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Fire Protection of Steel Structures — Examples of Applications

Protection contre le feu des structures acier — Quelques exemples d'applications

Brandschutz der Stahlkonstruktionen — Einige Anwendungsbeispiele

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SUMMARY

This paper presents a review of the practical aspects of fire protection of steel structures by different techniques taking the desired fire rating into account. Some guidelines for correct practice are given. A number of these concepts of fire protection are illustrated by recent examples of steel building structures in Dublin, London, Manchester and Paris.
The last part of the paper discusses the priorities for future action and research. The use of calculation methods for the design of structural fire protection is gaining increasing acceptance and there is a growing recognition of the need to clearly identify the safety objectives related to fire within the context of overall safety.

RÉSUMÉ

Cette contribution présente un rappel des aspects pratiques de la protection contre le feu des constructions métalliques, réalisée au moyen de techniques diverses avec prise en compte de la durée de résistance souhaitée. Quelques indications de bonne pratique sont données. Ces concepts de protection anti-incendie sont illustrés par quelques exemples de constructions récentes.
La deuxième partie est consacrée à la discussion des problèmes qui devraient constituer à l'avenir les priorités en matière de conception et de recherche. L'utilisation de méthodes de calcul pour la conception d'une protection efficace contre le feu est de plus en plus largement acceptée et la nécessité de définir clairement les objectifs de cette sécurité dans le cadre d'une conception globale de la sécurité est largement reconnue.

ZUSAMMENFASSUNG

Dieser Beitrag gibt einen Überblick über die praktischen Aspekte des durch verschiedene Massnahmen und unter Berücksichtigung der angestrebten Feuerwiderstandsdauer erreichbaren Brandschutzes. Regeln für die praktische Anwendung werden gegeben. Einzelne dieser Konzepte werden an Beispielen illustriert.
Im zweiten Teil werden die Probleme besprochen, welchen die Verfasser die grösste Priorität in der zukünftigen Forschungstätigkeit einräumen. Die Anwendung von rechnerischen Methoden zur Beurteilung eines wirksamen Brandschutzes wird immer mehr akzeptiert und die Notwendigkeit einer klaren Festlegung der Feuersicherheitsziele im Rahmen eines umfassenden Sicherheitskonzepts wird in steigendem Masse anerkannt.

1. INTRODUCTION

The decrease of steel strength properties at elevated temperatures (> 300 °C) is now well established. This might induce in the public mind a certain reluctance to use structural steel in buildings. To prevent loss of strength and consequent risk of structural failure due to fire, it is essential to provide protective measures which isolate structural steel elements from direct heat attack.

Obviously the more protection there is, the higher the fire resistance will be, but the question arises, to what extent is the increase in fire resistance justifiable economically ?

After discussing the cases where it is accepted that it might be unreasonable to protect steel structures, this paper presents, in its first part, some current types of passive protection measures and their effectiveness with regard to the expected fire resistance duration. The second part of the paper gives particular examples of recent buildings, which illustrate the applications of different types of structural fire protection, and the third part draws attention to several priorities for research which could stimulate the use of structural steelwork for buildings.

2. THE PRACTICAL ASPECTS OF FIRE PROTECTION OF STEEL STRUCTURES, SOME GUIDELINES FOR CORRECT PRACTICE

Under the conventional procedure to determine standard fire resistance, it has been proved that unprotected structural steel sections in common use will carry loads for some ten to fifteen minutes. This period is related to the standard fire exposure and is referred to as the "fire resistance time". With such a reduced response in fire, it may be thought that steel structures are unsafe without protection, but it should be borne in mind that this low fire resistance is related to the standard fire test procedure, which has definite limitations and has been the subject of numerous criticisms.

A major decision for the designer is to determine, whether or not it is necessary to provide fire protection for the steel elements, through insulating materials or cladding, or any protective measures provided by such techniques as screens (e.g. false ceiling) or systems like water-filled hollow sections. The decision is dictated by the necessary safety requirements, the cost and/or aesthetic considerations.

