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Safe fire-evacuation in venues that attract large crowds

Safety

Guaranteeing the safety of occupants is an overriding concern in fire protection engineering and therefore in the design of any building. One of the first tasks to take into account will hence be evacuation of building occupants, especially in venues that tend to draw in large crowds, with the consequent danger of crushes, trampling, avalanches and even suffocation. Such outcomes are caused both by building design and the reaction of building occupants to the danger situation.

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Article 11 of the Spanish Technical Building Code (*Código Técnico de la Edificación*: CTE), dealing with the evacuation of buildings, lays down the following: «The building shall be fitted with suitable means of evacuation to ensure occupants can leave it or reach a safe refuge therein in due conditions of safety». To do this it is essential to take into account diverse factors such as occupancy, number of exits, signage and the smoke control system, among others. Prediction of the evacuation is particularly difficult in the case of densely occupied buildings, due to the great variety of possible fire scenarios and the complex designs these constructions usually have. It is therefore essential to carry out occupant-movement simulations under different conditions as well as studying relevant standards and legislation. Nowadays, Performance-Based Design (PBD), which sets out to fill any design loopholes in fire-protection legislation, looks at the evacuation of buildings by comparing the time needed for evacuation with the time available for same. These concepts have been assigned the names of Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET). The former, RSET, runs from the start of the fire to the moment when all occupants are safe therefrom. The ASET, for its part is defined by SFPE[1] as the time until fire-induced conditions within a building become untenable. It depends mainly on the fire scenario and the fire protection measures taken.

All PBD aspects are bound up with people's real fire behaviour; a study is therefore made both of the fire causes and the psychology of human behaviour (Fig. 1).

Figure 1. Evacuation drill under real fire conditions (left). Evacuation down an emergency staircase (right).

Human fire behaviour

The first fire-evacuation studies were carried out at the beginning of the twentieth century[2,3]. These studies looked mainly at the flow of people through corridors, doors and on staircases; their main concerns were occupation density and speed of movements. The latter, depending on the age of the occupants, was seen to fall in fire situations[1]. It was not until the end of the twentieth century[4], however, that the Occupant Response Shelter Escape Time (ORSET) model included human behaviour as an evacuation risk criterion. This ushered in factors or concepts that had been overlooked hitherto, such as the pre-movement time and exit choice, among others. This new approach tended to stress the importance of building layout, floor plan and its interior design in terms of designing the evacuation procedure

In the mid-twentieth century studies also began to look at the relation between the fire and occupant evacuation[5], underlining the link between social behaviour and the evacuation procedure. One example was the fire of Arundel Park (1956), where the authorities noted that people who had acquaintances inside the building went back inside to try to save them.

By the mid-seventies studies were also taking into account occupant mobility in high-rise buildings[6-10], considering the need of using lifts or refuges within the building during the evacuation procedure. The most important studies of this matter were those concerning the Twin Towers catastrophe of New York, where it is estimated that up to 3000 people were saved thanks to an evacuation analysis carried out a few years previously, proposing the use of lifts for the evacuation[11,12].

The pre-movement time, defined as the period of time running from the fire alert to the beginning of purposeful evacuation behaviour, was seen to be especially important in hotels and residential buildings[13]. Reducing the pre-movement time could considerably bring down the number of fire victims, due to the importance of beginning the evacuation before the fire has developed to a critical condition.

Lastly, many studies nowadays are complemented by simulations. Most of these simulations, however, consider only the distance from exits and the speed and flow capacity through corridors, doors and stairs[14]. This is not enough from a safety point of view; consideration also has to be given to human behaviour in evacuation scenarios[4]. Studies also therefore needed to factor in the response of people to the various fire scenarios, building activity and occupancy, possible movement patterns, exit visibility and signage. The evacuation also had to be performed in due accordance with the design criterion, considering possible refuges during the evacuation, localisation of the occupants, arrival at the exits and the flows of people through doors and corridors.

Factors determining the fire response

The evacuation procedure in any building fire has to take into account three main factors: firstly, the typical characteristics of a fire, secondly, the characteristics of the building occupants and, thirdly, of the building itself.

