BUILD SIMUL (2012) 5: 383 – 392
DOI 10.1007/s12273-012-0082-7

Characterization of movement on vertical circulations

Nuno Pinto[1], António Leça Coelho[2](✉), Miguel Chichorro Gonçalves[3], Elisabete Cordeiro[3]

1. Faculty of Sciences and Technology, University of Coimbra, Portugal
2. National Laboratory of Civil Engineering, 1700-066 Lisboa, Portugal
3. Faculty of Engineering, University of Porto, Portugal

Research Article

Abstract

A few years ago, it began in Portugal the development of buildings fire risk analysis model, named MARIE, composed by eleven partial models according to the factors taking influence on that risk, having the model for the building egress (MEE), constituted by the building description model (MDE) and the occupants' movement model (MMO), already been completed. During MMO development, and due to the absence of national data allowing the characterization and quantification of people's movement kinematic aspects on adverse environments boosting building evacuation, as stated on fire emergency situations, it was adopted Predtechenskii & Milinskii (P & M) mathematical relations. MEE is, nowadays, being improved, regarding both MDE and MMO. These improvements affecting MMO are related, in one hand, with the occupants' behaviour, and, in the other hand, with the possibility of application to staircases of the mathematical relations of velocity and flow with density deduced by Predtechenskii & Milinskii. Therefore, several evacuation drills performed at the University of Coimbra Campus were filmed and analysed, where 321 people were involved, in order to obtain the expressions describing the movement in stairs, and later comparing them with P & M's expressions.

Keywords

evacuation,
drill,
velocity,
flow,
density

Article History

Received: 19 January 2011
Revised: 8 March 2012
Accepted: 16 March 2012

1 Introduction

Since a few decades, building evacuation on fire emergencies has been the aim of several studies that were firstly focused on the characterization of people's movement, having later progressed to the development of simulation models aiming the evaluation of the evacuation time.

A few years ago, it began in Portugal the development of a model of the fire risk analysis named MARIE, whose structure is schematically represented in Fig. 1, constituted by eleven partial models aiming the simulation of the main factors' impact influencing that fire risk (Coelho 1997).

The completion of these partial models composing MARIE is far from being a reality, but a few studies have already been made on its attempt, for one of them is now concluded, some are under development and a few others await its beginning.

The only partial model that has been developed is related to the building egress (MEE), constituted by two different models, one related to the building description (MDE) and another related to the occupants' movement (MMO).

During MMO development, and due to the absence of national data allowing the characterization and quantification of people's movement kinematic aspects on adverse environments boosting building evacuation, as stated on fire emergency situations, it was adopted Predtechenskii & Milinskii (P & M) mathematical relations (Predtechenskii and Milinskii 1978).

A few years after its conclusion, and while at the same time new studies are being developed aiming MARIE completion, MEE is, nowadays, being improved, regarding both MDE and MMO.

About MMO, it's been noticing some improvements starting with the occupants' behaviour till the evaluation of the kinematic aspects related with its movement; one part of that study related with the movement on staircases is

Architecture and Human Behavior

E-mail: alcoelho@lnec.pt

List of symbols

D	occupation density represented by persons per unit area
F	total flow of a circulation element
F_e	specific flow of a circulation element
N_p	number of people
V	displacement velocity
V_m	mean velocity
V_{mc}	modified mean velocity
V_{max}	maximum velocity
V_{min}	minimum velocity
EH	building, e.g., Hospital of the University of Coimbra (Present Faculty of Pharmacy of UC)
FE	faculty of Economy of the University of Coimbra
FP	faculty of Psychology and Sciences of the University of Coimbra
MARIE	model of the fire risk analysis in buildings
MEE	model of building egress
MDE	model of building description
MMO	model of occupants' movement
P & M	predtechenskii & Milinskii
UC	University of Coimbra

