

## PERFORMANCE BASED FIRE ENGINEERING TO MITIGATE NON-COMPLIANCE IN EXIT PROVISIONS

Shyam Dayanandan, Dan Chong, Oliver Shum, Vishwajeet Singh

Computational Engineering Solutions LLP  
 28 Kallang Place, #06-11  
 Singapore 339158  
 website: [www.ce-sol.com](http://www.ce-sol.com)  
 e-mail: [shyam@ce-sol.com](mailto:shyam@ce-sol.com)

### **ABSTRACT**

Addition and Alteration works to aging buildings have become common place in land scarce Singapore. For a recent retail development in the Central Business District, the developers choose to convert the basement parking facility in the existing building to a retail facility with a large F&B component. However, the exit provisions were insufficient to serve the larger occupant load demanded by F&B. This paper briefly describes the Performance Based approach to taken to mitigate the non-compliance.

Several strategies were implemented as part of the Performance Based approach to ensure that the inadequate exit provisions will not compromise tenable conditions needed for evacuation.

Appropriate Design Fire scenarios were conceptualized and associated Available Safe Egress Times (ASET) were evaluated using FDS. Appropriate pre-movement timings were derived from prior evacuation studies and the movement times were evaluated using evacuation modeling.

By demonstrating to the AHJ that the Required Safe Egress Times (RSET) was less than the ASET, the performance based design of the development was accepted.

### **INTRODUCTION**

Singapore is an island nation with a land area of about 712km<sup>2</sup> and a population density of 7,126 people/km<sup>2</sup>. The bulk of the business and commercial activities takes place in the central business district, which is only about 50km<sup>2</sup> in size. Numerous buildings within the CBD are aging and need to be extensively renovated. This can require major addition and alteration works to redesign these building to suit the tastes and needs of a more sophisticated population.

This study presents the engineering analysis undertaken to ensure life safety in the event of a fire for one such aging retail mall in the heart of the CBD.

The mall in question was constructed in the mid 80's. It consists of 2 basement levels and 4 above ground

levels. The 2 basement levels were previously designated as an underground parking facility for mall patrons. But with the intended future linking of the basement level (as part of the A&A works) to the underground rail system, the human traffic to the basement levels can potentially increase tremendously. So the client decided that it would make more economic sense to designate the basement levels as retail or F&B instead of car parking.

However, the basement levels which were originally designated as a parking facility (expected usage density of 30 persons/m<sup>2</sup>) had insufficient exit provisions to cater for retail and F&B (expected usage densities of 5persons/m<sup>2</sup> and 1person/m<sup>2</sup> respectively).

*Table 1: Exit provisions for B1 and B2 compared with exit requirement considering preliminary retail and F&B allocation*

	Provisional Occupant Load (people)	Desired Occupant Load (people)
Basement 1	750	2820
Basement 2	690	2417

*Table 2: Provisional (by Code) occupant load allocation for B1 and B2*

	Unit of Egress Width (0.5m = 1 unit width)	Persons per Unit Width	Permitted Occupant Load (persons)
B1	12.5	60	750
B2	11.5	60	690

*Table 3: Desired Occupant Load for B1*

Usage	Floor Area (m <sup>2</sup> )	Usage Density (m <sup>2</sup> /person)	Required Occupant Load (persons)
Retail	2622	5	525
F&B	1951	1	1951
Super-market	1716	5	344
Total:			2820

Table 4: Desired Occupant Load for B2

Usage	Floor Area (m <sup>2</sup> )	Usage Density (m <sup>2</sup> /person)	Required Occupant Load (persons)
Retail	973	5	195
F&B	2213	1	2213
Mech. Plant Room	270	30	9
Total:			2417

The large difference in usage densities (as prescribed by the code) between parking and retail/F&B creates a huge shortfall in the amount of protected staircase cores needed to lead evacuees to safety.

Furthermore, the option of creating more exit staircases or even increasing the widths of the existing staircases were not feasible, because the close proximity of the underground rail tunnels does not allow extensive piling works to be carried out.

If the client is unable to provide more exits, they would only be able to designate a small portion of the basement levels as retail or F&B, causing huge revenue losses.

In order to circumvent this limitation, the client opted to take a performance based approach to maximize the space usage in basement 1 and 2 and at the same time to ensure that tenability is maintained during the duration of egress.

This paper briefly describes the Performance Based approach to taken to mitigate the non-compliance.

