The concept of using a hollow column filled with water for fire protection is not new but interest in the obvious advantages has only recently been revived with the advent of the larger sizes of structural hollow sections and their rapidly growing use in high-rise buildings.

While steel is incombustible it softens under heat and when the critical temperature, generally agreed to be about 550°C, is reached the yield stress falls below the maximum designed safe working stress and permanent distortion takes place.

The traditional method of protecting steel structures from the effects of fire is to interpose a shield of heat-resisting material of a thickness designed to delay the rise in temperature of the steel for the necessary time laid down in the regulations for the particular case. The standard fire test BS 476 (ISO 834), based on the standard time temperature curve, is designed to check that the protection does, in fact, give the required result and is stopped when the steel reaches its critical temperature or ceases to carry its working load. This test does not take into account the volume of fuel used or its rate of consumption hence heat absorbed by the section or abstracted is simply replaced by increasing the fuel supply to achieve the temperature curve. Tests on steel columns protected by heat shields have generally been based on using the same sections, i.e. 8 × 6 × 35lb/ft RSJ or more recently 203 × 203 × 52kg/m universal columns and for RHS 7 × 7 × 0·375 × 33·6lb/ft (177·8 × 177·8 × 9·5 × 50kg/m) since these sections meet the 'deemed to satisfy' conditions in the Building Regulations.

Unfortunately there is as yet no recognised way of dealing with the case where heat is abstracted from the member under test. Nevertheless a series of single column tests carried out at the Fire Research Station a few years ago showed that a water-filled member without replenishment doubled the fire resistance of the bare steel and a subsequent test including an internal sleeve to improve circulation of the static water increased the resistance to three times.

A test lasting 75 minutes was carried out on a series of interconnected beams and columns. Equilibrium conditions were achieved, and the maximum rate of fuel supply had been reached. The standard time temperature curve could not be followed. It would seem, therefore, that a new basis is required for carrying out tests on water-cooled members which takes into account the quantity and rate of heat abstraction, e.g. it may be that by monitoring the fuel supply for the current standard test which would include flue losses, etc, and then using fuel supply instead of temperature as the control, satisfactory criteria could be established.

The principles involved in central heating, in steam raising and in the many industrial processes which are dependent on the use of cooling water have been applied to the structural problem of ensuring that, in the event of a fire, the temperature of the steel frame of a building is kept below the critical temperature at which its ability to carry its working load is impaired. Design data should be available in the near future.

The following article reprinted from *Building with Steel*, issue no. 15, reviews this subject and includes a comprehensive bibliography. At the recent CIDECT conference in London it was authoritatively stated that the use of water-filled columns is economic for buildings of more than five storeys.

British Steel Corporation Tubes Division

WATER FILLED STRUCTURES

Fire protection to structural steelwork by water-filled sections has been referred to in earlier issues of 'Building with Steel'. A fuller treatment has been needed for some time and in this article Gordon Cooke, BSc, CEng, MIMechE, MIFireE, of Pell Frischmann & Partners considers the subject in detail. He looks at the development of systems, considers their performance and gives data on a number of international projects.

Water cooling has now gained a respectable place among the more conventional forms of fire protection for structural steelwork in building projects. Although there are no completed projects in the United Kingdom, there have been a number of major projects in the United States and Western Europe where water-filled external steel members have proved to be a sensible solution to the client's brief.

Apart from the aesthetic merit, what does the client gain if water-cooled external steelwork is specified? Isn't it just another gimmick which further complicates the building approval and construction process? Do the economies brought about by the elimination of conventional encasure for fire resistance, together with increased usable floor space, really offset the cost of the water system? These are some of the thoughts the building designer may have.

This article describes the advantages and how they may be achieved. It also sets down the parameters to be considered in the design stage and describes by reference to a number of projects how the requirements have been met in practice.

The water-cooled steel structures of today probably would not exist were it not for two complementary developments which occurred within the last fifteen years. First is the architect's realization that steel can take on a new powerful aesthetic expressing the honesty of the bare structural medium if it can be placed externally without the protective covering normally required for fire protection or corrosion resistance – other advantages are the elimination of awkward detailing between intermediate columns and cladding, and the provision of column-free floor zones which are of clear benefit to the user. The second development is the commercial availability of high-yield strength low alloy weathering steels, notably the USS Cor-Ten. Saarinen & Dinkerloo first powerfully demonstrated these attributes in the Deere & Company Building, Illinois, some 13 years ago.

It is perhaps an obvious point, but nonetheless worth stressing, that the designer should not automatically assume that external steel members require fire protection by water cooling or, indeed, any other method. In general if it can be shown that emerging flames do not impinge on the steelwork then fire protection may not be required. With steelwork spaced well away from the façade, say 1 metre, and for buildings of low fire load, such as offices and residential buildings, the nil flame impingement criterion is likely to be satisfied. It should be emphasized that these are only rough guidelines: much depends on other factors such as geometry of fire compartment, size and position of openings in the external wall, size and shape of structural section, loading of structure, and differential expansion limits of the frame under fire conditions. The building designer is therefore advised to discuss the project at an early stage with specialists, e.g. the Joint Fire Research Organisation, Borehamwood.

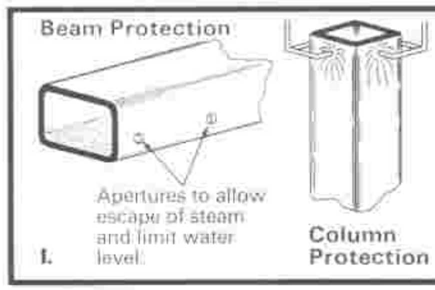
Butcher and Cooke have summarized[1] the results of a large programme of full-scale fire tests conducted in the UK on unprotected steel elements,[2] while Seigel (USA) has also studied in depth the thermal pattern of emerging flames in full-scale tests and correlated this data with design criteria for flame deflectors and water-filled steel systems.[3, 4] Such tests are invaluable for establishing the amount of fire resistance, if any, required by the external steelwork.

Principle

Unless an unprotected structural steel member possesses a large section area in relation to its periphery, it is likely to have little fire resistance when measured in the BS 476 fire test.[5] (In the case of a column the BS 476 furnace test establishes the period of time in minutes taken to cause collapse of a nominal 3m long specimen column when exposed to a standard fire and subjected to a loading which produces stresses of the same nature and order of magnitude as in the full-size element by the maximum permissible loads the element can carry.) For example, whereas an unprotected 150mm square solid steel column possesses a useful fire resistance of 40min in the BS 476 test, most structural sections used in buildings have a fire resistance in the range 15–20min and therefore usually require fire protection if the critical temperature of 550°C is not to be exceeded. Where, however, the fire load is small and there is good ventilation, it can be shown that unprotected steel members both inside and outside the building require no protection. This has been proved from full-scale tests in the case of partly open-sided multi-storey steel car parks of limited height[6] with the result that the then Ministry of Housing and Local Government issued a Circular stating that provided the conditions it contained were met a waiver would be granted permitting the use of unprotected steel.[7]

The traditional method of achieving fire resistance is to clad the outer faces of the member with a material which delays the passage of heat. In contrast, water-cooled steelwork does not present a physical barrier to the heat. In the earliest development of water cooling in 1884, to be described later, two methods of cooling were simultaneously employed: cooling by water filling, and cooling by a spray of water and steam directed over the outside face of the member.

