DESIGN OF STRUCTURES AGAINST FIRE

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Preface

Over the past two decades a considerable amount of effort has been directed towards producing what have been described as rational methods of design of structures to resist the effects of fire. It, therefore, also has become apparent that traditional methods of fire design using 'deemed to satisfy' clauses in Statutory Regulations or Design Codes of Practice are inadequate due mainly to their conservative and restrictive nature. Equally it has become recognized that the standard furnace test bears little or no relation to the actual structure behaviour in a real fire. Thus it has become necessary to propose new methods, and the approach known as Fire Engineering has been evolved.

In order to be able to produce calculation methods for fire design, it has been necessary to undertake research on the behaviour of structural materials at elevated temperatures. The current position here is exemplified by the recent reports on steel and concrete published by the RILEM Committee No 44-PHT under the chairmanship of Bill Malhotra. Calculation methods have progressed in two directions: those involving finite element techniques, including the solution of the heat transfer equations, and those involving simple numerical or graphical techniques. It is inevitable that whilst research will utilize the more complex methods of approach, the design engineer will need a simpler (but not necessarily simplistic) approach. At one end of the spectrum Fire Engineering may become a specialist discipline when dealing with large complex structures and unusual fire exposure conditions, but at the other, when dealing with normal structural problems, it should become assimilated into the normal design process.

The papers contained within this volume are concerned with evaluating the current state of Fire Engineering Design, and also with the ground work that will form the basis for an increased usage of such design methods in the future. In order to do this, five areas of importance were identified. These are dealt with individually:

1 *Fire Protection*. In this section the basic need for Fire Protection and the modelling of fire response is dealt with.
2 *Material Behaviour*. This section deals with modelling the behaviour of basic construction materials at elevated temperatures and their use in calculation methods.
3 *Design Concepts*. This section deals with the philosophy behind fire design—namely an extension of limit state methods—including computer applications.
4 *Design Implementation*. This considers the different approaches required for design in each of the common structural materials.
5 *Post-Fire*. The last section considers what happens after a fire and the measures needed to reinstate a structure.

It is anticipated that within the next decade, increasing advances will be made and that these papers will go some way to stimulating these advances.

The Editors wish to place on record their thanks to all the authors for having produced papers and for having been willing to share their knowledge with others. The Editors also wish to thank the Department of Civil Engineering and Construction, Aston University for their support during this venture.

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A SURVEY OF FIRE PROTECTION DEVELOPMENTS FOR BUILDINGS

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ABSTRACT

Fire protection requirements date back to middle ages but only over the last 100 years or so has some pronounced progress been made in the technical content. Whilst the fire protection needs are understood their specification is still far from rationally based. More progress has been made in the field of fire resistance and fire severity estimation, but less so in the inter-actions which exist amongst different measures. For a rational system fire engineering principles need to be applied to the whole field of fire protection for buildings.

INTRODUCTION

Concern with fires in buildings can be traced back to the fire tragedies which have occurred in the past and devastated cities and towns. The burning of Rome in AD 64, the Great Fire of London in 1666, the fire in Hamburg in 1891 and the destruction of Baltimore in 1904 are only a few of the examples. In each case there was a follow up particularly with the objective of improving constructional standards for buildings, their separation from each other and fire fighting facilities. Despite these rules serious fires have continued to occur, perhaps with less frequency and with only restricted spread to other buildings. Concentration of low rise buildings with narrow streets has been replaced by high rise or high density occupancies each housing a few thousand people.

The objectives of fire protection in buildings can be summarised as:

1) safety of occupants, i.e. life safety,
2) minimizing fire damage, i.e. property protection, and
3) prevention of conflagrations.

Life safety is the declared objective of most governmental or local authority control although some of the requirements are set at a level where property protection is also assured to a certain extent. Occupants are put at risk at the start of a fire and it is often suggested that they move to a place of safety, inside or outside the building, in less than 30 minutes, hence requirements in excess of this period could have property protection implications. Whilst this assumption may be true for low rise, low density occupancies, in larger buildings it is often necessary to assure the stability of the structure for the whole process of fire development and to protect the adjacent buildings for as long as the fire is likely to last. This is particularly the case with high rise structures and complex assembly type occupancies such as shopping malls.

Property protection was at one time considered to be of significant interest to the community and fire regulations made no distinction between requirements for life safety or property protection. However, when the insurance companies came into being and initially had their own fire fighting equipment, property protection became a matter of business agreement between an owner and his insurance company. The fire brigades became the responsibility of local authorities in the eighteenth century and fire insurance developed new approaches to property protection. Isolation of risks by substantial fire barriers and the use of sprinkler installations has become the mainstay of insurance philosophy.