## **DEFINE GOALS & OBJECTIVES**

### **PROJECT GOALS**

The fire and life safety goals of the performance-based fire safety analysis and design are as follows:

- 1) Safeguard occupants from injury due to fire until they reach a safe place.
- 2) Safeguard fire fighters while performing rescue operations or attacking the fire.
- 3) Add internal escape paths (where possible) to maximize the number of occupants that can safely be admitted to Basement 1 and Basement 2

### **PROJECT OBJECTIVES**

The objective of the study is to ensure that the goals of the study are achieved. To achieve the goals, the ignition, growth and impact of possible fires must be managed.

## **PERFORMANCE CRITERIA**

- 1) In the event of a fire, the fire products are managed such that the visibility within the basement level will be greater than 10 meters at 2.5m above finished floor level for the duration of the egress (i.e. ASET > RSET).
- 2) In the event of a fire, the fire products are managed such that the temperature at 2.5m above finished floor level will be less than 100°C for the duration of the egress (i.e. ASET > RSET).
- 3) The ASET must be at least 1.5 times of the RSET.

## **DESIGN FIRES**

### **Fire Characteristics**

The construction material and interior finishes of the retail mall will not be made of combustible material.

There will be kitchens in some F&B outlets in B2 and B1 using electric heaters to enable cooking activities.

The seats and tables in the retail mall are made entirely of non-combustible materials.

Some shops in B2 and B1 will contain combustible items like garments.

For Basement 1 (using DETAC-T2 for second ring activation), the activation time for a fast response sprinkler (RTI = 50) is 3mins and the maximum fire size of a fast t<sup>2</sup>-fire is 1.5MW.

For Basement 2 (using DETAC-T2 for second ring activation), the activation time for a fast response sprinkler (RTI = 50) is 2.6mins and the maximum fire size of a fast t<sup>2</sup>-fire is 1.13MW.

### **Fire Scenarios**

For both basement levels, it is very likely for a fire to result in many areas. The possible fire scenarios are as follows:

- 1) A fire can result in the kitchen of an F&B outlet, due to unattended electric stove or heater malfunction.
- 2) A fire can result in the storage area due to an electrical fault that results in a fire that goes undetected.
- 3) A fire can result in the housekeeping room due to paints and solvent that might ignite due to discrete smoking activities and resulting in an ultrafast growth fire.
- 4) A fire can result in the electrical room due to electrical fault that results in a fire that goes undetected.
- 5) A fire can result in the office room due to electrical fault that results in a fire that goes

undetected and the fire may originate in a trash can that is shielded from the sprinklers.

- 6) A fire can result in a retail shop due to an electrical fault that results that causes garments to catch on fire. The fire may go undetected because it may originate within the shelving and may not be initially visible to store staff and patrons.
- 7) A fire can result in the trash can along the common corridor of the retail mall, as a result of a carelessly discarded cigarette butt or an arson attack. The fire may spread to wall claddings and/or benches.
- 8) A fire that originates next to a critical load bearing structural beam may collapse due to thermal fatigue and cause catastrophic consequences.

Scenario 1 is a likely fire scenario that may be initiated unattended electric stove or heater malfunction. This fire may initially go undetected by busy kitchen staff.

The scenarios 2, 3, 4 and 5 are not a concern because the rooms mentioned will be compartmented and sprinkler protected as part of the Fire and Life Safety Strategies (see section 5).

Scenario 6 is a likely fire scenario that may be initiated by an electrical fault either by the electrical controller or electrical appliances within the wall lining. The initial fire may be small and located within the shelving in the store. This fire may go undetected by the occupants because it is initially not visible.

Scenario 7 is unlikely because there will a strictly enforced NO Smoking Rule within the entire retail mall and the 24 hour CCTV monitoring of the retail mall will minimize the possibility of arson attacks. Furthermore, the mall interior design will be made of non-combustible materials.

Scenario 8 is unlikely because the structural columns will be well protected and will be able to withstand close proximity fires of up to 5MW without reaching critical temperatures.

So scenario 1 and 6 is considered for both B1 and B2. Since the intended shop and layouts were not available at the time of the study, it was not possible to ascertain the most unfavourable location of retail shops or F&B outlets. Therefore both scenarios 1 and 6 are considered together at the most remote corner of Basement 1 and Basement 2.

However, this paper will only present the fire engineering study conducted for Basement 2 only. The Design Fire considered for Basement 2 is a 1.13MW fire at the most remote corner of the floor and the burning material considered to be polyurethane (since this material gives a high soot

yield of about 10%, which allows a degree of conservatism to the results).

