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Fire Protection of Steel Structure: An Overall Review

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ABSTRACT

Structures should be constructed in a manner that it becomes stable in the occurrence of fire. Most materials reduce the inherent resistance at the time of the fire. So to ensure the safe design, this resistance should be maintained. This paper summarizes the overview of existing fire protection systems, performance of steel at elevated temperature and factors affecting it. Also explain about experimental and analytical methods to predict the behavior of steel structure at the time of the fire and reviews the present applications of fire protective building throughout the world. This paper also tries to figure out the existing gap of the present knowledge and find out some recommendations for the future.

***Keywords*:** Fire protection systems, performance of steel and behavior of steel structure

1. INTRODUCTION

Fire protection is essential for the structural safety. As combustion occurs fire transfer energy to transient portion from stable condition. Proper fire design consideration delays the energy transfer and gives time to audience before failure. Fire loading is the main issue of the structural failure and in that case compertmentation is the way of fire localization [1]. This paper focuses on fire protection systems exist in the present study and find out its merits and limitations. The objective of this study is to revisit previous research of both unprotected steel and composite steel beams with idealized connections, to study the different methods of

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fire protection, investigate the previous cases of fire affected structures, investigate some properties and fire related tests of steel structures, investigate some practical fire protected steel structures. There is a limited number of researchers have been carried out based on fire test because of its cost [2]. For that reason to identify the behavior of steel under fire and creating the model based on the results progressing at a very slow rate.

2. STRUCTURAL STEEL EXPOSURE TO FIRE

All the materials reduce their strength when subjected to fire but steel can recover strength for incombustible nature. When steel exposes to fire it absorbs thermal energy, after a certain time of cooling it returns either stable or unstable condition [3]. During this heating and cooling operation the members may be

- Scrapped due to large deformation,
- Perfect for its straightness behavior after fire exposure,
- Reusable by straightening.

2. 1. Fire Loads And Fire Rating

The combustible elements which are generated the ultimate heat in a structure is termed as fire load [4]. Nowadays in the building design the rate of fire combustion material is concerned. Any structural elements mainly design to resist this fire, if it crosses the limit it will fail and collapse by losing strength. Fire rating is determined according to the fire safety of the building. Fire loading and fire rating are correlated in terms of the design issue. Fire rating is proportional to fire load and it depends on the combustible material and ventilation factor. From the following figure we can demonstrate that fire rating of unprotected steel is higher than the protected ones.

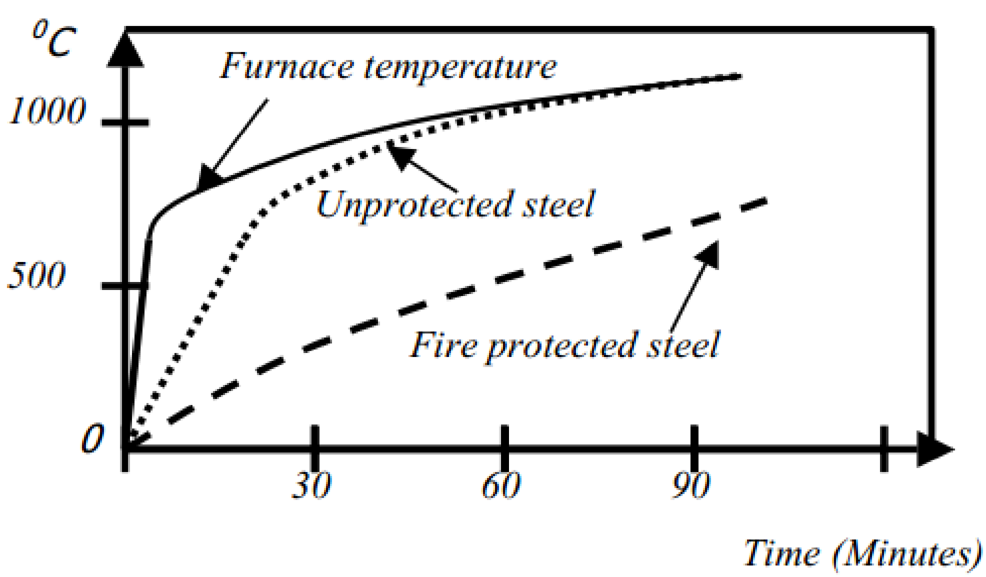


Figure 1. Rate of heating of structural steel work [4].