The current fire protection system in most countries is such that the central or local authorities make rules and regulations to ensure the safety of life and prevent the spread of fire from building to building and the property protection is left entirely to an insurance arrangement. Because some of the current regulatory requirements are a reflection of the past practices the measures have some relevance for property protection as well.

COMPONENTS OF FIRE PROTECTION

Comprehensive fire protection requirements need to consider a number of aspects from fire prevention to fire safety management. At least 10 distinct needs can be identified:

1) Prevention of fires,
2) Detection of fires,
3) Delaying fire growth,
4) Controlling movement of smoke,
5) Providing means of escape,
6) Restricting fire spread,
7) Preventing collapse of the structure,
8) Controlling fire,
9) Fire fighting, and
10) Fire safety management.

The first and last are usually not included in any building control system and are taken care of by some subsidiary system on the use of energy producing or using appliances and licencing requirements for the premises. Such measures also have no direct relevance to the construction of a building. The other measures can be divided into two categories, passive and active. Passive measures are those which are provided as an in-built feature of the building and are operative at all times, whereas the active measures may be provided during or after construction but they become operative only on the occurence of a fire. Eight of the measures listed above will be categorised as passive or active as below;

Passive	Active
Delaying fire growth	Detection of fire
Controlling movement of smoke	Controlling movement of smoke
Means of escape	Controlling fires
Restricting fire spread	Fire fighting
Preventing collapse of structure	

Measures for the control of smoke movement can be partly of a passive nature and partly of an active type. The provision of smoke control doors is a passive measure but the extraction of smoke by mechanical means will come into operation when a fire occurs and a signal is received from the detection system.

The other passive measures are concerned with providing a construction with such surfaces, and where possible with such contents, that a fire will not grow rapidly. The quicker a fire grows less time is available for occupants to escape to a place of safety. Control on linings has been the traditional approach to controlling growth rate. However, it is now (1) recognised that the rate of heat release and the thermal inertia of linings can also be critical factors and some additional control is needed to ensure that the growth rate will be predictably slow. Provision of means of escape requires protected escape routes, smoke control facilities, fire resisting doors and the maintenance of compartmentation. Two purposes of these measures are that the conditions will remain reasonably safe for occupants and sufficient protection is available to move to a place of safety. In large and complex buildings immediate total evacuation will not be possible and the need for places of temporary refuge in the building exists.

The other main purpose of passive measures is to contain a fire and its effects within defined boundaries. This is the main purpose of compartmentation and is achieved by having compartment boundaries which do not collapse in a fire and maintain their integrity. Fire can spread by the collapse of barriers, by the formation of openings which permit hot gases capable of causing ignition passing to the non-fire side and by excessive transfer of heat through the construction such that the materials in contact with the barrier may ignite. Acceptable limits for gaps related to their size and position are specified together with limits on the temperature rise of the unexposed face. There are no statistical data available to show whether fires in practice exploit these mechanisms and whether the limits are correct. Some limited experiments show (2) that the temperature rise limits are very safe.

The whole of a building may be a single compartment if it is small or a building may be divided vertically and/or horizontally into smaller portions. Empirical rules for compartmentations are contained in many regulations and building codes but it is difficult to untangle the precise logic behind these requirements. The sizes of compartments are related to the building occupancy, the building height and the fire resistance of the boundaries. Sometimes the nature of the construction is also taken into account. It is often suggested that a direct relation may exist between the size of the compartment and its fire resistance, i.e. by doubling the fire resistance the size of the compartment may be proportionally increased. An increase in the floor area of a compartment will obviously increase the size of a fire but not necessarily its severity, at least not in the same ratio unless the fire regime changes from fuel bed controlled to ventilation controlled. (Fig. 1)

A more rational basis for the size of a compartment can be the number of occupants at risk or the ability of the fire brigade to fight a fire. Due to the difficulty of attacking a fire in a high rise building it is customary to make every floor a compartment floor above a certain height, usually when outside the reach of fire brigade ladders. Building codes in North America also allow the sizes to be increased if a building can be approached by the brigade with their appliances on more than one side. An island site can be theoretically four times the size of a building approachable from only one side. May be the compartment dimensions could also be linked with the throw of a hose jet. (Fig. 2)

The association of the fire resistance requirements for different occupancies with their expected fire load seems to be based on the work done by Ingberg (3) in 1928 (Fig. 3). This has often been used to justify the regulatory requirements and sometimes the steps used. Experimental work in the late 50's and early 60's showed that fire severity depended on a number of other factors, most significantly the ventilation conditions (4). The most commonly accepted relationship used for this purpose is,

$t_f = q_f \times A_f \times k$ (min), where

t_f is the fire resistance

q_f is the fire load density (MJ/m^2),

A_f is the floor area (m^2), and

k is a constant.