Almost a century later, the water spray method has received further attention. Rasbash then working at the Joint Fire Research Organisation completed a theoretical analysis of the method and a number of techniques have been patented[8] (see Fig. 1). In these the structure remains dry, water being released when a heat detector operates in fire conditions: water can either flow along the member or be sprayed on. The system exploits the efficient heat transfer from steel to boiling water in the temperature range 100–150°C. A foaming agent would increase the wetted area, and he claims that the steel should remain below the critical temperature of 550°C provided that at least one-tenth of the area is wetted. While his philosophy of heat transfer is clear, it is fair to point out that theoretical behaviour has yet to be verified by experiment on full-size elements, and industry has yet to evolve a system of distribution pipework which is economical, aesthetically acceptable and reliable in the event of fire.



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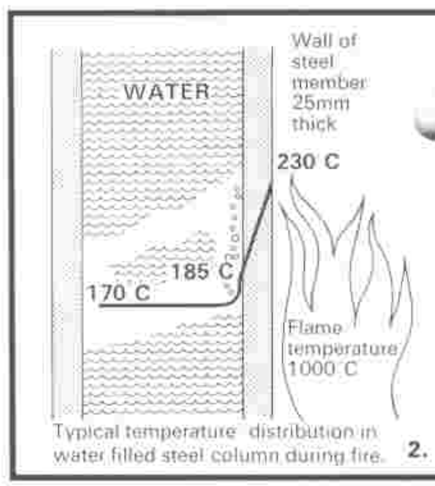
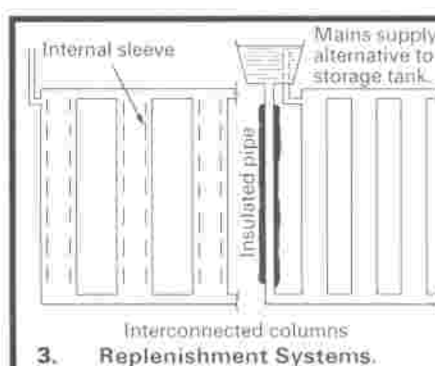


Typical temperature distribution in water filled steel column during fire. 2.

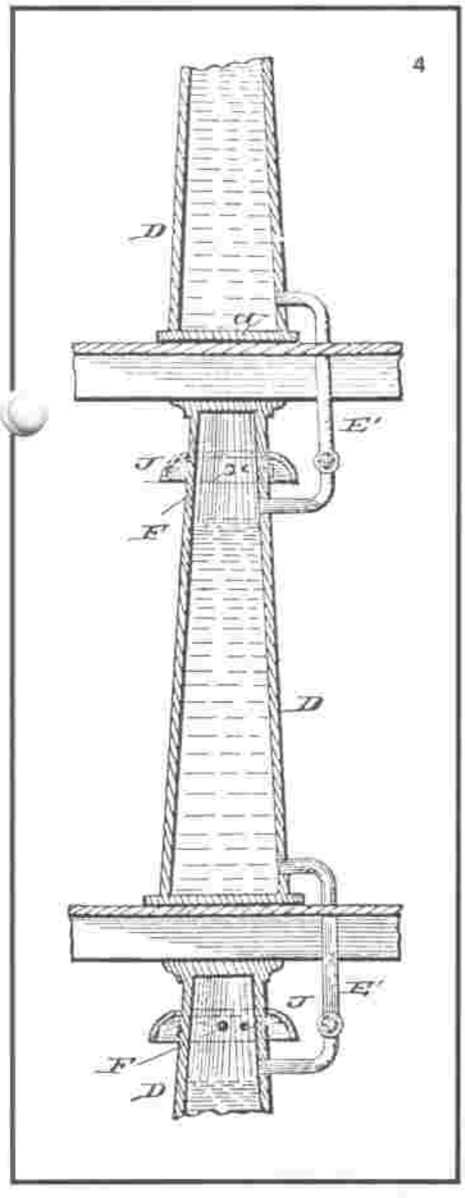


3. Replenishment Systems.

With water-filled steelwork, however, the method is now well proven. Here the excellent thermal properties of steel, water and steam are being fully exploited. The high thermal conductivity of steel ensures that the outer face as well as the inner face is kept well below the critical temperature. The large heat transfer through the wall of the steel element which this entails is quickly absorbed by the water and steam which both possess the requisite thermal conduction and convection properties. Thus the heat is evacuated from the steel member; a typical equilibrium temperature distribution curve is shown in Fig. 2.

There are two distinct systems of water-filled elements – the replenishment and unreplenishment systems. These are shown in Fig. 3. As its name suggests, the unreplenishment system is one in which water lost by evaporation during a fire is not replenished. It is simple, inexpensive, trouble free but, importantly, provides a limited amount of fire resistance and is therefore limited to those applications where only a marginal increase over the inherent fire resistance of the unprotected member is desired, or where the member has an exceptionally large water capacity – a feature which is inconsistent with structural economy and space saving except for large buildings.

In the replenishment system, which has been used in all the buildings so far constructed, the steam is vented to atmosphere and the water is replenished from a storage tank connected to the mains, or, in the case of small systems, replenished direct from the mains as with the SNCF Paris offices described later.



Convective flow varies from nil for a horizontal element (beam) to a maximum for the vertical element (column). The inherent difficulty presented by horizontal elements accounts for the absence of water-filled beamwork in most building projects; in the one case where it has been used – the US Michelson Plaza building – it serves as supplementary water storage to roof-top tanks. If, however, the elements are inclined to the horizontal then convection under the effects of different densities of water and steam will occur, the effect increasing with increased inclination. This introduces the idea of using a steeply inclined diagonal lattice of hollow elements in which the circulation, hence fire resistance, can be quite accurately predicted. McDonald may have envisaged this when he patented the concept in 1957.[9]

Whatever the configuration of the structural elements, it is sensible for design purposes only to take account of the predictable parts of the cooling process, i.e. the heat taken to raise the water to boiling point followed by the latent heat of evaporation. Other cooling effects, such as the emission of heat from cooler parts of the column remote from the fire, should be ignored. If the design is such that the replenishment water arrives from the storage tank or other columns without appreciable preheat then this, often large, bonus may be accepted. Here a note of caution, for it is sometimes difficult, because of the capricious nature of fire, to predict either its spread through the building or its severity, and there is, therefore, a large element of doubt as to how other structural elements will be affected.[10]

Theory and experiment

The concept of fire protecting hollow steel structures by water filling is not new. Some ninety years ago in the USA, Wright patented a method[11] for protecting columns in a multi-storey structure. This is illustrated in Fig. 4. Each storey-high column was a separate unreplenished water-filled member, the valved pipes connecting head and base of column at each floor level serving to facilitate the initial filling of the columns. After filling, which he envisaged could be achieved using branch pipes connected to the water mains, the perforations at the head of each column would be sealed with a fusible substance which would prevent evaporation of the water in normal circumstances, but which, in the event of a fire, would melt and so allow the ejection of boiling water and steam onto the outer face of the column via a deflector hood. This was a remarkably far-sighted idea although it is doubtful if the system would have worked efficiently as a localized sprinkler cooling the outside faces of the column as Wright intended, and he seemed to under-rate the cooling effect of the water within the column – a principle which is fully exploited in current developments.

