International Journal on Engineering Performance-Based Fire Codes, Volume 1, Number 3, p.156-161, 1999

APPLICATION OF FIRE MODELS TO FIRE SAFETY ENGINEERING DESIGN

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ABSTRACT

Fire engineering approach or a performance-based approach gives fire safety engineers opportunities using advanced technology and knowledge to fire-safety system design. Fire models are essential tools for the purpose of fire engineering approach. This paper addresses the application of a fire model, CFAST, and tenability analysis for the fire safety system design of a ferry pier building. It is indicated that a restaurant floor over the normal pier can not comply with the building codes. However, occupants can be evacuated from the building during a fire before the conditions reach untenable situation.

This paper discusses the principles of fire safety design. Approval of the fire safety design is subject to adjudgement of the Buildings Department and the Fire Services Department.

1. INTRODUCTION

A fire engineering approach to fire-safety system design in buildings is gradually being adopted worldwide [1,2]. The approach is unevenly developing in different parts of the world. In Hong Kong, fire safety design mainly complies with the Building Codes. However, in many cases, the code cannot cover the situations in practice. The Building Codes offer an alternative, that is fire engineering approach, to the practical design. The fire safety design is slowly moving toward the engineering approach in Hong Kong.

Fire engineering or performance-based approach to fire safety design means that design of the fire safety system of a building will be based on the analysis of the fire environment, spread of fire and smoke, means of escape, evacuation, tenability conditions, etc. The analysis will depend on the latest knowledge and techniques, which are recognized by authorities and related institutions, instead of the prescriptive codes. An engineering approach to fire safety design is always carried out case by case and will provide a similar or higher degree of safety, which could be provided by the prescriptive code.

Safety of occupants and firefighters is the major concern in both engineering approach and prescriptive approach. In fire safety engineering design, analysis of evacuation and tenability conditions in a building will dominate the design process. Fire models are essential tools for fire safety design in engineering approach. Fire models predict the fire environment based on design fires, which are accepted by authorities. Then tenability analysis can be carried out. The zone models are mainly used for simulation of design fires.

This paper discusses the principles of an engineering approach to fire safety design for a two-storey ferry pier with a restaurant on the top of the pier. A two-zone fire model, CFAST, is applied to simulate design fire scenarios. The CFAST model provides the fire environment. Further fire safety analysis is based on the results of CFAST model.

2. DESCRIPTION OF CFAST MODEL

The CFAST (Consolidated Model of Fire Growth and Smoke Transport) [3,4], is a model which intends to predict fire growth and smoke transport in multi-compartment structures. The model has been developed by fire research scientists at the National Institute of Standard and Technology (NIST), USA. The research activity of the development was started early 80's. The early release of the model was called FAST. The model has been improved, modified and re-released as CFAST early 90's. The latest is Version 3.10 released recently. The model incorporated the latest research results of fire safety science. The model has been widely used and accepted in fire safety community.

The CFAST model uses a two-zone concept, which divides an enclosure of consideration into an upper hot layer and a lower cool layer. The model solves the conservation equations for mass, energy and momentum at the vent, the plume and the relevant zones. The CFAST model predicts the environment of a specified fire in a multi-enclosure multi-level building. The model can also handle forced ventilation conditions. The CFAST has been carefully tested against a wide range of experimental data.

In using the CFAST model, it is essential to use the principle of design fires by prescribing the heat release rate or mass release rate. The model can then estimate the transient values of the smoke clear height in each room, the associated temperatures in the upper hot layer and the lower cool layer, the concentrations of combustion products (including O_2, CO_2, CO and other toxic gases), and other physical quantities associated with fire growth and smoke spread processes.

By using the results of CFAST model (smoke layer temperature, concentrations of O_2, CO_2, CO and other toxic gases), tenability analysis can be carried out by calculating the fraction of incapacitating dose (FID). Also many other fire safety-engineering analyses can be conducted based on the CFAST model results.

The CFAST model is one of the two-zone models, which is readily available and described in the literature. To assist the fire engineering approach, the CFAST model is used to assess the fire or smoke spread.

3. TENABILITY ANALYSIS

Tenability analysis is based on calculation of the fraction of incapacitating dose (FID) [5]. In fire environment, toxic gases (CO and CO_2), depletion of oxygen and heat are attributed to the value of FID. If an occupant exposes to fire environment and the accumulative value of FID reaches 1.0 because of intake smoke, the occupant may become unconsciousness.

