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Ascending stair evacuation: what do we know?

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Abstract

During ascending evacuation in long stairs, there is reason to believe that factors such as physical exhaustion, human behaviour and the mental state will influence the possibility of satisfactory evacuation and affect walking speed and flow rate of people. Based on these hypotheses, a research project was initiated. As a part of the project, an initial literature study has been conducted. The literature study has made an attempt to summarize the most important findings of previous research about physical exhaustion and design of stairs for ascending evacuation in long stairs. This paper presents the findings from the literature study.

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1. Introduction

In order to meet with the society's increased and/or reformed demands related to (among other things) environmental concerns, urbanization and optimization of travel times, the development of underground facilities, such as underground transportation systems, has increased rapidly during the last decades. Road and rail tunnel systems are, for example, not only becoming more and more, but also longer and deeper. However, as the main principle for buildings under ground is the same as for buildings above ground (i.e., that people should be able to leave it safely in case of fire), the increased exploitation of underground facilities introduce new challenges in terms

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fire safety design. As an example, people may be required to evacuate long vertical distances in (in this paper termed ascending evacuation) in order to reach a safe place (Delin and Norén (2014)). Often, these evacuation routes consist of stairways.

In contrast to research on descending stair evacuation, ascending stair evacuation has received very little research attention (see, for example, the summary by Frantzich (1993)). The consequence is that the design of (ascending) stairways for evacuation has not changed significantly during the last 40 years, and often this part of the overall evacuation is treated with oversimplified models based on relationships between, e.g., the walking speed of individuals and the population density (Frantzich (1993); Lord et al. (2005)). For descending evacuation in stairways, single initiatives have been taken to include other engineering variables (e.g., design parameters and distances to safe places), but a recent study demonstrated that even these engineering models have a very low explanatory value in terms of describing the total variation in walking speed (just over 13%) (Peacock et al. (2009)).

Predicting walking speeds during ascending stair evacuation in long stairways is difficult for a number of reasons. Apart from the fact that little data exists due to the lack of research, the nature of ascending stair evacuation suggest that parameters such as physical exhaustion, human behaviour and also subjective, psychological emotions, will determine the walking speed and in turn the chances of a satisfactory evacuation of an underground facility (Frantzich (1993, 1996)). In addition, it is likely that the evacuation behaviour of a tall stairway will differ from a short stairway, as the required workload can be expected to be higher (and increase with increasing height).

It is argued that the high uncertainty related to ascending stair evacuation assessments, as well as the increasing trend to build underground (for example) transportation systems, require a fundamental, holistic approach to increase the understanding of the phenomenon. In Sweden, a 2-year research project was therefore initiated in October 2013 to study and quantify the expected evacuation process during ascending stair evacuation in long stairways. One of the goals of the project is to investigate whether physical exhaustion is a descriptive parameter during ascending evacuation, and whether or not it affects walking speed, flow rate of people and/or other human behaviour activities. Within the project, three full-scale evacuation experiments will (among other things) be carried out; two experiments in regular stairwells and one in an escalator.

As a first part of the project, a literature review was performed. The purpose of this paper is to present this literature review by summing up and reproduce previously published research results on the topic of ascending stair evacuation, and the link to walking speed, flow rate of people and the effects of physical exhaustion. The goal of this paper is to, in a condensed manner, present these results and the possible effects that they will have on the fire safety design process including ascending stair evacuation. This paper is based on an extensive report by Delin and Norén (2014), in which a more comprehensive description of the literature review method as well as the results can be found.

2. Methodology

The methodology of the literature review was structured in a clearly defined working process in an early stage of the study. To ensure that the research project's objectives were met, a number of hypotheses were defined. They were then discussed within the project group and reformulated to ensure that the literature review focused on relevant parts. As a result of this process, the following two hypotheses were defined (related to ascending evacuation in long stairs):

a. Physical exhaustion is a descriptive parameter for the evacuation process, and will affect walking speed, flow rate of people and behaviour.
b. The design of stairs will affect the evacuation processes.