2. 2. Thermal Expansion

Thermal expansion is the property to indicate the time of heating of the structure. Variation of the thermal expansion is the cause of failure and this effect is more essential in case of fire. It is the main cause of additional pressure on connection and it creates sagging of the structure, when cooling down it tries to return its original stage and creates buckling [5].

2. 3. Ultimate Strength

Exposure to fire the mild steel represents the following pattern shown in Figure 2.

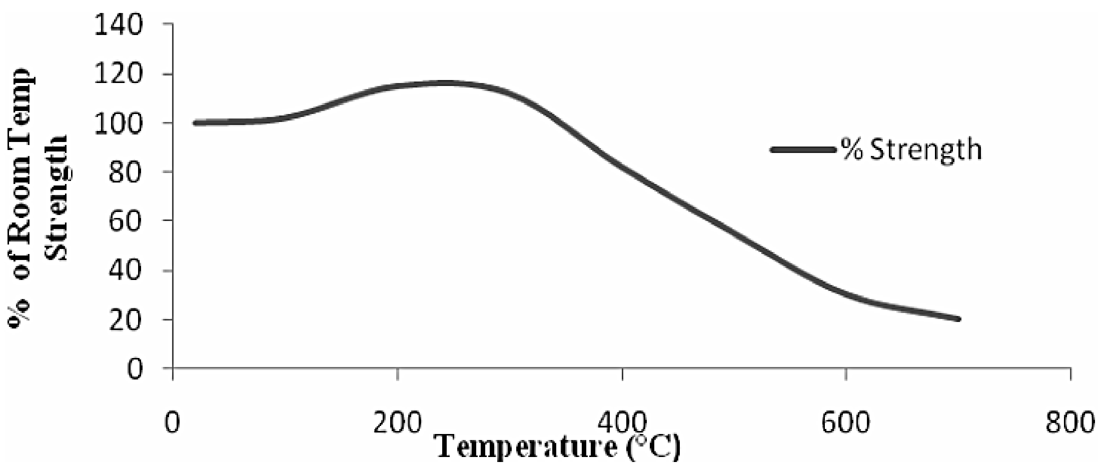


Figure 2. The relative strength of mild steel as a function of temperature to that of mild steel at room temperature [5].

As the temperature increases the strength of the material decreases and increases about 10% as the temperature at 200 °C and 350 °C it is almost at room temperature rise to 550 °C the strength will be half of the initial strength.

2. 4. Modulus of Elasticity

It is deformed by the application of force, Modulus of elasticity of steel usually 230×103 MPa. This value decreases with the increasing temperature.

2. 5. Factors Influencing The Behavior of Structural Steel In The Fire

- **Loading:** Loading is one of the major factors which affect the behavior of steel structure. Decreasing the applied load on the structure the fire endurance and temperature increases. If the applied load crosses the limit or reach the ultimate strength it creates failure. So, it always is lower to increase the fire resistance of structure [6].
- **Connection:** The connections of column to beam in modern steel buildings are generally designed with shear connections. Bracing element resists the forces. If the

structure deforms because of fire loading moments are transferred to connection due to reduce the moment at mid span. Due to this, it increases the load ratio and fire resistance of the beam [6].

- **End restraint:** Deflection and fire resistance of steel structure depends on its end restraint. For the same fire loading, the simply supported beam survives more than the rotation end restraint. Application of extra axial load on the beam increases the deflection and further heating it decreases the deflection [7].
- **Interaction effect:** It is the effect of the different elements of the whole element. Interaction creates a great bonding between the metals and the damage of a material is not a big deal in that case as the subsequent matter can sustain the load which is applied through the load path [8].
- **Localization:** Compartmentation is the way of localization of fire in buildings. Thermal expansion in the heated parts can extend the instability which can divert the load and weakling the members [8].
- **Tensile action:** It occurs in the composite section of the steel framed building. When steel section resists the load, crack initiates in the concrete portion. It improves the resistance of a structure to provide an alternative load path and also minimize the need for fire protection [8].
- **The distribution of temperature:** It mainly varies along the cross section or the length of the member. Variation of temperature in section shows better resistivity than the uniform distribution of temperature [8].

