Analysis on the Distribution Regularity of Fire Load in Hotel Buildings

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ABSTRACT

This paper presents survey results on fire loads distributions for hotel buildings in the cities of Hefei, Lanzhou, Shenyang, Chengdu, Yantai and Tianjin surveyed in China. Details of the survey methodology, data collection and processing are given. Furthermore, the influence of the hotel rating, room type, region and room floor area on fire loads are discussed in detail. Based on the probability statistics and test of normality, the fire load densities of all the surveyed hotels show a lognormal distribution with the mean value of 349.2 MJ/m², the maximum value of 886.4 MJ/m², the minimum value of 117.8 MJ/m², and the standard deviation of 142.1. The fire loads obtained from the survey have been compared with those of similar surveys in other countries. According to the survey results, the fire dynamical theory and characteristics of building fire, the evaluation methods of the fire duration time and the collapse probability of building caused by fire are also developed in this paper. The statistical parameters of the fire load presented in this paper will be useful in the design of fire prevention and fire fighting measures of hotel buildings.

Keywords: Fire load, Fire load density, Lognormal distribution, Fire duration time, Collapse probability

1. INTRODUCTION

Fire load is basic data to the performance-based fire protection design regarding the overall development stage of fire as well as the intensity and duration of the fire [1, 2]. Knowledge of the statistical distribution of the fire load is essential for designing a building against fire. A review of the current state of knowledge indicates that considerable progress is yet to be made in correctly assessing the design fire load.

The loads are random in nature, time dependent and often depend on living habits, living standards and many cultural and social aspects. It is thus necessary to conduct load surveys periodically to review the validity of prevailing loads, etc. Surveys have shown that fire load is dependent on occupancy, for example, residences, offices, libraries and hotels have different kinds of fire loads. At present only meager data exist concerning the fire load in buildings [3, 4, 5].

This paper presents the results of a survey, which was conducted in the Chinese cities of Hefei, Lanzhou, Chengdu, Shenyang, Yantai and Tianjin(which was surveyed by Cai Yun [6]) to characterize fire loads in hotel buildings. The survey includes double rooms, quad rooms, six beds rooms, deluxe suites, dining halls, conference rooms and scriptoriums.

2. FIRE LOAD

Fire load is the starting point for estimating the potential size and severity of a fire, and thus the endurance required of walls, columns, doors, floor-ceiling assemblies and other parts of the enclosing compartment. The term “fire load” is defined as the total heat content upon complete combustion of all the combustible material contained inside a building or the fire compartment. In that case, the heat content per unit area is called the fire load density. The higher its value, the greater the potential fire severity and damage as the duration of the burning period of the fire is considered proportional to fire load, it is given as [6]:

$$q = \frac{\sum M_v \Delta h_c}{A_f} \quad (1)$$

Where q is the fire load density, (MJ/m²). M_v is the total weight of each single combustible item in the fire compartment, (kg). Δh_c is the effective calorific value of each combustible item, (MJ/kg). A_f is the floor area of the fire compartment, (m²).

3. SURVEY METHODOLOGY

Determining the fire loads in a building involves determining the floor area of the fire compartment, the mass of all the different types of combustibles and their effective calorific values. The floor area of a compartment can be determined by measuring its dimension. The mass of an item in a compartment can be determined by weighing it (weighing technique) or by determining its volume and identifying its density (inventory technique). In this survey, all the techniques have been employed. The direct weighing method was used for the items that could easily be weighed, such as chairs and garbage cans. The inventory method was used for the items such as large objects and built-in shelves. In this method, dimensions of items were measured and their volume was calculated [1, 7, 8]. The mass was then computed by multiplying the volume by the density of the material [9]. The densities of some typical materials are shown in *Tables 1-3*. The calorific values of combustible substances given in *Table 4* were used in the fire load calculations [10]. For some special combustible substances such as computers, the heat of combustion could be determined by consulting literatures.

