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Author:	Yoshikatsu Yoshida, Takenaka Corporation
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ANALYSIS OF SIMULTANEOUS EVACUATION OF THE WORLD TRADE CENTER

Y. YOSHIDA
Office of Design Management Division, Takenaka Corporation, Tokyo, Japan

Abstract

The studies described herein examined the evacuation during the World Trade Center in New York in an attempt to seek measures for life safety design in future tall buildings. A notable point during the escape from the Towers was heavy congestion at the stairs. This paper presents a dynamic simulation of evacuation using Fluid Model to study the evacuation of the two Towers. The human and physical parameters for these studies were obtained from the Internet and the results of analyses compared to the conventional static method.

Keywords: Tall buildings, World Trade Center, Escape Simulation, Simultaneous Evacuation, Phased Evacuation, Fluid Model

1. Introduction

During the World Trade Center disaster in New York on September 11, 2001, many people managed to escape however, faced many difficulties amongst them, congestion in the stairs resulting from simultaneous evacuation of the whole building. Simultaneous evacuation was also conducted at the bombing of the WTC on February 1993 (Yoshida, 1996).

Currently there is no accurate method of analysing the simultaneous evacuation of multiple floors in buildings September 11. The report on September11 incident in 2001 by FEMA (2002) indicated that the simultaneous evacuation time was estimated based on the flow rate of a door at the bottom of the stairways. The reason in which the bottom door controls the *Total Escape Time* (time for all the occupants to escape from a building) is because that a stairway has only one exit however has many entry points. The above theory is analogous to the flow of water in pipes. Consequently, a fluid model was applied to simulate simultaneous evacuation.

The work presented herein is on the development of a fluid model to analyze simultaneous evacuation in the WTC Towers. Major assumptions were based on a survey; such as number of occupants in each floor at the time of the attack and transit time in descending floor-by-floor, etc. The mechanism of the Fluid Model and discussion of its results will be reported in this paper.

2. A Survey on Human Behavior

2.1 Outline of Survey

Survivors' stories were collected through information obtained from the Internet web sites. The information were acquired from 106 survivors of two groups i.e. 75 survivors in WTC1 and 31 survivors in WTC2. The number of tenants and employees were also surveyed through data from the Internet (Table 1). The number of employees was the actual number of occupants of the tower but they do not represent the number of occupants present during the attack.

	WTC1	WTC2
Number of Tenants	203	105
Number of Employees (On the Register)	13,555	13,648 (Floor unknown 387 in addition.)
Vacant Floors	30 (27%)	36 (33%)

Table 1. Tenants in the WTC Towers (Except for 1st and 2nd floor)

2.2 Situation in the Stairs

According to survivors the situation at the stairs were beyond normal. Fig.1 shows eight major situations at the stairs as reported by survivors. According to them the stairs were congested with people and the movement of the queue often stopping. However, in some other occasions the stairs were not crowded at all. Remarkably, many people behaved gently and orderly manner. At the bombing of the WTC in 1993, similar behavior was reported by people evacuated from the Towers (Yoshida, 1996).

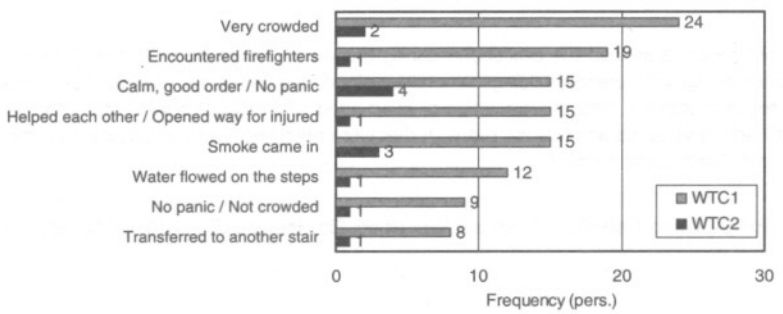


Fig.1 Situation and Evacuees' Behavior in the Stairs

3. Description of Fluid Model

3.1 Flow Diagram of the Fluid Model

Fig.2 illustrates the flow diagram of the Fluid Model. Since three stairs in each Tower were considered as one hence, the door width, stair width and space capacity of stairs were added and the exits at the bottom of the stairs were assumed to be placed at the 1st floor. In addition, the exit of Stair A and C around the sky lobbies were ignored. The model is described using a simulator STELLA™ and calculation made at every one-second.

