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Determination of fire load and heat release rate for high-rise residential buildings

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Abstract

In recent years, high-rise residential building fires are drawing more and more concerns. It was reported that a large number of fire accidents occurred in residential buildings which resulted in casualties and damage to properties. In some buildings, large amounts of combustibles are stored in units of small area. Fire safety provisions are not adequately provided as required in public buildings. Performance-based design has been introduced in many places and the determination of design fires is one of the most important steps in the design process. Fire load and heat release rate are important inputs to a design fire. In order to assess the fire risk of high-rise residential buildings, possible fire scenarios should be identified. There is an urgent need to collect data on fire load and identify the heat release rate for this type of buildings. In this paper, a literature review was made on design fires and fire load survey methods for buildings. Characteristics of heat release rate in the fire growth stage and post-flashover stage were explored. Issues that should be considered for high-rise residential buildings were presented. Then, the advantages and limitations of different fire load survey methodologies were summarized and a fire load survey method suitable for residential buildings and the data needed to be collected were recommended. Finally, conclusions were made.

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Nomenclature

A_0 area of the opening
 H_0 height of the opening

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m_{air} mass flow rate of air into the compartment

1. Introduction

With the rapid economic development and urbanization, more and more high-rise residential buildings are built, especially in densely populated areas [1]. The fire safety of high-rise buildings have attracted people's attention over years, due to their unique challenges, such as long evacuation time and distance, smoke movement and control, and fire department accessibility. Fire protection features are provided to ensure safety of these buildings in case of a fire. In recent years, more residential building fires were reported prompting concerns over fire safety in this type of buildings, like the 2010 Shanghai fire [2]. In some of residential buildings, large amounts of combustibles are stored in units of small area [3]. Fire safety provisions might not be adequately provided as those required in public buildings. With the adoption of some design features, like green building [4] and open kitchen [5], new fire risks might be posed.

Performance-based design, which is becoming more popular in many places, is adopted for buildings with difficulties to comply with prescriptive codes [1]. Identifying design fires is one of the most critical tasks in a performance-based fire safety design [6]. There are many methods used to characterize design fires [7]. It is important to select an appropriate and relevant design fire representative of the building considered. Heat release rate for a design fire is described as the single most important variable in fire hazard [8]. It provides information on heat output of the fire varying with time. Once the heat release rate is known, the fire resulting environment can be calculated as time progresses. Then when the untenable conditions are to reach and the damage to the structure can be estimated.

Characteristics of combustibles, ventilation openings, compartment geometry, material properties of enclosure boundary [9] and environmental factors [10] (such as wind effect on high-rise buildings) are important factors in determining how severe a fire is. In order to characterize fires for use in performance-based design and fire risk analysis, information on fire load must be obtained. Fire load survey is the direct way to collect associated information which can provide a basis for the design fire. It has been proven in literature [3,11-17] that fire loads are dependent on the occupancy type and building use. There are many surveys made for office buildings [e.g.11-14] and a few are made on schools [e.g.15] and other type of buildings [e.g.16, 17]. Due to privacy issues, it is more difficult to make a fire load survey in residential buildings than in other buildings. Thus, fire load data on high-rise residential buildings are relatively few and up-to-date information is even scarce. Since heat release rate for design fires is closely related with the corresponding fire load data, the heat release rate for design fires and fire load survey techniques for high-rise residential buildings are discussed in this paper.

2. Design fires

The design fire involves things like heat output, smoke production and toxic gases generation of a fire. Information of toxic gases is of great importance in fire hazard assessment, while due to the complex of combustion process [1, 7] it is difficult to quantify the type and amount of gaseous products generated in real fire. With the aid of oxygen consumption principle [8], heat release rate can be measured in full-scale or bench-scale tests. Heat released varying with time becomes the important representation for a design fire. The process of compartment fires is usually divided into several stages: ignition, growth, flashover, fully developed fire, decay. Taking flashover as the demarcation point, the fire can also be divided into pre-flashover stage and post-flashover stage [9]. The development of a fire depends upon a range of variables, such as the ignition source, properties and arrangement of fire loads, the size and location of compartment openings, and the material properties of enclosure boundary. Admittedly, actions of occupants and fire protection features installed affect the size and rate of development of a fire.