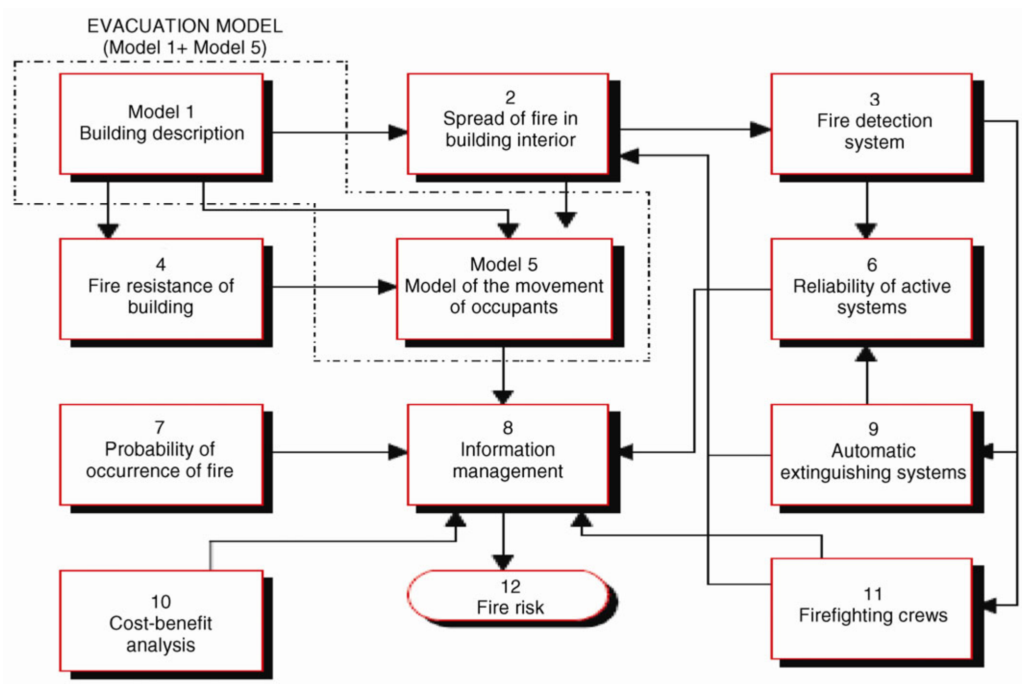

Fig. 1 Suggested diagram for fire risk analysis in buildings

discussed in this article.

Fruin (1971) was one of the pioneers to study the occupants' movement in stairs, having concluded that the speed of the occupants in stairs differ according age, sex and the direction of the movement (upwards or downwards).

Templer (1974) came to the conclusion that movement in stairs consumes ten to fifteen times more energy than walking an equivalent distance in a horizontal path and that the absence of a handrail, as well as an insufficient illumination, increases the probability of happening an accident.

Several authors, such as Watanabe (1973) and Nelson and Maclennan (1996), found mathematical expressions relating velocity and flow with density.

Predtechenskii and Milinskii (1978) developed a study during several decades that would allow them to define mathematical relations between density and velocity and between velocity and flow for three different types of movement.

Pauls (1984), for instance, after analysing several evacuation exercises, found expressions for the evacuation time in stairs, according to the number of people using them.

Another author, Proulx (2002) concluded that movement in stairs is also affected by the space occupied for each individual, carrying, or not, any child or personal object, and by their own mobility conditions.

Other authors also came to several conclusions regarding the movement in stairs, highlighting:

- 19% of the occupants move with a velocity lower than 0.4 m/s and only 2% of them move at a rate above 1 m/s (Peacock et al. 2009, 2010);
- the mean velocity in stairs (in general, the evacuation process implies this downward movement) is 30% lower when compared with the mean velocity in a horizontal path (Choi et al. 2009);
- the global mean velocity in stairs without counter flow is slightly superior than the one with counter flow (Kratchman 2007);
- the existence of a counter flow increases occupation density and 86.5% of the occupants find other people when entering the stairs, causing a bottleneck effect (Kratchman 2007);
- 91.2% of the occupants acknowledge the decrease of speed when moving in stairs if other people are involved (Choi et al. 2009).

Other authors, such as Kholshevniikov et al. (2008) have been trying to evaluate the influence of occupants' emotional state in displacement velocity. About this subject, it is considered that movement in stairs is majorly influenced by its geometric properties (e.g., number of steps, inclination of the stair, depth and height of the steps, as well as the existence and localization of the handrail), by the density and the obstacles that occupants may find on their way down (e.g., firemen going up to attack a fire, people with mobility limitations, occupants in each floor trying to enter the stair, among others) and not by people's emotional aspects. In fact, it is assumed that movement in stairs is, in general, highly conditioned, for the influence of people's behaviour and their emotional state is not felt. The occupants already using the stairs have made the decision to leave the building and only in the presence of highly severe environmental conditions (smoke and toxic gases), which are not common to happen, that decision might be changed, so when entering the stairs the occupants are willing to feel some emotional tranquillity.

About the obstacles that may arise during the occupants' movement in stairs, as previously mentioned, there are some studies regarding the impact of the occupants during the movement in stairs that, in each floor, want to enter the stair. Defining rate of contribution as the relation between the number of occupants in a stair, at a specific landing of a floor, and the number of people entering the stair on that floor, Pauls (2004), states that it usually is 2:1, meaning, in three occupants arriving at the landing of a stair in a floor level, two came from the superior section of the stair and one came from that floor; however, he also states that, for certain conditions, the flow on the stair may stop due to the flow on the floor. Takeichi et al. (2006) came to the conclusion that the junction of both flows at the stair landing is easier when the density is lower. Moreover, when the density increases at the stairs, the flow from the floor to the stairs decreases. The flow from the floor to the stairs is higher when the door giving access to the stairs is located so that both flows converge at the landing and with the same direction. If both flows converge at the landing but in different directions, the flow on the stair decreases approximately 15% – 20%. They also concluded that the flow entering the stair decreases in 30% when the door is closed.

Aiming the characterization of the kinematic aspects of movement (Pinto 2008), a few results established during the analysis of several evacuation drills in different buildings of UC are exposed in this article.

2 Characteristics of the population and the buildings in study

All the evacuation drills analysed for this study were performed in several buildings of the University of Coimbra, and the occupants partaking it are, essentially, people who develop their activity within an academic context. So, the universe of analysis is, majorly, constituted by college students aged 18 to 25, professors and other employees.

