AN ANALYSIS OF THE EFFECT OF STAIRCASE INTERMEDIATE LANDING FLOOR ON THE EVACUATION TIME

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ABSTRACT: *Escape routes in high-rise residential buildings are an important element for emergency escape. Escape stairs are normally designed with intermediate landing floors to connect two staircases between the floor levels in high-rise buildings. This paper discusses an analysis of the effect of this intermediate landing floor on the total evacuation time during evacuation in emergency situation e.g. fire emergency. Analysis was done by comparing two different staircases width i.e. 914mm designed with and without intermediate landing floors and 1524mm designed with and without intermediate landing floors as well. Evacuation simulation software i.e. SIMULEX was used to simulate a number of people evacuating the predesigned floor models with the different staircase specifications. Total evacuation time recorded from those simulation processes are then compared with the time different taken by the same number of people evacuating the models. It is found that there was an effect on the total evacuation time for the staircase designed with and without intermediate landing floors. The simulation suggested that people will take 15% to 24% longer to evacuate the building if staircase was designed with intermediate landing floors.*

Keywords: Fire safety, evacuation, staircase design, landing floor.

Introduction

High-rise residential buildings have become a common structure in urban areas in Malaysia especially in the capital, Kuala Lumpur. Rapid development of Kuala Lumpur during the last few decades has attracted a large number of people from rural areas, rapidly increasing the population. People migrated to Kuala Lumpur for various purposes e.g. working, business, seeking a new life, etc, and this has created a high demand for new homes. This trend seems to have drastically increased in the past decade. With the limited land available in the town area, construction of high-rise residential buildings by various developers e.g. private or Government Link Companies to cater for the demand of new homes, near to the urban area, seems to be an alternative solution for the immediate needs. However, even though there is a high demand for new buildings fire safety should not be compromised.

Purser, (2004), explains that the prescriptive approach concentrates on the structural aspects of means of escape and acknowledges only in a general sense the point that fire hazard and safe escape are basically time dependent. It does not consider occupant behaviour in emergencies and the time required for occupant responses. Best practice for structural design in relation to fire safety therefore takes into account the needs of building occupants for structural performance. This can be achieved by means of a performance-based Fire Safety Engineering approach. However Rasbash *et al* (2004) mentions that the consequences of inadequate means of escape have been highlighted in a number of incidents in which the absence of properly designed escape routes, inadequate protection, failure of alarm or warning systems, or some other shortcoming, has resulted in serious loss of lives.

In this paper, the effect of intermediate landing floor designed in escape stairs will be discussed by simulating a number of people evacuating the study models on two difference staircases width. Although means of escape can be tested by conducting a fire drill, the ultimate test of whether or not occupants are able to escape safely in an emergency comes when there is a fire. If it had happened, it was too late to rectify any problems arisen. The best possible way is by using the existing advanced technology to identify or predict plausible solutions to the future problems.

2.0 Evacuation Time

Evacuation from building fire is essential and has to be initiated as soon as the fire alarm is sounded or fire cues have been detected. When evacuation is in progress, two important elements have a strong influence on the evacuation time i.e. Occupants' characteristics and building characteristics. Purser (2004) mentioned that the behaviour of occupants escaping from fire depends on a range of factors including building characteristics i.e. occupancy types, method for detection and the provision of warnings, fire safety management systems and building layout. Other equally important building characteristics are spatial complexity of the buildings, travel distances, and escape route and final exit. However, occupant characteristics themselves also have a large influence on the evacuation time i.e. occupant numbers, state of alertness, whether they are awake or asleep, familiarity with the building environment, experience of fire drill, and physical abilities.

According to Rasbash *et al.* (2004), means of escape facilities such as maximum travel distance, number and widths of staircases should be designed according to the total evacuation time ($\Delta Tevac$) based on the following equation:

$$\Delta Tevac = (D + B + E). \quad (1)$$

$\Delta Tevac$ = Total time from when the fire started to ignite until all occupants have completely evacuated the building. However, only sub-time E is generally considered explicitly in fire regulations, codes, and standards.

D = the period since the start of the fire until occupants are notified about the existence of fire.

B = refers to the recognition time and response time, i.e. the time between the occupants being notified about the fire and beginning to evacuate. This is known as pre-movement time.

E = an escape time that refers to an emergency or non-fire situation. It means that E is the total time for an evacuee's actual movement between beginning to evacuate and reaching a place of safety; i.e. entrance to a protected staircase, or outside the building.

Purser (2004) stated that for each occupied enclosure in a building, total escape time ($\Delta Tesc$) depends upon a series of basically additive, sequential processes summarized in the following equation:

$$\Delta Tesc = \Delta Tdet + \Delta Ta + \Delta Tpre + \Delta Ttrav \quad (2)$$

where:

$\Delta Tdet$ = time from ignition to detection.

ΔTa = time from detection to the provision of a general evacuation warning to occupants. Alarm time varies and largely depends on the types of alarm system installed in the buildings. It can range from 0 for the A1[1] alarm

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[1] A1 alarm system: Automatic fire detection system which generally activates immediately after fire starts.