In order to examine whether the hypotheses could be verified or falsified, different sub-questions were defined and answered. The questions examined, and presented in this paper, were:

- Can physical exertion influence on the evacuation process?

If the answer is yes, the following questions were addressed:

- What is the impact on walking speed, flow rate of people and human behaviour when evacuation upwards in long stairs?
- Are there any former research results related to mathematical modelling of ascending evacuation in long stairs?
- Are there any recommendations related to the design of stairs for stairs primarily used for ascending evacuation?

3. Ascending stair evacuation, physical exhaustion and evacuation modelling

Based on the defined hypotheses, the initial part of the literature review focused on investigating if there were any prior research that have highlighted physical exhaustion, and the effects that it may have on the evacuation process in general. To do so, a brief search was made on different databases for the words *evacuation*, *exhaustion* and *fatigue*.

The result from the literature review was that there are strong arguments for the hypotheses that physical exhaustion may influence the evacuation process. Different studies have highlighted the issue in discussions and conclusions during the last 40 years. For example, Egan (1978) highlighted the effects of physical exhaustion and that effects that can be expected to appear and have impact on the evacuation processes, given that the evacuation takes longer than 5 minutes. However, this has, according to Khisty (1985) never been confirmed in any evacuation experiments. In another study, by Peacock et al. (2009) about evacuation of high rise buildings, the authors stated that the average walking speed will decrease in correlation to the height of a building. The change in walking speed was according to the authors, caused by physical exhaustion. The effect of physical exhaustion was also highlighted in a literature review conducted by Frantzich (1993). Frantzich (1993) concluded that the walking speed would be lower in longer stairwells according to the additional physical work needed to move forward. However, past research studies have only been on a limited part of the population (younger persons) and no general conclusions have been presented.

In terms of physical exhaustion related to ascending stair evacuation, only one study was found that had tried to explicitly study and quantify the degree of influence that physical exhaustion may have on the evacuation process. The study was performed by Choi et al. (2013). The conclusions from this study were that the effect of physical exertion varies from individual to individual depending on the type of exercise that has been undertaken and by personal factors such as health status, physical condition and previous physical work during the trial. The authors concluded that a reduction in walking speed during ascending stair evacuation might depend on the increased physical effort. The physiological phenomenon, which may generate effects of fatigue, was however not clarified. Still, the authors speculated that the reduction in walking speed might depend on the initial physical exertion, which can generate an anaerobic metabolism that cannot be maintained for a longer time.

3.1. Evacuation modeling

In the discussion by Choi et al. (2013), the question concerning modelling of physical exhaustion during evacuation was highlighted. They did conclude that it might be possible to incorporate the result in agent based evacuation models as an individual reduction parameter for walking speed. But no mathematical models or equations were presented.

4. Physical exhaustion, walking speed, flow rate of people, and behaviour

The walking speed is affected when walking a long distance in stairs. This has been demonstrated, both during ascending and descending evacuation, but it is most evident for ascending evacuation. For example, in the study by Choi et al. (2013) the average walking speed in floor 26-50 compared to floor 1-25 was reduced by 27% for men and 21% for women. In that study, the mean walking speed changed after about 90 seconds of ascending evacuation (according to the figure presenting the mean travel time). By that time, the men were in the area of floor 12, and the women were in the area of floor 9. The walking speed is also affected by whether or not a person is walking alone or in a group. Table 1 presents a summary of walking speeds during ascending stair evacuation, reproduced from the studied literature. Most of the studies present the walking speed along the stair slope (otherwise it is stated below).

Only two of the studied papers involved long ascending evacuation, (Kretz et al. (2006) and Choi et al. (2013)). The collected data origins from different decades and stem from different parts of the world, and in addition, the experiments have often involved only young and healthy persons. It is suggested that it should be interpreted and used with this in mind.

Table 1. Walking speeds upwards stairs from the studied literature.