It is not surprising that the leading UK producer of hollow steel sections, the then Stewarts and Lloyds Ltd, now part of BSC Tubes Division, have shown a continuing interest in water-filled systems. Seven years ago they sponsored a series of tests according to BS 476 on unreplenished water-filled columns roughly 3m long and 250mm square.[12] The fire resistance, measured by temperature rise, was 30min compared with 15min for an empty column. By inserting a sleeve to improve circulation the time was increased to 45min, and with the addition of an intumescent coating on the exposed surface the fire resistance was raised to 75min. These results suggested that the fire resistance of an unreplenished water-filled column was severely limited: to achieve the minimum useful statutory grading of 1 hour would require a substantial increase in the section size so that the water and heat capacities could be increased to the required value.

As a result, developments of the unreplenishment system appear to have stopped. The author feels that this is particularly unfortunate on two significant counts. First is the established but little known fact that the BS 476 test, and its international counterparts, treats a water-filled member onerously in relation to other structural mediums. This occurs because the flow of fuel to the furnace is regulated throughout a test so that the standard time-temperature curve will always be indicated by the thermocouples which are sited close to the surface of the element under test. If the surface of the element is hot, as with concrete and particularly timber, the thermocouple readings will result in a much reduced fuel supply in relation to a substantially cooler element such as a water-filled column. Governing the fire test environment by thermocouple temperature rather than fuel supply not only seriously under-rates the true fire resistance of water-filled members; it makes a travesty of real fire conditions since it is inconceivable that the combustible contents of a builting alter when it discovers it has a water-filled element in its midst. The second factor is the realization that an element placed outside the façade may not require more than a half-hour fire resistance measured in the stringent BS 476 test. This could correspond to, say, a 2-hour BS fire test for its counterpart within the building which is very much in excess of the requirements for offices and other buildings of similar fire load where water-filled systems have so far been used. As already mentioned, the unfilled element may already have an inherent fire resistance of 15 to 20min so one is only looking for a further 15min contribution from the water. Thus the author would like to see renewed interest in unreplenishment systems.

Little development has taken place in water-filled horizontal beamwork because of the difficulties of establishing the reliable convective water circulation to guarantee heat removal. Quite recently, however, a test on an interconnected rectangular hollow section framework of beams and columns partly sponsored by the British Steel Corporation, Tubes Division, was conducted in the BS 476 floor furnace at JFRO.[13] Fig. 5 shows the framework and the elbow pipes which

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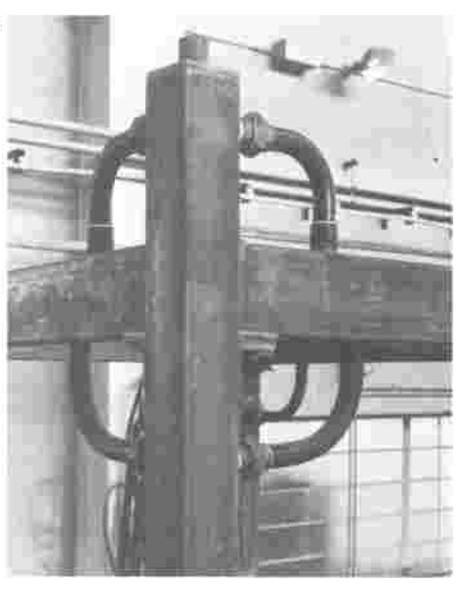

serve to provide water continuity between adjoining elements. The test was run for 75 minutes during which time the steel temperatures had reached equilibrium well below the critical temperature. It is understood that work is now in hand to develop a practical system.

Test work has not been confined to the UK. An early demonstration of the cooling effects of water was made using the Multin system in France.[14] The ladder structure of tubular steel was placed in a crude wood fire in the open and cooled with a continuous flow of water. Very limited measurements were taken and the experiment was merely a demonstration of successful water cooling.

More recently, a fire test has been conducted on a column which forms part of the new Iron & Steel Research Institute building in Dusseldorf which employs a water-filled framework.[15] After a period of 90 minutes in the purpose-made fire chamber operating at a temperature up to 1,000°C, the water replenished 180 × 180 × 10mm rectangular hollow section reached an equilibrium temperature of 200°C.

All these tests clearly demonstrate that a water replenishment system can be relied upon to keep the steel temperatures within the range 150–320°C which is well below the critical limit of 550°C.

Early detailed theoretical analyses of the cooling effects in water-filled steel tubes based on the ISO time-temperature (furnace test) curve were carried out by Ehm & Bongard.[16] They considered unreplenished and replenished water-filled columns, with and without boiling, for various section sizes. Following this, in 1969, Knublauch reported[17] a furnace test on a 220 × 220 × 18mm water-replenished steel column exposed to the ISO fire in which the measured heat transfer rates were 50 per cent higher than predicted by Ehn & Bongard. Accounting for this difference, Ehm suggests that cooling of the thermocouples by radiation to the cool steel surface would lead to a higher fuel input and hence a higher test transfer rate. This view supports the author's previously stated contention that furnace tests on water-filled elements severely under-rate their true fire resistance.

Seigel, the principal protaganist in the USA of water cooling and flame shielding, has also completed theoretical analyses of water cooling effects.[18] He believes that there is so much reliable heat transfer data for water in tubes that fire tests are generally unnecessary. His approach to the design of such systems is admirably simple: knowing the fire severity in the region of the column, the thickness of the column plates, the height of the column and the pressure of the water therein, an estimate of the maximum column temperature may be made. Using this approach he has succeeded in convincing the fire regulation authorities in a number of states of the safety of this technique, although, as will be seen later, this has generally led to an increase in the amount of fire resistance demanded by the regulation authority rather than a reduction one should expect.

A very recent study sponsored by CONSTRADO provides much needed guidance on the detailed procedure for designing a replenishment water-filled column system.[19] It provides a comprehensive review of the theory of heat transfer from which the water storage requirements can be determined and the pipework designed. A useful body of basic data is contained in the Appendices which is adequate for most design studies. Perhaps the most useful part of the report is the worked example which illustrates the total design process for a hypothetical multi-storey steel-framed building with internal and external columns subjected to different fire exposures. On the other hand it is unfortunate, in the author's view, that no consideration has been given to alternative starting points in the design process. It is tacitly assumed that there is no alternative but to accept the fire rating laid down in the building regulations and to derive from this the heat transfer to the elements using configuration factors and the standard furnace time-temperature flux. The alternative approach is to calculate the temperature of the real fire and flame trajectories for the particular building from a knowledge of fire load, ventilation, shape of window opening, etc.

It has been the intention in this article not to describe in detail the theoretical basis of design since this has been comprehensively dealt with elsewhere. In the area of practical design however there are a number of 'common sense' considerations which can be given concisely, and some are now outlined.

Design considerations

Where the total heat transfer to the structural elements is small, i.e. if only a low fire rating is required and/or if the area of all the elements exposed to the fire is small, it may be possible to use an unreplenishment system or a mains fed system with no storage tank. The proposed New Parliamentary Building in Westminster and the Champs Elysées building described later are examples of mains fed systems, but these are at present in the minority.