[2] A2 alarm system: Automatic fire detection system with pre-alarm to management or security with pre set a fixed time-out delay usually 2 or 5 minutes. If a fire is genuine, alarm throughout the building will be activated manually. If there is no fire, the alarm can be cancelled manually. If neither of the both actions are taken, alarm will sound automatically according to the time-out delay set.

[3] A3 alarm system: Manual alarm system that relies on the personal detection and activation of the alarm system.

system, 2 to 5 minutes for A2[2] alarm system and possibly longer and more unpredictable for A3[3] alarm system.

$\Delta T pre$ = pre-movement time is the time from when occupants become aware of the emergency to when they begin to move towards the exits. This may include the time required to recognise the emergency and then carry out a range of activities before traveling to exits.

$\Delta T trav$ = travel time. (The time required for occupants to travel to a place of safety. Initially this might be by a protected escape route such as a corridor or stairway; ultimately it will be a place of safety outside the building)

In general, Total Evacuation Time is a sum of pre-movement time and travel time. Therefore;

$$\Delta T evac = \Delta T pre + \Delta T trav \qquad (3)$$

Where pre-movement time consists of detection time and alarm time ($\Delta T det + \Delta T a$). To summarise, Purser used terms Evacuation Time ($\Delta T evac$) in equation (3) to differentiate the terms used in equation (2) i.e. Total Escape Time ($\Delta T esc$) that consists of the last two terms in the escape equation:

In addition, Marchant (1976), mentions that there are three main components which contribute to the cumulative total escape time ($\Delta T esc$) in an emergency situation i.e. perception time (T_p), action time (T_a), and travel time ($T trav$). The relationship between them is written in mathematical form as follows:

$$\Delta T esc = T_p + T_a + T trav \qquad (4)$$

Where:

$\Delta T esc$ = a total escape time

T_p = perception time, i.e. that time from ignition to where people start to realise there is a fire or perception of fire,

T_a = a time from perception to the start of escape action, and

$T trav$ = a travel time, i.e. time taken to move to a safe area.

From the above descriptions, the terms total evacuation time and total escape time have the same meaning. In the opinion of the author the term Total Evacuation Time is more appropriate to be used because it refers to prior, pre and post time action of occupants in the evacuation process. However the terms used by Purser, Rusbash and Marchant are not contradictory but can be understood as the same things. One thing that they agreed on is that Total Evacuation Time consists of Pre-movement time and Travel Time.

Travel time has two components mainly known as horizontal travel time (T_h) and vertical travel time (T_v). Horizontal travel time refers to the time taken to evacuate the building by moving horizontally where occupants are walking from any room or along a corridor to the storey exit or protected staircase shaft or to the safe area or assembly area if the storey exit is also a final exit. Meanwhile vertical travel time refers to the time taken to walk down through the escape stair. If we incorporate this time into equation 4, it becomes:

$$\Delta T_{esc} = T_p + T_a + T_h + T_v \qquad (5)$$

To conclude, these three periods of time basically refer to (i) Time from when fire started until occupants are notified, (ii) time when occupants started to evacuate after been notified about the fire (this is called delay time or response time), and (iii) time taken for evacuees to completely evacuate the building. This is called travel time. However, periods one and two can be incorporated into one term i.e. Pre-Movement Time. Therefore equation (3) i.e. $\Delta T evac = \Delta T pre + \Delta T trav$ is more appropriate.
Where;

