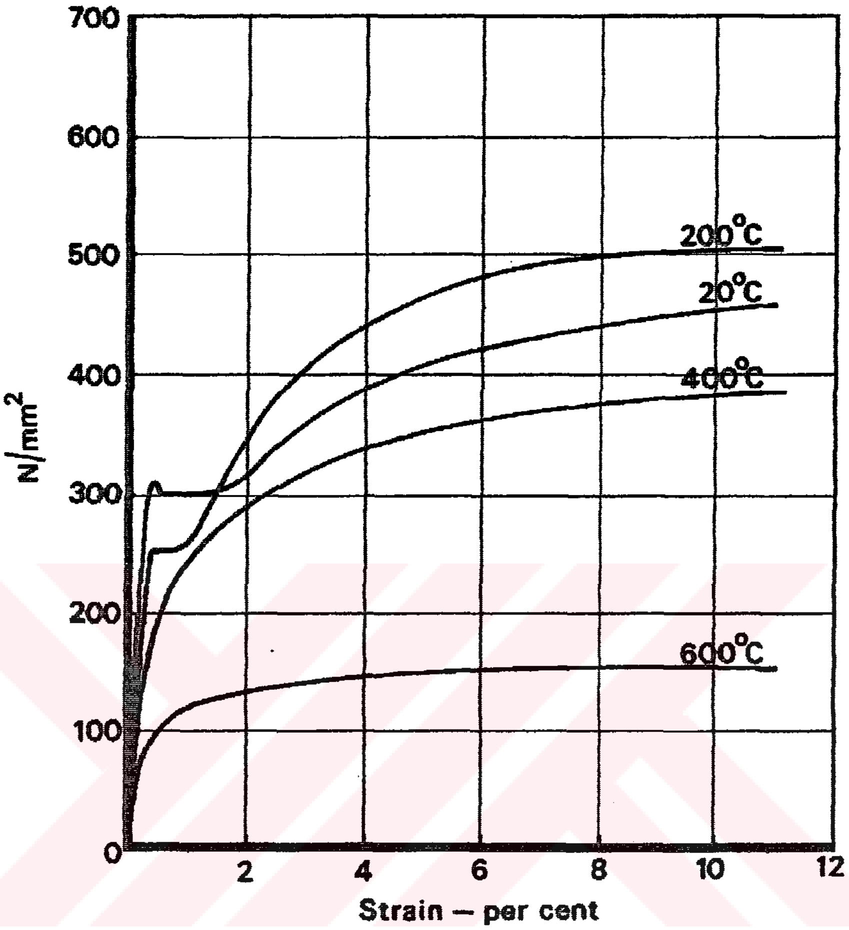


Figure 3.7 Stress – strain curve for structural steel at various temperatures

The yield strength is generally the bases for the design of steel structures at working loads. A specific point on the stress – strain curve, at which a distinct increase in strain is observed without a corresponding increase in applied stress, characterizes it. At elevated temperatures, this characteristic reduces, until the curve becomes rounded. There is an increase in the ultimate strength of structural steel at temperatures up to 300°C, but after this point the strength starts to reduce, which the yield strength decreases half of its initial at about 600°C. [17]

3-6- Deformation Properties of Structural Steel

Temperature elevations causes structural steel to tend to expand by differing amounts through the member, inducing stresses ranging from compression at the hotter surfaces to tension within the member and moreover the effect of both expansion and contraction of the member on the surrounding structure is an important consideration to the structural integrity of the building (Figure 3.8).

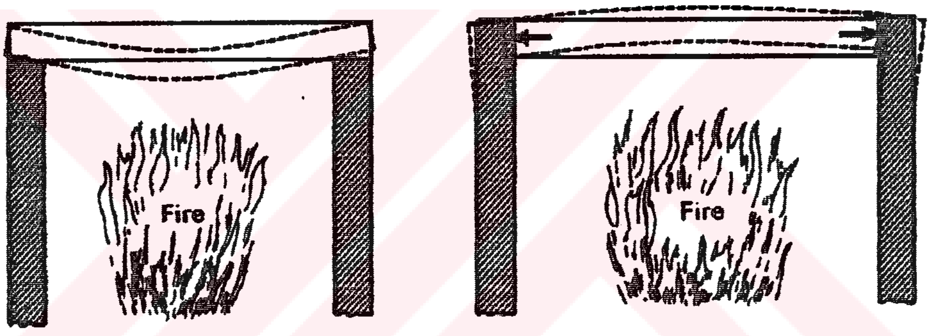


Figure 3.8 Deformation and thermal stresses caused by fire

The unequal expansion will cause deformation of the section, with a tendency to bulge towards the heat source. The thermal expansion of steels can be related to its temperature by a coefficient of expansion that can be defined as the expansion of a unit length of the steel when it is raised one degree in temperature and naturally the value of this coefficient of thermal expansion increase with increasing temperatures. The thermal expansion values of structural steel are given in Figure 3.9. [17]

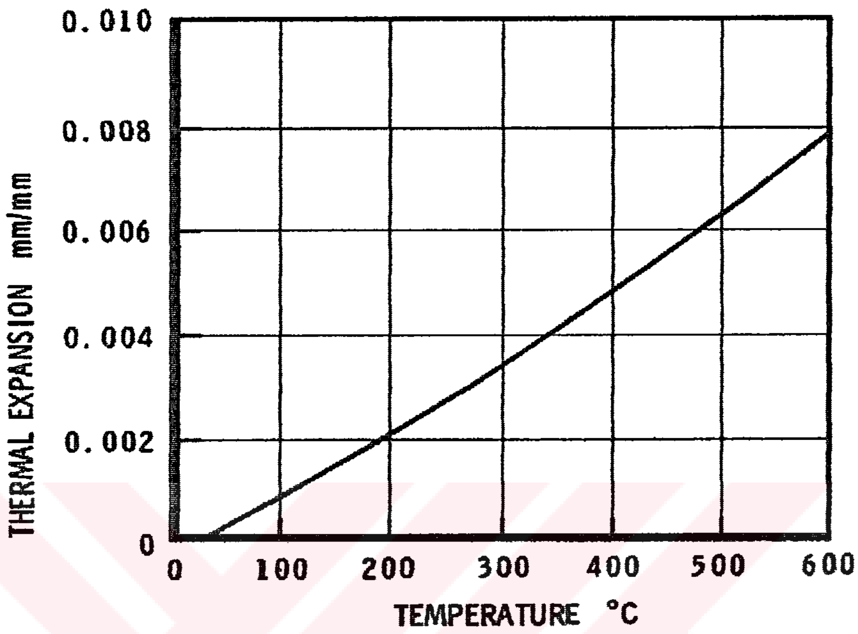


Figure 3.9 Thermal expansion of structural steel

The significant coefficient of linear expansion at temperatures of up to 1000°C is given as:

$$\alpha = (0.004T + 12) \times 10^{-6} \qquad 3.3$$

where:

α = coefficient of thermal expansion

T = Steel temperature, °C [29]

If the structural member is axially restrained against displacement, the expansion due to heat will be translated into thermal stresses that will increase the overall stress level in the member and cause an earlier collapse. Without axial restraint, a steel member will expand and could set up eccentric loading of adjacent structural members by displacing one of their ends (for example, a beam displacing the top of a column or of a load bearing masonry wall), as illustrated in Figure 3.8. A good fire-engineering concept designates the limiting steel temperatures, or its effects on the structure, prevents either thermal expansion that exits in the design. [17, 29]

Another deformation property is the creep deformation can be defined as the time dependent deformation of a material. Creep characterized by three periods, which are primary, secondary and tertiary (Figure 3.10).

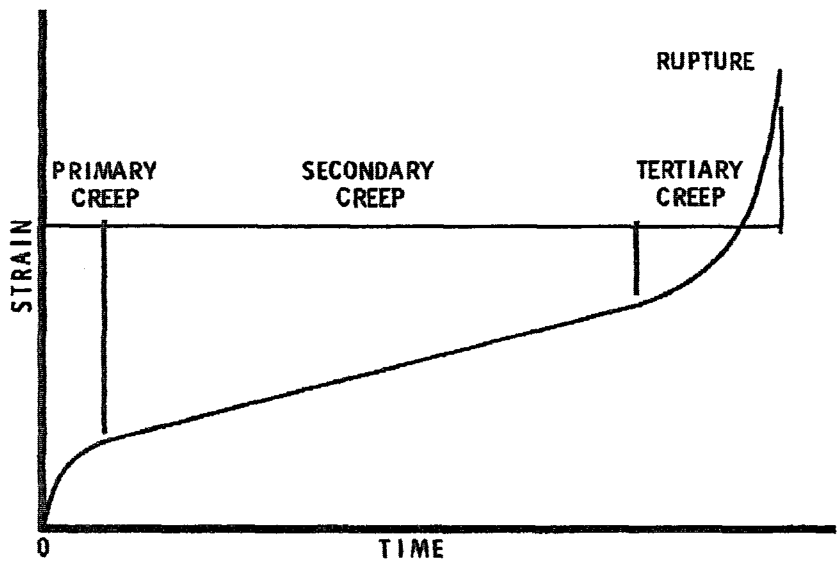


Figure 3.10 Typical creep curve

The primary creep begins with load application and is reflected by a continuous but decreasing strain after the deformation, which then continuous at a constant strain rate for a given temperature is the secondary creep. Finally, tertiary creep begins when, under the same conditions, the strain rate begins to accelerate rapidly where the creep strain curve becomes nearly vertical again and eventually leading to failure by rupture. Deformation proceeds at a varying rate depending on both temperature and length of time at the elevated temperatures of a fire. [17]

In any design of steel structures to resist fires, it is essential to know the properties of the steel. The fire exposure may be the standard time-temperature curve or a more realistic fire curve, depending on the design philosophy. Many protection methods are all based on standard fire exposure, but calculations are often based on simulated real fires.

3-7- Multi-story Steel Structures Exposed to Fire

In recent years, a number of large fires in steel framed buildings, have demonstrated that the fire performance of large steel framed structures is often much better than can be predicted by consideration of the fire resistance of the individual structural elements. [30] This behavior results from the ductility of steel, which allows large rotations and deflections without significant loss of strength.

A large series of full-scale fire tests was carried out between 1994 and 1996 in the Cardington Laboratory of the Building Research Establishment in England. A full-size eight story steel building was constructed with composite reinforced concrete slabs on exposed metal decking, supported on steel beams without applied fire protection. (Figure 3.11)

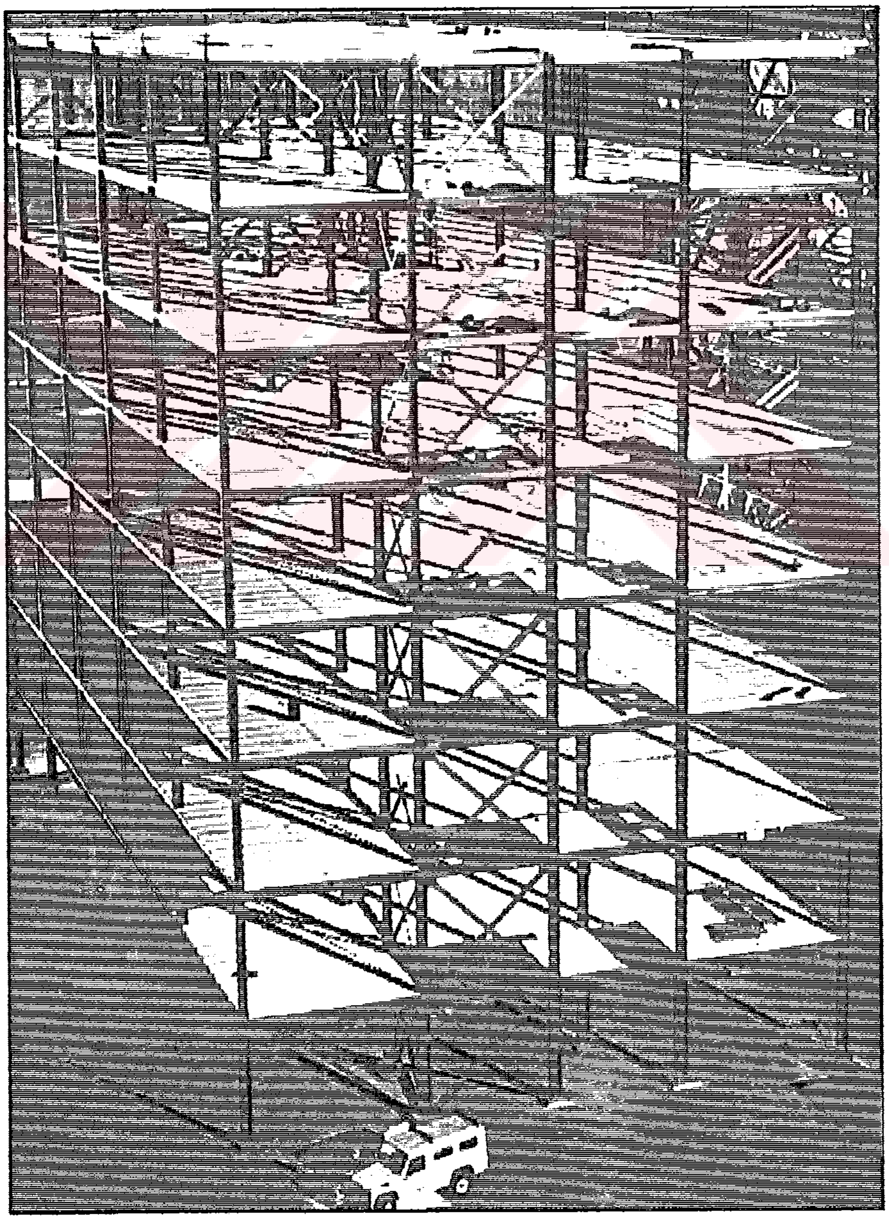


Figure 3.11 Eight-story steel-framed building used in Cardington Tests

The steel columns were fire protected. A number of fire tests were carried out on parts of one floor of the building, resulting in steel beam temperatures up to 1000°C, leading to deflections up to 600 mm, but no collapse and generally no integrity failures. (Figure 3.12) [31]

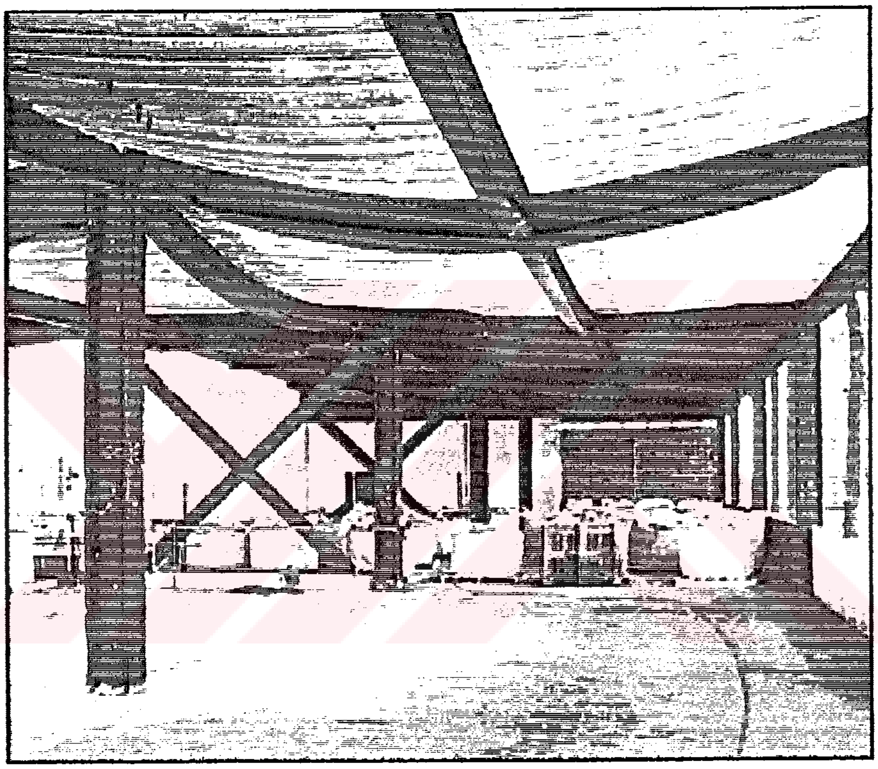


Figure 3.12 Deflections of unprotected steel beams supporting a composite floor slab

According to Johnson the good performance of the floor-beam systems in such buildings in Cardington tests has been attributed to a complex series of events, described rather simply as follows. [31]

- The fire causes heating of the beams and the underside of the slab.
- The slab and beam deform downwards as a result of thermal bowing.

- Thermal expansion causes compressive axial restraint forces to develop in the beams.
- The reaction from the stiff surrounding structure causes the axial restraint forces to become large.
- The yield strength and modulus of elasticity of the steel reduce steadily.
- The downward deflections increase rapidly due to the combined effects of the applied loads, thermal bowing and the high axial compressive forces.
- The axial restraint forces reduce due to the increased deflections and the reduced modulus of elasticity, limiting the horizontal forces on the surrounding structure.
- Higher temperatures lead to a further reduction of flexural and axial strength and stiffness.
- The slab beam system deforms into a catenary, resisting the applied loads with tensile membrane forces.
- As the fire decays, the structural members cool down and attempt to shorten in length.
- High tensile axial forces are induced in the slab, the beam and the beam connections.

These actions can take place in two dimensions or three dimensions, depending on the geometry of the building and the layout of the structure. The large deformations are often resulted by local buckling of the steel members. [31, 32]

CHAPTER 4

HOW CAN STRUCTURAL STEEL WITHSTAND FIRE RESISTANCE REQUIREMENTS?

The present chapter will show the methods for steel structures to safely withstand fires. Different methods are listed and compared. As stated in the previous chapter; when a steel structure is exposed to fire, the steel temperatures increase and the strength and stiffness of the steel are reduced, leading to possible deformation and failure. The increase in steel temperatures depends on the severity of the fire, the area of steel exposed to the fire and the amount of applied fire protection. There are many methods of protecting steel members from exposure to fire, so that the structural steel buildings with applied fire protection can be designed to have excellent fire resistance. Structural performance in fire can be based either on fire tests or on calculation. First it is necessary to define the factors, which influence the fire resistance of structural steelwork.

4-1- Factors Effecting the Fire Resistance Time of Steel Structures

There are two main group of factors influence the fire resistance time of a steel structure. The first group influences the critical temperature and the other group effects the steel-heating rate. In order to satisfy the fire resistance requirements, the temperature developed in a steel member at the required time must be less than its 'collapse temperature'. The collapse temperature is approximately 500°C this is the point that structural steel loses its half of its strength. [33] The factors influencing the collapse temperature are:

- the fire load level
- the temperature distribution
- the section dimensions.

