Assessment of Total Evacuation Systems for Tall Buildings: Literature Review

Final Report

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FOREWORD

Building evacuation strategies are a critical element in high rise building fire safety. Research to date has focused on elevators and exit stairs; however, there is a need to apply this research to relocation and evacuation systems which may include combinations of these two exit strategies as well as new egress components such as sky bridges for tall buildings.

Accordingly, the Fire Protection Research Foundation initiated this project with the objective to study possible improvements to life safety of tall buildings through an investigation of occupant relocation and evacuation strategies involving the use of exit stairs, elevators, sky bridges and combinations thereof. The study consists of a review and compilation of existing information on this topic as well as the conduct of case study simulations of a multi component exit strategy. This review provides the architectural design, regulatory, and research communities with a more thorough understanding of the current and emerging evacuation procedures and possible future options. This report documents the literature review that was undertaken for the project.

The Research Foundation expresses gratitude to the report authors Enrico Ronchi, PhD, and Daniel Nilsson, PhD, who are with Lund University located in Lund, Sweden. The Research Foundation appreciates the guidance provided by the Project Technical Panelists and all others that contributed to this research effort. Special thanks are expressed to the National Fire Protection Association (NFPA) for providing the project funding through the NFPA Annual Code Fund.

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Fire Evacuation in High-rise Buildings:

a Review of Human Behaviour and Modelling Research

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Abstract. A review of literature related to fire evacuation in high-rise buildings was carried out with the objectives to (1) identify the key behavioural factors associated with the event of a fire in a high-rise building, (2) review the current procedures and strategies currently adopted in high-rise buildings (e.g. horizontal and vertical evacuation methods, phased evacuation, total evacuation, defend-in-place, etc.), (3) review the capabilities of the currently available egress models to simulate high-rise building evacuations, (4) review the previous applications of egress models for high-rise building evacuations, and (5) suggest areas on which future research should focus on. The review included both findings on human behaviour in high-rise building and modelling techniques and tools. Different categories of high-rise building use were taken into account, namely office buildings, residential buildings (e.g., hotels, apartment buildings) and health care facilities. The use of different egress components was analysed, either individually or in a joint manner. Egress components include the use of stairs, elevators as well as alternative means of escape (e.g., sky-bridges, helicopters, etc.). The effectiveness of the egress components is strongly affected by the building use and the population involved. The review shows that evacuation models can be effectively employed to study relocation strategies and safety issues associated with high-rise buildings. The suitability of egress models for high-rise building evacuations is associated with their flexibility in representing different egress components and the complex behavioural processes that may take place. The review highlights that there is not a definitive model to be used for this type of environments but that the predictive capabilities of evacuation modelling techniques would be enhanced if more than one model is employed to study different egress aspects. Future research and model developments should focus on the study of the impact of staff actions, group dynamics and people with disabilities. Given the increasing height of buildings and the gradual reduction in the physical skills of the population, the effects of fatigue on evacuation need further studies.

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Fire Evacuation in High-rise Buildings: a Review on Human Behaviour and Modelling Research

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1. Introduction

According to the definition of the National Fire Protection Association [NFPA, 2012], high-rise buildings are defined as "*buildings greater than 75 feet (approximately 23 m) in height where the building height is measured from the lowest level of fire department vehicle access to the floor of the highest occupiable story*". According to Hall [2011], the main building uses that can be identified to categorise this type of buildings are office buildings, residential buildings (e.g., hotels, apartment buildings) and health care facilities. Each of these categorise present different characteristics from the point of view of both the infrastructure and the population. The analysis of the building use is therefore crucial to predict the possible behaviour of the occupants and provide an adequate fire safety design.

Although building codes establish the minimum requirements for the design of a high-rise building, additional life safety features are often necessary to mitigate the issues deriving from the complexity of this type of buildings and the additional difficulties in fire-fighting and rescue operations. The perspective of the technical International guidance, e.g., NFPA101 in the U.S. [NFPA, 2012], or the Approved Document B [The Building Regulation, 2006] in the UK, etc. is to provide information on the design of the egress components (e.g., geometric characteristics of the stairs) that can be applied for high-rise buildings. On the other hand, further information on the behavioural issues associated to the egress performance during high-rise building evacuations is still required. General concepts can be employed although additional specific recommendations are required given the particular features of this type of buildings. Dedicated recommendations have been provided by national and international committees, e.g. the GB50045-95, Code for Fire Protection Design of Tall Buildings in China [GB50045-95, 2005], the Fire Safety Requirements for super high-rise residential buildings in Singapore [Singapore Civil defence Force, 2006] or the chapter 7 of the Fire and Life Safety of National Building Code of India [Bureau of Indian Standards, 2005].