$$\Delta T pre = T_p + T_a \qquad (6)$$

$$\Delta T trav = T_h + T_v \qquad (7)$$

3.0 Staircase landing floor

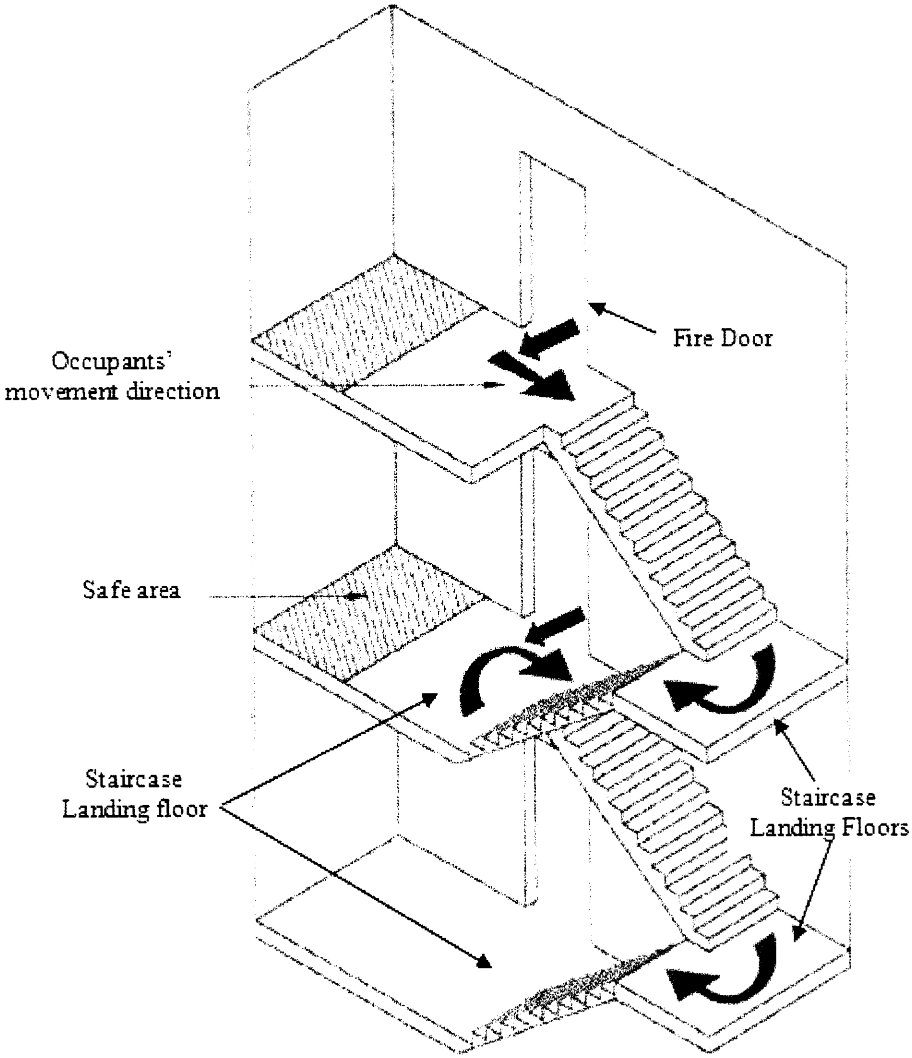


Figure 1: Schematic drawing of common staircase in high-rise residential buildings.

Figure 1 shows an example of a two storey schematic drawing of a common staircase in a high-rise residential building. There are four staircases with five landing floors for floor 2, 1, and ground floor. For the high-rise building, the same form of staircase is repeated to the number of the storeys required. In Clause 108 sub-clause 1 stated that the depths of landings shall be not less than the width of the staircases. Figure 2 shows the landing depth and width of the staircase.

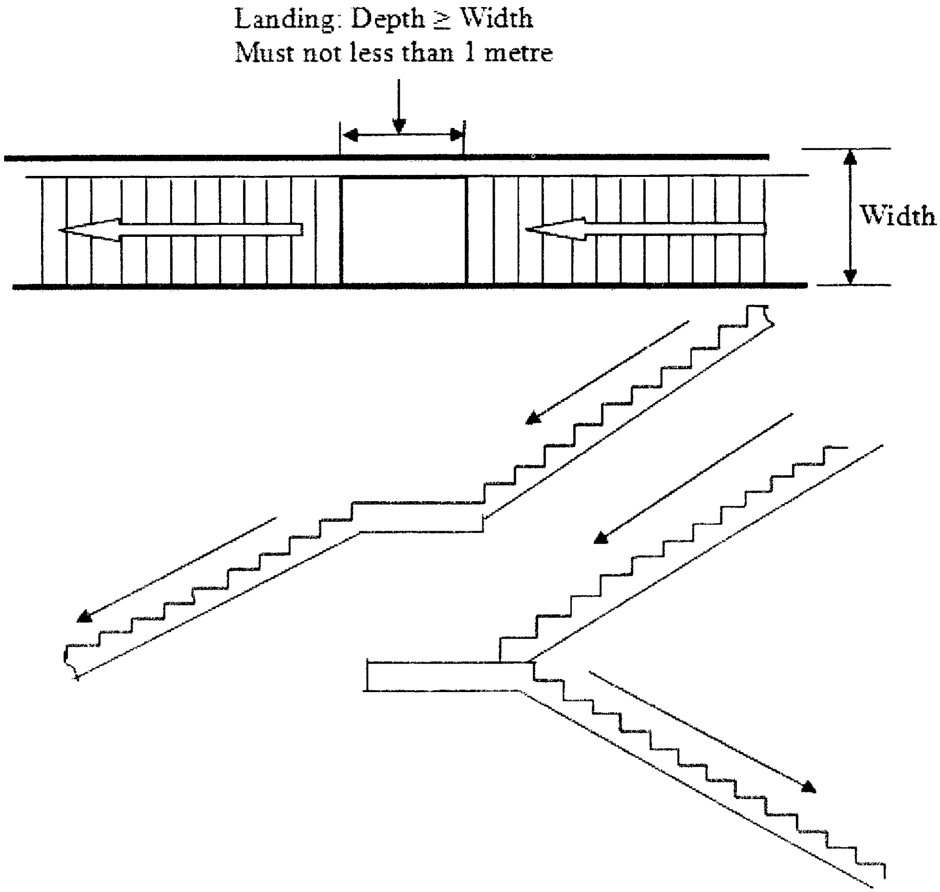


Figure 2: The landing depth and width of the staircase

4.0 Simulation procedure on the study models

Models were designed using CAD software and saved in a dxf file. If more than one floor needs to be analysed, dxf files have to be uploaded as many times as desired and the floor then named accordingly. All floors have to be connected to each other by using staircases designed in the SIMULEX environment.

