Design Fire in Performance-based Fire Safety Design for Green and Sustainable Buildings

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ABSTRACT: Construction industry in the Far East is developing rapidly with many new architectural features for achieving green and sustainable designs. Fire safety has drawn public attention consequent to the serious accidental fire occurred at the Garley Building in 1996. Therefore, fire safety provisions have to be assessed vigorously. There might be difficulties for some of these new architectural features to comply with the current prescriptive fire safety codes. The environmental friendly design might even be in conflict with the fire safety requirements. Special design considerations are required individually for such buildings.

Performance-based design known as the "fire engineering approach FEA" is accepted in Hong Kong since 1998. Basically, this applies to passive protection constructions in demonstrating that the building elements which did not satisfy the code requirements are of equal safety to what specified. The problem is more serious especially for glass construction. Hazard assessment is required and the heat release rate of the design fire is a key issue. All the fire safety provisions were determined based on that. The fire safety strategy for bigger organizations such as railway systems will be worked out based on the estimated heat release rate. As the responsibility lies with the Authority, not the fire engineer concerned, there were lots of arguments on the design fire. This point will also be discussed in this paper.

On the estimation of the probable heat release rate, empirical equations on ceiling jet for assessing the thermal response of sprinkler heads were commonly applied. Whether this approach is good will also be discussed with support from full-scale burning tests on measuring the heat release rates with sprinkler. It should be pointed out that operating the suppression system might not necessarily keep the heat release rate of the fire at the estimated value.

1. INTRODUCTION

Construction industry in the Far East is developing rapidly with many new architectural features for achieving green and sustainable designs [1]. Some of these new architectural features could not comply with the fire safety codes. Current prescriptive codes [e.g. 2], though demonstrated to be workable for existing buildings, might not be good enough on specifying the fire safety requirements in new buildings. Some of those requirements are even conflicting with the environmental friendly design.

Fire safety has drawn public attention consequent to many big fires, starting from the serious accidental fire occurred at the Garley Building in 1996 [3]. People have become more concerned about whether they are sufficiently protected while staying inside a building. Fire safety features must be provided to the satisfaction of the local authorities. This is a key part in the building approval process which has to be considered seriously before issuing the 'occupant permit'.

This suggests that individual design considerations [4] are required for those green buildings. Therefore, "Fire engineering approach FEA" with performance-based design (PBD) is accepted by the authority in Hong Kong since 1998 [5]. Basically, this applies to passive fire safety provisions in demonstrating equal safety as specified in the codes [2]. Over 100 projects having difficulties to comply with the prescriptive codes were submitted for the Authority to consider in the past seven years. Glass construction is found in many such projects.

The heat release rate of the design fire is a key issue in fire hazard assessment of PBD. All the fire safety provisions were determined based on that. The type of fires to be dealt with in designing the fire safety objectives must be clarified. In most cases, small accidental fires in an empty room without fire load are usually considered. The fire safety strategy for bigger organizations such as railway systems will be worked out based on the results. There are numerous arguments on selecting the design fire. Small values down to 0.5 MW were proposed by the professionals. High values are required by the Authority as they are responsible for the safety issue. Aspects on furniture fires will be discussed with heat release rates reported in the literature reviewed. These included the big project [6] on studying Combustion Behaviour of Upholstered Furniture (CBUF) in Europe. These data are useful for working out a design fire in buildings of different uses. Important phenomena such as the possibility to flashover can be assessed.

On the estimation of the probable heat release rate in sprinkler protected area, empirical equations on ceiling jet for assessing the thermal response of sprinkler heads were commonly applied. For example, the activation time of the sprinkler was estimated and put into the NFPA t^2-fire equation [7] in estimating the heat release rate. Whether this approach is good will also be discussed. It should be pointed out that operating the suppression system might not necessarily keep the heat release rate of the fire at the estimated value [8].