2. 6. Fire Design Consideration

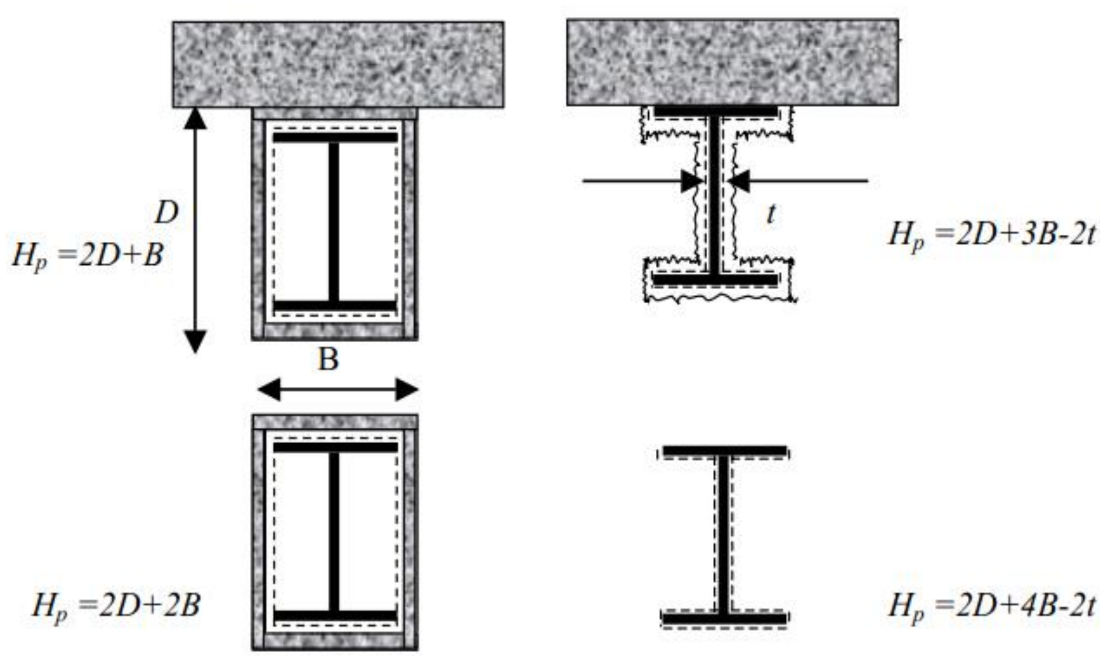


Figure 3. Typical values of HP of fire protected steel sections [9].

The main basic of the fire engineering is to give adequate time to escape the audience before failure of the structure. There are two methods for fire design of the structure. In the first method, section factor is the issue to consider the normal temperature considering structure where fire protection is needed for full protection of the structures. By considering section factor, can determine the rate of heating and it defines the ratio of heating and it defines the ratio of the structure exposed to fire and cross sectional area of the structure. A member of low HP/A value has high fire resistance and higher HP/A has low fire resistance. The section factor indicates the fire protection is needed or not and also determine the range of fire protection is required. In the second method, high fire resistance material is used and in that case at elevated temperature there is no need of temperature protection. In the first method the load ratio determines the fire protection if it is less than 1, then there is no need of Protection and the second method is mainly used in the beam if the moment capacity is applied beyond the moment, it is fire resisted [9].

3. FIRE PROTECTION SYSTEMS

There are two strategic ways of fire protection system, such as

1) Active fire protection,
2) Passive fire protection.