SIMULEX is an evacuation tool which specialises in modelling the physical aspects of evacuation movement, and is widely used as a consultancy and analysis tool around the world. Simulex enable the user to simulate occupant behaviour in the event of a building evacuation, identify potential problems and find solutions. It uses a series of 2D floor plans, with exits and staircases linked together. Each floor plan and staircase is displayed in its own simulation window so that every event in Simulex environment can be viewed simultaneously (Thompson, IES 03/2008). Further application of the Simulex programme can be found in Thompson and Marchant (1995a, 1995b, 1996) and validation references can be referred to Olsson and Regan (1998) and Thompson and Marchant (1995c).

Analysis of the effect of the staircase landing floor i.e. floor connecting between two staircases (see diagram in figure 3b) on the evacuation time, will be carried out using Simulex comparing with the staircase designed without landing floor as in figure 3a. The staircase needs to be linked to the appropriate floor. The link must be the same as the door width. After links have being made, an exit or exits need to be assigned to enable the occupants to evacuate the building. The exit assigned is the end destination for the occupants in evacuation process.

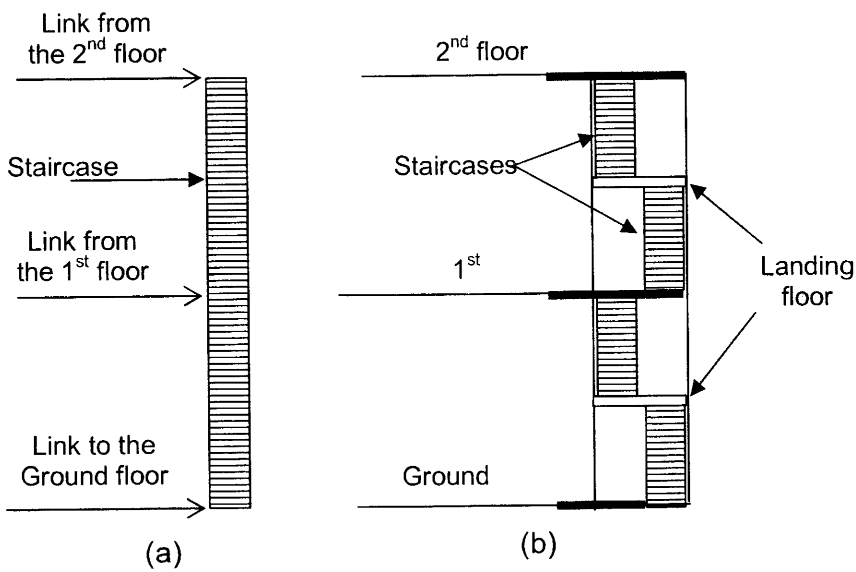


Figure 3: (a) Staircase without landing floor link to every floor, (b) Staircases with landing floors connecting the floors.

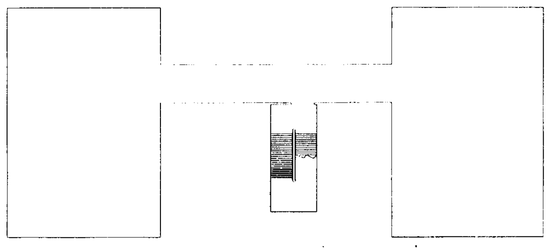


Figure 4: Example of the 1st and 2nd floor model

There are three building floor models for this purpose, floor one and two, and ground floor as shown in figure 4 and 5. Floor 1 and floor 2 models designed as in figure 4 and the ground floor model designed as a rectangle to indicate the building line to enable people to move toward the final exit.

Both models were then uploaded into Simulex and named accordingly to indicate the appropriate floor level they represent. Staircases are then designed according to the width and length of staircases to test. In general, the simulation procedures were as follows;

(i) Add floor; by clicking 'Building' button, floor plan can be added. Dxf file saved in appropriate folder can be imported and named accordingly i.e. ground floor.

(ii) Procedure (i) can be repeated to add other floor plans i.e. Floor 1, 2, 3 etc. The number of floor plans to be added depends on the number of floors we wanted to investigate.

(iii) Add staircases i.e. staircase 1, 2, 3, 4, etc by putting in the staircase specification e.g. staircase width and name them accordingly.

(iv) Add links to every staircase designed to the floor level i.e. link 1 is to link staircase 1 to the ground floor plan, link 2 is to link staircase 1 to the 1st floor, link 3 is to link staircase 2 to the 1st floor, link 4 to link staircase 2 to the landing floor, link 5 to link staircase 3 to the landing floor, link 6 to link staircase 3 to the 2nd floor and so on. All links widths have to be the same width as the staircase designed.