Some national regulations have begun to reflect the relative importance of the fire resistance of structural elements among the fire safety measures in building. Also some national fire codes do not require fire resistance for low-rise construction (1), or for structures used for activities which do not lead to excessive fire loads. In sport halls, certain industrial halls,etc... there are very low risks of flash-over or even fire which could result in any danger for an unprotected steel structure. Experimental evidence (fig. 1) of real fire behaviour shows that for fire loads less than 15 kg of wood equivalent per square metre of floor area, it would generally be unnecessary to improve the structural fire resistance by protective measures. The costs of fire protection are sometimes not fully justified in terms of loss reduction, and more advantages can be obtained from control and fire prevention measures.

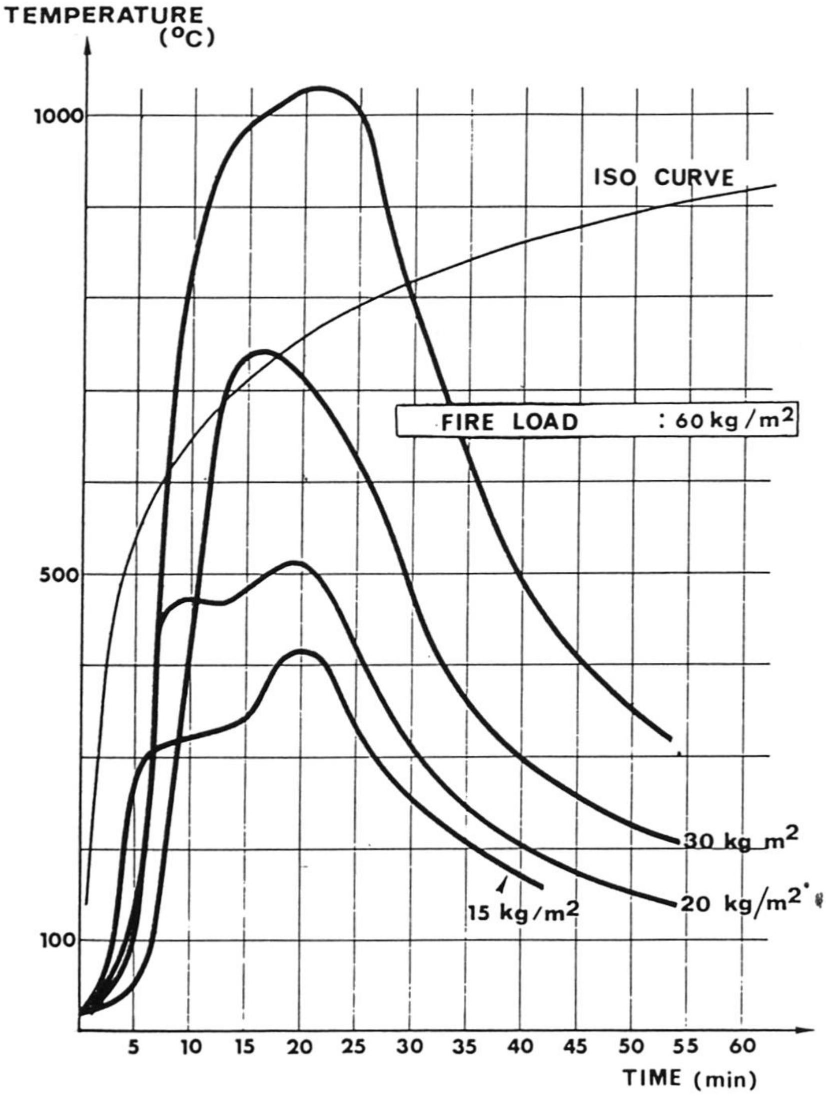

Fig. 1
Natural fires behaviour under different fire loads

It is generally accepted that casualties, structural damage, and damage and loss to the contents of the building are more efficiently avoided by using active fire protection measures rather than passive protection measures.

Active fire protection measures include detection systems, sprinklers, which suppress a fire at an incipient stage, and smoke controlled dilution or ventilation systems.

Clearly, arbitrary requirements for fire resistance serve little purpose. Much can be gained by a careful and coordinated fire design which makes use of complementary fire safety measures.

2.1. Accepted cases of unprotected steel structures

In some countries, the official regulations do not require any fire resistance for single storey buildings. However, specific safety measures may be required by the regulations or be demanded by the controlling authorities depending upon the type of activity associated with the building, the floor area and the number of people occupying or using the building.