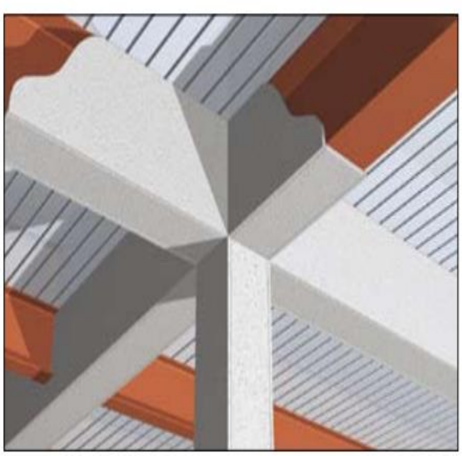
3. 1. Active Fire Protection

Active fire protection is the system which is active in the occurrence of fire. It is an alarm detecting or a sprinkling system to reduce the effect of fire. Its function is to inhibit the small fire or the initiate steps to control the fire before the action of the fire service. In the developing countries the sealed bulb of sprinkler is broken and active the head of the sprinkler in the meantime of fire action. The building which height is above 30m should need a sprinkler system [10]. The use of this system has a greater economic savings and safety of life. The main reason of death in the action of fire is smoke and the most cost effective matter is the content of the building not the structural safety. So, before reaching and set the fire equipment on the site, it is the best way to minimize the action of fire.

3. 2. Passive Fire Protection

Table 1. The advantages and disadvantages of some passive fire protection systems

Board system	**Sprays**	**Thin film intumescent coating**
Advantages	**Advantages**	**Advantages**
• It offers a clean and a suitable place for decoration, but in the place of cheaper broad appearance is not a great deal [10].	• Less costly than board protection system.	• Attractive decoration is easily possible.

• It is applicable in dry manner and do not effect on other element of the object [11].	• Easy application in complex frame.	• The shape of the steel rough surface is fulfilled [10].
• The quality of the board is guaranteed as it is manufactured in a factory.	• It can be used externally [11].	• Complex frame is easily protected.
• It can be applied above untreated work.	• Don't require any surface preparation.	• Post fire performance is excellent.
Disadvantages	**Disadvantages**	**Disadvantages**
• Erection time of setting is higher [25].	• Sprays are used only in non visible place as it is not appealing invisible.	• It is costlier than spray system.
• Difficult to set in a complex system.	• Masking is required in the application of the spray [25].	• It is wet trade as it requires good atmospheric condition and precaution during application [26].
• A decorative system is more costly [26].	• Its effects on the construction stage as it is a wet in the form of application.	• A limited fire resistance capacity might be 60 min of fire resistance, though there is coating in market highest 90 min fire resistance capacity.
 **Fig. 4.** Board protection system [11]	 **Fig. 5.** Spray protection system [11]	 **Fig. 6.** Thin flim intumescent coating [11]

Flexible/Blanket system	**Concrete encasement**	**Off site fire protection**
Advantages	**Advantages**	**Advantages**
• It is the cheapest system, • No hamper in construction stage as it is dry during application [12].	• It reduces the impact damage for that reason it uses warehouses, external structures and car parks.	• It reduces the construction time, • It reduces the construction cost, • Installation of this service is simple • High quality of application is possible, • Weather relative problem can avoid.
Disadvantages • It can't be used in visible steel for appearance [27].	Disadvantages • One of the most expensive system, • Time consuming system, • Reduce space for the large thickness of coating, • Weight of the building can be increased [28].	Disadvantages • Time consuming system.
 **Fig. 7.** Flexible blank protection system [12]	 **Fig. 8.** Flexible blank protection system [12]	 **Fig. 9.** Manual application of off-site intumescent coatings [12]

Passive fire protection is the system which protects the structure from high temperature in the action of fire. It is applied during the construction, concerning the rate of fire and required for the structural safety. Table 1 shows advantages and disadvantages of some passive fire protection systems.

4. FIRE TEST

There is a limited number of researchers have been carried out based on fire test because of its cost. For that reason to identify the behavior of steel under fire and creating the model based on the results progressing at a very slow rate.

United Kingdom: Full scale fire test has been carried out on eight story building at British research center.

(a) BSC and DOE compartment fire test: The research relates to

- Test at ceiling height of full scale 2-D steel beam,
- Steel column having two blocks.