3.2 Number of Occupants used in Modeling

The number of employees registered on each floor was obtained from the information acquired from the internet web pages. The number of occupants on each floor at the time of the attack was based on the newspaper article "Half Empty" (Cauchon, 2001). With the above assumption, total number of evacuees was 5,326 in WTC1 and 6,812 in WTC2 (Fig.3). This gives a mean value of the number of occupants in each floor as less than 100. In the case that a tenant occupies two or more floors and the distribution of employees were divided equally into the occupied floors.

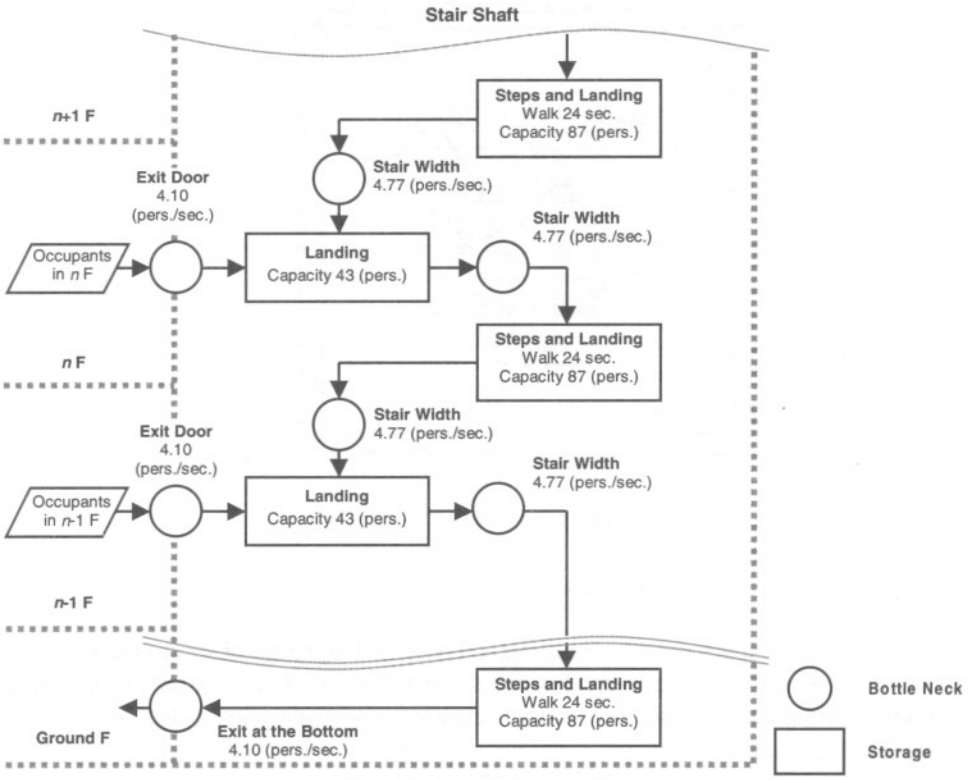


Fig.2 Flow Diagram of the Fluid Model Simulation

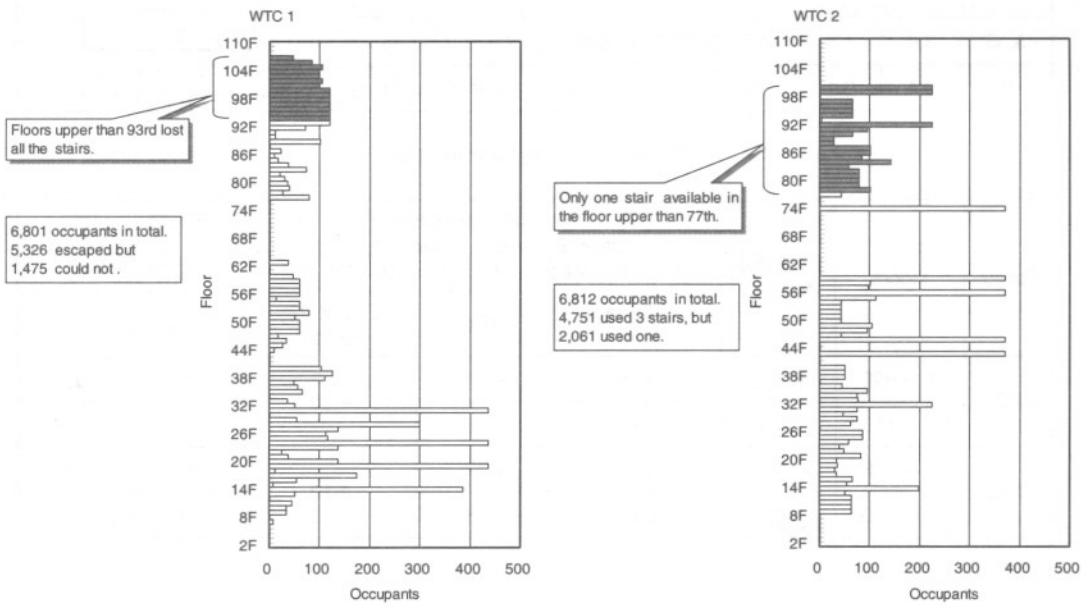
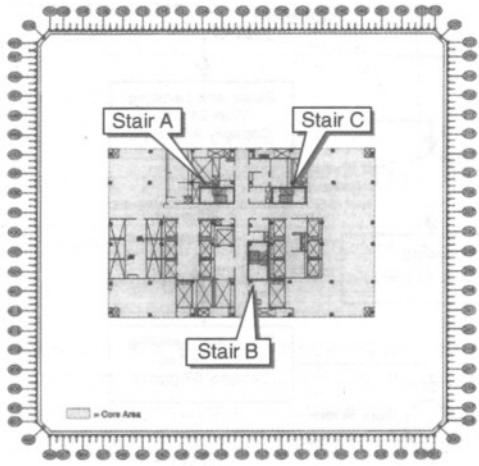


Fig.3 Assumed Number of Occupants in each Floor at the Time of the Attack

3.3 Assumptions of Stairs

3.3.1 Number of Stairs

Each Tower comprised three stairways. The aircraft hit the 94th - 98th floor in WTC1 and destroyed all the stairs placed closely in the core. For WTC2, the aircraft hit the 78th ~-84th floor with one stair (Stair C) remained for evacuation as the aircraft hit eastwards.



(FAMA, 2001)

Fig.4 Layout of Stairs (94th floor in WTC1)

3.3.2 Dimensions and Capacity of the Stairs