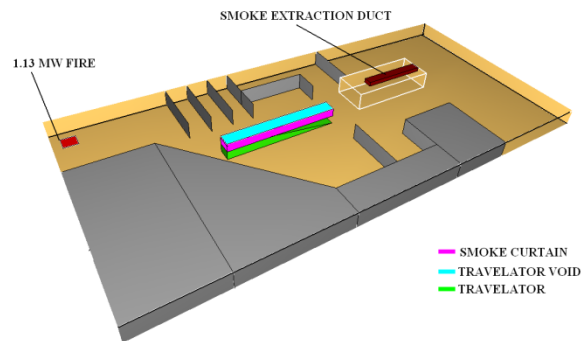


Figure 1: 1.13MW Design Fire (Scenario 1 & 6) at most remote location of Basement 2

Upon automatic detection of the fire (by sprinklers, or smoke detectors), the occupants will be alerted by the alarm and the emergency voice communication. The trained duty personnel will also be deployed to quickly guide occupants to safety.

### TRIAL DESIGN

To manage the ignition, growth and impact of possible fires the following Fire and Life Safety Strategies will be implemented in the retail mall:

- 1) Fire Detection and Notification
- 2) Suppression and Fire Fighting
- 3) Evacuation Control
- 4) Compartmentation of Rooms
- 5) Staircase and Lobby Pressurization
- 6) Engineered Smoke Control of the entire retail mall
- 7) Enforcement of No Smoking Rule
- 8) No serving of alcohol within Basement 1 and Basement 2 **OR** Enforcing the Ejection of Very Intoxicated Individuals from the Premise

### Fire and Life Safety Strategies

#### *Fire Detection and Notification*

- This building will be installed with Fast Response Automatic Sprinkler System. The activation of the sprinkler system will trigger the fire alarm.
- The building will be equipped with the Smoke Detector System.
- The building will be equipped with the Automatic Fire Alarm System.

- Entire premises will be equipped with Emergency Voice Communication System.

### ***Suppression and Fire Fighting***

- The building will be equipped with its dedicated fire sprinkler pump room and water storage tanks serving the entire building. This building is installed with **Fast Response** Automatic Sprinkler System for Ordinary Hazard classification.
- The building will be provided with manual fire extinguishers, dry risers and hose reels. The retail mall staffs will be trained to operate manual fire extinguishers effectively.
- The façade walls on the North and South, are easily accessible to the fire brigade.
- External fire hydrants are strategically located along this access way.

### ***Evacuation Control***

- The premises will be installed with exit lighting system.
- The 24hour duty personnel will be trained to assist in the evacuation of the patrons in the event of an emergency.

### ***Compartmentation of Rooms***

- The retail mall consists of various rooms that may cause fire hazards like offices, storage rooms, electrical rooms, housekeeping rooms and kitchen. These rooms will be compartmented.
- The doors are self-closing to ensure that compartmentation is not breached.

### ***Staircase and Lobby Pressurization***

- The staircases and lobbies in the building will be pressurized to ensure that smoke will not infiltrate into these area and compromise egress.

### ***Engineered Smoke Control of the Retail Mall***

- The Engineered Smoke Control, System will be designed, installed and maintained as per BRE Report No. 285 by Morgan and Gardner.

### ***Enforcement of No Smoking Rule***

- The enforcement of a No Smoking Rule within the entire retail mall will ensure that potential ignition sources are minimized.

### ***Enforcing the Ejection of Very Intoxicated Individuals from the Premise***

The F&B outlets within Basement 1 and 2 will not be allowed to serve alcohol to dining patrons **OR** the enforcement of ejection of Very Intoxicated Individuals from the premise can reduce the risk of an occupant passed-out and unable to react to fire notification.

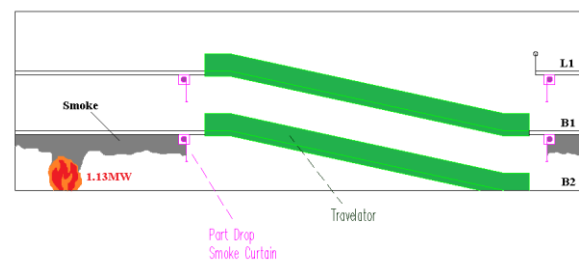
### **Provision of Internal Escape Paths**

According to the Singapore Fire Code 2007, an internal escape path (e.g. an internal escalator) cannot be considered as an egress path (when determining occupant load) because the smoke from a fire may spill into the unprotected internal escape path and hamper or prevent evacuation along that path. Furthermore, during an emergency, occupants who choose to use the internal escalator for egress would have to manually walk up the escalator, because the escalator would be shutdown. This might be difficult for most evacuees, because the step height of escalators is higher than that of stairs.

