Article

JFPE

Journal of Fire Protection Engineering
22(4) 301–314

DOI: 10.1177/1042391512464966
jfe.sagepub.com
SAGE

An analysis of occupant evacuation time during a hotel fire using evacuation tests

Jen-Hao Chi
Department of Fire Science, Wu Feng University, Minsyong, Chiayi, Taiwan

Abstract
The fire floor of a hotel fire that resulted in serious casualties in Taiwan was reconstructed as the site of a full-scale evacuation test. Health status assessments were conducted on 50 adults between ages of 25 and 75, and then their horizontal movement speed was measured as a function of three physical conditions: normal health, wheelchair bound and on crutches. The 50 subjects were divided into nine groups for three kinds of evacuation strategies in order to measure the evacuation time of each group. In addition, taking into consideration the three aforementioned kinds of physical conditions, 40 of the 50 subjects were organized into six types of conditions to conduct exit width tests by measuring the evacuation time for passing through exits with widths of 0.75 m and 1.2 m. The two kinds of evacuation test results can be used as a reference for improving fire safety strategies for future hotel construction.

Keywords
Hotel fire accident, full-scale test, evacuation time, exit width tests, evacuation test, fire safety strategies

Introduction

Hotel occupants are usually unfamiliar with the layout of a hotel building. Such a situation tends to cause death or serious injury during a fire accident. In recent years, a number of major hotel fires have occurred in the international community.

Corresponding author:
Jen-Hao Chi, Department of Fire Science, Wu Feng University, 117 Jianguo Rd., Sec. 2, Minsyong, Chiayi, 62153 Taiwan.
Email: chi.jen-hao@wfu.edu.tw

For example, a fire happened in a hotel in Pomerania, northwestern Poland, on April 13, 2009, at around 1 am in which 21 people died and 20 others were injured; a motel fire occurred at around 10 am on June 7, 2007, in Riverdale Georgia, USA, resulting in five people being killed and six injured; around 2 am on April 15, 2005, a hotel fire in the ninth arrondissement of Paris, France, killed 21 and injured 19 people [1]. This shows that old and small hotels do pose a high fire risk. This study was inspired by a Taiwan hotel fire accident that resulted in serious loss of life. The fire broke out at 2:42 am on March 2, 2009, at the Snow White hotel located on Tai-Yuan road, Da-Tong District, Taipei. The first floor of that building is used by a store, while the second through fifth floors are used by the hotel [1]. According to the official fire investigation information, arson was suspected and the initial fire was determined to be in an unoccupied room, No. 106, on the second floor. There were 23 people inside the hotel when the fire broke out; four of them evacuated by themselves, 11 people were rescued by ladder truck, six people burned to death, one jumped to his death and another died of a serious head injury due to a fall during evacuation. In total, eight people died as a result of this fire [2].

In order to investigate occupants' evacuation time under various environmental conditions in small hotel fires, this study reconstructed the aforementioned scenario on the second floor where the fire originated as a site for a full-scale test of hotel fire evacuation. Fifty subjects 25 to 75 years old were invited to participate in this evacuation test. The horizontal movement speed of each subject was measured. Everyone's health condition was also evaluated before the test. Subjects were divided into nine groups and carried out three kinds of evacuation strategies. All subjects' evacuation behaviors were photographed and each evacuation time was also measured in order to compare the test results for each group.

In addition to the hotel fires already referenced, a fire occurred at the Station nightclub [3] in Rhode Island, USA, on February 20, 2003. The fire caused a death toll of 100 due to panicking customers rushing into a mere 1-m-wide exit, which made it extremely difficult to evacuate when the fire broke out.

Multi-purpose buildings commonly seen in the metropolitan areas in many countries are the subject of this study. In general, this kind of building serves two or more purposes, such as hotel, pub, nightclub, commercial store, restaurant or residential area. For a multi-purpose building, the occurrence of customer evacuation and crowding through an entrance/exit when a fire breaks out is highly likely, just as occurred at the Station nightclub. To study the flow capacity of the entrance/exit during a fire, 40 volunteers from the above referenced 50 subjects were invited to have their horizontal movement speeds measured under three physical conditions: normal health, wheelchair bound and with crutches. A total of six scenarios are included to investigate the subjects' evacuation time when passing through exits with widths of 0.75 and 1.2 m.

Finally, conclusions that may influence future fire safety strategies for hotels are presented.

