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A pedestrian merging flow model for stair evacuation

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ABSTRACT

Pedestrian merging flows on stairs are defined as the confluence of a flow of pedestrians from a stair and pedestrians from each floor of a multi-storey building. This paper introduces a novel simplified mathematical model for the calculation of evacuation times on stairs which takes into account the impact of merging flows. The model allows calculating the impact of merging ratio (people accessing the stair landing from the floor and from the stair) on pedestrian flows and evacuation times at each floor in congested situations. The assumptions and implementation of the model are presented. A hypothetical model case study of a 10-floor building evacuation is investigated, where the results of the new model are compared with the results of an evacuation simulation model using SimTread. Advantages and limitations of the new model in relation to the existing methods adopted for the simulation of merging flows on stairs are discussed.

1. Introduction

The calculation of the evacuation time during vertical egress is crucial to assess the safety conditions of a multi-storey building in the context of fire safety engineering. In fact, stairs today represent the main egress component for such types of buildings [30]. Different calculation methods are available, ranging from simple hand calculations (such as the hydraulic model provided in the Society of Fire Protection Engineering Handbook [5]) to more complex computational evacuation models [19]. Evacuation models may be based on different assumptions (e.g. multi-agent models [16], cellular automata [27], etc.) and the interpretation and use of their results highly depend on the user's understanding of the methods employed for the simulation of pedestrian movement.

The calculation of the evacuation times on stairs relies on the assumptions considered while representing the movement of pedestrians [10,20]. This includes, among other issues, both the relationship between walking speeds, densities and flows [2] as well as many other behavioural variables (e.g. fatigue [33], motivation [4], etc).

In particular, an important factor in the calculation of the evacuation flows is the way in which people from the stair and the floor merge in the stair landings, i.e. pedestrian merging flows. Merging has an impact on the way the floors are emptied, i.e., from the top to the bottom or vice versa. Different experimental studies have been conducted so far on this subject. Data are often collected with different methods/conditions and they may take into account different behavioural factors. As a consequence, these studies often show disagreement on th7eir findings. For example, based on qualitative observations, Pauls [26] suggested that stair flow defers to the floor flow on a fairly consistent basis in congested situations. In contrast, Ronchi et al. [32] found that in the case of low occupant load and low densities, stair mergers seem often having priority over floor mergers. In contrast, different experiments in the UK [1] and in Japan [12,13,34,9] have shown that, when the occupant load is high, the merging ratio seem to correspond to approximately 50:50. Many studies also highlight how the configuration of the stair (i.e. the position of the door in the landing) can have a significant impact on the evacuation time of a floor [14,23,24,3,35].

The findings of these studies highlight the need to systematically investigate how an assumed merging ratio can impact flows and subsequent floor evacuation times during stair evacuation. To address this issue, this paper presents a simplified mathematical model for the calculation of pedestrian flows on stairs which takes into consideration different merging flow ratios. The new simplified model is deemed to be useful for different purposes, such as a rapid estimation of evacuation times in stairs, the evaluation of the impact of merging ratios on evacuation time of each floor, the estimation of the assumed merging ratios in existing evacuation modelling tools by comparison with the simplified model.

The assumptions adopted in different evacuation modelling tools to represent movement in stairs are discussed by different authors [22,29,30,33]. This includes the analysis of the methods assumed to

