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Lau, K.W. and Chow, W.K., "A Study on the Fire Safety Issues for Large Window Openings in Supertall Residential Buildings in Hong Kong" (2014). *International High Performance Buildings Conference.* Paper 104.
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A Study on the Fire Safety Issues for Large Window Openings in Supertall Residential Buildings in Hong Kong

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ABSTRACT

The trend in building supertall residential buildings with large glass pane and window openings has becoming a modern building design. It is well understood that with this design, better views and borrowing more light from the outside environmental are well known and accepted by people living in metropolitan city like Hong Kong. However, there is no report specifically on the fire safety issues related to this kind of building feature.

The study aims to look into the trend and associated fire risks for large window pane opening area, wall area and floor area of each flat (unit) on the building storey as well as the relationship amongst each other. These specific design features will be studied separately using statistical method to ascertain the general trend in the latest building designs. Other issues on how big are the glass panes used in the design and the minimum heat release rate leading to a flashover fire in the compartment are also investigated. In view that fire spreading to upper floor through breakage of the window pane is common in fire situation and might resulting more fatalities and injuries, a brief account on the glass breakage is also presented.

Keywords: Supertall building, refuge floor, compartment fire, flashover

1. INTRODUCTION

For better view and allow more light enter each unit (flat), architects will adopt in their building design with glazing wall or large window pane. Plan survey inspections were conducted to look into the matter from those supertall residential buildings in Hong Kong since an average of about 79% building fires were from residential flats (FSD 2005-2012).

Due to limited land use in Hong Kong, new residential buildings are very tall and built in small area flats on each floor with suitable fire resistance rating (FRR) (BD 2011). Storage of different types of combustibles in the flat is common. That is the fire load density (MJ/m^2 of floor area) is high in these flats and produces high heat release rate when burnt in fire (Chow 2002a, Chow 2002b, Chow *et al* 2004). High fire load density of combustible storage might not give a big fire when air intake rate through openings in building is small (small in window-to-wall area ratio) (Chow and Chow 2010). However, once a fire has occurred in the flat would have more un-burnt combustible gases through pyrolysis of the combustibles in the compartment under the ventilation-controlled fire situation. The trend of having larger window pane/opening will give more air supply for combustion in case breakage in fire particularly when this supply being facilitated by the stack effect due to its building height and the wind effect through leakage areas and broken glass pane. The result is providing adequate oxygen to ignite and burn up stored combustibles and leads to a larger fire.

The window pane/s might crack, break and fallout in high temperatures. The breakage of glass panes will form vent openings of the compartment where fire plume will be ejected and spread to upper floor/s through these openings and windows. For wide window panes, the trajectory flame will attached to the wall above the fire floor damaging the building structure and early breakage of window/glass panes. Falling of broken glass and wall tiles will cause injuries to people on ground. Burning debris might lead to a secondary fire below particularly for building design with cloth drying racks installed outside the building wall. More importantly is the rising fire plume from fire floor below when reaches the external wall opening of the refuge floor (a statutory building requirement in Hong Kong) (BD 2011) of the supertall building will enter the floor thus hamper the evacuation process and rescuers in exercising their duties on this floor.

2. FIRE DYNAMICS FOR FLASHOVER

Breakage of window pane plays a key role in compartment fire as the characteristic of window panes/openings are changed from a barrier to an opening vent during the course of fire. The problem is that once window breakage has taken place in the enclosed fire compartment, an opening is created. Fresh air will enter the fire compartment from the ambient side. The combustion process might be changed from ventilation control to fuel control (depending on the fuel amount) because of the increased air supply resulted in further development to a larger fire. Fire spreads within the compartment occurred until the whole compartment involved in fire. Whether flashover will occur or not depends on the fuel load and ventilation condition in the compartment. That is under the conditions that the temperature at the upper hot smoke layer has reached 600^{o}C and the heat flux at the floor level is 20kW/m^2 (Quintieri 1998, Drysdale 1999). Since a vent is formed in the fire compartment, fire may spread to other compartments or floors and cause further damage to the building. The most undesirable situation would be a fire broke out causing the breakage of the window pane. Very high heat flux incident onto the glass would result in cracking or even fallout depending on its location from the seat of fire. Situation will be even worse if in direct contact with the flame causing tremendous thermal stresses on the glass surface and might break in an earlier stage. In this case, the window pane will be broken before the flashover to occur. The result is speeding up the combustion process and facilitating the flashover to occur thus shortening the initial evacuation time and cause even more serious consequence to life and safety of occupants in the building.