The objectives of this study:

- Add this result into the design guidelines and simulate stability of the structure.
- Find out the deflection behavior of the structure.

Fire load of timber cribs 25 kg/m^2 and 1/8 compartment ventilation is applied. The service time is greater than the assumed time and the construction resists the fire 30 minute without any fire protection [13].

(b) BSC/FRS fire test: Sweden and United Kingdom collaborate workout this test:

- Columns in a compartment in various locations,
- Frame structure.

The objectives of this study:

- Fire resistance capacity of unprotected element.

Fire load of timber cribs 20 kg/m^2 using and 1/2, 1/4 and 1/8 compartment ventilation is applied. Rise of temperature depends highly on section factor and position. Temperature of combustion gas is affected by the lining of compartment [14].

(c) BRE fire test: Experimental study relates to:

- 5 bays long by 3 bays wide of eight story composite column,
- Two corner tests were carried out to examine the shedding and bridging operation.

The objectives of this study:

- Examine the multistory building under fire,
- Exceed this data to numerical analysis.

Fire load of timber cribs 40 kg/m^2 and for the unprotected beam at upper flange the maximum temperature 903 °C and for the totally covered fire edge beam 690 °C. Maximum deflection 266.9 mm and it reduced to 159.7 mm when cooling [15].

Australia:

Fire test of Melbourne laboratories office building: This test deals with

- Prototypical structure of 41 storey,
- Every storey of prototype divides into two parts: purpose part and existing parts.

The objectives of this study

- Find out the nature and severity of fire in the prototype,
- Study the active and passive fire system effectiveness.

In the open area there is a large number of fire combustible elements and the fire load is 53.5 kg/m^2 and in the small place fire load is 52 kg/m^2.The structure was not damaged during the experiment and there is no deflection for extended load [16].

Japan:

Fire test of Chiba University and Nippon Corporation: Study details:

- Fire resistance steel column, beam and frame test for safe fire design,

The objectives of this study

- The fire protection thickness could be reduced,
- Strength could be retained in high temperature.

From this study it is concluded that, the fire steel column can sustain the fire load up to 600 °C without any damage [16].

5. NUMERICAL STUDIES

Several numerical studies have been carried out fire on the structural steel. The purpose of this study is to examine the fire resistance of structural steel without any fire protection and examined the required fire protection of the material. Developments of the models are the main issue and by thermal distribution determine the temperature distribution. University of Sheffield, Loughborough University of Technology, University of Nottingham in UK research on the numerical model and the same kind of study have been conducted in China, Japan, Australia and Belgium. Continuity, floor slabs and end restraint are examined which affect the heated frame. The standard fire test gives limited guidelines compare with the real fire of the building. The full scale test is very expensive for that reason numerical modeling is preferable in two dimensional and three dimensional analysis [17].

6. INTERESTING USES OF STEEL IN BUILDINGS IN RELATION TO FIRE SAFETY

6. 1. U.S. Steel Corporation Headquarters, Pittsburgh, USA

In this 64-storey office building the external columns are of weathering steel and are filled with water for fire protection. The columns are fully connected and designed on the assumption that the water flow will be induced when fire heats some columns while others remain cool. Despite the columns being at a distance of about 0.9 m from the external facade, the authorities required a fire resistance of 4 hours and it was necessary to provide storage tanks to replenish the water which would be boiled off by this length of exposure. The height of the building (about 257 m) could have produced very high water pressure and therefore the system is divided into 4 vertical zones. The Performance of the cooling system and the amount of water storage was established by calculation [18].

6. 2. W.D. and H.O. Wills, Head Office, Bristol, England

Architects: Skidmore, Owings and Merrill, Chicago; York Rosenberg Mardall, London.

Structural Engineers: Felix J Samuely and Partners.

This an example of the use of exterior weathering steel without cladding, the waiver of the requirements of building regulations for fire resistance being based on calculations.