The value of FID contributed by CO is expressed as equation 1 for constant concentration of CO,

$$F_{ICO} = \frac{K(CO)^{1.036}t}{D} \qquad (1)$$

For a transient fire environment, concentration of CO varies with time. Equation 1 can be expressed as a derivative format in equation 2,

$$dF_{ICO} = \frac{K}{\mathrm{D}} d\left((CO)^{1.036}t\right) \qquad (2)$$

During time interval (t_1,t_2) an occupant exposes to smoke, the value of FID contributed by CO can be calculated by equation 3,

$$F_{ICO} = \int dF_{ICO} = \frac{K}{D}\int_{t_1}^{t_2} d\left((CO)^{1.036}t\right) \qquad (3)$$

Adopting the same approach expressed above, the value of FID contributed by CO_2 can be express as,

$$F_{ICO_2} = \int_{t_1}^{t_2} \frac{dt}{\exp\left(6.1623 - 0.5189 \times \%CO_2\right)} \qquad (4)$$

The existence of CO_2 can greatly increase the volume of air breathed, which causes the rate of uptake of other toxic gases including CO. The expression for this factor is:

$$VCO_2 = \frac{\exp\left(0.2496 \times \%CO_2 - 1.9086\right)}{6.8} \qquad (5)$$

Incapacitation due to oxygen lack occurs when the oxygen supply to cerebral tissue falls below a certain critical value. Contribution to the FID can be found:

$$F_{IO} = \int_{t_1}^{t_2} \frac{dt}{\exp\left(8.13 - 0.54 \times (20.9 - \%O_2)\right)} \qquad (6)$$

Heat can contribute a significant part of the total value of the FID, which is expressed in equation (7).

$$F_{Ih} = \int_{t_1}^{t_2} \frac{dt}{\exp\left(5.1849 - 0.0273 \times T\,^{o}C\right)} \qquad (7)$$

Incapacitation can cause either by toxic gases or heat. The fraction of incapacitating dose for narcosis is the sum of FID for toxic gases.

$$F_{IN} = F_{ICO} \times VCO_2 + F_{IO} \quad \text{or} \quad F_{ICO_2} \qquad (8)$$

whichever is larger. The total fraction of the FID is assumed to be the sum of the contributions of toxic gases and heat.

$$FID = F_{IN} + F_{Ih} \qquad (9)$$

4. APPLICATION

4.1 The Case

There is a ferry pier building. The first two floors are used as a normal ferry pier, which is designed in accordance with the building code. The developer requests an additional commercial floor over the ferry pier, which is used for a restaurant. It is obvious that incorporating the commercial floor on the top of the ferry pier results in higher fire risk than a normal pier.

4.2 Difficulties to Meet the Building Codes

The ferry pier is built over the sea. It is not possible to fully conform to the requirements of the Hong Kong regulations, such as the requirements of the maximum travel distance, the dead-end distance, and the staircases. Particularly, the building can only be accessed on the landward side and no principal facade is accessible by fire appliances.

The total population of the restaurant exceeds 1000 persons. It is required by the Code of Practice for the Provision of Means of Escape (MOE) in Case of Fire that five separate escape routes with a total of 7.5 m width of exit doors and 7.5 m width of route need to be provided. Because of the difficulties in practice, the design can not meet the requirements of the MOE code. An fire engineering approach has to be used for the design of means of escape. Several schemes have been investigated. This paper discusses two cases:

1. two staircases with 2.4 m width of exit door and 3.0 m width of exit routes
2. four staircases with 7.5 m width of exit door and 7.5 m width of exit routes

4.3 Engineering Analysis

Because the lower two floors of the building will be designed as a ferry pier only, the fire load and fire risk in these areas are very low. Incorporation of the restaurant floor on the top of the ferry pier will increase the fire risk of the building. However, as the building is fully protected by sprinklers, the potential for a large fire to develop is low. The fire engineering approach focuses on the following areas:

- fire risk of the building
- fire spread control
- smoke spread control
- means of escape
- fire firefighting access

4.4 Fire Risk

As mentioned previously, incorporating an additional restaurant floor on the top of the ferry pier will increase the fire risk of the complex. The analysis will focus on the higher risk area and the interaction between the commercial floor and the pier levels. Attention has also been given to the low risk areas. In this paper, we introduce only the analysis of the restaurant floor.

It should be noted that the principle of the design is to separate the ferry pier and the commercial floor. Fire or smoke would not spread to another part within the fire resistance period should a fire occur in one part.