On these evacuation drills, it was studied the movement of 321 occupants, not detecting the presence of people with limited mobility capacities.

The drills were performed according to the evacuation plans provided in each building, and can be distinguished in two different types:

- Type A drills—Occupants are guided by security team members;
- Type B drills—Occupants are not guided by security team members.

The type of evacuation drills performed in each building and the number of occupants per stair involved in each drill is stated in Table 1.

Table 1 Type of evacuation drills per building

Building	Type A	Type B	No. of occupants using the stair during the drill
FE	Yes	No	67
FP	Yes	No	191
EH	No	Yes	63

As stated in Table 2, the drills were performed in three different buildings, hence with different characteristics.

Each building has only one stair whose major characteristics are stated in Table 3. The length of the stair was measure by its axis and the area was measured in plan.

Table 2 General characteristics of the buildings

Building	Number of floors	Exits to exterior	Type of occupation	Number of people	Evacuation time (s)
FE	4	8	Educational	736	669
FP	3	1	Educational	396	439
EH	2	3	Educational	145	401

Table 3 Characteristics of the stairs

Characteristics		Buildings		
		FE	FP	EH
Number of floors		4	3	2
Width (m)		1.07	1.56	1.20
Handrail		Both sides	No	Both sides
Total length (m)		34.89	24.60	12.63
Total area (m^2)		41.78	41.64	20.16
Landing between floors		Yes	Yes	Yes
Steps	Number of steps	64	36	20
	Width (m)	0.30	0.30	0.30
	Height (m)	0.18	0.14	0.185

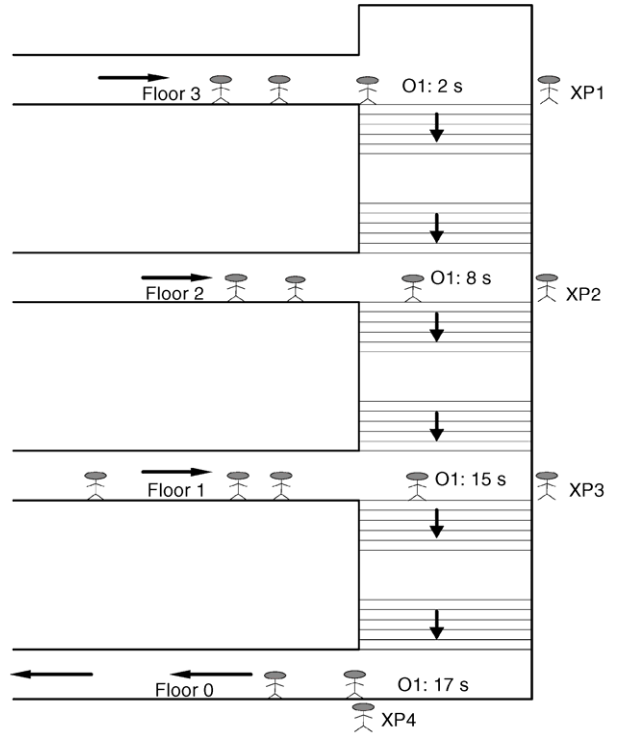

Fig. 2 Position scheme of the shooting equipment (XP) for data collection at each floor of FE building and the record of passage times of occupant O1

3 Methodology and used means to obtain data

3.1 General aspects

To shoot the evacuation drills, it was necessary to call upon various means, both material and human, as listed in Table 4, according to each drill.

A shooting equipment was installed in each landing of the staircase, as a scheme representation of its position (XP1, XP2, XP3 and XP4) can be observed in Fig. 2, for FE building. It can also be observed the evolution of occupant O1 movement, since its entrance, at Floor 3, till its exit at Floor 0.

This procedure was repeated for all occupants, thus keeping a record of each occupant's entries and exits from the stairs; as a result, it was possible to acknowledge the evolution of the movement at each instant.

Table 4 Type of evacuation and the used resources to shoot the evacuation drills

Building	Type of evacuation	Number of people involved			Participation of civil protection team
		Internal security team	Promotion and evaluation	Camera operators	
FE	With team	15	3	9	Yes
FP	With team	14	3	7	Yes
EH	Without team	—	2	6	Yes

3.2 Organising data from footage

With the footage collected from the evacuation drills, it was possible to establish, for each drill, the different types of movement in stairs, in order to deduce the influence of density in velocity and flow.

To achieve that, and after viewing all the footage, it was organised a table with the identification of all observed users (occupant 1: O1, occupant 2: O2, etc.), for each section of the stair, and with its passage time at the shooting spots.

Taking the stair of FE building as an example, the results attained for that building are shown in Table 5.

Analysing Table 5, it is possible to state, for example, that occupant O1 reaches shooting spot XP1 (landing of the stair at Floor 3) after 2 s, XP2 after 8 s, XP3 after 15 s,

Table 5 Passage time at the floors for the stair of FE building

Occupant	Timing (s)			
	Floor 3	Floor 2	Floor 1	Floor 0
O1	2	8	15	17
O2	3	7	14	18
O3	5	11	17	20
O4		3	10	17
O5		4	9	21
O6			2	9

and exits the stair after 17 s, knowing that the time counting starts when the automatic fire detection and alarm system is activated.