The evacuation has to be carried out in keeping with the design criterion, considering such factors as any possible refuges on the evacuation route, the localisation of occupants, arrival at exits and flows

First and foremost, the fire in itself might impinge on evacuation routes; factors that need to be taken into account here are the perception thereof, growth rate, heat generated, smoke production and smoke toxicity. The fire might be perceived by sight or smell, i.e., directly seeing flames or smoke or picking up the smell of the smoke, or even by hearing in the case of alarms. This perception is an important factor in determining any delay in starting the evacuation procedure; the later the fire is detected, the longer will be the delay in beginning the evacuation; hence the importance of a good fire alarm and detection system. Secondly the fire growth rate will determine the speed at which the evacuation needs to be conducted; fires are broken down into slow, fast or ultra fast, depending on the fuel involved[15]. As regards smoke concentration and toxicity, individuals following smoky evacuation routes will be more likely to lose their way; as well as visibility problems they might also have breathing problems and even succumb to panic[16]. Smoke concentration usually reduces visibility[17], while smoke toxicity produces respiratory irritation[18].

The critical human factors, for their part, usually boil down to individual traits, social traits and the situations bound up with the fire. Individual traits depend mainly on the personality of each person, their knowledge and experience, observation capacity, judgement and mobility. The personality of the occupants is related to behavioural factors like whether they tend to act as leaders or followers, their stress resistance and general approach to life. The first factor will come out during the evacuation; the second will determine their ability to fend off panic and the third their way of overcoming obstacles. Observational powers take in the ability to see, hear, smell and feel, determining their capacity of perceiving the danger[19]. How they then react, their judgement, will also depend on their familiarity with the building[20]. The last factor is mobility; this obviously depends on the capacity of movement: high, temporarily reduced, permanently reduced and dependent mobility. Secondly, the social factor, as a critical human value, can show up in the degree of confidence felt in the rest of the people involved in the evacuation and their roles and responsibilities. Trained people responsible for the evacuation have to be involved, and they should be recognisable by audio-visual means[11]. Lastly, the features of the fire situation, within the human factors, are those related to perception, the physical position (stopped or moving) and familiarity with building layout. Perception of the fire might be lessened by consumption of alcohol or drugs of any kind[21]; as for the physical position, it has been found that occupants in constant activity evacuate a building before those who have been seated or standing still[22]; finally, familiarity with the building helps people to choose the quickest and safest escape route[2].

Last but not least, the environmental factors of the building itself impinge on the level of fire response. The two crucial factors that will determine said response are the situation and the fire protection facilities. The variables of the situation pool such factors as occupancy density, the ease of finding escape routes, the presence of a starting point and the existence of an evacuation team. The amount of people inside the building, occupancy density, is directly related to fire fatality probability[22]. The ease of finding escape routes involves such factors as visual access, architectural differentiation of the different parts of the building, their distribution, the occupants' familiarity with the building and signage. The latter is particularly important to ensure a safe evacuation[23]. The starting point is important in buildings such as theatres, universities or colleges, where the actors or teachers, respectively, will be responsible for initiating movement among the occupants[22]. Lastly, the members of the evacuation team will be responsible for overseeing the evacuation, liaising with the intervention teams and other members of the evacuation team itself. They have to be trained up to deal with emergency cases[23]. The particular building features, for their part, such as layout, materials, compartmentalisation and size, will determine how the response is organised. The layout parameters are the signposted escape routes, the design of these routes and the localisation of emergency exits and staircases. Many previous studies have concluded that the exit capacity is 650 people per minute and metre[24]. Furthermore, the installation of physical barriers to baffle smoke propagation, preventing it from invading the evacuation routes, together with the fire protection facilities, are deemed to be crucial for a safe evacuation. Such facilities might comprise extractors to remove the smoke, sprinklers to control or put out the fire and impede its growth and detectors to detect the fire. Compartmentalisation will make it possible for the evacuation to be carried out by stairs or lifts, to suit the particular needs of the building involved in each case. Combustible material must never be allowed to build up in escape routes, to ensure the fire does not spread to these routes during the evacuation.

