EVACUATION OF HIGHRISE BUILDINGS AND ITS EVALUATION METHOD

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ABSTRACT

The time characteristics of evacuation of people in highrise buildings under emergency conditions are analyzed in this paper, in an attempt to provide architects a quantified evaluation method for evacuation safety, so as to help them assess the evacuation safety of their design of building plan.

1. INTRODUCTION

Safe evacuation of highrise buildings refers to the safe and rapid evacuation of people endangered or will be endangered by fire and smoke under a fire situation to outside of the building or a safe place inside the building within permitted time through the evacuation route constituted of corridors, anterooms and staircases [2].

In designing the evacuation safety facilities, the evacuation time should be considered first. Practically, as well as theoretically, major factors affecting the evacuation time include density of people, geometry of staircase, conditions of evacuation routes, design of evacuation path, concentration and toxicity of smoke during the fire, and fire resistance of interior decoration materials [7]. Generally, the higher the density of people, the slower will be the evacuation rate, and the longer the evacuation time if queuing is the dominant factor. When the density reaches 0.25 m^2/person, i.e., 4 persons in 1 m^2, the walking speed of a person is almost zero [1], the flow velocity is also close to zero [1]. If the evacuation route is not concise or well-communicated, having blind angles or obstacles, the evacuation rate will be affected. A standard quantified evaluation method for evacuation will be helpful to architects in designing the evacuation plan layout.

2. EVACUATION CALCULATION MODEL

A simplified evacuation model of a highrise building is shown in Fig. 1. The model follows the assumption that all people in the building would evacuate using the escape route as designed by the architects to the safe place.

As shown in Fig. 1, it is assumed that there are n exits in the compartment. When there is a fire on a certain floor, people on that particular floor would evacuate through these n exits to the main egress leading to outside of the fire compartment. Suppose the width of the i^{th} exit is B_i, the flow coefficient is $N_i(t)$ (persons/s.m), then the number of people concentrated at the main egress is [6]:

$$y = \sum_{i=1}^{n} \int_{0}^{t_e} N_i(t) B_i \, dt \qquad (1)$$

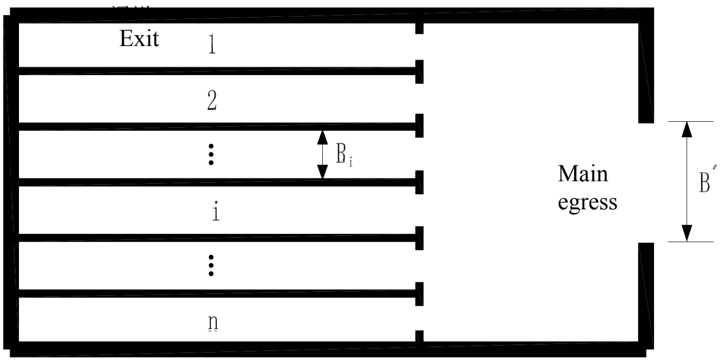

Fig. 1: Simplified model of a highrise building plan

where t_e is the time (s) required for all the people on that particular floor to evacuate to outside the compartment through the main egress.

Throughout the whole evacuation process at the main egress, the evacuation time (without including pre-movement time effect) can be divided into two periods:

$0 \sim t_{min}$: free flow time, i.e. the number of people concentrated at the main egress is less than or equal to the maximum runoff of the main egress

$t_{min} \sim t_e$: blockade flow time, i.e. the number of people concentrated at the main egress is greater than the maximum runoff of the main egress

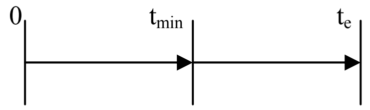

Fig. 2: Time period of evacuation process

Assume the width of the main egress is B(m), the maximum flow coefficient is N(persons/s.m), then the number of people evacuated from the main egress to outside the compartment is:

$$y' = \sum_{i=1}^{n} \int_{0}^{t_{min}} N_i(t) B_i dt + (t_e - t_{min}) BN \qquad (2)$$

where t_{min} is the time(s) from the beginning of evacuation to blockade flow at the main egress, t_e is the time from the beginning to termination of evacuation when all occupants have been evacuated.