Full-scale burning tests on measuring the heat release rates with sprinkler, water mist and clean agents were also performed to justify the argument. Such experiments [9] were carried out at a remote site in Northeast China. An office fire scenario was established. The changes in heat release rate curves of the fire upon discharging such agents were measured by the oxygen consumption method.

2. GLASS CONSTRUCTION

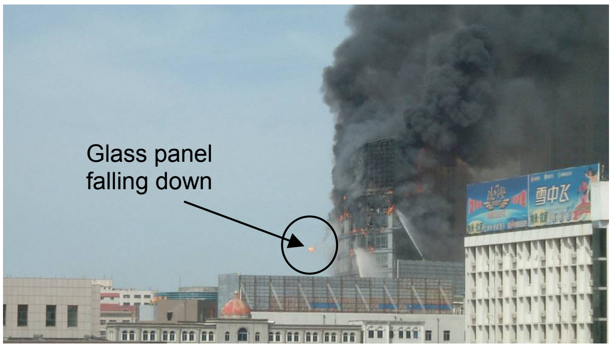
Architectural features with glass constructions [1] might give additional problems. As demonstrated years ago, glass panes fell off the wall of a full-height glass tower office building in a typhoon. This suggested that there are potential risks associated with the glazed buildings. Attention should also be paid to the ability to resist wind load. Though glass is not combustible in a fire, it will be weakened when heated up to a certain temperature. Toughened glass is able to endure higher temperature, but might be fragile after exceeding its critical limit. For example, cracking may occur when heated up to 295 °C [10]. Glass itself is a poor conductor, difficult to transfer heat from the area exposed to the fire to the other region. Temperature difference between the hot and cool sides will give thermal expansion. Cracking will occur when the induced thermal stress reaches the critical value [11]. Aluminium window framework will be weakened when heated up to 200 °C, even melted at about 550 °C. Severe distortion may induce stresses across the glass plate being held up by the frame. The whole glass panel might fall down [12].

Cracking and falling down of glass panels due to explosion or failure of the fittings for fixing the glass panels would give a higher air intake rate to sustain combustion. As a result, higher heat release rates would be emitted to cause severe damages. Big fires might be resulted due to providing fresh air to burn the large amount of combustibles (allowed storing up to 1135 MJm^{-2} in Hong Kong [13]). Wind action might lead to fire whirls [14] or mass fire [15].

A big fire occurred in a new building with glass features in Dalian, Liaoning, China recently on 18 September, 2005 as in Fig. 1. Flashover occurred with flame coming out of many levels. As observed by the author, some glass panels fell down as in Fig. 1b. Fire safety of glass features with double skin façade [16] is a concern. Smoke, heat and even flame might be trapped inside the air gap. The consequence will be very serious when the interior glass panels are broken, but not the external ones.

Heat release upon breaking the glass should be watched. This should be a key area in green buildings.

(a) Fire site



(b) Falling down objects

(c) Extinguishing by firemen

Figure 1: Fire in a glass building in Dalian, Liaoning, China, 18 September, 2005.

3. DESIGN FIRE

It is well-known in PBD that the heat release rate is the most important parameter in fire hazard assessment. Once the heat release rate is known, the resultant fire environment such as smoke temperature, smoke layer thickness, smoke flow rate, radiation heat flux, possibility to flashover, and the effects on adjacent combustibles and construction elements in the fire room can all be estimated with empirical expressions or fire models.

A design fire [17] has to be agreed on in applying FEA. However, data on heat release rate available in the literature are very limited. There are even no reliable data for local products used and manufactured in the Far East [18]. Different design fires were used for different purposes. Very low values of 0.3 MW to 0.5 MW were estimated in designing fire protection systems for terminal halls, shopping malls, atria, and train compartments. The same value was accepted in one project, but rejected in another similar project, giving many arguments and debates. This is due to the lack of a database for local products. Heat release rates of burning combustibles in typical building arrangements should be measured experimentally in a full-scale burning facility with and without discharging the fire suppressing agent. The results can then be applied for scenarios analysis on PBD.