Average speed (m/s)	General information	Source	Year	Country
0.67	Men younger than 30 years	Fruin	1971	USA
0.64	Women younger than 30 years			
0.63	Men between 30 and 50 years			
0.59	Women between 30 and 50 years			
0.51	Men over 50 years			
0.49	Women over 50 years			
0.52[a]	Single person	Kretz et al.	2006	Germany
0.47[a]	Group of people not affecting each other (low density)			
0.44[a]	Group of people affecting each other (high density)			
0.27[b]	Elderly women (> 65 years)	Yeo and He	2009	Singapore
0.28[b]	Elderly (> 65 years)			
0.29[b]	Elderly men (> 65 years)			
0.29[b]	Children (< 13 years)			
0.30[b]	Adult women			
0.31[b]	Adults			
0.32[b]	Adult men			
0.75[c]	Men floor 1-25 (average)	Choi et al.	2013	Korea
0.55[c]	Men floor 26-50 (average)			
0.53[d]	Women floor 1-25 (average)			
0.42[d]	Women floor 26-50 (average)			
	The building was 50 floors high			
0.5	High density (but not higher than 2 persons per square meter)	Boverket	2013	Sweden
0.6[e]	Low density			
	Design values in the Swedish building code			

[a] The stair had a slope of 35.1° and was 35.8 meters high. The speed was measured after 25 meters.
[b] Vertical speed. Several short stairs at different metro stations was studied. 643 commuters were studied. The slope of the stairs is not known.
[c] The study involved 30 men in the age 20-28 years (average 24.6 years).
[d] The study involved 30 women in the age 20-28 years (average 22.2 years).
[e] The value is based on a few observations.

Table 2 presents a summary of walking speeds during ascending evacuation in escalators from the studied literature.

Table 2. Walking speeds upwards escalators from the studied literature.

Average speed (m/s)	General information	Source	Year	Country
0.8[a]	Single person	Kadokura et al.	2009	Japan
0.7[a]	Group			
	The escalator had a height of 13.2 meters.			
0.77[b]	Single person	Okada et al.	2009	Japan
0.49[b]	Single person with obstructing gear [c]			
0.54[b]	Group without obstructing gear			
0.47[b]	Group with some peopled carrying obstructing gear [c]			
	The escalator had a height of 22 meters.			

[a] The studied group consisted of 79 university students.
[b] The studied group consisted of 35 male and 15 female university students with the average age 21 years.
[c] ”Instant senior” is a young person equipped with obstructing gear to simulate an elderly person concerning moving ability and seeing ability.
[d] The persons equipped as ”*instant senior*” affected the whole group.

Walking speed can be expressed in several ways:

a. Along the stair slope.
b. The horizontal component of the movement.
c. The vertical component of the movement.

These different methods are visualized in figure 1, and as stated below, alternative *a* dominates in most past research studies.

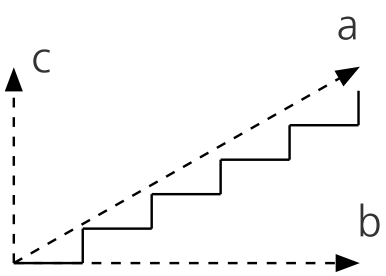

Fig. 1. Different ways of measuring the walking speed in stairs.

The interpersonal distance in the walking direction plays an important role for the flow rate of people through the stair. However, in the studied literature, the opinions diverge whether the interpersonal distance is longer or shorter during ascending evacuation compared to descending. Only one study enables a comparison to the interpersonal distance for the same walking speed (Københavns brandvæsen og Tryg i Danmark (2000)), and in that study the interpersonal distance was demonstrated to be longer when walking upward in a stair with the same speed downward.

There are different opinions in the studied material about the correlation between the population density and the walking speed. It seems, though, that the differences may depend on whether the discussion concerns high or low density. In high densities, there seems to be a quite strong correlation between walking speed and density but in low densities the correlation seems to be week (Frantzich (1993)).

The flow rate of people in a stairwell is a very important design parameter, but the studied materials offer no data (only some assumptions) on that. Experiments seem to not study both speed and interpersonal distance and flow rate of people, and therefore calculations can only be done with assumptions about the interpersonal distance for a known walking speed, or with assumptions on the flow rate.