Regarding similar tables to Table 5, the following step was dedicated to the development of a Visual Basic Applications macro, aiming the automatic creation of other tables, allowing to identify, over time, the number of occupants found at each section of the stair, as stated in Table 6, for FE building.

Analysing Table 6, it is possible to state that, for example, after 10 s the occupants' distribution at different sections of the Stair is as follows:

– 1 occupant at Section 3-2;
– 2 occupants at Section 2-1;
– 2 occupants at Section 1-0.

Also by analysing Table 6, it can be concluded that after 17 s the number of occupants decreases at Section 1-0, meaning that there is one person at that instant who is exiting the stair, which agrees with what was stated in Table 5, for the first occupant entering the stair (O1) arrives at Floor 0 after 17 s.

However, both previous tables do not include enough information required to evaluate when there is a variation on the number of occupants at each section of the stair between landings, for a new macro was developed, using the first one, allowing the construction of Table 7.

Table 6 Number of occupants over time, by sections of the stair in FE building

Timing (s)	Number of occupants		
	Section 3-2	Section 2-1	Section 1-0
2	1		1
3	2	1	1
4	2	2	1
5	3	2	1
6	3	2	1
7	2	3	1
8	1	4	1
9	1	3	1
10	1	2	2
11		3	2
12		3	2
13		3	2
14		2	3
15		1	4
16		1	4
17			3
18			2
19			2
20			1

Table 7 Identification of courses and its timing for each occupant of the stair in FE building

Timing (s)	Occupants								
	Section 3-2			Section 2-1			Section 1-0		
	Number	In	Out	Number	In	Out	Number	In	Out
0									
1									
2	1	O1					1	O6	
3	2	O2		1	O4		1		
4	2			2	O5		1		
5	3	O3		2			1		
6	3			2			1		
7	2		O2	3	O2		1		
8	1		O1	4	O1		1		
9	1			3		O5	1	O5	O6
10	1			2		O4	2	O4	
11			O3	3	O3		2		
12				3			2		
13				3			2		
14				2		O2	3	O2	
15				1		O1	4	O1	
16				1			4		
17						O3	3	O3	O1; O4
18							2		O2
19							2		
20							1		O3
21									O5

In Table 7, for each instant, there is a set of information allowing the characterization of the movement according to each occupant, highlighting:

– number of users per section at each instant of time;
– identification of the occupant at each instant;
– passage times on floor landings for different users;
– total time taken by each occupant to exit the stair.

Therefore, observing Table 7, it is possible to conclude that, for example, at instant $t = 10$ s Section 3-2 only has occupant O3. At that same instant, there are 2 occupants at Section 2-1 (occupants O1 and O2) and occupant O4 left the stair. For each building and for each stair it was established a table similar to Table 7, containing all necessary information to analyse the occupants' movement in stairs.

4 Analysing the different types of movement

4.1 General aspects

The analysis made for this particular study led to the evaluation of several mathematical relations describing occupants' movement and its comparison with P & M relations (Predtechenskii and Milinskii 1978).

Although the main intention was to study the movement in group, this analysis was also focused on the following types of occupants' movement:
– free movement;
– movement in group;
– movement behind the group.

To identify these types of movement, it was established a criteria explained in the following sections.

4.2 Free movement

The definition of free movement describes a condition of low density, where the movement of any occupant is not disturbed by the nearness of other occupants.

To define this movement, it was adopted the criterion of not having more than 5 people in a section between 2 successive floors, when a new occupant enters that section.

Observing the tables keeping record on the number of occupants at each instant and section of the stair, and regarding the defined criterion, it was possible to identify those who have this type of movement and, later, the time they take to complete that course (t_p).

Knowing t_p, the velocity of each occupant was calculated. Therefore, considering these several values for velocity (V), its mean value (V_m), was calculated for each building and for each stair. Table 8 shows, for each stair, the calculated values for V_m, as well as the values for maximum velocity ($V_{máx}$) and minimum velocity (V_{min}) observed in this study.

The value for modified mean velocity, V_{mc}, accurately describes the occupants' velocity in each situation, for it excludes circumstances of atypical behaviour in which movement is excessively slow or fast. In this case, all velocity values outside the interval $[V_m - \sigma; V_m + \sigma]$, where σ is the standard deviation for velocity, were not taken into account. The standard deviation is a homogeneous value and is the same for all density values.

When comparing the values for modified mean velocity, stated in Table 8, for each building, there's a significant difference between EH building and the other two, for it is notably inferior. This can be partially explained by the total length of the course and the number of steps, which are also inferior when compared to the other two buildings. In fact, EH building has the smallest course length (12.63 m) and the lowest number of steps (20), while FP building has 24.60 m and 36 steps and FE building has 34.89 m and 64 steps. This difference may suggest that occupants need to take some time to adjust themselves to a movement that is distinct from the horizontal, and only then they gain normal velocity, all the more noticeable the lower is the height of the building.