3. TRAJECTORY OF FLAME THROUGH WINDOW OF THE FIRE FLOOR

In the study of Yokoi (1960) on the trajectory of flame from the fire floor window to upper floor/s, he found that the effect of the width to height ratio of a window was that the wider the window to its height, shorter the distance required for the flame to return back to the front surface of the building wall above the window. Studying on the relationship between the trajectory flame distance from building face and the window height of the fire room Butcher and Parnell (1983) found that none of the flames has more than half the window height distance from the building face. For wide window the flames will return to the building face at a distance from the top edge of the window of just over three quarters of the window height. Besides when the fire room temperature is 1100^{o}C, the temperature of the attached flame at the window opening of the immediate above floor is between 400^{o}C to 500^{o}C. In the investigation of the trajectory and temperature distribution of fire gases ejected from fire compartment, Galea *et al.(*1995) concluded that for a given rate of heat release, compartment with wide windows potentially pose a greater threat of fire spread to the floors above through external fire spread than compartments with narrow windows. Narrow windows will project the fire plume further away from the side of the building than a wide window thus reducing the thermal exposure to the wall. This finding was also supported by Satoh and Kuwahara (1991) through their study by adopting the two - dimensional numerical simulations which showed that upward flows adhere closely to the wall surface and also agreed with the experimental flow patterns.

4. PERFORMANCE OF GLASS IN FIRE

Since window panes are responsible to maintain a barrier between the fire side and the non-fire side and has great impact on the fire development in case of fire, therefore quite a no. of academics have conducted studies on the performance of window panes experimentally and analytically in the past.

Skelly (1990) found that breakage of the glass at average temperature of 90^{o}C differs from the study of Keski-Rahkonen (1988) 70^{o}C and for Pagni (1988) 58^{o}C. Pagni and Joshi (1991) revealed that temperature difference between the exposed glass surface and the glass shielded by the edge mounting play the dominant role in controlling window pane cracking and predict the temperature difference of about 70°C between the heated glass temperature and the edge temperature to initiate cracking. Hassani et al. (1994/95) concluded in their experimental study that the formation of the continuous bifurcation route is a main but not the only condition for glass fallout; glass cracking can only occur in the edges experiencing tension and cracks first appeared at the top edge but did not propagate to the bottom of the pane; tall window with large glass pane would experience a significant temperature gradient over its height; and the state of stress in the glass subjected to non-uniform temperature gradient with tensile stresses in the top edge and compression stresses in the bottom edge of the glass pane. Shields, Silcock and Hassani (1997/98) found in their fire tests on glass panes that small pane received less measured edge strains than the larger ones. That is small pane will be harder to crack than the larger ones under the same level thermal effect; factors influencing the propensity of glass to crack and subsequent fallout include the location and size of the fire, glass/frame assembly, geometry of the glazing and its edge quality; total fallout only in large pane; all the panes resulted in similar cracking patterns by forming of closures; and the heating mode and rate will significantly affect the behaviour of the glass. Shields, Silcock and Flood (2001) reported that cracking on a single glazing could be initiated when incident heat flux is at $3kWm^{-2}$ or the heat release rate (HRR) in the enclosure at 100kW. The glass panes would fall out if they are subjected to heat flux of at least $35kWm^{-2}$ or HRR approaches 500kW. The upper part of the panes will crack or break faster. Pagni (2002) commented that initial crack formation in glass after exposure to fire forming bifurcated cracks will normally move from the edge into the heated region and later achieve a closure around a piece of glass isolating it from the frame. However in real growing compartment fires, the existence of the built-up pressure will remove pieces of glass once they are isolated by cracking. Thermal stresses over the glass panes upon uneven heating with respect to different temperature fields and boundary conditions of the window frame were studied by Chow and Gao (2008). With the fitted temperature correlation, the distribution of stresses on the glass pane by varying the temperature field in one typical experiment result was calculated. The results are that for glass panes without fixed frame, fracture is not induced by temperature variation along the height at the top portion. The temperature difference between the glass pane and the framing material is the main cause lead to the fracture. Xei *et al.* (2009) found in their study that thermal stress of a glazing edge is not only caused by the temperature difference between the exposed and shaded areas of glass at the fire side but also the temperatures between the non-fire side and the fire side of glass surfaces. The whole piece of toughened glass cracks and falls out when any part of the pane breaks. Chow and Gao (2010) by referring to the experimental data from the literature deduced the temperature profile of window glass panes. The calculated results are useful to predict the positions on the glass panes where cracking is likely to occur when exposed to fire. They also found that for about 10 to 20 mm. thick glass pane if the edges are not covered, the cracks will not formed easily at the edge of the top portion but will be formed at the middle and lower part. Wu *et al.* (2014) conducted experimental tests to fire-resistant glass products to examine their performance under fire by adopting the TG-FTIR, Py-GC-MS and TF-FTIR techniques. Results show that product compositions are mainly water vapour, water-soluble salt, polyamide, metal silicates and small percentage of carboxylate and alcohols. Water vapor, carbon dioxide, carbon monoxide and hydrogen chloride gases were emitted upon heating. Gases emitted from the protective layers heated in air, in argon and in vacuum are similar in that water vapor, carbon dioxide and hydrogen chloride are the main components. These bench-scale measurements give important information on possible toxic behaviors of fire-resistant glasses in real fires.

