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People's Movement in Narrow Paths with Different Width

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One of the most critical issues to manage in case of accidents in industrial facilities is people evacuation. The outcome of the evacuation process depends on many factors, including the adversity of the accidental event, the behavioural features of people involved, the functional vulnerability of the system, such as the geometrical layout of the egress system.
In order to reach a safety place in industrial facilities, people can be driven to go through narrow corridors or passages due to the peculiarity of the work place. Such passages force people to move in a single line and can reduce the movement speed, thus increasing the time required to evacuate.
In this work we analyse people's movement in paths with two different widths (0.8 and 0.9 m) and with the presence of different types of curves (90° and 180°). The data were collected in the LabCUBE$_{egress}$ experimental laboratory, a portable structure with a flexible layout designed by researchers of University of Udine. In this paper we present the results obtained from the experiments and simple relationships between people's speed and the path width. These equations can be a useful tool to help in designing the egress paths as well as in assessing the vulnerability of existing egress systems where narrow paths are present.

1. Introduction

When a fire grows in an enclosure, evacuation is one of the measures that workers can take to preserve their safety. Evacuation requires people to move away from hazards and to reach a safety place. In general, life safety is achieved if the Available Safe Egress Time (ASET) is greater than the Required Safe Egress Time (RSET). The ASET is defined as the time when fire-induced conditions in an enclosure become untenable (Nelson and Mowrer, 2002). Analyses of ASET are beyond the scope of this work and can be found in Tosolini et al. (2012). RSET is the time that people take to reach the safety place and it depends on many factors: the time from fire ignition to detection, the time from detection to notification to people, the time from notification until decision to evacuate is achieved, the time from decision to evacuate until its start and the time from the start of evacuation until it is completed (Nelson and Mowrer, 2002). In this work we focus on the last of these time intervals, the so-called evacuation time or movement time, which is simply a function of distance and speed. While the first is a function of the exit path, the second is more complex, indeed previous observations have shown that movement speed depends on both occupants' and building characteristics (SFPE, 2003).
In industrial facilities, people can be forced to go through narrow and complex corridors or passages due to the peculiarity of the workplace. Such passages force people to move in a single line and this can reduce the movement speed, thus increasing the time required to achieve a safety place.
In order to design or assess evacuation plans or egress systems in such workplaces, it is necessary to understand how people actually move in such paths.
A literature survey shows that over the years many studies on walking speed have been developed considering different situations: in public buildings (Predtechenskii and Milinskii, 1978), in subway station walkways (Hankin and Wright,1958), in shopping streets walkways (Older, 1968), in downtown walkways (Mori and Tsukaguchi, 1987). Other studies considered movement on stairs (Hoskins, 2013), tunnels (Fridolf et al., 2013) or in laboratory experiments, analysing different configurations, e.g. movement in a single line along a circular path (Seyfried et al., 2005), different flow types in large hallway (Daamen and

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Hoogendoorn, 2005), people moving on four in straight paths (Kady, 2012). From this survey it emerged a general lack of information about movement in narrow and complex paths. This poses a challenge in the design and assessment of industrial facilities evacuation plans and egress systems.
During the "Evaluation and Management of Venice Fire Safety Program", Grimaz and Pini (1999) developed PASS (Preliminary Assessment of the egress-System Safety) methodology to assess rapidly egress system safety in terms of capability to respond to the adverse effects of accidental events. PASS was initially included in Gri.S.U. (Grimaz and Pini, 1999), a methodology for the assessment of fire risk and equivalent safety in non-conventional buildings such as industrial facilities, workplaces or heritage buildings and it was further developed by Grimaz and Tosolini (2010 and 2013) as a stand-alone method. PASS method includes checks that allow to identify critical points in an egress system, such as narrow corridors, merging paths, etc. These criticalities are related to analytical equations that allow estimating the reduction of egress system performance compared to a standard ideal system.
In the next sections we present the results of a new study on people movement obtained from a series of experiments in the LabCUBE$_{egress}$ laboratory, in which we analyzed people movement in horizontal paths with different widths and with or without turns. The purpose of this work is to assess whether walking speed is negatively affected by such configurations and to validate the PASS flow factor coefficient specifically designed to estimate reduction of walking speed due to narrow paths.