(v) Add 2 metres exit to indicate the normal main entrance width at the ground floor which is normally uses by the occupants to enter and leave the building. It is placed opposite to the link 1 made in procedure (iv).

(vi) Add people into all models by dividing equally into every chamber available in the study models. People characteristics are then set; in the analysis of the models the same typical distribution of people is used in each model tested to reflect the normal occupancy type of people in residential buildings, i.e. male, female, children and elderly.

(vii) Calculate the distance maps by clicking 'DistMap' button and then click 'Calculate All'.

(viii) Run the simulation by click 'Simulation' and then click 'Begin'. The simulation can be recorded and saved in an appropriate folder under an appropriate name.

(ix) After the simulation has been completed a popup window will show the simulation time. Click 'Yes' and another popup window will tell the time taken by all people who have reached the exit.

(x) Note down the evacuation time in table for further analysis.

Figure 5 shows one of the models that have been simulated in Simulex.

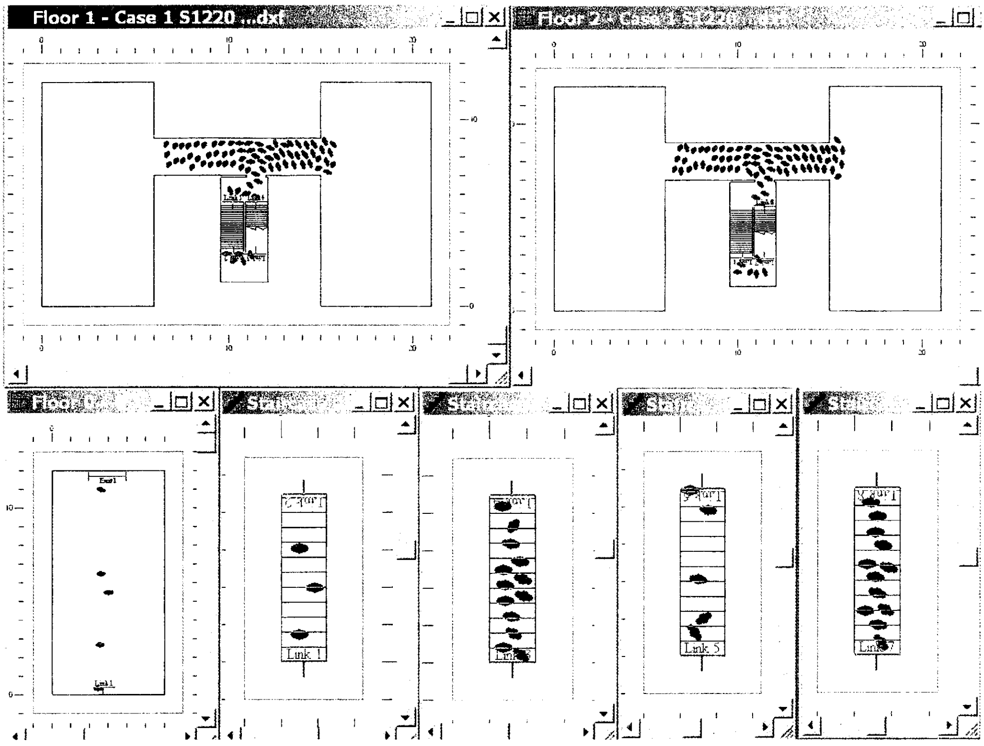


Figure 5: Example of simulation process

Result and discussion

To analyse the effect of staircase with and without landing floors, comparison of two staircases sizes have been done i.e. staircase width 914 mm and 1524 mm. Both sizes are designed with and without landing floor and tests have been carried out using Simulex software. The test results are shown in figure 6. The tests were carried out in two phases where phase one was conducted by adding the number of people in the model studied from one people to 10 people and second phase was by using a different number of people occupying the flat i.e. normal occupying, high occupying and overcrowded occupying that 36, 72 and 180 people respectively.

The purpose of the test is to know the effect of landing floors on staircases on the people movement. Comparison is made on two different staircases i.e. the smallest width of staircase is compared with the widest width of staircase. First test was by increasing the number of people gradually from one to ten to investigate the effect of the number of people evacuation using both types of staircase i.e. with and without landing floor.

No. of People	1	2	3	4	5	6	7	8	9	10	**36**	**72**	**180**
914w	33.0	33.0	33.1	35.5	42.3	43.0	45.4	43.1	48.6	48.1	87.0	163.4	391.7
914wo	28.2	28.3	29.8	31.1	32.1	32.5	33.4	35.5	36.8	38.0	54.3	93.6	196.9
1524w	30.9	32.5	33.2	33.5	34.5	36.9	37.5	39.0	40.6	45.8	77.6	119.1	294.9
1524wo	28.4	28.7	29.5	30.2	31.3	32.3	33.1	33.5	33.8	34.5	42.1	60.8	115.0

Figure 6: Total evacuation time for staircase 914mm and 1524mm with and without landing floor