It is accepted that steel is a highly conductive material; therefore the rate of temperature rise of a protected or unprotected structural steel member exposed to fire depends on its 'section factor'. This is a measure of the ratio of the heated perimeter to the area of the cross section. In simple words it can be said that, the more massive the section, the more energy is needed to heat it. In order to take account of this effect the section factor P/A m^{-1} is used in which P(m) is the perimeter of the member directly exposed to the fire and A(m^2) is the cross sectional area of the same member. [15]

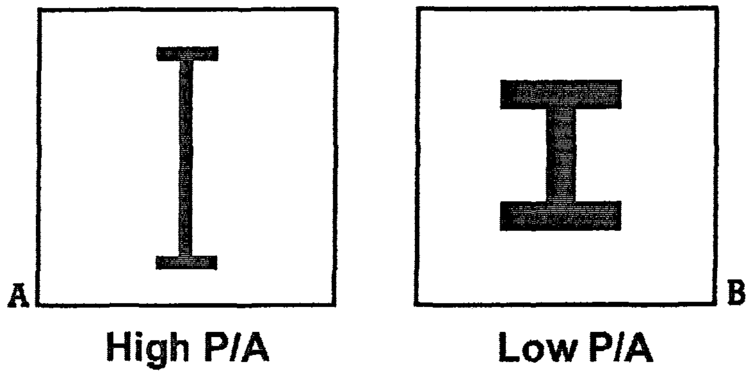
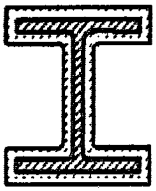
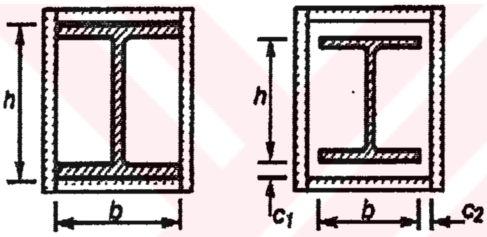
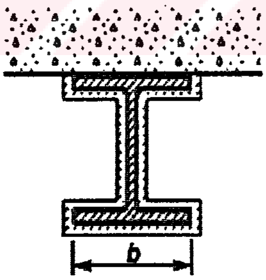
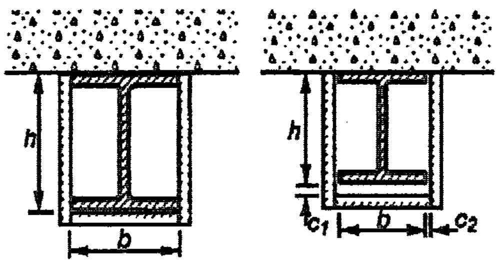


Figure 4.1 P/A concept: A = high P/A; B = low P/A

The P/A concept is shown graphically in Figure 4.1. Naturally, the higher the ratio P/A, the faster is the temperature rise. Therefore the rate of temperature rise in a small thick section will take a slower time than a large thin section. In calculating the section factor (P/A) values, the full cross sectional area (A) is used as the whole of the steel section exposed to heat. In the case where a beam supports a concrete floor for example, the perimeter is reduced by the width of the top flange, which is protected by the floor itself.

The section factor is important because the rate of heat input is directly proportional to the area exposed to the fire environment, and the subsequent rate of temperature increase is inversely proportional to the heat capacity of the member. This is equal to the product of the specific heat, the density and the volume of the steel segment. Below is the definition of the section factor in the Eurocode 3. [18]

Table 4.1 Definition of section factor in the Eurocode 3 (EC3, 1995)

Sketch	Description	Section factor (P/A)
	Contour encasement of uniform thickness	$\frac{\text{Steel perimeter}}{\text{Steel cross-sectional area}}$
	Hollow encasement[(1)] of uniform thickness	$\frac{2(b + h)}{\text{Steel cross-sectional area}}$
	Contour encasement of uniform thickness, exposed to fire on three sides	$\frac{\text{Steel perimeter} - b}{\text{Steel cross-sectional area}}$
	Hollow encasement[(1)] of uniform thickness exposed to fire on three sides	$\frac{2h + b}{\text{Steel cross-sectional area}}$

(1) The clearance dimensions c_1 and c_2 should not normally exceed $h/4$

Similar to the principles above, the contours of an unprotected steel element even have different temperatures in various parts of steel sections. Figure 4.2 shows the temperature contours in an unprotected heavy steel section (Universal Column, 356 x 406 x 634 kg/m) after 30 minutes exposure to the standard fire curve. It can be seen that there are temperature differences of over 100°C within the cross section, the largest difference being between the high temperatures in the thin web and the lower temperatures in the much thicker flanges. [18]

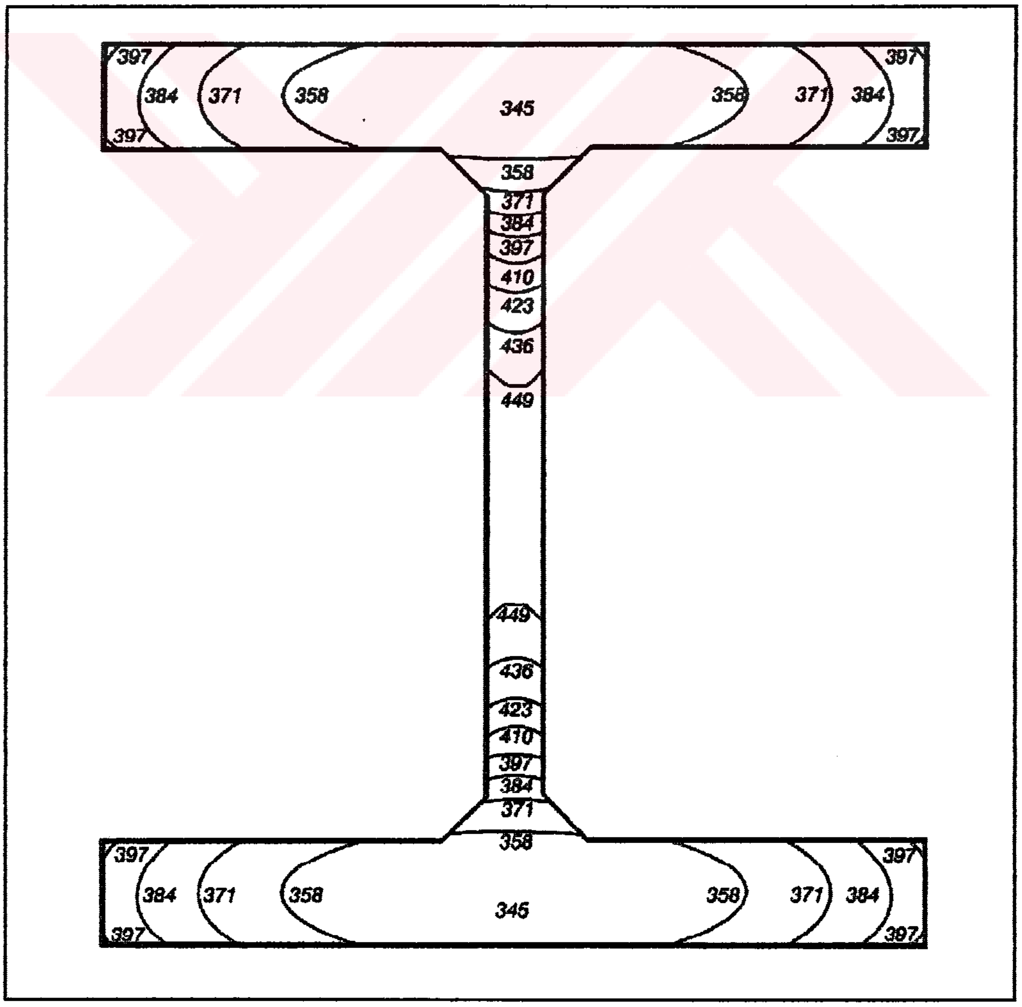


Figure 4.2 Temperature contours (°C) in a heavy steel beam exposed to fire

For insulated steel sections the development of the steel temperature is apart from the section factor, also dependent on the coefficient of heat conduction (λ) and the thickness (d) of any applied insulation material. (Figure 4.3)

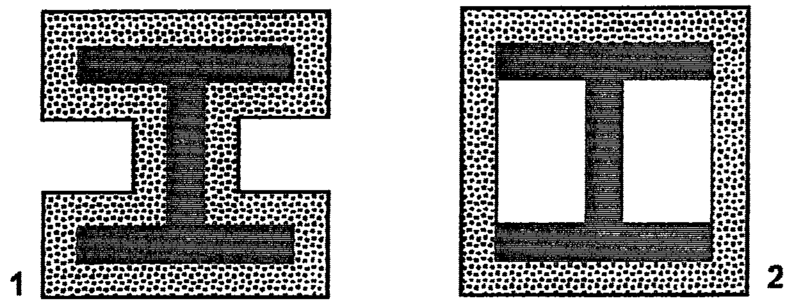


Figure 4.3 Section factor for insulated steel sections

(1) Contour encasement or spraying: $P/A = \dfrac{\text{perimeter of steel section}}{\text{Steel cross section}}$

(2) Hollow encasement: $P/A = \dfrac{\text{interior perimeter of encasement}}{\text{Steel cross section}}$

The heated surface is the actual surface area of unprotected members or members with sprayed-on fire protection, and the area of the equivalent rectangle for box protection, with allowance for any unexposed surfaces, as shown in Table 4.1. There are a variety of insulating materials for steel elements. Other structural materials like brick or concrete can be used, but this is a very expensive solution. The more common materials are insulating boards, sprayed coatings or intumescent paints. A small value for conductivity in combination with a high value for thickness will result with a slow temperature increase in the steel section. (Figure 4.4)

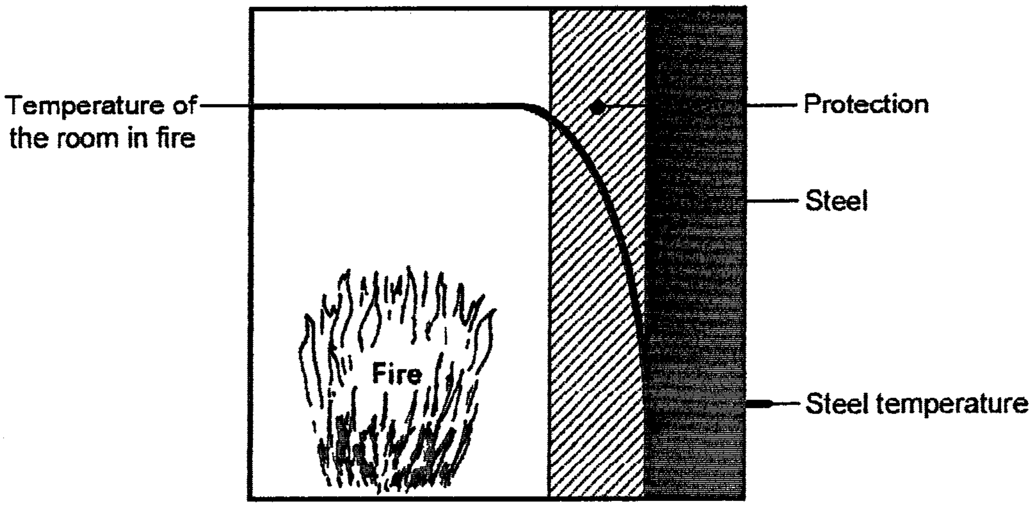


Figure 4.4 Temperature distributions in insulation materials and steel

4-2- Protection Methods for Structural Steel Elements Against Fire

There are many alternative passive fire protection systems available to reduce the rate of temperature increase in steel structures exposed to fire. Each type of fire protection method should have at least one fire resistance rating obtained from full scale testing, even if the fire resistance is achieved by calculation. Bare steel structures can meet fire resistance duration of 30 or 60 minutes if one or more of the following conditions are met:

- low load level,
- low value of the section factor (P/A),
- high degree of static redundancy.

Most of the fire protection systems are applied after erection of the structural frame and takes the form of an insulating barrier between the steel and the fire to slow down the transfer of heat. The first protective coatings were made from heavy weight materials such as concrete, brick and plaster, which are still be the optimum solution in some circumstances.

The characteristics of the insulation material can be expressed by the d/ λ amount (thickness of the insulation material / coefficient of heat conduction). The main principle of the insulating materials like boards is; the evaporation of water contains. Water consumes the heat energy coming out of the fire in this period of time. This procedure retards the conduction of heat to the steel element. The conduction values to be used in a fire engineering design are different from those normally given in references on heat transfer for room temperature conditions. Special procedures are developed to determine the insulation characteristics under fire conditions. [19, 33]

The European Commission for Constructional Steelwork (ECCS) [35] gives the following approximate formula for predicting the time (t) in minutes for a steel member protected with light, dry insulation to reach a limiting temperature T_{lim} (°C) when exposed to the ISO 834 fire:

$$t = 40\,(T_{lim} - 140)\left[\frac{d/\lambda}{F/V}\right]^{0,77} \qquad 4.1$$

where:

λ = Thermal conductivity, W/mK

d = Thickness of the insulation material, m

F = Surface area of unit length of the steel member

V = Volume of steel in unit length of the member

This equation is valid in the range of t from 30 to 240 minutes. For insulation containing moisture, a time delay t_d in minutes can be added to the time t calculated from the above equation, using

$$t_d = m\,\rho\,d^2 / (5\,\lambda) \qquad 4.2$$

where:

m = Moisture content of the insulation, %

ρ = Density of the insulation, kg/m^3

λ = Thermal conductivity, W/mK

d = Thickness of the insulation material, m

Typical values of thermal properties of insulating materials are given in Table 4.2, from ECCS [35]. Again it should be noted that this is an empirical approximation.

It is recommended to use improved computer technology programs for more advanced calculations.

Table 4.2 Thermal properties of insulation materials

Material	Density ρ (kg/m³)	Thermal conductivity λ (W / mK)	Specific heat cp (J/kg K)	Equilibrium moisture content (%)
Sprays:				
Sprayed mineral fibre	300	0.12	1200	1
Perlite or vermiculite plaster	350	0.12	1200	15
High-density perlite or vermiculite plaster	550	0.12	1200	15
Boards:				
Fibre-silicate or fiber-calcium silicate	600	0.15	1200	3
Gypsum plaster	800	0.20	1700	20
Compressed fiber boards:				
Mineral wool, fiber silicate	150	0.20	1200	2

The analysis of the fire resistance of a steel structure is made complex by the number of variables involved. Recent developments in the computer technology allow a reliable computer aided design of fire resistant structures. The aim of these new methods is to assess directly the real behavior of natural fires and structures. They use sophisticated computerized thermal and mechanical analysis. The advantages of the numerical methods are that they permit the designer to take into account the various heat transfer problems, the changes in material properties, the character of the fire environment and the reaction of the structure to the thermal loadings.

4-2-1- Concrete Encasement

Concrete encasement was a common method of protecting steel structures in the early part of the century. But this added a considerable amount of dead weight to the buildings. The load could be reduced by using lightweight concrete with a density of 1600 kg/m³, (as compared to normal concrete with a density of 2400 kg/m³) but it still was on the heavy side compared to the other coatings. The thermal conductivity of concrete depends upon the nature of the aggregate, porosity of the concrete and the moisture content. For example, in order to reach a 90 minutes fire resistance, the steel element must be encased into 40 mm thick B160 quality concrete.

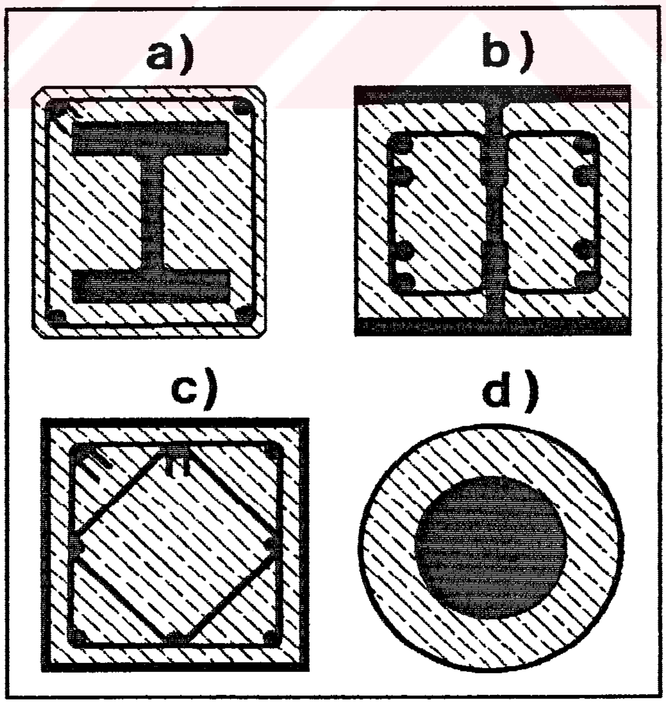


Figure 4.5 Typical cross sections of composite columns

As a steel element is encased in concrete, it has usually been assumed that concrete provides thermal insulation only. However, with the improvements in the design of composite elements, concrete also strengthens the load-carrying ability of the steel. Also the excellent durability in corrosive environments is another advantage of this method. There are four main types of composite columns considered, according to their performance under fire conditions. (Figure 4.5). [19, 34]

a) Rolled H-profiles encased in concrete – The cross section of this type of column is composed of a steel profile placed at the center of an appropriate reinforced concrete block. The fire resistance depends on the cross section of the encased profile and the external dimensions of the concrete block, which is normally 90 minutes or more.

b) Rolled H-profiles concreted between flanges – the concrete between the flanges is used as an insulating and load bearing material. The vertical columns and horizontal girders reinforcing bars substitute, during the fire, for the heated flanges of steel profile. Such composite sections can reach any desired fire resistance level. (Figure 4.7)

c) Concrete filled circular or rectangular hollow sections with or without reinforcing bars – The mechanical properties of steel element decrease, and the concrete core, still retained by the steel envelope, gradually takes over the load-bearing function during the fire. The fire resistance can reach 120 minutes if the concrete is reinforced, where it can only reach 30 minutes without reinforcement.