2. LabCUBE$_{egress}$ experiments and methodology of analysis

The experiments were carried out in the LabCUBE$_{egress}$ laboratory (Figure 1), that was created to study the factors that characterize people-people and people-environment interrelationships during egress situations. The frame of LabCUBE$_{egress}$ is composed by several elements that can be assembled to create different pathway layouts. This flexibility allows to deal with different issues characterizing egress situations, e.g. people's choice at a decision point (Tosolini et al., 2012), flow of people converging to a gap or people's behaviour in presence of a dead-end path. The laboratory is equipped with CCTV video cameras that allow to record data. For more details about the laboratory refer to Tosolini et al. (2012).
The experiments were carried out during the European Researcher Night (September 2011) and during a local festival (May 2012) in Udine (I); altogether they have involved more than 400 people.

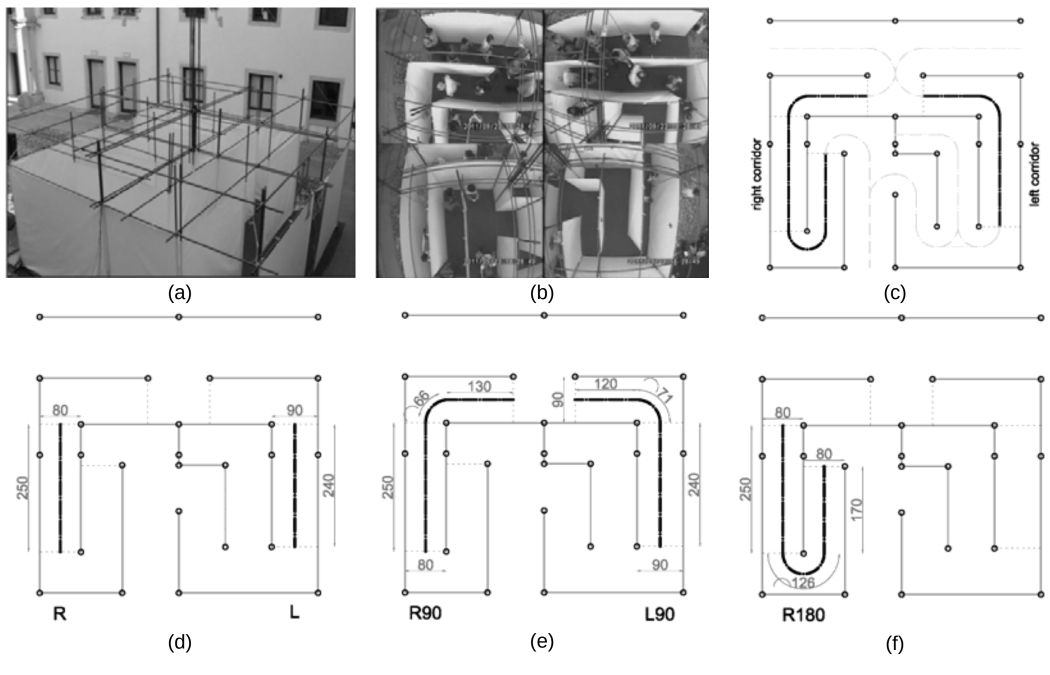


Figure 1: Views and paths studied in the LabCUBE$_{egress}$ laboratory: (a) general view; (b) snapshot from CCTV video recordings; (c) general layout; (d) straight corridors; (e) corridors with 90° turns; (f) corridor with a 180° turn.