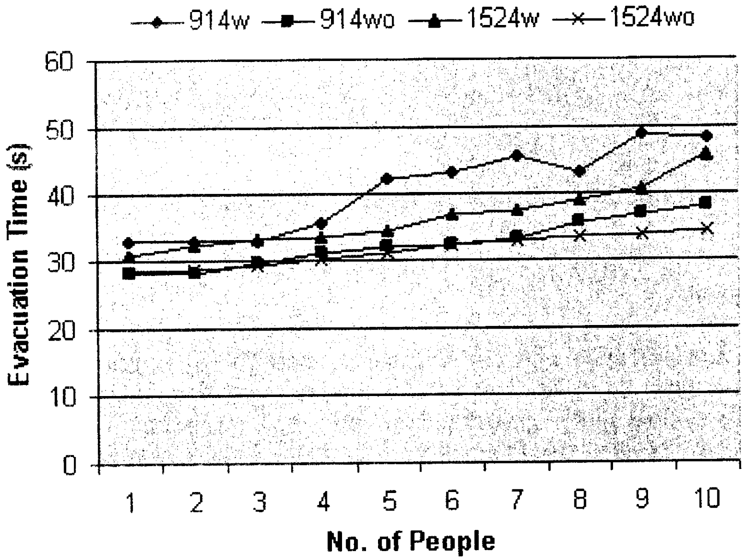
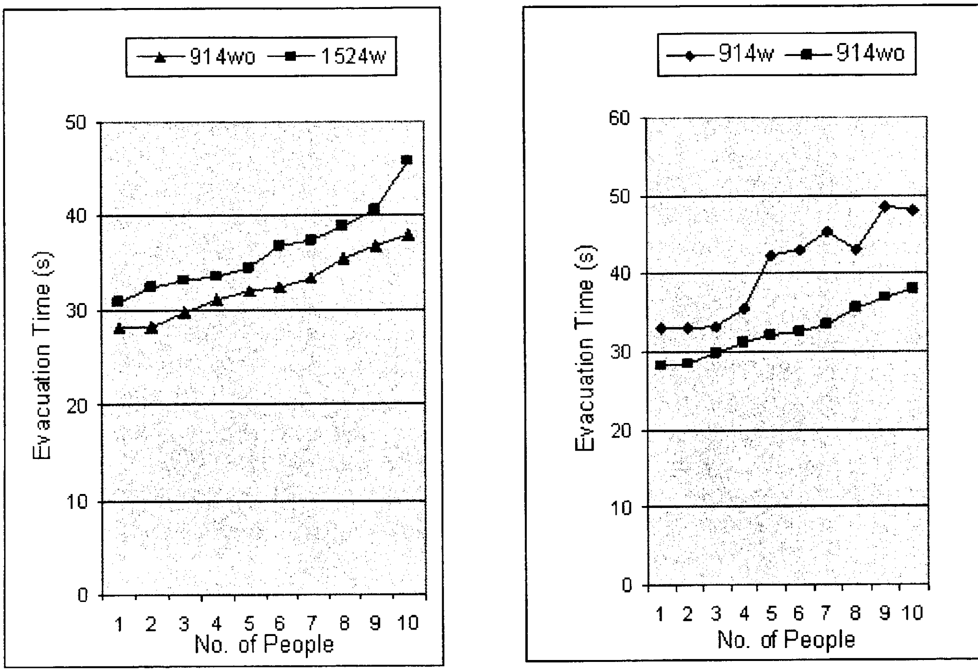


Figure 7: Evacuation time Vs No. of People of low occupancy for staircase 914 mm and 1524 mm with and without intermediate floor.

Second test was by increasing the number of people based on the different category of people in the flat. There are three types of occupying i.e. Normal occupying, that assumption of 2 persons per room; High occupying, 4 persons per room; and Over crowded occupying i.e. 10 persons per room. Based on the number of residential flats per floor level i.e. six flats with three bedrooms, number of people for normal density is 2 x 3 x 6 = 36 persons, high density is 4 x 3 x 6 = 72 persons, and over crowded density is 10 x 3 x 6 = 180 persons per floor.

All tests used a constant people walking speed i.e. 1.3 m/s and similar body type and characteristics. For staircase design without landing floors, Staircase Equivalence Length have been used which takes into consideration the distance that occupants have to walk on the staircase and through the landing floors. There will be only one staircase designed in Simulex that links from floor level to the ground floor. For staircase with landing floors, actual staircase length designed and links from floor level to landing floor then to the ground floor. There will be two staircases, one staircase from floor lever to landing floor and another from landing floor to ground floor. Occupants have to change staircase at the landing floor on their way out. Those test results are as in figure 7 and 9, evacuation time verses no. of people of low occupancy and high occupancy respectively.



(a) (b)

Figure 8 (a) Comparison of staircase 914 mm without and staircase 1524 mm with landing floor. (b) Comparison of staircase 914 mm with and without landing floor. Note: (w_o) = without landing floor, (w) = with landing floor.

