FIRE ENGINEERING IN EAST ASIA

Peter Bressington
Arup Fire, Ove Arup and Partners Hong Kong Ltd

ABSTRACT

This paper examines the advantages of designing fire safety from first principles and the potential for this approach in East Asia. In order to show how this approach can be used, actual case studies are discussed. These studies demonstrate the way in which fire science and research can have a positive impact on fire safety design for buildings.

INTRODUCTION

Internationally, fire engineering is being adopted as an alternative approach to prescriptive fire safety codes, this is also true of East Asia. The use of fire engineering in East Asia is gaining momentum, particularly where tall or complex buildings are being designed. Some countries, notably Australia, have embodied fire engineering into a formal code which is used by designers and approving authorities. This structured approach to fire engineering could well be the way forward for East Asia. However, in the meantime fire safety designers who wish to adopt a fire engineering approach must ensure that their design is based upon sound criteria, which can then be readily scrutinised and understood by approving authorities.

Fire engineering can lead to new solutions and innovative developments in fire safety systems. This is because the fire safety design for a particular building is targeted to meet the specific needs of the project under consideration.

Acceptance of a fire engineering approach becomes more widespread following successful implementation and approval of designs. In this respect precedence is important in giving confidence to clients, architects and authorities.

FIRE ENGINEERING

Fire engineering, or fire safety engineering, is the application of engineering principles to all aspects of fire safety. In much the same way as a structural engineer will design a building to withstand various loads and conditions a fire engineer will look at hazard, risk and the performance of materials, buildings and the behaviour of people.

Fire engineering is developing as a genuine design discipline, with advances in understanding spatial and complex buildings and their occupants. The result of a fire engineering approach will often lead to flexible alternatives to the code or prescriptive route, especially when designing unusual or 'difficult' buildings .Fire engineering can successfully remove obstacles to innovative building design and provide an opportunity for the architect to create a fire safe environment by introducing new ideas or developing a better understanding of fire safety. This increases the overall building design options.

All aspects of fire safety must be addressed individually, and as part of a comprehensive strategy. For example, escape distances and times will be affected by occupant response, and tenable conditions. Fire engineering will need to consider all of the following:

- compartmentation
- means of escape
- fire suppression
- fire detection
- fire resistance
- firefighting
- management.

In the context of East Asia, a fire engineering approach can be particularly beneficial as national fire codes tend to be either quite rigidly prescriptive, or do not exist in any comprehensive form. In the first instance fire engineering can provide the flexibility previously discussed, in the second instance, where codes have been underdeveloped, fire engineering can be used to give clear guidance on all aspects of fire safety design.

CASE STUDIES

The way in which fire engineering can be applied is best shown by describing actual case studies. In both of the cases considered in this paper, fire measures have been targeted to achieve the most appropriate, and cost effective design solutions.

1.0 Cabin Concept

In transport terminals the fire load in the public circulation spaces is low, however there will be areas which have been subject to special consideration. These areas, such as shops, have a higher than average fire load and as such demand a different approach if the concept of extended escape and large compartments is to be adopted. In Hong Kong, Japan and Malaysia the Cabin Concept has been used in airport terminals and railway stations.

The Cabin Concept is used to protect these higher fire load areas so as to prevent fire spread and prevent smoke, affecting escape and fire fighting activities, from entering the concourse areas. The Cabin Concept works by isolating the fire within the affected area. This is achieved by controlling the fire using sprinklers and extracting smoke. To accomplish this a down stand is arranged around the area to form a reservoir, the depth of the down stand will depend on ceiling height, extract rate, and the design fire size. The remaining perimeter area can then be left open to the surrounding concourse.

First of all the design fire had to be determined, for example using the US National Institute of Technology program DETACT· This program can be used to determine the fire size when sprinkler operation has occurred, a conservative assumption is made that sprinklers do not extinguish or reduce this fire size, but that a steady state condition is maintained.