With greater heat transfers implying a larger fire compartment or a more severe fire of longer duration, a storage tank is usually required. This should have sufficient spare capacity to accommodate the larger volume of water associated with a temperature rise in fire conditions from normal ambient to boiling point, and a water expansion allowance of 10 per cent can be taken as a rough design criterion. The tank should also contain sufficient water to replenish the water lost by evaporation for the expected duration of the fire. Knowing the total heat transfer, the required storage can be calculated.

For high buildings employing water-filled columns it may be necessary to have separate vertical zones to limit the hydrostatic pressure within reasonable limits which do not give rise to distortion of the section shape and elastic instability or leakage. The 256m high columns of the USS Pittsburgh are divided into four such zones which were determined primarily by the strength of economical welded joints under the bursting pressure of 900kN/m^2. There can be no clear cut rule here since the permissible hydrostatic pressure will be dictated not only by head of water but also by the size and shape of hollow section and the method of welding.

Again, with buildings of large plan area it may be desirable to adopt horizontal zoning so that the size of storage tanks are reduced and more easily accommodated while the increased number of tanks which this entails gives greater safety against the effect, however unlikely, of a single system failure.

It is also important that the pipework which provides water continuity between the elements of the frame should be of sufficiently large diameter to avoid excessive frictional losses which could reduce the natural circulation to a dangerously low level. Allowance should also be made for scaling and pitting of the internal surfaces of the pipe, but the use of inhibitors against corrosion and algae growth together with a filling of clean (mains) water provides the necessary safeguards. Strength of pipework is equally important where there is a possibility that buried pipes would be subjected to large differential movement as in earthquake zones. Paradoxically, the pipework should also be flexible and carefully supported so that it is able to move without giving rise to high stresses under temperature movement and this is perhaps most important with pipework exposed to the weather for example on the roof where expansion bends may be necessary in long runs. Adequate long-term protection against external corrosion is of course essential especially with inaccessible pipework.

A feature which should be considered in conjunction with the building approval authority at an early stage in design is the need to ensure that an explosion which may remove some structural elements does not render the water system inoperable leaving primary structural elements unprotected. Another consideration, fortunately not necessary in the UK, is the performance of the structural system in an earthquake.

Potassium carbonate is universally accepted as a suitable anti-freeze additive, although it is not always necessary as demonstrated by the Michelson Plaza Building, Newport Beach.

Design based on these and other relevant

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factors is well within the capability of a competent designer although some reservation is necessary when specialist advice is required. For example, the designer may experience difficulty in deciding the basis of the heat transfer calculations. Again, the designer should co-operate with the mechanical services specialist who will be able to concentrate on the detailed design of pipework, storage and the various valves and devices for pressure testing, monitoring water level, isolating and draining down, etc. Finally there is the matter of patents, which the designer should be careful not to infringe.

Building Regulation requirements in the UK

British building regulation fire gradings for external structural elements are expressed in a simple way, varying only with occupancy, size and height of building or compartment, and relation to the site boundary. It follows that they are incapable of dealing with exceptional cases, even where it can be shown from a rigorous scientific assessment that the regulation grading is exceedingly severe or otherwise inappropriate. Admittedly, the regulation dispensation procedure is intended to cope with exceptions, but it is often time consuming and even though the outcome is certain if the conditions are met the delay is often untenable to the designer who is generally under pressure to keep design and construction periods to the minimum.

What is wrong with the present regulations in the UK? They dictate that elements of frame require the same fire resistance, typically 1 hour for multi-storey offices and dwellings up to 28m high, irrespective of where the elements are placed. At the time when the present regulations were formulated, external structural members were unknown and it is therefore not surprising that the gradings assumed that all structural elements were contained within the external envelope. The result is that steelwork, placed external to the building façade, perhaps spaced away from the window or shielded behind a brick wall or mullion, is required to have the same fire resistance as an element at the seat of the fire. This is clearly wrong. Yet, whilst the regulation authorities recognize the anomaly and will consider favourably an application for dispensation if it is supported by the Joint Fire Research Organization, they are reluctant to talk about basic changes in the regulations until they are satisfied that any test work can be shown to be fully representative of the many possible fire conditions in real buildings and that the necessary building controls can be effectively enforced.

Drawing on recent experience of attempts to bring changes both in regulations and, equally important, the enforcing bodies, governing the acceptance of open-sided multi-storey steel-framed car parks, suggests that it will be exceedingly difficult to alter the basic regulations to allow for external steelwork in the short term.

WATER-COOLED BUILDINGS IN THE USA

American Securities Insurance Co., Offices, Atlanta

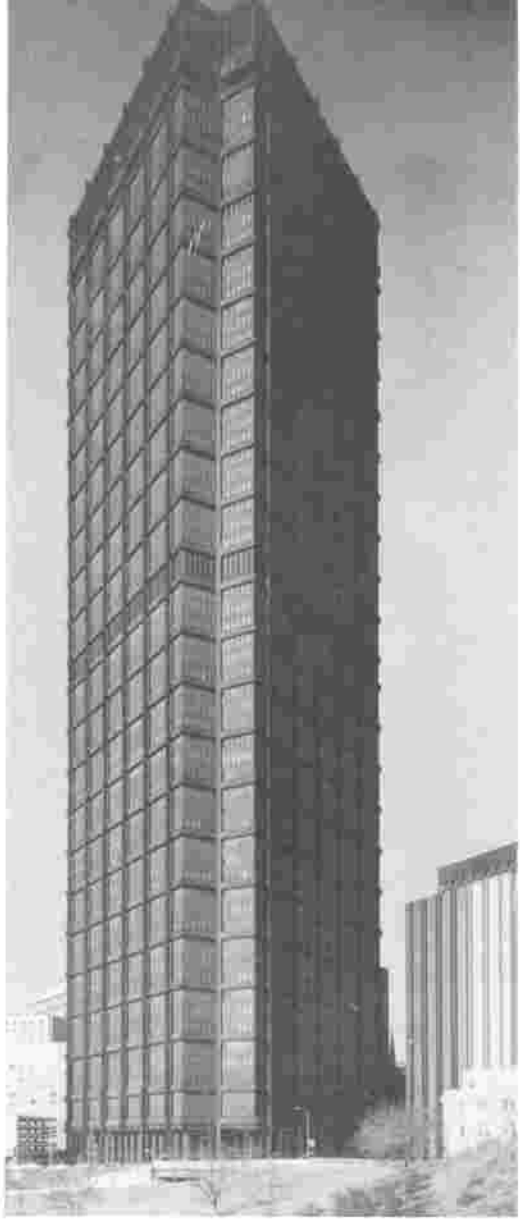
This four-storey building, employing twenty water-filled external columns of Cor-Ten from the first floor upwards, was the first water-cooled building to be completed (1970) in the USA (see Fig. 6). The 250mm × 250mm × 98kg/m I-section columns have a Cor-Ten closure plate welded to the inner flange tips to contain the water, and a detail of the beam to column junction is shown in Fig. 6a.