Table 1 The densities of common wooden materials

Materials	Density(kg/m ³)	Materials	Density(kg/m ³)
korean pine	440.00	sophora japonica	722.00
cinnamomum camphora	535.00	quercus mongolica	766.00
liquidambar formosana	588.00	quercus acutissima	930.00
birch	635.00	dalbergia hupeana	987.00

Table 2 The densities of common fabric materials

Materials	Density(g/m ²)	Materials	Density(g/m ²)
lining fabric	99.00	twill(100% cotton)	230.00
OPTOH	270.00	glove fabric	260.00
disguise fabric	244.00	canvas	400.00
twill C50EX	245.00	flax	420.00

Table 3 The densities of common plastic materials

Materials	Density(g/cm ³)	Materials	Density(g/cm ³)
silicon rubber	0.80	phenol formaldehyde resin	1.26~1.41
high pressure polyethylene	0.89~0.93	polyvinyl fluoride	1.30~1.40
low-pressure polyethylene	0.92~0.98	PVC R	1.38~1.50
polystyrene	1.04~1.08	polyoxymethylene	1.41~1.43
epoxy resin	1.10~1.40	chlorinated polyvinyl chloride	1.47~1.55
Polyacrylic	1.14~1.14	PVDF	1.70~1.80

Table 4 Calorific values of common combustible materials

Materials	Calorific value(MJ/kg)	Materials	Calorific Value(MJ/kg)
Clothes	18.80	Wool	23.00
Kerosene	37.20	ABS	36.00
Leather	18.60	Linoleum	20.00
LPG	49.90	Silk	19.00
Paper	16.30	Rubber	39.50
Plastic	22.10	Wood(average)	18.60
Epoxy Resin	34.00	Urea Formaldehyde Foam	14.00

For each survey, a similar procedure was followed to ensure that data were collected in a systematic and consistent fashion for all buildings. Firstly, the building name, as well as, the type of establishment, and the date of the investigation were recorded. Secondly, the dimensions of the building were measured and the types of wall, floor, and ceiling lining materials were determined and noted in the fixed fire load section of the survey form. Thirdly, all contents in the building were identified and classified. The items that could be weighed were weighed to determine their mass. If the items were made by one material, the material was determined and recorded. For the items consisting of more than one material type, the percentage of each type was determined and quantified. The mass of items that could not be weighed was determined by measuring their volume and using the density of the material to calculate their mass. For the following data analysis procedure, it was assumed that combustibles within the compartment are uniformly distributed, and that at the time of fire, all combustibles would be involved in a fire and would experience complete combustion.

4. SURVEY RESULTS

The influences of hotel rating, room type, region, room floor area on fire load and the detailed analysis on the distribution regularity are presented in this section.

4.1 *Influence of Hotel Rating*

According to the consumption level, the hotels were divided into low-rating hotels, middle-rating hotels and high-rating hotels. The low-rating hotels are generally facing to the low-income population. The housing conditions are very poor, and the rooms were merely conducted preliminary internal decorations. Only common electric equipments, such as televisions exist in the rooms. The middle-rating hotels are generally facing to the general income people. The most common electric equipments exist in the rooms, such as televisions, air conditioning equipments and so on. The interior finishing materials are massive high-quality wooden materials, plastic materials, cotton ramie silk materials and other synthetic materials in the middle-rating hotels. Most of these hotels also open dining halls. The high-rating hotels are generally facing to the high expense crowd. This kind of hotels open all kinds of halls, such as specialty restaurants, dancing halls, coffee shops, grand auditoriums, assembly halls and so on. The rooms usually have multiple functions. Except for the common electric equipments, there also exist office supplies in the rooms.

For of the three different rating hotels, a summary of statistical calculations is shown in *Table 5*. Considering all hotels together, the mean fire load in the low-rating hotels, middle-rating hotels and high-rating hotels were obtained as 223.13 MJ/m^2 , 329.70 MJ/m^2 and 408.27 MJ/m^2 , respectively. The fire load density increases with the raising rating of the hotels. This is due to the interior finishing materials which are massive high-quality wooden materials, plastic materials, cotton ramie silk materials and other synthetic materials in some middle-rating and high-rating hotels, which result in the greater fire load density. In addition, with the popularity of electrification and automation, a large number of electrical equipments such as refrigerators, televisions and vacuum cleaners were arranged in the hotels, which also increases the fire load density. Besides, the elegant environment of high-rating hotels also attracted some companies to carry on their daily office in them. Therefore, some modern office equipments, such as photocopiers, fax machines, computers, paper shredders and so on are employed in the offices, which increases the fire load density as well.