The particular building features, such as layout, materials, compartmentalisation and size, will all determine the fire response

There are many contradictions in building safety design in terms of construction and management of the building. Standards and legislation take into account technical and social criteria and their efficiency is gauged in terms of fire fatalities. Most deaths occur in houses or flats and in crowded sites like discotheques or shopping centres[25]. Legislation considers the main fatality-determining factors to be high occupancy, a high fire load (decoration) and the non-existence of emergency exits. Another important point dealt with by legislation is signage, laying particular stress on its colour (green), the pictograms used and the siting thereof, and also the fire evacuation route. It has been shown, however, that many fires survivors leave the building along routes they know rather than the established route.[20]. Another example of these contradictions is the legislation's assumption that building occupants begin to move as soon as the alarm sounds; in fact this almost never happens[1,26].

The particular building features, such as layout, materials,

For this reason Kobes *et al*.[27] propose the introduction of aspects of behavioural psychology such as social factors, individual factors, mobility, awareness of the fire or motivation of the people being evacuated. A reciprocal influence is *compartmentalisation and size, will all determine the fire response.*

mooted between fire behaviour and persons and also the characteristics of the people involved and the building itself. Awareness of the existence of the fire, knowledge of the building, responding to the alarm, choosing one exit route over another, etc, all need to be brought into the picture.[28]. An in-depth study needs to be made of how people react to the highly stressful situations provoked by a fire[29].

To implement this approach, the building has to be so designed as to allow occupants to reach a safe refuge before the fire conditions become untenable. This involves introduction of the concepts of Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET)[10]. The former is the time running from the fire outbreak to the generation of fatal conditions; the latter is the time running from the fire outbreak to reaching a safe refuge. ASET depends mainly on the fire scenarios and the suppression thereof, while these scenarios in turn depend on the fire dynamic and the building dynamic. RSET, for its part, depends on evacuation scenarios, which are based on a prior knowledge of the psychological behaviour when faced with these scenarios

Materials and Methodology

This study sets out to improve the fire evacuation of occupants from buildings that tend to draw in large crowds, thus guaranteeing their safety. To do so a study has been made of fire and smoke behaviour in large venues and also of the fire behaviour of people in high occupancy situations.

An assessment has been made of specific numerical codes for simulating the movement of people, using the FDS+ EVAC open-source code. FDS (Fire Dynamics simulator) is the most commonly used fire simulation software in the fire protection field, while EVAC is a specific evacuation module.

A series of evacuation drills was therefore carried out, under nil visibility conditions (blindfolded), in the conference room called *Aula Pérez del Pulgar* of the *Universidad Pontificia Comillas* (ICAI). This conference room has two exits, enabling a study to be made of individuals' exit choice during an evacuation. In fact, in view of the limited availability of venues for carrying out these drills, it was decided to take advantage of the fact that the whole university community is familiar with this conference room, and carry out blindfolded drills therein. The study therefore focused mainly on the response of subjects who, knowing the only escape route, have to cross untenable smoke conditions to reach the exit.

The subjects were chosen from the students of the *Universidad Pontificia Comillas*, and also the teaching staff, broken down by gender and age. A study was also made of their group behaviour and individual behaviour, trying to record or quantify psychological aspects like the collaborative response, possible leadership and also the sense of disorientation.

The drills carried out are listed in tables 1, 2 and 3. They were divided into three phases. In the first phase (table 1) the mean room-crossing time was sought, at individual level by gender and taking into account aspects of disorientation within the room. To do so the blindfolded subjects were guided around the room to try to get them to lose their bearings.

Table 1.

Nº	Drill participants	Description	Additional information
1	Man	Crossing the room	Repeatability: gender
2	Man		
3	Man		
4	Woman		Repeatability: gender
5	Woman		
6	Woman		
7	Man	Disorientation	Repeatability: gender
8	Man		
9	Man		
10	Woman		Repeatability: gender
11	Woman		

Nº	Drill participants	Description	Additional information
12	Woman		

The second phase (Table 2) involved group drills. Other variables were factored in such as alarm and various types of obstacles. Some of these obstacles were easy to overcome and others blocked off passage completely. This phase also looked into the collaborative aspect and decision taking about the shortest route to the exit when disorientated. In these first two phases the mean age was 21.5.

Table 2.