In a particular underground corridor project, a very low value of 0.5 MW for normal scenarios was suggested, though 2 MW was used finally [19]. But as pointed out by local fire officers, what they encountered in big fires, accidental or arson, were not under normal conditions. A flashover fire with a long duration in a restaurant as in Fig. 2a is commonly used as an example by fire officers to demonstrate how serious the consequence was. The big Garley Building fire [3] as in Fig. 2b is a painful lesson to learn. Cause of that fire is still under investigation, whether the building management or the authorities should do more gives another debate. Anyway, it is strange to have no temporary fire protection while removing all lift doors for replacing new lifts for a rather long time inside there. Now, many buildings including the campus of The Hong Kong Polytechnic University, temporary fire-rated partitions were erected to shelter the lift shafts when replaced [20].

(a) Restaurant fire due to flashover
(Apple Daily, 7 January, 2005)

(b) The Big Garley Building Fire
(South China Morning Post, 21 November, 1996)

Figure 2: Examples on fire outbreak.

4. FURNITURE FIRES

Past fire record indicated that burning a furniture, particularly a sofa or cushion foam, was the main cause of accidental fires. Several such cases happened in Hong Kong before [e.g. 3]. Heat released might be strong enough to ignite adjacent items such as wood partition walls, floor coverings and other furniture which are not easy to ignite by electric sparks or cigarettes. This point should be taken note of, particularly for public entertainment places like those karaokes with partition walls made of timber product. It is important to understand the heat release rates of burning furniture foam and their contributions to a compartment fire at the preflashover stage.

As listed in NFPA-92B [7], burning upholstered furniture, stacked furniture near combustible lining and non-fire retarded plastic foam storage might give an ultra-fast t^2-fire. Burning horizontally distributed office furniture would give a medium t^2-fire. There might be an incubation period for all cases. But there are always arguments among the Authorities and the designers on taking which 'cut-off' value as the design fire.

Upholstered furniture is quite complicated with several fuel elements including cover fabric, seat cushion material and the padding. How these fuels would burn depends on the material composition, thickness and density. There have been extensive studies on upholstered furniture over the past 10 years [e.g. 6,21]. One of the recent biggest projects is perhaps the project on CBUF in Europe [6].

Heat release rates generated from burning common furniture and their constituting materials should be studied. Typical heat release rate curves for foam and fabrics measured from the CBUF project were reported [6]. Selected materials for furniture are:

- Padding
  Materials are FR cotton batting; polyurethane foam (fire-rated FR or non fire-rated NFR); foam, cotton, polyester; Combustion Modified High

Residence CMHR/Melamine or PU foam; neoprene; PS beads; and latex foam.

- Fabrics
  Materials are leather; PVC; PU; polyolefin; cotton/linen/rayon; nylon/olefin; and blend.
- Frame
  Materials are wood product; polypropylene; polyurethane; metal/non-combustible; and structural foam (charring).

One of the earliest systematic studies on furniture fires was perhaps due to Babrauskas and Walton [21]. Based on the results from a furniture calorimeter, the heat release rate of a single item of burning furniture can be described by a curve of triangular shape determined by the peak heat release rate Q_p (in kW); time to the peak t_p (in s); triangular base width t_{bw} (in s); and time to start of base t_s (in s) as shown in Fig. 3.

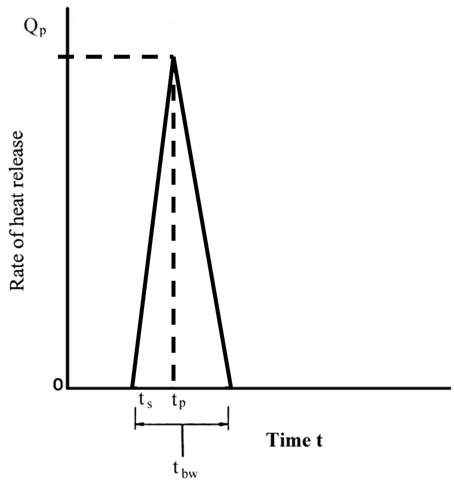


Figure 3: Heat release curve for upholstered furniture.