Recent US statistics [Hall, 2011] show that an average of 15,700 fires were reported in high-rise buildings per year in the USA, causing a total of 53 deaths, 546 injured, and $235 million in direct property damage per year. High-rise buildings present a lower number of fatalities than low-rise buildings of the same type. However, the attention on this type of buildings is raised by the fact that even a single high-rise building fire may cause a significant number of fatalities due to the possible high number of people involved. Researchers have performed in-depth analyses of particularly memorable incidents in order to study the high-rise fire problem. Examples are available in the literature, such as the MGM Grand Hotel Fire where the total number of fatalities was 85 [Best & Demers, 1982, Clark County Fire Department, 1981], the bombing of the Oklahoma Murray Federal Building resulting in 168 fatalities [Mallonee et al., 1996] or the Chicago Cook County Administration Building Fire [Proulx & Reid, 2006] that resulted in 6 fatalities.

The Research on high-rise buildings became a growing concern to safety committees working on codes near the end of the 60ies [Galbreath, 1969, Melinek & Booth, 1975]. The design of exit stairs was the main issue analysed at the time, providing formulas of exit stair width and minimum total evacuation times. Significant work in this area was performed in the 70ies and 80ies [Pauls, 1978, Pauls, 1988]. The focus of these studies was the application of the hydraulic movement models taking into consideration the behavioural factors. This permitted to include the pre-evacuation activities of the occupants in the analysis of the actual evacuation times of tall buildings.

More recently, a great sense of awareness on this topic was raised by the World Trade Centre terrorist attack of 9/11 [Averill et al., 2005]. The event results in a paradigm shift to the assessment of high-rise buildings safety. It showed the importance of providing robust means of egress and the need for further investigating the interactions between the infrastructure, the procedures and the behaviour of the occupants [Galea et al., 2008a, Galea et al., 2008b].

Several questions have been prompted about the adequacy of our current safety regulations and emergency procedures for high-rise buildings. For what type of evacuation scenarios should we design high-rise building? What egress components are recommended to evacuate a high-rise building? Are elevators suitable for evacuation purposes? What design measures or procedures should be employed to improve egress efficiency? These questions do not have a simple answer and the specifics of each building need to be taken into account. In addition, the lack of knowledge in terms of the behavioural aspects taking place during a high-rise building evacuation is still evident [Kuligowski, 2011]. Specific recommendations on single aspects of the evacuation process rely therefore on a previous analysis of the single variables to be investigated. For this reason, there is a need to perform a review of the literature available on the main variables affecting high-rise evacuations, such as the egress components employed (i.e., stairs, elevators, etc.) and the strategies in use (phased evacuation, total evacuation, defend-in-place, etc.). In particular, there is a need for an analysis of the studies concerning the evacuation through vertical transport and methods to encourage the use of elevators for evacuation. There is also the need to investigate if the use of different components has been studied individually or if there are attempts to investigate the combinations of different egress strategies.

Evacuation models are often used in the safety design process in the context of the performance-based design approach. They may be employed both to compare different safety designs as well as define the adequate egress strategies of a building. There is a subsequent need to review the state-of-the-art of the different tools available and their applicability for the specific case of high-rise buildings. Are they suitable to provide qualitative and quantitative information on the impact of the use of different egress components? Are they adequate to compare different design solutions and relocation strategies? These are some of the questions that need to be studied further to achieve a better understanding on the capabilities of egress models for simulating high-rise building evacuation scenarios. This analysis is a fundamental step to evaluate the strengths and weaknesses of the current egress models and consequently identify the aspects that need further research studies.

1.1 Objectives

In order to answer to the questions provided in the previous chapter, a set of objectives of this literature review have been identified. The objectives of this study are to:

(1) identify the key behavioural factors affecting the performance of people during a fire in a high-rise building and the singularities associated to this type of buildings.

(2) review the current procedures and strategies currently adopted in high-rise buildings (e.g. horizontal and vertical evacuation methods, phased evacuation, total evacuation, defend-in-place, etc.).
(3) review the capabilities of the currently available evacuation models to simulate high-rise building evacuations.
(4) analyse the previous applications of egress models for high-rise building evacuations by identifying the major concepts and findings deriving from these studies.
(5) suggest areas on which future research should focus on in order to improve the safety of high-rise buildings.