The closed loop system is fed by a roof tank with enough replenishment water to provide a 4-hour rating which is in excess of the building code requirement. The project is fully described elsewhere.[22]

USS Corporation Head Office, Pittsburg (Fig. 7)

The major impetus to water-cooled developments came in 1967 when United States Steel Corporation announced that its new 64-storey building in Pittsburg was to have exposed steel columns filled with water instead of the traditional US method of spray coating concealed by column covers. The architects, Harrison Abramovitz & Abbe, considered that columns placed outside the façade would not only produce a bold architectural expression but also preserve unimpaired modular flexibility of interior office space. The triangular building has six Cor-Ten welded plate columns 915mm deep by 610mm wide along each of the three sides spaced 1m away from the wall. The primary beam stubs, which transmit the loads to the columns at every third floor level, project beyond the façade and are also filled with water to provide fire protection. The arrangement is shown in Fig. 8. The 256m high columns are divided into four vertical zones to limit the hydrostatic stresses to 900kN/m^2; and to prevent the development of high bursting stresses caused by freezing water some 625 tonnes of potassium carbonate are mixed with the 1·8 million litres of water which is also corrosion inhibited (with potassium nitrate). Inside the triangular service core at the top of each zone is a single, vented storage tank connected by pipe loops to the tops and bottoms of the 18 columns within that zone. This impressive building has been fully described elsewhere.[20]

In a building which is innovatory in so many



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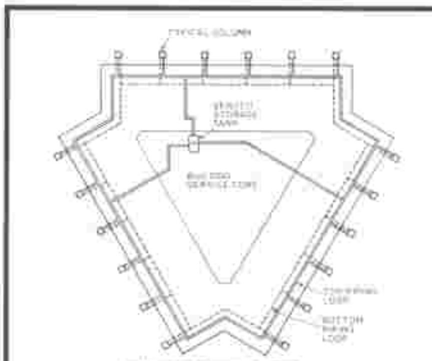
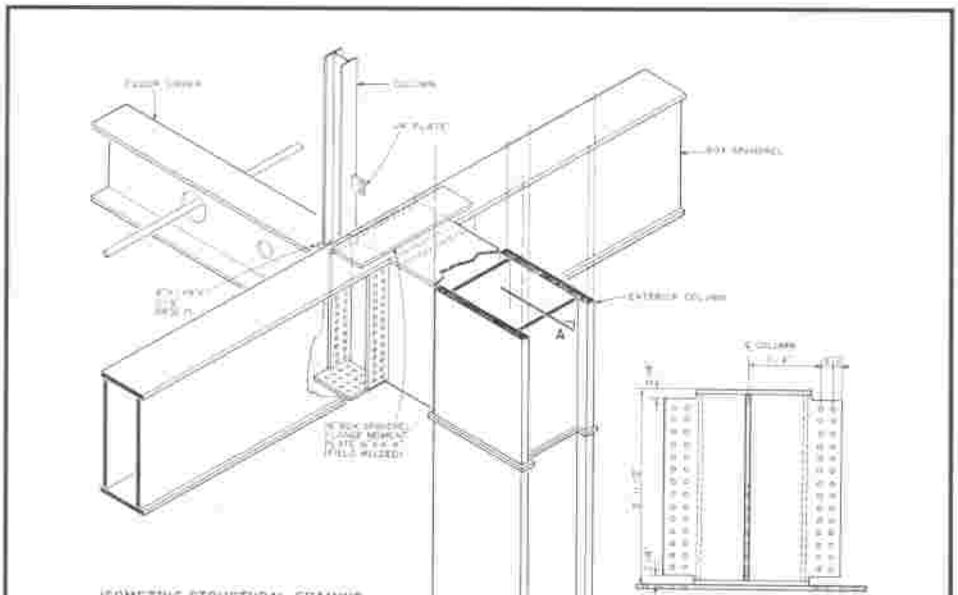


8 SCHEMATIC PLAN OF FIRE-PROOFING SYSTEM



ISOMETRIC STRUCTURAL FRAMING SCHEMATIC AT EXTERIOR WALL

END VIEW AT C

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ways it is a pity, and more than a little ironical in the author's view, that it offers a classic example of the enforcement by the fire regulation authority of excessively high safety factors. Detailed fire-load surveys in offices such as this have shown[21] that the combustible contents are small and cannot give rise to high fire ratings. So it is surprising to discover that interior columns and bracing elements in the Pittsburg building require a 4-hour fire rating, while other structural members require 3 hours.

It could be argued that such a massive external column construction, employing 100mm and 38mm thick flange and web plates respectively at the base of the building, would have sufficient inherent fire resistance to make water filling superfluous in the lower most zone.

Airport Business Centre, Newport Beach, California

Architects Craig Ellwood Associates have achieved a Meisian aesthetic of simplicity and elegance which would have been difficult, if not impossible, to achieve without resort to water cooling[23] (Fig. 9). The whole development, which includes 2 single-storey banks and 2 four-storey office buildings, employs a common 150×100mm fabricated hollow section of Cor-Ten based on a 1·5m external wall module, but only the columns in the larger buildings are water filled. The columns not only carry the usual vertical loading of the building but also act as mullions for the window wall with the aid of neoprene gaskets. In the case of the four-storey office building a lattice truss floor joist is used to span from the central concrete services core to the external columns. This means that a sloping soffit can be used for each floor around the periphery (see Fig. 10) resulting in narrow spandrel details. The building displays a dominant aesthetic both internally where a sensation of increased height is achieved and externally where the angled soffit softens the otherwise grid-like design.

Michelson Plaza, Newport Beach, California

A bold exterior, using an 'honest' exposed steel structure, and a column-free first floor were two of the main objectives of Bissell/August Associates, architects for this four-storey office building which is notably the first to employ water cooling in the roof beams as well as the external columns[24, 25] (Fig. 11).

The exterior structural system consists of large portal frames of 16m span and 15m height spaced 7·5m apart. Wind and seismic loads are carried by concrete towers at the end of the building. Exterior water-filled columns and beams are 610 × 200mm and 1,370 × 300mm overall respectively and are fabricated from Cor-Ten plate. The details are shown in Fig. 12.

The exposed roof-level beams have a dual function. First, because of their large water capacity, they are fortunately able to supplement and thereby reduce the size of the two separate water service tanks. Secondly, they act to suspend at mid-span the underlying roof and intermediate floor structures using simple suspension straps of steel plate.

Water cooling is by the water replenishment system and is shown diagrammatically in Fig. 13. Frames are filled to within 150mm of the top of the beam and because freezing does not occur in the area only a rust inhibitor is necessary. It should be noted that in addition to the usual practice of connecting each element of a frame to allow gravity circulation, there is interconnection between frames at ground and roof levels. Evaporation during a fire is allowed for with the use of a pressure relief valve or rupture disc set to open at 20kN/m².

The fire rating requirements for this building are a little unusual.[26] Under the Uniform Building Code (one of the four main codes in the US) the building was rated as a Type IV structure requiring 1-hour fire protection. However, like the British fire regulations, the American code does not specifically cover water-filled structures and it was therefore necessary to discuss the requirements with the Orange County Department of Building and Safety. After a thorough examination, the Department decreed that the columns should be capable of withstanding a 4-hour ASTM-E 119 furnace test (this is comparable to the BS 476 test), whereas the beams need only possess a 1-hour rating. It is difficult to understand why such high standards of fire resistance should be required for the external columns since, as the author has already pointed out, it is impossible in low fire-load buildings such as offices to achieve such a high fire severity.