2.2. Unprotected steel complying with the 1/2 h resistance requirements

In relation to fire resistance requirements, many building codes single out structural elements according to their particular functions. In general, the only structural elements to be checked for their fire resistance rating are those which actually ensure the proper general load bearing function of the structure, or which contribute to the effectiveness of the fire compartmentation.

Compared to other constructional materials (concrete, wood) the fire resistance time of 1/2 h under standard fire conditions is certainly the most unfavourable requirement for steel construction, from an economical point of view.

2.2.1. Bare structural elements

The fire rating of 1/2 h may be obtained for structural elements with a so called "section factor" or "massivity factor" less than $F_s / V_s = 30 m^{-1}$, (where F_s is the fire exposed surface and V_s the volume per unit length of the steel structure. However, these massive elements are rare in building construction, where most steel elements in current use have a section factor greater than 200 m^{-1}. Depending upon the critical temperature of the bare steel element, a fire resistance of about 15 minutes may be expected when these elements are subjected to the standard fire test.

To achieve a greater fire resistance, by increasing the critical temperature of the steel elements, it is necessary to alter simultaneously or separately the section factor, the stress level and the grade of steel. Certainly, the most efficient way of improving the fire resistance of a steel structure is to make use of design concepts which involve statically indeterminate structures.

2.2.2. Mixed construction of steel and concrete

By conveniently associating steel and concrete, fire stability may be improved beyond the critical 30 min without externally protecting the steel. The structural elements of composite construction comprise :

- composite floor consisting of a steel beam and a concrete slab,
- concrete-filled hollow tubular sections,
- composite deck composed of a corrugated metal sheet and concrete slab.

The steel which is associated with the concrete slab to form the composite structural element does not itself have improved fire resistance. The increase in fire resistance for standard fire exposure above 30 minutes is generally provided by additional reinforcing bars which are incorporated in and protected by the concrete. In the case of continuous composite beams, special care must be taken in choosing the type of reinforcing bars under negative bending moment, as premature failures have been experienced with low-ductile bars.

A great number of experimental results is given in the literature (2) for these elements, and the data are still being analysed. Calculation methods are being developed, and as soon as their reliability has been established, the methods will be incorporated, in the form of technical notes, in the European Recommendations for the calculation of fire behaviour of steel structures (3). In addition, much information exists in the form of data bases, which may be useful in evaluating the fire resistance of such structural elements by means of a judicious analogy.

2.2.3. External structural elements exposed to fire

It is known that structural elements which are in the open air outside the fire compartment, and thus not exposed directly to the fire, may not reach a critical temperature.

The fire exposure of elements such as external columns and beams varies not only with the position in relation to distance from the façade, but also with the fire load of the compartment, the window opening and shape, and random influence of wind speed and direction.

In order to lower the rate of temperature rise, external columns should be placed at a certain distance from the façade, or should be protected by screens, so as not to be placed in direct contact with the flame and also to be protected from radiated heat. A screen may be naturally provided by the mullions. Furthermore, experimental evidence shows that beam to column connections are of major importance and much can be gained from using rigid connections (4).

But, on account of the very complex fire behaviour, the knowledge concerning the heating process of the external steel elements during these last years has been greatly improved, the evaluation of the external heating process tending to become as reliable as the determination of the temperature field evolution inside the compartments. Compared with experimental observations, calculated structural response gives prediction on the safe side (4,5).

Tests on pins ended columns may provide us with some useful information on the heating process, but more may be gained from sub-assemblies of structural elements. They show the role played in the fire resistance by the connections (4,5) ; together with the non uniform temperature field, this may explain the remaining difficulty in getting inaccurate prediction of the outside column fire response.

2.3. Protected structures

Depending upon the fire insulation material and its thickness, 1/2 hour to 4 hours fire resistance for load bearing structures subjected to the standard fire exposure can be achieved.

A great variety of fire-protection methods and techniques exist which may be summarized under the following headings :

- intumescent paint
- spray applied material
- individual encasement of the steel structural element with wallboard type of material or concrete
- structural elements protected by membrane systems.