The angle of the stair is suggested as a describing parameter for the walking speed (Fruin (1971); Fujiyama and Tyler (2010a, 2010b); NAHB Research Center (1992)), but the available data consist of very few observations and the angle is not isolated in the studies.

The studied material implies that the variation in walking speed is large for ascending evacuation (see Table 1). Taken into account that the populations studied normally are young, healthy people, it is hypothesized that the variation would be even larger if a population representative for the reality is studied.

The studied material does not present any observations concerning human behaviour during long ascending evacuation. The only thing mentioned within that field is the difficulties in passing slower persons in escalators or narrow stairs (Okada et al. (2009)).

Kholshevnikov et al. (2008) suggest that psychological factors may be of importance during long evacuations, i.e., those emotions can affect the walking speed. The authors argue that increasing the walking speed (if not hindered by other people) can be positive in order to lower the experienced stress, and feeling tired can make it more laboriously to walk.

5. Design of stairs for ascending evacuation

Based on the hypothesis that the design of stairs will affect the evacuation processes during ascending evacuating in long stairs, the literature review also tried to find studies according design on stairs to examine whether the hypotheses could be verified or not.

The findings of the review were that the basis for stair design today is the result of research carried out during the 1970s, and the Swedish design criterions for stairs are primarily based on the results of a mayor research project by Kvarnström (1977) and Kvarnström and Ericson (1980). In their studies they have, among other things, studied the design of steps, the walking line in stairs and the effects of having handrails installed in the stairs. In connection to their studies they also summarized the existing knowledge about stairs.

The main focus for the design of stairs in Sweden is for declining movement due to the fact that the risk of accidents is larger when moving downwards compared to moving upwards (Kvarnström and Ericson (1980)). This is an important parameter that needs to be considered in the design of stairs that primarily will be used for ascending movement. There is hence a need to use other design criterions for the correlation between the tread and riser, and the height of a handrail, compared to the recommendations that building regulations defines. However, the reviewed literature have not presented any clear recommendations on how to design stairs that are primarily intended for ascending movement, and as result from this, no studies has been found that explicitly deal with the design of ascending stairs and physical exhaustion.

5.1. Design of steps

Design of steps has been a subject for research since the late eighteenth-century and one of the most used correlations between the riser and tread was defined (Kvarnström and Ericson (1980)). An equation was developed for ascending movement, and studies were made on adult men. The different parts of a step (riser, nosing and tread) are illustrated in figure 2, and the equation is presented in equation 1.

$$2H+B = 60 - 63 \text{ cm.} \quad (1)$$

H = Height of the riser
B = length of the tread

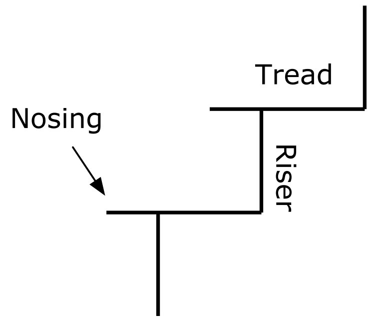

Fig. 2. Different parts of a step - riser, nosing and tread.

Lichtneckert (1973), who studied movement in stairs from a physiological perspective, did however conclude that there are no universal correlations between risers and treads, which will be optimum for all people during both ascending and descending movement. Lichtneckert (1973) also studied the difference in physiological movement when walking upwards and downwards in stairs, and concluded that ascending stair movement primarily involves movement in the hip and knee, and that descending movement in stairs primarily involves movement by bending the knee and the ankle. According to this, and the way people move their feet over the tread, Selvik and Sonesson (1974) concluded that when designing stairs for descending movement, the riser should be longer compared to stairs designed for ascending movement. Selvik and Sonesson (1974) also recommended that the dimensions for the riser should be between 25-30 cm, to ensure that the user did not have to take too long strides when walking downwards, and that the riser should not exceed 20 cm. According to the authors, risers over 20 cm would generate a complex muscular and skeletal movement. Others have also recommended the same levels of dimensions; see for example Fruin (1971). Finally, to increase the safety in the stairs, Selvik and Sonesson (1974) concluded that there should not be any variations in risers and treads within a stairwell.