Fortunately it was found that the additional water required to give the column the extra fire resistance was already within the roof beams which served to supplement the 14,500-litre tanked storage also at roof level. With the greater water flow it was merely necessary to increase the strength and diameter of the underground line from 38 to 63mm and similarly increase the size of water passages in the beam plates from 50 to 100mm diameter.

The Building Department also made a number of other safety measures mandatory which appear reasonable. There should be provision to inspect the water level within the system; pressure testing of the underground piping; and water treatment. To satisfy these requirements the following provisions were made. Water level would be checked with pressure gauges in the two expansion tanks, and as a second precaution removable pressure relief caps on the tanks are provided which allow visual inspection of the water level. For water treatment the system is filled with clean water, free of suspended solids, treated with a corrosion inhibitor. The underground loop system is hydrostatic pressure tested to 345kN/m² in situ, and the columns are pressure tested to 240kN/m² at the fabricator's works.

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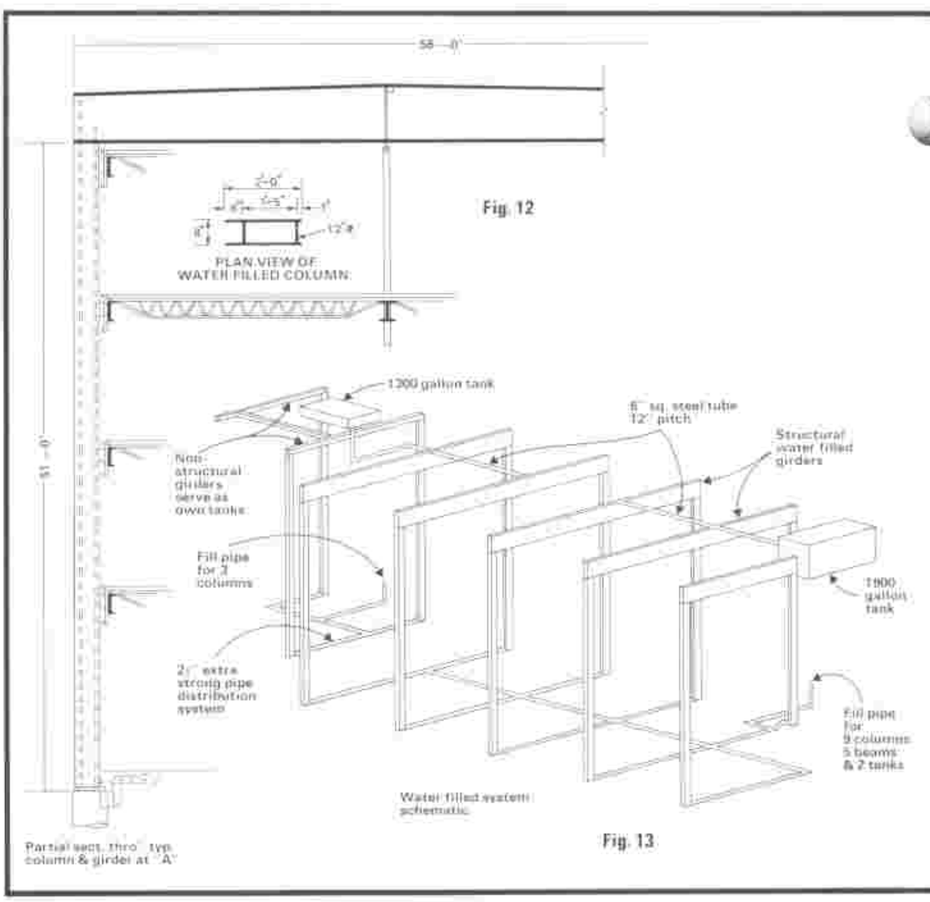


Fig. 12

Fig. 13

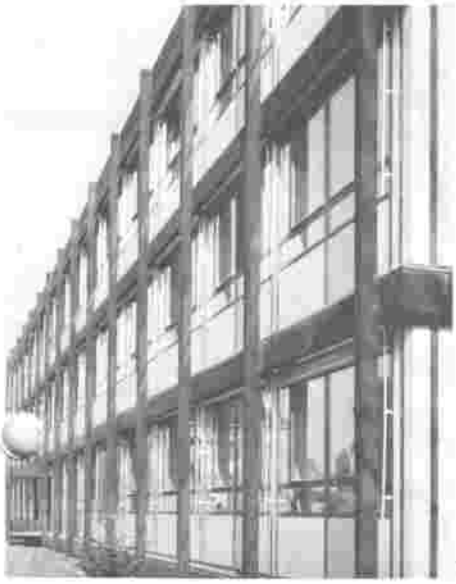
10

11

Other recent buildings in the US

The most recent US construction to use water-filled exterior columns is a seventeen-storey office block of 330,000ft² in Southfield – second only in size to the USS Pittsburg building. Now under construction, it forms one of two identical office blocks as part of a $40m cluster of high-rise buildings in the North Park Plaza.

Again based on Seigel's work, a twenty-storey building is planned for St Louis. This will be fire protected externally with a combination of flame shields and water cooling.[27]



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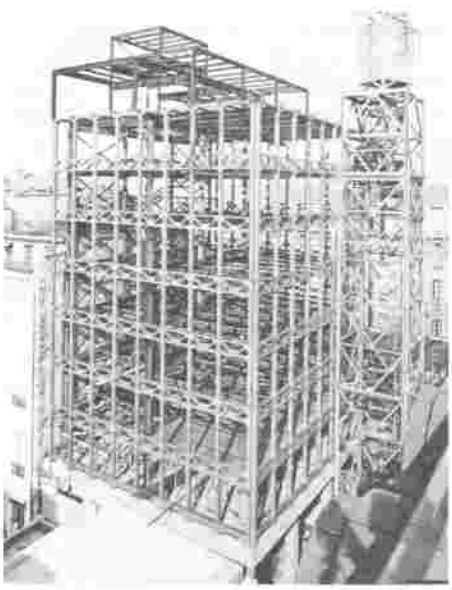
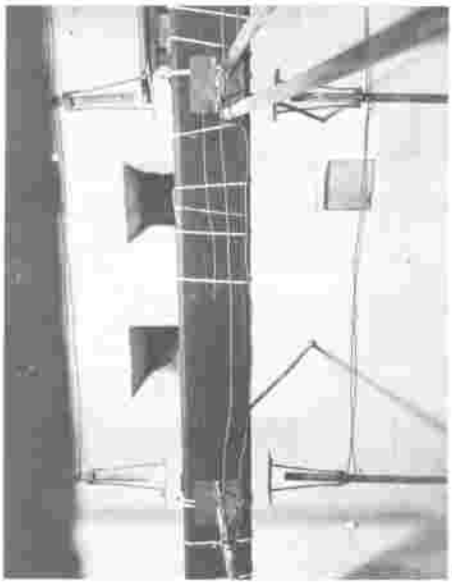


16

WATER-COOLED BUILDINGS IN EUROPE

The BFI Building, Dusseldorf

Completed in 1971, the new Operations Research Institute of the German Iron and Steel Producers Association, Dusseldorf, is the most recent building project to use water cooling in Europe[16] (Fig. 14). The three-storey office building, known as the BFI Building, has a concrete core, internal columns of asbestos-cement encased I-sections, and external water-filled columns of 180 × 180 × 9mm RHS in Cor-Ten which are spaced a short distance outside the façade.