In sum, plain glass could be cracked and broken at temperature lower than 100°C. The glass under the effect of convective and radiative heat in fire compartment will receive more heat from the edge of the topmost part and will crack first and spread downwards forming the continuous bifurcation route towards the centre. Grouping of the routes weakened the strength of the glass and will be broken. Window with large glass pane would experience a significant temperature gradient over its height and the state of stress in the glass would be subjected to non-uniform temperature gradient with tensile stresses in the top edge and compression stresses in the bottom edge of the glass pane. Whether the glass will fallout or not depends on the difference in distribution of stresses between the pane and the frame of the window. Tempered glass, commonly used will be smashed under high temperature leaving a big vent in the compartment. In the cause of flashover to occur, window glass will normally be broken and might fallout due to the high temperature of 500 - 600°C. Larger glass panes will break easier than with smaller area.

5. BUILDING PLANS INSPECTION SURVEY

5.1 Survey Results

Building plan inspections to 211 residential flats from 31 supertall buildings of different developments were conducted. The total no. building plans on window and wall areas inspected amounted 1157. Their relationship is analysed and quantified. Ventilation factors derived are used for calculating the heat release rate required to initiate flashover by adopting the Babrauskas pre-flashover equation (Babrauskas 1980, NFPA 2013).

From plan inspections, the floor heights of the supertall buildings are ranged from a minimum of 2.9 to a maximum of 4.4 meters. About the profile of the floor heights, 77 flats having the floor heights from 2.9 to 3.1 meters; 68 flats from 3.1 to 3.4 meters; 48 flats from 3.4 to 3.7 meters and the remaining 18 is greater than 3.7 meters to a maximum of 4.4 meters.

The range of minimum height to the maximum height of the window panes is 0.5 to 3.3 meters and the widths are o.3 to 7 meters. The range of resulting window pane areas is 0.3 to 11.6 m^2 and the average no. of window pane in each flat is 5.5. There are 650 window panes with height of 1 - 1.4 meters; 226 nos. of 1.8 – 2.2 meters; 161nos. of 1.4 – 1.8 meters. The remaining sizes are ranged from 0.5 to as tall as 3.3 meters.

As to the width of the window panes, 367 nos. with the width of 0.3 - 1 meter; 330 nos. of 1 – 2 meters; 359 nos. of 2 – 3 meters and 80 nos. of 3 - 4 meters. The remaining sizes are ranged from 4 – 7.0 meters.

Regards the no. of window pane in each flat, 57 flats each installed with 5 window panes; 42 flats with 6 nos. and 42 flats with 4 nos. The remaining units are ranged from 1 to 11nos.

5.2 Analysis and discussion of Survey Results amongst Flats and Rooms

The analysis is focussed on the fire hazard posed due to the large window pane design and the correlation amongst the areas of the window panes/openings, the external wall areas in which the window/s located and the floor areas. Based on the survey results and measurements taken respective areas required in this study are summarized and presented either in the form of tables or graphical presentation as below:

There is a wide range of floor areas in the survey of 211 no. of flats. In which the minimum area is 21.2 m^2 and the maximum is 236.3 m^2. The average area is 49.5 m^2 and 165 no. of flats (78.1% of the total nos.) are within the range of 20 – 60 m^2. Table 1shows the distribution of the four categorical variables in floor areas in which the minimum and maximum values are 6.6 and 37.3 m^2 respectively and the average value is 15.1 m^2. Majority of the flats are within the category of 20 – 60 m^2 giving 78% of the total amount. Window opening areas of the rooms in a flat are categorized into five types as in Table 2. The largest average area is the sitting and dining room and bedroom is the second largest. The respective area is 5.41 and 3.15 m^2.

