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Experience on implementing performance-based design in Hong Kong

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Abstract

Many new buildings, particularly those with 'green' or 'sustainable' architectural features have difficulties in complying with prescriptive fire codes due to many reasons. Examples in Hong Kong include residential buildings with internal voids, glass façades with spandrel design, good thermal insulation, natural ventilation provision and many others. Consequently, performance-based design known as 'fire engineering approach' (FEA) is allowed for active systems since 1987, and then later for passive constructions since 1998. This is similar to Performance-Based Design (PBD) in other places. Over 300 FEA/PBD projects for new buildings and renovations of the existing buildings had been submitted to the local government since then. There are many problems associated with such approach. In this paper, problems on projects with fire safety provisions determined by FEA/PBD in the past two decades will be pointed out.

Keywords: Performance-based design; Fire research; Big construction projects

1. Introduction

Projects with difficulties to comply with prescriptive fire codes in Hong Kong are allowed [1] to determine fire safety provisions by performance-based design (PBD) [2-4] for active fire engineering systems since 1987. One of the first projects was on designing fire shutters in a big exhibition hall without partitioning the huge interior space. Later, PBD was implemented for passive constructions (including fire resisting constructions, means of escape and means of access for firefighters) as fire engineering approach (FEA) in 1998 [5-7]. There are many reasons for using FEA/PBD as summarized in the literature:

- Allow innovative architectural design.
- Structures are too tall above the ground such as supertall buildings.
- Structures are too deep underground for subway stations.
- Big hall space.
- Long travel distance.
- High occupant loading.
- Small cross-sectional areas for tunnels.

Over 300 FEA/PBD projects were considered by the authority as reported [8].

However, similar to other places as discussed in several conferences [9], FEA/PBD was also applied in many such projects to reduce the construction cost. Cost reduction is a strong driver for PBD. While cost reduction is an appropriate variable to consider in engineering solutions, it needs to be treated with care. Cost reduction cannot justify unsafe solutions nor can it be recommended without an analysis of adequate detail. The pressure for cost reduction can potentially result in unjustified fire scenarios or analysis/reports that leave hidden fire problems to watch.

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Typical examples of FEA/PBD projects requiring special attention [10] are:

- Crowded shopping malls, particularly those linked to subway stations, with large amount of combustibles during festivals. Example of having a tall plastic Christmas tree in the atrium of several storeys high was always observed [11].
- Proposed long exit distance up to 1.5 km protected only by Emergency Evacuation Passage (EEP) in long subway tunnels [12].
- Low design fire in long vehicular tunnels [8]. Burning a heavy goods vehicle (HGV) can give over 200 MW, but common design values are below 5 MW!
- Smoke management system design in tilted tunnels, particularly those with barriers assuming scenarios, without in-depth experimental justification [13].
- Applying fire resisting partitions with low fire resistance period, and using improper engineering calculation such as estimating thermal radiative heat flux only with metal board of the partition, but without the fire gases!
- Hazards due to glass façade buildings under post-flashover fires [14]. There is possibility of breaking [15, 16] the glass system with window panes, frames or accessories for achieving acoustic effect or relieving wind pressure in rainstorms to prevent water leakage, and thus resulting in big fires involving the whole building.
- Crowded subway stations without sprinkler coverage, but evacuation studied with low design fires to get long Available Safe Egress Time (ASET) [2, 4]. No data on human behaviour of local citizens was included in estimating the Required Safe Egress Time (RSET). Consequently, ASET might only be slightly larger than RSET as pointed out recently [17, 18].
- Open kitchens without full coverage by fire suppressions system in small residential flats in tall buildings [19]. Again, some cases are with ASET slightly above RSET, considered only smoke spread. Small residential flats used to have crowded supermarkets packed with large amount of combustibles. Heat release rate resulted from burning a flat can be very high.

Flawed concept on estimating ASET and RSET by the timeline analysis was also pointed out by Babrauskas et al. [20, 21]. Such concerns on not applying the timeline analysis properly in fire safety assessment in crowded subway stations were also raised in Hong Kong [17-19]. Officers approving FEA/PBD projects are reminded to read those articles carefully. They are now watching the concerns and requesting appropriate justification on all new and existing projects involving timeline analysis. This is particularly important in crowded underground subway stations [22] with ASET very close to RSET.

Several areas should be watched and are pointed out in this paper:

- Extended travel distance with potential health effect to firemen in firefighting and rescue.
- Small design fires far from real scenarios experienced in firefighting.
- Cabin design not to provide full coverage protection of sprinkler and smoke exhaust in big public halls including airport terminals.
- Possible high risks on firefighting.