The head office building for W.D. and H.O. Wills has a five-story steel frame section above a two-story concrete podium, the upper floors being 67 x 28.8 m on the plan. The exterior structure stands about 1.8 m in front of the glazing line on all sides of the building. The outer columns and the tie beam connecting them in the outer plane are in exposed weathering steel. The transverse beams that penetrate the facade are encased in concrete and clad in weathering steel sheet. A weathering steel grille is placed at each floor level, between the facade and the exterior structure. Calculations were made of flame projections from the Windows and the heat transfer to the exterior steel, in conjunction with the Fire Research Station, Borehamwood, to support the application for a waiver [18].

6. 3. Liberty Plaza Building, New York City

Architect: Skidmore, Owings and Merrill.

Structural Engineers: Weidlinger Associates and Weiskopf&Pickworth (Joint venture).

This is an example of using deep spandrel girders to form the facade of the building. Because tests demonstrated that the fire exposure above the window openings would be low, the external face of the web is fully exposed.

The 54-storey office building was developed by the Galbreath-Ruffin Corporation in association with the US Steel Corporation. Each floor is approximately 68.5×49.5 m with 2.59 m floor to ceiling height. The structure is a rigid steel frame with wide bays on the exterior and clear span from the exterior to the core. The long elevations have five structural bays, with three bays on the short sides. The deep spandrel girders are the same depth as the window openings, 1.78 m. The flanges are protected with a sheet steel flame shield and sprayed mineral fire protection is applied to the inside surfaces. The webs of the spandrel girders are fully exposed externally, and painted black. Approval for the use of the exposed spandrel girders was only given by the New York City authorities after füll scale fire tests on a mock-up of one bay had been carried out [19].

6. 4. The Royal Exchange Theatre, Manchester, England

Architects: Levitt Bernstein Associates.

Structural Engineers: Ove Arup & Partners.

For this building, a fire engineering appraisal was used to demonstrate that the cladding of the steel was not essential for the purposes of building regulations. The Royal Exchange Theatre is a concentric auditorium standing within the Great Hall of the Manchester Royal Exchange - formerly used for trading in cotton. There is an open-stage auditorium, seven-sided in plan with stage and seating for 450 at the level of the Exchange floor and two galleries above, each of which seats a further 150 people. The Theatre is clad with toughened glass and roofed with metal decking. It was imperative to develop as light a structure as possible and this, taken together with the desire to achieve a high degree of transparency, led to a System of tubular steel trusses from which the galleries are suspended, the trusses being supported by existing brick piers.

A full fire engineering appraisal was carried out, in Cooperation with the city authorities, and this led to an agreement that the steelwork could remain unprotected, thus avoiding the cost and additional weight and bulk of fire cladding. The appraisal included an examination of means of escape, smoke generation and crowd movements being carefully analyzed, and a generous number of exits were provided. It was established that the fire remains unchecked after the evacuation, the floor of the Exchange could survive the collapse of the structure and consequently there would be no additional hazard to firefighters. Non-combustible or low flammable materials are used throughout, and arrangements have been made to ensure detection of a fire and for surveillance by the theatre staff whenever the public is present [20].

6. 5. Centre Pompidou, Paris, France

Architects: Piano and Rogers.

Structural Engineers: Ove Arup & Partners.

Much of the structure of this building is exposed externally. Where calculation of the external fire exposure showed protection of the elements to be necessary to reach the 2 hours fire rating required, protection was provided generally by water cooling or by shielding although a few parts have conventional fire protection. The Centre Pompidou has a steel superstructure rising above a concrete substructure. The main building has six stories above ground, each 7 m high and 166 m long. The main lattice girders span 44.8 m between short cantilevers projecting from the main columns, the outer ends of the cantilever members being restrained by vertical ties.

The glazing line generally follows the junction between the lattice girders and cantilever brackets. The main columns are 1.6 m outside this line and are water filled for fire protection, the circulation being achieved within each column by pumps. The cantilever brackets are 7.6m long; thus the outer line of tension "columns" and associated bracing members are 7.6 m from the Windows.