Nº	Drill participants	Description	Additional information
13	7 men, 3 women	Crossing the room	Base conditions
14	7 men, 3 women	Crossing the room	Alarm. With the obligation of arriving all together
15	7 men, 3 women	Crossing the room	Alarm and movable obstacles
16	7 men, 3 women	Disorientation	Two open doors
17	7 men, 3 women	Disorientation	Closed door and return to starting point
18	2 men, 2 women	Disorientation	With human obstacles

Table 3.

Nº	Drill participants	Description	Additional information
19	7 men, 3 women	Crossing the room	Base conditions
20	7 men, 3 women	Crossing the room	Alarm. With the obligation of arriving all together
21	7 men, 3 women	Crossing the room	Alarm and movable obstacles
22	7 men, 3 women	Disorientation	Two open doors
23	7 men, 3 women	Disorientation	Closed door and return to starting point
24	2 men, 2 women	Disorientation	With human obstacles

The third phase (Table 3) involved a repetition of the above drills but this time with an older population (mean age of 44.7).

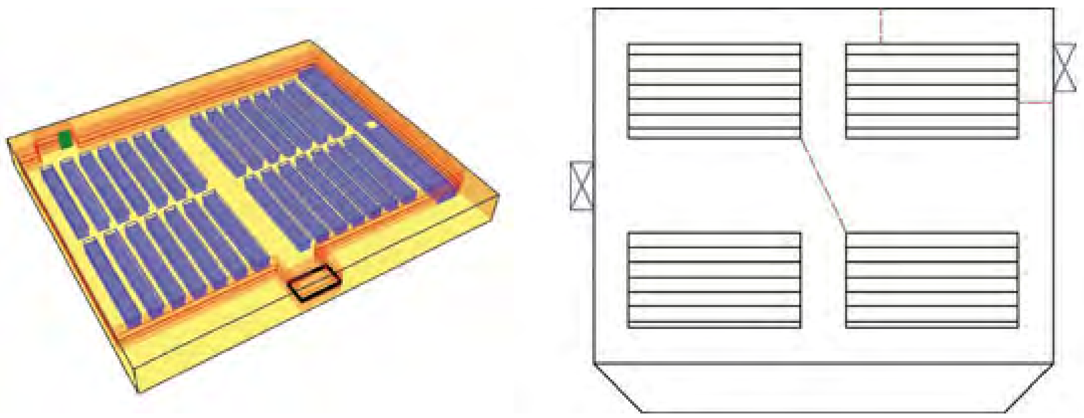

Figura 2. Model of the *Aula Pérez del Pulgar* conference room of the *Universidad Pontificia Comillas* (ICAI). The broken red line shows the fixed obstacles formed by people.

For the numerical simulations, the room was modelled as shown in figure 2. The figure also shows the obstacles set up with people (red line) to block off passage.

A questionnaire-based survey was also conducted to record the most important aspects and thus find out the opinion and feelings of the subjects carrying out the drills. In this survey the individual drill participants were asked the following questions:

1. Stress level produced by the lack of vision: (1= none, 5 = a lot).
2. Did your stress level fall as the drill progressed? (1= not at all, 5 = a lot).
3. Did you always try to get out at the same speed? (1= no, 5 = yes).
4. Did the situation get you worked up? (1= not at all, 5 = a lot).
5. Did you lose your bearings upon starting in a random point of the room? (1= not at all, 5 = a lot).
6. Do you think you would have taken less time in the company of someone else? (1= no, I would have taken the same time, 5 = yes, I would have taken a lot less).

The questions for the group participants' survey were

1. Stress level produced by the sound of the alarm: (1= none, 5 = a lot).
2. Did you feel better fleeing the site in a group and collaborating? (1= not at all, I would have been better alone, 5 = a lot).
3. Do you think you would have taken longer getting out alone? (1 = no, I would have taken the same, 5 = I would have taken a lot longer).
4. Did you prefer to follow others or lead the way yourself? (1 = follow, 5 = lead).
5. Did the situation get you worked up? (1= not at all, 5 = a lot).
6. Did you lose your bearings when each individual started in a different position? (1 = not at all, 5 = a lot).
7. Did you give indications to the other individuals during the drill? (1 = not at all, 5 = I helped all I could).
8. Did you try to get out always at the same speed? (1 = no, 5 = yes).
9. Did you take your cue from the behaviour of others? (1= not at all, 5 = a lot
10. Did your stress level fall as the drill progressed? (1 = not at all, 5 = a lot).