2. Extended travel distance

As raised recently [23], firemen should follow some firefighting and rescue practices supported by appropriate training. There would be challenges on not following the scheme [24]. Such training had been demonstrated to be appropriate for fighting against building fires with fire safety provisions following the prescriptive codes [25-29]. For construction projects with difficulties to comply with those prescriptive codes, FEA/PBD [5-7] can be used since 1998. This is a good practice following overseas PBD development for green architectural features [30], particularly those claimed for providing sustainability but might be in conflict [31] with fire safety requirement. Large halls to provide natural ventilation and daylighting are good examples. Implementing FEA/PBD might be the only choice during the transition period before updating and upgrading the code. Note that codes in Hong Kong cannot be set up so quickly as in other places such as Mainland China. A long consultation period is needed. The karaoke establishments bill is an obvious example [32].

As pointed out recently [9], PBD was not only used for cases where the prescriptive codes were not yet updated, but simply used in many places for reducing the construction cost. FEA/PBD certainly should not be implemented just for reducing the cost. On the contrary, implementing FEA/PBD projects might be even more expensive for buildings without prescriptive fire code yet. Taking supertall building (classified to be over 300 m by CTBUH [33]) as an example, applying the same set of code for buildings of 100 m tall to buildings of 1000 m tall should be reviewed. It is obvious that a 1000 m tall building should have much more fire safety provisions than required.

There are many examples of FEA/PBD projects extending the travel distance in large and tall halls due to many reasons, such as providing daylighting and natural ventilation. Some even require people to walk a distance [25-29] much longer than the specified values in overseas design guides. Such design, including emergency escape passage (EEP) [12] in subway tunnels, should be watched. The FEA/PBD reports only demonstrated that occupants can evacuate in time by computer software. Some subway stations are even not fully covered by sprinklers, leaving firemen to fight against big fires. Not until recently [34], very few FEA/PBD reports touched upon the effect on firefighting and rescue strategy, potential health impact on firefighters and intervention of installed fire service systems. Note that firemen are expected not only to carry heavy equipment for fighting fires, but also carrying people out.

Training for firefighters is well-established on suppressing building fires following prescriptive codes as demonstrated in the past decades. Extending the maximum travel distance [25, 29] would impose difficulties in firefighting and rescue, and might even affect the valuable life of brave firemen. Note that they have to wear heavy portable breathing apparatus (PBA) and the associated air bottles, firefighting equipment and fire hydrant into the fire site with hazardous environment. They need to carry injured occupants or the disabled out. A normal PBA can only operate for 30 minutes.

A question is therefore raised:

Is it fair for firemen to walk a long travel distance exceeding the maximum allowed value?

This is a big issue referring not only to new projects. All existing buildings going through FEA/PBD since 1998 with extended travel distance much longer than code specification [25, 29] should be carefully reviewed. It is already very unfair to leave the responsibility of fighting against big fires to firemen under hazardous environment with fire safety provisions not complied with the codes. Asking them to walk through such extended long distances from 30 m to over 100 m in large halls, and 750 m to 1500 m in EEP of subway tunnels for firefighting and rescuing people trapped inside must be prevented.

Fighting fire in buildings without adequate fire safety provisions is very dangerous for firemen. Academics were blamed for not training fire engineers properly so that they cannot work out responsible fire safety design; but only keep on saying that hall (such as airport terminal) is safe without any experimental evidence.

An immediate action is to implement appropriate fire safety management by assigning more security guards to those places with extended travel distance to avoid any small accidental fire from happening. Big halls for public transport and tunnels going through FEA/PBD with timeline analysis should be checked carefully [17, 18, 21, 22]. Of course, full-scale burning tests must be carried out to avoid using flawed concept [20].

3. Low design fires

Consequent to so many big building fires in Hong Kong with one happened recently at Fa Yuen Street [35] in end November, 2011, there are deep concerns [10] on providing building fire safety in projects going through FEA/PBD. There are problems [36] that the fire safety provisions did not comply with the prescriptive codes, such as partitions without fire resistance, storage of large quantities of combustible goods and extended travel distance. In most of the FEA/PBD projects [6, 8], fire hazard assessment was focused only on evacuating people trapped inside the building. Very few FEA/PBD reports appeared in the past two decades talked about impact to firefighting and protecting firemen. The hard job of fighting against the big fires is left to the firemen!