The flow rate at exits and space capacity is estimated based on the design of stairs (Table 2 and Table 3). The flow factor is 1.5 persons/meter/second at doors and 1.3 on the steps. The space capacity is defined by 0.3 square meters/person. These are standard assumptions usually used in Japan.

Table 2 Dimension of Stairs

Stair	L_1 (m)	L_2 (m)	W_s (m)	W_e (m)	Door Width (m)	Floor Area (m^2)		
						Part A	Part B	
A, C	3.4	1.5	2.3	1,12	0.91	7.82	3.45	
B	3.4	2.1	3.1	1.42	0.91	10.54	6.51	

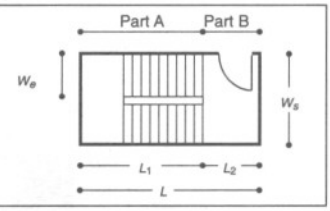


Table 3 Model Parameters

Tower	Floors	Available Stair(s)	Flow Rate (pers./sec.) (For an Exit : W*1.5 pers./m/sec.) (For Steps : W*1.3 pers./m/sec.)			Space Capacity (pers.) ($0.3m^2$/pers.)	
			Exit in each Floor	Step	Exit at the Bottom	Part A	Part B
WTC1	1 ~ 93F	A, B, C	4.10	4.77	4.10	87	43
	94 ~ 110F	None	--	--		--	--
WTC2	1 ~ 77F	A, B, C	4.10	4.77	4.10	87	43
	78 ~ 110F	C	1.37	1.46		26	11

3.4 Transit Time in Descending the Stair

In the Fluid Model, it is necessary to define the parameter for the time of descending stairs from floor-to-floor. Fig.5 illustrates the escape time by people at the bombing of WTC in 1993 (Yoshida, 1996) and data based from survivors of WTC1 and WTC2 on September 11, 2001. Each point indicated in Fig. 5 represents one people. The above data varied widely, even on the same floor, as a result of the situation in the stairs, i.e. either crowded or otherwise. The time of descending stairs from floor-to-floor is not influenced by congestion hence a value of 24 second were used in the Fluid Model.