To overcome these issues, the escalator (30° slope) leading from Basement 2 to Level 1 will be replaced with a gradually sloped travelator (12° slope).

In addition, the void around the travelator will be protected by a part drop smoke curtain (which drops from the ceiling to 2m above finished floor level). This will prevent smoke from spilling into the travelator void and hamper evacuation.

This internal escape path (travelator) will provide an extra 5 unit widths (where 0.5m is 1 unit width) for evacuees to utilize in the event of an emergency.



**Figure 2: Smoke Curtain around Travelator Void of Basement 2**

**Engineered Smoke Control System**

Work by Hinkley has confirmed that the rate of entrainment of air into a plume of smoke rising above a fire as:

$$M = 0.38PY^{3/2}$$

where M = mass flow rate of smoke entering the smoke layer within the shop (kg/s)

P = the perimeter of the fire (m)

Y = the height from the base of the fire to the smoke layer

To maintain the smoke layer above 2.5m (as required by the Performance Criteria) and assuming a 12m perimeter fire, the mass flow rate of smoke entering the smoke layer, M = 18kg/s.

It must be noted that from the recommendations of Morgan and Gardner, a 12m perimeter fire is recommended for a 5MW fire, so using P = 12m for the calculation of extract requirements introduces a degree of conservatism to the results.

So in order to ensure the smoke layer does not descend below 2.5m, the mechanical extraction rate from Basement 2 should be at least 18kg/s.

When there is fire in Basement 2, the fire products will activate the smoke detectors and the sprinklers. The activation of the detector will trigger the alarm as well as the engineered smoke control system. When the system is triggered, smoke curtains will drop around the travelator void (to about 2m from finished floor level). This will prevent the smoke from entraining into the travelator void, causing untenable conditions to the evacuees using the travelator and also prevent the smoke from spilling into the upper levels.

The smoke detection will also trigger the extraction fans (at least 18kg/s), to manage the smoke and maintain the smoke layer at 2.5m.

**EVALUATION OF TRIAL DESIGN**

**Evacuation Movement Timing**

From the database compiled by Fahy and Proulx, able-bodied and alert occupants have an average horizontal travel speed of the 1 m/s and an average vertical travel speed of at least 0.4 m/s.

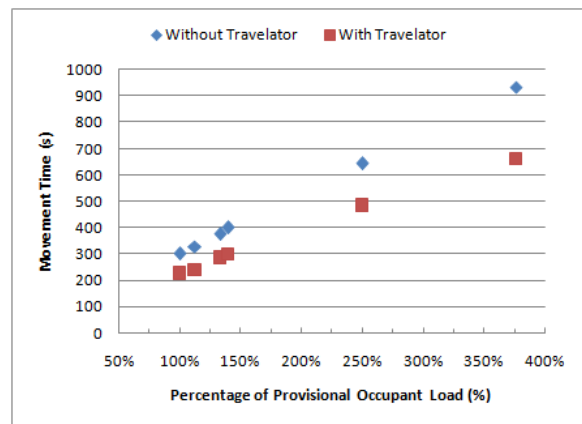
*Table 5: Evacuation Simulation for Various Occupant Loads*

	B1 Occupant Load (persons)	B2 Occupant Load (persons)	Percentage of Provisional Occupant Load
1.	750	690	100% (Provisional)
2.	825	759	110%
3.	975	897	130%
4.	1050	966	140%
5.	1875	1725	250%
6.	2820	2417	376% (Desired)

A total of 6 different occupant load configurations were simulated for the building with and without travelator. The 6 occupant load configurations ranged from the prescribed load for B1 and B2 to the required load.

*Table 6: Movement Timing for Various Occupant Loads for B1 and B2*

	Percentage of Provisional Occupant Load	Movement Time (s)	
		Without Travelator	With Travelator
1.	100% (Provisional)	300	227
2.	110%	325	241
3.	130%	370	279
4.	140%	392	298
5.	250%	643	484
6.	376% (Desired)	933	660



*Figure 3: Movement Timing for Various Occupant Loads*

The movement time of 140% of the provisional occupant load (with travelator) is the same as that of the provisional load (without travelator). So it can be assumed that increasing the occupant load to 140% of the provisional occupant load, will not compromise the level of fire life safety (with an internal escape path / travelator).