2.3.1. Intumescent paint

Although similar in appearance to normal paintwork, intumescent paint is a coating which swells at about 150°C to 300°C to form a "meringue" whose thickness may reach several centimetres and which acts as a heat shield.

Generally, intumescent paint applied to a steel structural element provides a fire rating of up to one hour. Particular attention should be paid to the quality control of those coatings, and particularly to the durability of the intumescent crust.

2.3.2. Spray applied material

The composition of sprayed products generally involves gypsum, which includes 20 % crystalisation water, or cement and expanded vermiculite, perlite, glass or mineral fibres.

The use of abestos fibres mixed with gypsum or cement has been prohibited in many countries, because of the health hazard they represent, both for workers and occupants.

The fire performance of these spray compound product depends largely on :

- the thermal conductivity, specific heat capacity and thickness of the material itself. Test methods have been proposed for measuring these properties (7, 11).
- the mechanical behaviour of the material under impact if subjected to knocks at ambient temperatures and the tendency to fall off during a fire. Good adhesion to the steel surface is an important requirement for spray applied fire protection materials. Spray material may be applied directly to the steel element or on metal lath fixed to the steel. High fire resistance up to 4 hours may be achieved with such protection.

Several methods of calculation now exist which give the thickness of the protection to be sprayed on structural steel elements. The most sophisticated and general (3,8) takes into account the loading to determine the critical temperature, and then the resistance time. Others have derived (9) empirical formulas based on tests which give directly the resistance time for a fixed critical temperature (550°C).

2.3.3. Individual steel structural elements encased with concrete or boards

In this case, the concrete encasement serves only as a protective material and does not carry any load. An empirical equation has been developed (9) which is based on the thermal properties of concrete and on the equilibrium moisture content by volume of the concrete.

References (3,8) also provide a general approach to evaluating the fire resistance of steel sections encased in concrete.

Columns or beams may also be protected against fire by gypsum wall-boards, supplied in a range of thicknesses, which are assembled around the steel shape. The fire resistance is very sensitive to the fabrication and special care should be taken, on site, to verify that the wallboard assembly fixing system (type and spacing of fasteners), furring channels, seam joints, and sheet steel covers, if any, are the same as for the particular fire-resistance assembly tested.

2.3.4. Structural elements protected by membrane protection systems

Because of the complexity of a load carrying stress system, the best method of achieving the desired standard of protection is to encase the whole structural element between partition walls, thus preventing the passage of fire. In this case, it is particularly important to give careful consideration to any constructional details which may cause the fire to spread.

The technique of compartmentation is also very important in floor and roof construction. Floors in multi-storey buildings generally constitute the major compartment boundaries which prevent the spread of a fire and provide horizontal barriers which force the smoke into the shafts.

Many tests, under standard fire, have been performed on all types of construction systems. The most common type of floor system used in steel construction is the composite floor, with structural steel beams (steel joist, castellated beams, rolled or welded shape) shear-connected to a concrete slab or a composite slab (cold formed steel floor and concrete). Fire protection methods for these types of floor consist of various suspended ceiling systems and spray-applied fire protection. No calculation method exists for such types of floor systems, and fire resistance performance should be evaluated from results of available tests. Monographs (2) have been published which show how to estimate, on a comparative basis, the structural fire resistance of the proposed construction.

2.3.5. Water filled hollow section

Many of the protection systems which have been described do not allow the structural steel to be exposed, and this is detrimental to the architectural character of steel structures.

The idea of liquid-filled columns between floors and unconnected with pipe loops was originally patented in 1884 by G.F. WRIGHT.

Important structural systems have been achieved using the techniques of water-filled hollow structural elements; they are now well accepted methods in the U.S.A. and Europe.

The application of this technique requires particular attention to the design of the water circulation system. The replenishment of the water evaporated is assured either by gravity through a storage tank or by a pressure pump system. Corrosion inhibitors should be incorporated in the water and in cold climates an antifreeze agent is required. The water flow pattern of a locally heated column is not yet well understood.
An experimental standard fire test on a 250 x 250 mm column filled with water shows a fire resistance of 30 minutes. Water cooled steel columns will be largely below the critical temperature value of the steel, if water circulates properly and if the formation of steam traps is avoided.