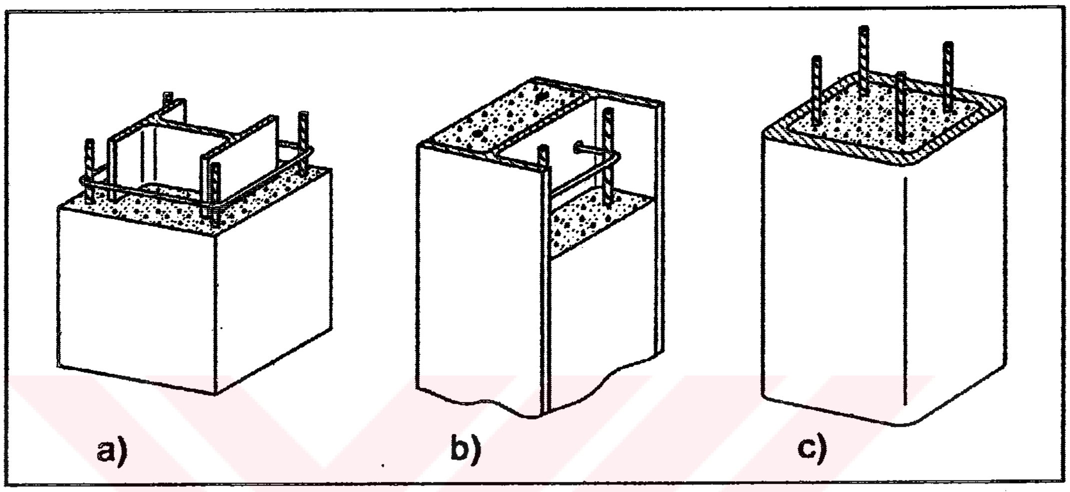


Figure 4.6 Reinforced composite columns

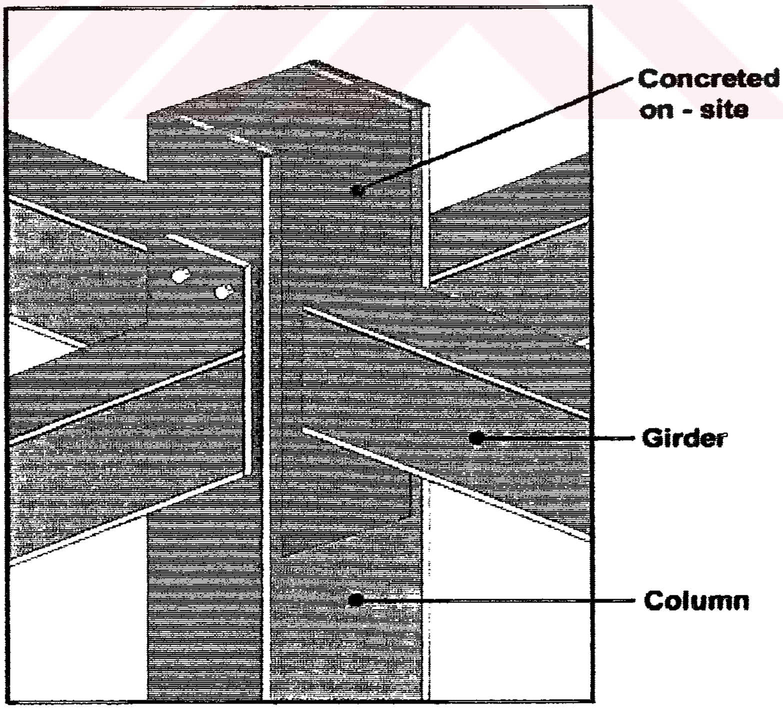


Figure 4.7 Connection of steel girders and column concreted between flanges

d) Steel core columns embedded in concrete with outer circular or square steel sheet – The fire resistance of this type of column varies from 60 minutes to any higher value according to thickness of the concrete layer.

Partially exposed members to fire are another situation in composite constructions with steel members protected by concrete because they are embedded in walls, floors or other elements of the structure (Figure 4.8), achieve a significant fire resistance by redistribution of stress hot regions to cooler areas of the section. [18]

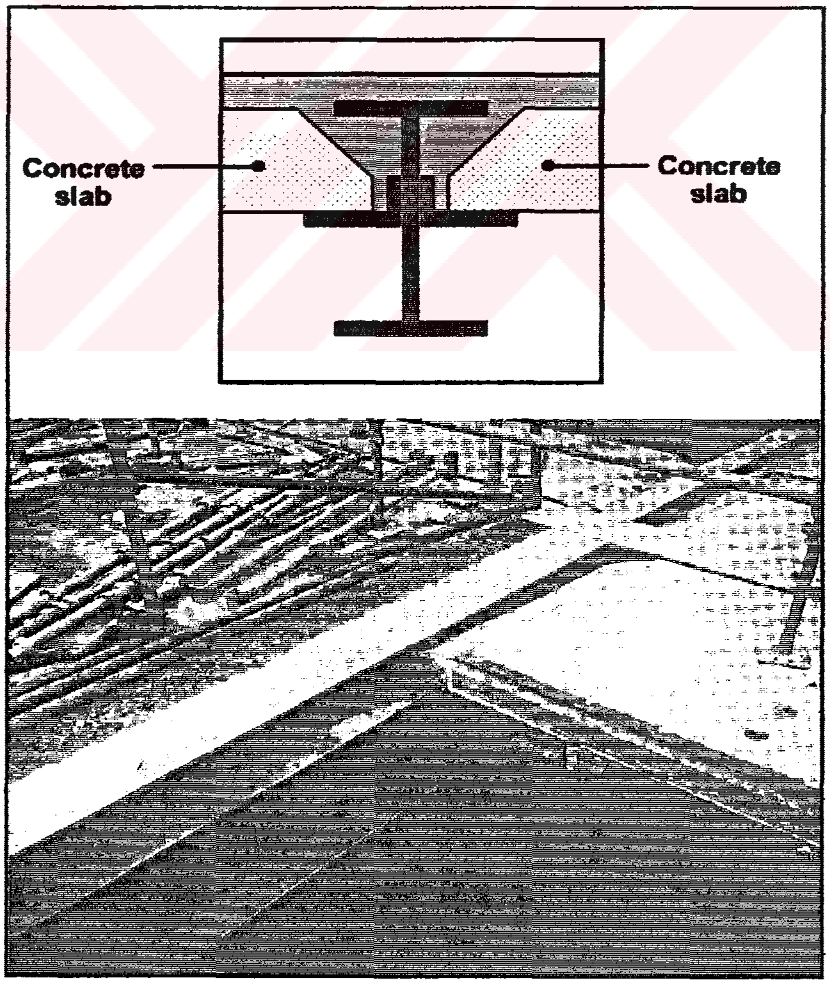


Figure 4.8 A steel beam embedded in concrete floor slab

One of the great advantages of the composite columns is their constant outside dimensions in multi-story buildings. By varying the thickness of the steel section, the material qualities of steel and concrete, the percentage of reinforcement, the cross section of the column may be adapted to the increasing load without changing significantly the outer dimensions. Every type of composite column has its typical advantages and its proper range of use. [34]

4-2-2- Boarded Encasements

There are many proprietary board systems for protecting steel structures. Asbestos insulation boards were commonly used for a long time, but asbestos-free boards have now replaced these boards in which asbestos fibers are substituted by mineral fibers. The most used materials for boards are, gypsum boards, vermiculate (sodium silicate) boards, mineral fiberboards and calcium silicate boards. However calcium silicate boards are more expensive than others in many countries, because they are manufactured only in few countries.

The density of the boards varies from 600 to 800 kg/m^3 and the thermal conductivity varies from 0.15 to 0.20 W/m°C. Lime or cement is used as a binder and some organic materials are mixed to improve fixing characteristics. Vermiculite slabs are made by bonding exfoliated particles with a silicate binder and are available in thickness of ranging from 25 to 50 mm. They have a density of between 350 and 550 kg/m^3 and the thermal conductivity ranges from 0.09 to 0.15 W /m°C between 100 and 800°C. Mineral wool slabs are lighter and more flexible, with a density around 150 kg/m3. They can be attached to steel by adhesive or pins but may require some additional method of retention. The thermal conductivity is around 0.035 W/m°C at normal temperatures and increases about ten times to 0.32 W/m°C at 800°C related partly to the melting of the fibers at surface layers. [12]

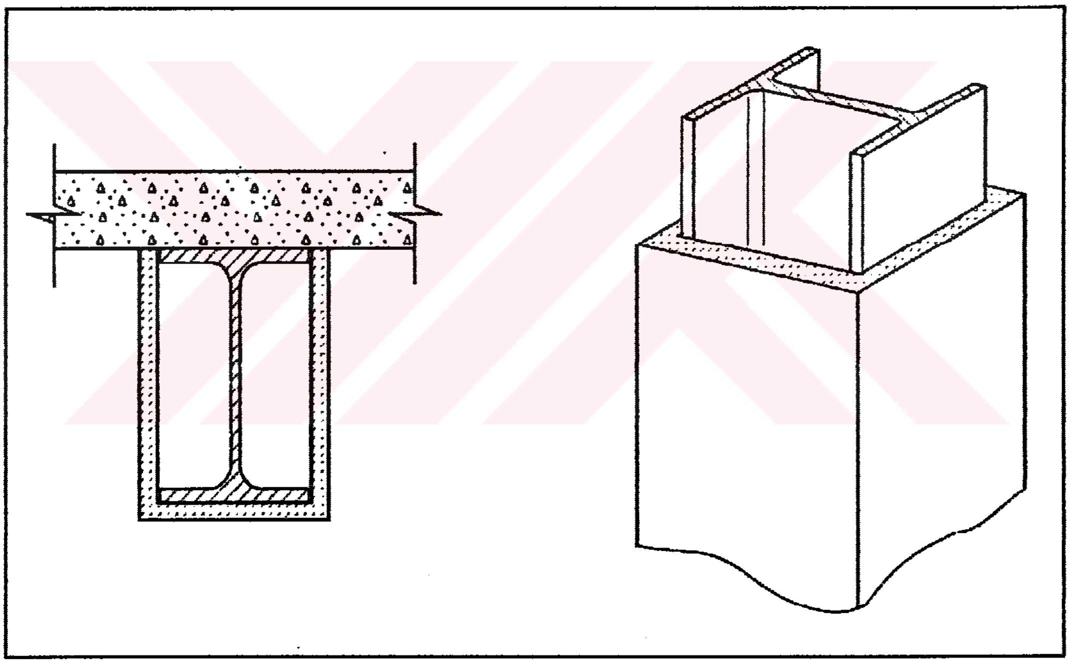


Figure 4.9 Steel beam and column protected with board materials

Board systems have the advantages of easy installation in a dry process and easy finishing with decorative materials but have disadvantages like slow installation, and higher cost than spray-on materials. Since, columns are more visible in the building, board systems are more often used for columns than for beams. The boards can be either fixed directly steel surface or in the form of box encasements which are cut to size and screwed to each other or to a light angle frame and provide a rigid and hard encasement (Figure 4.10). In both cases a careful examination of joints is necessary in order to avoid local heating of inadequately covered parts. The number and thickness of layers can be easily adapted to the particular application. By the use of board encasements any desired level of fire resistance can be achieved, depending on the thickness and the composition of the board. [18, 19]

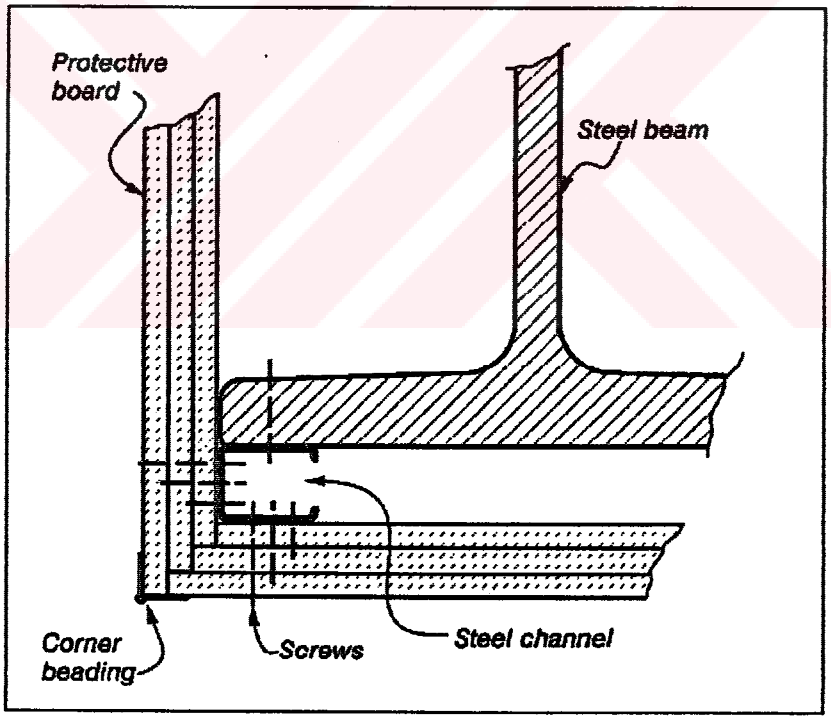


Figure 4.10 Detail of steel beam protected with board materials

The most commonly used boards; gypsum boards are high quality cladding systems offers excellent fire protection to building structures up to 2 hours. This is due to the unique behavior of gypsum when exposed to fire. The main reason of its frequent use in Turkey is its domestic production. Pure gypsum plaster contains %21 of chemically combined water of crystallization and %79 of calcium sulfate, which is inert below a temperature of 1200°C. When it is exposed to fire the dehydration and calcination processes begins. This chemical reaction has an endothermic character. Because of the reason that the temperature degree of the calcination area on the exposed side stays at the temperature of the evaporation of water, which is about 100°C, and the unexposed side of the gypsum board remains under 100°C until the dehydration process comes to an end. This special feature is the reason to use many gypsum plaster products for successful fire protection. The fire protective types of the gypsum boards, which is coded as Fire Resistive (FR) type, contains fire resisting fiberglass bounders as a reinforcing element, for prevention from breaking off the calcined section from the normal section. [36, 37]

In most of the developed countries, the FR type gypsum board producers test their own products by fixing them to steel structural elements, in standard fire tests. The test results are converted to section factor tables (P/A), in order to make the selection simpler for the decision makers. The Table 4.5 is supplied by Tepe Structure & Industry Inc. Directorate of Product Development, using the available structural steel sections and FR type gypsum boards in Turkey.

Table 4.3 Lining Thickness of Gypsum Boards for Encasement of Steel Elements

Code	FR Gypsum Board Thickness	Code Color
A	: 12,5 mm	
B	: 15 mm	
C	: 12,5 mm + 12,5 mm	
D	: 15 mm + 12,5 mm	
E	: 15 mm + 15 mm	
F	: 12,5 mm + 12,5 mm + 12,5 mm	
G	: 15 mm + 12,5 mm + 12,5 mm	
H	: 15 mm + 15 mm + 12,5 mm	

Table 4.4 Section (P/A) Factor of Available Hot-Rolled Steel Sections in Turkey

Section Code	Height	Width	P/A Factor
NPI-160	160 mm	74 mm	252
NPI-180	180 mm	82 mm	229
NPI-200	200 mm	90 mm	212
NPI-220	220 mm	98 mm	196
NPI-240	240 mm	106 mm	183
NPI-260	260 mm	113 mm	170
NPI-300	300 mm	125 mm	149
NPI-380	380 mm	149 mm	119
2xNPU-160	160 mm	130 mm	121

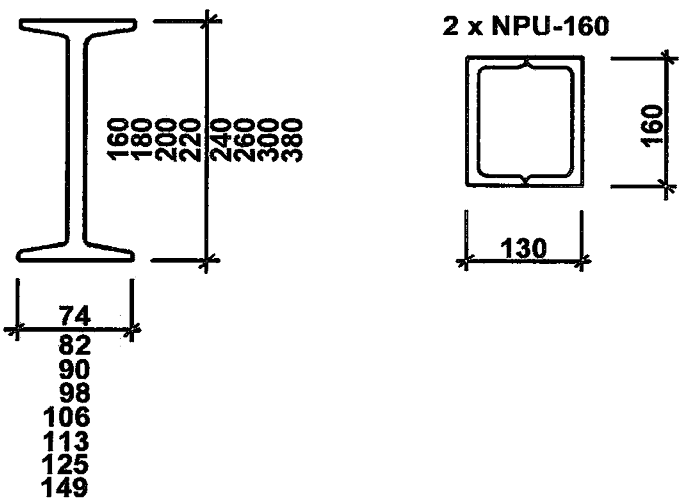
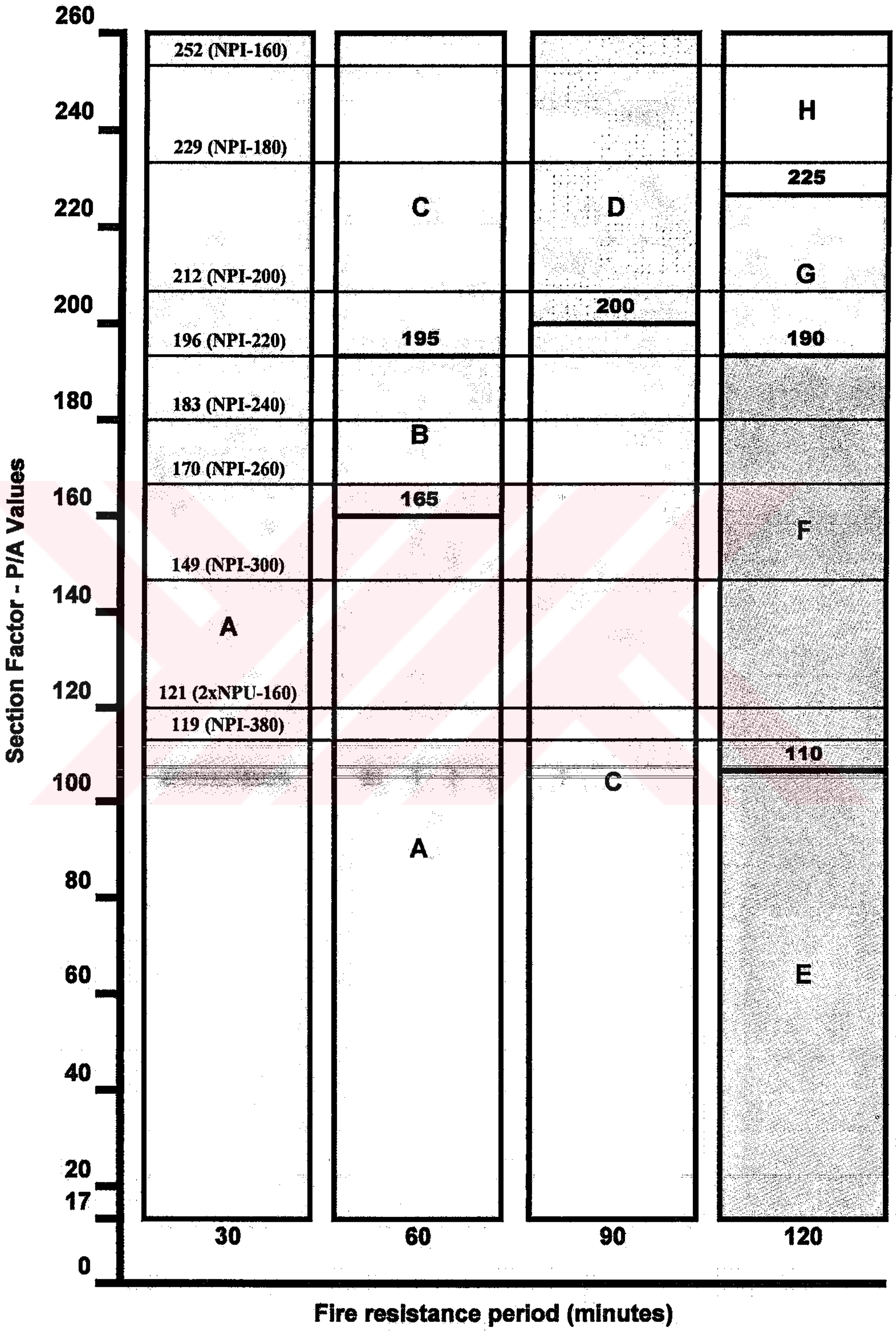