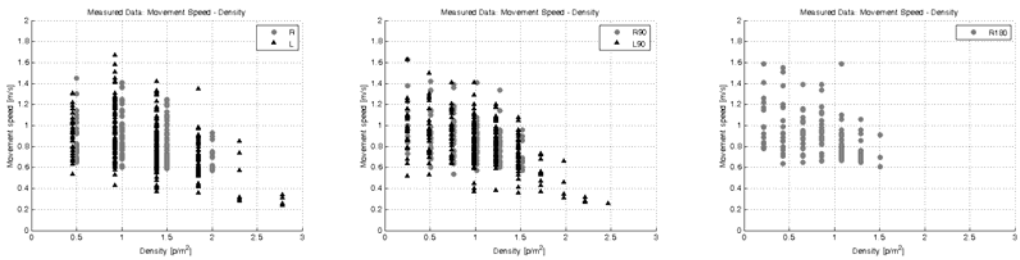
The population involved in the experiments was heterogeneous (gender, age), untrained and representative of a wide cross-section of society. People were asked to walk through the laboratory; the path widths are such that people moved in a single line.
In this work, we are interested in analyzing walking speed of adult participants only because they represent people usually present in workplaces, so the video recordings were analyzed to filter out elderly and children participants from the database.
The paths selected to study walking speeds are straight corridors with two widths of 0.8 m and 0.9 m and corridors with two types of turns: 90° and 180° turns. The studied paths are summarized in Figure 1 (d,e,f) and Table 1.
We calculate the walking speed of each subject involved in the experiments simply dividing the path length by the time it takes for each subject to tread it. The calculated walking speeds are then reported as a function of people density in each path. An analysis of video recordings was necessary to calculate time and density. People density is a measure of how the space is occupied by people during movement. There is no agreement in literature on how to calculate this density, with different authors using different equations (Hoskins, 2013). In this study people density is calculated as the number of people present in the path studied, divided by the path area. Such density is calculated when each person enters the path.

Table 1: Characteristics of the studied paths.

Case ID	People involved	Path type	Corridor width (m)	Total length (m)
R	150	Straight	0.80	2.50
L	295	Straight	0.90	2.40
R90	149	90° curve	0.80	4.50
L90	293	90° curve	0.90	4.30
R180	150	180° curve	0.80	5.50

3. Experimental results

The experiments allowed testing the movement of people in a single line in different paths types. We can notice that the number of people involved in cases L and L90 (Figure 1) is larger than in the other cases (Table 1); as a consequence we find a greater dispersion of the measured speeds due to the larger sample size.
Figure 2 shows, as an example, the measured data for the cases R and L and R90 and L90. Two observations can be done: 1) in each of the two cases a clear relation between people density on the corridor and movement speed exists, with speed decreasing as density increases; there is also a lack of data for high people densities, say larger than 2 people per square meter (p/m^2); 2) given a range of people density values, we can’t note a sensible difference between walking speeds in the two paths due to corridor width. We find similar results when comparing the paths with turns with straight ones.



(a) (b) (c)

Figure 2: Measured walking speeds as a function of people density: (a) in straight paths with widths of 0.8 m (R) and 0.9 m (L); (b) in paths with 90° turns (R90 and L90 cases); (c) in paths with 180° turns (R180 case).

In order to better evaluate the influence, if any, of the specific path characteristics (width, presence and type of turns) on the walking speed a statistical analysis of the measured data is done; the results are reported in Table 2 in terms of five-number-summary, where the mean and standard deviation are also included. Comparing measured speed on the two straight paths with width 0.80 m (R case) and 0.90 m (L case) respectively, there are no sensible differences considering the same range of density values.

Similarly, there are only little differences comparing walking speed in paths with and without 90° turns. This last result is in accordance with the findings of Predtechenskii and Milinskii (1978).
We achieved the same results comparing the speeds on the straight path (R case) with those measured on the 180° curve path.

Table 2: Summary of movement speed measured in LabCUBE$_{egress}$ experiments for different path types.