There are many ways to develop a design fire as reviewed in [7, 10]. A steady state fire is the simplest way to specify a design fire which is based on the expected largest size of a fire under a certain scenario. In some cases, an arbitrarily given value is used as the constant heat release rate. If this value is much less than the actual value in real situation, it can be very dangerous [18]. Time-dependent design fire is closer to a real fire. There are many

mathematical models of this kind of fires. One that is widely known is the T-square fire for growth stage which is based on extensive experimental data. It consists of fires of ultrafast, fast, medium and slow in terms of growth coefficient according to the time reaching 1 MW. The standard fire curves as ISO834 and parametric design fire curve as that specified in Eurocode 1 Part 2 [19] are fully developed fires [10] which are usually used to evaluate the fire performance of building structure elements.

3. Heat release rate

In order to estimate the fire hazard, the heat release rate must be known. It gives useful information such as the fire size, rate of smoke production, the possible fire environment, and other relevant data for hazard assessment [20]. The main factors that control the fire development at growth stage and fully developed stage are different.

3.1. Heat release rate in the growth stage

In the fire growth stage, there is sufficient oxygen for combustion and the fire is so-called fuel-controlled. The characteristics, distribution and arrangement of the fuel dominate the heat release by the fire.

After initiation of a fire, whether the surrounding items will be ignited depends on the radiation heat flux received by the exposed items and how easily they can be ignited [21]. For example, the fire spread might be considerably affected by the location of the ignition source, as experimentally demonstrated in ref [22]. When the fire load is close to each other, the fire may become intense more quickly; otherwise it may self-extinguish due to burn up of the fire source. Types of combustible materials will typically be of primary concern. Heavy wooden furniture might be difficult to ignite, but once ignited, it lasts a relatively long time. On the other hand, a vertically hanging curtain can be ignited with ease and pose a rapid flame spread, burning very shortly.

The consequence of the combustibles being ignited plays an important role in the determination of heat release rate. There are many experimental data for heat release rate of single items. How to obtain the total heat release rate of burning more than one item needs to be investigated. The principle of superposition [23] is sometimes used to combine heat release rate of combustibles. The ignition temperature or critical heat flux are usually taken as ignition criterion. Where practical, full-scale burning tests [24] should be conducted for typical arrangement of combustibles items found in the fire load survey. The heat release rate and other parameters measured can be used for a design fire.

3.2. Heat release rate for fully-developed fire

After flashover, all the exposed surfaces of combustibles in the compartment are involved in the fire. Excessive combustible gases are emitted and there is not enough air for combustion. Therefore, the fire becomes ventilation-controlled. The higher the value of the fire load is, the longer the duration of the fire, and the greater the potential damage. Fire load or fire load density is incorporated into some mathematical models to predict the time-temperature curve or the fire duration time. During post-flashover stage, the concern is on the structural stability. The time-temperature curves are used to estimate the fire resistant performance of structural elements. The energy release rate of the fire can be roughly determined by the air inflow from the openings. Based on the assumption that all of the air entering the compartment is used for combustion, a maximum heat release rate can be achieved by the expression:

$$m_{air} = 0.5A_0\sqrt{H_0} \quad (1)$$

It is important to note that in tall buildings, the wind effect and stack effect might have substantial effect on the heat release of the fire, especially for floors at a high level. More air will enter into the fire room due to wind and stack effect resulting in a much higher heat release rate [25]. Since there are coupled effect of wind action, stack effect and fire itself, it is difficult to determine the mass flow rate across the openings and the application of the equation (1) should be validated.

4. Fire load survey made on residential buildings

As mentioned above, an appropriate and rational design fire should be based on the fire load of the buildings of consideration and characteristics of the fire load depend largely on occupancy and building use. Fire load, expressed in MJ, is defined as the total energy released by combustion of all combustible materials in the enclosure [9]. It is customary to divide the fire load into two categories: moveable fire load (also termed as content fire load) and fixed fire load (also termed as nonmovable fire load or permanent fire load). Fire load density is the fire load averaged by characteristic area of the compartment. Normally, it is expressed as the fire load per unit floor area.

A relatively small number of surveys were conducted in residential buildings in recent years, due to privacy issues and other considerations.

Kumar and Rao [26] carried out a fire load survey in residential buildings by inventory technique in Kanpur, India in early 1990s. Movable fire load and non-moveable fire load were recorded. The effect of housing type, floor area, room use and floor level on fire load was analyzed. The mean fire load varied from 278 MJ/m² to 852 MJ/m². It is noteworthy that they found that the mean and maximum fire load decreased as the room floor area increased and the fire load had no direct relation with the height of the building.