4.3 Movement in group

Group formations are common during evacuation, where in this case the mutual influence of nearby occupants is significant. This is an essential type of movement deserving an accurate analysis, for the following criteria was adopted to identify all groups formed during the performed evacuation drills:
– when there are 10 occupants between consecutive landings of a stair, or:
– when the number of occupants between consecutive landings of a stair is less than 10, after an equal or superior state, rapidly reaches it (maximum of 3 seconds).

The method of analysis was similar to the one used for occupants with free movement, calculating the mean velocity V_m for all occupants, then evaluating the interval $[V_m - \sigma; V_m + \sigma]$ and later calculating V_{mc}, as Table 9 summarizes its values.

Analysing V_{mc} velocity, and regarding the conclusions taken for free movement, it is possible to state that:
– The value of V_{mc} for downward movement decreases as the number of steps and the total length of the course increases.

Another analysis was focused on the relation between velocity and density and between specific flow and density.

The number of occupants (N_p) was assumed to be the mean of occupants at a section when the occupant being studied enters and leaves that section, meaning:

$$N_p = (\text{No. of people entering the section of the stair} + \text{No. of people leaving the section of the stair})/2 \quad (1)$$

Density is calculated using the expression:

$$D = \frac{N_p}{A} \quad (2)$$

Table 8 Mean velocity for free movement in stairs

Building	Direction of movement	V_m (m/s)	$V_{máx}$ (m/s)	V_{min} (m/s)	V_{mc} (m/s)
FE	Downward	0.949	1.075	0.591	0.983
FP	Downward	0.841	1.025	0.559	0.851
EH	Downward	0.649	1.053	0.361	0.616

Table 9 Mean velocity for movement in group in stairs

Building	Direction of movement	V_m (m/s)	$V_{máx}$ (m/s)	V_{min} (m/s)	V_{mc} (m/s)
FE	Downward	0.785	1.248	0.510	0.773
FP	Downward	0.728	1.118	0.559	0.708
EH	Downward	0.454	0.789	0.371	0.424

where:

N_p: mean number of people at the section;

D: density (person/m^2);

A: area measured in plan of the section of the stair between two floors (m^2).

As for specific flow, it is given by the expression:

$$F_e = V \cdot D \tag{3}$$

where:

F_e: specific flow (person/(m·s));

D: density (person/m^2);

V: velocity (m/s).

After the evacuation drills, the analysis of these calculated values was made regarding each building and the three buildings as a set. It was found the expressions relating velocity and flow with density, as well as its correlations. Besides, it was established a comparison with P & M expressions regarding to normal conditions of the movement (P & M–N) and to emergency conditions (P & M–E).

Equations (4) and (5), regarding the calculated approximations for FE building, are represented in Fig. 3(a) and (b), as well as P & M expressions concerning emergency movement; it can be stated that the properties of the movement in the drills fit between these two types of movement.

$$V = -0.320 \cdot D + 1.031 \quad R^2 = 0.290 \tag{4}$$

$$F_e = -0.4669 \cdot D + 0.2437 \quad R^2 = 0.5272 \tag{5}$$

The highest values for density and the lowest coefficient of correlation were registered during the study of this building's stair.

As for FP building, Eqs. (6) and (7) were established, as represented in Fig. 4 (a) and (b) along with P & M expressions. Also for this building, the movement in the drills fits between emergency movement and normal movement.

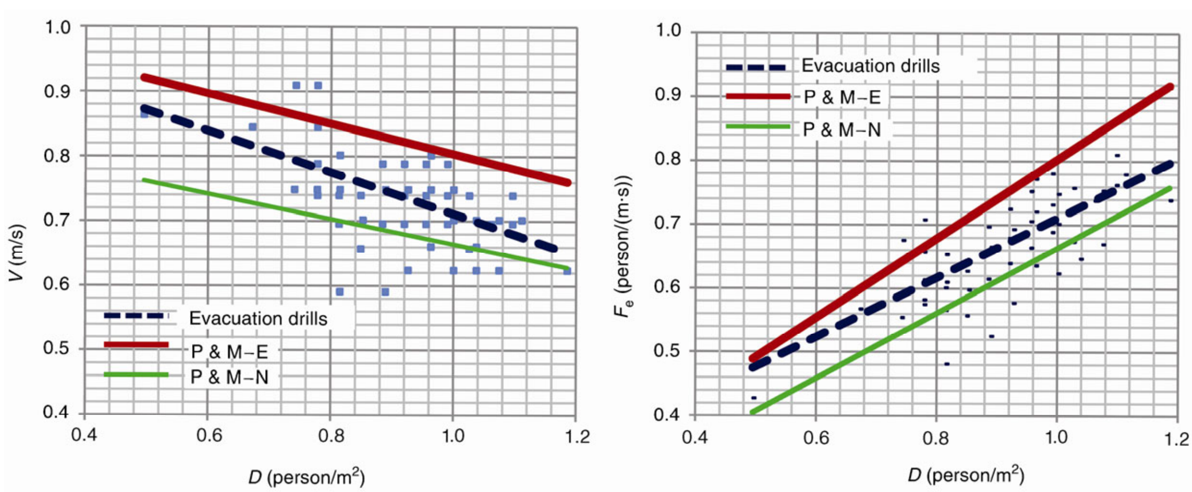

Fig. 3 FE building, variation of: (a) velocity with density; (b) specific flow with density (upward movement in group)