### Required Safe Egress Time

The computation of RSET is as follows:

$$\text{RSET} = (\text{alarm activation time}) + (\text{pre-movement time}) + (\text{movement time})$$

The Alarm Activation Time for Basement 2 is 156s as derived from DETAC-T2 sprinkler activation timing. However, it must be noted that the smoke detection timing will be much shorter (about 1-2 mins)

From the database compiled by Fahy and Proulx, the maximum pre-movement or delay time recorded for unannounced drills in department stores with trained staff is 1.7mins. To add a degree of conservatism, the pre-movement time is taken as 120s.

The total evacuation timing or RSET for the 6 occupant load scenarios shown in Table 6 is as follows:

Table 7: RSET for Various Occupant Loads for B1 and B2

	Percentage of Provisional Occupant Load	RSET (s)	
		Without Travelator	With Travelator
1.	100% (Provisional)	576	503
2.	110%	601	517
3.	130%	646	555
4.	140%	668	574
5.	250%	919	760
6.	376% (Desired)	1209	936

### Available Safe Egress Time

Fire Dynamic Simulator software (FDS) was used for the Computational Fluid Dynamics simulation of the Design Fire Scenario. The visualization of the FDS results was performed using Smokeview. FDS and Smokeview were developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce, in cooperation with VTT Technical Research Centre of Finland.

The FDS input file was created using the PyroSim FDS Graphical Interface from Thunderhead Engineering.

The simulation of the 1.13MW fast  $t^2$ -fire at the most remote location of Basement 2 (see Fig. 1) was a transient simulation marched in time for 1200s. The material burnt was considered to be polyurethane with a soot yield of 10%.

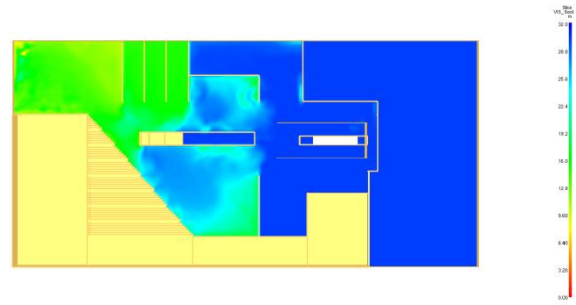


Figure 4: Contours of Visibility at horizontal plane 2.5m from the floor, at 20mins after start of fire.

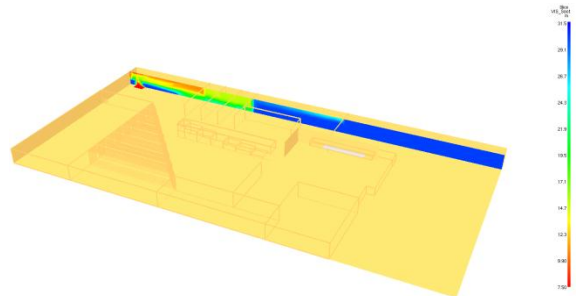


Figure 5: Contours of Visibility at vertical plane across fire, at 20mins after start of fire.

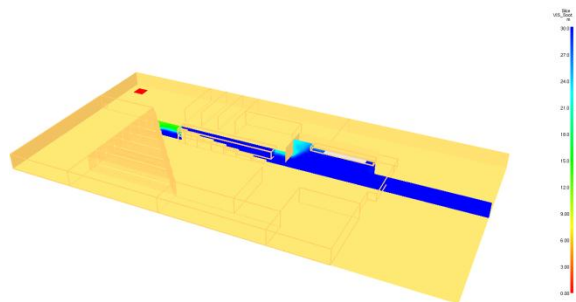


Figure 6: Contours of Visibility at vertical plane across travelator, at 20mins after start of fire.

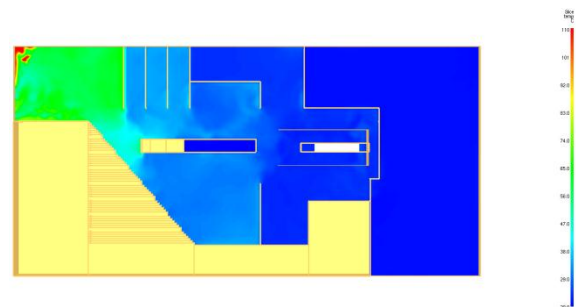


Figure 7: Contours of Temperature at horizontal plane 2.5m from the floor, at 20mins after start of fire.