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Nomenclature

ET_i [s] Evacuation time at the floor i, expressed in seconds [s]. This corresponds to the movement time since no pre-evacuation delays are considered.
ET_n [s] Evacuation time at the top floor, i.e. floor n, expressed in seconds [s]. This corresponds to the movement time since no pre-evacuation delays are considered.
ET [s] Total evacuation time of the entire building, expressed in seconds [s]. This corresponds to the movement time since no pre-evacuation delays are considered.
k Merging ratio from the floor, i.e., the ratio between the flow of floor mergers Q_i^f divided the total pedestrian flow rate at floor i Q_i.
m Total number of floors in which merging occurs below the floor i.
n Total number of floors in the multi-storey building.
P [p] Number of pedestrians in the building (i.e. the sum of pedestrians on each floor), expressed in number of pedestrians [p].
$P_{a,t}$ [p] Accumulated number of pedestrians that left the floor i at each stage t, expressed in number of pedestrians [p].
$P_{a,t-1}$ [p] Accumulated number of pedestrians that left the floor i at each stage $t-1$, expressed in number of pedestrians [p].
$P_{a,ETn-1}$ [p] Accumulated number of pedestrians that left the floor $n-1$ at the evacuation time of the floor n−1, expressed in number of pedestrians [p].
P_i [p] Number of pedestrians at the floor i, expressed in number of pedestrians [p].
P_p [p] Present number of pedestrians evacuated at the floor i, expressed in number of pedestrians [p].
P_{pt} [p] Present number of pedestrians evacuated at the floor i at a certain stage t (e.g. P_{p1}, P_{p2}, etc.) expressed in number of pedestrians [p].
Q_i^s [p/s] Pedestrian flow rate from the stair to the landing at floor i, expressed in pedestrians/second [p/s].
Q_i^f [p/s] Pedestrian flow rate from the floor to the landing at floor i, expressed in pedestrians/second [p/s].
Q_i [p/s] Pedestrian flow rate at floor i corresponding to the sum of Q_i^s and Q_i^f, expressed in pedestrians/second [p/s].
Q [p/s] Total pedestrian flow rate at the ground floor, expressed in pedestrians/second [p/s].
Q_n^f [p/s] Total pedestrian flow rate at the top floor, expressed in pedestrians/second [p/s].
t Stage, i.e. interval in which a floor is getting empty at a certain flow rate.
t_e Evacuation stage, i.e. stage in which the evacuation of a floor is finishing.
T_d [s] time interval corresponding to the difference between the time needed to evacuate the top floor in the last evacuation stage t and the previous evacuation stage t−1.
T_t [s] time interval corresponding to each stage.
w [cm] width of the stair, expressed in centimetres [cm].

represent pedestrian movement on stairs which include merging as well as the options that the model user have to modify (implicitly or explicitly) merging ratios and subsequently affect evacuation times. To date, the representation of people movement on stairs is made in evacuation models adopting different methods, which may be the result of the general assumptions adopted for the simulation of people movement in horizontal planes [30] or be based on simplified calculations based on external sub-models [6]. Evacuation models generally produce approximately a 50:50 merging ratio when representing crowded evacuation scenarios in configurations where the floor entrance is opposite to the incoming stair and they have also been used for evaluating the impact of the geometry on the observed merging ratios [22,3,36]. Nevertheless, the population composition and local conditions may affect the merging ratios and subsequently the evacuation times (which may be under or over-predicted at different floors with possibly negative consequence on the assessment of the safety conditions of a building.). To date, this issue has not been thoroughly investigated and no systematic attempts have been made to quantify the impact that merging ratios may have on evacuation times at each floor.

The representation of people movement in evacuation models is currently made using different approaches. One of the main classifications concerns the type of structure employed to represent the space where people move (continuous, fine network, course network or hybrid approach) [31] and the methods used to simulate people movement, e.g., social force model [8], cellular automata [21], steering model [28], etc. In this context, models may adopt different solutions to simulate behaviours which aim at representing the current knowledge of human behaviour in fire [18] and allow the representation of the impact of different variables on evacuation time.

The impact of merging flows on the evacuation time of individual floors can significantly affect the safety conditions of a building since the fire source may be located at different floors. The purpose of this paper is the presentation of a simplified mathematical model for the calculation of evacuation times at different floors in multi-storey buildings considering the impact of pedestrian merging ratios. The model can be seen as a tool for rapid calculations which can be used to produce results independently and compare the results produced with evacuation models. For this reason, the present model could be used both as a calculation tool *per se* as well as a sub-model in existing evacuation modelling tools. This model is deemed to fill one of the existing gaps in evacuation modelling tools concerning movement on stairs, i.e. the lack of understanding the impact of merging flows on evacuation times at individual floors.

2. The model for pedestrian merging on stairs

This section introduces a new simplified mathematical model for the representation and calculation of merging flows on staircases in case of simultaneous total evacuation of a multi-storey building.

2.1. Model assumptions

Prior to presenting the model, a set of assumptions needs to be introduced in order to explain the field of applicability of the model.

Assumption 1**.** The arrival of pedestrians merging in the staircase is continuous and there is no delay in the arrival of pedestrians in the staircase, i.e., Q_i^f is constant.

Assumption 2**.** Only steady state conditions of pedestrian flows are considered and the starting conditions assume that the staircase is filled with people at the same density as the constant conditions at the start (i.e. the initial phase in which the staircase is empty is not taken into account).

Assumption 3**.** The number of pedestrians accessing the staircase is sufficient to get congestion while accessing the landing of the stair.

Assumption 4**.** The floor merging ratio is equal for all floors and constant over time at every floor, i.e., k is constant.

Assumption 5**.** The travel time through the stair is not considered and people are assumed to reach the floor below immediately and then the flow will be the main restricting factor.

Assumption 6**.** No pedestrians come from the ground floor.