15

Above: The column prepared for the fire test. Column wall thermocouples, fire chamber measuring thermocouples (with radiation protecting shields against cooling effect of cold column walls).

17

Like the other projects already discussed, the water replenishment system of the BFI Building uses connecting pipework at ground and roof level to permit circulation, and roof-top storage tanks.

Due to lack of knowledge of the effectiveness of this fire-protection system in Germany, the client had to provide detailed calculations, apply model test techniques, and finally verify the data by resort to a full-scale fire test. The test was conducted on one of the columns of the building (Fig. 15) and it proved that at the end of a 1½-hour furnace test to DIN 4102 (comparable with the BS 476 test) the temperature of the steel had reached a maximum equilibrium temperature of only 200°C.

It is expected that this project will pave the way for others in Germany especially if the results of Grossman's cost study are accepted.[28] He claims that water-cooled buildings which are over five-storeys high and based on the same plan and structural system as the BFI project are cheaper than buildings using traditional encased columns. Certainly this is not at odds with the claims of the promoters of water cooling elsewhere.

Again, the publication of Polthier's wide-ranging Note 467[29] should do much to promote water-cooled projects in Germany. Amongst other things, the publication gives guidance on likely fire ratings for different water-filled columns, economics and building approval.

UAP Offices, Marseilles

This eight-storey building, the second water-cooled project in France, illustrates that it is feasible to fire protect by water filling both the internal and external columns.[30] The building which also has seven basement storeys constructed in reinforced concrete, abuts another with the result that there are three external walls employing 180 × 180mm RHS columns (which act with lattice perimeter beams to take the wind load) and a single row of three internal columns of 250 × 250mm RHS. Other structural elements, including those in the party wall, are encased in concrete or protected by masonry (Figs. 16 and 17).

127 Champs-Elysées, Paris

Water-cooled elements were chosen for the replacement external columns in the ground-floor offices of the French National Railways because they occupied the least possible space.[31] Four hollow steel column sections 500 × 400mm fabricated from 20mm plate occupy only one-fifth the space taken by the previous masonry pillars.

Unlike other projects, the water replenishment system is based solely on mains supply so that a storage tank is unnecessary. In the event of fire the water circulates through the columns via concealed 110mm diameter pipes at floor and ceiling level by natural convection giving an estimated 40min fire resistance. Greater, possibly unlimited, fire resistance is achieved by running the water to waste and replenishing it with a continuous supply from the mains.

This conversion, designed by Forester and Goldfinger, provides a convincing demonstration of the enormous transformation that is possible using slender water-filled elements (Fig. 18). Further, by coating the sand-blasted steel with a robust clear varnish, the external surfaces exhibit an attractive tint which again expresses the honesty of the structural medium.

Fig. 18a & b. Before and after conversion.

a
b

New Parliamentary Offices, Westminster, London

The prize-winning design in the 1970 Commonwealth Architectural Competition incorporates four reinforced concrete service cores which support a 3-layer high-strength steel space frame roof 90×60×7m deep, clad with transparent plastic roofing panels (Fig. 19). Five intermediate floors are suspended from the primary nodes of the roof, leaving the ground-floor area free of the usual network of columns. It may be of interest that the column-free ground floor also simplifies the foundation problems associated with the London Transport underground railway which runs diagonally across the site between the supporting towers.

The architects, Spence & Webster, originally proposed using a forced water circulation throughout the tubular space frame roof to achieve the required one-hour fire rating. The high-strength steel tubes, up to 450mm diameter with wall thickness of 10mm, would be assembled on site using hollow spheres at the nodes. Two alternative methods of fire protection were considered:

(i) a hollow circuit through the whole of the steelwork filled with water with facilities for topping up and water circulation. The water would have anti-freeze and anti-corrosion additives, and the structure would be connected to the water mains and would be at mains pressure, with a thermostatically controlled valve leading directly to a drain to the river. At a predetermined temperature, the valve would open, allowing water to circulate through the structure, providing indefinite fire protection.

(ii) sprayed concrete on a high-tensile steel mesh, clad in sheet metal casings.

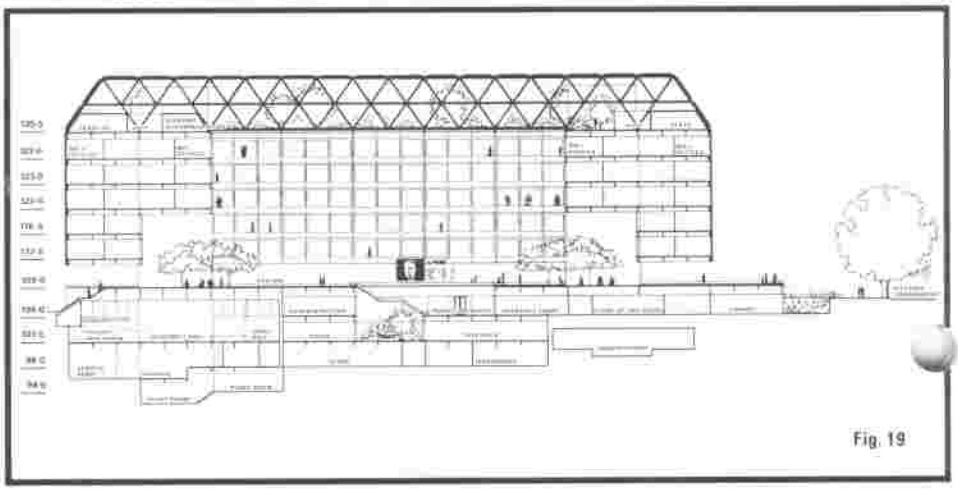


Fig. 19

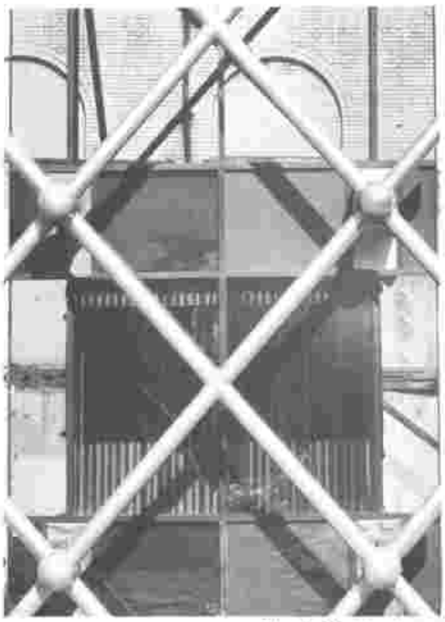


Fig. 20. Model under test.

However, subsequent architectural development has led to the abandonment of the 3-layer space frame roof in favour of a 2-layer grid which, because of the non-availability of larger circular hollow sections in standard form, now incorporates rolled steel I-sections fire protected in the conventional manner and clad with sheet metal.