5.2. Walking line and effective width

In the study by Kvarnström and Ericson (1980), the effect of walking line in a stair was been highlighted. The concept of the walking line is a theoretical line that defines where you should design the step ratio within the stairs. Walking lines have been demonstrated to vary between different people depending on age, gender and walking speed, and furthermore, the walking line has been demonstrated also to depend on the design of the stairs. According to Kvarnström and Ericson (1980), the walking line should be measured 30 cm from the handrail.

Pauls (1995) presented similar conclusions in his study concerning the effective width-model. According to the model, the flow rate of people relates linearly to the effective width. As a result of this, Pauls (1995) recommended that effective width should be used instead of actual stair width when analysing the flow rate of people in stairs. The difference between actual width and the effective width was, according to Pauls, 150 mm on each side of the stairs, measured from the centre of the handrail.

5.3. Handrail

Kvarnström (1977) and Kvarnström and Ericson (1980) have analysed the impact on handrails. According to the authors, the purposes of handrails are to facilitate the use of stairs and make them safer to use. The presented recommendation was that a handrail should be placed 90 cm over the nosing in order to ensure that it could be used for both descending and ascending movement. For ascending movement it was recommended that the handrail was placed higher over the nosing, but no exact recommendations have been found.

6. Discussion, conclusions and future research

The results of the literature review presents that there are strong arguments for accepting the hypotheses that physical exhaustion may influence the evacuation process during ascending evacuation. However, few studies have explicitly studied and quantified the degree of influence that physical exhaustion has on the actual evacuation process. Effects of physical exhaustion has been identified during longer ascending evacuations, and earlier studies have showed that this may affect the evacuation in terms of reduced walking speeds. But, it has not been determined when physical exhaustion begin to affect the walking speed, nor to what extent. According to reviewed literature, there are also uncertainties related to whether the movement of people in ascending stairs is controlled by the walking speed in relation with interpersonal distance, or not.

Based on past research studies, the design of stairs has been shown to impact the safety when walking in a stair, which in many ways determines its design. Due to the fact that the risk of accidents is higher during descending movement compared to ascending movement, today's design guides and building codes for stairs is primarily adapted to downward movement. The movement of the body when walking upwards in a stair do, however, differ from the movement when walking downwards, concerning the physiological movements of the legs and hips. Still, no studies have been identified that that explicitly deals with the design of the stairs for ascending evacuation.

Based on the questions and the result of the present literature reviewed, the study's hypotheses cannot be falsified, but they have rather been strengthened. However, the evaluated literature did not provide sufficient evidence to fully accept them or in-depth describe them. Therefore further studies are needed before a definitive answer can be given concerning the correlation between physical exertion and evacuation, and design criteria for stairs mainly designed for upward movement. Future studies are recommended to focus on:

- Walking speed and the flow rate of people, including behaviour, and whether maximum heights for ascending evacuation processes are necessary to recommend for design purposes.

- Proper design criterions of long stairs intended primarily for upward evacuation for optimizing flow and safety.

7. References

Boverket, 2013. Boverkets ändring av verkets allmänna råd (2011:27) om analytisk dimensionering av byggnaders brandskydd (BFS 2011:27 med ändringar t.o.m. 2013:12). Boverket, Karlskrona, Sweden.

Choi, J-H., Galea, E.R., Hong, W-H., 2013. Individual Stair Ascent and Descent Walk Speeds Measured in a Korean High-rise building. Journal: Fire Technology December 2013. Online ISSN: 1572-8099, Publisher: Springer US.

Delin, M., Norén, J., 2014. Fysisk ansträngning vid utrymning uppför trappor – Kunskapsöversikt. Lund University, Department of Fire Safety Engineering, Lund, Sweden.