4.5 Fire Scenario

T-squared fires, that is, fire that grows as a function of the square of time, are widely used to define the scenarios of fire growth in different situations. There are four accepted design fires in t-squared formula, namely, ultra-fast, fast, medium and slow growth fires. The ultra-fast growth fire is true for thin plywood, fastest burning upholstered furniture and pool fires such as petrol and other flammable liquid fires. The fast growth fire is applicable to shop fires and restaurant fires, and the medium growth fire is applicable to office fires.

Using the FPETool program [6], the activation times of sprinklers under the fast and medium growth rate fires are given in Table 1.

For these two types of fires, the activation times of the fast response sprinkler are 100s and 185s and the predicted fire size at the sprinkler activation is less than 0.5 MW. It is recommended that fast response sprinkler heads are applied to the sprinkler system throughout the building. Conservatively, the risk analysis will be based on the fast growing fire up to 1.5 MW, then remain steady state at 1.5 MW level for the restaurant floor.

Table 1: FPETool predicted sprinkler activation time and fire size

Fire type	Fuel surface to ceiling (m)	Plume axis to sprinkler (m)	Activation time (s)	Fire size at sprinkler activation (MW)
Fast response sprinkler (RTI=50)				
Fast	2.7	2.2	100	0.46
Medium	2.7	2.2	185	0.38
Standard sprinkler (RTI=150)				
Fast	2.7	2.2	150	1.1
Medium	2.7	2.2	243	0.7

4.6 Risk Analysis

It is considered that the fire load and fire risk are low on the first and second levels, which are used as a normal pier. The restaurant floor is categorized as a high fire risk areas although the main hazard is the kitchen, which has full fire separation from the dining area. The analysis focuses on this area and demonstrates the application of fire engineering approach. Fig. 1 gives the layout of this floor. Two scenarios are investigated: (1) fire starts in the kitchen; (2) fire starts in the restaurant area. Fast growing t^2-fire is applied to both cases. It is assumed that the fire size remains constant after reaching 1.5 MW, which reflects the sprinkler system controlling fire development. Given in Figs. 2 and 3 are the predicted conditions of the two scenarios using the CFAST model.

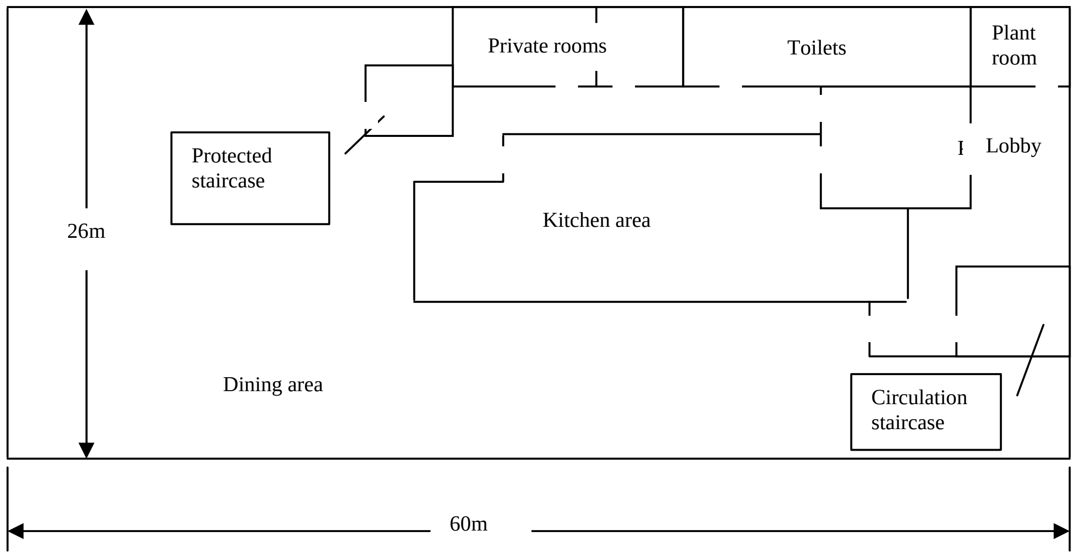

Fig. 1: Layout of the restaurant floor

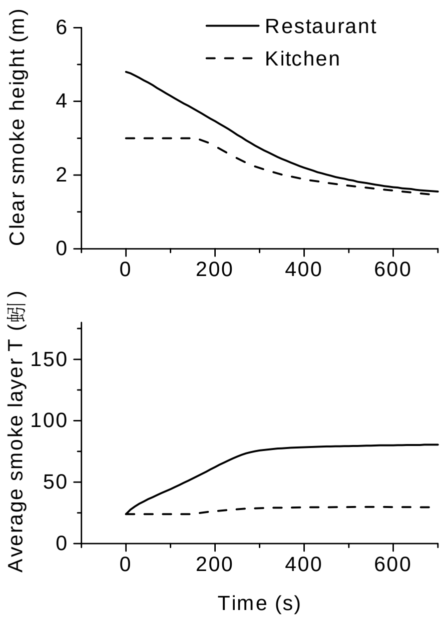

Fig. 2 Fast growth fire in restaurant, assuming fire remain constant heat output after reach 1.5 MW