This relationship is a simplifcation of the actual fire conditions into an equivalent period under the standardised furnace heating conditions which will cause similar damage for specified type of structures.

ACTIVE FIRE PROTECTION MEASURES

Detection of a fire by the use of automatic sensors is an active measure as it functions only when a fire has started. Detectors indicate that a fire has been noticed but will do nothing to control it unless some other system is also activated as a consequence. By noticing a fire at an early stage more time is available for occupants to escape and earlier action can be taken to control the fire. A detection system needs to be coupled with an alarm system, the alarm can be to the management, occupants of the building and to the fire brigade. In the last case there is direct positive action towards controlling a fire. Fire detection signals can be used to function other systems such as closing doors, shutters, escalators, operating smoke extracts or pressurization systems.

The active control of a fire requires the provision of an extinction

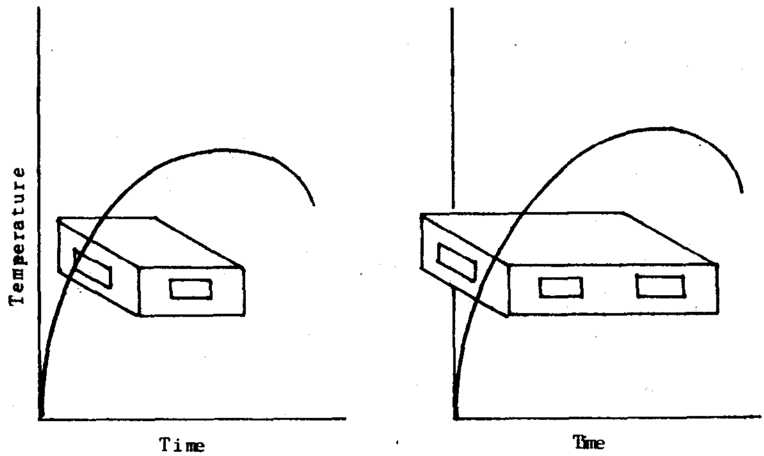

FIG. 1 EFFECT OF COMPARTMENT SIZE ON FIRE SEVERITY

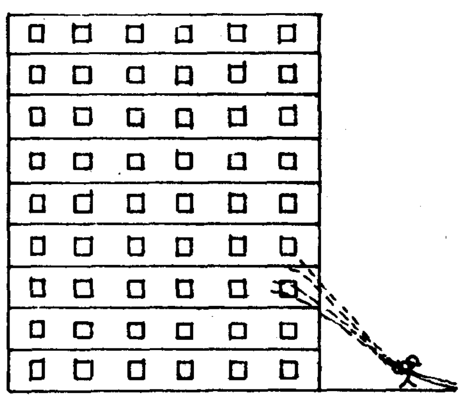

FIG. 2 COMPARTMENTATION AND FIRE FIGHTING

system, the most common example of which is an automatic sprinkler installation. The sprinkler head acts as a detector, opens the orifice through which a spray of water can be applied to the fire underneath. When properly designed and installed the fire will either go out or its rate of growth severely curtailed. Theoretically extinction is the objective but practically the control of the fire size is the main achievement. Statistical data from industrial fires show (5) almost all fires where sprinklers operate are contained within the compartment or the floor of origin.

The sensitivity of the normal glass type or the fusible link type sprinkler heads, with an operating temperature of around 80°C is less than that of a smoke or even a heat detector. The fire is not detected early enough to make a substantial difference to the escape facilities. Recent developments in the design of sprinkler heads have led to the emergence of fast response sprinklers. Their response time is of the same order as heat detectors, hence they can contribute towards life safety as well as fire control (Fig. 4). Sprinkler systems are frequently connected through alarm valves to the fire brigade, this can lead to an early extinguishment of the fire.

Under many building codes, regulations or other legislation in some buildings facilities have to be provided for the access of the fire brigade to the site, and the availability of water supply. In the case of high rise buildings or special risk multi-storey buildings some stairways and lifts may be specially protected to remain available to the brigade. Factors which affect fire brigade contribution are the time at which it is informed, its nearness to the building and ease of access to the seat of fire.