Evacuation tests

Site description

According to the fire investigational data for the Snow White Hotel, there were six rooms and a storage room on the second floor and only one internal staircase leading to other floors. The size of each room's door was 0.8 m in width and 1.8 in height [2]. The aforementioned second floor area where the fire originated was reconstructed in the Fire Laboratory Center of the Building Research Institute, Ministry of the Interior, Taiwan. Its layout is shown in Figure 1.

Health status assessment and horizontal movement speed

This study invited 41 young people between the ages of 25 and 30 years (35 male and 6 female), 5 males between the ages of 31 and 45 years and 4 males between the ages of 46 and 75 years, making a total of 50 subjects involved in this evacuation test. Prior to the test, all participants received health status assessments, in which the condition of 6 subjects was considered excellent, 21 good, 19 average, 4 below average and none in poor health.

The measured horizontal movement speeds of all subjects before the test are as follows: for the 41 young people, speeds were from 1.07 to 1.68 (m/s), with an average of 1.35 (m/s) and a standard deviation of 0.25 (m/s). For the remaining nine people, speeds were from 0.91 to 1.14 (m/s), with an average of 1.05 (m/s) and a standard deviation of 0.10 (m/s).

Speeds of 40 volunteers from the group of 41 young people were also measured in a wheelchair. Their horizontal movement speeds were from 0.25 to 0.42 (m/s), with an average of 0.31 (m/s) and a standard deviation of 0.1 (m/s). The horizontal movement speeds of these same 40 volunteers using crutches were from 0.78 to 1.28 (m/s), with an average of 0.92 (m/s) and a standard deviation of 0.25 (m/s). The health status assessments for these volunteers yields an excellent condition for 5, good for 19, average for 13 and below average for 3.

Full-scale evacuation test description

The full-scale test site shown in Figure 1 was constructed to observe evacuation behavior and obtain results for different types of evacuation strategies. The 50 subjects noted above, who were not familiar with the test site, were grouped as described below and accommodated in different rooms. After being aware of penetration of smoke into the rooms (a harmless smoke was emitted in the corridor), subjects had to walk out into the corridor filled with smoke and grope forward in a completely unknown environment and, finally, enter the stairwell and refuge to other floors. Every subject's evacuation behavior was fully photographed and individual evacuation times were also measured, which was then used to build an evacuation base model or Base Case for short.

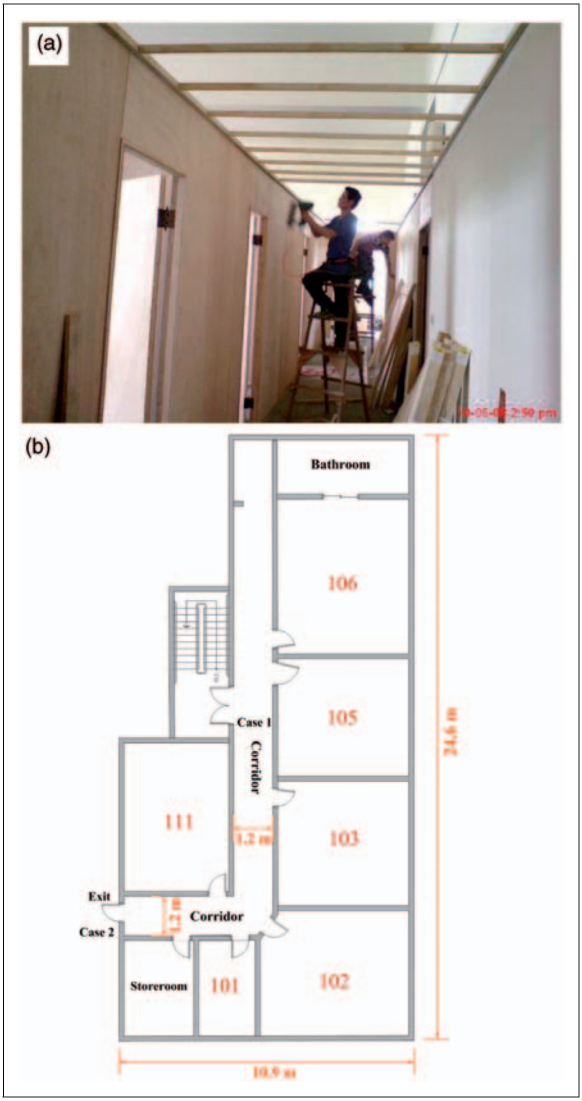

Figure 1. Construction photos and layout of the full-scale tests site. (a) Construction photos. (b) Layout of the full-scale tests site.