Egan , M. D., 1978. Concepts in building fire safety, John Wiley and sons Inc., New York, USA.

Frantzich H., 1993. Utrymningsvägars fysiska kapacitet, sammanställning och utvärdering av kunskapsläget. Lund University, Institute of Technology Department of Fire Safety Engineering, Lund, Sweden.

Frantzich, H., 1996. Study of Movement on Stairs During Evacuation Using Video Analysing Techniques. Lund University Institute of Technology Department of Fire Safety Engineering, Lund, Sweden.

Fruin, J., 1971. Pedestrian planning and design, Metropolitan association of urban designers and environmental planners. New York, USA

Fujiyama, T., Tyler N., 2010a. An Explicit Study on Walking Speeds of Pedestrians on Stairs. Centre for Transport Studies, University College London, UK.

Fujiyama T., Tyler, N., 2010b. Prediction the walking speed of pedestrians on stairs. Transportation Planning and Technology 33(2), 177-202.

Kadokura, H., Sekizawa, A., Takahashi, W., 2009. Study on availability and issues of evacuation using stopped escalators in a subway station, 4th International Symposium on Human Behaviour in Fire Symposium, Cambridge, UK.

Khisty, J., 1985. Pedestrian flow characteristics on stairways during disaster evacuation. Transport Research Record 1047, 97-102.

Kholshevnikov, V.V., Shields, T.J., Boyce, K.E., Samoshin, D.A., 2008. Recent developments in pedestrian flow theory and research in Russia. Fire Safety Journal 43. 108-118.

Kretz, T., Grünebohm, A., Kessel, A., Klüpfel, H., Meyer-König, T., Schreckenberg, M., 2006. Upstairs Walking Speed Distribution on a Long Stairway. Physik von Transport und Verkehr, Universität Duisburg-Essen, Duisburg, Germany.

Kvarnström, L., 1977. Trappor, en sammanställning av delrapporter rörande trappor och trappgåendet. Arkitektur 1 B, Lunds tekniska högskola, Lund, Sweden.

Kvarnström, L., Ericson, L., 1980. Spiraltrappan, en diskussion om risker och rörelseer. Arkitektur 1 B, Lunds tekniska högskola, Lund, Sweden.

Københavns brandvæsen og Tryg i Danmark, 2000. Brand og brandsikkerhet i forsamlingslokaler – et fælles ansvar. Copenhagen Fire Brigade, Department of Fire Prevention, Copenhagen, Denmark.
Lichtneckert, S., 1973. Arbetsfysiologisk undersökning. Fysiologiska institutionen, Lunds universitet, Lund, Sweden.
Lord, J., Meacham, B., Moore, A., Fahy, R., Proulx, G., 2005. Guide For Evaluating the Predictive Capabilities of Computer Egress Models. National Institute of Standards and Technology, Gaithersburg, USA.
NAHB Research Center, 1992. Stair Safety, A Review of the Literature and Data Concerning Stair Geometry and Other Characteristics. Prepared for U.S. Department of Housing and Urban Development Office of Policy Development and Research, Washington, USA.
Okada, N., Hasemi, Y., Moriyama, S., 2009. Feasibility of upward evacuation by escalator – An experimental study. 4th International Symposium on Human Behaviour in Fire Symposium, Cambridge, UK.
Pauls, J., 1995. Movement of people, chapter 3-13, The SFPE handbook of fire protection engineering, second edition. Society of Fire Protection Engineers, Bethesda, MD, USA.
Peacock, R.D., Averill, J.D, Kuligowski, E.D., 2009. Stairwell Evacuation from Buildings: What We Know We Don't Know, NIST Technical Note 1624, National Institute of Standards and Technology, Gaithersburg, USA.
Selvik, G., Sonesson, B., 1974. Rörelsemönster vid gång i trappor. En funktionell-anatomisk studie. Byggforskningens rapportserie, Lund, Sweden.
Yeo, S.K., He, Y., 2009. Commuter characteristics in mass rapid transit stations in Singapore, Fire Safety Journal 44, 183-191