Table 1: Minimum, average and maximum window opening area (m^2) of different-sized flats

Floor Area (m^2)	Min	Max	Average	Count
20-60	6.6	35.5	13.5	164
60-100	9.2	33.5	18.3	35
100-140	19.5	37.3	27.6	10
220-260	31.9	31.9	31.9	2
Total	**6.6**	**37.3**	**15.1**	**211**

Table 2: Minimum, average, maximum window opening area (m^2) in different types of rooms

Type of Room	Min.	Max.	Average	No. of Rooms
Bathroom	0.30	1.59	0.63	177
Bedroom	0.42	11.55	3.15	512
Kitchen	0.25	3.70	1.02	212
Living and Dining Room	0.64	11.40	5.41	225
Storeroom	0.35	1.27	0.68	29
Utility Room	1.21	1.21	1.21	2
Total	**0.25**	**11.55**	**2.75**	**1157**

Figure 1 shows the maximum, minimum and average values between the window opening area and the wall areas at which these window opening areas are situated. Again the sitting and dining room and bedroom have the largest average area ratios of 0.53 and 0.39. Kitchen is the area where naked flame usually found with a maximum ratio of 0.74 and an average value of 0.19. Storeroom where combustibles are usually found and piled up has an average ratio of 0.11. The maximum value is only 0.2.

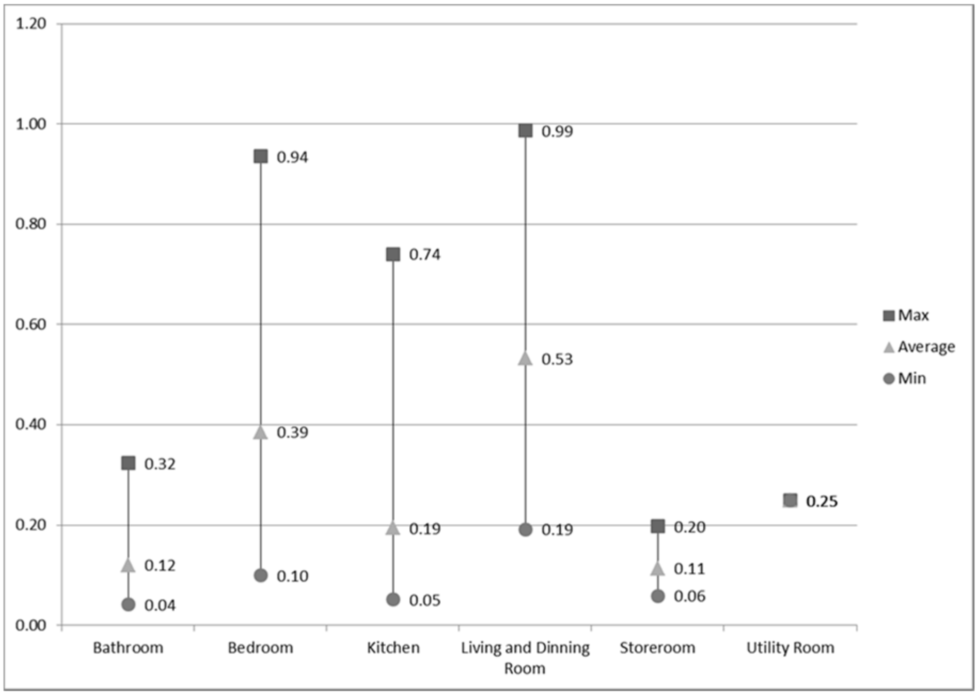

Figure 1: Minimum, average and maximum ratio between window opening areas and wall areas (where windows situated) amongst different types of rooms

Table 3 shows the categorical variables of floor area and the window opening area in a room. To look for the relationship between these two variables, Contingency Table and Chi-square Test of Independence are employed. The result is that the p-value=0.000 (with significant value if p-value<0.05). It can be concluded that total floor area and total window opening area are dependent. Frequency table indicates that for small floor area (i.e. 20~60 m^2), most cases have a total window opening area less than 20 m^2. For larger floor area (i.e. >60 m^2), it is more likely to have a larger total window opening area.