Table 5 Influence of grade on fire load (MJ/m^2)

Statistical Parameter	Low- Rating Hotel	Middle- Rating Hotel	High- Rating Hotel
Number	29	64	82
Mean	223.13	329.70	408.27
Median	165.40	318.70	405.20
Variance	9523.80	11205.32	22219.35
Std. Deviation	97.59	105.86	149.06
Minimum	117.80	167.20	141.50
Maximum	426.70	698.60	886.40
Range	308.90	531.40	744.90
Interquartile Range	160.40	123.00	182.30
Skewness	0.70	1.34	0.85
Kurtosis	-0.85	2.35	1.05

Figure 1 Fire load histogram---low-rating hotel

Figure 2 Fire load histogram---middle-rating hotel

Figure 3 Fire load histogram----high-rating hotel

4.2 Influence of Room Type

Room type may play a significant effect on the composition and magnitude of the fire load in hotel buildings. For each room type, a summary of statistical calculations is also shown in *Table 6*. For all rooms, the mean and standard deviation of fire load were obtained as 349.2 MJ/m^2 and 142.12 , respectively. The maximum fire load of 886.40 MJ/m^2 was encountered in a double room. Deluxe suites were most heavily loaded, followed by double rooms. The least mean load was found in the six beds room and dining hall. However, the variation of standard deviations is not different from the mean fire load. The standard deviation of scriptorium was most heavily loaded, while the dining hall is the least value. As for the double rooms and deluxe suites which have limited floor areas, the interior finishing materials adopted massive high-quality wooden materials, plastic materials, cotton ramie silk materials and other synthetic materials, meanwhile, up-market combine-units, sofa, refrigerators, televisions, air conditioning equipments and vacuum cleaners were widely arranged in the hotel buildings. These resulted in the increasing fire loads. The quad rooms and six beds rooms were widely investigated in the low-grade hotels, and the fire loads are lower, which is due to the tatty interior decorations. The larger floor areas in the conferences, dining halls and scriptoriums limited the value of fire loads.

Table 6 Influence of room type on fire load(MJ/m²)

Room Type	Fire Load (MJ/m ²)			
	Minimum load	Maximum load	Mean load	Standard deviation of load
Double room	167.20	886.40	395.20	133.10
Quad room	117.80	329.80	204.00	57.90
Six beds room	127.00	161.00	137.60	12.60
Deluxe suite	228.30	511.80	401.10	71.70
Dining hall	193.30	297.30	238.40	26.80
Conference room	358.60	446.90	389.40	30.70
Scriptorium	141.50	815.70	377.00	217.00
All rooms	117.80	886.40	349.20	142.12

4.3 Influence of Region

Figure 4 shows the minimum, maximum, mean and standard deviation of the hotels fire load in different cities. The distribution shows that the fire loads are different even for the same kind buildings. The maximum, mean and standard deviation of fire load all achieved the maximum value in Shenyang, while these parameters in Yantai are lowest. Different living habits, living standards, culture and social aspects in different cities resulted in the different fire loads.

Figure 4 Fire load histogram----influence of region

4.4 Influence of Room Floor Area

Because of the huge differences on floor area for different type rooms, the double rooms were selected to examine the influence of room floor area on fire loads. Figures 5-7 show the maximum, mean and standard deviation of fire load with the floor area of all the rooms taken together. The maximum fire load, the mean fire load and the standard deviation of fire load decrease with the increase in floor area of rooms up to 25m², but thereafter they show increase trend with further increase in floor area. For the same

rating hotels (low-rating hotels, middle-rating hotels) with limited floor areas, the furnishings and electric appliances in large and small rooms are similar. Therefore, the fire loads gradually decrease with the increasing floor area. But for some middle-rating hotels and high-rating hotels which have larger floor areas, the quantities of furnishings and electric appliances increase with the increasing floor area, which forms great fire loads in the hotel buildings.

Figure 5 Influence of room floor area on maximum fire load

Figure 6 Influence of room floor area on mean fire load

Figure 7 Influence of room floor area on standard deviation of fire load

4.5 Statistical Interpretation of Fire Load Density

Figure 8 shows the frequency distribution of fire load densities of all the surveyed hotels. It can be seen that the frequency distribution is positively skewed indicating that on the whole, high values of fire load have low occurrence. The distribution regularity is not the normal distribution that other type buildings obey. The characteristics of the fire load for all the hotels are presented in Table 7, in which the skewness is greater than zero also indicates the data collected show the right-skewed trend and may be similar to the lognormal distribution. The standard lognormal probability density function is as follows [11]:

$$f(x) = \frac{1}{\sqrt{2\pi}x\sigma} e^{-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2} \quad (2)$$

Where μ is the population mean, σ is the standard deviation, for the domain $0 \leq x \leq +\infty$, the parameters $\mu > 0$, $\sigma > 0$.