Table 4.5 Table of FR Type Gypsum Board Encasements for Available Steel Sections in Turkey



As it can be seen, the Table 4.5 is valid for the steel sections up to section factor (P/A) of 260. For more smaller or special sections, the empirical formula below can be used in order to identify the thickness of the gypsum board. [37]

$$t = 130 \left[\frac{0.672 \times d \times (W' / P)}{2} \right]^{0,75} \qquad 4.3$$

where:

t = Fire resistance, minutes

W' = unit weight of the steel member + gypsum board encasement, kgf/m

d = Thickness of the gypsum board, mm

P = Perimeter of the steel member, mm

$$W' = W + \left[\frac{0,54\ h\ D}{1000} \right] \qquad 4.4$$

where;

W = unit weight of the steel member, kgf/m

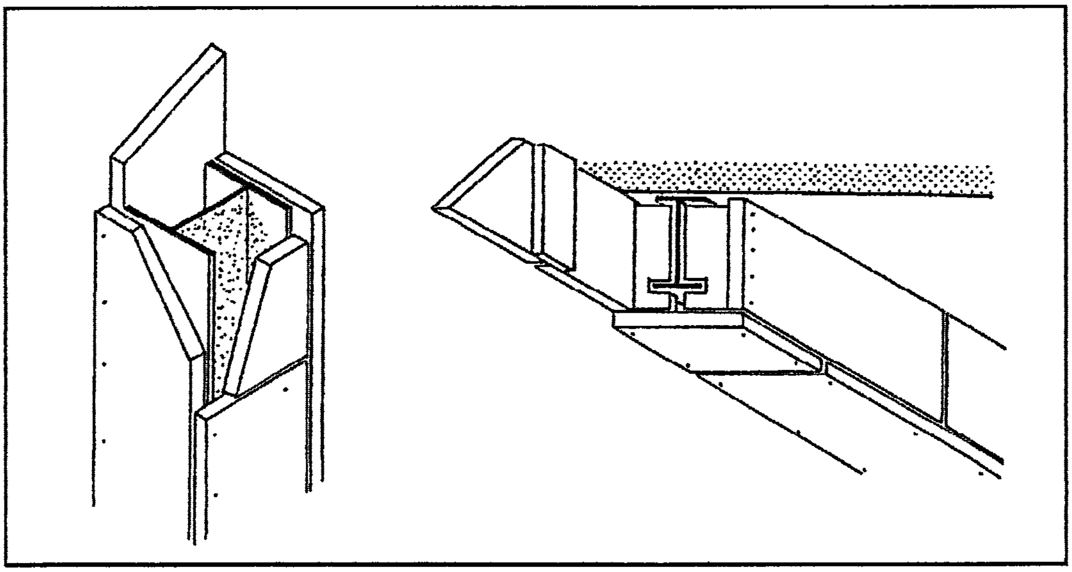


Figure 4.11 Details of frameless gypsum board encasement of steel beam and column

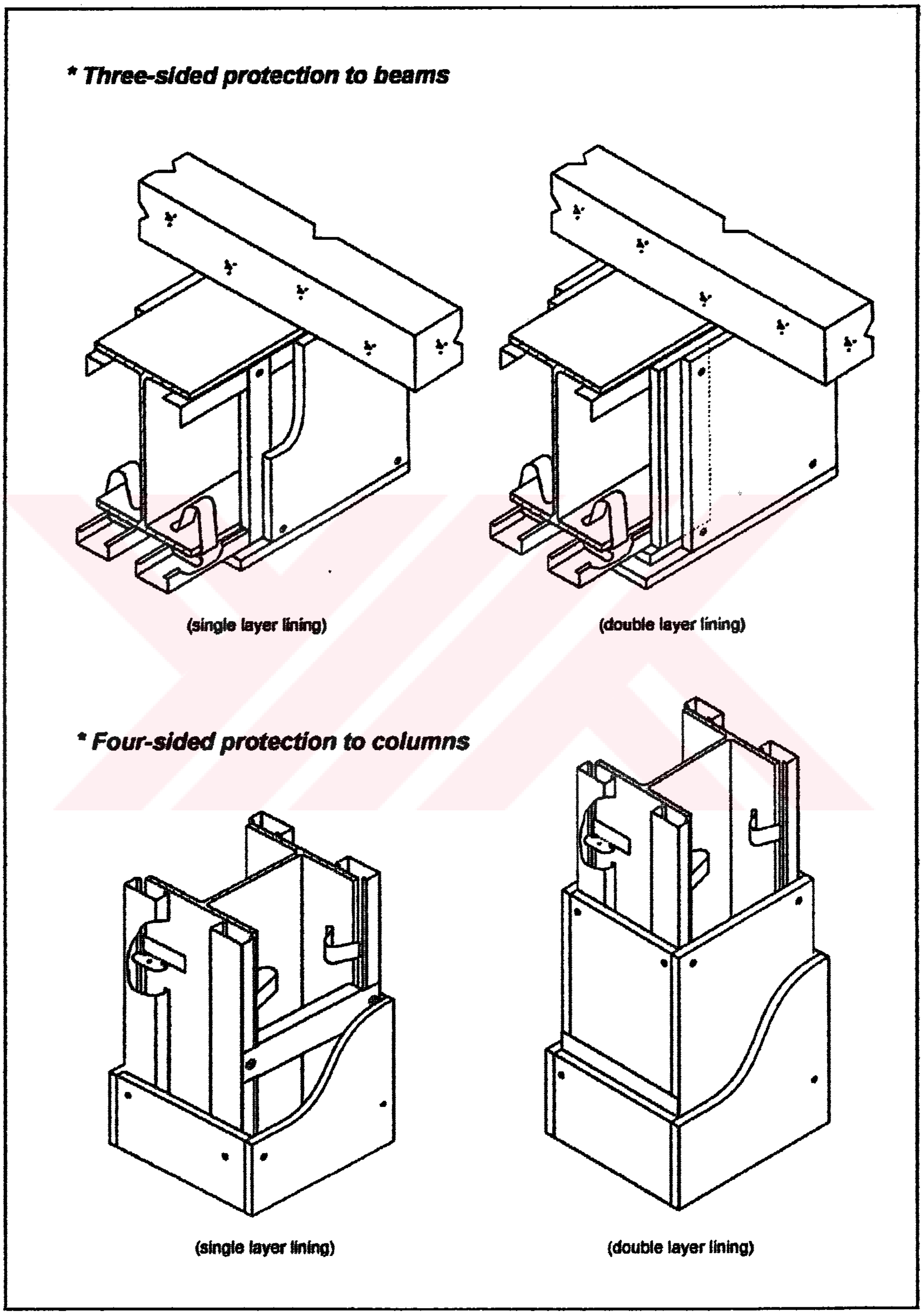


Figure 4.12 Details of framed gypsum board encasement of steel beam and column

4-2-3- Spray-on Systems

Spray-on systems are usually the cheapest and the fastest applicable type of passive protection for high-rise steel structures. These systems are mainly called as SFRMs (Spray Applied Fire Resisting Materials) and consist of projecting a material in the wet or dry state, usually in several layers on the members to be protected. The insulating material can be vermiculate particles, mineral or slag fibers. This method of protection is easy to apply to complicated details such as bolted connections or steel brackets. Approved systems must have proof that they have sufficient stick ability to remain in place during fire exposure. Spray-on materials are usually cement based with some form of glass or celluloid fibrous, which reinforces and holds the material together. [19]

Figure 4.13 Spray-on application to a steel column

It has been about 40 years since SFRMs are used in construction industry. Earlier spray-on materials also used asbestos fibers, which are no longer used for health reasons. There are some disadvantages pertaining to spray-on materials. Firstly the process is usually wet and messy. Secondly the spray-on materials are rather soft, so that they have to be protected from damage and also the resulting finishes are not suitable for decorative finishing. For the latter reason, this system of protection is generally applied to hidden elements. But it may also be possible with the aid of the color effects to integrate these elements to the architectural aspect of the structure. [18]

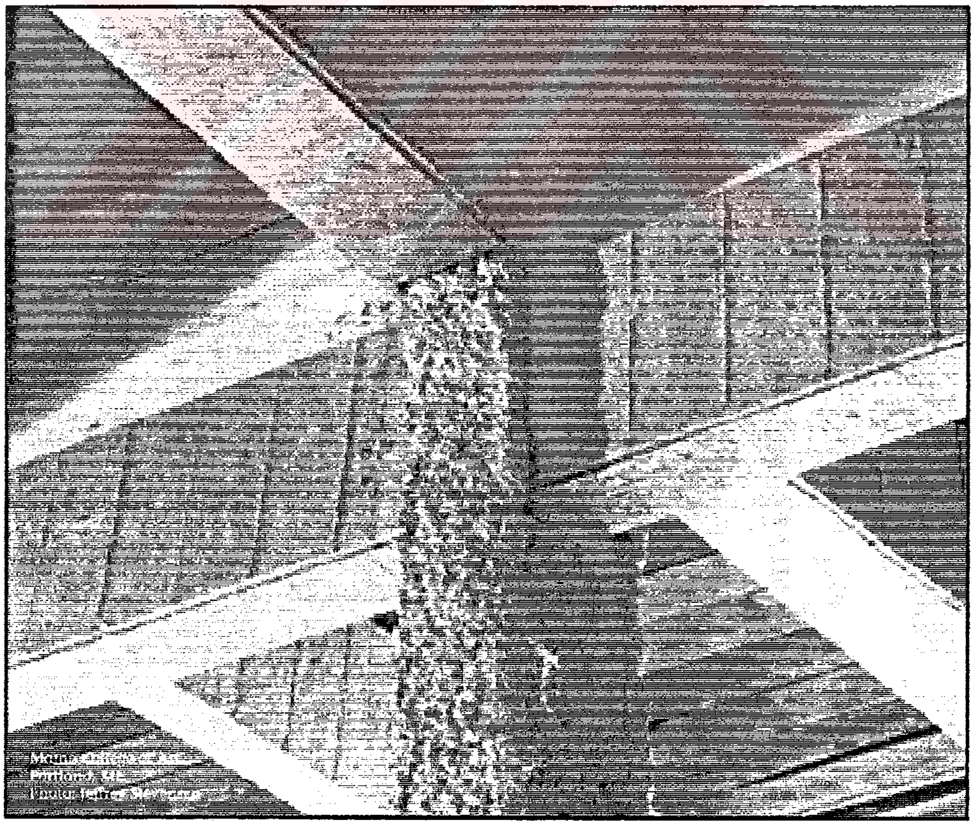


Figure 4.14 Spray-on application to a steel column

The required thickness of proper SFRMs to cover the fire resistance codes can usually be found in individual manufacturers literature or trade applications. In Turkey spray-on systems are rarely used because they are imported products. One of the leading companies in the world in this field, Cafco International products are available in the Turkish market. Table below gives the properties and performance of the Cafco Blaze-Sheild SFRM. This product has been used for the passive fire protection for the three tallest steel buildings in the world; the World Trade Center New York, the Sears Tower Chicago and the Petronas Towers Kuala Lumpur. This non-combustible SFRM is based on a mixture of mineral wool fibers and cement binders. It offers fire protection for up to 240 minutes and does not crack or spall under reasonable deflection. It has a density of 264 kg/m^3 and thermal conductivity of 0.043 W/mK at 24°C.

Normally, in order to establish the correct thickness of the SFRMs the manufacturers provides computer based thickness calculations to meet specific fire ratings. Tables 4.6 and 4.7 shows the thickness of Blaze-Shield SFRM for **I**-section beams and **H**-section columns according to their section (P/A) factors for required period of time, in order to make the selection simpler for the decision makers. A hydraulic pump is used for the application and the applied steel surface must be clean, dry and free from dust, rust and oil, in order to prevent the good adhesion. [38]

Table 4.6 Blaze-Shield thicknesses for I-section beams (3 sided exposure)

Section Factor (P/A)	Blaze-Shield thickness (mm) for fire resistance of:					
	30 (mins)	60 (mins)	90 (mins)	120 (mins)	180 (mins)	240 (mins)
30	15	15	15	15	25	35
50	15	15	15	18	32	42
70	15	15	15	20	37	45
90	15	15	15	23	40	49
110	15	15	17	25	42	50
130	15	15	20	27	44	60
150	15	15	20	30	45	60
170	15	15	22	33	48	-
190	15	15	23	35	52	-
210	15	17	24	37	55	-
230	15	18	27	39	57	-
250	15	19	28	42	-	-
270	15	19	30	43	-	-
290	15	20	32	44	-	-
310	15	22	34	47	-	-
330	15	23	35	48	-	-

Table 4.7 Blaze-Shield thicknesses for H-section beams (4 sided exposure)

Section Factor (Hp/A)	Blaze-Shield thickness (mm) for fire resistance of:					
	30 (mins)	60 (mins)	90 (mins)	120 (mins)	180 (mins)	240 (mins)
30	15	15	15	20	30	48
50	15	15	15	22	38	52
70	15	15	17	24	42	55
90	15	15	20	27	44	-
110	15	15	22	30	47	-
130	15	17	24	35	50	-
150	15	18	25	37	53	-
170	15	18	27	38	57	-
190	15	19	30	40	-	-
210	15	20	32	43	-	-
230	15	22	33	44	-	-
250	15	23	34	47	-	-
270	15	24	37	48	-	-
290	15	25	39	49	-	-
310	15	26	40	52	-	-
330	15	27	43	57	-	-

4-2-4- Intumescent Coatings

The intumescent coatings achieve insulation in a totally different way. When these materials exposed to fire, they react to heat by expanding and forming an insulating layer. It contains a compound in its formulation, which releases a gas when heat is applied. The gas inflates the coating into thick carbonaceous foam, which provides heat insulation to the steel underneath. (Figure 4.15) These coatings are mainly in the form of mastics or paints and in a range of colors that may be used for decorative and practical reasons on visible steel work.

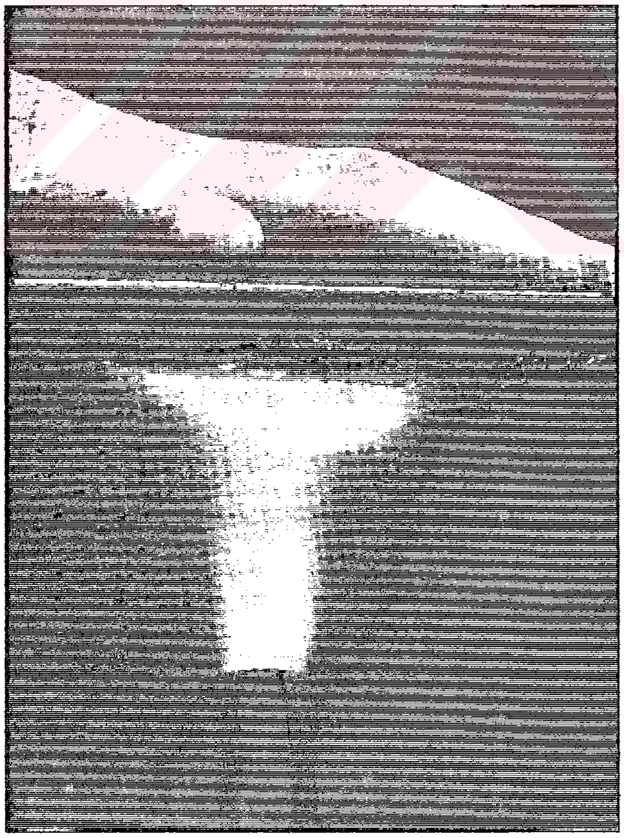


Figure 4.15 Effect of heat on intumescent coating

The advantages of these products are, they do not occupy much space; they can be applied by brush, airless spray or trowel by a layman and the quick application period. They are usually preferred in situations where the shape of the steel structure remains visible. Their main disadvantage is the high cost, and lower duration fire resistance ratings. The present intumescent coatings can provide from 30 to 60 minutes fire resistance in accordance to standard temperature-time curve ISO 834. Some special intumescent products incorporating multiple layers of fiberglass reinforcing have been developed for high-level protection of structural steel in the offshore oil platforms. [18, 19]

Usually the application of these products consists of three major layers. The first layer is the anti-corrosive primer. The second layer applied is the intumescent film causes the swelling reaction and the third layer, which is called as top sealer decorative color finishing, provides also dehydration. For example, 1 mm thickness of intumescent paint coating is enough for F60 code fire resistance. In the following Table 4.8 shows the second layer (dry film) thicknesses in unit of microns and required coats for the various beams and columns according to their section (P/A) factors. The table prepared by the Steelcote product available in the Turkish market. [39] Again the reason for the rare use of intumescent paints in Turkey is the high cost.