The concept of water filled structures has been largely extended to fulfil more than one function. Several examples (10) of water filled structures coupled with an integrated heating and cooling system have been built which have permitted greater economies of the project. Moreover truss systems have been erected whose main members are hollow sections, filled with water, which serves as a network for a sprinkler system.

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

The building described in this chapter illustrate some of the design approaches outlined in paragraphe 2.

3.1. U.S. Steel Corporation Headquarters, Pittsburgh, USA (12)

Architects : Harrison & Abramovitch and Abbe
Structural Engineers : Worthington, Skilling, Helle & Jackson, and Edwards & Hjorth.

For 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 façade, 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 (13).

3.2 W.D. and H.O. Wills, Head Office, Bristol, England (14)

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-storey steel frame section above a two-storey concrete podium, the upper floors being 67 x 28.8 m on 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 beams connecting them in the outer plane are in exposed weathering steel. The transverse beams that penetrate the façade 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.

3.3. Liberty Plaza Building, New York City (15)

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 façade 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 x 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 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 full scale fire tests on a mock-up of one bay had been carried out (16,17).

3.4. The Royal Exchange Theatre, Manchester, England (18)

Architects : Levitt Bernstein Associates,
Structural Engineers : Ove Arup & Partners

For this building, figure 2, a fire engineering appraisal was used to demonstrate that 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 analysed, and a generous number of exits was provided. It was established that should the fire remain unchecked after evacuation, the floor of the Exchange could survive collapse of the structure and consequently there would be no additional hazard to fire fighters.

Non-combustible or low flammability 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.

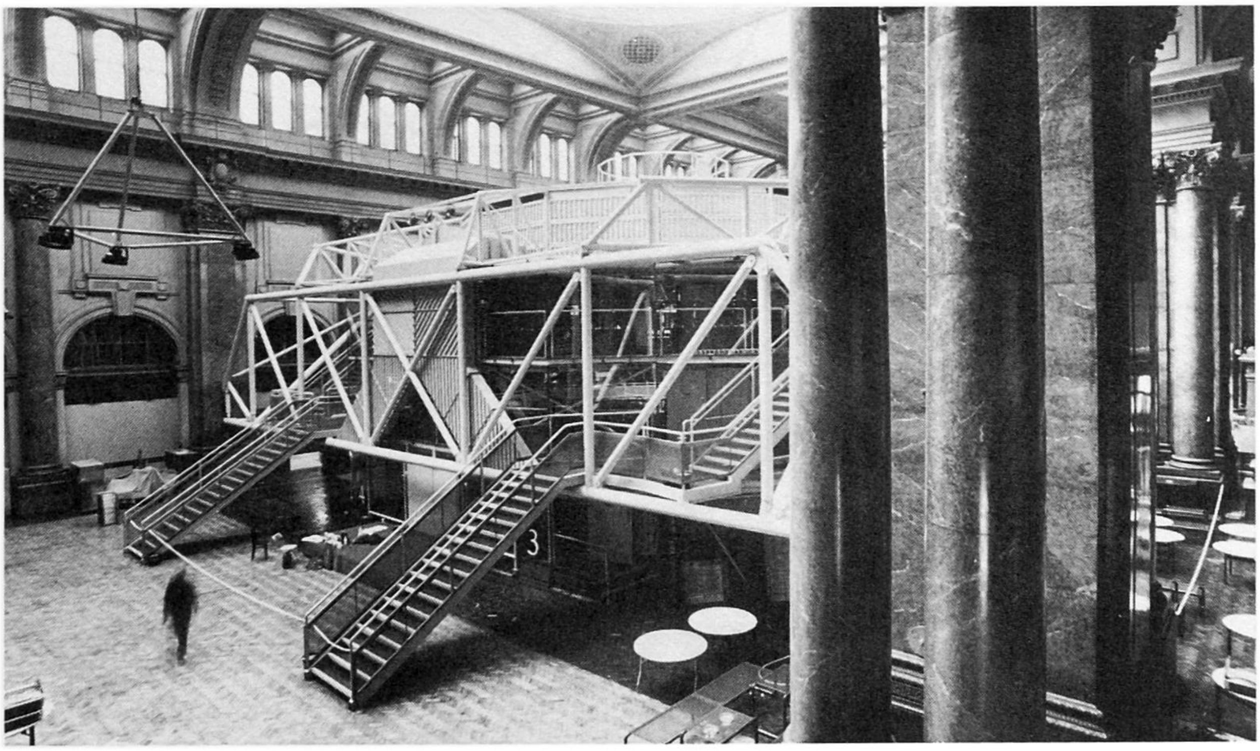

Fig. 2 Royal Exchange Theatre-Manchester

3.5) Centre Pompidou, Paris, France (19)

