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A conceptual fatigue-motivation model to represent pedestrian movement during stair evacuation

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ABSTRACT

Evacuation models often neglect the impact of fatigue on pedestrian movement during stair evacuation. While a limited number of sub-models are available in the literature to represent fatigue during evacuations, they mostly refer to simple, fixed walking speed reductions due to physical fatigue. This paper introduces a more comprehensive conceptual model for the representation of the impact of fatigue on the performance of evacuees during building stair evacuation. The model is presented considering its conceptual formulation and the issues associated with its implementation. First, a comprehensive conceptual representation of the factors concerning fatigue affecting human behaviour is discussed. The model takes into account (1) physical factors (i.e., physical fatigue), and (2) psychological factors (i.e., motivation, intended as the variable balancing the perceived risk and the perceived fatigue). Second, the application of the proposed fatigue-motivation model to a hydraulic or Newtonian based evacuation modelling tool is discussed at various levels of sophistication.

1. Introduction

Evacuation models are often used to assess the life safety performance of a building in case of an emergency [1,2]. Current evacuation models focus mostly on representing the impact of crowding on walking speeds [1]. To date, more than sixty evacuation models (both commercial and research models) are available, each with different features or modelling methods [3]. Although those features have been categorized and analysed in different reviews and studies [1,4–7], no discussion on the impact of fatigue on occupant walking speed is included.

The need for the inclusion of fatigue in evacuation modelling is a known issue in the research community. For instance, Pelechano and Malkawi [8] explicitly pointed out that fatigue should be included in evacuation models used for engineering calculations. Additional studies highlighted the same issue in various applications such as high-rise building evacuations [9] and fire-fighter intervention during evacuations [10]. The experimental studies conducted by Denny [11] implemented in the simulations performed by Koo et al. [12] show that the reduction in speed due to fatigue may reach up to 66% of the initial speed for people without disabilities and up to 41% of the initial speed for people with disabilities. In such cases, the use of walking speeds which do not consider the impact of fatigue would lead to significantly shorter estimated evacuation times. The consequence of the lack of a comprehensive model for the representation of fatigue can thus lead to overly optimistic results (i.e. the actual walking speeds of people could be slower than the simulated walking speed, with subsequent shorter simulated evacuation times) which may impact the life safety design of a building.

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Nomenclature

$c_f^{i,j}$	crowding factor for an occupant *i* at the time-step *j*; $c_f^{i,j} \in [0, 1]$, where 0 is the maximum achievable impact of crowding on walking speed, and 1 = no impact of crowding on walking speed
$c_t^{i,j}$	threshold of crowding conditions for an occupant *i* in which crowding starts affecting walking speeds.
c_s	normalized speed
d	pedestrian density
$D_f^{i,j}$	building damage factor; $D_f^{i,j} \in [0, 1]$, where 0 is the case in which the occupant stops due to the highest impact of building damage, and 1 is the case in which the occupant walks at his/her current speed.
$f(F_p, R_p)$	function that calculates a “balance point” between perceived fatigue and perceived risk
$f^{i,j}$	the “balance point” for individual *i* at specific time-step *j* between fatigue and risk perception
f_n	fraction of the maximum achievable speed that an individual *i* at a specific time-step *j* would walk when risk perception and fatigue perception are balanced
$F(\cdots)$	physical fatigue function for an occupant
$F_f^{i,j}$	physical fatigue factor for an occupant *i* at time-step *j*
$F_p^{i,j}$	fatigue perception for an occupant *i* at time-step *j*
G	group behaviour
i	individual occupant
j	time-step
l	layout of the stair
$M(f)$	global motivation function
$M_f^{i,j}$	motivation factor for an occupant *i* at the time-step *j*; $M_f^{i,j} \in [0, 1]$, where 0 is the case in which the occupant stops due to extremely negative motivation, and 1 is the case in which the occupant walks at his/her current maximum achievable speed.
$P^{i,j}$	psychological factors affecting perceived fatigue (e.g., mental fatigue) for an occupant *i* at the time-step *j*
$R_p^{i,j}$	risk perception for an occupant *i* at the time-step *j*
$S_f^{i,j}$	smoke reduction factor for an occupant *i* at the time-step *j*; $S_f^{i,j} \in [0, 1]$, where 0 is the case in which the occupant stops due to extremely low visibility, and 1 is the case in which the occupant walks at his/her current speed.
U	variable referring to the direction of the stair (upwards or downwards i.e., ascending or descending) with $U \in [0, 1]$
$v_a^{i,j}$	actual speed of an occupant *i* at the time-step *j*; $v_a^{i,j} \in [0, v_{max}^{i,j}]$
$v_d^{i,j}$	desired speed of an occupant *i* at the time-step *j*; $v_d^{i,j} \in [0, v_{max}^{i,j}]$
v_{max}^{i}	maximum achievable walking speed of an occupant *i*
$v_{max}^{i,j}$	maximum achievable walking speed of an occupant *i* at the time-step *j*

The impact of fatigue on human performance may vary substantially, i.e., it can range from very low to extremely severe [13]. Experimental research [14] and case studies [15] showed that fatigue can occur in high-rise buildings as a result of physical effort and may have a significant impact on evacuation times. The National Institute of Standards and Technology (NIST) investigation of the 2001 World Trade Center disaster noted that occupants in some cases chose to rest during their evacuation, either on the stairs, or more frequently, on a landing [15]. The UK World Trade Center investigation reported that 85% of the sample studied in the stair evacuation in the North Tower stopped during their descent of which at least 8% were due to the need of evacuees to rest [16]. This created a delay in the individual and the global evacuation times and affected the life safety performance of the building. The latter study also highlighted the interactions among evacuees and the fact that altruistic behaviour tended to reduce the movement speed of groups of evacuees rather than affecting only individual performance, i.e., the reduced speed of an individual due to fatigue can affect the walking speed of an entire group of evacuees.

Fatigue can also play an important role in stair evacuation for building contexts other than high-rise building evacuations. For example, building evacuation strategies may also include ascending stair movement (for instance in the case of an evacuation from an underground metro station), with the impact of fatigue being likely to occur even after walking smaller distances [17]. For example, during a group evacuation experiment [18] on a stopped escalator in a metro station, median walking speeds dropped from approximately 0.8 m/s to 0.52 m/s (an approximately 35% speed reduction) in about 70 m of walked distance. Issues concerning fatigue can be increased by the changes in occupant demographics, such as an aging or less fit building population [19] or those with health problems [15].

However, a very limited number of models are available to represent the impact of fatigue on people movement [11,20,12]. Models representing the impact of fatigue are used in the field of biology [11] and sport science [21,22]. The main limitation of those models is typically that they represent fatigue from a physical perspective, i.e., they only consider fatigue as a simple, fixed reduction of movement speed in relation to walked distance, without taking into account varying physical and psychological factors.