Table 4.8 Specification table for Steelcote intumescent coating

SECTION	COVER	SECTION FACTOR (P/A)	DRY FILM THICKNESS (microns)	REQUIRED COATS BRUSH	REQUIRED COATS SPRAY	LITRES m²
I-SECTION BEAMS 3 sided	1/2 hour	0 - 310	255	1	1	0,36
	1 hour	0 - 170	675	2	1	0,96
		171 - 210	850	3	1	1,21
		211 - 260	1025	3	1	1,46
		261 - 275	1200	4	1	1,71
		276 - 290	1375	4	1	1,96
		291 - 310	1550	5	2	2,21
		311 - 325	1725	5	2	2,46
		326 - 350	1900	6	2	2,71
	1 1/2 hours	0 - 160	1025	3	1	1,46
		161 - 170	1200	4	1	1,71
		171 - 180	1375	4	1	1,96
		181 - 195	1550	5	2	2,21
		196 - 210	1725	5	2	2,46
		211 - 225	1900	6	2	2,71
		226 - 245	2075	6	2	2,96
		246 - 250	2250	7	2	3,21
		251 - 260	2425	7	2	3,46
		261 - 265	2600	8	2	3,71
		266 - 275	2775	8	2	3,96
		276 - 285	2950	9	3	4,21
		286 - 300	3125	9	3	4,46
4 sided	1/2 hour	0 - 300	325	1	1	0,46
		301 - 310	500	2	1	0,71
	1 hour	0 - 140	375	2	1	0,96
		141 - 175	850	3	1	1,21
		176 - 215	1025	3	1	1,46
		216 - 225	1200	4	1	1,71
		226 - 235	1375	4	1	1,96
		236 - 250	1550	5	2	2,21
		251 - 270	1725	5	2	2,46
		271 - 295	1900	6	2	2,71
		296 - 325	2075	6	2	2,96
		326 - 350	2775	8	2	3,96
I-SECTION COLUMNS	1/2 hour	0 - 300	325	1	1	0,46
		301 - 310	500	2	1	0,71
	1 hour	0 - 140	675	2	1	0,96
		141 - 175	850	3	1	1,21
		176 - 215	1025	3	1	1,46
		216 - 225	1200	4	1	1,71
		226 - 235	1375	4	1	1,96
		236 - 250	1550	5	2	2,21
		251 - 270	1725	5	2	2,46
		271 - 295	1900	6	2	2,71
		296 - 325	2075	6	2	2,96
		326 - 350	2775	8	2	3,96
RHS/SHS/CHS COLUMNS	1/2 hour	0 - 85	325	1	1	0,46
		86 - 110	500	2	1	0,71
		111 - 140	675	2	1	0,96
		141 - 165	850	3	1	1,21
		166 - 195	1025	3	1	1,46
		196 - 220	1200	4	1	1,71
		221 - 250	1375	4	1	1,96
		251 - 275	1550	5	2	2,21
		276 - 305	1725	5	2	2,46
		306 - 310	1900	6	2	2,71
	1 hour	0 - 35	1025	3	1	1,46
		36 - 50	1200	4	1	1,71
		51 - 60	1375	4	1	1,96
		61 - 75	1550	5	2	2,21
		76 - 85	1725	5	2	2,46
		86 - 100	1900	6	2	2,71
		101 - 110	2075	6	2	2,96
		111 - 125	2250	7	2	3,21
		126 - 135	2425	7	2	3,46
		136 - 150	2600	8	2	3,71
		151 - 160	2775	8	3	3,96
		161 - 175	2950	9	3	4,21
		176 - 185	3125	9	3	4,46
		186 - 200	3300	10	3	4,71
TOP SEALER COAT			40	1	1	0,10

4-2-5- Water Filled Systems

Filling of hollow section columns with water can also attain fire resistance of steel structures. In this system the steel members do not need external protection so that they remain visible. It is not as common a method as others but is a very effective method. The principle is simple; a plumbing system is designed to ensure that the water can flow by convection from member to member, so that the temperature of the steel section remains below 200°C and thus, it can withstand to fire for an unlimited duration.

When the water filled columns are exposed to the fire, the heat flows to the column by radiation and to a lesser extent by convection of the hot gases. It then passes through the column plate by conduction. Boiling occurs on the inside of the column plate and heat is transferred to the water by convection and conduction. This heat is then absorbed chiefly as latent heat when the water is converted to steam and removed from the column by the vent. (Figure 4.16) To do this most effectively, the columns are normally interconnected by a piping system which permits gravitational circulation during a fire, the steam generated being vented to the atmosphere and the water evaporation is compensated by supply of fresh water from a storage tank. A schematic sketch of a possible system has shown in Figure 4.17. [18, 40]

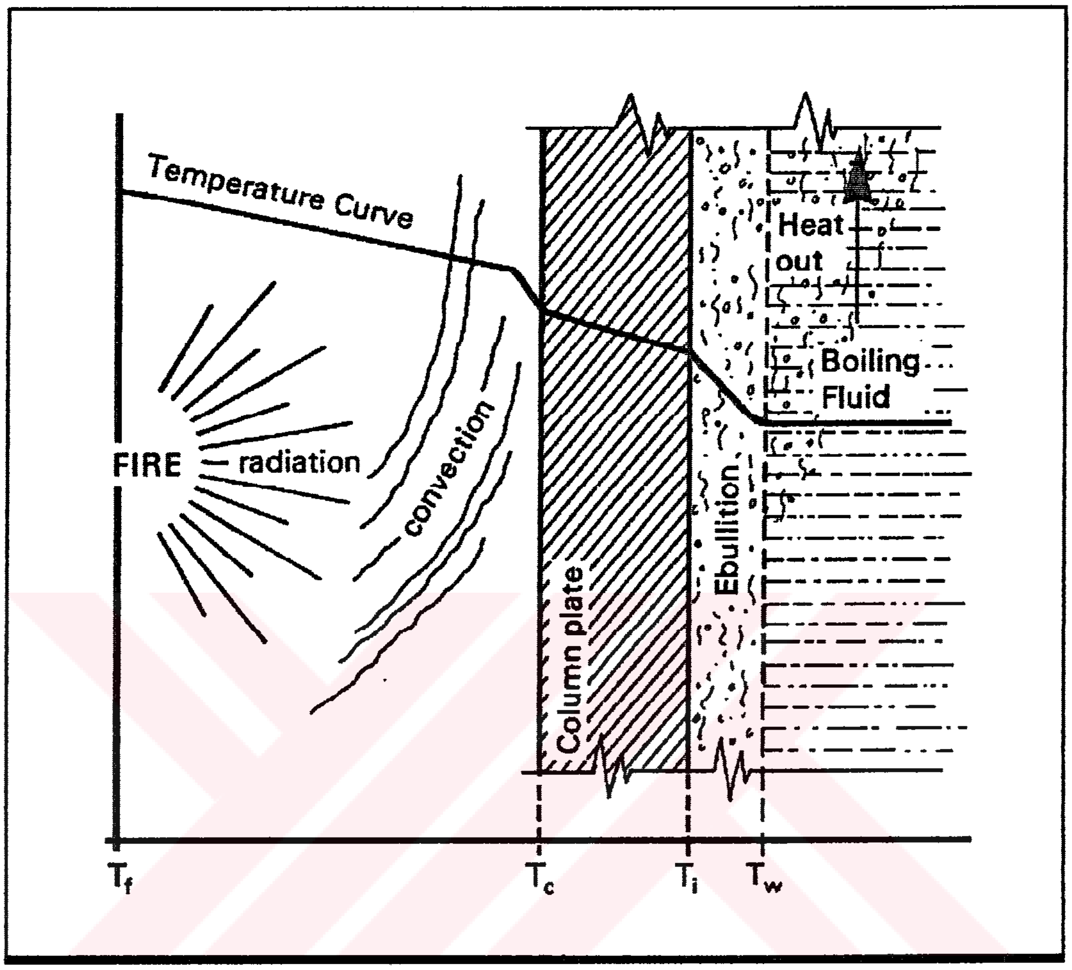


Figure 4.16 Theory of heat transfer and removal

In cold climate regions, potassium carbonate must be added to the liquid in exterior column systems as antifreeze, to maintain protection at low temperatures and prevent from ice damage. Also rust inhibitors such as potassium nitrate can be used in order to prevent the internal membrane of the steel columns from corrosion. It is desirable that an oil film is maintained on the free surface of the water in the storage tank to inhibit evaporation and to reduce the gradual contamination of the coolant by oxygen, algae, etc. [41]

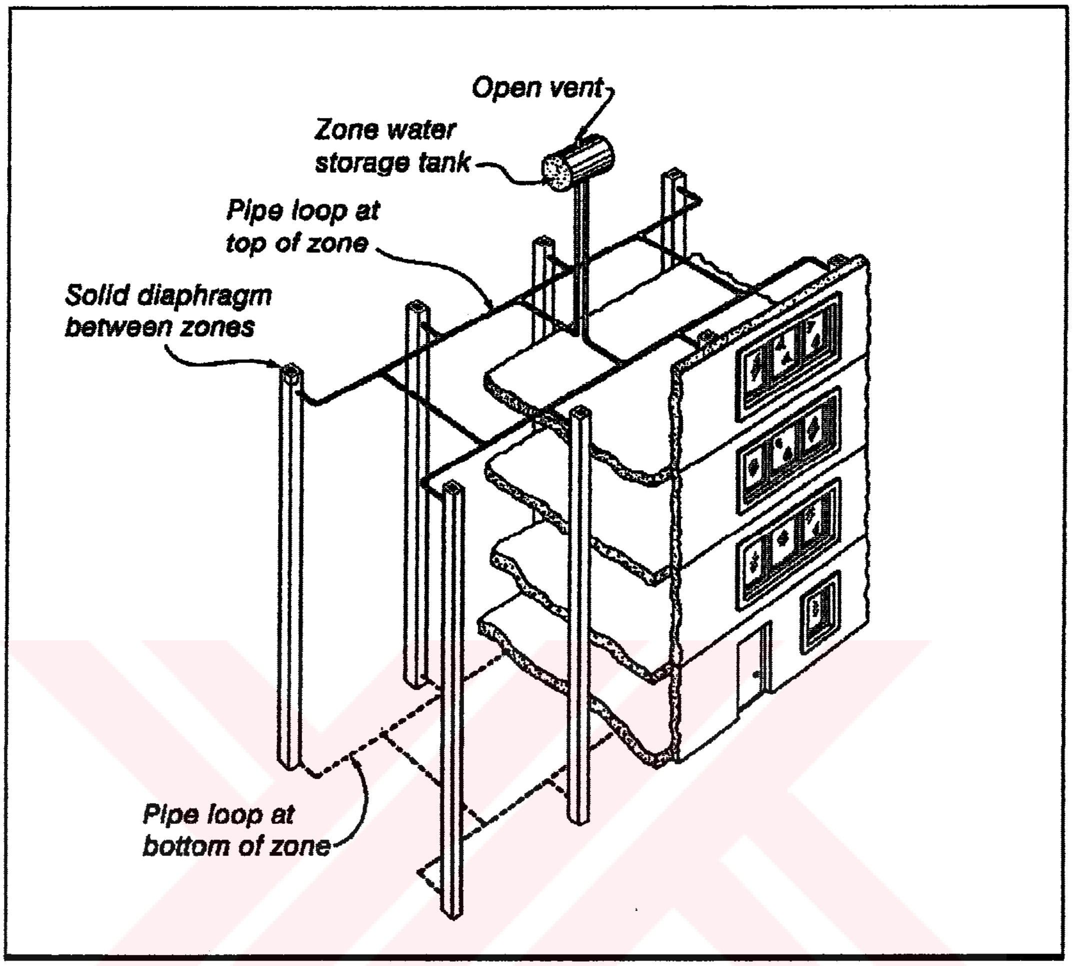


Figure 4.17 Schematic sketch of water filling system

This system has been used in all the buildings so far constructed with water filled hollow steel sections but actually it is not suitable for super tall structures. Many known special steel structures are protected by water filling system like the very famous Pompidou Center in Paris. (Figure 4.18) The primary advantages of water filled protection system are:

- The elimination of coatings results in a reduction in overall column size that providing more floor area.

- Potential savings in the cost of fire protection occur, which tend to increase with the size of the building.
- The structure of buildings can be more clearly expressed architecturally as the steelwork is exposed.
- The columns are more likely to be serviceable after a fire and consequently the insurance cover could be less expensive.

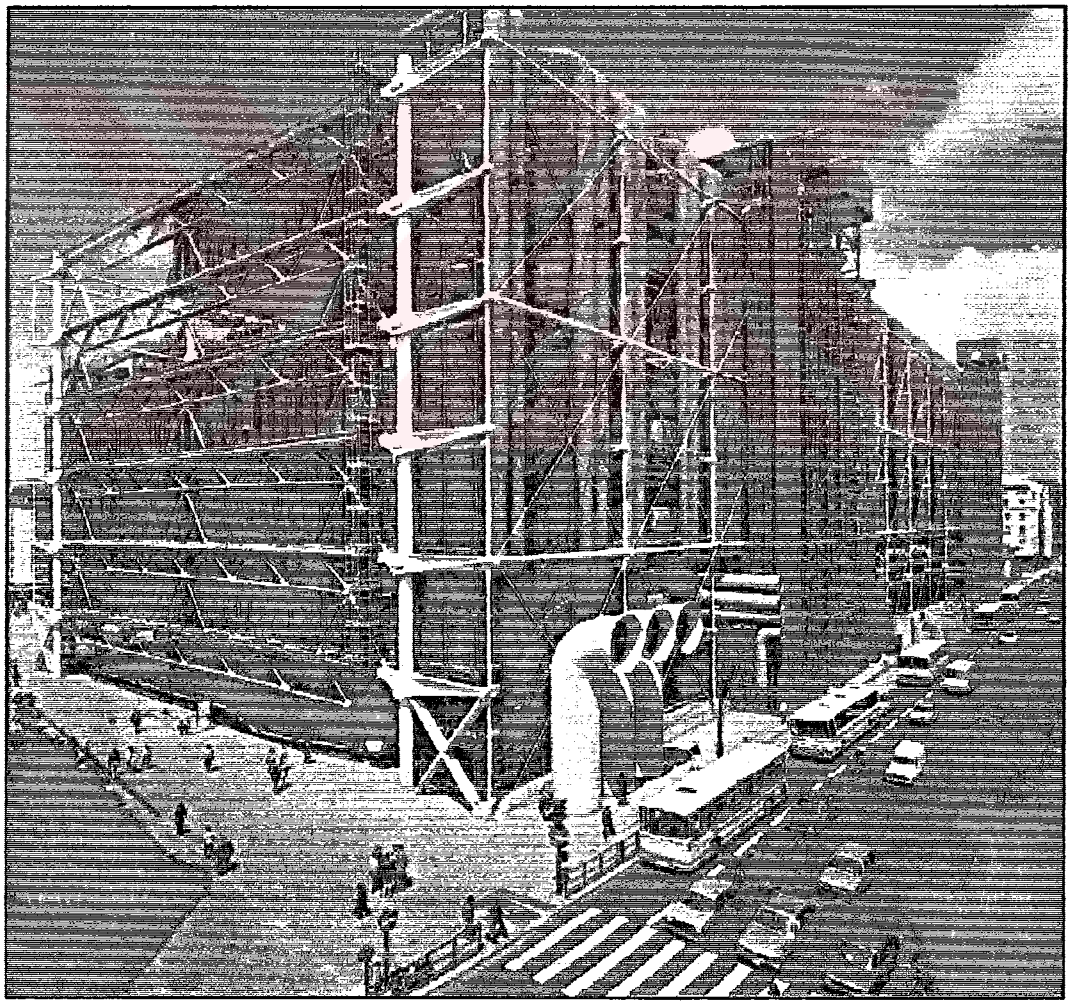


Figure 4.18 Pompidou Center Paris – 1977

4-3- Cost of Passive Fire Protection of Steel Structures in Turkey

In Turkey, structural steel is not a common construction material like concrete for civil buildings; steel is more common in industrial and shopping structures. Parallel to its use, many passive fire protection methods were introduced to the construction material market in the last decades. This diversity brought with it competitive prices. This section of the study aims to show the cost of the several systems available in Turkey, but it should noted that these prices are gathered from the manufacturers and suppliers, only to form an opinion and comparison; not for cost estimation. The total cost can vary according to the project, fire resistance requirement and the type of application. Below four basic types of fire protection systems are compared.

- **Spray-on Systems**

This is the cheapest method with its costs commonly in the range of **13** to **35 € / m ^{2}** applied (2001prices), depending on the fire rating required and the size of the job. Application is fast and it is easy to coat complex shapes or connections.

- **Boarded Encasements**

In spite of its domestic production, board encasing tend to be more expensive, commonly in the range of **18** to **46 € / m ^{2}** (2001 prices) because of the higher labor content in the installation. The price depends on the resistance required and the surface finish chosen but tends to be less sensitive to job size. The systems are dry-fixed by gluing, stapling or screwing, so there is less interference with other trades on site.

• **Intumescent Coatings**

Two types of intumescent coating are currently available. The first one, which is water resistant, has a maximum fire resistance of 2 hours. Its' cost is expensive, costing **96 € / m²** at two hours rating (2001 prices). The second type of coatings has a maximum rating of 1.5 hours. This type of coating is not well resistant to moisture and is not recommended for wet applications but is satisfactory in dry buildings. The costs ranges are from **20** to **42 € / m²** (2001 prices).

• **Concrete Encasement**

Lastly, when compared with these kind of lightweight materials, protection by massive concrete encasing would cost an affordable amount about, **32** to **57 € / m²** (2001 prices).

CHAPTER 5

THE WORLD TRADE CENTER DISASTER

As it is mentioned before the World Trade Center's (WTC) twin towers were the tallest buildings in the world at the time of their opening in 1973. They each stood 110 stories tall and they were the dominant features in an enormous office complex totaling more than one million square meters of office space and together they made up one of the most recognizable structural landmarks in the world.

Today they are reduced to heaps of rubble after one of the worst catastrophes in the entire world history. A pair of jetliners crashed into them on 11th of September 2001, which damaged its innovational structure. The impacts created fires and, ultimately, brought about the collapse of both buildings.

This part of the research mainly deals with the possible reasons for the collapse of WTC, in the light of the data presented in the previous chapters and available information. There are five separate investigations going on at the time of this time; to determine the reasons for the collapse of the WTC. The National Science Foundation (NSF), the American Society of Civil Engineers (ASCE), the American Institute of Steel Construction (AISC), the Council on Tall Buildings and urban Habitat (CTBUH) and the National Fire Protection Association (NFPA) brought experts (engineers architects) together and formed research groups and task forces to study what had happened at the WTC. ASCE findings should be available by April 2002.

5-1- The World Trade Center Twin Towers

Before discussing about the possible scenarios, it is necessary to know some of the technical specifications of the WTC. These are presented in the following pages. The effect of the impacts can only be assessed in light of these details and moreover the reasons that caused different structural fire resistance periods of the two towers can be understood.