As raised openly in a recent conference in Singapore [9], most of the FEA/PBD projects are only for reducing the construction cost. There are now many challenges on firefighting procedures not following guidelines [24]. This leads to concerns on how FEA/PBD would affect firefighting strategy, rescue strategy, intervention of fire service systems, and most importantly, potential health and safety impact on firemen. Note that toxic gases are not included in smoke assessment [2, 4, 29], but only heat and at most, carbon monoxide concentration deduced from free computing software without professional liability. Even so, a very low design fire less than 5 MW used to be estimated and adopted in many FEA/PBD projects.

Heat release rate [37] is the most important parameter affecting the course of a fire in hazard assessment in FEA/PBD while determining the fire safety provisions. Using a low design fire much less than the real incident [35] is very dangerous. Full sprinkler protection was not provided in many public places such as crowded subway station platforms [38] and large airport terminals [39]. Note that any disturbance in the burning process would increase the heat release rate, giving a fire much bigger than the design fire [40]. Firemen then have to fight against the big fires, if happened. However, there was no special consideration in FEA/PBD reports on evaluating the impact on firefighting strategy, rescue strategy, and health and safety of firemen under a big fire. These were only briefly discussed even in overseas PBD design guides with due reference to occupational safety and health practices not specifically worked out for fighting big fires (*e.g.* [2-4]). FEA/PBD design with assumed low heat release rates would give a much less hazardous environment, very different from those in real fires experienced by firemen [35]. Further, firemen might presume fighting fires in buildings with fire safety provisions complied with the code. Extending the travel distance, for example, would require longer operating time of portable breathing apparatus.

Fire load was surveyed by different research groups in the past 25 years in factory buildings, retail shops, karaokes, higher education institutes, residential buildings and shopping malls. Local residential buildings are observed to store much more combustibles [41] than the upper limit imposed by the codes [28]. It is very easy to get heat release rates higher than the low design value of only 5 MW assumed in many FEA/PBD reports, once adequate ventilation is provided due to whatever reason.

Data on heat release rate for local combustible products are not available. Estimations were based on very crude assumptions under low radiative heat fluxes in most of the FEA/PBD projects. Most of these calculations (*e.g.* [42]) were not supported by systematic full-scale burning tests. Some calculations were even wrong in just taking overseas combustibles to be the same as local ones, and assumed that the average heat release rate is the peak heat release rate. Correct calculation on the design fire is necessary for implementing the new generation of building fire safety codes [29] in view of the big post-flashover fires encountered [24, 35, 43]. Methods of estimating low probable heat release rates by burning those combustibles were just reviewed [44]. The trick of getting low heat release rates was pointed out. Further, it is difficult to model [45] the consequence of a big fire scenario realistically with Computational Fluid Dynamics (CFD). That is why some fire consultants even said that the ASET predicted by CFD is independent on the design fire higher than a certain value!

Therefore, immediate actions for new FEA/PBD submissions are to justify heat release rates estimated by full-scale burning tests on acceptable scenarios to ensure appropriate fire safety can be provided. An additional section on the effect on firefighting must be included in the FEA/PBD report. Firemen must be informed to ensure that they can take appropriate actions in firefighting. FEA/PBD projects only for reducing cost should not be allowed [9]. A cost analysis report on fire safety provisions in those places with difficulties to comply with fire code should be submitted to demonstrate that the objective of PBD is not for cost reduction. FEA/PBD should only be implemented when there are no fire safety codes.

Further, all FEA/PBD on fire safety provisions for existing projects assuming such low heat release rates must be reviewed again, with impact to firefighting and protecting firemen included. Appropriate fire safety management with more security guards assigned in those places [10] should be implemented to ensure that the amount of combustibles is kept low. The heat release rate of burning the stored combustibles might be low, say kept below 5 MW if the guards are properly trained. When there are difficulties in keeping low fire load density to match with the assumed low design fire, additional passive building designs and workable active fire protection systems should be provided. For example, large airport terminals and crowded deep underground subway stations likely to store more combustibles might give rise to big fires. These places must be fully protected by appropriate fire suppression systems and smoke management systems. Firemen should be warned that they might be going to a more hazardous environment for fighting against the big fire and rescue occupants. They must take appropriate precautions with suitable training, and be provided with additional firefighting equipment.