Case ID	People density (p/m^2)	Movement speed (m/s)						
		Min.	1st quart.	Median	3rd quart.	Max	Mean	SD
R	<0.55	0.7	0.8	0.9	1.1	1.5	0.9	0.2
	0.55÷1.05	0.6	0.8	0.8	1.0	1.4	0.9	0.2
	1.05÷1.55	0.6	0.7	0.7	0.9	1.3	0.8	0.2
	1.55÷2.05	0.6	0.6	0.7	0.8	0.9	0.7	0.1
L	<0.55	0.5	0.8	0.9	1.1	1.9	1.0	0.3
	0.55÷1.05	0.4	0.8	0.9	1.2	1.7	1.0	0.3
	1.05÷1.55	0.4	0.7	0.8	0.9	1.4	0.8	0.2
	1.55÷2.05	0.4	0.6	0.7	0.8	1.4	0.7	0.2
	2.05÷2.55	0.3	0.3	0.4	0.7	0.9	0.5	0.2
	> 2.55	0.2	0.3	0.3	0.3	0.3	0.3	0.0
R90	<0.55	0.6	0.8	0.9	1.1	1.6	0.9	0.2
	0.55÷1.05	0.5	0.8	0.9	1.0	1.4	0.9	0.2
	1.05÷1.55	0.6	0.6	0.7	0.9	1.3	0.8	0.2
L90	<0.55	0.5	0.8	0.9	1.1	1.6	1.0	0.2
	0.55÷1.05	0.4	0.7	0.9	1.0	1.4	0.9	0.2
	1.05÷1.55	0.4	0.7	0.8	0.9	1.2	0.8	0.2
	1.55÷2.05	0.3	0.4	0.5	0.7	0.7	0.5	0.1
	2.05÷2.55	0.3	0.3	0.3	0.3	0.3	0.3	0.0
R180	<0.55	0.6	0.8	0.9	1.2	1.6	1.0	0.2
	0.55÷1.05	0.7	0.8	0.9	1.0	1.4	0.9	0.2
	1.05÷1.55	0.6	0.7	0.8	0.9	1.6	0.8	0.2

4. PASS analytical relationship

In PASS methodology, quantification of walking speed reduction due to narrow paths is expressed as a function of three widths (Figure 4): body width that is conventionally assumed equal to 0.55 m for healthy adults, nominal width of the path and effective width. The effective width is justified by experimental observations that people moving through the exit routes of a building maintain a boundary layer clearance from walls and other stationary obstacles (Nelson and Mowrer, 2002). In PASS method a narrow path is defined as a path such that its nominal width is larger than body width, but its effective width is smaller than body width increased by 0.20 m (Figure 3). In such paths PASS flow factor coefficient forecast a speed reduction in the order of 13 % with respect to the speed in an ideal large corridor, say a corridor whose effective width is larger than body width increased by 0.20 m.

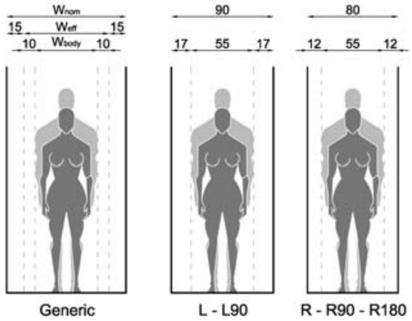


Figure 3: Corridor width types (W_{nom} = nominal path width, W_{eff} = effective path width).

We compared the well-known equation developed by Nelson and Mowrer (2002), in the following called standard curve, which relates walking speed to people density for corridors, with measured speeds in the LabCUBE$_{egress}$ experiments. Figure 4 compares the standard curve forecasts with the 1st quartile of measured data and we can notice a walking speed reduction in the order of 30 % over all densities. Considering the median of measured speeds, the speed reduction is in the order of 20 %. Finally, considering the 3rd quartile of measured speeds, the speed reduction is in the order of 5 %. These findings stand for all path types considered in this work and they are summarized in Table 3.