Architects : Piano and Rogers,
Structural Engineers : Ove Arup & Partners

Much of the structure of this building is exposed externally (figure 3). 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 storeys 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, circulation being achieved within each column by pumps. The cantilever brackets are 7.6 m 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 in the façade. 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.

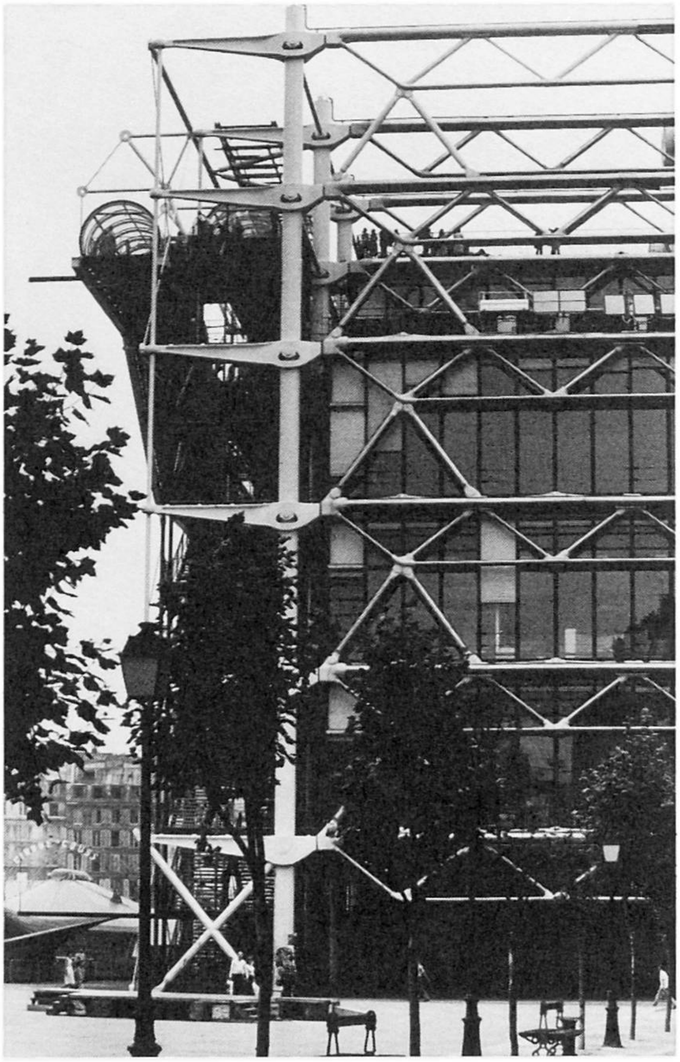

Fig.3. - Pompidou Center
Paris

3.6) Bush Lane House, London, England (20).

Architects & Structural Engineers : Arup Associates.

Prior to the construction of this building (figure 4), 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 x 16 m wide, supported by the lift core and three columns set 11 m 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.

Fig. 4 - Bush Lane House
London

3.7) Central Bank Offices, Dublin, Eire (21)

Architects : Stephenson Gibney and Associates,
Structural Consultants : Ove Arup & Partners, Dublin.

For this building (figure 5) 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-storey block with 8500m^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 x 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 façade 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 aluminium tube not exceeding 120 mm diameter. A research programme was necessary to establish the Macalloy steel characteristics, thus leading to a definition of the critical condition for 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 Marinite machined to form interlocking sections round the bars.