Results

The results have been broken down mainly into three parts: the first part shows the results of the evacuation drills; the second crosschecks this against the FDS+EVAC numerical models; the third records the results of the questionnaires.

Table 4.

Nº	Drill participants	Description	Additional information	
1	Man	Crossing the room	Repeatability: gender	31.43
2	Man			80.15
3	Man			52.32
4	Woman		Repeatability: gender	30.12
5	Woman			31.22
6	Woman			32.98
7	Man	Disorientation	Repeatability: gender	29.61
8	Man			45.37
9	Man			28.08
10	Woman		Repeatability: gender	33.05
11	Woman			33.34
12	Woman			46.87
13	7 man, 3 women	Crossing the room	Base conditions	58.86
14	7 man, 3 women	Crossing the room	Alarm. Collaborative	65.14

Nº	Drill participants	Description	Additional information	
15	7 men, 3 women	Crossing the room	Alarm and movable obstacles	52.89
16	7 men, 3 women	Disorientation	Two open doors	42.66
17	7 men, 3 women	Disorientation	Door closed and return to starting point	83.52
18	2 men, 2 women	Disorientation	With human obstacles	68.45
19	7 men, 3 women	Crossing the room	Base conditions	102.89
20	7 men, 3 women	Crossing the room	Alarm. Collaborative	67.79
21	7 men, 3 women	Crossing the room	Alarm and movable obstacles	54.08
22	7 men, 3 women	Disorientation	Two open doors	44.16
23	7 men, 3 women	Disorientation	Door closed and return to starting point	69.26
24	2 men, 2 women	Disorientation	With human obstacles	76.32

As regards the drills, Table 4 shows the times taken to reach the exit under the established conditions. In the group cases the time given is for the complete evacuation of all group members.

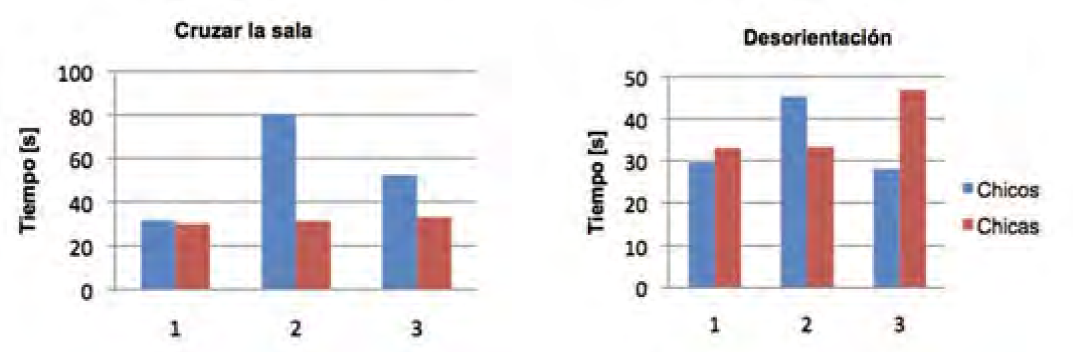

Figure 3. Graphical representation of times taken in individual drills.

The above results are shown graphically in figures 3 and 4 for ease of comparison.