5-1-1- General Information

The WTC twin towers were designed by the very famous Japanese architect Minoru Yamasaki and Associates and Emery Roth & Sons Consulting for the owners, the Port Authority of New York and New Jersey, in 1964. Skilling, Worthington, Helle and Jackson were the structural engineers. The site excavation began in 1966 and the towers were finished in 1970 and 1973. Both north and south towers were 110 stories tall and their heights were 417 and 415 meters respectively. They were the tallest buildings in New York City and the 5th and 6th tallest in the world as declared by the Council on Tall Buildings and Urban Habitat. Besides the twin towers, the WTC complex consisted of a 47-story office building (Seven World Trade Center), two 9-story office buildings (Four and Five World Trade Center), an 8-story U.S. Custom House (Six World Trade Center), and a 22-story hotel (Three World Trade Center), all constructed around a central five-acre landscaped Plaza. The total investment done by the Port Authority for the complex was approximately 2 billion USD (2001 prices) . (Figure 5.2)

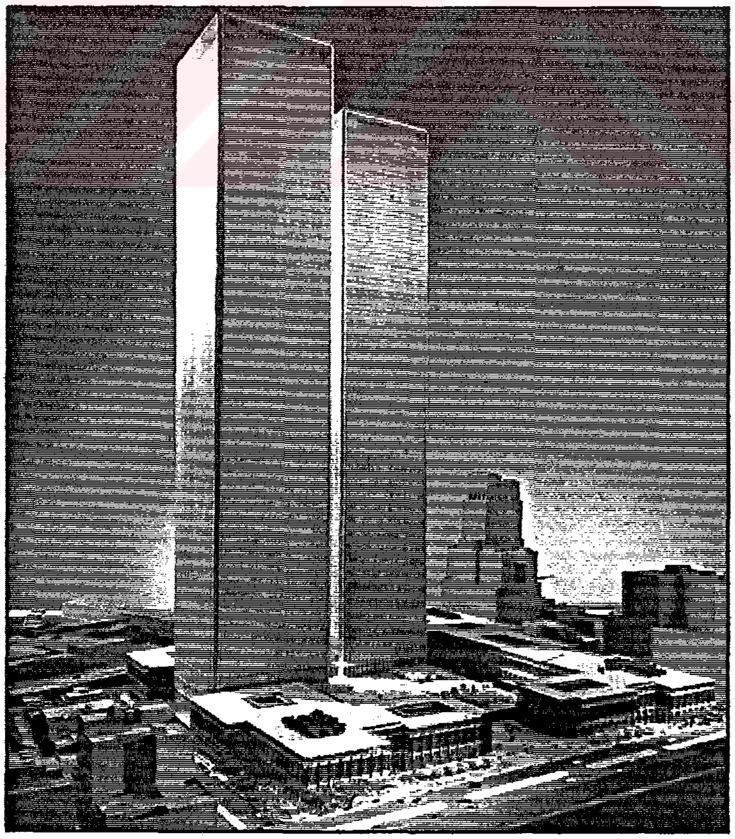


Figure 5.1 Design model of World Trade Center Complex

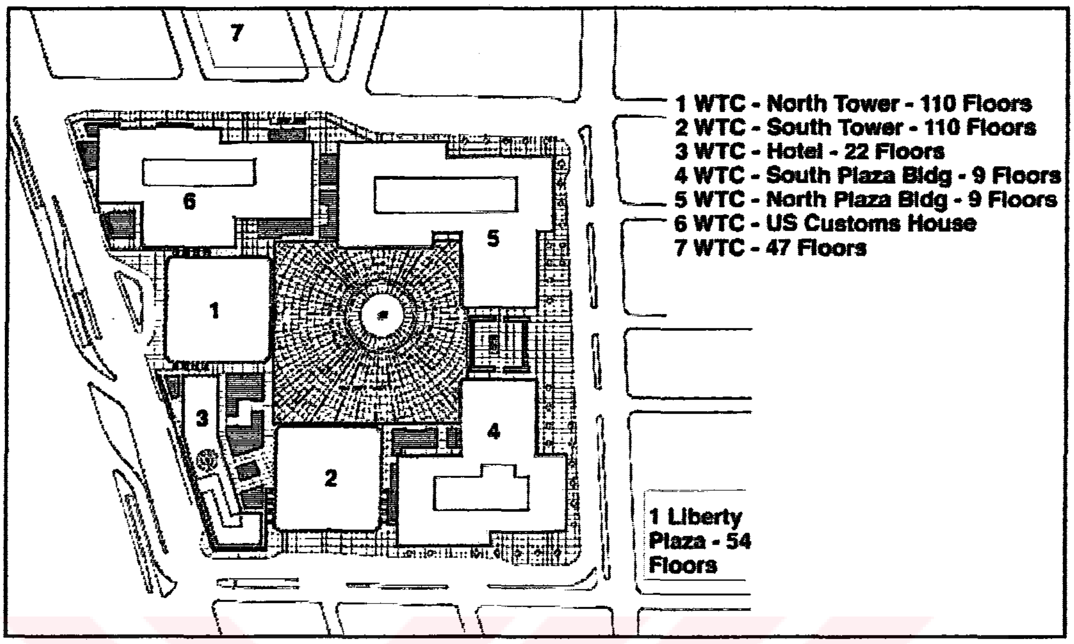


Figure 5.2 Site Plan of World Trade Center Complex

The Center contained approximately 1.115.000 square meters of office space, including the 186.000 square meters of office space in Seven World Trade Center. Each Tower was contained 446.000 square meters of floor area. Some 50.000 people worked in the WTC and another 70.000 business and leisure visitors were entering the WTC daily. Besides their enormous volume the Towers included some architectural and structural innovations that should be considered. [42]

5-1-2- Details of the Towers

Many architectural critics defined the Twin Towers as square, steel shafts clad in aluminum rising from a low cluster of steel and glass buildings. The Towers did not win any architectural awards. There were no architectural embellishments or decorative windows. The only spire was a 100 meters television antenna on the top of the North Tower. (Figure 5.3) As Michael Rockland says in Gillespie's book; "The buildings are tall, and that's all!" [43] Actually, the World Trade Center was a global symbol, instantly recognized to stand for United States, just as the Eiffel Tower or Big Ben stand for their respective countries.

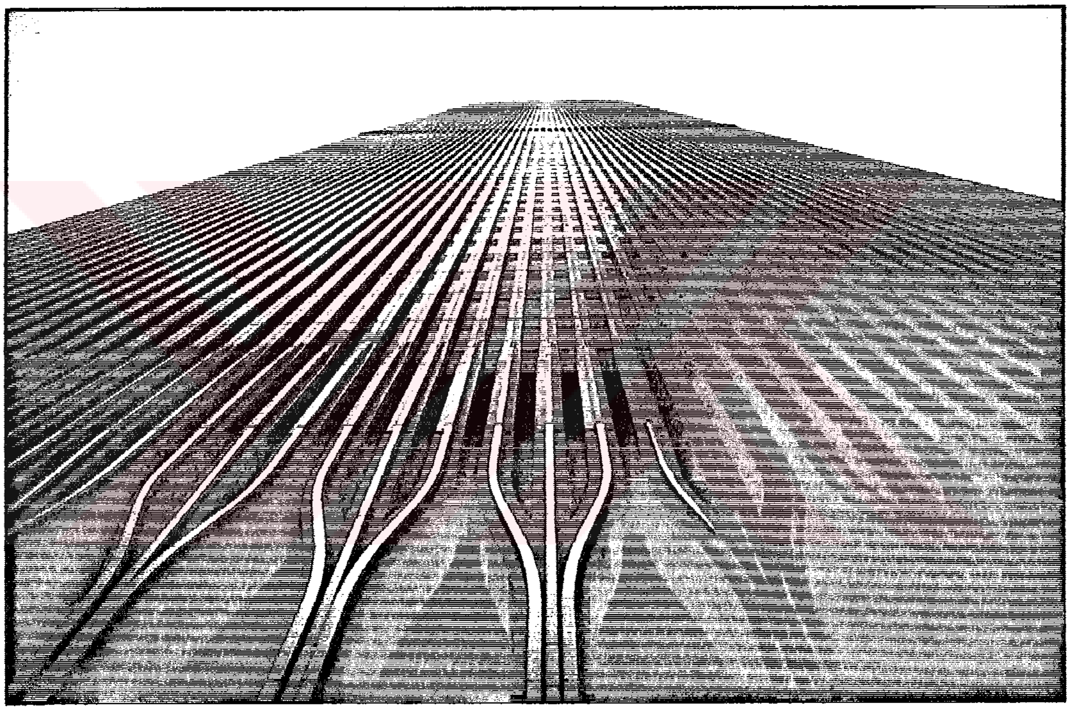


Figure 5.3 Façade Details of Twin Towers

Besides its architectural simplicity, the buildings included two other important technological innovations. Each was a response to a particular problem: the elevators and the structural system. As it is mentioned before, it was the developments of elevators in the first place that led to the construction of skyscrapers, but there was a big problem. The higher you go, the more people in the building. The more people in the building, the more elevators you need. The more elevators you have, the less floor space you have. Yamasaki solved this problem by the unique skylobby system and Twin Towers had 75 percent of usable office space per floor rather than just 62 percent. (Figure 5.5) In this system Yamasaki divided each tower into three zones and designed two more lobbies on the 44th and 78th floors, which were called as skylobbies. People were moving up to these skylobbies by extremely fast express elevators and then transferring from express to local elevators in the second and third zones. Thus, all the local elevators were sitting on top of another sharing a single shaft, which increased the usable space of each floor by 13 percent. [42]

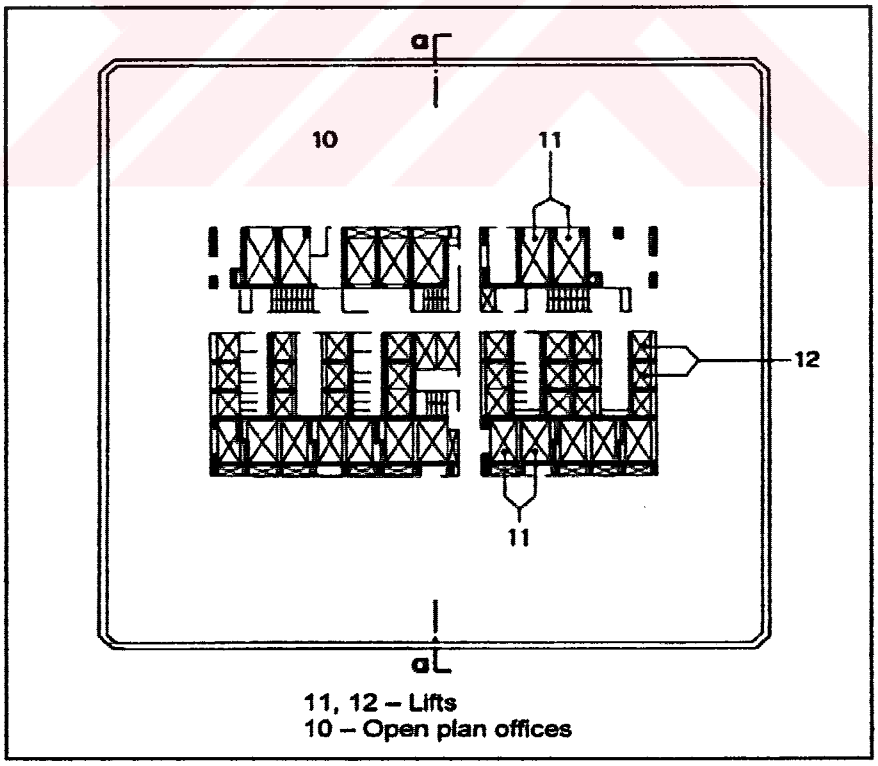
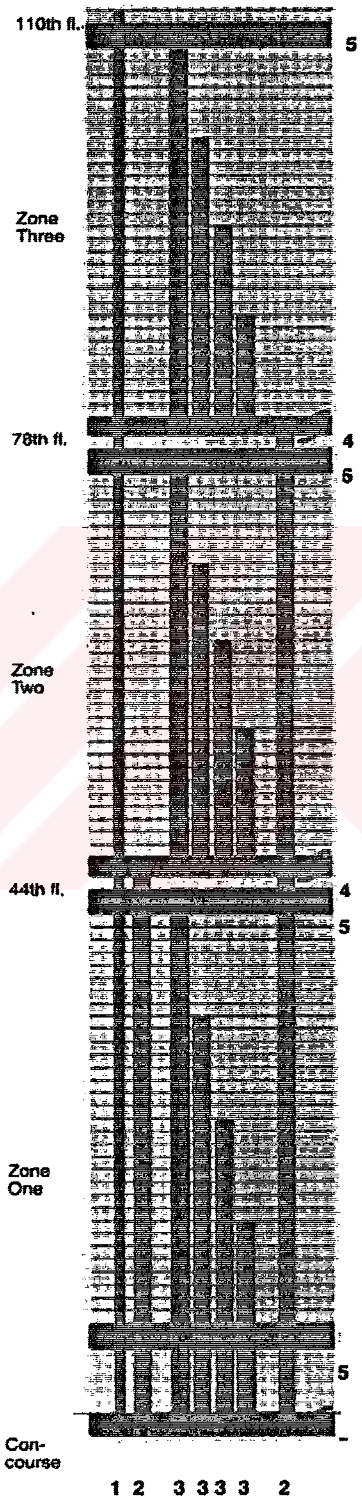


Figure 5.4 Typical Floor Plan of Twin Towers



Elevators: The Unique Skylobby System

Schematic view of Tower building elevators shows how express and local runs are separated for maximum performance—a pioneering translation into the vertical of horizontal mass transportation.

KEY
1 Express to Top
2 Express to Skylobbies
3 Local Service
4 Skylobby Floors
5 Mechanical Floors
Escalators
▮ Floor Stops

Figure 5.5 Elevators: The Unique Skylobby System

The second important technological innovation was the buildings structural system. The system was entirely new and different from the other conventional high-rise buildings. Until that time, the usual skyscrapers had been built with interior supporting columns that forms a skeleton for the structure. The exterior walls were just "curtain walls" that admitted the light and kept out the rain. But in the Twin Towers, a new type of system was introduced to build a higher and also lighter building. This structural system is called "steel-framed tube." In this type of system, the perimeter columns and beams form a closely spaced grill of steel that runs along the full height of the building. This lattice is connected to the internal frames, which had fewer columns. The outer lattice acted like a tube, which was very strong in torsion and strong against wind and gravity loads. (Figure 5.6) [6]

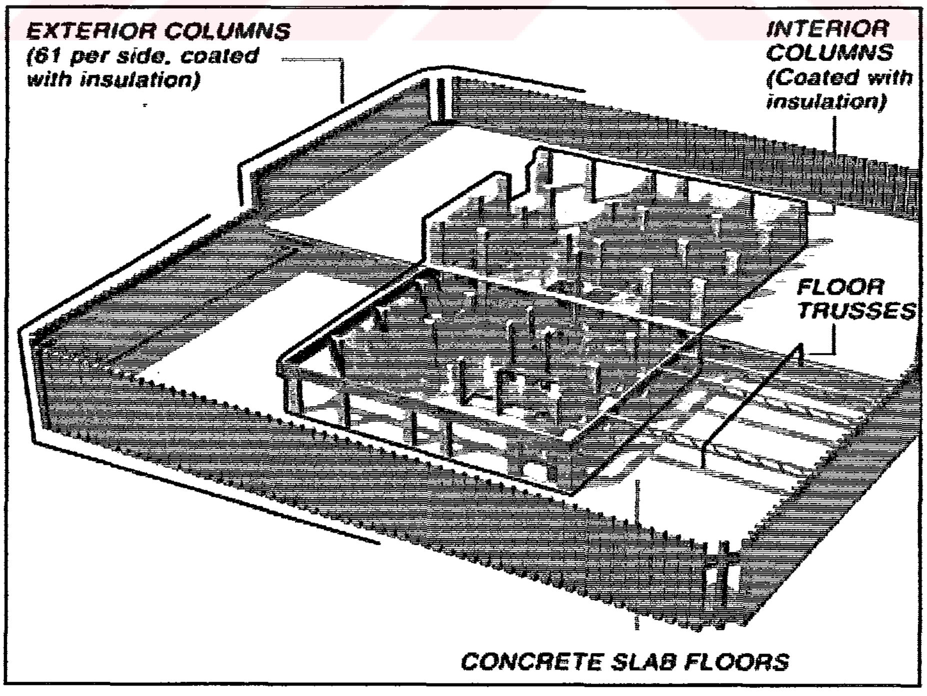


Figure 5.6 Isometric View of the Steel Framed Tube Structure in WTC

The Twin Towers was one of the best examples of steel-framed tube system. This system was accomplished by the use of 87.000 tons of high-strength steels in each Tower. Each tower was 63.5 m x 63.5 m in size and the cores were 24 x 42 meters square on plan. On each façade a rigid moment resisting frame was formed comprising of 61, 450 x 450 mm size box section exterior columns, (Figure 5.7) spaced at 1.02 meter centers, connected by deep spandrel beams. The frames did not run into the corners, however, there a shear connection between the two adjacent frames was provided so that the frames, together with the floors, formed a torsionally rigid framed tube fixed to the foundations. This framed tube was designed to withstand winds with speeds of 100 mph and higher. [44]

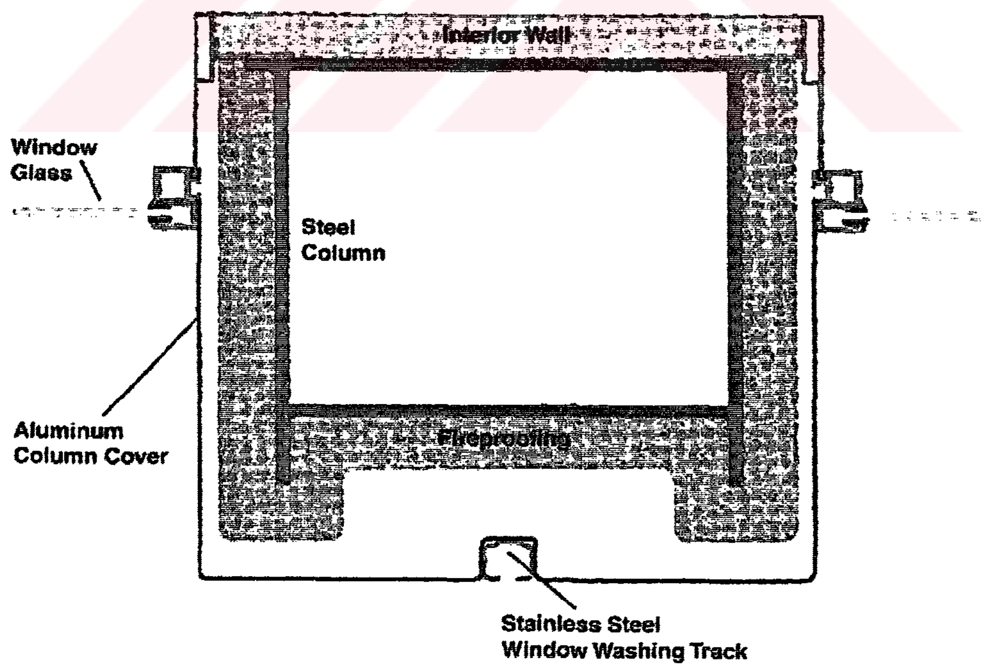


Figure 5.7 Plan View of Perimeter Columns

The floors spanned 18 meters without intermediate columns. They were supported by joist beams, which rested on 47 heavy columns of box section. The interior columns were designed to carry 60 percent of the total vertical load. The core contained the elevators, stairwells and mechanical equipment. The floor system comprised of 900 deep bar joists spaced at 2.04 m centers and braced by secondary joists. These secondary joists supported metal decking, which in turn supported a 100 mm thick lightweight concrete slab. The top of the bar joists stood above the soffit of the decking and were cast into the concrete slab to make the bar joists composite.