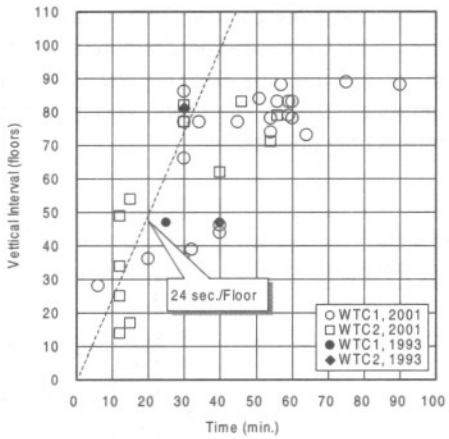


Fig.5 Time Descending for One Floor

4. Result of Fluid Model Simulation

4.1 Inflow and Outflow of the Stair

Fig.6 illustrates the inflow and outflow rate of pedestrians for the stairways. The inflow is the number of people entering the stairways from floors. The end of the inflow indicates the end of pedestrians entering the stair in the building, while the end of outflow indicates the *Total Escape Time*. The outflow starts at 145 seconds in both Towers with the floors lower than 7th floor became vacant. The first evacuee for an occupant on the 7th floor spend 24 x 6 seconds (144 seconds) to arrive at the bottom exit.

The graph for the outflow of the Towers are entirely different. At some point the outflow in WTC1 was interrupted , and whilst in WTC2 the rate appears to change with time. The outflow rate is less than 4.10 persons/second, as given by the Fluid Model. The reason being that the stair was vacant in both Towers, and additionally, the stairs were fewer at the upper floors in WTC2. Therefore, the stair was not filled with evacuees, forming an unsteady flow.

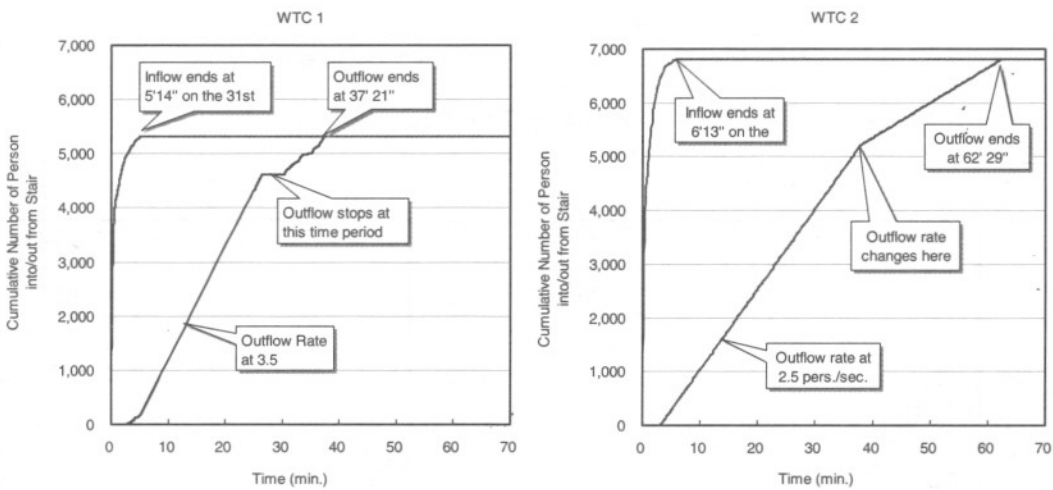


Fig.6 Inflow and Outflow of the Stair

4.2 Floor Escape Time

Fig.7 illustrates the *Floor Escape Time* –a time used for the last evacuee to enter a stair in each floor- with its number of occupants. The stairway of WTC1 has a capacity of 12,090 for the total number of 5,326 evacuees in WTC1. WTC2 has a capacity of 14,170 for the total 6,812 evacuees during the incident. These are given by the Fluid Model. Accordingly, if the number of occupants in each floor is less than 131, they could enter the stair within 32 seconds (130/4.10) without any obstacle.