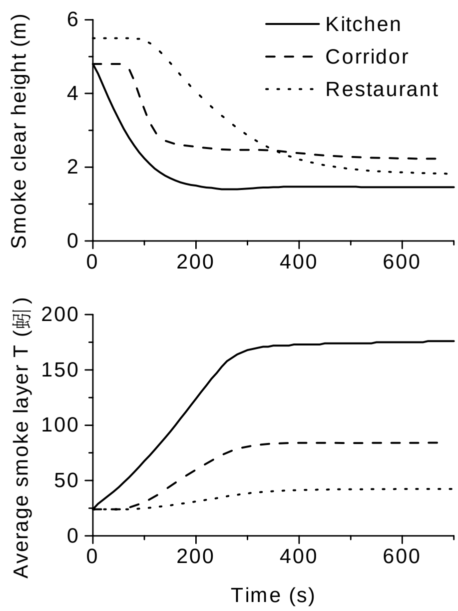

Fig.3 Fast growth fire in kitchen, assuming fire remain constant heat output after reach 1.5 MW

Based on the results of CFAST and applying equations 3-9 to these two cases, the time, when the fraction of incapacitating dose (FID) reaches 0.5 and 1.0, can be estimated and given in Table 2. As expressed previously, occupants will become unconsciousness when the FID value reaches 1.0. To ensure the safety of occupants during fire, 0.5 is used as the maximum value of FID for a tenable condition.

Table 2: Time to fraction of incapacitating dose reaching 0.5 and 1.0

Description of worst case	Analysis location (smoke layer)	Time to FID=0.5 (s)	Time to FID=1.0 (s)
Fast growth fire in kitchen	Kitchen Dining	250 1100	320 >1200
Fast growth fire in restaurant	Kitchen Dining	>1200 650	>1200 1090

The threat to which people are exposed in a fire is directly related to how quickly they can move away to safety compared to the time over which conditions might become dangerous. The evacuation time comprises of pre-movement time and travel time [7]. The pre-movement time can break down to recognition time and response time. The travel time includes the walking time to the exit, time through exit doorway (queuing time) and time within the exit route. Refer to the British Standard [7] and Hong Kong Building codes [8,9,10], the components of the evacuation time are estimated and listed in Table 3.

Table 3: Time components for evacuation of restaurant and kitchen

Pre-movement time (s)	Max. Walking time (s)	Queuing time at exit (s)	Time in protected route (s)	Evacuation time (s)
Case 1: two exit routes with 2.4 m width of exit door and 3.0 m width of staircase				
120	24	360	45	525
Case 2: four exit routes with 7.5 m width of exit door and 7.5 m width of staircase				
120	24	105	45	270

In the case of a kitchen fire, the FID value in the kitchen reaches 0.5 in 250s and 1.0 in 320s. However, it is expected that occupants in the kitchen escape to the dining area before the FID value reaches 0.5. In the dining area, the FID becomes 0.5 in 1100s. If fire starts in the dining area, the tenable time in this area is 650s when the FID value arrives 0.5. The evacuation time of the restaurant is estimated to be 525s (8.75 minute). It may be concluded that the occupants in the restaurant can be evacuated safely under the design fire conditions of case 1 (2 exit routes).

However, it is required by the MOE code that for sprinkler protected buildings the maximum evacuation time should be less than 5 minutes. It is recommended that four protected exit routes will be provided for the restaurant floor and the total width of the exit doors and the staircases will be 7.5 m. The evacuation time from the restaurant floor is reduced to 270s (4.5 minutes).

5. CLOSURE REMARK

Application of a fire engineering approach in Hong Kong is at its early stage. The analysis indicated that two escape staircases (3.0 m wide) would allow 1000 occupants in the restaurant floor to evacuate safely before the fire environment reached untenable conditions. However, it is recommended to provide four staircases (7.5 m wide). The evacuation time from the restaurant floor reduces to 4.5 minutes, which is complied with the MOE code.

The analysis is based on the fact that the fast sprinkler system controls fire development. The fire size will not exceed 1.5 MW.

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