Q_p (in kW) can be modelled by generic materials identification with values assigned for different fabric, padding, frame, mass and style of the furniture; or based on bench-scale measurement with Q_p given in terms of the rate of heat release rate per unit area $\overline{Q}_{BT}$ (in kWm^{-2}) in bench-scale test by:

$$Q_p = 0.63\,\overline{Q}_{BT}\,\alpha_{mass}\cdot\alpha_{frame}\cdot\alpha_{style} \qquad (1)$$

When using a cone calorimeter, the radiative heat flux is 25 kWm^{-2}, and $\overline{Q}_{BT}$ is determined over an averaging period of 180 s after ignition [e.g. 22]. The other factors are the mass factor α_{mass}, the frame factor α_{frame} and the style factor α_{style}. Recommended values are reviewed in the literature and would not be reported here.

As quoted by Babrauskas [22], the data for $\overline{Q}_{BT}$ over 180 s are higher than 280 kWm^{-2} for ordinary PU, less than 280 kWm^{-2} for melamine PU, less than 60 kWm^{-2} for American CMHR PU foam, less than 85 kWm^{-2} for hydrophilic PU, and less than 45 kWm^{-2} for neoprene.

t_{bw} (in s) is given in terms of the mass of combustible item m (in kg) and the effective heat of combustion Δh_c (in $kJkg^{-1}$) by:

$$t_{bw} = \frac{C_3 m\,\Delta h_c}{Q_P} \qquad (2)$$

Note that C_3 is an empirical factor equal to 1.3 for wood frame and 1.8 for metal or plastic frame.

At least four types of furniture can be observed in the CBUF project [6]:

- Quick development with high peak heat release rate.
- Delayed development, moderate peak heat release rate.
- Slow development, low peak heat release rate.
- Very limited burning.

With the heat release rate curve identified, a fire model can be used for predicting the probable fire environment. For instance, the smoke layer is a measure of tenability which can be predicted accurately by a fire zone model once the heat release rate is known. That is why the heat release rate curves are so important.

5. ESTIMATION OF HEAT RELEASE RATE WITH FIRE SUPPRESSION

In estimating the probable heat release rate for a design fire with fire suppression system such as sprinkler protected area, a common practice is to apply an empirical equation [23] for the maximum ceiling jet temperature rise ΔT_{max} at a ceiling height H (in m) due to a fire of convective heat release rate $\dot{Q}_c$ (in kW):

$$\Delta T_{max} = \frac{16.9\dot{Q}_c^{3/2}}{H^{5/3}} \qquad (3)$$

Results will be combined with a thermal balance equation on relating the activation temperature of the thermal sensing element of the sprinkler heads with a certain Response Time Index (RTI). The activation time t_a will be calculated based on RTI from a heat balance equation. Upon activation of sprinkler, the heat release rate is assumed to be kept at a constant value in many projects with FEA [5].

For example, a t^2-fire [7] with a heat release rate $\dot{Q}(t)$ (in kW) at time t (in s) given by the equation through a constant t_g:

$$\dot{Q}(t) = 1000\left(\frac{t}{t_g}\right)^2 \qquad (4)$$

where t_g is 75 s, 150 s, 300 s and 600 s respectively for ultra-fast, fast, medium and slow t^2-fire.