Figure 8(a) shows that staircase 914 mm without landing floor performed much better compared to the staircase 1524 mm with landing floor. Simulation shows that in increasing the number of people up to ten people, there is no congestion at any point on the staircase. People are smoothly moving down the staircase. It is different from the staircase designed with landing floors, people have to change the staircase at the landing floor and it has caused the walking speed to slow down. It causes a significant delay in the travel time even when the wider staircase has been used. It is a significant evidence that the landing floor does have an effect on the travel time. It shows that staircase 1524 mm with landing floor takes about 10% – 20% longer if compared to staircase 914 mm without landing floor.

Figure 8 (b) shows the analysis of travel time on the same width of staircase, i.e. 914 mm with and without landing floor. It shows that the staircase with landing floors has taken longer to complete evacuation. The difference was 11.07% minimum to 35.93%

maximum, with the average time difference was 23.89%. A similar phenomenon happened when staircase 1524 mm with and without landing floors was analysed, that analysis result shows that the staircase with landing floors took a longer time to complete the evacuation. The difference was between 8.87% minimum to 29.74% maximum with the average time difference was 14.63%. It is significant evidence that the landing floors have an effect on the travel time. It takes 15% to 24% longer if compared to staircase designed without landing floor.

Figure 9 shows that time taken for cases of staircases with and without landing floors when the number of people simulated is being increased to 36, 72 and 180. It shows that time taken increased at a steady rate. The graph shows that value Y increased when value X increases. It is significant evidence that there is a correlation between variable Y (dependent variable) i.e. evacuation time and variable X (Independent Variable) i.e. number of people. This graph suggested that it is a positive linear correlation between variable Y and variable X. The graph has followed the rule $Y_i = mX_i + c$, where m is an acceleration rate or *slope* and c is a constant. Value m and c can be determined by taking two points on the correlation line and put into the equation $Y_i = mX_i + c$.
Analysis of acceleration rate (m) and constant (c) can be done by prudent analysis of the correlation line in figure 9. Value m and c can be calculated as an example below and can be found in figure 10 (b). Figure 10(a) shows the coordinate of variable X and variable Y. Value for variable X and Y i.e. numbers of people and evacuation time respectively can be found in figure 6. Example calculation of value (m) and (c) for staircase 914 mm with landing floor is as follow:

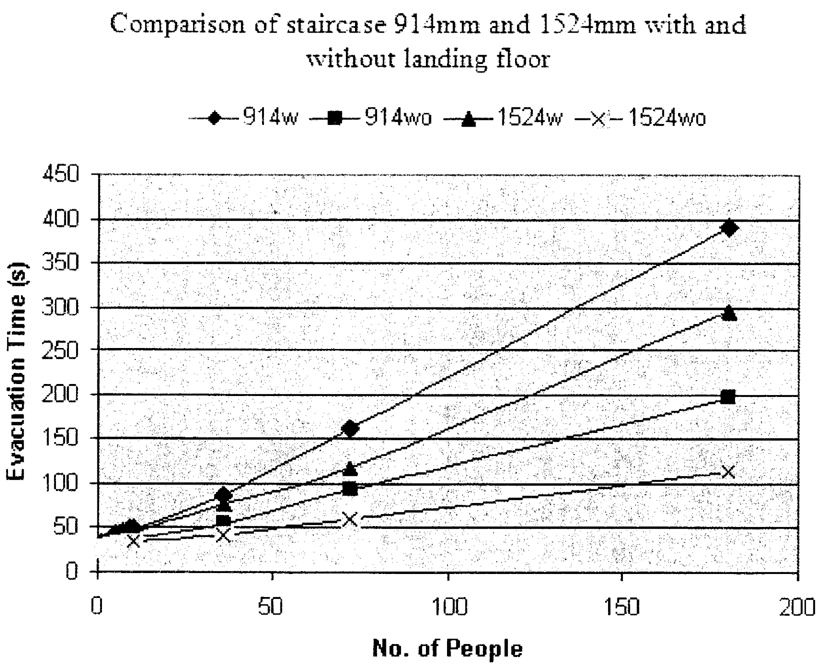


Figure 9: Total Evacuation time Vs No. of People of high occupancy for staircase 914 mm and 1524 mm with and without landing floor.

By taking two points on figure 9 as a coordinate in linear correlation line, value *m* and *c* can be determined. Coordinate one (X_1,Y_1); $X_1 = 72.0$, $Y_1 = 163.4$ and coordinate two (X_2,Y_2); $X_2 = 180.0$, $Y_2 = 391.7$. By putting those values into equation $Y_i = mX_i + c$, it becomes;

$$163.4 = 72m + c \quad (8)$$

$$391.7 = 180m + c \quad (9)$$

$$180m + c = 391.7$$

$$c = 391.7 - 180m \quad (10)$$

Putting equation (10) into equation (8), it becomes;