1.2 Method

A literature review was performed in order to achieve the objectives of this study. The first step was the definition of a number of keywords to ensure a systematic search in databases. The keywords were: *high-rise building, tall building egress, emergency evacuation, evacuation strategies, evacuation elevator, stair evacuation.* The literature was retrieved from different databases, primarily ScienceDirect, Summon and www.Evacmod.net. The material was integrated with relevant literature from colleagues and other publications/reports known to the authors prior to the review.

The material analysed can be divided into three main categories; (1) human behaviour in high-rise building fire evacuations, (2) egress components and strategies, and (3) modelling studies. The material collected contributes to the definition of the problems that need to be considered when analysing high-rise building evacuations and assess the field of studies in which further research is required.

1.3 Limitations

This work focuses on the study of the use of different egress components for the evacuation of high-rise buildings by means of egress modelling. Due to the fact that the literature review is carried out within this context, it primarily addresses issues concerning evacuation and human behaviour in the event of fire and the application of egress models.

The study focuses on the most common building uses, namely office buildings, residential buildings (e.g., apartments, hotels) and health care facilities. According to Hall [2011], these building uses account for the most significant part of high-rise building fires. Nevertheless, other types of uses are possible (e.g., assembly, recreation, storage, etc.) and the associated design and behavioural issues may present different characteristics.

Only literature considered relevant for the project has been included in this review. The literature is therefore limited to high-rise building evacuation studies. This includes the analysis of human behaviour in fire, occupant relocation strategies and modelling studies. These topics are considered valid for the objectives of the project and relevant for the follow up of the project, which will include the analysis of a model building case study.

1.4 Outline

The study is divided into six sections. Section 1 deals with the introduction of the problem, namely the definition of a high-rise building, relevant statistics on fire evacuations and the historical background of this field of research. A set of questions on high-rise building safety are identified. The legislation context is also briefly presented. The objectives and the research method of the study are described together with the limitations.

The aim of Section 2 is to identify the key factors associated with different uses of high-rise buildings. This includes office buildings, residential buildings (apartment and hotels) and health care facilities. Design and behavioural differences are analysed from an egress perspective.

Section 3 deals with the issues about the use of different egress components. Egress components include the use of stairs, evacuation elevators, sky-bridges, and alternative means of escape (e.g., helicopter evacuation, etc.).

Section 4 of the study provides an analysis of the evacuation strategies that can be employed to evacuate a high-rise building. The combined use of different egress components is described, with a particular focus on the joint use of evacuation elevators and stairs. The main strategies are analysed, namely total evacuation, phased evacuation, defend-in-place, and delayed evacuation. The issues associated with people with disabilities are described as well.

Section 5 is a review of the capabilities of the main evacuation models for simulating high-rise building evacuations. A set of previous examples of applications have been described, such as the simulation studies of the World Trade Center evacuation and the use of different type of modelling techniques (i.e., coarse network models, fine network models and continuous models).

Section 6 presents a discussion on the material that has been analysed in the literature review. The last part of the study, namely Section 7, provides suggestions on future research topics that need to be investigated.

2. Design and Behavioural Issues Associated with Building Use

The use of the building is one of the key aspects for the definition of the design and behavioural issues associated with the different egress components (either vertical or horizontal). Three main categories of use have been identified:

1. Office buildings
2. Residential buildings (e.g. apartment, hotels, etc.)
3. Health care facilities

The building use affects several factors concerning the egress performance of a high-rise building such as the design, the characteristics of the population, the training of the population, the staff available, the fire safety installations, etc.

The study of the characteristics of the different types of high-rise buildings is crucial to understand the possible egress strategies to be adopted. In particular, the occupant on the upper floors could need to walk very long distances to reach the ground level. This may cause the need for rest periods during the evacuation and a subsequent additional increase in the evacuation times [Proulx, 2001]. Solutions should be therefore found to perform a rapid and safe evacuation.

2.1 Office buildings

From a design perspective, office buildings have generally open concept floor plans, which cause a reduction of the possibility to contain the fire within a compartment. Occupants are generally better prepared to evacuate the building since they are generally trained through evacuation drills and they are dressed, alert and responsible mainly for themselves [Proulx, 2001]. Occupants are often familiar with the environment and the escape routes [NFPA101, 2012, BSI, 2004]. Fire systems are generally well-maintained, and may include recorded voice messages and fire alarms. Staff is generally available on hand.