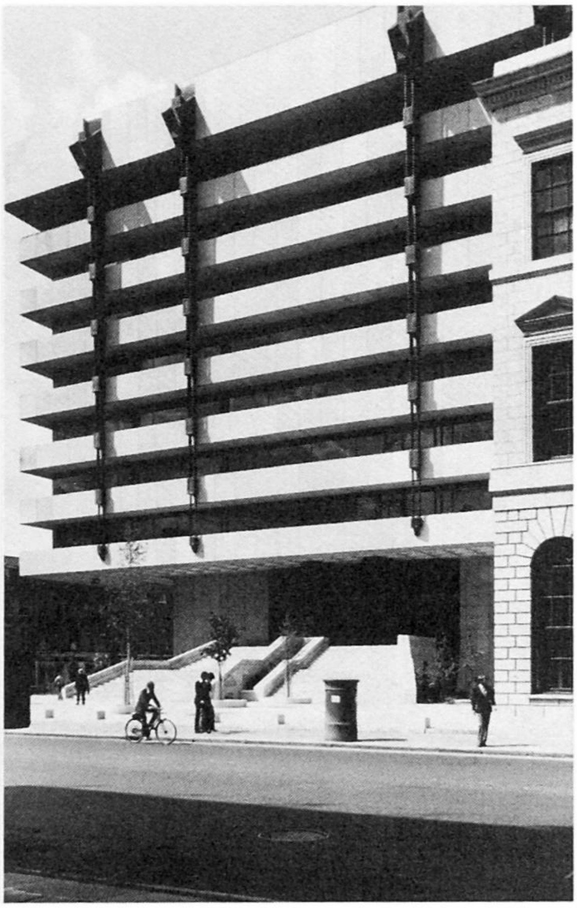

Fig. 5 - The Central Bank, Dublin

4. PRIORITIES FOR FUTURE ACTION AND RESEARCH

During the last two decades a great deal of research has been devoted to studying structural behaviour under different fire conditions. Certainly the knowledge gained by the experimental and analytical studies is the reason why the calculation methods to determine fire behaviour and resistance are now recognized on a regulatory basis as equivalent to laboratory tests. Now is the time for a change of priorities for research programmes. They should be more oriented towards a better assessment of fire risks in relation to safety considerations in order to establish more rational requirements for structures and components (25).

a) Most of the existing building regulations for fire safety are not based on a clear definition of safety objectives. The reason may be attributed to the fact that existing building regulations are the results of a compilation of rules based on history and past experience in the country concerned.
Obviously, comparison of the national fire building requirements of different countries will show considerable discrepancies. Consequently, it is thought that harmonization of regulations is unlikely to be achieved through a comparison of existing national code requirements, but it should be the consequence of a thorough examination and definition of the potential risk that society is ready to accept. It should be borne in mind that in some circumstances, it is impossible to guarantee full protection against fire, e.g., when fire has a criminal origin.

Some tentative approaches have been made in this direction (22,23,24,26) and they need to be more widely developed and justified.

In this context, a thorough examination of data and a survey of potential hazards is certainly of a major importance.

Quantitative methods need to be derived, to evaluate the fire risks, and to scale the required structural fire protection together with alternative protection measures. For example, statistics indicate that the risk of a serious fire occurring in open parking place is negligible ; despite this fact, not all countries accept unprotected steel structures in open car parks.

b) Substantial reduction in structural fire resistance requirements should be allowed in the presence of an approved automatic sprinkler system. For some countries but not all, recommendations exist for the design, the installation, the quality control and the inspection of sprinkler systems, and the reliability of such systems has been established.

c) Studies should be carried out to determine the fire endurance of various structural components such as floor and ceiling assemblies, load-carrying structural members or stability members encased between wallboards. Attention should be paid to the overall fire behaviour of such assemblies ; for example, a very flexible floor system under fire may fail to prevent flame passage at the horizontal intersection between the floor and the wall or the ceiling and the wall.

d) Codes of good practice need to be developed for architects, and decision makers, which explains when structural fire protection is needed, and which give information on different methods of providing fire protection to steelwork and their relative costs.

e) It has been argued that at present in several countries the insurance policy for individual buildings often discriminates againt structural steel. Efforts should be intensified to remove the difference in insurance premiums for steel and concrete structures.

5. 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 on 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 frame work 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 of 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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