In order to calculate the required smoke extract rate to contain the bulk of the smoke within the Cabin reservoir, Heskestads(3) equation was used:

$$M = 0.071\, Q^{1/3} (y - y_o)^{5/3} [1 + 0.026\, Q^{2/3} (y - y_o)^{-5/3}]$$

where y is the clear height between the top of the combustible material to the base of the smoke reservoir. For a conservative approach the top of the combustible was assumed to be at floor level. The variable y_o is the virtual source of the fire and is given as:

$$y_o/D = -1.02 + 0.083\, Q^{2/5}/D$$

The quantity Q is the convective rate of heat release from the fire. The above equation applies if the smoke layer is above the flames. Where the flames reach the smoke layer:

$$M = 0.0054\, Qy/(0.166\, Q^{2/5} + y_o)$$

where the flame height y_f is given by:

$$y_f/D = - 1.02 + 0.230\, Q^{2/5}/D$$

Tests

We were asked by the Fire Services Department in Hong Kong to carry out a series of fire tests to verify that the design of the Cabin Concept achieved the criteria laid down. This was to demonstrate that a combination of smoke detection, sprinkler protection and smoke extraction can keep the space outside of the test area substantially free of smoke even in the event of a serious fire within the test area.

A specially constructed test cell was built at the Fire Services Training Ground designed to represent a typical open retail area with down stands and fire services as previously described. The test was carried out on Friday 31 March and witnessed by representatives of the Fire Services Department, Buildings Department, the Railway Inspectorate, and the client MTRC.

Three tests were conducted as planned:

i) crib test;

ii) shelved plastics goods test;

iii) unsprinklered crib test.

The crib used was a standard 1m^3 constructed of narrow softwood sticks which would reach a maximum heat output of approximately 3300 kW.

The systems installed were conventional installations in Hong Kong except that:

i) the required smoke extract volume was established by calculations and not by an air change rate;

ii) the sprinkler system pressure/flow was reduced to allow for the fact that only four heads were fitted as opposed to the maximum of 18 heads normally allowed for in design, this means that the minimum 5mm per m^2 was applied;

iii) the signal from the smoke detector/sprinkler flow switch was arranged to switch on the smoke extraction system.

Results

No formal measurements of flame temperature or smoke volume were made during the fires in the test rig. However, temperature recordings of the smoke being extracted was carried out. The timings of significant events were noted and a narrative of the tests was recorded as they took place. This narrative forms the basis of the observations noted :

Crib Test 1

The combustion rate increased rapidly as more of the crib sticks became involved in the fire. Flames reached a height of about 3m above the surface of the crib. It is estimated that the fire reached about 2,500 kW, before the first sprinkler operated (3 minutes 50 seconds).

Subsequent sprinklers operated at 5 minutes. The flames were gradually reduced in size.

Initial collapse of the crib occurred at 18 minutes. At this point more of the burning material was exposed to the spray, and control became much more rapid.

Throughout the test, no leakage of smoke into the spectator space was observed. The smoke extraction system effectively removed all hot gases. In fact, this was so efficient that no build-up of a smoke layer was observed within the test area.

The residual material indicated that perhaps 25-30% of the wood remained unburnt showing that the fire had been controlled by the sprinklers, and had not burnt out naturally.

It was noted that the maximum smoke temperature recorded was 86°C.

Shelved Goods Test

The shelving constructed was 450mm deep x 2.5m high to represent a shop arrangement. It covered one wall of the test area. The shelving was stacked with cardboard boxes of waste plastics material to achieve a fire load equivalent to that which might be found in, for example, a toy shop.

The fire was ignited between boxes below the lowest shelf. Fire spread upwards within the flue created between the boxes and flame spread laterally beneath the shelf above. This caused adjacent boxes to become involved and flames to curl over the shelf to spread to the shelf above.

The smoke detector operated at 35 seconds. The smoke extraction system came on as expected and the fan was up to full speed in 30 seconds.

Fire continued to spread up the face of the stacked material with large flames extending above the top shelf. The first sprinkler operated at 8 minutes.

Subsequent sprinklers operated at 12 minutes.

The boxes on the top shelf, exposed fully to the sprinkler spray were largely undamaged by fire. No new boxes of material were ignited once the sprinklers operated.

The fire was brought under control by the sprinkler system and FSD were called in to extinguish the burning embers at 30 minutes.

The maximum smoke temperature recorded during the test was 67°C.

Crib Test 2

The crib was ignited as before and the test proceeded as in test (1) except that the sprinkler valve was shut, allowing no water onto the fire. In the initial stages the fire grew in the same manner as previously observed, except that with no control, it continued to grow. Flames clearly reached the ceiling and spread beneath it. Data from previous experiments on such a crib suggests that the peak heat release rate was around 3,500 kW.