The bar joists spanned between the perimeter frames and the core, as shown in Figure 5.8, and Figure 5.9 shows an isometric of part of the floor and exterior wall, illustrating some of the details described above. The gravity and lateral load-resisting systems were designed to deliver the strength and stiffness with minimum dead load. This was achieved, with a steelwork weight of only 44.5 kg/m^2 floor area. [44]

5-1-3- Fire Resistance of the Towers

According to the requirements of existing building codes and standards in Manhattan district, nearly all known passive and active fire protection systems were provided in the buildings. For active measures, both monitoring systems and

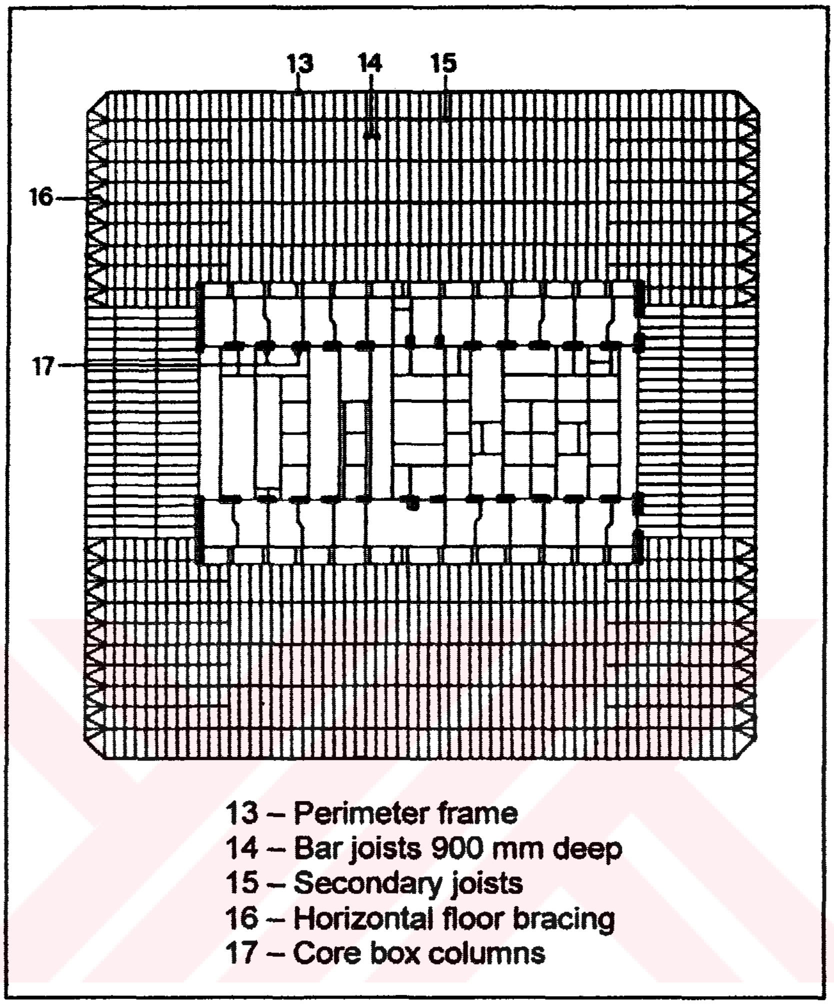


Figure 5.8 Structural System Plan for Typical Floor

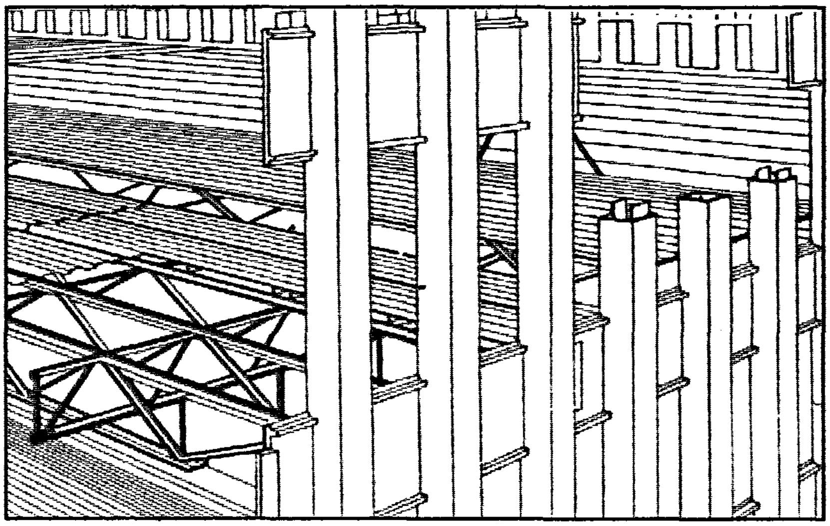


Figure 5.9 Isometric Views of Floor and Exterior Wall System

extinguishing systems were installed. But unfortunately, the fire suppression system in the towers did not include the foam sprinklers that could deal with the jet fuel fires.

In fact, fireproofing of the Twin Towers had a questionable history. The product specified for the passive protection on the structural steel members was SFRM (Spray Applied Fire Resisting Material) Cafco Type D. But in 1969, just as application was well under way on the North Tower, the use of Cafco Type D containing asbestos had come under investigation by Environmental Sciences Laboratory (ESL) and this research proved, what medical researches had long suspected, that asbestos caused cancer. As a result, the Environmental Protection Agency (EPA) issued a restrictive set of standards covering the spraying of asbestos containing materials. The EPA was especially concerned because in the spraying process as much as 50 percent of the asbestos escapes into the air. [45] By this time, construction had already reached the 34^{th} floor (Figure 5.10). A difficult decision was made to stop using fireproofing with asbestos and change all of the spray in the WTC, at the huge cost of 300.000 USD. Fortunately, a new type of asbestos free SFRM came on the market by Cafco called as Blaze-Sheild, at that time.

However problems were not solved with this decision. Wind-driven rains peeled the fireproofing from the steel members it was meant to protect and workers had to improvise dams and diverters to channel the water. Then, the fireproofing was reapplied. Over 12.000 tons or 480.000 bags of Blaze-Shield were used in the two 110 story Towers. The spray-on mineral wool fiber had a density of 11 to 15 pounds per cubic foot, which gave the steel members a fire resistance rating of 2 hours (F 120) under ASTM test conditions. [46]

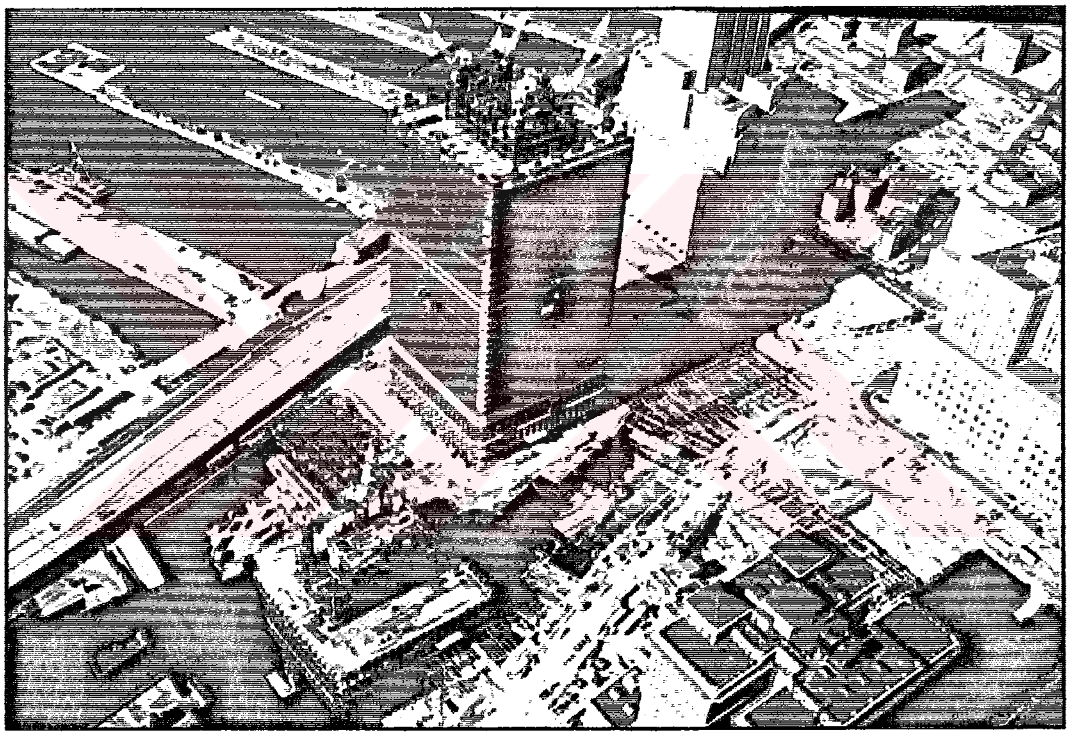


Figure 5.10 Situation of the WTC Site on September 1969

5-2- The Impacts

The Twin Towers were the target of an attack before. On February 26, 1993, terrorists planned and carried out a truck bombing in the parking garage. The weapon was a 600-kilogram bomb loaded truck. Six people died and more than

1,000 were injured in the attack. The explosion created a five-story crater beneath the building, but the structure held. On September 11, each tower was hit by a hijacked Boeing 767. The attacks appeared to be coordinated and in parallel. Both planes were hijacked en route from Boston to Los Angeles but owned by two different Airlines Companies. The first one, which was the American Airlines plane, hit onto the North Tower (WTC One) with 92 passengers on board at 8:45 AM local time. The second one, which was the United Airlines plane, hit the South Tower (WTC Two) with 65 passengers on board at 9:06 AM local time.

The impact on the North Tower was near the center of the north face between floors 94 and 99. The plane hit the building at 90° (Figure 5.12). The impact on the South Tower was some 15 stories lower about between floors 78 and 84, with the plane hitting the South face near the South East corner and impacting at an angle to the face of the tower. Figure 5.11 shows the impact directions and crash zones on both Towers.

Boeing 767 is a plane with a 47.5 meters wingspan and 48.5 meters length and can weigh a maximum of 200 tons. (747's are more than 60 meters long and can weigh 400 tons.) Unfortunately the planes were at the very beginning of their long journey and each were full of jet fuel about 68.000 liters (50 tons).

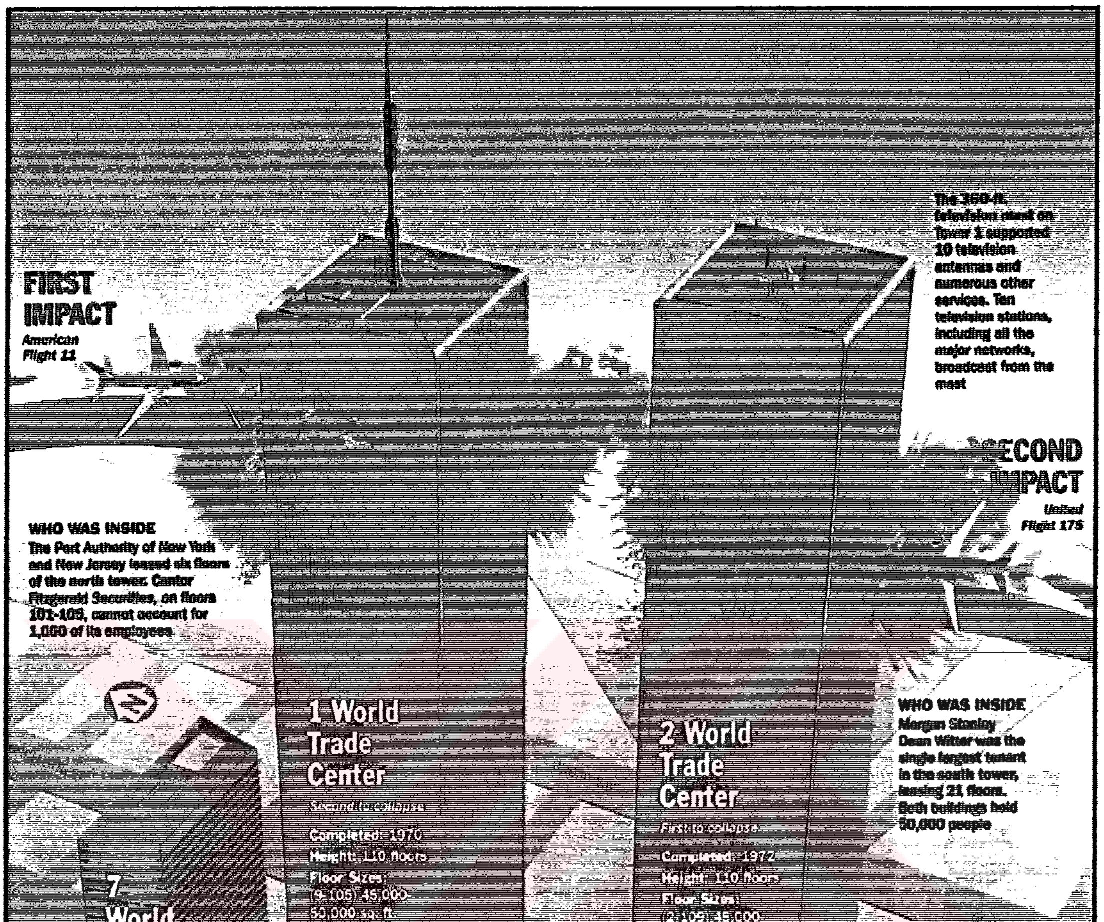


Figure 5.11 The Impact Directions and Crash Zones on Both Towers

The potential force of the impact from each plane can be approximately calculated and the figures are very large. The weight of each 767 plane is approximately 200 tons according to the Boeing data. The plane would have been traveling at around 800 km/hr at the moment of impact. This gives a momentum of (200 / 9,8) x 800 / 3.6 = 4,535 tons.m/sec. If the plane was stopped by the building in 1.5 seconds, then the force exerted on the building is the momentum / time to arrest, i.e. Force = 4,535 / 1.5 = 3,023 tons = 30,230 kN. To put this value in perspective, the ultimate limit state (ULS) design wind pressure over the entire height of the building is 1,5 kN/m^2. This gives a ULS wind force on one face of the building of 42,862 kN. Thus the potential force of impact from the plane is about % 75 of the design ULS wind load on the building.

Especially in the case of the North Tower, not much of the plane was ejected from the building, so it is reasonable to assume that the building absorbed most of that potential force. Also the above calculation does not take into account any additional force generated inside the building from blast loading due to the exploding jet fuel. [47] Having done this calculation it is easier to understand the wings, slicing through the perimeter columns "like a knife through butter" as one reporter has stated. (Figure 5.12)

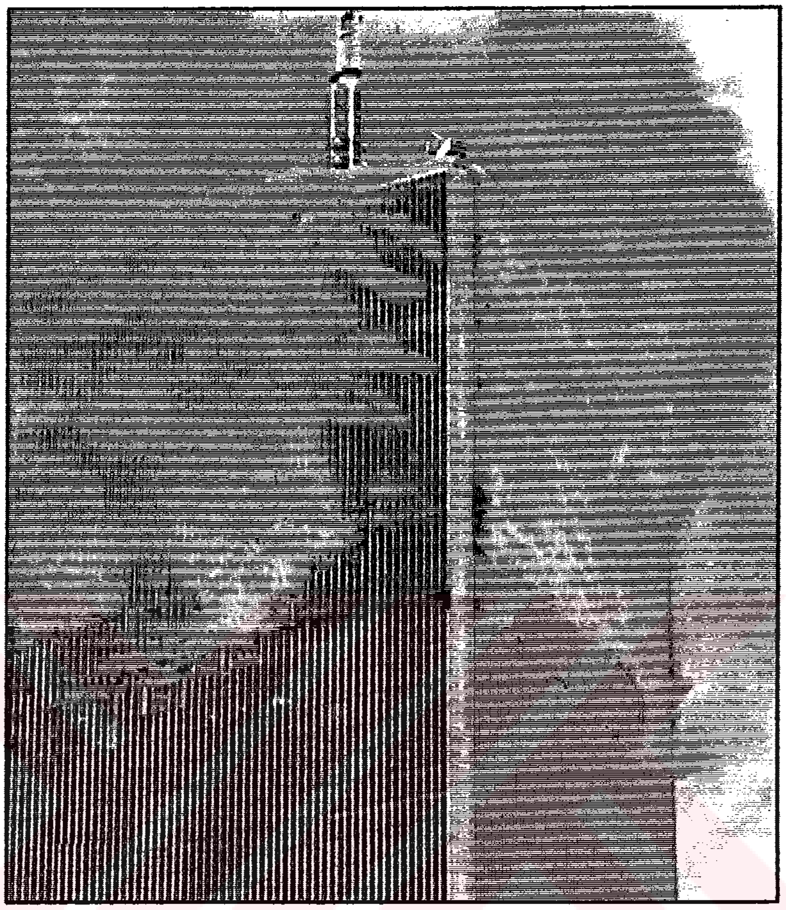


Figure 5.12 A Close View of the Perimeter Columns of North Tower After Impact

It appears likely that the impacts of the planes crash destroyed a significant number of perimeter columns on several floors of both building, severely weakening the entire system. Initially this was not enough to cause collapse. Having penetrated the perimeter columns, the planes would have done much more than just stripping the fire protection off the columns. The effect would have been to completely shatter and eliminate large areas of floor slab and many of the internal supporting columns, thereby immediately destroying much of the vertical load carrying system and leaving the rest vulnerable to any subsequent fire attack.

However the nature and position of impact was different in each case and this led to different effects on each tower, with different collapse mechanisms. Despite the fact that each Tower had showed the same type of collapse behavior, the time difference between that each building stood before collapse was attracted attention. The North Tower, which received the first impact, collapsed at 10:29 AM and stood for 104 minutes. The South Tower collapsed at 10:00 AM and stood for 54 minutes after the second impact.

Figure 5.13 Fireball from Impact on South Tower

There is more than one reason to explain this situation. The video shot in Figure 5.13, shows the plane disappearing into the building followed by a fireball erupting from the East and North sides of the building and out from the opposite side on the South façade. Subsequent video shots and photos of the North side (the side opposite to the impact) show a large amount of façade destruction and smoke being discharged. This shows that a considerable amount of material erupted the building on the opposite side of the impact. The other reason was that the impact zone of the South Tower, which was much lower than the North Tower impact zone. This meant that there was much more weight bearing down from the damaged floors, which initiated the progressive collapse in a shorter period of time.

One other reason that was announced by the U.S government is, according to the calculations, the plane that hit the South Tower had been flying faster, at 937 km/h, while the first plane to hit, was traveling at 790 km/h. The energy of motion carried by any object, called the kinetic energy, varies with the square of its velocity. Thus even modest differences in speed can translate into large variations in the impact load. That means that while the second plane was traveling only about a quarter faster than the first plane, it would have released about 40 percent more energy on impact. [48]

5-3- How Severe were the Effects of Fires ?

Before dealing with the question "How Severe were the Effects of Fires ?" one of the questions that should be answered is, "Would the building, as damaged structurally, have collapsed if there had been no fire ?" The answer should be NO, because the towers did not collapse upon impact, in fact the North Tower stood for an hour and forty-five minutes after it was hit.