After completing the Base Case, each subject was led by research staff back to their own room and the second trial was conducted. This time, smoke was emitted again but with a verbal announcement informing all subjects to evacuate immediately. The observation of test result behavior for all subjects during evacuation with the verbal announcement as well as in a more familiar environment is called the alarm equipment improved strategy, or Case 1 for short.

Table 1. Occupant distribution in each room at the full-scale test site

	Occupant distribution count							
	Room							
Group	101	102	103	105	106	111	Corridor	Total
Group 1	3	3	3	0	0	3	2	14
Group 2	1	2	1	1	1	1	1	8
Group 3	1	1	1	1	1	1	1	7
Group 4	1	1	1	1	0	1	1	6
Group 5	1	1	0	1	0	1	0	4
Group 6	1	0	0	0	0	0	0	1
Group 7	1	0	0	0	0	0	0	1
Group 8	1	1	1	1	0	1	0	5
Group 9	0	3	0	1	0	0	0	4

After completing the Case 1 trial, again, each subject was led back to their own room and smoke was emitted from the corridor to conduct the third trial. In this test, the emergency lights and evacuation direction lights in the corridor were turned on, and the emergency exits at the end of the corridor was also opened, as shown in the bottom left exit of Figure 1(b). The observation of test result behavior for all subjects evacuating into the smoke-filled corridor after being aware of smoke penetration under familiar conditions and then deciding to evacuate to a safe area by means of evacuation to other floors or through emergency exits is called the evacuation equipment and facility improved strategy, or Case 2 for short.

As shown in Table 1, the 50 subjects were divided into nine groups and arranged within the rooms of the test site. Of the 41 young subjects, 39 were randomly selected and divided into 1 to 5 Groups; the sixth Group consisted of one young woman, while the seventh Group contained one young man. Group 8 comprised five male subjects aged between 31 and 45 years. Group 9 included four male subjects aged between 46 and 75 years. In order to understand the effect of the above improvement strategies, after completing the Base Case, each group, under the same test condition, immediately conducted Case 1 and Case 2 sequentially.

Exit width test description

In order to investigate the influence of flow capacity of an exit, or exit width, on occupants' evacuation time, an additional experimental site was constructed. As shown in Figure 2, all subjects' evacuation time was measured passing through exit widths of either 0.75 or 1.2 m (for this latter case, both the 0.75 and 0.45 m doors in Figure 2 were open at the same time), under the three different physical conditions of normal health, in a wheelchair and with crutch support.

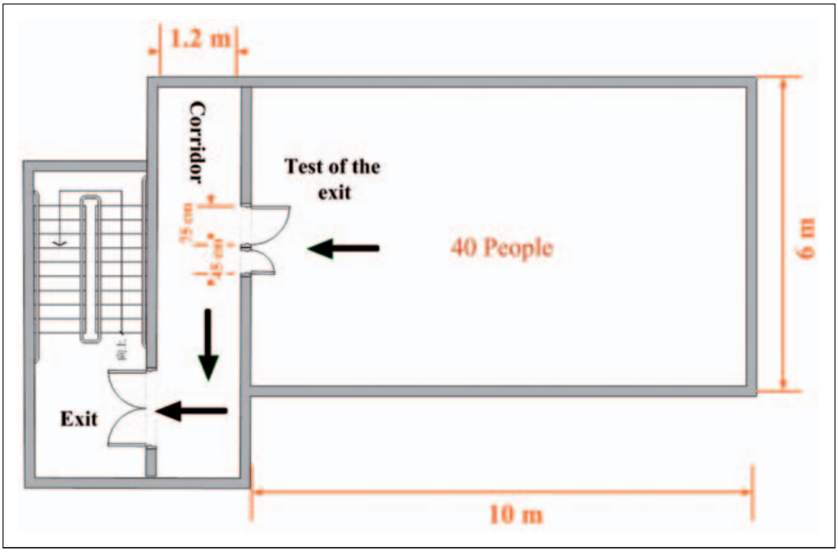

Figure 2. Layout of the exit width test site.