Table 3: Contingency table between floor area and total window opening area

Floor Area (m^2)	**Total Window Opening Area of the Flat**			
	0-10	**10-20**	**>20**	**Total No. of Flats**
20-60	46	105	14	**165**
>60	1	22	23	**46**
Total	**47**	**127**	**37**	**211**

6. SUMMARY ON CALCULATING THE REQUIRED HEAT RELEASE RATE FOR FLASHOVER AND DISCUSSION

6.1 Prediction of likelihood of flashover in compartment fire

By applying the energy balance equation $\dot{Q} = \dot{m}_g c_p(T_g - T_\infty) + q_{loss}$ (McCaffrey, Quintieri and Harkleroad 1981), the approximation of gas flow rate through openings as $\dot{m}_g = 0.5A_0\sqrt{H_0}$ (Babrauskas 1980). The heat loss in the compartment boundary wall area A_T (m^2) due to radiation as assumed to 40% is estimated as $q_{loss} = \epsilon\sigma(T_g^4 - T_\infty^4)0.40A_T$. The emissivity ϵ is assumed to be 0.5 and σ is the Stefan-Boltzmann constant (5.67x10^{-11} kW/m^2·K^4). Combining the equations and using a gas temperature for flashover of 873 K (600^{o}C), specific heat of air of 1.0 kJ/kg·K, emissivity of 0.5 and assuming the correlation between compartment wall and the opening area of $A_T/A_0 \cdot \sqrt{H_0} \approx 50$ gives a minimum $\dot{Q}$ required for flashover i.e. $\dot{Q} = 600A_0\sqrt{H_0}$. Since the air flow into the compartment has been approximated as $0.5A_0\sqrt{H_0}$and for most fuel for stoichiometric combustion is approximately 3000kJ/kg in air. That is$\dot{Q}_{stoich} = 1500A_0\sqrt{H_0}$. Comparing with fire test results, Babrauskas suggested a best fit relationship, $\dot{Q} = 0.5\dot{Q}_{stoich}$ giving the minimum heat to have flashover at $750A_0\sqrt{H_0}$ kW.

Referring to Babrauskas (1980), SFPE (2003) and NFPA (2013) on the adoption of Babrauskas method to predict the energy release rate is required to initiate flashover in a compartment, the representing equations are:

$$\dot{Q} = 750A_{vent_{equivalent}}\sqrt{H_{vent_{equivalent}}} \tag{1}$$

$$A_{vent_{equivalent}} = H_{vent_{equivalent}} \cdot W_{vent_{equivalent}} \tag{2}$$

$$W_{vent_{equivalent}} = \frac{(A_{vent}\sqrt{H_{vent}})_1 + (A_{vent}\sqrt{H_{vent}})_2 + \cdots}{H_{vent_{equivalent}}^{\frac{3}{2}}} \tag{3}$$

6.2 Analysis of result and discussion

The heat release rates generated by adopting the equations (1), (2) and (3) are compared with the areas of different sized flats and rooms and are presented in Figure 2 and Figure 3.

For the case of heat release rates verses floor areas of the flats as in Figure 2, four categories of floors areas are used. Based on the total window areas and window height of the flat, the averaged heat release rate is 13.9 MW in 164 flats which is 77.7% of the total no. of flats. The maximum value of 45.5 MW is from the 100 – 140 m^2 category and the minimum values of 6.1 MW from the category having floor area of 20 – 60 m^2. The average heat release rate for all the flatted areas is 15.3 MW. The largest area category of 200 – 260 m^2 does not give the largest heat release rate probably due the size and area of the window pane, the design feature and the small sample size.

Figure 3 shows the heat release rates verses six categories of rooms in the flats. Window opening areas and window heights of the rooms are used in the calculation. Since the dining and sitting rooms have larger and taller window pane/openings, it is reasonable to see that largest averaged heat release rate of 6.1 MW is from this category. The next largest is from bedrooms having averaged value of 3.1 MW. It is interesting to note that the maximum value for the category of bedroom is 15.6 MW and is a bit larger than the category of sitting and dining room which has a value of 15.0 MW. Besides the no. of window panes/openings in bedrooms composing 44.3% of the total no. of windows in all flats. The maximum and minimum heat release rate for kitchens is 3.2 and 0.19 MW respectively. The average value is 0.82 MW. The comparatively low heat release rates is possibly because of the there is no window or some of the kitchens are open type design.