Prestige Office, London (Fig. 20)

Pioneered in the United States of America and Europe, the first building using water filling for fire protection of steelwork in the United Kingdom is an eight-storey prestige office building planned for the City of London.[32]

Arup Associates, the architects and engineers, have designed a structure capable of resolving the large cantilever moments created by the inset columns. The position of these was imposed by restrictions stemming from sub-soil conditions. This structure is a lattice of welded tubular sections set 600mm outside the line of the glass curtain wall, thus providing an uninterrupted floor space.

The lattice, which forms a suitable shape for circulation of the water filling which provides the required one-hour fire protection, is constructed in stainless steel, the nodes being castings and tubes spun castings.

This steel structure provides a relatively light building, necessary here because of the limited area for foundations referred to previously. It also assists in the speedy construction required to meet time considerations.

The building is innovatory in at least two respects – it uses cast stainless steel structurally and it overcomes the problem of indeterminate water circulation in horizontal beamwork through the shape of the inclined lattice members in which natural circulation occurs.

Availability of weathering steels in the UK

Before finally committing himself and his client to the use of water-filled bare steelwork the designer should check on the availability of weathering steel in the sizes and quantities required. The most widely known weathering steel is the original USS product marketed under the Cor-Ten trademark which the BSC is licensed to use. Available in two grades A and B, Grade A is suitable for welded structures up to about 13mm thick while Grade B is weldable in greater thicknesses and has better impact properties. Other brands previously produced by the BSC have been discontinued and, apart from Tubes Division who market their own Stalcrest, Cor-Ten is now the only weathering steel currently produced by the BSC. Weathering steels are included in the latest 1972 edition of BS 4360: Cor-Ten being covered by grades WR50A1, etc, for plates, sections and bar, and Stalcrest under grade WR50 for structural hollow sections.

While, in principle, the full range of structural products (i.e. sheet, plate, structural shapes and bars) is available in Cor-Ten steel, the BSC does not stock finished products, a situation which incidentally also applies to other qualities of steel, and as yet stockholders do not carry Cor-Ten. There is, however, one stockholder in Scotland carrying a range of Cor-Ten in strip mill sheet gauges and light plate up to 6·5mm and also heavy plate above 6·5mm. In addition, BSC has made arrangements with a private re-rolling mill on the north-east coast of England to supply small sizes and quantities of Cor-Ten plate to order.

Mill quantities for Cor-Ten sheet and light plate up to 6·5mm are generally available in 10-tonne lots of a size, i.e. length by width by thickness, whereas for plates the minimum quantity per size is about 3 tonnes depending on gauge. From the strip mill cold reduced sheet is available from 0·787–1·65mm and hot rolled sheets and light plate from 2–6·5mm thick. Plate mill sizes are available within the same range as other specifications such as 43A, 50B, etc, subject to the maximum thicknesses recommended for Cor-Ten.

Generally, all structural shapes are available in Cor-Ten and where projects using Cor-Ten are involved, every effort should be made to keep the number of sizes to a minimum. For joist sections the BSC endeavour to supply minimum quantities of about 2–4 tonnes per size according to the actual type of section involved, whereas for universal beams and columns the minimum quantity is in the region of 8–10 tonnes. All are suitable for weathering applications in the mill finished condition or descaled.

Hollow sections beyond the size range of Tubes Division products can be fabricated by welding plates across the toes of suitable rolled sections such as channels, by welding two channels together or by using four plates, etc. This was the method adopted with the US water-cooled projects so far because of the large sizes involved. In contrast the structural system of the BFI building in Düsseldorf uses 180 × 180mm rectangular hollow sections (RHS) in Cor-Ten steel. Tubes Division can provide a wide range of sizes and thicknesses of circular hollow sections (CHS) and square and rectangular hollow sections in Stalcrest, Grade WR50 of BS 4360. This steel has similar weathering properties to Cor-Ten but a slightly higher yield strength in line with the requirements for Grade 50. There are, however, limitations on the minimum thicknesses which can be produced. For example, in the largest sizes the minimum thickness is 12·5mm, whereas in other grades, e.g. ordinary mild steel, it is 8·8mm for CHS and 9·5mm for RHS. Further, the percentage increase in minimum thickness varies with the process of manufacture. There are also limitations of the minimum tonnage order which can be accepted for mill rolling and there are at present no stockholders. As a rough guide there are minimum requirements for both total order quantity and for each size and thickness involved, i.e. for the steel and for the rolling mill depending on the processes involved. This can vary from 3 tonnes up to 90 tonnes for steel and from 3 tonnes up to 30 tonnes for item size and thickness rolled. In the design the range of sizes used should be kept to the minimum since it is not possible to produce small quantities of a large number of sizes.

Even accepting these transient limitations, the present availability in the UK of various qualities and forms of weathering steel should provide a big boost to water-filled steel developments: increasing demand for rolled hollow sections or fabricated forms should be matched by the provision of ingot stocks leading to the elimination of a minimum steel requirement and ultimately to a number of stockholders carrying at least a limited range of sizes likely to be required.

Economic advantages of water cooling

If the element requires a fire resistance greater than its inherent unprotected value, water cooling can provide an economic advantage when compared with traditional methods of protection. In the case of the sixty-four-storey USS building a saving of $1 million is claimed against the cost of conventional fireproofing which would have involved a sprayed-on cementitious material faced with $1\frac{1}{2}$ha of light gauge Cor-Ten column covers for the 5km of columns.

By placing the structural steel elements outside the building it is possible to use a weathering steel which provides a bonus of higher strength and requires no maintenance. The 20 per cent extra 'first cost' of high-strength weathering steels compared with mild steels can usually be more than offset by the continuing cost of the periodic painting and cleaning necessary for coated mild steel.

Again, the space saving gained by the elimination of a conventional encasure can be useful while the important space savings achieved by repositioning columns outside the façade are matched by the greater convenience and flexibility of internal planning. These are not marginal advantages but substantial; optimum use of floor space is gaining greater importance in central urban areas where, for example, office rentals have now exceeded £220 per square metre for prime locations in London. It is also possible that reduced insurance premiums will be obtained with the use of water-replenished systems because of their permanent fire resistance.

Conclusions

It will be clear from the developments described that water cooling of hollow structural steel elements appears most beneficial when the elements are placed outside the façade. These are some of the advantages: less severe fire environment; the provision of maximum areas of column-free floor space; the attainment of optimum slenderness ratios for columns with aesthetic merit; the possibility of using a nil-maintenance weathering steel with an attractive purple-brown patina; and a virtual guarantee of unlimited fire protection in the case of a water-replenishment system. Economic advantages are less easy to predict, but it does appear that the additional cost of providing water storage, pipework and accessories is more than offset by the elimination of conventional fire-resisting encasure and the savings in floor space which can result.

Although most water-cooled projects covered in this review have employed a weathering steel, other possibilities should be considered at the feasibility stage. Where the location of the building is such that the initial run-off of corrosion products in wet weather might cause a nuisance to passers-by, it might, under these seldom occurring conditions, be necessary to consider a painted structure or even one constructed of stainless steel.

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