It was very significant that though the peak heat release rate in this test was probably not too different from that in the previous test, the level of radiation received by spectators was very significantly greater. In neither of the previous tests had it been necessary for spectators to move out of the rig or to protect themselves from heat. In this test the radiation was sufficient for people to feel slightly uncomfortable and to move away, or to screen exposed skin. This suggests that in the previous tests the sprinkler spray, as well as bringing the fire under control, had also screened spectators from radiation.

The increased radiation levels observed have no practical implications for the cabin concept. In the first instance, the sprinklers will in fact be expected to operate and in the second, walking only a couple of metres away removed any discomfort from radiation.

The smoke extraction system coped well with the smoke from the fire. No leakage was observed into the spectator area. As a demonstration of the size of fire which could be handled by the system even in the absence of sprinklers, it was seen to be quite dramatic.

The smoke extract fan was rated at 250°C for an hour. In order to ensure that it could continue to function for future tests, it was decided that the sprinklers should be turned on when the extract temperature reached 230°C. This was done and the temperature at the fan fell to 80°C over the next 30 seconds.

The test was terminated shortly afterwards and FSD called in to extinguish the remaining material.

The Building

Hong Kong Air Cargo Terminals Ltd (HACTL) are building a cargo handling facility, Superterminal 1, at Chek Lap Kok Airport Hong Kong. The facility is designed to cope with 2.4 million tons of cargo. Two centralised automated bulk storage systems(BSS)are installed, together with two container storage systems (CSS). These are augmented by bulk cargo storage systems on all three bulk cargo operations levels. The facility covers a floor area of 26,000 ^{2}.

The Issue

The CSS Canopy structure is located between the Container Storage System (CSS) and the Terminal Building. The canopy which is 200m long, and set approximately 35m above the CSS roadway, is critical to the safe and efficient operation of the Terminal, as it enables the speedy transfer of air cargo to and from the airport apron in all weathers.

The canopy is made up of circular hollow steel sections which form leaf like trusses linked by rectangular section purlins. The conventional approaches to provide the required 2 hours fire resistance would be to cover the truss members with fire resisting material, or to paint with an intumescent coating. Covering with a fire resisting material was not acceptable architecturally, painting with intumescent would present problems due to availability, cost and future maintenance. It was also a requirement to install sprinklers under the roof.

The Solution

An idea formed that perhaps advantage could be taken of the circular hollow sections, and develop a water cooled structure as an alternative to the conventional passive fire protection approach. We then considered the possibility of eliminating sprinkler distribution and range piping by fitting the sprinklers directly into the truss members. It was decided to pursue this alternative approach, and to integrate sprinkler protection into the CSS Roadway Canopy. An in depth study followed.

Effect of Water Cooling

Water cooling can be an effective alternative approach to passive fire protection, such as intumescent paint and cladding systems, and works principally by the rapid removal of heat internally by water as it is transmitted through the external steelwork surfaces by the fire. Passive fire protection, on the other hand, works by delaying the passage of heat from the fire to the steelwork and therefore only offers a limited period of fire resistance under a sustained heat source.

The present approach to water cooling, as set out in the CONSTRADO report is to have a gravitational replenishment system, which makes up the loss of water within the system. Loss is caused by the conversion of water to steam, which is vented through safety valves to the air.

The report states that a cheaper and easier approach is not to replenish the water which is lost, but this approach obviously will limit the period of fire resistance provided.

The CONSTRADO report lists five ways in which cooling can be effective during a building fire:

(a) By local convection within the column itself and emission of heat from parts of the column which are least exposed to the fire.

(b) By convection currents in parts of the column and pipe circulation system, in which the cooler sections act as heat sinks and cooling radiators for the hotter parts of the steel structure.

(c) By the initial heating of the water in the columns to boiling point.

(d) By absorption of the latent heat of vaporisation when the water is converted into steam

(e) By heating water from the storage tanks which replaces water lost as steam.

Our design incorporates elements of these concepts, although, since the water is flowing rapidly to the hottest parts of the structure (the locations where the sprinklers have been activated) it can never be heated up sufficiently to produce steam. This has been vindicated by the tests carried out at Faverdale Technology Centre in Darlington, as the maximum exposed steel (and water) temperature recorded was 45.5°C. The design works by sprinkler(s) responding to a localized heat source, leading to a water flow which is constantly replenished at ambient water tank temperatures, and the water does not convert to steam.