The heat release rates $\dot{Q}_{des}$ of the design fire were estimated in many projects by:

$$\dot{Q}_{des} = 1000\left(\frac{t_a}{t_g}\right)^2 \qquad (5)$$

6. FULL-SCALE BURNING TESTS

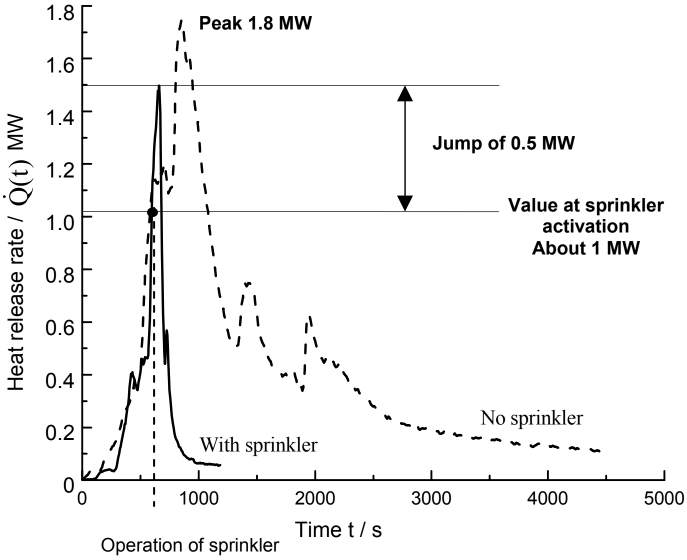
To assess how sprinkler would control a fire, full-scale burning tests were carried out. Office fire scenarios with and without the operation of sprinkler were considered. A full-scale burning facility was developed by the author with strong support from the Harbin Engineering University. This facility [18] is located in the remote area Lanxi at about 150 km from Harbin, Heilongjiang, China. Flashover office fires [8,9] were studied in the summer of 2004.

The office scenario considered is shown in Fig. 4a. There were a chair, a desk with paper and books on top, a computer box and a cupboard in the burn room. This setup was burnt under an accidental fire to give flashover for determining the heat release rate. The heat release rate curve for this scenario is shown in Fig. 4b. The peak heat release rate was about 1.8 MW at 800 s.

Tests were then repeated by operating a sprinkler system at pressure 0.52 bar and flow rate 60 litres/min when the heat release rate reached 1 MW. The heat release rate curve for discharging water from the sprinkler on the office fire is also shown in Fig. 4. It is observed that operating the sprinkler could control the fire for this scenario. However, the heat release rate did not stay at the value once the sprinkler was activated, but moved up to 1.5 MW. Note that the value was about 1 MW at the time of discharging water. There is a jump of 50% of the value at sprinkler activation. It is not too wrong to say, though local data is insufficient, that even operating the sprinkler will give over 80% (i.e. 1.5/1.8) of the possible maximum heat release rate. The scenario without sprinkler gave a small fire of peak heat release rate less than 1.8 MW, only burning for about half an hour.

Following this procedure with the above measured results, the heat release rate for the scenario with sprinkler protection should be 50% higher than that estimated from the cut-off value when sprinkler is activated. The hazard measures due to the extra heat released will give a quicker smoke filling rate and higher temperature distribution. In view of the heat release rate curve of the office fire scenario as shown in Fig. 4b, generating an additional 0.5 MW of heat release rate is quite dangerous. Adjacent items might be ignited to further generate much more heat.

(a) Office fire scenario



(b) Heat release rate

Figure 4: Office fire test

7. CONCLUSION

FEA is necessary to cope with the rapid changes in the design of buildings with green features, especially those with glass constructions. This is a solution in the transition period before updating the prescriptive codes. In applying FEA in Hong Kong, reference is made to the prescriptive codes, or at least, to the fire safety objectives stated in there. But there are difficulties in implementing FEA as experienced for EPBFC in overseas.

Heat release rate has to be estimated properly in FEA. It is even more important when there is a suppression system. As observed in a small office fire as in the above test, the heat release rate cannot be controlled at the value once the sprinkler system is activated. The heat release rate can be up to 80% of the maximum value, and about 50% higher than the value at the time of discharging water. Therefore, in estimating the heat release rate for sprinkler protected area with a t^2-fire, the 'cut-off' value at activation time should not be taken as the design figure. Much higher heat release rates will be resulted, depending on the scenario.

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