2.2 Residential buildings

Residential buildings present completely different characteristics from both a design perspective as well as the characteristics of the population involved. In fact, occupants may be asleep, not dressed, etc. i.e., they are not ready to evacuate, thus causing a long delay in the start of the evacuation. Pre-evacuation times are therefore generally higher [NFPA101, 2012, BSI, 2004]. Occupants are familiar with the environment in the case of apartments/dormitories, while they are not familiar with it in hotels. The population in hotels is in fact transient, causing possible difficulties in adopting the appropriate escape route in the case of fire. Compartments offer means to defend-in-place such as sheets, towels, etc.

2.3 Health care facilities

Few studies have specifically addressed the issues concerning the last category considered here, namely health care facilities (named here HCF) [Frantzich, 1996]. In particular, the population in this type of environment presents different characteristics, involving people with temporary or permanent disabilities. HCFs usually involve different issues than the previous categories, since they do have staff on hand but they also have a higher number of occupants that are not able to perform self-rescue activities [Sime, 1987]. The intrinsic characteristics of a high-rise building, i.e. long travel distances for people in the upper floors and vertical evacuations, demonstrate the importance of an effective egress strategy for this type of population. Many problems need to be addressed, such as the issues concerning fatigue, way-finding, use of vertical components (e.g. stairs, elevators), etc. These problems may be exaggerated in the case of a significant percentage of people with impairments [Christensen, et al. 2006]. The level of training of the staff becomes therefore another key factor in the evacuation performance of the building [Gwynne et al, 2010]. From both an individual and group perspective, little research has been carried out in order to study the evacuation behaviours of vulnerable users, e.g., people with disabilities, elderly, etc., whose behaviour may strongly affect the egress performance of a building [Boyce & Shields, 1999a, 1999b, 1999c, Boyce et al., 1999, Hedman, 2009, Spearpoint & MacLennan, 2012]. These studies include the impact of disabled occupants on high-rise building evacuations and demonstrate the importance of this type of population in the calculation of the evacuation times [Shields, Boyce & McConnell, 2009, Koo, Seog & Kim, 2012]. On the other hand, the variability of the possible impairments and the subsequent effects on occupant behaviours demonstrate the need for further studies on this topic [Ronchi et al., 2011].

3. Egress components

The evacuation process of a high-rise building is substantially affected by the characteristics of the vertical egress components. Modern egress design should take into account several variables, including the change of occupant demographics [Spearpoint & MacLennan, 2012], occupant behaviours [Nilsson & Jönsson, 2011] and the advances in technologies that lead to the design of extremely complex buildings (and the subsequent increase in the building height). This section describes the main issues concerning the use of stairs, together with the alternative components that have been recently employed, e.g. evacuation elevators, sky-bridges, etc.

3.1 Stairs

The traditional method to evacuate such type of buildings is the use of stairs. Systems are designed following the concept of providing an adequate stair capacity in relation to the largest occupant load floor. Different factors have been investigated, such as the design of the stairs in general, e.g., number of the stairs, stair width, staircase length, location in the building, etc. [Pauls, 2002, Pauls et al., 2007] or their specific features, e.g., the slope of the stairs [Graat, Midden & Bockholts, 1999], the values for capacity on stairs [Pauls & Jones, 1980, Pauls, 1988], etc. These studies provide different methods to design stairs taking into account evacuation considerations. Stairway egress issues are currently reflected in building codes, e.g., NFPA101 [2012], International Building Code, [2009]. Apart from design issues, behavioural aspects should also be taken into consideration, such as ergonomics, motivation levels, group behaviours, etc. [Pauls, 2007]. Gender or role may also have influence on evacuation performance from a behavioural perspective. For example, the experiments carried out by Boyce et al. [2011] showed that deference behaviours may arise during the evacuation process in stairs (e.g. male groups giving priority to women or groups with children, staff guiding other occupants, etc.).

Merging streams of evacuees in the floor-stair interface is another important factor during stairwell evacuations in high-rise buildings. The impact of merging behaviours can dictate the speed of the agents and consequently affecting the total evacuation time. Galea et al. [2008c] suggested that in high-rise buildings, floors should be linked to the landing on the opposite side to the incoming stair. Boyce et al. [2011] discussed the merging ratios, performing experiments that show that despite differences in the geometric location of the door in relation to the stair, the merging ratio was always approximately 50:50.