Figure 8 Frequencies of fire load density of all the surveyed hotels

Table 7 Characteristics of the fire load for all the hotels (MJ/m²)

Statistical Parameter	Statistic	Std. Error
Mean	349.20	10.682
95% Confidence Interval for Mean Lower Bound	328.12	
Upper Bound	370.28	
5% Trimmed Mean	340.41	
Median	340.40	
Variance	20199.02	
Std. Deviation	142.12	
Minimum	117.8	
Maximum	886.4	
Range	768.6	
Interquartile Range	173.9	
Skewness	0.948	0.183
Kurtosis	1.395	0.363

In terms of the data collected obey lognormal distribution or not, three test methods which are normal probability plot, Jarque-Bera test (JB) and Lilliefors test are presented after taking logarithm of all the data. Figure 9 shows the normal probability plot of fire load in all the hotels. It can be seen that most data conform with the expected value. The results of Jarque-Bera test and Lilliefors test are presented in Table 8. If the result of hypothesis testing H is equal to 0, the hypothesis that the underlying distribution is a lognormal distribution could not be rejected. In the table, P is the check value. $JBSTAT$ and $KSTAT$ are the test statistics and CV is the critical value. All the three test results clearly confirm that the fire load frequencies have a lognormal distribution at the 5% significance level. The probability density function is as follows[12]:

$$f(q) = \frac{1}{\sqrt{2\pi} * q * 0.41} e^{-\frac{1}{2} \left(\frac{\ln q - 5.78}{0.41} \right)^2} \quad (3)$$

Figure 9 Normal probability plot of fire load

Table 8 The results of Jarque-Bera test and Lilliefors test

Jarque-Bera test				
DATA	H	P	JBSTAT	CV
Gaussian noise	0	0.2927	2.0932	5.6458
Lilliefors test				
DATA	H	P	KSTAT	CV
Gaussian noise	0	0.1238	0.0598	0.0671

Figure 10 shows the cumulative frequency distribution of all hotels taken together. The 50th, 80th and 90th percentile of fire load are 327.7 MJ/m^2 , 457.6 MJ/m^2 and 548.9 MJ/m^2 , respectively.

Figure 10 Cumulative frequency distribution of all hotels

4.6 Comparison with Other Country Surveys

The results of the present work are compared with those of the hotel building surveys in other countries. Table 9 summarizes the comparative values of the results of the present work with other country surveys[1, 6, 13, 14, 15]. It can be seen from Table 9 that the results of the present survey are considerably different from other country surveys. The differences in the results of other country surveys and those of the present one are due to the following reasons. Other country surveys were mostly conducted in the early 1990s and the results were pertinent to the hotel infrastructural facilities then existing, while the results reported in this note are for the presently prevailing conditions in China. The increasing use of massive high-quality wooden materials, plastic materials, cotton ramie silk materials and other synthetic materials in hotels may account for the greater fire load. On the other hand, different living habits, living standards and many cultural and social aspects also result in the different fire loads.

Table 9 Comparison of fire load densities in the hotel buildings

Survey conducted by	Mean(MJ/m ²)	Standard deviation(MJ/m ²)
Mabin (1994)	251	58
Barnett (1984)	263	--
F.E.D.G (1994)**	300	--
Pettersson (1976)**	270	--
B.S.F.S.E. (1993)	310	--
Swedish Data*	310 ⁺	92 ⁺
European Data*	310 ⁺	104 ⁺
Present work	349	142

5. FIRE DURATION TIME

For high-rise buildings and large space buildings, the duration time is an important basis for the building fire protection design. The duration time not only depends on the fire load in the buildings, but also the spatial characteristics, opening size and position of the buildings. Assuming the consumption of combustibles during the growth period can be ignored, the fire duration time is given by the fire load density and the mass burning rate[16].

$$t_{dur} = \frac{W}{\dot{m}} \quad (4)$$

Where t_{dur} is the fire duration time, (s). W is the total weight of combustibles in the fire compartment, (kg). $\dot{m}$ is the mass burning rate, (kg/s).

During the full development period, the rate of burning is generally controlled by the ventilation conditions, the mass burning rate can be obtained by using[17]:

$$\dot{m} = 0.092 A \sqrt{H} \quad (5)$$

Where H is the height of the window, (m). A is the area of the window, (m²).