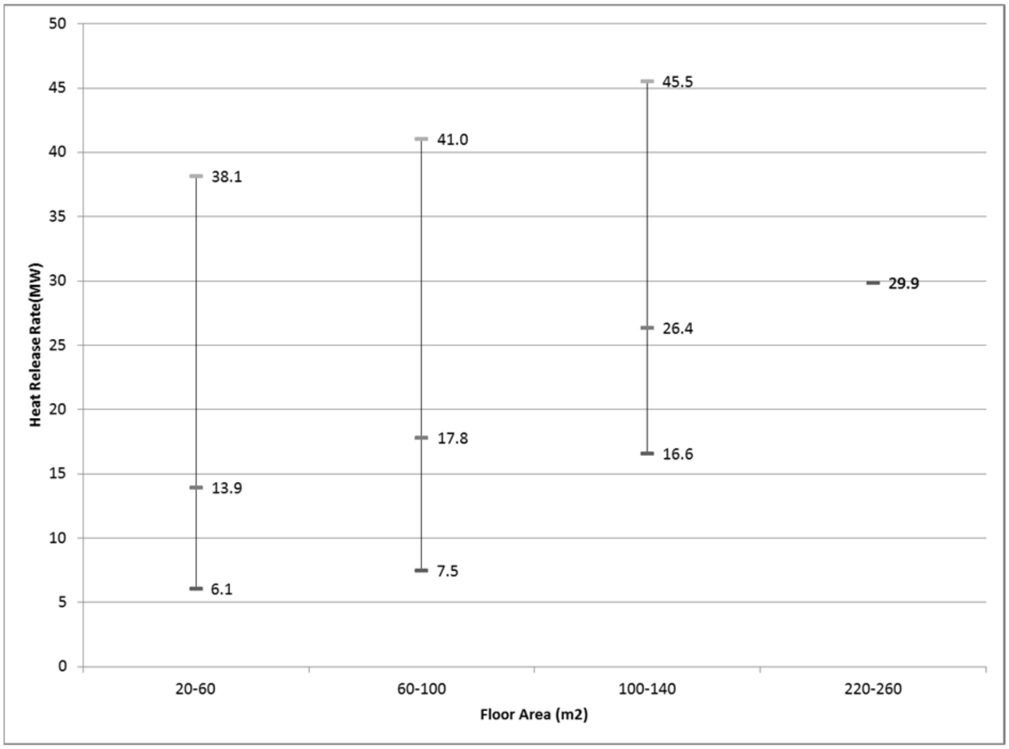

Figure 2: Minimum, average and maximum heat release rates for flashover to occur in different-sized flats