A series of fire load survey was conducted on residential buildings in Canada. A pilot survey [27] on movable fire loads in residential living rooms was conducted. Questionnaires consisting of 64 questions were distributed through the Internet to collect pertinent information. The distribution of living room floor areas, window number and areas, main combustible contents, fire load and fire load density were analyzed. The mean fire load density was 600 MJ/m² with a standard deviation of 200 MJ/m². In a project named CFMRD (Characterization of Fires in Multi-Suite Residential Dwellings), a survey [28] was conducted on floor area and combustible contents in multi-family dwellings. A novel method was adopted. Information was obtained through the real-estate website which offered the size and photographs of main rooms. Then the fire load was evaluated primarily based on this kind of information. The average fire load densities were found to be 807 MJ/m² for kitchens; 393 MJ/m² for dining rooms; 288 MJ/m² for basement living rooms; 534 MJ/m² for Primary bedrooms; 594 MJ/m² for secondary bedrooms.

There are many high-rise residential buildings in Hong Kong. People are concerned with the fire safety of these buildings. Chow et al. [3] had selected and surveyed eight old high-rise residential buildings in Hong Kong. The movable fire load was reviewed by visual inspection. Due to small average living area, the fire load density in half of the buildings surveyed exceeded the upper limit of 1135MJm⁻² specified in the local code [29]. Another fire load density survey[30] conducted in 50 typical residential flats in Hong Kong indicated that the average fire load density was about 1400 MJ/m².

Residential buildings can be subdivided into several categories, such as apartment building or house; high-rise building or normal building. They have an effect on the characteristics of fire load. Moreover, ages, culture and geographical location of a building also have an effect.

5. Methodology of fire load survey

From literature review, several methods were employed in fire load surveys in buildings. These are weighing, inventory, combination of weighing and inventory, questionnaires, and website review. The weighing and inventory methods were most often used by different surveyors in the past. The NFPA Standard 557 [31] also proposes that a fire load survey can be conducted by either the weighing or the inventory technique or a combination of them. Each survey method has its own advantages and disadvantages.

1) The weighing technique

Weighing is the most direct and simply way to obtain the mass of items. This method needs surveyors to physically enter the building to weigh the mass of combustible objects. It is easy to weigh small items, such as books, chairs. Large items like heavy furniture are difficult to weigh. Besides, this technique is applicable to movable fire load, while it is impractical for fixed combustibles. Some items consist of not only combustible materials but also non-combustible materials. Then, the proportion of the combustible part should be determined.

2) The inventory technique

In the inventory technique, there are two ways to obtain the mass of an item. One way is to measure the dimensions of the object and then the mass is determined by multiplying the measured volume with the

corresponding density. The other way is to weigh the commonly encountered items in advance or get their weight from the manufacturers and then create an inventory list. Thus, the mass of surveyed items will be estimated based on the inventory list. This technique can be used for items that cannot be weighed. The problem is that sometimes it is difficult to determine the volume of irregular shaped items and the density of various types of materials. Error will arise when the surveyed item is mismatched with the ones from the inventory list.

3) The questionnaire technique

A printed paper questionnaire or an electronic one is designed first consisting of questions to be answered by occupants. The questionnaires will then be distributed by traditional methods or through the Internet. Occupants' participation might be very poor [33]. Whether a satisfactory survey result can be achieved depends largely on the design of the questionnaire and occupants' understanding of and commitment to it. This method is used in only a few surveys due to big uncertainty in the data.

4) Website review technique

Fire load survey can be made through website information, as done by Bwalya [28]. Sale information listed on the real estate websites usually offer the floor plan of the house or apartment with dimensions of the major rooms. Digital photographs of various rooms provided can give a general picture of typical furnishings and their layouts in a particular building category. In this technique, fire load is estimated according to these photographs. The application of this method is limited because it is not easy to find a real estate website providing enough information you want. And these photographs usually cannot show all the combustible items in a room, for example, contents in cabinets or things hidden by others and there is a big uncertainty in estimating the mass and calorific value of these items just through the photos. The surveyor's judgment and experience will have great impact on the result.