According to the result of the analyses the *Floor Escape Time* is comparatively short, except for the case of five floors in WTC1 and nine floors in WTC2 exceeding 2 minutes. The time taken for evacuees of these floors to enter the stairways are shown in Fig.8. The *Floor Escape Time* in these floors are greater because evacuees have to wait until there is space to enter the stairs. This in particular is the problem for the case of 77th floor and higher where there is only one stairway.

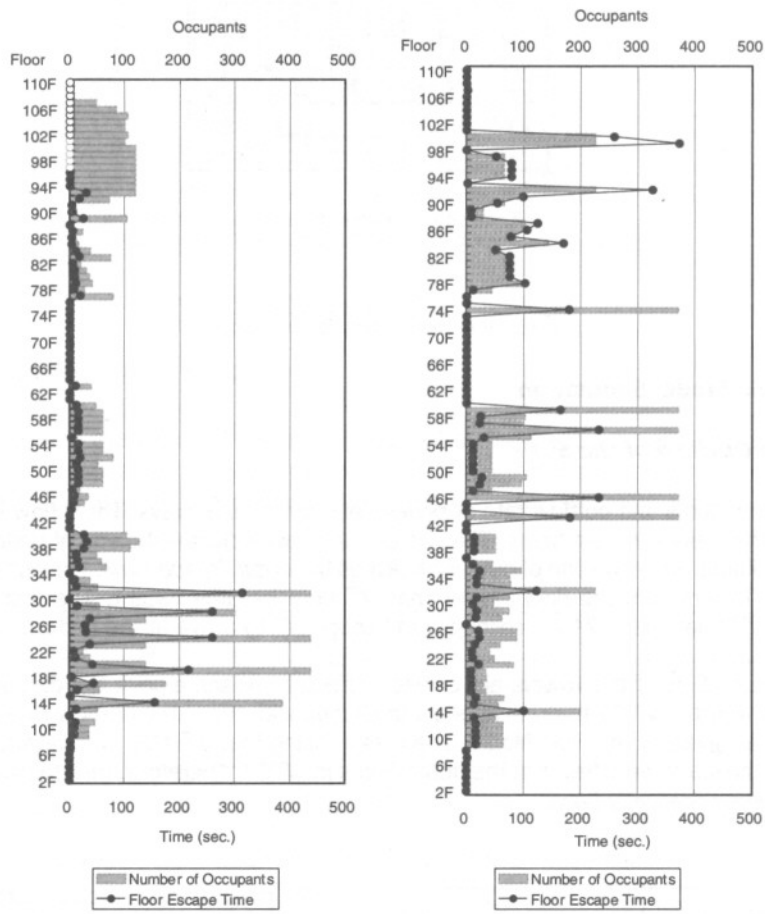


Fig.7 Floor Escape Time in Each Floor

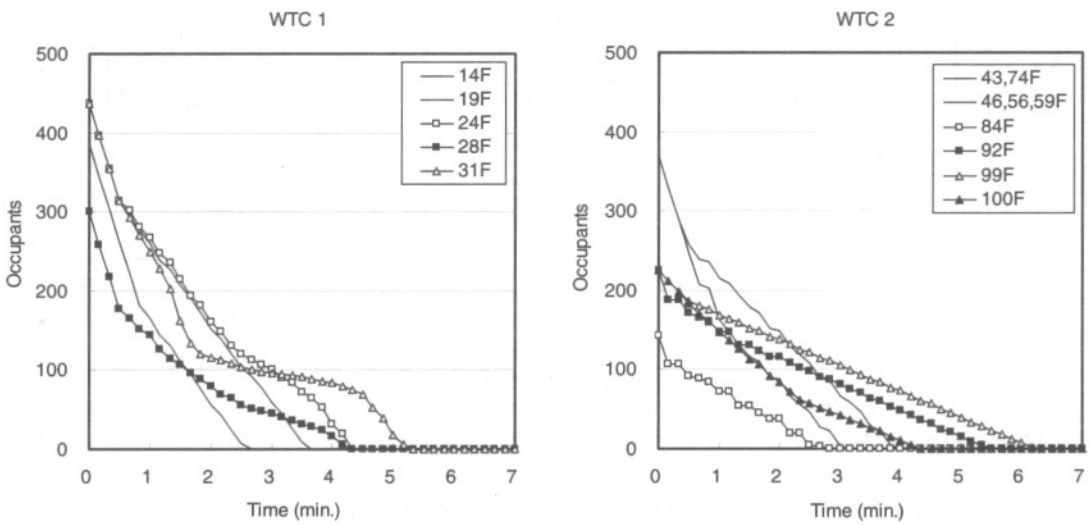


Fig.8 Time taken by Evacuees to enter stairways

4.3 Down Flow in the Stair

Fig.9 and Fig.10 illustrate the variation in the number of occupants in the stairway with time. Congestion is evident for these cases. The maximum value on the x-axis of the graph indicates the capacity of the stair, i.e. 130 persons.

For these analyses it can be seen that for WTC2, the last evacuee was still descending the stairs from around the 80th floor after 30 minutes, whilst in WTC1 the last evacuee was descending the 20th floor at the same time. This clearly shows the effect of missing stairs in the floors above the 77th of WTC2. In WTC1, the number of occupants in the stair was 130 only at the 35th until 15th floor while several other floors were not full. The portion of occupied stairs were at the upper floors due to the congestion.

In both Towers the portion in the upper level merges into a crowded situation, at nearly the same level.