$$72m + 391.7 - 180m = 163.4$$

$$(72m - 180m) = (163.4 - 391.7)$$

$$-108m = -228.2$$

$$m = 228.2 / 108$$

$$m = 2.11$$

Therefore, acceleration rate or slope (m) for staircase 914 mm (w_o) is 2.11. By putting (m) = 2.11 into equation 7.3, value c is,

$$c = 391.7 - (180 \times 2.11)$$
$$= 11.9$$

Another method to calculate the value m and c is by simplifies equation $Y_i = mX_i + c$ as follows:

$$Y_1 = mX_1 + c \qquad (11)$$

$$Y_2 = mX_2 + c \qquad (12)$$

Given any two points (X_1, Y_1) and (X_2, Y_2) on the linear graph, equation (11) and (12) can be written;

$$(Y_2 - Y_1) = m(X_2 - X_1) + (c - c)$$
$$(Y_2 - Y_1) = m(X_2 - X_1)$$

$$m = \frac{(Y_2 - Y_1)}{(X_2 - X_1)} \qquad (13)$$

$$c = Y - mX \qquad (14)$$

By putting value X and Y as shown in figure 10(a) and (b), value m and c can be determined as in figure 10(b). Referring to figure 10(b), staircases designed with landing floors have a high m value compared to the staircases designed without landing floors. Analysis has also been done on the smallest width of staircase i.e. 914 mm compared to the widest staircase i.e. 1524 mm.

It shows that the narrower the staircase, the higher the value of m and the wider the staircase, the lower the value of m. Therefore it can be concluded that m value for the other staircase widths between 914 mm and 1524 mm designed with landing floor will be within 1.63 to 2.11. Meanwhile, c value i.e. constant value, for the staircases designed with landing floor is high i.e. between 23.2 and 25.9 and both values are included for the widest and the smallest staircase respectively. There is a significant evidence of high correlation between the crowds and the travel time for the staircases designed with landing floor because of multiplying factor i.e. m value is more than 1.0. It can be concluded that increasing the number of people will also increase the travel

Stairs \ X	X_1	X_2	*m*	*c*
914 w	Y_1	Y_2	?	?
914 w_o	Y_1	Y_2	?	?
1524 w	Y_1	Y_2	?	?
1524 w_o	Y_1	Y_2	?	?

Stairs \ X	72	180	*m*	*c*
914 w	163.4	391.7	2.11	11.9
914 w_o	93.6	196.9	0.95	25.9
1524 w	119.1	294.9	1.63	1.5
1524 w_o	60.8	115.0	0.51	23.2

time by multiplying factor of 1.6 to 2.11.

(a) (b)

Figure 10: (a) Variable (X) i.e. No. of People and variable (Y) i.e. Evacuation Time for staircases 914 mm and 1524 mm with and without landing floor.

(b) Value for variable X, Y, and calculated value for *m* i.e. slope and *c* i.e. constant.

Analysis of staircases designed without landing floor shows it has a small *m* value i.e. less than 1.0. Even for the smallest width of staircase i.e. 914 mm, shows that *m* value is only 0.95 and the widest staircase i.e. 1524 mm, *m* value is 0.51. Observing the constant value i.e. *c*, it shows that staircases designed without landing floor has a high constant value.

Conclusions

It can be concluded that landing floors has an effect on the evacuation time i.e. it will longer the evacuation time by 15% to 24%. There is significant evidence that there is a high correlation between the number of people and the evacuation time. The simulation suggested that there was significant difference between staircase designed with and without intermediate landing floors. The widest staircase designed with landing floors has longer travel time compared to the narrowest staircase designed without landing floors.

References

IES, (03/2008), www.iesve.com/content/mediaassets/pdf/simulex.PDF - (19.03.08)

Marchant, E.W. (1976), Some aspects of human behaviour and escape route design. *5th International Fire Protection Seminar, Karlsruhe,* Sept 1976

Olsson, P.A., and Regan, M.A., (1998), A comparison between actual and predicted evacuation times, *1st International Symposium on Human Behaviour in Fire*, University of Ulster.

Purser, D., (2004), *BRE Digest 490, Structural Fire Engineering Design: Aspect of Life Safety*, BRE Press.

Rasbash, D.J., Ramachandran, G., Kandola, B., Watts, J.M., Law, M., (2004), *Evaluation of Fire Safety*, John Wiley and Sons, England.

Thompson (a), P.A. and Marchant, E.W., (1995), A computer model for the evacuation of large building populations, *Fire Safety Journal* **24,** pp. 131–148.

Thompson (b), P.A. and Marchant, E.W., (1995), Computer and fluid modelling of evacuation. *Safety Sciences Journal* **18,** pp. 277–289.

Thompson (c), P.A. and Marchant, E.W., (1995), Testing and application of the computer model SIMULEX. *Fire Safety Journal* **24** pp., 149–166.

Thompson, P.A., and Marchant, E.W., (1996), Modelling Evacuation in Multi-Storey Buildings with SIMULEX, *Fire Engineering Journal*, 56 (185), Pg. 6-11.

UBBL, *Uniform Building By-Laws, 1984*, International Law Book Services, Malaysia.