The 40 subjects in this study were divided into six groups for different testing conditions. Group 1 consisted of 40 healthy subjects, Group 2 consisted of 5 subjects in wheelchairs, Group 3 consisted of 10 subjects in wheelchairs, Group 4 consisted of 5 subjects on crutches, Group 5 consisted of 10 subjects on crutches and Group 6 consisted of 10 subjects in wheelchairs and another 10 subjects on crutches.

Results and analysis of the evacuation tests

The Base Case of the full-scale evacuation test

The full-scale test yields evacuation time, which is the total amount of time it takes from the test start to test completion. It factors in the reaction time before movement, which is then added to the movement time after the evacuation begins.

While conducting the Base Case test, 2 of the 14 subjects in Group 1 of Table 2 discovered the smoke first. However, owing to unfamiliarity with the test site, they stayed in place and did not act immediately. Subsequently, three subjects in Room 103 found the smoke penetrating the room. They then immediately opened the door and evacuated through the corridor. Alerted by the noise from Room 103, all 11 subjects from Rooms 101 and 102 stepped out and entered the smoke-filled corridor. They fumbled to reach the entrance to the stairs and then arrived at the safety zone on the lower floor. Their reaction and movement time was approximately 8 and 56 s, respectively. However, despite hearing this noise, the three subjects in Room 111 at the end of the corridor remained in the room and

Table 2. Full-scale test results for each strategy by group

Group	Case type	Reaction time (s)	Movement time (s)	Evacuation time (s)	Reduce time (s)	Percentage[a] (%)
Group 1	Base Case	34	56	90	–	–
	Case 1	0	50	50	40	44
	Case 2	7	50	57	33	37
Group 2	Base Case	10	50	60	–	–
	Case 1	0	47	47	13	22
	Case 2	8	32	40	20	33
Group 3	Base Case	10	120	130	–	–
	Case 1	0	41	41	89	69
	Case 2	5	25	30	100	77
Group 4	Base Case	8	38	46	–	–
	Case 1	0	35	35	11	24
	Case 2	4	37	41	5	11
Group 5	Base Case	15	170	185	–	–
	Case 1	0	50	50	135	73
	Case 2	2	50	52	133	72
Group 6	Base Case	10	30	40	–	–
	Case 1	0	29	29	11	28
	Case 2	3	9	12	28	70
Group 7	Base Case	5	26	31	–	–
	Case 1	0	24	24	7	23
	Case 2	3	25	28	3	10
Group 8	Base Case	15	57	72	–	–
	Case 1	0	47	47	25	35
	Case 2	10	50	60	12	17
Group 9	Base Case	18	67	85	–	–
	Case 1	0	52	52	33	39
	Case 2	12	56	68	17	20

[a]Percentage is reduced time for each group divided by evacuation time of the Base Case.

did not take any action due to fear from unfamiliarity. Finally, they started to evacuate when smoke penetrated their room. Their reaction time was 26 s more than that of the 11 subjects from the same group, and their movement time was approximately 50 s. The total reaction time for the 14 subjects in Group 1 of Table 2 was approximately 34 s (8 plus 26 s), movement time was approximately 56 s (the longer of 50 and 56 s) and evacuation time was 90 s (34 plus 56 s).

In Groups 2 and 4 of Table 2, one subject who was assigned to stay in the corridor while conducting the Base Case test continuously called out after spotting the smoke. This action alerted other subjects from the same group to begin to evacuate. The reaction, movement and evacuation time for Group 2 was approximately 10, 50 and 60 s, respectively. In addition, the reaction, movement and evacuation time of Group 4 was approximately 8, 38 and 46 s, respectively. Because the leader among the evacuees got disorientated, seven subjects from Group 3 were constantly moving about in the corridor after they walked out of the rooms. Their final evacuation time was approximately 130 s, including both reaction and movement time, which was approximately 10 and 120 s, respectively.

For Group 5 (no one was assigned to stay in the corridor), subjects in Room 102 found the smoke penetrating the room first. They went out to the corridor to alert others to prepare for evacuation. However, the same as Group 3, the leader was disoriented and their final evacuation time was approximately 185 s, including both reaction and movement time, which was approximately 15 and 170 s, respectively.

For Group 6 of Table 2, one young female was assigned in Room 101. Her evacuation time was around 40 s, including both reaction and movement time, which were approximately 10 and 30 s, respectively. Group 7, also with one young man in Room 101, successfully evacuated in approximately 31 s, including both reaction and movement time, which were approximately 5 and 26 s, respectively. Under identical conditions, movement time for the male is 4 s less than that of the female or about 13.3% ((30–26)/30) less.