5) Fire load survey methods recommended for residential buildings

For residential buildings, occupants are usually reluctant to allow strangers into their personal space, not to mention weigh the content at their home item by item. In view of this, questionnaire might be a good choice. If the samples size is large enough and the questionnaire is designed carefully, the disadvantage of questionnaire technique might be compensated. But the later data processing work may be troublesome. For some newly-built high-rise residential buildings, in kitchens and similar places, fire detectors or sprinklers are required to install and should be maintained periodically. It is better that fire load surveys can be incorporated with this kind of maintenance work. The surveyors measure and record the dimensions of the compartment and openings. At the same time, pictures are taken to record the required data on combustible items at different rooms. This method is time-saving and cause fewer disturbances to the occupants. There is also an apparent advantage that pictures can provide a permanent record and can be reviewed when needed. Information on the type and composition of combustibles, their arrangement and distribution, even brands and types of furniture can be inferred from these pictures. Consultancy with the furniture manufacture or visit to selling stores can get more information about the items. It is expected to offer result data of good high quality and more suitable and acceptable for residential buildings.

In summary, the weighing method and inventory method need physical entry into the building. The latter is relatively convenient and time-saving. In most cases, a combination of the weighing and inventory methods is used to incorporate their advantages. The questionnaire method is less laborious, but the results obtained might not be satisfactory. Since website review is a novel method and information is obtained through limited photographs which are taken not for survey purpose, the survey data should be validated. Suitable fire load survey methods for residential buildings should be more time-saving, and cause little trouble to the occupant.

6. The content of fire load survey

Till now, there is no consensus on what data should be collected in a survey. Though many surveys have been conducted on different building categories, the range of the survey vary greatly. Some only reported the mass of various combustible items present and the corresponding floor area, while some also reported on the window size and composition of the fire load. Besides, surface area of fire load [e.g.33, 34] or percentage of floor area covered by furniture [e.g.15] was included in a few surveys. Since the design fire is affected by many factors, it is better to get more information about the combustion on a practical basis. It is suggested that the following basic information should be surveyed:

- 1) Information about the building surveyed

It includes, but not limited to, the height and layout of the residential unit, and the use and geometry of each room.

- 2) The location and size of openings

When the fire becomes ventilation-controlled, the size and location of the openings play an important role in determining the heat release rate of a fire. Openings include windows that may be broken in a fire and doors that might be left open. In high-rise buildings, the orientation of the window is of special importance due to expected strong wind.

- 3) The fire load

Both movable fire load and fixed fire load need to be recorded. Information collected for combustible items include, but not limited to the type, quantities, and the proportion that are combustible.

- 4) Fire protection system installed

Fire detection and alarm system, fire suppression system and other fire protection systems will intervene with the process of a fire. Therefore, systems installed and their configurations should be recorded.

The survey data should be analyzed carefully. Statistics such as the mean fire load density, standard deviation, and a cumulative probability distribution should be given [31]. The main composition and typical arrangement of the combustibles should also be reported.

7. Discussions

Literally, fire load surveys are to obtain information on the fire load or fire load density of a certain type of buildings. The objectives of the survey should not be limited to only getting information on the mass of different types of combustibles and their calorific value. The fire load itself can just tell the total energy content present in the compartment. There are other factors that influence the development of compartment fires. More information that characterizes the buildings surveyed should be collected, in order to get a more rational design fire.

Furthermore, there are some disagreements about the details in conducting fire load surveys. With respect to enclosed combustibles (like combustible items stored in cabinets), a “derating” factor [e.g.15, 32] was introduced in some but not all surveys. The reason for derating is that people might think that items stored in noncombustible cabinets would not burn efficiently as those exposed. The spread of a fire in the early stage is influenced by the arrangement or distribution of combustible materials in the compartment. The layout of these items may vary largely especially in residential buildings, which is dependent on the occupants’ preference. In a few surveys, floor area covered by combustibles was reported. But this parameter cannot necessarily reflect to what degree items are concentrated.

The importance of heat release rate in compartment fires has been recognized for years. Since the fire load cannot tell how the combustibles are burned, and then even based on the results of fire load survey, time-dependent heat release rate is difficult to develop, especially for the fire growth stage.

It is noteworthy the wind effect on compartment fires in high-rise buildings should be considered carefully. There are many residential buildings of more than 200m in height built [1]. When a fire occurs at a higher floor level, it is more likely that the fire will burn more intensively with more air supply. How to measure the wind effect needs further discussion.

8. Conclusions

With the number of home fires increasing in recent years, more attention has been paid to high-rise residential buildings. Though there are many difficulties in conducting fire load surveys in terms of time, labor and organization, it is the more effective way to collect basic information that can help to develop the design fire. Methods suitable for residential buildings and fire load survey content are recommended. Full preparation work should be done to ensure a high quality of survey data. When determining the heat release rate for a fire, the dominant factors in different stages should be considered. More work should be done to investigate the magnitude of wind effect on high-rise building fires and how to incorporate it into the design fire.

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