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A probabilistic approach for the analysis of evacuation movement data

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ABSTRACT

This paper presents a probabilistic approach to analyse evacuation movement data. The approach relies on a detailed video analysis of people movement and pattern reconstruction. Conditional probabilities for travel path trajectories, walking speeds, and physical area occupied on stair landings are calculated for the evacuee population. The approach has been applied as a case study using data from an evacuation drill performed in a six-storey office building in the United States. The evacuation drill was filmed and occupant's behaviours on stairs were analysed using the new method. A comparison with the deterministic methods currently employed in engineering practice has been performed. The benefits of the probabilistic approach are discussed, including (1) a more accurate representation of people movement and (2) the use of probabilistic data for modelling purposes, i.e., model validation and model development.

1. Introduction

The methods adopted for the representation of people movement during evacuation may be based on deterministic or stochastic assumptions [4,25]. Although stochastic descriptions of people movement are available in the literature (especially in the field of physics and applied mathematics) [8,26], the majority of models employed in the engineering community (and their subsequent use in current fire safety engineering practice) make use of average values or deterministic assumptions [14]. For example, occupants are assumed to walk on a pre-determined travel path (generally the shortest path available or an assumed fixed route) and average values are used for the calibration of the input of evacuation models. Evacuation drills (e.g., [19]), actual events (e.g., [2]) and experimental data (e.g., [12]) demonstrate that there is significant variability in the possible behaviours of the occupants during an evacuation which may impact both their travel path and movement speed. Consequently, the use of deterministic assumptions – intended as assumptions where no randomness is involved – to model occupant behaviours can decrease the accuracy of predictions compared to a probabilistic representation of people movement [1].

Most of the evacuation models available are microsimulation tools, i.e., individuals are treated as autonomous entities [24]. Nevertheless, datasets employed for the development and calibration of those models are based on average populations and hypotheses rather than an individual analysis of occupant behaviours. This is reflected in the use of deterministic assumptions or average values (e.g., a single route, a single value, etc.) to represent the actions of the individuals whose behaviours are instead probabilistic.

Evacuation data are generally not presented or used in a probabilistic manner. The closest that researchers in the engineering community come to a probabilistic description of people movement during evacuation is the use of distributions, e.g., a distribution of pre-evacuation times, a distribution of movement speeds, etc. [15]. The probabilistic approach to study people movement during evacuations in different environments has been rarely employed (e.g., the building evacuation model proposed by Fraser–Mitchell [5] or the train evacuation model by Capote et al. [3]). In addition, datasets – on which evacuation models are based – are not collected with the aim of providing a probabilistic representation of people movement.

Although attempts have been made to create a standard detailed method to collect and present evacuation data [9], datasets are generally presented by researchers referring only to the observed walking speeds, flows and densities [15]. However, almost no data are provided about detailed movement or the conditions affecting the behaviours of the occupants.

This paper presents a probabilistic approach to represent evacuation movement on stairs employing a probabilistic analysis of occupant travel paths. The scope of this paper is therefore to provide a method for an individual probabilistic description of people movement. Data from an evacuation drill performed in a

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six-storey building have been employed to demonstrate this approach. The benefits of the approach are presented in relation to the current methods adopted in engineering practice to represent people movement on stairs.

The present work also describes the advantages of the analysis of people movement data employing the new probabilistic approach from a modelling perspective. In fact, individual evacuation movement data can be aggregated using conditional probabilities, or employing a discretisation of the space in a grid or a combination of them. The uses of this type of data are discussed in relation to two categories of evacuation models, namely agent-based and cellular automata models.

2. Current approaches in stairs

Different methods and equations have been proposed to calculate the evacuation of people on stairs, based on different assumptions and datasets. The calculation methods can be based on observations from evacuation drills (e.g., [17,20]), normal operations (e.g., [7]), or a collection of different studies (e.g., [15,22]). The type of data employed together with the limitations associated with the data collection procedures may produce significant differences in the calculation methods [11], causing inconsistencies in the subsequent safety design. In particular, Hoskins and Milke [11] note that the calculation of the evacuation time in stairs can be significantly affected by the assumed travel distance and the areas used by the population.