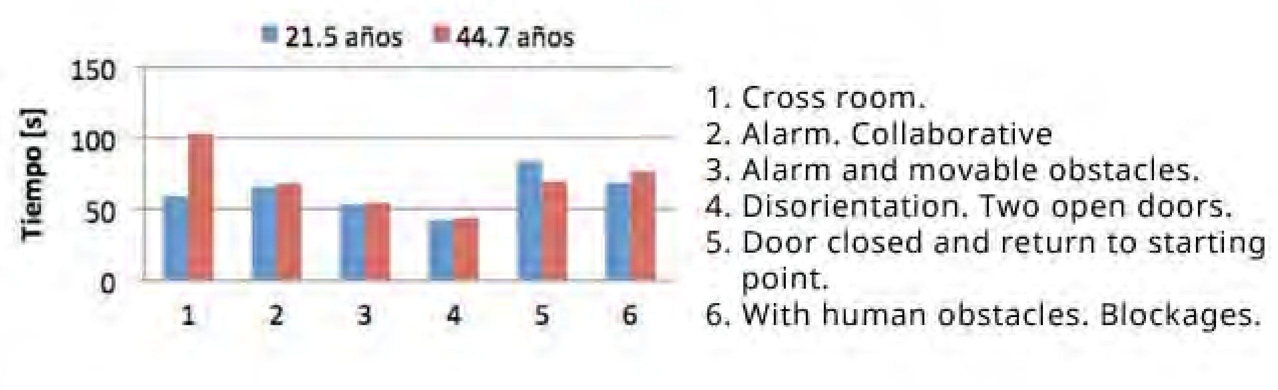

Figure 4. Graphical representation of times taken in group drills.

Some images are also shown of the drills carried out (Figures 5, 6 and 7).

Figure 5. Group drill.

Figure 6. Collaborative group drill.

Figure 7. Group drill: disorientation.

Various simulations of *Aula Pérez del Pulgar* were conducted with different smoke scenarios, as shown in figure 8. The numerical results obtained therefrom were always found to exceed mean experimental values; they therefore need a population-dependent initial vetting.

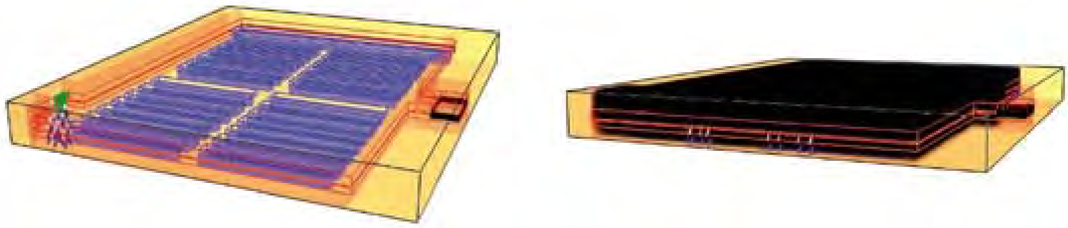

Figure 8. FDS+EVAC simulation of the room evacuation process with normal visibility and with nil visibility.

As for the surveys, an age-dependent comparison was made of the questionnaire results obtained between the groups. Figure 9 shows the results for each one of the questions asked.

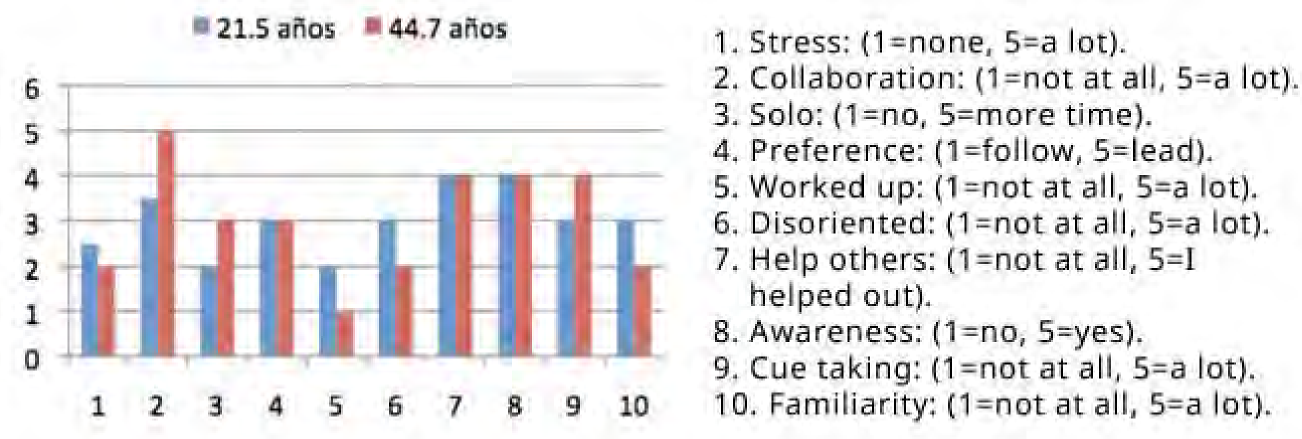

Figure 9. FDS+EVAC simulation of the room evacuation process with normal visibility and with nil visibility.