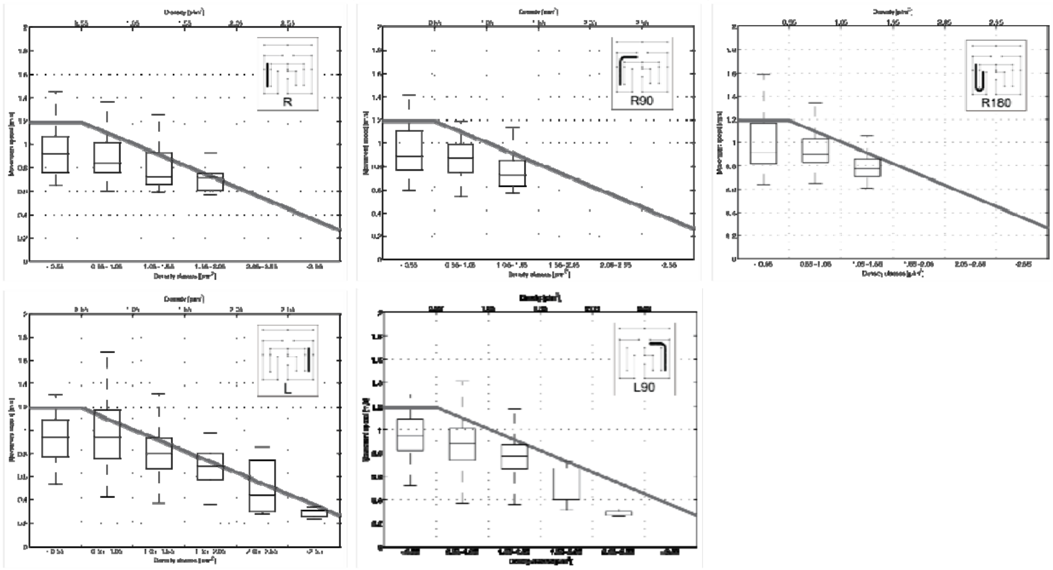


Figure 4: Comparison between measured data (boxplots) and the standard curve (solid lines) for every studied path.

We can eventually note that PASS flow factor coefficient correctly forecast a reduction in movement speed due to narrow paths, however data acquired in the experiments suggest to further reduce the correction factor from 13 % to 20-30 % (Table 3).

Table 3: Mean speed reduction for corridors due to narrow paths.

Case ID	W_{nom} (m)	PASS	Measured data		
			1st quart.	Median	3rd quart.
R - R90 - R180	0.8	13 %	28 %	20 %	4 %
L - L90	0.9	13 %	28 %	18 %	0 %

5. Conclusions

Experiments conducted in $LabCUBE_{egress}$ allowed testing people's movement in a single line in horizontal narrow paths with two different widths (0.8 m and 0.9 m) and with or without turns of 90° and 180°. The results obtained from the experiments were statistically analyzed; a first result is that there are not sensible differences in measured walking speeds between the two path widths. A second result drawn from the data was that, in the case of movement in a single line, the turns seem not to reduce walking speed if compared with speeds measured on the straight paths. These results stand for people densities ranging from very low (less than 0.55 p/m^2) to densities in the order of 2 p/m^2.

Data from the experiments allow also testing the flow factor coefficient developed in PASS methodology in order to evaluate the reduction in walking speed due to narrow paths. In the framework of PASS, a narrow path is a path such that its nominal width is larger than body width, but its effective width is smaller than body width increased by 0.20 m. We assumed as reference for walking speed in an ideal large corridor those calculated with the Nelson and Mowrer (2002) relation, and after comparing the reference values with measured speeds we note a mean speed reduction with respect to the standard curve ranging from 5 % considering the 3rd quartile of measured data, to 30 % considering the 1st quartile.

The results substantially confirm the validity of the flow factor coefficient developed in PASS, but for a more precautionary forecasting of speed reduction due to narrow paths we suggest to assume this factor equal to 20 % of the speed in an ideal large corridor, say a corridor whose effective width is larger than body width increased by 0.20 m.

These findings can be usefully applied in the design or assessment of egress systems or evacuation plans of industrial facilities as well as other non-conventional buildings where narrow and complex paths can be find, in order to more realistically consider people's walking speed in such paths. A final remark concerns the fact that experiments were performed outdoor, in no emergency conditions and with a good visibility of paths. Therefore the results could be not representative of a real emergency scenario in an industrial facility, where different conditions could be present.

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