4. Cabin fire design for protecting large halls

Many big public transport terminals in the Far East including the airport and many subway stations [46] in Hong Kong are not fully covered by fire suppression and smoke exhaust systems. Only the cabin concept [39, 47, 48] was used in many big halls, but mostly protecting some areas for retail and catering. Apart from the hard efforts of the author and his students [49, 50], very few systematic experimental studies were reported to demonstrate that the design [51, 52] can control the heat release rate to a certain value, nor smoke would not spread to the entire big hall. Heat removed by operating the sprinklers in a cabin was not measured, but only presumed to be controlled within a small value such as 2 MW. Almost no full-scale burning tests appeared in the literature to demonstrate that the cabin concept would work as expected [53], particularly in the Far East, where social responsibility and education of citizens are very different from those in advanced countries. Taking the Hong Kong airport terminal as an example, it was observed that combustibles (apart from luggage) are always placed outside the cabin! Research results compiled in advanced countries might not be applicable to such developing areas. Strong justification with full-scale burning tests is needed on watching flashover in a cabin fire as proposed [54, 55].

A ‘full’ cabin is required [47] to have a sprinkler system to control the fire, and a smoke exhaust system to remove smoke. Preliminary studies showed that burning a typical newsstand [56] would give heat release rates up to 8 MW. Values higher than 8 MW are expected if large amounts of combustibles including wine are stored. Therefore, it is difficult to convince the public that the heat release rate in a retail shop fire in a cabin can be controlled at low values such as 2 MW even with sprinklers [53].

A long-term research programme with very limited resources [8, 46, 50] on cabin fires was worked out by the author for over ten years, in collaboration with several research groups in China. The project started with theoretical analysis on the fire environment inside a ‘bare cabin’, possibility of onset of flashover, and shop spill plume. Experiments on such bare cabin fires and smoke spilling out to the hall were then carried out to understand the possible hazards. The performance of sprinklers and smoke exhaust systems in a cabin of length 3.5 m, width 4 m and height 3 m was studied. The study was only on a 0.6 m by 0.6 m wood crib fire of height 0.4 m ignited over a pool of size 0.25 m by 0.25 m with mass of fuel 0.2 kg. The steady heat release rate of the wood crib was measured experimentally in an oxygen consumption room calorimeter to be 650 kW over 300 s. The heat release rate of two wood cribs placed within 0.3 m was up to 1.3 MW.

The following were observed in those preliminary tests:

- Air temperature inside a bare cabin fire would increase quickly upon burning the crib. The ceiling temperature could be up to 600 ^{o}C when two such wood cribs were burnt.
- Mechanical smoke exhaust system would control smoke in the cabin. However, smoke cannot be controlled, after operating the sprinkler, because of disturbing the stability. Large quantity of hot smoke was then observed to be spilling out to the hall outside. Therefore, a smoke exhaust system should be provided in the entire hall to keep smoke at high level.
- For cabins not completely closed, known as ‘open cabin’ in Hong Kong, air supply might lead to flashover in the cabin. The cabin itself would then become a big burning object. Therefore, the outside hall should have a fire suppression system.
- It was observed that sprinklers operating under normal design conditions [28] could not extinguish such a small wood crib fire with low heat release rates of 1.3 MW. All combustibles inside the cabin were burnt out even with the sprinklers operating. Those preliminary tests suggested that sprinklers might not be able to control a cabin fire if the combustible content inside the cabin is not controlled. Those retail shops storing many combustibles should be watched carefully.
- In particular, open cabins with only sprinklers inside but no fire suppression system in the outside hall should be reviewed carefully. This is because flashover inside a small cabin can be initiated easily to give a big fire!
- A normal sprinkler system using design parameters specified in the local fire code [28] might not be adequate. It cannot control fires with two wood cribs of 1.3 MW. Note that experimental data by the Swedish suggested that burning potato crisps bags [57] would give a heat release rate curve following a fast t^2-fire up to 6 MW quickly. Such a big starting fire would ignite adjacent combustible items (observed many times, apart from luggage) to give a much bigger fire. An alternative suppression system, such as a water mist system, should be provided inside the cabin if the fire load inside is not limited to very low values. Full-scale burning tests with such a water suppression system should be carried out to justify whether such big fires can be suppressed. Otherwise, appropriate fire suppression systems should be installed in the entire hall.
- As demonstrated in the preliminary tests on small wood crib fires and typical newsstand fires, water mist discharged from a high speed water fog nozzle might be able to control the fire if designed properly.

Anyway, the above are just preliminary results at two remote sites in China with limited funding. It is difficult to say that the cabin concept is safe as assumed in advanced countries [47, 48, 53] in protecting against the big hall, far too many problems were identified while using the cabin concept in the developing countries. Further systematic research should be carried out to demonstrate that the cabin concept would work for big public transport terminals in the Far East. In particular, full-scale fire tests under realistic big fires should be carried out in big terminals. The heat release rates of burning bigger retail cabins should be measured.