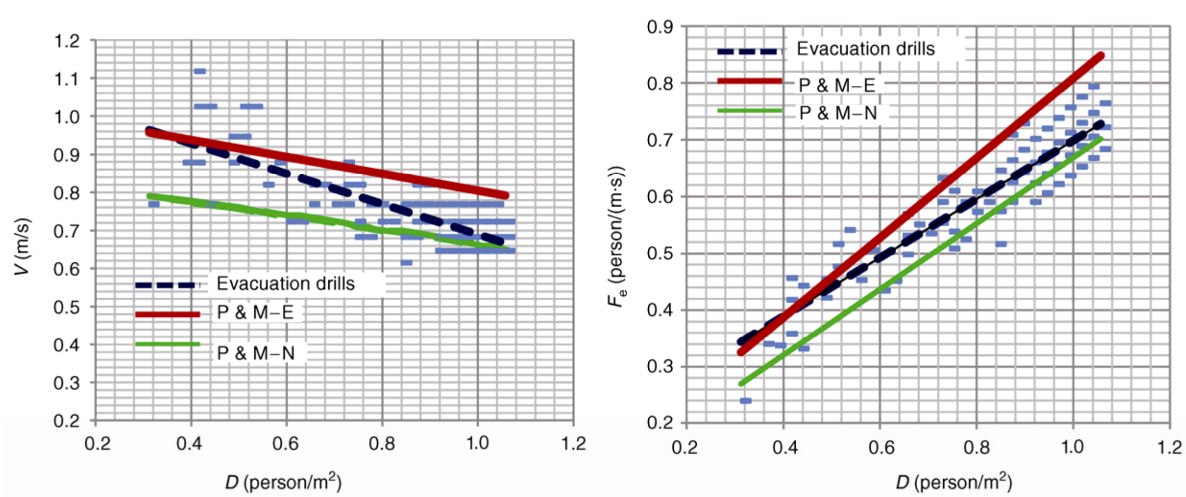

Fig. 4 FP building, variation of: (a) velocity with density; (b) specific flow with density (upward movement in group)

$$V = -0.397 \cdot D + 1.087 \quad R^2 = 0.629 \tag{6}$$

$$F_e = 0.5157 \cdot D + 1.831 \quad R^2 = 0.8548 \tag{7}$$

Regarding EH building, Eqs. (8) and (9) are represented in Fig. 5 (a) and (b), along with P & M expressions. The values obtained from the drills are, as it can be observed, inferior to the ones from P & M's normal movement. Comparing with the other two buildings, this difference can be explained, on one hand, by the absence of a security team and, on the other hand, by the low length of the course. In fact, the absence of a security team guiding evacuation may contribute to increase the velocity, as the influence of the course length was already discussed for free movement.

$$V = -0.4061 \cdot D + 0.8005 \quad R^2 = 0.562 \tag{8}$$

$$F_e = 0.2456 \cdot D + 0.1741 \quad R^2 = 0.5601 \tag{9}$$

Now considering the set of the three buildings, the following expressions and its correlations were determined:

$$V = -0.3313 \cdot D + 1.029 \quad R^2 = 0.4336 \tag{10}$$

$$F_e = 0.5398 \cdot D + 0.1642 \quad R^2 = 0.8031 \tag{11}$$

It is possible to state that both the velocity (Fig. 6(a)) and the flow (Fig. 6(b)) of the movement during evacuation drills are according and between the values obtained from P & M expressions for normal movement and emergency movement, approaching the emergency movement for lower densities and normal movement for higher densities.

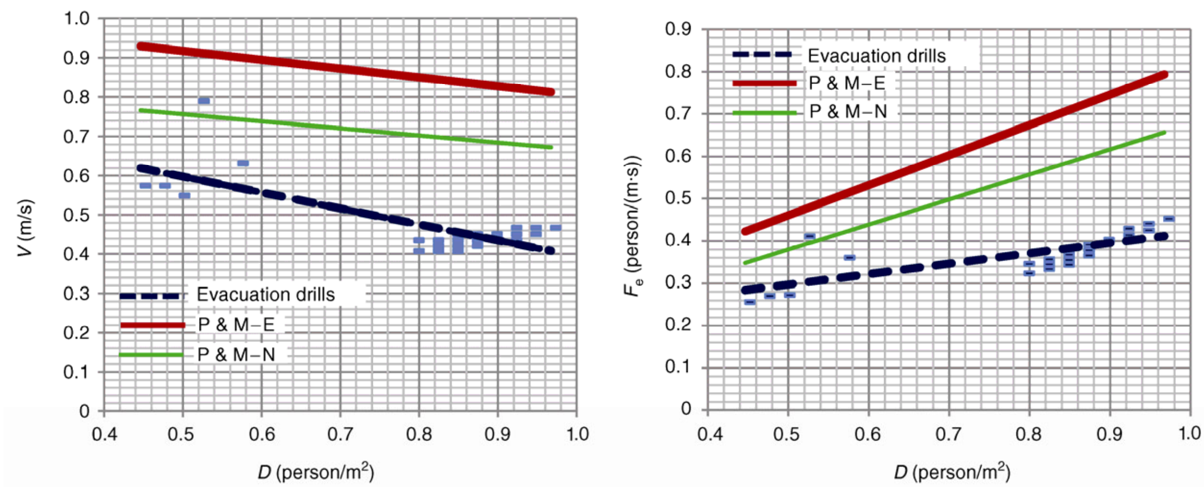

Fig. 5 EH building, variation of: (a) velocity with density; (b) specific flow with density (upward movement in group)