After knowing the total weight of combustibles and the mass burning rate, the fire duration time can be calculated by:

$$t_{dur} = \frac{A_f q}{0.092 A \sqrt{H}} \quad (6)$$

Substituting k for $\frac{A_f}{0.092 A \sqrt{H}}$, where k which is related to the floor area, the height and area of the window is a parameter to characterize the structural features of buildings. Hence, the fire duration time can be expressed:

$$t_{dur} = k \cdot q \quad (7)$$

The distribution regularity of fire load in the hotel buildings is lognormal distribution and the probability density function is as follows:

$$f(q) = \frac{1}{\sqrt{2\pi} * q * 0.41} e^{-\frac{1}{2}(\frac{\ln q - 5.78}{0.41})^2} \quad (8)$$

After taking logarithm, the Equation 7 can be expressed as:

$$\ln t_{dur} = \ln k + \ln q \quad (9)$$

Based on the characteristics of the normal distribution, $\ln t_{dur}$ also obeys the normal distribution. Compared to $\ln q$, the probability density curve shifted $\ln k$ units to the right, that is :

$$f(\ln t_{dur}) = \frac{1}{\sqrt{2\pi} \sigma_{\ln t_{dur}}} \exp\left[-\frac{(\ln t_{dur} - \mu_{\ln t_{dur}})^2}{2\sigma_{\ln t_{dur}}^2}\right] \quad (10)$$

Where $\mu_{\ln t_{dur}}$, $\sigma_{\ln t_{dur}}$ are the mean and standard deviation of the normal distribution $f(\ln t_{dur})$, respectively.

The mean and standard deviation can be respectively obtained as:

$$\mu_{\ln t_{dur}} = \ln \frac{\mu_q}{\sqrt{1 + \frac{\sigma_q^2}{\mu_q^2}}} + \ln k \quad (11)$$

$$\sigma_{\ln t_{dur}} = \sqrt{\ln\left(1 + \frac{\sigma_q^2}{\mu_q^2}\right)} \quad (12)$$

Statistical parameters of hotel buildings are presented in Table 10.

Table 10 Statistical Parameters of hotel buildings

Building	Mean(kg/m ²)	Standard deviation (kg/m ²)	k
Hotel	19.4	7.9	91.1

Based on the Equation 10,11,12 and Table 10, the probability density distribution function of the fire duration time can be obtained:

$$f(t_{dur}) = \frac{1}{t_{dur}} * \frac{1}{\sqrt{2\pi} * 0.39} \exp\left[-\frac{(\ln t_{dur} - 7.4)^2}{2 * 0.39^2}\right] \quad (13)$$

Figure 11 gives probability density curve versus fire duration time.

Figure 11 Probability density curve of fire duration time

Fire load in the hotel buildings is relatively large. When fire occurs, it generates more heat and lasts for a long time.

6. THE COLLAPSE PROBABILITY

When fire occurs, whether the building will collapse depends on the fire duration time and the fire resistance time. When the fire duration time is more than the fire resistance time t_{max} , the building will collapse. The collapse probability can be expressed in the following way [18,19,20]:

$$P_{fail} = \int_{t_{max}}^{\infty} f(t_{dur}) dt_{dur} \quad (14)$$

The collapse probability of hotel building can be expressed as:

$$P_{fail} = \int_{t_{max}}^{\infty} \frac{1}{t_{dur}} * \frac{1}{\sqrt{2\pi} * 0.39} \exp\left[-\frac{(\ln t_{dur} - 7.4)^2}{2 * 0.39^2}\right] dt_{dur} \quad (15)$$

Figure 12 shows the relationship between fire resistance time and the collapse probability of hotel building.

Figure 12 The collapse probability of hotel building

From Figure 12 it can be seen that, the collapse probability will decrease with the increasing fire resistance time at the mean fire duration time.

7. CONCLUSIONS

A study has been made into fire loads in hotel buildings of China. The effects of several factors on the fire load were considered. Based on the survey results presented herein, the following conclusions can be drawn.

- (1) In hotel buildings, the mean fire load and standard deviation of fire load increase with raising rating of the hotels.
- (2) The magnitude of fire load is related to the room type. Deluxe suites are the most heavily loaded, followed by double rooms. The least mean load is the six beds room and dining hall.
- (3) Fire load is also affected by the region. The maximum, mean and standard deviation of fire load all achieved the maximum value in Shenyang, while these parameters in Yantai are the lowest ones.
- (4) The maximum fire load, the mean fire load and the standard deviation of fire load decrease with the increasing floor area of rooms up to 25m^2 , but thereafter they show increasing trend with further increase in floor area.
- (5) The fire load densities of all the surveyed hotels have a lognormal distribution with a mean value of 349.2 MJ/m^2 , a maximum value of 886.4 MJ/m^2 , a minimum value of 117.8 MJ/m^2 , and a standard deviation of 142.12.
- (6) The fire duration time and the collapse probability of building caused by fire were also developed by the corresponding calculation model.

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