INTER-ACTION

Not only is there inter-action between measures for life safety and property protection but also between some in each category. If a measure influences the fire phenomenon or the time base in any way it will have some consequence for other fire dependent measures. There is at no universal recognition of these inter-actions and no quantification of the influences. A number of countries have made allowances for some of the measures, usually by giving a compensation in passive requirements if an active measure has been provided. Some of these influences are shown below:

Fire detection ← Means of escape
Fire detection ← Fire resistance

Sprinkler system ← Fire resistance
Sprinkler system ← Compartmentation
Sprinkler system ← Building separation

Fire detection by ensuring the awareness of a fire to a predictable early point increases the time available to occupants to escape and therefore they can either travel longer distances or at a slower speed. This can influence the design of escape routes and exit facilities. An early awareness of a fire can also enable an early attack on the fire provided

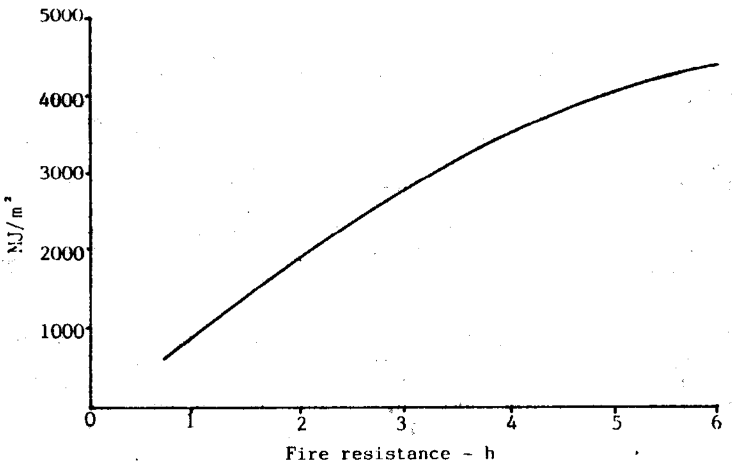

FIG.3 FIRE LOAD V FIRE RESISTANCE (ref 3)

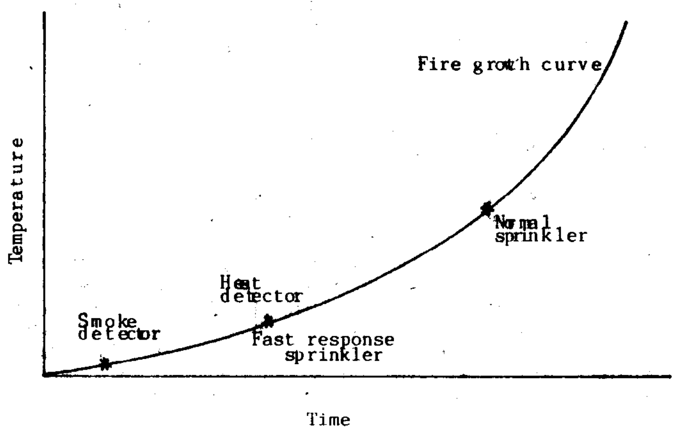

FIG. 4 RESPONSE TIMES OF VARIOUS APPLIANCES

trained personnel are available or the alarm is linked to the fire brigade.

Automatic sprinkler installations have been shown to have a marked effect on the pattern of fires as indicated by an assessment of fire damage or fire spread. (5) The influence on the growth stage can be assumed only if rapid response sprinklers are fitted. Once the system operates it may quickly extinguish a small fire or if the fire seat is concealed it may still control its rate of growth and keep its severity low. With a properly designed, installed and maintained system a significant influence on fire resistance can be foreseen, and as a further consequence on the compartmentation requirements and on the separation specifications to prevent the spread of fire from building to building. It has been suggested that with a sprinkler system a compartment may be of unlimited area except for multi-storey buildings.

The current concessions do not indicate that the authorities have developed any precise rules for this purpose. As the regulatory requirements are expressed in a system of steps, the only possibility is to move one or more steps in the direction of reduced requirements. As many regulatory requirements are applied independent of each other, different steps may be applied in different cases. Only two dimensional interaction is considered at present, if at all.

FIRE SAFETY ENGINEERING

The use of an engineering approach to fire safety is not new, some simple procedures existed 50 years ago which could be considered to be the application of engineering concepts. Fire safety engineering globally applied means an evaluation of risks in a given building and an assessment of the safety measures to see if a net hazard is present. The difference between the two can be construed to indicate the degree of hazard and the design intention would be to reduce the net hazard to zero or a negative value.