Current methods [11,22] are deterministic, i.e., they assume that all occupants walk along a fixed line. Hypothetical equations are proposed by Hoskins and Milke [11] (see Eq. (1), which corresponds to an arc-based path) and Predtechenskii and Milinskii [22] (see Eq. (2), which corresponds to a rectangular path) to calculate fixed travel distance length in stair landings (see Fig. 1)

$$L_h = \pi b/2 + n_w + 2n_l \quad (1)$$

$$L_p = 2b + n_w + 2n_{l,} \quad (2)$$

where L_h (Hoskins and Milke) and L_p (Predtechenskii and Milinskii) are the hypothetical travel distance, b is the width of the stairs, n_w is the newel width, and n_l is the newel length (see Fig. 1). Predtechenskii and Milinskii do not mention the possible presence of the newel in the landing. The assumption is therefore to add the terms n_w and n_l within Eq. (2) in order to account for this additional element.

The use of a deterministic approach to represent occupant travel paths in stairs is a simplistic representation of the problem. In fact, actual events and experimental observations demonstrate that there is a significant variability of walked distances [27] and occupant speeds [2,12,19] in relation to the conditions of the evacuation (e.g., congestion levels, merging flows, etc.). In addition, the estimations of average travel paths on stairs may cause a distortion of evacuation timing. The impact of this assumption can be exaggerated in the case of high-rise building evacuation since hypothetical travel paths are employed for several floors. In this context, if a hypothetical inaccurate travel path is used in high-rise building evacuation calculations, the resulting error associated with this assumption would be repeated for each floor.

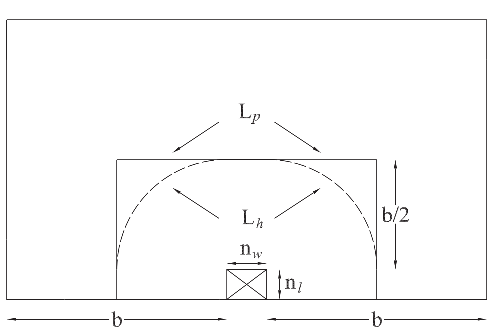

Fig. 1. Schematic representation of the hypothetical travel paths on stair landings assumed by Hoskins and Milke [11] (arc-based dashed line) and Predtechenskii and Milinskii [22] (rectangular continuous line).

Another important aspect to be considered is the estimation of the area of the stair (e.g., stair landing areas) used by the occupants during the evacuation process. Pauls [18] introduced the concept of *effective width* to describe the space available for people movement along escape routes. Calculations based on this concept are currently adopted in engineering practice [10]. Effective width is defined as the "*boundary layer clearance from walls and other stationary obstacles*" that persons moving through the exit routes maintain [10]. This concept is generally used for the calculation of people movement along different parts of their escape route, including stairs.

The concept introduced by Pauls [18] and adopted by Gwynne and Rosenbaum [10] is therefore based on the assumption that occupants do not use a certain portion of the space. In this case, there is a gap between the simplistic representation of space usage, i.e., a dual representation of space availability (either equally used by all the occupants or not used at all) and the actual behaviours of the occupants. The area used by the evacuees is a key aspect for the analysis of evacuation movement data since it affects the calculation of people densities and the subsequent level of service [7].

3. Probabilistic approach

The use of a probabilistic approach for the analysis of evacuation movement data relies on the tracking of individual occupant trajectories. Tracking individual trajectories allows the analyst to record travel path distance and area usage during evacuation (as shown by Nilsson and Petersson [16]) – in this case, stair landings. For instance, these data permit an evaluation of the assumptions currently adopted in engineering calculations in relation to the evacuation conditions [22,11]. This approach aims to capture the probabilistic nature of occupant movement, in turn producing more accurate evacuation datasets. In the present paper, this is made by presenting the probabilities associated with the movement of the occupants in different landings of the same stair of a building (the landings of the same stair generally have the same geometry), thus permitting repeated measurements of occupants' behaviours in different conditions. The probabilities of performing different actions (i.e., the observed paths, walking speeds, etc.) can then be analysed using different approaches (generally divided into frequentist or Bayesian methods). A frequentist approach is used in this paper, i.e., the probabilities are obtained by dividing the number of observed behaviours for the total number of observations. This permits the obtainment of the percentages corresponding to the probabilities of performing certain behaviours (i.e., the probability of having certain travel paths in the landing, walking in a certain portion of the landing area, etc.). Video monitoring of people movement on stairs during evacuation drills is used to capture these types of data.

While actual emergency data is most desirable and might provide the most realistic reflection of occupant behaviours, it is not as readily available as fire drill data. For practical purposes, fire drill data is often used to represent emergency behaviour. A key assumption is that fire drill data can be used to approximate the response of individuals in an actual emergency [23]. This is dependent on whether the population is directly exposed to