Group 8 in Table 3 consisted of five males 31 to 45 years of age. The person in Room 103 first noticed smoke penetrating the room and called out to alert others. Perhaps because the members in this group did not know each other, they did not wait for or follow each other during the evacuation. The people in Room 111 were the last to exit and it took them approximately 72 s.

Group 9 consisted of four males 46 to 75 years of age. The person in Room 105 first noticed the smoke infiltrating the room, but he did not alert anyone. It took him about 60 s to evacuate by himself. The three remaining people evacuated together and it took them approximately 85 s. Comparing the test results of Groups 8 and 9 with Group 4, which all took place under similar conditions, it can be seen that the reaction, movement and evacuation time of senior subjects are longer than those of younger subjects.

Evacuation efficiency of other cases

For the Case 1 test, since the subjects are familiar with the test environment and they received a verbal warning, the reaction time for all groups in Table 2 was close to zero. As the subjects got familiar with the test site after the Base Case, the group leaders did not get disoriented. This shows that the extent of familiarity with a site affects evacuation behavior significantly. Table 2 indicates that comparing the improved evacuation time for Groups 3 and 5 to the Base Case, their evacuation time is reduced by more than approximately 69% due to the absence of disorientation during evacuation.

Table 3. Exit test results for 0.75 m width, by group

No.	Case type (people)		Evacuation time (s)	Increased time[a] (s)	Percentage[b] (%)
Group 1	Health	40	35.5	–	–
	Wheelchair	0			
	Crutch	0			
Group 2	Health	35	58.2	22.7	63.9
	Wheelchair	5			
	Crutch	0			
Group 3	Health	30	68.2	32.7	92.1
	Wheelchair	10			
	Crutch	0			
Group 4	Health	35	41.2	5.7	16.1
	Wheelchair	0			
	Crutch	5			
Group 5	Health	30	45.4	9.9	27.9
	Wheelchair	0			
	Crutch	10			
Group 6	Health	20	71	35.5	100
	Wheelchair	10			
	Crutch	10			

[a]Increased time is the result of subtracting evacuation time of Group 1 from evacuation time of each group.
[b]Percentage is increased time of each group divided by evacuation time of Group 1.

As noted before, Case 2 provides more evacuation routes for the subjects than Case 1. The results in Table 2 show that in the improved Case 2 strategy, subjects from Groups 2, 3 and 6 found the emergency exit next to Room 111 and used it to evacuate to safety. Therefore, the movement time of these three groups in the Case 2 test was less than that in the Case 1 test. On the other hand, as none of the subjects in Groups 1, 4, 5, 7, 8 and 9 found the emergency exits next to Room 111 in Case 2 test, all of them still used the former route to evacuation. The movement time for these six groups in Case 2 test was longer than that in the Case 1 test.

The exit width test

The test measures the time it takes to evacuate through the two exit widths, starting from the first to final subject. Therefore, reaction time is not considered in Tables 3 and 4 for the evacuation time results.

Tables 3 and 4 show that for the Group 1 condition, the evacuation time for all subjects to pass the 1.20 m wide exit was 21.3 s, which is 14.2 s faster than the 35.5 s, it took to pass through the 0.75 m wide exit, about a 70% reduction. This result

Table 4. Exit test results for 1.2 m width, by group

No.	Case type (people)		evacuation time (s)	Increased time[a] (s)	Percentage[b] (%)
Group 1	Health	40	21.3	–	–
	Wheelchair	0			
	Crutch	0			
Group 2	Health	35	29.8	8.5	39.9
	Wheelchair	5			
	Crutch	0			
Group 3	Health	30	38.3	17	79.8
	Wheelchair	10			
	Crutch	0			
Group 4	Health	35	24.1	2.8	13.1
	Wheelchair	0			
	Crutch	5			
Group 5	Health	30	27	5.7	26.8
	Wheelchair	0			
	Crutch	10			
Group 6	Health	20	42.6	21.3	100
	Wheelchair	10			
	Crutch	10			

[a]Increased time is the result of subtracting evacuation time of Group 1 from evacuation time of each group.
[b]Percentage is increased time of each group divided by evacuation time of Group 1.

indicates that appropriately increasing the width of exits in small and old hotels would be quite helpful for occupant evacuation.