Calculations showed that in the event of fire, all the members on the outer plane are protected by virtue of the 7.6 m distance from the Windows; the cantilever brackets are shielded by fire-resistant panels on the facade. There are Sprinklers on the external walls and the cantilevers. Horizontal bracing members close to the Windows would be lost in a fire, but with each floor divided into two compartments, the loss of a proportion of the bracing does not endanger resistance [21].

6. 6. Bush Lane House, London, England

Architects & Structural Engineers: Arup Associates.

Prior to the construction of this building, water cooling had only been used for the protection of vertical columns, since its use for beams raises considerable difficulties in ensuring that adequate controlled water flow occurs and no steam pockets develop. In Bush Lane House, water cooling is used for the external structural steel and protects columns, lattice members, and a critical top horizontal member. Bush Lane House provides eight office floors above a first floor plant room.

Each typical floor is approximately 35 m long × 16 m wide, supported by the lift core and three columns set 11m from the extremities of the building. The stainless steel lattice which transmits the floor loads is external to the building envelope and leaves the office space uninterrupted.

The steel members are water filled and inter-connected, so that in the event of fire the water circulates and steam is vented at high level or separated in a tank on the roof. This tank also serves as a reservoir to replenish and keep the system full of water. The patterns of water flow, maximum potential steel temperature, and the amount of water storage were all established by calculation [22].

6. 7. Central Bank Offices, Dublin, Eire

Architects: Stephenson Gibney and Associates.

Structural Consultants: Ove Arup & Partners, Dublin.

For this building the critical condition for failure of the steel hangers was established by calculation, since no Standard test method was appropriate for tension members. In addition, the fire exposure of the hangers, being external, was calculated so that the necessary cladding could be determined. The main building of the Central Bank Offices complex in Dame Street, Dublin, is an eight-story block with 8500 m^2 of office space. Uninterrupted floor areas and minimal obstruction to Windows were considered to be of significant architectural advantage. The floors, measuring 45 m × 30 m are supported at 12 hanger points around the perimeter and on twin reinforced concrete cores.

From the hanger points the loads are transmitted directly to roof level through pairs of high tensile Macalloy steel bars. Cantilever frames transmit the vertical reactions to the cores. The fire protection of the Macalloy bar hangers presented a somewhat unusual problem. They were to be exposed on the facade of the building and it was of considerable architectural importance that they be expressed as separate bars.

It was essential therefore to provide a fire cladding which would give adequate protection without being very thick, since each 40 mm bar was to be encased in an aluminum tube not exceeding 120 mm diameter. A research program was necessary to establish the Macalloy steel characteristics, thus leading to a definition of the critical condition of the structure under fire exposure. Fire engineering calculations established that the bars would be less severely exposed than internal members and the cladding finally adopted was 20 mm thick Marinate machined to form interlocking sections round the bars [23].

7. RECOMMENDATIONS

- Improved Structural Design Methodology.
- Improved Testing of Fire Protection Materials, Technologies, and Systems.
- Charging Building Operations and Maintenance Functions with Sustaining the Technologies, Systems, and Materials that Constitute Elements of the Fire Protection System [24].
- Maintaining Stakeholder Involvement in Development of Improved Methodologies.
- Providing Incentives for Improved Approaches to Design, Construction, Maintenance for Hazard Resistance in Buildings.
- Adjustments in Professional Education to Adapt to Multi-Hazard, Holistic Approaches to Design, Construction, and Maintenance of Buildings.

8. CONCLUSIONS

The competitiveness of structural steelwork for buildings, in relation to other structural materials, is impaired both by excessive requirements with regards to fire protection and also by higher insurance premiums for steel than concrete structures. Certainly a rethinking of the current fire regulations, with a view to a better assessment of the fire risk and safety objectives, would give a better approach to an optimum level of fire protection design. Despite the implications of the above mentioned problems with the use of steel in buildings, much will be gained if suitable fire design strategies relative to active or passive protection measures are clearly defined at an early stage, in the conception of a project. In such a design within the framework of these strategies, the load bearing structure should be dealt with as a component in an integrated fire hazard evaluation of the total active and passive fire protection for a building. This would open the door for assessing the effects of trades off and for comparing alternative designs for the total fire protection with the same level of safety from the cost point of view.

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