Obviously, the first term in equation (2) denotes the number of people evacuated from the main egress to outside the compartment in the free flow time ($0 \sim t_{min}$); and the second term denotes that in the blockade flow time ($t_{min} \sim t_e$). If all the people on the floor of fire origin have been safely evacuated, where p = y' (p is the total persons in the compartment), then the total evacuation time of that compartment can be obtained from equation (2):

$$t_e = \frac{1}{BN}\left(P - \sum_{i=1}^{n} \int_{0}^{t_{min}} N_i(t) B_i dt\right) + t_{min}$$

During the process of blockade flow, the time characteristic equation for detaining at the main egress and waiting to be evacuated is:

$$\Delta y = y - y'$$

i.e.

$$\Delta y = \sum_{i=1}^{n} \int_{0}^{t_e} N_i(t) B_i dt - \left[\sum_{i=1}^{n} \int_{0}^{t_{min}} N_i(t) B_i dt + (t_e - t_{min}) BN\right]$$

$$= \sum_{i=1}^{n} \int_{t_{min}}^{t_e} N_i(t) B_i dt - (t_e - t_{min}) BN$$

3. DETERMINATION OF PEOPLE CONCENTRATION AND FLOW-OUT CURVES

The plan of the 12th floor of a technical education centre as shown in Fig. 3 is taken for calculation as an example.

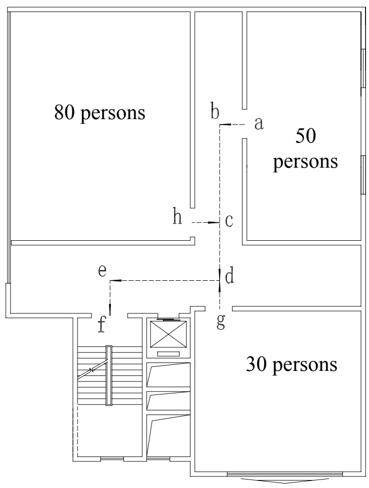

Fig. 3: Evacuation plan of the 12th floor

In Fig. 3, the width of each opening is: $W_a = W_h = W_g = 1.5$ m, $W_f = 2.0$ m; the distance between every two points of the evacuation route is: $D_{ab} = D_{hc} = 1.3$ m, $D_{bc} = 16.7$ m, $D_{cd} = 2.7$ m, $D_{gd} = D_{ef} = 1.5$ m, $D_{de} = 6.3$ m. Taking the average flow velocity as 1.0 ms^{-1} [2], the flow coefficient of each exit N is 1.5 persons/s.m [3].

(1) The average time required for all the people in rooms a, h and g to move to their respective exit is [7]:

$$t_a = \frac{P_a}{N_a W_a} = \frac{50}{1.5 \times 1.5} = 22.22 \text{ s};$$

$$t_h = \frac{P_h}{N_h W_h} = \frac{80}{1.5 \times 1.5} = 35.56 \text{ s};$$

$$t_g = \frac{P_g}{N_g W_g} = \frac{30}{1.5 \times 1.5} = 13.33 \text{ s};$$

(2) From the beginning of evacuation, the time required for all the people to evacuate from their respective exit to the egress F via the corridor is:

$$\left.\begin{aligned} t_{af} &= \frac{D_{ab} + D_{bc} + D_{cd} + D_{de} + D_{ef}}{\bar{v}} = 28.5 \text{ s} \\ t_{hf} &= \frac{D_{hc} + D_{cd} + D_{de} + D_{ef}}{\bar{v}} = 11.8 \text{ s} \\ t_{gf} &= \frac{D_{gd} + D_{de} + D_{ef}}{\bar{v}} = 9.3 \text{ s} \end{aligned}\right\} \quad (3)$$

From the above calculations, it can be concluded that since the time the fire is discovered (or informed by fire broadcast),

- at $t \le t_{af} = 28.5$ s, $t \le t_{hf} = 11.8$ s, $t \le t_{gf} = 9.3$ s, no one in the fire compartment can reach the egress f;
- when $t \ge t_a + t_{af} = 50.72$ s, $t \ge t_h + t_{hf} = 47.36$ s, $t \ge t_g + t_{gf} = 22.63$ s, all people in the fire compartment can reach the egress f.

From equation (3), $\min(t_{af}, t_{hf}, t_{gf}) = 9.3$ s.

Suppose the time from the beginning of evacuation to termination of free flow is t_{min}, then, balance equation for people flow will be:

$$N_aW_a(t_{min} - 28.5) + N_hW_h (t_{min} - 11.8) + N_gW_g (t_{min} - 9.3) = N_fW_f (t_{min} - 9.3) \quad (4)$$

Substituting $N_aW_a = N_hW_h = N_gW_g = 2.25$, $N_fW_f = 3$ into equation (4) gives $t_{min} = 21.9$ s.