The wheelchair used in this study was 0.80 m (W) × 1.1 m (H). The comparison between Tables 3 and 4 shows that for the Groups 2 and 3 conditions, the greater the quantity of wheelchairs, the greater the impact of a narrower exit. Table 3 shows that the increase in evacuation time for Groups 2 and 3 was 63.9% and 92.1%, respectively. The main reason for such an increase in evacuation time is that the width of the wheelchair (0.8 m) is larger than the exit (0.75 m). In order to pass such an exit, others must help push the wheelchair through at an angle. Therefore, the greater the quantity of wheelchairs, the longer it takes to pass through the exit. Table 4 indicates that for the Group 2 condition, the percentage increase in evacuation time for this group was approximately 39.9%. The main reason for the lower percentage increase than Group 2's 63.9% shown in Table 3 is that it is easier for a 0.8-m-wide wheelchair to pass through a 1.2-m-wide exit. For the Group 3 condition, although the increase in evacuation time in Table 4 was lower than the 92.1% shown in Table 3, it was still as high as approximately 79.8%. Reasons for such results are that the quantity of wheelchairs in this group was as large as 10 and the wheelchairs clogged the exit because no one commanded and arranged the sequence of departure.

Table 3 shows the percentage increases in evacuation times under the conditions of Groups 4 and 5 to be 16.1% and 27.9%, respectively, which demonstrates insignificant variation compared with the percentage increases in evacuation times for Groups 4 and 5 shown in Table 4, about 13.1% and 26.8%, respectively. The main reason for such a result is that the width of a subject's crutch is much narrower than the width of the exits (0.75 m and 1.2 m), while the increase in overall evacuation times is due to the slower speed caused by the use of crutches.

Tables 3 and 4 show that, for the Group 6 condition, the percentage increase in evacuation times were as high as 100%. The main reason for such results is the blockage at the exit by 10 wheelchairs as well as the slower speed of people on crutches.

Discussion of evacuation tests

Test of horizontal movement speed

The 1.35 ± 0.25 (m/s) average movement speed of 41 young subjects is slightly different from the 1.25 ± 0.3 (m/s) of average movement speed of adults in [4 and 5]. The main reason for this variation is that the 41 young subjects in this study comprised of 35 men and 6 women, about 85% male.

The five subjects aged between 31 and 45 years and the four subjects aged between 46 and 75 years were male. In terms of health and safety assessment, as only one subject was considered in below average condition and the remaining eight were above average, all these nine subjects were generally in good health. Therefore, it is understandable that the horizontal movement speed of 1.05 ± 0.10 (m/s) of these nine subjects is higher than the 0.80 ± 0.3 (m/s) in [4 and 5].

Of the 40 volunteers mentioned from the 50 subjects, the measured average horizontal movement speeds using wheelchair and crutches were 0.31 ± 0.1 (m/s) and 0.92 ± 0.25 (m/s), respectively. The 0.280 (m/s) of horizontal speed of the wheelchaired elderly in [6] and 0.507 (m/s) to 0.803 (m/s) of the crutch-supported elderly in [7] are significantly lower than the test results of this study. The main reason for such differences is that subjects in this study are healthy people without any movement problems, asked to simulate the role of the elderly with the use of wheelchair and crutches. Therefore, their higher horizontal mobile speed can be understood.

Full-scale evacuation test

According to research results in [3], the evacuation time of customers in unfamiliar building environments should be less than 90 s. Table 2 of this study shows that, under the nine different combinations of conditions, both the two improved strategies demonstrated significant results in reducing the evacuation time. Regardless of the high or low of the Base Case test, both the evacuation times of this study's two improved strategies were less than 60 s, which is much lower than the preceding 90 s. In addition, the above two strategies have not only relatively low engineering costs but also low impact to existing buildings as well as shorter construction periods to make the improvement. Therefore, they would be more acceptable to the hotel owners for upgrading the fire safety level of hotel buildings.

Exit width test

According to [8], the time it takes for people in good health to pass through exits of a certain width is calculated using equation (1):

$$t_{queue} = \frac{P}{N_{eff} \cdot B_{eff}} \tag{1}$$

where P is the number of occupied people (40 subjects in this study); N_{eff} is the effective flowing coefficient, according to [9], it would be 1.5 (p/s/m) in this study; B_{eff} is the effective exit width (m), which in this study was 0.75 m and 1.2 m. After substituting in equation (1), the exit evacuation times are 35.56 s and 22.22 s, respectively, which are very close to the test results of Group 1 in Tables 3 and 4. This shows that the findings of this study should be of reference value. As equation (1) can only be applied to people in good health and there is no credible international formula to calculate the evacuation time for people with mobility problems, it is difficult to directly verify the test results of other Groups in Tables 3 and 4. However, the experimental data presented in this study will be able to provide an important basis for the future development of evacuation time formulas for mobility problems.