Discussion

The drills conducted and the questionnaire responses showed the difficulty of reproducing a real sense of danger in a drill of this type. The participants recorded a low stress level despite being blindfolded, the strident alarm and the possibility of running into obstacles in their path. This is in fact one of the main criticisms of all evacuation drills, where the conditions are normally far from realistic.

The degree of collaboration between the subjects was rated as much more important by the older population and this also came out in the drills. The teachers group always offered messages of help and tried to guide the rest of the participants. This was also borne out by the higher score in the answers to questions 2 (Did you feel better fleeing the site in a group and collaborating?) and 9 (Did you take your cue from the behaviour of others?).

The familiarity built up in repeat drills is a very notable factor in the times clocked up in the three first drills. In fact the lowest time was recorded with obstacles, when it should by rights have increased. This would confirm the importance of the degree of familiarity with the evacuation routes.

The shape of the room and its rows of chairs made it difficult to get the subjects to lose their bearings. In fact they confessed in the survey that they never really became disorientated. Even so, in this test all the participants could have left by either door and only one chose the shortest route. Once more the degree of familiarity and learned conduct from previous drills had more effect than searching out the exit in the shortest possible time.

The times generated by the numerical models, with their mean values, were always much higher than those recorded in the drills. This reflects the difficulty of modelling situations of this type, which always call for a previous vetting to adjust speeds or even ages, depending on the possible situations or scenarios that might be studied.

Moreover, several situations were observed that the numerical models did not manage to reflect. It proved difficult to establish a pattern repeated in nearly all drills. When the subjects were able to touch the walls of the room, their speed always increased even though they might run into additional obstacles. This once again reflects the importance of their familiarity with the evacuation route and confirms their difficulty in imagining unexpected situations during the drill.

Bonds were established between some of the subjects in nearly all the drills. This collaborative feeling, as mentioned above, was much stronger among the older population. In fact communication between the participants proved to be a help, for example, in the drill with the blocked door; some did not have to complete the journey to get there because those who had got there beforehand passed on the warning and they turned back to the starting point. Inter-subject communication is something that the programme at the moment does not cater for but it would seem to be a crucial factor in situations of this type.

Conclusions

The experimental and numerical study of the evacuation of occupants in buildings attracting large crowds, and more specifically in conference rooms, has thrown up interesting results to be considered in the design of evacuation procedures from diverse buildings.

The drills described herein and also analysis of the simulations carried out throughout the project have produced not only expected results, chiming in with past literature on the subject, but also some new results. One of the findings, subsequently borne out in the questionnaire survey, is that it is very hard to subject drill participants to a high stress level even when blindfolded, blasted with strident alarms and likely to run into unknown obstacles. This means that realistic drills are almost impossible to perform.

The drills show that the level of collaboration is greater among older people. This collaboration reduces the chaos level of the evacuation and also the stress level of the participants

The drills have shown that the level of collaboration is greater among older people. This collaboration reduces the chaos level of the evacuation and also the stress level of the participants; it would therefore be useful to encourage cooperation among people in incidents of this type to ensure a safe evacuation. Furthermore, familiarity with the building is a key factor in a quick evacuation. Occupants who know where the main exits are and also the evacuation routes get out of the building more quickly even when running into unexpected obstacles. And finally, progressive learning of the best behaviour from repeat drills cuts down the evacuation time even more. Fire drills therefore help not only to verify evacuation plans but also at the same time favour a more detailed knowledge of the best fire response.

The numerical models, for their part, throw up higher evacuation times than those observed in the drills. There is therefore a need for an in-depth study of the adjustment of speeds according to age and gender for possible fire situations or scenarios. Moreover, a uniform speed in any scenario may not correspond with the real situation. It has for example been observed in the drills that the occupants' evacuation speed was lower if they did not have contact with the walls.

In sum, this study has shown that different behaviour profiles, such as familiarisation or cooperation among the occupants, could play a key role in a successful evacuation. It has also been shown that it is very hard to conduct realistic drills. Individuals feel real panic and stress only when they really see their physical integrity under threat. Lastly, it has been observed that a lot of further development is still necessary in the numerical field.

Acknowledgements

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