Therefore, the correlation between the number of people evacuated P and evacuation time t at each evacuation stage can be obtained:

(a) Time equation for free flow and concentration of people in the compartment:

$$P = 2.25(t - 11.8) + 2.25(t - 9.3) \quad (5)$$

$$\min(28.5, 11.8, 9.3) < t \le t_{min} = 21.9$$

(b) Time equation for blockade flow and concentration of people in the compartment:

$$P = 2.25(t - 28.5) + 2.25(t - 11.8) + 2.25(t - 9.3) \quad (6)$$

$$t_{min} = 21.9 < t \le \max(50.72, 47.36, 22.63)$$

(3) Time characteristics of flow-out at the main egress:

a) Idle waiting for flow-out time

Within this period, there is no one at the main egress f. This can be expressed by the following equation:

$$P_e = 0 \quad 0 < t < \min(28.5, 11.8, 9.3) = 9.3$$

b) Time equation for free flow-out:

$$P_e = 2.25(t - 11.8) + 2.25(t - 9.3)$$

$$\min(28.5,11.8,9.3) < t < t_{min} = 21.9$$

c) Time equation for blockade flow-out:

$$P_e = N_fB_f(t - t_{min}) = 3(t - 21.9) \quad (7)$$

$$t_{min} = 21.9 < t < \max(50.72, 47.36, 22.63)$$

d) Blockade waiting

Obviously, when t = max(50.72, 47.36, 22.63), because of the limit of the runoff of the egress f, some people might still be waiting there to be evacuated. Therefore, the time equation for blockade waiting to flow-out with total population 160 should be:

$$\Delta P = 160 - 3(t_e - 21.9) \quad (8)$$

$$\max(50.72, 47.36, 22.63) = 50.72 < t < t_e$$

where t_e is the evacuation termination time, where $\Delta P = 0$, giving $t_e = 75.23$ s. i.e. After 75.23 s, all people in the compartment are evacuated through the egress f.

From the above calculations, the curves of the number of persons and flow-out time can be obtained as shown in Fig. 4. In the figure, the dotted line represents the relation curve between the maximum runoff of egress f and time, while the solid line represents the curve of number of people concentrated in the fire compartment.

It can be seen clearly that:

- When the solid line is below the dotted line, the number of people concentrated is smaller than the maximum runoff of the egress. Under these circumstances, the occupants movement emerges as free flow, there would not be any chaotic situation at the egress. The evacuation will be in good order. This is the target which architects are pursuing [5].

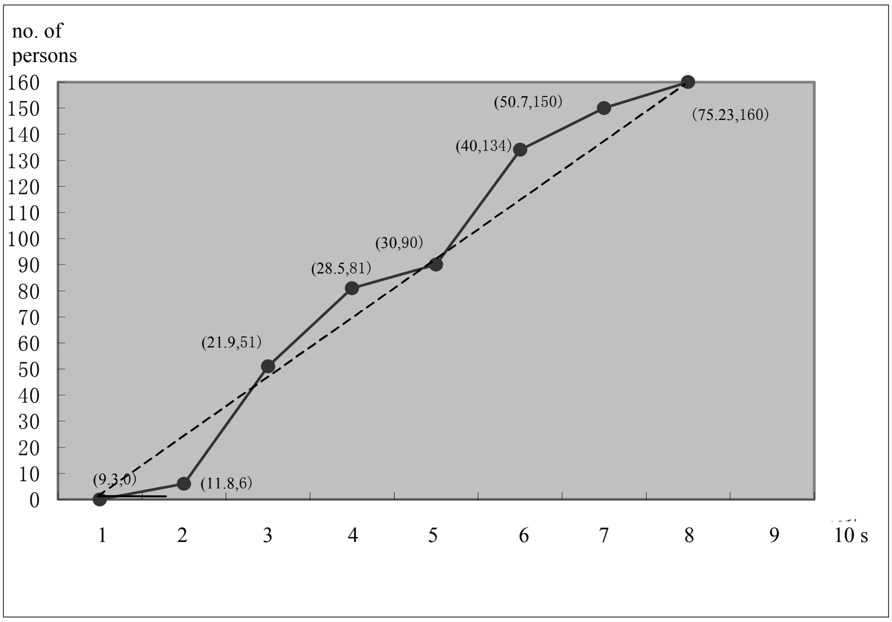

Fig. 4: Curve of evacuation time and people concentration

- When the solid line is above the dotted line, the number of people concentrated is larger than the maximum runoff of the egress, the occupants movement emerges as blockade flow, there might be panics and chaos [2], even casualties would be resulted. This situation should be prevented in designing the evacuation plan.

To sum up, in verifying the design layout, architects should make the curves of people concentration close to or below the maximum runoff of the egress, to ensure safe evacuation of people in case of fire. Otherwise, according to the above analysis and calculation, the following measures should be taken: increase the width of the main egress B', i.e., increase the runoff of the egress B'N'; increase the number of exits; and reduce the distance between two exits. These are clearly specified in fire codes for highrise buildings in many countries.

4. CONCLUSION

In practical engineering design, if the geometry of the room, corridor and exit, and the total number of people in the fire compartment are known, then the curves of people concentration and evacuation time can be drawn using the method described in this paper. Architects can apply this method to evaluate their design and similarly, the fire services management can assess the safety of existing buildings and those being built.

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