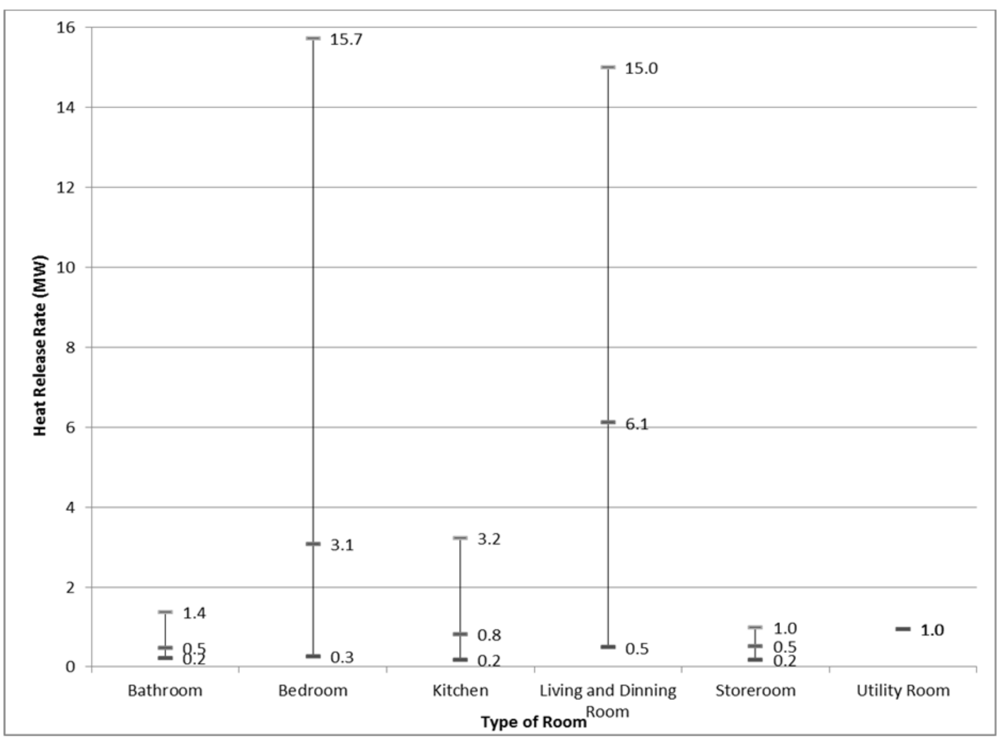

Figure 3: Minimum, average and maximum heat release rates for flashover to occur in different types of rooms

Similar approach is adopted to evaluate the relationship between the two variables on floor area and flashover fire size as in Table 4. The result p-value=0.000 is obtained. It can be concluded that floor area and flashover fire size are dependent. The frequency table indicates that for small floor area (i.e. 20~60 m^2), most cases have a flashover fire size less than 20 MW but for larger floor area (i.e. >60 m^2) will be more likely to have a larger flashover fire size.

Table 4: Contingency table between floor area and flashover fire size

Floor Area (m^2)	Flashover Fire Size (MW)			
	5-10	**10-20**	**>20**	**Total No. of Flats**
20-60	52	89	24	**165**
>60	3	24	19	**46**
Total	**55**	**113**	**43**	**211**

7. CONCLUSION

The survey result has given a latest building design feature of the residential flats in supertall buildings. The large window pane design has created fire hazards in fire situation. Upon the breakage of the window pane, the inrush of air from the ambient side gives large amount of oxygen for combustion and will greatly increase the chance or bring flashover to occur earlier. The fire will change from ventilation-controlled to fuel-controlled with higher compartment temperature. The trajectory of flame and fire spread to upper floors become imminent. The high temperature of the attaching fire plume from wide window pane breakage of the fire floor below will liable to break the window pane of floor above and cause fire spread. The falling of broken window panes, wall tiles and other structural damage due to fire, the possibility of initiating secondary fire spread and hampering the safety of evacuees and rescuers in the affected building give some negative impact to these building designs. The heat release rate generated in the category of 20–60 m^2 composing 77.7% of the total no. of flats under study is a concern. The average heat release rate of 15.3 MW from this category poses a high fire hazard to the occupancy and damage to the building structure. Occupants should be more careful in the combustibles storage in their flats and building designers have to take note of the large window design. To alleviate the situation, one of the possible solutions is to provide sprinkler system in these flats such that the fire once occurred can be controlled and extinguished.

NOMENCLATURE

$A_{vent_{equivalent}}$	a virtual vent that has an are equivalent to the combined area of all individual vents from the room of consideration	(m^2)
A_0	the opening area	(m^2)
A_T	the boundary surface area	(m^2)
$A_{vent(i)}$	the area of the *i-th* vent within the room	(m^2).
$H_{vent_{equivalent}}$	the difference between the elevation of the highest point among all the vents and the elevation of the lowest point among all the vents	(m)
H_0	the opening height	(m)
$H_{vent(i)}$	the height of the *i-th* vent within the room	(m)
$\dot{m}_g$	the mass flow rate out of the opening	(kg/s)
$\dot{Q}$	heat release rate of the fire	(kW)
q_{loss}	the net convective and radiative heat transfer from the upper gas layer (kW) through the boundaries	
T_∞	the ambient temperature	(K)

T_g	the temperature of the upper layer gas	(K)
$W_{vent_{equivalent}}$	the width of a virtual vent that has an area equivalent (for the purposes of determining flashover) to the combined area of all individual vents from the room of consideration (m)	
$W_{vent(i)}$	the width of the *i-th* vent within the room	(m)
c_p	the specific heat of gas (kJ/kg·K)	
ϵ	the emissivity value, assumed to be 0.5	
σ	the Stefan-Boltzmann constant (5.67×10^{-11} kW/m^2·K^4)	

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HPB2014LauKWa