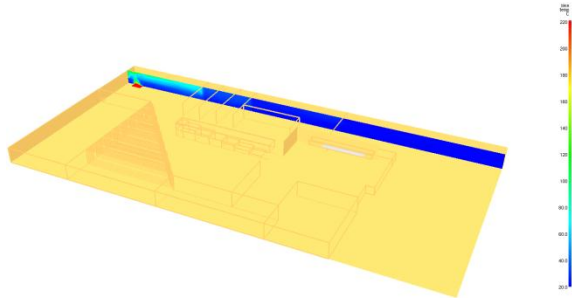


Figure 8: Contours of Temperature at vertical plane across fire, at 20mins after start of fire.

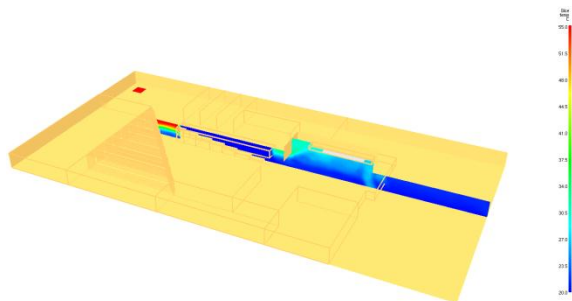


Figure 9: Contours of Temperature at vertical plane across travelator, at 20mins after start of fire.

From the CFD results, it is clear that the smoke layer is maintained above 2.5m from the floor. The visibility at 2.5m from the floor is more than 10m for 20mins (see Fig. 4) and the temperature at 2.5m from the floor is less than 100°C for 20mins (see Fig. 7). In addition, from the contour slices across the travelator (see. Figs. 6 & 9), it is clear that the fire products do not spill into the travelator void for at least 20mins. This will prevent untenable conditions to the evacuees using the travelator and also prevent the smoke from spilling into the upper levels. Therefore, tenable conditions are maintained within Basement 2 for at least 20mins. If the simulation was carried out for greater than 20mins, the tenable conditions would still have been maintained (because steady state conditions were achieved after about 600s), so the ASET should be much higher than 20mins. However, because of stakeholder concerns, the ASET was capped at 20mins.

Table 8: ASET and RSET Comparison for B2

Percentage of Provisional Occupant Load	ASET (s)	RSET (s)	ASET / RSET
100% (Provisional)	> 1200	503	2.39
110%	> 1200	517	2.32
130%	> 1200	555	2.16
140%	> 1200	574	2.09
250%	> 1200	760	1.58
376% (Desired)	> 1200	936	1.28

Fire Simulation for a 1.5MW at the most remote corner of Basement 1 (not presented in this paper), also gives an ASET of at least 1200s for Basement 1. Since the Performance Criteria indicates that ASET must be at least 1.5 times of the RSET, 250% of the Provisional Occupant Load for Basement 1 and Basement 2 is chosen as the Trial Design or Occupant Load (i.e. 1875 persons allowed for B1 and 1725 persons allowed for B2).

### CRITICAL DESIGN FEATURES

In this performance-based design, the following critical design features shall be ensured:

- All the Fire and Life Safety Strategies discussed above shall be implemented and maintained.
- The area surrounding the travelator shall be strictly kept clear of any combustibles and obstructions. The usability of the travelator is critical in ensuring fire life safety.

### CONCLUSION

The Performance Based Engineering Study of Basement 2 (and Basement 1) has demonstrated that the proposed system is able to comply with the required performance criteria. Therefore, the increase of the occupant load (250% of provisional load) does not compromise the life safety of occupants. The ability to increase the occupant load allows the client to increase the amount of shops and F&B outlets in Basement 1 and Basement 2. This will potentially greatly increase their rental revenue.

### REFERENCES

Fahy, R. F., Proulx, G., "Toward Creating a Database on Delay Times to Start Evacuation and Walking Speeds for Use in Evacuation Modelling," *Human*

*Behaviour in Fire 2001* - Proceedings of the 2nd International Symposium, pp. 175-183.

Hinkley, P.L., "Rates of Production of Hot Gases in Roof Venting Experiments," *Fire Safety Journal*, 1986, **10** 57-65.

Morgan, H.P., Gardner, J.P., "Design Principles for Smoke Ventilation in Enclosed Shopping Centres," *BRE Report No: 258*, 1990.

Singapore Civil Defense Force (2007) Code of Practice for Fire Precautions in Buildings 2007.