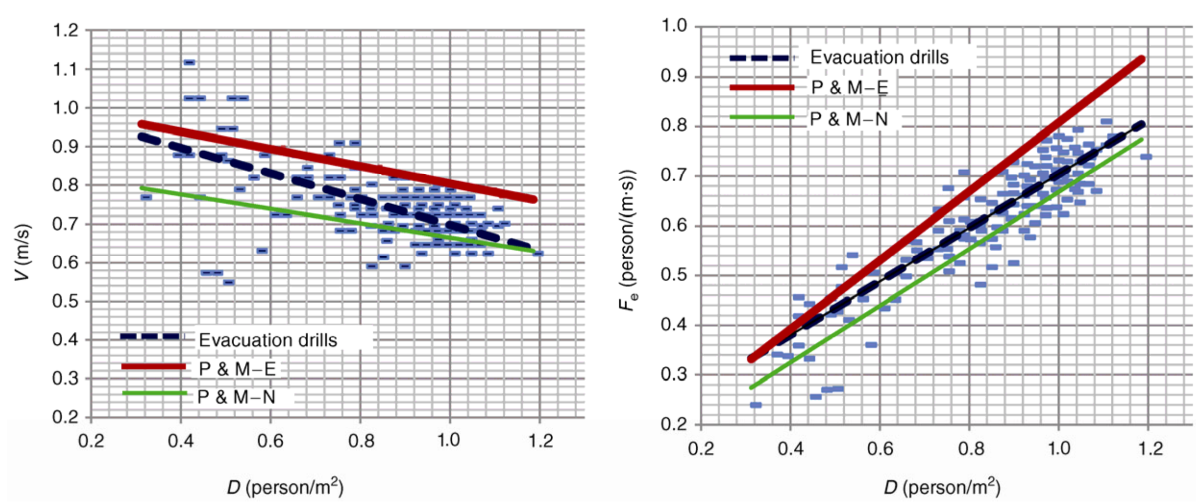

Fig. 6 FE, FP and EH buildings, variation of: (a) velocity with density; (b) specific flow with density (upward movement in group)

4.4 Movement behind the group

The analysis of the movement behind the group aimed the evaluation of the occupants' approach regarding a group following ahead.

To identify the occupants with this type of movement it was considered the last five people entering a group, regardless of the number of people at the section.

The method to treat and analyse the movement behind the group is similar to the one described for previous situations, calculating a mean velocity V_m for all occupants, then evaluating the interval $[V_m - \sigma; V_m + \sigma]$ and later calculating V_{mc}, as Table 10 summarizes its values for each building.

The mean velocity for the movement behind a group is significantly inferior when comparing EH building with the other two, as previously stated for free and in group movements.

The decrease of velocity stated for the other two types of movement regarding the stair with less development (number of steps and length) is not, however, that significant for the movement behind a group.

Table 10 Mean velocity for movement behind the groups in stairs

Building	Direction of movement	V_m (m/s)	$V_{máx}$ (m/s)	V_{min} (m/s)	V_{mc} (m/s)
FE	Downward	0.777	0.910	0.696	0.757
FP	Downward	0.910	1.025	0.820	0.912
EH	Downward	0.659	0.702	0.665	0.648

4.5 Comparison of different movement situations

Table 11 was created on the attempt to identify the differences for the occupants' velocity regarding each type of movement, where, for each stair, the modified mean velocities are compared according to each type of movement and the percentage of occupants involved.

Table 11 Mean velocity for each situation of movement

Building	Characteristic	Type of Movement		
		Free	Group	Behind
FE	Velocity (m/s)	0.983	0.773	0.757
	% Occupants	10	80	10
FP	Velocity (m/s)	0.851	0.708	0.912
	% Occupants	12	81	7
EH	Velocity (m/s)	0.616	0.424	0.648
	% Occupants	27	63	10
Global mean values	Velocity (m/s)	0.828	0.693	0.871
	% Occupants	20.5	71	9.5

Analysing Table 11, it is possible to state that, for each building and for the three considered types of movement, there is, regarding the values for velocity, the following pattern, except for FE building:

- of the three considered types, the movement behind the group is the one with the highest velocity, following the free movement and, at last, the movement in group, which has the lowest velocity;
- there is a tendency of approach from the occupants to the preceding group, as velocity increases for this type of movement.

As for the percentage of involved occupants in each situation, and regarding the global mean values, there are 70% of occupants moving in group, 20.5% in free movement and only 9.6% moving behind groups.