There is a consensus among the worlds' renowned fire and structural engineers from across United States and around the world that the jet fuel about 50 tons per plane, spilled and immediately began burning at a degree of 1080°C (2000°F) which is much higher than those of ordinary office fires. As it is mentioned in Chapter 3, steel begins losing much of its tensile strength and so begins to deform and buckle under loads at roughly 600°C. It was proven by the remaining deformed steel members that, in some places inside Towers the temperature rose raised above 1000°C within seconds (Figure 5.14) In minutes the heat should be spread by air and by conduction through the steel itself.

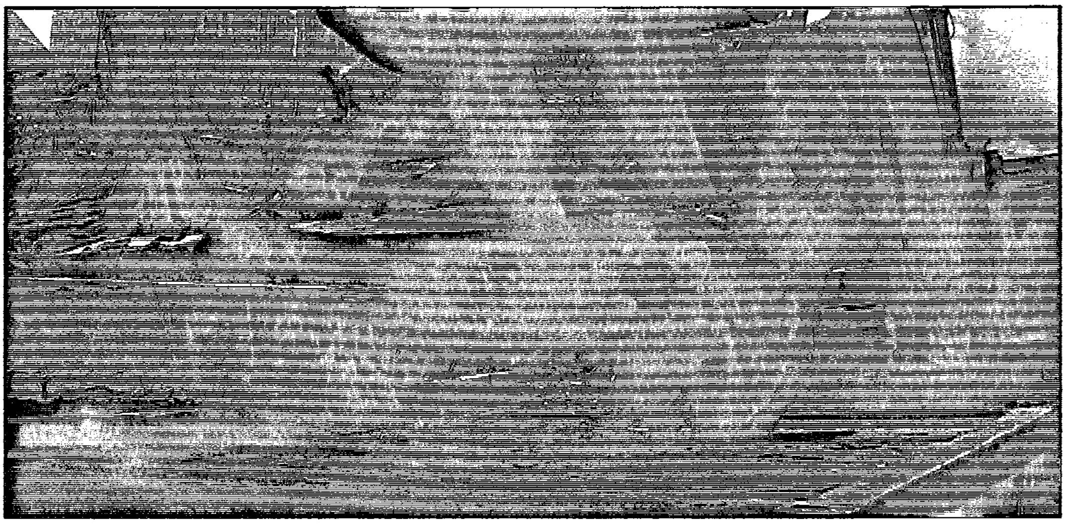


Figure 5.14 Deformed Steel Elements Shows the Severity of the Fire After the Impacts

It is also important to understand that commercial Spray Applied Fire Resistive Materials (SFRMs) were tested in accordance with UL 263 Time Temperature Criteria (Figure 5.15). Under UL 263, furnace temperatures reach 1000°F (540°C) at 5 minutes, 1550°F (837°C) at 30 minutes, 1850°F (999°C) at 2 hours, 1925°F (1040°C) at 3 hours and 2000°F (1080°C) at 4 hours.

More typical of a "Jet Fuel Fire" yet still not as severe as the WTC explosion and inferno is the UL 1709 hydrocarbon fire standard. This is utilized in petro-chemical plants where temperatures are raised to 2000°F (1080°C) in 5 minutes in the test and are maintained at elevated temperatures through the duration of the fire test. [46]

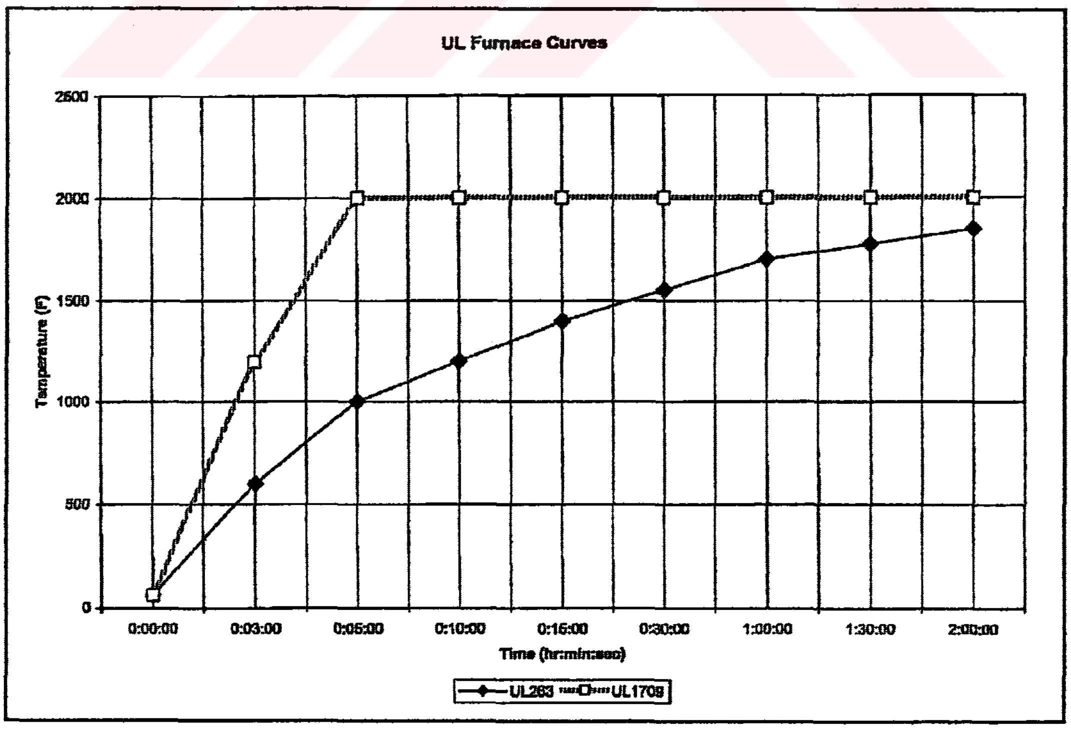


Figure 5.15 UL Time – Temperature Curves

Despite the external forces, the SFRM fireproofing of both Towers performed beyond expectations thus, providing valuable time that saved thousands of lives.

5-4- How did the Towers Collapsed ?

The Twin towers were well engineered and, as it is known that they are very well built. It should be noted that, only a containment building at a nuclear power plant is designed to withstand such an impact and blast. In the WTC disaster the fire after impacts, further damaged all of the support columns. (Figure 5.16) So it was a two-step event; initial damage by plane and further damage or subsequent loss of structural stability due to fire that caused the collapses. The high-strength light steel members heated up first, and in the next 20 – 30 minutes, the floors began to sag between the interior and exterior columns. The steel trusses were particularly vulnerable because their Section Factor (P/A) is large, causing them to heat up quickly. Extreme heat softened the steel and reduced its ability to support of the floors. As the floors weakened, they lost their connections and they tore away from the core and exterior columns. Having lost their lateral support, the exterior columns, already softened by the fire, failed catastrophically. The top portion of the building plummeted and the progressive collapse like a domino effect was finished in 12 seconds. (Figure 5.17, 5.18) A stone dropped from the top of the tower would have taken 9.2 seconds to fall to the ground.

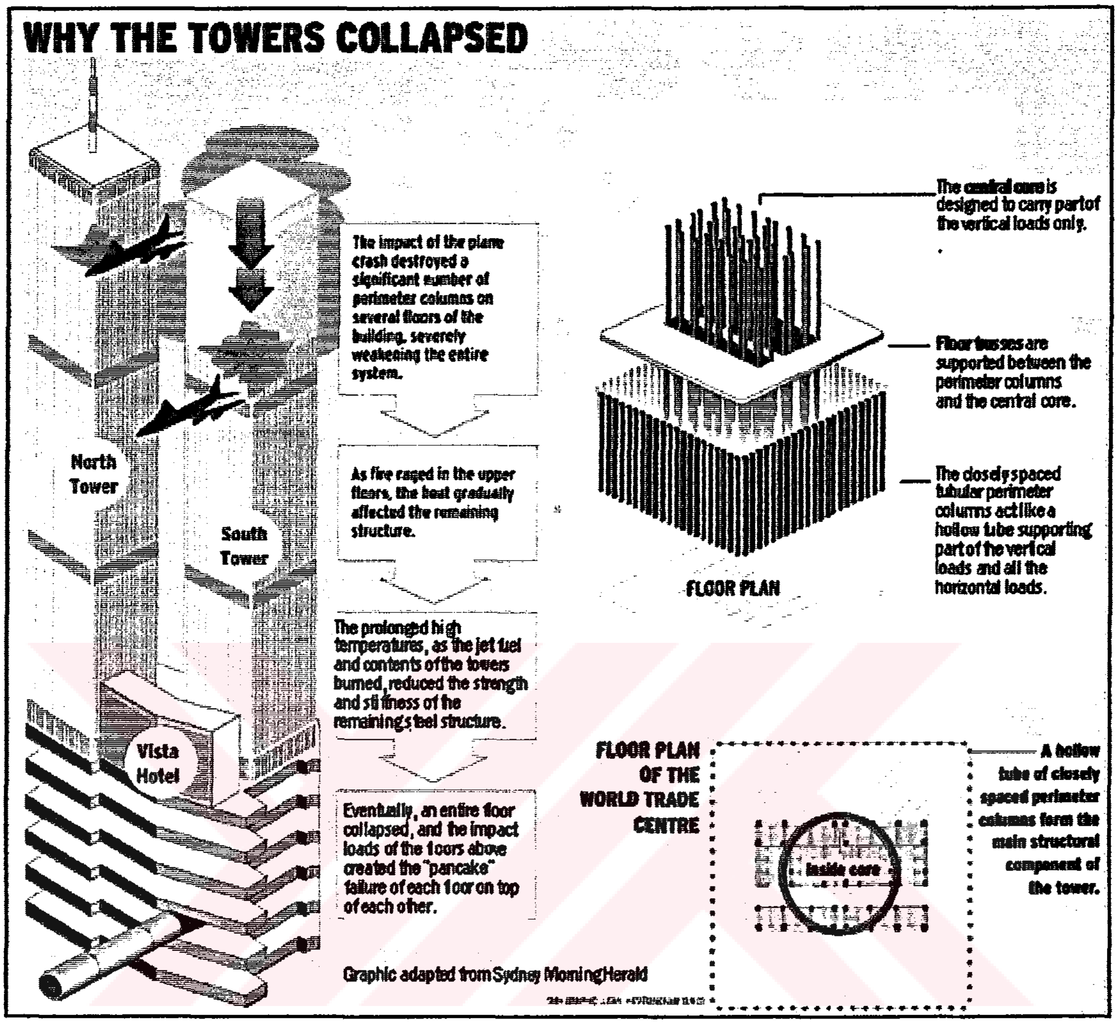


Figure 5.16 Overall Development of the WTC Disaster

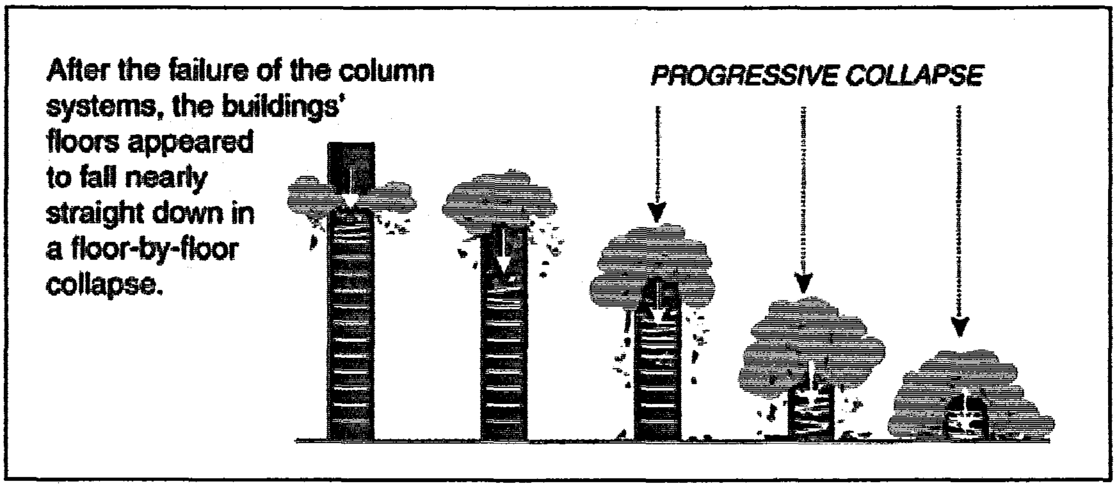


Figure 5.17 The Progressive Collapse of Each Tower

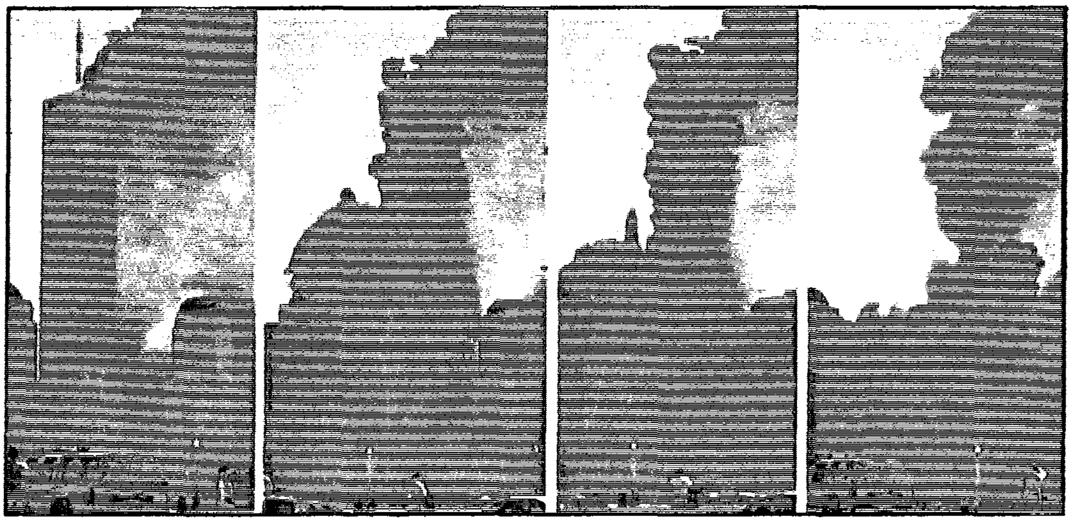


Figure 5.18 Sequence of Collapse of North Tower Recorded by CNN

The WTC disaster taught the authorities several lessons. First one is that the conventional structural fires are meant to be fought in localized areas. In other words, if a fire breaks out in the 15th floor, the sprinklers should go off on the 15th and 16th floors and so on. However in this case it was not a conventional fire. There were damages of planes and there were fires located on 15 to 20 different floors. So there was never enough water or even sprinkler system to arrest the fire to prevent structural soundness. In spite of all the negative conditions, the sprinkler systems at lower floors were working after the impacts. This could be observed from the photos taken inside the building by people who were able to escape.

The second fact is the required time to evacuate the high-rise buildings. For example, the egress time for the Twin Towers was approximately two hours and that is why the fire authorities have requirements for fireproofing buildings for

for one or two hours to allow an orderly discharge. Had the building collapse occurred two or to four hours after the initial impact, they would have been able to evacuate everybody.

CHAPTER 6

CONCLUSIONS

In this research, it is aimed to clarify the fire problem of high-rise steel structures with all respect and the reasons that constitute the World Trade Center Disaster according to the existing information and data collected. In order conclude by the end of this research the 10 items below can be listed in order:

1. Fire hazards are of crucial importance in steel structures and have to be reduced to a minimum. This is provided by strict adherence to standards and codes. Eurocode 3 and NFPA 220 are such codes.

2. Fire precautions in developed countries aims to:
   - reduce the probability of fire starts,
   - prevent or slow down the spread of fires,
   - provide the safe evacuation of buildings,
   - facilitate the interference of fire brigades and first aid services.

3. In order to achieve a fire safe structure, designers must consider:
    - the choice of structural and finishing materials,
    - the location of structure,
    - the distance between the neighboring structures,
    - the degree of fire resistance according to the function and properties of the building, (those should be clarified in regulations)
    - the type of passive fire protection method,
    - the monitoring systems,
    - the smoke control systems,
    - the extinguishing systems,
    - the design of escape routes.
4. There is no existing comprehensive national fire safety regulation and codes in force in Turkey. Only several city government restrictions exist and the Regulations on Protection of Buildings Against Fire by General Directorate of Civil Defense for Turkey is in prepare at moment. But these are far from being comprehensive and do not cover special data and restrictions about high-rise steel structures. Such a strict code must go in to effect as soon as possible.

5. As one of the most important materials used in building structures, steel has no resistance against fire. Steel looses half of its strength at 500°C. For this reason it must be protected by passive measures.

6. The rate of temperature rise of a protected or unprotected structural steel member exposed to fire depends on its 'section factor' (P/A), which is a measure of the ratio of the heated perimeter to the area of the cross section of the member. It can also be stated that, the more massive the section, the more energy is needed to heat it. This factor is necessary to calculate the thickness of the fire insulation according to its method.

7. The most common fire protection methods to protect steel structures in the world are:
   - concrete encasements,
   - board encasements,
   - spray-on systems,
   - intumescent coatings,
   - water-filled steel structural systems.

8. Among their fire protection measures:
   - Concrete encasing adds on a considerable amount of dead weight to the high-rise steel structures buildings and takes more time for installation when compared to the other coatings. But on the other hand, concrete strengthens the load-carrying ability of the steel and also protects against corrosion.

- Board encasement systems have the advantages of easy installation in a dry process and easy finishing with decorative materials but have disadvantages like slow installation, and high cost.
- Spray-on systems are the cheapest and the fastest applicable type of passive protection for high-rise steel structures, but the process is usually wet and messy and the spray-on materials are rather soft, so that they have to be protected from damage and also the resulting finishes are not suitable for decorative finishing.
- Intumescent coatings are usually preferred in situations where the shape of the steel structure remains visible but the high cost, and lower duration fire resistance ratings are their main disadvantages.
- Water filling the steel structural systems is usually preferred in order to clarify and express the structure of buildings as architecturally. But it is not suitable for high-rise steel structures.

9. The variable relative costs of these methods in Turkey according to 2001 prices are:

   - concrete encasements : 32 to 57 € / m²
   - board encasements : 18 to 46 € / m²
   - spray-on systems : 13 to 35 € / m²
   - intumescent coatings : 20 to 96 € / m²

10. It is an undeniable fact that the effect of the impacts of the jetliners on the World Trade Center Twin Towers was enormous but the main reason that caused collapses was the Jet Fuel Fire that as severe as the hydrocarbon fire standard which is utilized in petro-chemical plants where temperatures are raised to 2000°F (1080°C) in 5 minutes.

It should also be stated that, besides the 2.830 deaths in this terrifying disaster, the approximate remaining 47.000 rescuers owe their lives thorough to the strict fire regulations, codes and standards.

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