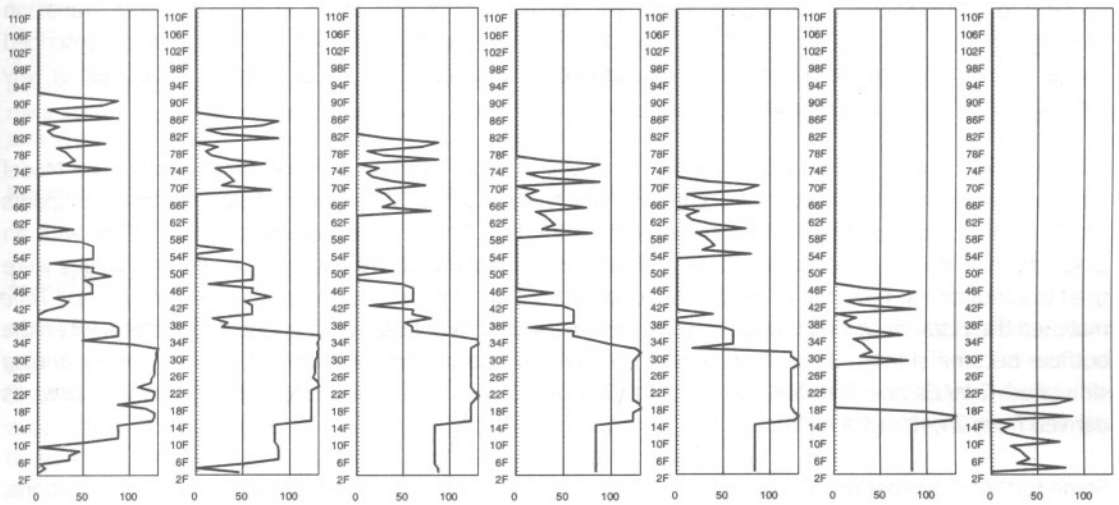


Fig.9 Down Flow in the Stair at WTC1

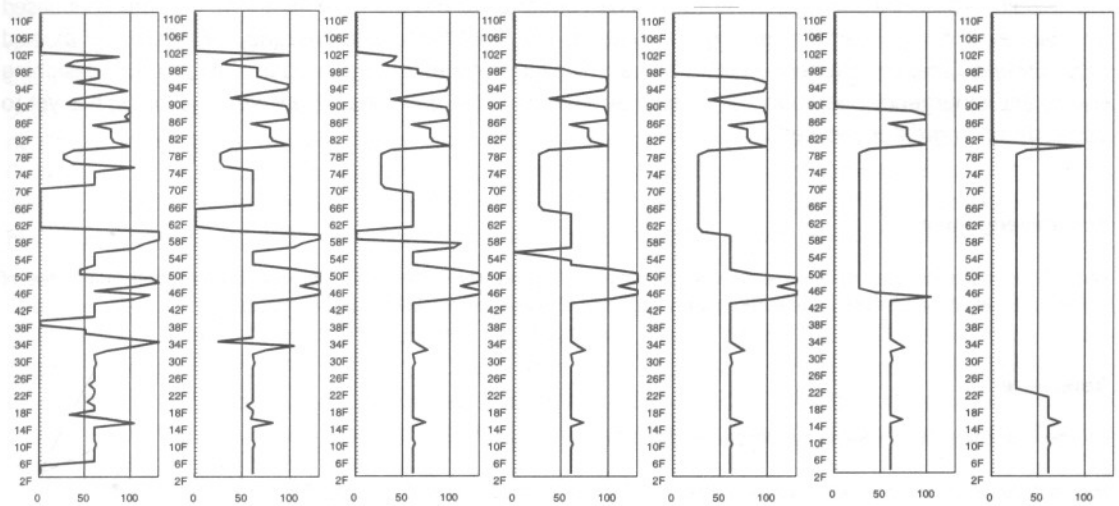


Fig.10 Down Flow in the Stair at WTC2

4.4 Total Escape Time

In the conventional method (static method), the *Total Escape Time* is determined by the time for all occupants to pass the last exit door at the bottom of the stair. *Bottleneck Time*, or the transit time is the time for the last evacuee to arrive at and pass the door (*Transition Time*). Table 4 gives the *Simulated Time* with *Bottleneck Time* and *Transition Time*. In both Towers, the *Simulated Time* exceeds both the

Bottleneck Time and *Transition Time*. This implies that the bottom door does not have a role in determining the *Total Escape Time* for this particular case.

Method	WTC1 (5,326 Occupants)	WTC2 (6,812 Occupants)
Time by Simulation	37′ 21″	62′ 29″
Time by Bottleneck	24′ 04″ (=5,326/4.1+145 sec.)*	30′06″ (=6,812/4.1+145 sec.)*
Time by Transition	30′ 48″ (=77*24 sec.)	43′ 36″ (=109*24 sec.)

*) Above "145" is the time until the first evacuee comes out, i.e. 24(seconds/floor)*6(floors)+1.

Table 4. Comparison of Total Escape Time

It is unpredictable when the *Total Escape Time* equals the *Bottleneck Time*. However to some extent, it appears to depend upon several parameters such as number of occupants, number of floors, transition time, stair width, door width at each floor and door width at the bottom floor. In the simulation described above, the outflow from the bottom door illustrated an unsteady flow, which seemed to be a factor why the *Simulated Time* exceed others.

Additional study was carried out, in order to examine if the outflow ever become steady. The Model remained except for the number of occupants, which was fixed at 300 in every floor. The total occupants for 98 floors corresponding to this assumption is 29,400. There is no occupant on 12th floor with an assumption that it is a mechanical floor and atrium. Under the above assumption, several values were tried to simulate the flow rate of the bottom door. According to the study, the simulated *Total Escape Time* matched the *Bottleneck Time* in cases at 3.4 persons/second and less, and it appears that this is when the outflow became steady. If the flow rate of the bottom door is 3.4 persons/second, the corresponding simulated *Total Escape Time* is 8,792 seconds (2 hours 27 minutes), which equals the *Bottleneck Time*, as derived from 29,400/(3.4+145).

Some further examination on the validity of the Fluid Model is certainly required for future investigations.

Conclusions

The simultaneous evacuation of WTC Towers was undertaken using a Fluid Model with parameters based on a survey of human behavior during the incident. The Fluid Model analyzed the *Total Escape Time* and *Floor Escape Time*, and situation in the stairway. The Fluid Model is considered useful for future designing egress and emergency operation and phased evacuation in tall buildings. However, the model has yet to be validated in greater detailed.

Acknowledgements

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