5 Conclusions

From this analysis it was possible to take some preliminary conclusions, still awaiting its confirmation, or not, as studies progress, highlighting:

- the highest velocity occurs for movement behind groups (there is a tendency of approach from the occupants to the preceding group) following the free movement and, at last, the movement in group;
- as for the percentage of the occupants involved in the movement, and regarding the global mean values, there are 70% of occupants moving in group, 20.5% in free movement and only 9.5% moving behind groups. Therefore, the most significant movement in stairs is the movement in group;
- occupants need to take some time to adjust themselves when moving from a horizontal plan to a staircase, for the movement in stairs has different characteristics from the movement in horizontal circulations, so it is common that velocity in stairs is lower at the first instants, all the more noticeable for lower buildings;
- in the absence of a security team, the values of velocity and flow for the movement in the evacuation drills are inferior when compared with the values from P & M expressions for normal movement;
- P & M expressions for the emergency movement lead to higher values of velocity and flow, when compared with the evacuation drills' values, for the characteristics of the movement are amongst normal and emergency movements, even in the presence of a security team;
- if these results are confirmed as future studies arise, it means that using P & M expression for emergency situations may lead to unsafe conclusions;
- taking all the records from the evacuation drills into account, the following expressions for the movement in group were obtained:

$$V = -0.3313 \cdot D + 1.029 \quad R^2 = 0.4336$$

$$F_e = 0.5398 \cdot D + 0.1642 \quad R^2 = 0.8031$$

It is important to keep acquiring new data about movement in stairs, in order to confirm, or change, the deduced mathematical relations and, also, to evaluate the impact of several factors in that movement, such as:

– influence of the opened doors in the movement of the occupants already in the stairs;
– influence of new occupants' entry in the stairs, regarding those who are already in the stairs.

References

Choi J, Hwang H, Hong W, Choi Y, (2009). Analysis on occupants' escape speed and reason of bottle-neck occurrence through the trial evacuation experiment at a high-rise apartment housing. In: Proceedings of the 4th International Symposium on Human Behaviour in Fire, Cambridge, UK (pp. 123 – 134).

Coelho AL (1997). Modelação Matemática da Evacuação de Edifícios Sujeitos à Acção de um Incêndio. PhD Thesis, Civil Engineering Department of the Faculty of Engineering of the University of Porto, Portugal. (in Portuguese)

Fruin JJ (1971). Pedestrian Planning and Design. New York: Metropolitan Association of Urban Designers and Environmental Planners.

Kholshevniikov VV, Shields TJ, Boyce KE, Samoshin DA (2008). Recent developments in pedestrian flow theory and research in Russia. *Fire Safety Journal*, 43: 108 – 118.

Kratchman JA (2007). An investigation on the effects of firefighter-counterflow and humambehavior in a six-story building evacuation. Master Thesis, University of Maryland, USA.

Nelson HE, McLennan HA (1996). Emergency movement. In: Beyler CL, Custer RLP, Walton WD, Watts JM Jr., Drysdale D, Hall JR Jr., Dinenno PJ (eds.), the SFPE Handbook of Fire Protection Engineering, 2nd edn, Section 3/Chapter 14 (pp. 3.286 – 3.295), Quincy, USA: National Fire Protection Association.

Pauls JL (1984). The movementof people in buildings and designs solutions for means egress. *Fire Technology*, 20: 27 – 47.

Pauls JL (2004). Suggestions on evacuation models and research. In: Proceedings of the 3rd International Symposium on Human Behaviour in Fire, (pp. 23 – 33), Belfast, UK.

Peacock RD, Averill JD, Kuligowski ED (2009). Stairwell evacuation from buildings: what we know we don't know. NIST Technical Note 1624, Gaithersburg, USA: National Institute of Standards and Technology.

Peacock RD, Hoskins BL, Kuligowski ED (2010). Overall and Local Movement Speeds During Fire Drill Evacuations in Buildings Up to 31 Stories. NIST Technical Note 1675, Gaithersburg, USA: National Institute of Standards and Technology.

Pinto NM (2008). Novos Contributos para a Modelação da Evacuação de edifícios em Situação de Emergência. Master Thesis, University of Coimbra, Portugal. (in Portuguese)

Predtechenskii VM, Milinskii AI (1978). Planning for Foot Traffic Flow in Buildings. New Delhi: Amerind Publishing.

Proulx G (2002). Movement of people: the evacuation timing. In: DiNenno PJ, Drysdale D, Beyler CL, Walton WD, Custer RLP, Hall JR Jr., Watts JM Jr. (eds.), The SFPE Handbook of Fire Protection Engineering.Society of Fire Protection Engineers, 3rd edn, Section 3/13 (pp. 3-341 – 3-366, Quincy, USA: National Fire Protection Association.

Takeichi N, Yoshida Y, Sano T, Kimura T, Watanabe H, Ohmiya Y (2005). Characteristics of merging occupants in a staircase. In: Gottuk DT, Latimer BY (eds), Proceedings of the Eighth International Symposium on Fire Safety Science (pp. 591 – 598), Beijing, China.

Templer J (1974). Stair Shape and Human Movement. PhD Dissertation, Columbia University, New York.

Watanabe Y (1973). Report of Fire. *Research Institute of Japan*, 37: 15.