Conclusions

The following conclusions can be drawn from the full-scale test results:

1. Factors of age and gender do significantly affect people's ability to evacuate.
2. The extent of familiarity with a building interior does shorten evacuation times.
3. The effect of mutual familiarity, care and following behavior among hotel occupants on evacuation action during the fire accident is obviously important because the consequence is very serious should the evacuation leaders lose their orientation.
4. When fire breaks out, corridors inside the hotel are full of smoke, which inevitably hampers occupants' evacuation. If an additional emergency exit and clearer evacuation route description can be provided, the occupants' evacuation time can be shortened.
5. According to records of interviews with fire survivors, although the alarm device did sound when fire broke out late at night, most hotel occupants who are still

asleep might not be consciously sure of the situation. Therefore, if the hotel can accompany the alarm sound with a verbal announcement to advise evacuation, it will be able to shorten the preparation time for evacuation.

The following conclusions can be drawn from the exit width tests:

1. Appropriate increases to the exit width in small and old hotels would be quite helpful for occupant evacuation, especially wheelchair users.
2. When the width of wheelchair is slightly greater than the exit width, occupants with such mobility problems will need others' assistance to push the wheelchair at an angle through the exit.
3. When the wheelchairs are numerous, even if the exit width is large enough, someone is still needed to come forward to command the sequence of departures to avoid wheelchairs blocking the exit.
4. Although occupants on crutches normally cause a slightly slower movement speed, if wheelchair blockage at the exit is added, the two simultaneous factors may result in serious casualties.

Acknowledgments

During the study, National Fire Bureau, Ministry of the Interior (MOI) and Fubon Insurance Company provided valuable fire data. Their help is truly appreciated.

Funding

The research budget for this study was provided by the Architecture and Building Research Institute, Ministry of the Interior, Taiwan (project number 099301070000G1009).

References

1. Chi JH, Shen TS, Shu YL, et al. *The improvement's strategy on the fire refuge facility using verification of experiment and computer simulation for legal inn buildings*. Report, Architecture and Building Research Institute, Ministry of the Interior, Taiwan, March 2011.
2. Chi JH. Reconstruction of an inn fire scene using the fire dynamics simulator (FDS) program. *J Forensic Sci*, 2012. doi: 10.1111/j.1556-4029.2012.02297.x.
3. Bryner N, Madrzykowski D and Grosshandler W. Reconstructing the station nightclub fire – computer modeling of the fire growth and spread. In: *Interflam'07, 11th International Fire Science and Engineering Conference* (ed CA Franks and S Grayson), London: Interscience Communications Ltd, 3–5 September 2007, Vol. 2, pp.1181–1192.
4. Korhonen T, Hostikka S, Heliövaara S, et al. FDS + Evac: An agent based fire evacuation model. In: *4th international conference on pedestrian and evacuation dynamics* (ed Klingsch W. et al.). Wuppertal, Germany, 27–29 February 2008, pp. 109–120. USA: Springer.
5. Korhonen T, Hostikka S, Heliövaara S, et al. FDS + Evac: Modelling social interactions in fire evacuation. In: *7th interntional conference on performance-based codes and fire*

safety design methods (ed Fire Protection Engineering). Auckland, New Zealand, 16–18 April 2008, pp. 241–250. UK: SFPE.

6. Xu MS. *Tactics for medical institute and senior rest homes' fire safety and horizontal evacuation*. PhD Thesis, The National Taiwan University of Science and Technology, Taiwan, 2004.
7. Huang CH. *The study of senior moving ability applied to evacuation plan verification*. PhD Thesis, The National Taiwan University of Science and Technology, Taiwan, 2007.
8. Chen CC and Chien WH. *Technical manual of performance verification for fire evacuation safety of building*. Report, Architecture and Building Research Institute, Ministry of the Interior, Taiwan, 2008.
9. Chi JH, Wu SH and Shu CM. Using fire dynamics simulator (FDS) to reconstruct a hydroelectric power plant fire accident. *J Forensic Sci* 2011; Vol. 56(6): 1639–1644.