Fire safety engineering concepts can be used for sub-systems of the total system. Most progress has been made in the area concerned with fire resistance. It started with a need to extrapolate and interpolate data from standard fire resistance tests and to predict fire resistance which would be obtained in a furnace test. The next development was the quantification of fully developed fires in order to better define fire resistance needs for different buildings. The approach developed after experimental studies (6) takes account of the relevant factors of fire load, ventilation and the compartment boundaries and quantifies the fire severity as an equivalent time in the standard furnace test which would cause the same degree of distress to the structure. A real fire is translated into the furnace test parameters. The impetus for this work came from the steel industry in its competition with concrete to find cost-effective solutions to protecting steel constructions.

These studies highlighted a number of problems which have as yet not been fully resolved. The furnace tests, owing to their simplistic nature, is not capable of reproducing a real fire condition. Some of the main differences between the two are due to the random characterstics of real fires, e.g.

1. The heating conditions in rooms are not uniform,
2. The heat transfer characteristics are different,
3. The environment temperatures fluctuate,
4. The elements are not heated uniformly,
5. Moisture in materials has a delaying effect,
6. Material properties change at high temperature,
7. Building elements interact with each other,
8. Fire duration is usually less than assumed,
9. Fire brigade applies water to heated surfaces,
10. Fire grows at different rates in different parts.

Some of these factors have received attention in the past but others are not so easy to quantify although some account can be taken by introducing adjustment factors. The procedure for estimating fire severity referred to previously has been accepted on an international basis by the CIB(7). It is termed as Method 2 to distinguish it from the standard furnace test, known as Method 1. The difference between these methods is not fundamental but only lie in the definition of the end point, in one case it is given in the regulations, in the other it is obtained from a knowledge of the fire load, etc. In the long term Method 3 should be of greater interest because it attempts to reproduce the heating regime likely to be experienced in practice. This is largely an unchartered territory although a range of idealised relationships has been proposed.

More recently the effect of rate of heating, particularly if it increases rapidly as in fires involving hydrocarbon fuels, on structures has become of some concern. A new relationship known as the "hydrocarbon" curve has been gaining ground in the petro-chemical industry and the associated safety authorities for a more realistic expression of the hazard. Taking 1100°C as the maximum temperature of such fires, the time to reach has been shortened from about 90 minutes to 9 minutes. The relationship can be expressed exponentially as below (8) (Fig. 5):

$T = 1100\,[1 - 0.325 \exp(-0.16667 \times t)]$, where

T is the temperature in °C and
t is the time in min.

The prediction of fire behaviour of building elements has required the development of computational techniques to determine heat transfer from the heated surface to the inside of the heated element. The transient heating conditions and multi-dimensional heat flow requires use of relationships such as Fourrier equations. For hand calculations these were simplified with assumptions about heat transfer characteristics, surface temperature and the effect of moisture etc. However with the advent of mini and micro computers more elaborate calculations can be made by designers. The best example of the simplified procedure is that given in the code prepared by the ECCS technical committee for the protection of steel structures (9). Of computer programes FIRES-T (10) is well known for calculating heat flow using a finite element technique, whereas Fires-RC calculates the behaviour of concrete elements. Recent developments have produced TASEF program (11) which combines heat transfer and structural calculations and FASBUS (12) which calculates the performance of steel structures.

One of the inputs into such programs is on the properties of materials

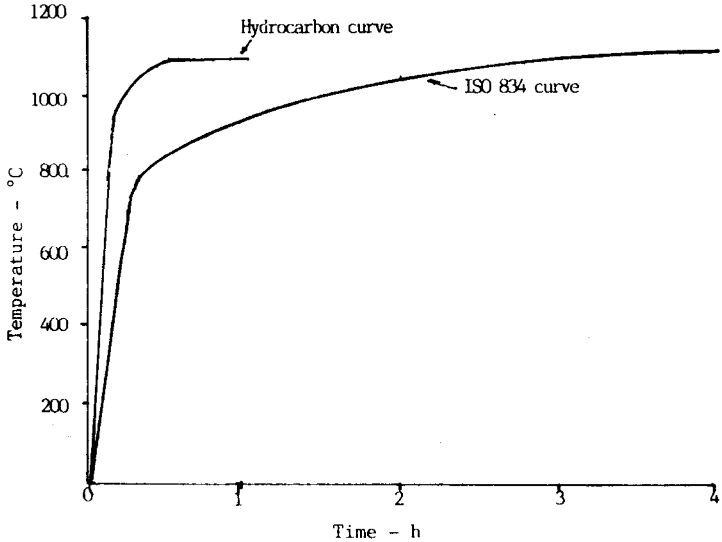

FIG.5 CELLULOSIC & HYDROCARBON CURVES