Water cooling calculations were carried out to give an approximate expected level of effectiveness. These design calculations were based on "Water Cooled Hollow Columns" by Bond and are specifically for a system using water cooling <u>without</u> evaporation.

Sprinklers

Sprinkler design standards set out the criteria for water density, sprinkler layout and material specifications; this design which incorporates sprinklers into circular hollow sections (pipes) complies or exceeds the requirements of these standards. In reality the performance of the sprinklers will be enhanced over that set down in the Rules due to:-

- pressure and flow of water availability from the drencher supply is considerably greater than the minimum requirements
- 20mm orifice sprinklers in place of 15mm
- m^2 coverage reduced due to closer spacing of sprinklers

the water cooling flow requirement has led to an enhanced pressure flow availability at the sprinkler heads.

Corrosion Considerations

For corrosion of steel to happen it must occur in an environment capable of sustaining the necessary chemical reactions. For steel in neutral pH solutions (normal WSD water supply) corrosion can only occur if oxygen is present, and the rate at which corrosion occurs is dependant on the quantity of oxygen present and the rate it can diffuse to the steel surface which is corroding. Once that oxygen is used up, no further corrosion can occur.

In principle when the structure is filled with water, corrosion of the steel will occur, as it would in any conventional sprinkler system. The degree of corrosion however would be slight and only continue until all the oxygen in the system has been consumed in the corrosion process; this would occur in a relatively short time but the resulting corrosion will be structurally insignificant. Provided that the oxygen is not renewed no further corrosion can occur. The water filled trusses are permanently charged, with water and air tight joints, and replenishment of the system would only occur under fire conditions. If for any reason air were to enter the system then corrosion will continue at a rate controlled by the ease with which it can reach the base steel surface. Under conditions of near zero flow this diffusion rate will be extremely slow. In addition the initial corrosion products also act as an oxygen diffusion barrier further retarding the corrosion rate; it would therefore be expected that the rate would be negligibly slow and that the risk of significant loss of section insignificant.

Fire Tests

The test programme involved two main full scale fire tests, these were carried out in order to demonstrate the effectiveness of an integrated sprinkler/water cooled design approach. To ensure that the design could satisfy both the requirements for fire resistance, and sprinklers, full scale tests were carried out at an accredited test facility in the UK. The tests were carried out at the Faverdale test site in Darlington UK on 2 April 1996, and were witnessed by a representative of the Loss Prevention Council.

The structural cooling test was carried out, with no cooling effect on the fire, to demonstrate that the critical steel temperature of 550 °C would not be achieved. Steelwork temperatures stabilised after 30 minutes, it was then that the test was ended as a longer test period would not contribute further data. During the structural cooling test a maximum flame temperature of 981 °C was recorded. Non-cooled exposed steel temperatures recorded was 400°C. Importantly, the maximum exposed water cooled structure temperature was 80 °C.

During the sprinkler operation test, where water was discharged onto the fire, the maximum temperature on the exposed cool structure of 45.5 °C was recorded. This test most accurately represents a real fire condition on site where external cooling by sprinklers will enhance the internal cooling.

The tests, which have been carried out, prove very clearly that the integrated system will function as a sprinkler system and maintain temperatures below the 550°C critical temperature previously identified. If the external sprinkler cooling is discounted (structural cooling test) temperatures no higher than 80°C were recorded. However, in reality sprinklers will externally cool the structure, and when combined with internal cooling will reduce exposed surface temperatures to a 45.5°C maximum.

The water supply for the canopy roof trusses is taken from the drencher water supply. This supply gives a higher pressure and flow whilst at the same time providing an alternative to the sprinkler supplies.

The tests confirmed the theoretical work. It has meant that the objectives of design effectiveness, cost efficiency and aesthetic considerations have been met.

CONCLUSION

It should be noted that fire engineering does not always lead to new system design, in most cases the analytical approach taken will lead to a strategy which uses available alternative solutions. The main point is that fire safety issues are subjected to scrutiny, rather than an un-questioning acceptance of prescriptive requirements.

An understanding of fire, and it`s effect on buildings and people should be a priority of architects and designers. Fire engineering provides the direction and structure for the decision making process.