If the cabin design is demonstrated to have difficulties in functioning as expected in limiting the fire to 2 MW and unable to avoid spreading smoke out to the halls, workable fire suppression and smoke exhaust systems must be installed as soon as possible to protect the entire hall. Most of the public transport terminals in airports and subway stations in the Far East are very busy. Any disturbance to normal operation of the terminals will lead to disasters. Difficulty in locating the fire source encountered in the Chek Lap Kok airport fire was a good lesson to learn [58]. More importantly, improper fire safety design would also affect the firefighting and rescue strategies, and bring ill effects to the safety and health of firemen. They took several hours to locate the burning source as experienced at the Hong Kong airport fire in April 1998! With the possibility of developing new phases of the airport, the fire safety strategy proposed over 20 years ago should be reviewed. Further systematic experimental studies on the cabin design [47, 48] to cope with local operation practices must be carried out, not just relying on doing one or two demonstration tests with small fires in a few days.

5. Possible high risks on firefighting

There have been mounting public concern over post-flashover big fires, including the recent fire on Fa Yuen Street [35]. As discussed previously [10], projects with difficulties to comply with prescriptive fire codes should be watched closely. There are problems in the fire hazard assessment while projects go through FEA/PBD using fire model [59] and evacuation model [60]. CFD predictions are now under challenges. It is suggested that all assumptions and predictions have to be justified [61] by physical scale modelling experiments [62] on a minimal basis. Robotic motions are assumed [20] in the evacuation simulation model, which should be ensured in actual incidents. Many evacuation packages were developed without including appropriate data on human behavior measured for the Far East [18].

An important point is that very few of the FEA/PBD reports include intervention of fire services, impact on firefighting and rescue strategies, and potential safety and health effect on firefighters. This point was not vigorously addressed in overseas PBD guides [2-4], only referring to occupational safety and health practices. This matter was just highlighted and discussed in a railway conference [34]. For example, one should consider carefully before requesting firefighters to travel a long distance. The portable breathing apparatus can only operate for 30 minutes, thus making it very dangerous for extended travel distance. Very few FEA/PBD reports include vigorous analysis on safety and health of firefighters since 1998: they fail to urge firefighters to upgrade their equipment in very hazardous environment and revise their normal training schedule to prepare them for deadly fire.

The intervention of fire service system, impact on firefighting and rescue strategies, and potential safety and health effect on firefighters were not evaluated specifically in most of the FEA/PBD projects. The daunting task of extinguishing fires is left to the firefighters in FEA/PBD projects [2-4]. Consequently, firefighters must be warned beforehand that they are going to face a very hazardous fire environment which is different from a small accidental fire in a building with adequate fire safety provisions. They should be properly trained to tackle dangerous fires in buildings which fail to comply with prescriptive codes. They might have to enter large underground halls without adequate fire resistance [63] and walk a very long distance. They need to pass through long emergency evacuation passages in tunnels with fires higher than 17 MW [64], as low as 40 m below the ground; and they might need to use elevators to go up to supertall buildings over 300 m [33] without sufficient protection to work under a big fire.

Health effect on firefighters is an overriding concern [34]. Firefighters must upgrade their personal protection equipment under such severe fire scenario. Very few in-depth studies on this special issue were carried out even in advanced countries with good PBD research [2-4].

6. Conclusions

Consequent to the big stall fires at Fa Yuen Street [35] in the morning of 30 November, 2011, citizens are now worrying about fire safety, particularly those buildings with fire safety provided by FEA/PBD. Four areas on extended travel distance, low design fires, cabin design in big halls and the possible risks on firefighters were discussed in this paper. Immediate actions on the associated existing projects are:

- All FEA/PBD projects must be clearly notified to commanders of fire stations concerned, with fire safety provisions inspected seriously, thoroughly and regularly.
- Fire suppression facilities and personal protection equipment of firefighters must be upgraded.
- Their current practice of putting out fires in buildings with fire safety provisions which comply with the prescriptive codes should be reviewed.
- Additional training in fighting big fires under such hazardous environment in FEA/PBD projects is necessary.
- Fire safety management must be enhanced, such as keeping low fire load density in tall atria with long-throw sprinkler.
- Security guards should be assigned to direct occupants to leave the atrium with ‘robotic’ motion [20] as assumed in the evacuation software.

Anyway, this implies that fire research to support PBD should be carried out properly, particularly in Asia-Oceania regions with so many tall buildings, deep subway stations, large halls, long tunnels and green buildings. Further detailed studies will be made through empirical equations and computer fire models. Scale-modeling or real-scale experiments might be applied to justify the possible fire scenarios.

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