Fatigue has also been identified as a key factor during stair evacuations in high-rise building. Investigations of actual accidents [Averill et al., 2005, Galea et al., 2008a] showed that evacuees may need to stop their journey due to fatigue, causing an additional delay in the evacuation process. This problem will constantly become more evident since the population of the buildings is gradually reducing their physical abilities [Spearpoint & MacLennan, 2012].

Stair evacuations present significant issues regarding people with disabilities. Different evacuation problems have been analysed in the literature such as the ability of the occupants to use stairs with or without aid [Boyce & Shields, 1999b], the impact on evacuation of the formation of groups with their assistors or others, [Shields et al., 2009], the use of dedicated stair devices [Adams & Galea, 2010, Hedman, 2009], etc. The variability of the possible impairments causes a relevant scatter in the behaviours of this type of occupant while using stairs and their movement speeds. The Americans with Disabilities Act (ADA) in buildings [Cummings & Jaeger, 1993] highlights the need of an adequate design taking into considerations all these issues which shall be an integral part of the safety design.

Several other aspects should be also considered during the design of stairs. They include counter-flows [Kratchman, 2007], presence or absence of fire-fighters during the stairwell evacuation, delays in the evacuation initiation [Peacock et al., 2008], etc.

The WTC terrorist attack and several other high-rise building evacuations show the deficiencies of the safety designs that were relying only on stairs without taking into account all these aspects.

3.2 Evacuation elevators

A great debate is arising about the use of evacuation elevators. Public awareness on the topic was particularly raised by the evacuation issues showed by the 09/11 terrorist attack of the WTC [Kuligowski, 2011, Galea & Blake, 2004]. Elevator evacuation in buildings was object of research studies since the beginning of the 1930ies [Bukowski, 2009], but the WTC attack has pushed researchers and regulators in investigating the problem of vertical evacuation in a more systematic way.

The traditional concept that elevators should not be used during an emergency has been overcome by the need for looking for faster and effective methods to evacuate tall buildings. In particular, their possible use has been significantly prompted by the issues associated with the evacuation of people with disabilities using stairs. There are several problems concerning the use of evacuation elevators from a design perspective. The limited space in elevators may create issues related to the crush of the people involved. Flame, heat and smoke may invade the elevator shaft. In particular, while elevators move, negative pressure will suck smoke inside the elevator [Chien & Wen, 2011]. Special requirements are also related to emergency power supply and water protection [Bukowski, 2005, Bukowski, 2010b]. Evacuation elevators should be also designed to take into account earthquake protection, provision of emergency communication systems and resistance to the spread of contaminants [Klote et al., 1993]. Evacuation elevators should be located in as secure positions as possible (e.g. in the proximity of the structural core of the building). The pick-up locations should be in a floor that can be occupied by large crowds and be linked to the areas of refuge of the exit stairs [Weismantle et al., 2007].

The American Society for Mechanical Engineers (ASME) committee [ASME, 2007] that is responsible for elevator code investigated the feasibility of the use of elevators during fire evacuations putting particular attention on human factors. This is reflected in the current building code in the US [International Building Code, 2009] and UK [BS5588-8, 1999] and recent research studies [Bukowski, 2012, Bukowski et al., 2009] that have investigated the associated behavioural issues. The design of an egress strategy based on elevator use should therefore take into account not only the design problems of the emergency elevators but also the behavioural factors, such as the willingness of the occupants of using them instead of the stairs in relation to the floor where they are located when the evacuation starts [Nilsson & Jönsson, 2011, Heyes, 2009, Kinsey, 2011]. Another advantage of the use of evacuation elevator as an additional egress component is that they can help people with mobility impairment to perform the evacuation without external aid.

3.3 Sky-bridges

Alternative means of escape have been proposed for the safety design of high-rise buildings. One of the possible methods is the introduction of a horizontal evacuation means at height, i.e. the use of sky-bridges to link towers. The sky-bridge concept is not new. The first sky-bridge was the *Ponte dei Sospiri*, designed by the architect Antonio Contin in Venice at the beginning of the 17th century [Wood et al., 2005]. In recent times, this design solution has been already implemented in several building all around the world, e.g., the Petronas Towers in Malaysia [Ariff, 2003].

Sky-bridges can be employed in order to evacuate occupants at a level different than the ground floor. However, the feasibility of this safety design solution is linked to several factors, such as the height of the building and its design in general. The immediate benefit deriving from the use of sky-bridges is the reduction of the vertical evacuation travel distance. Nevertheless, the effectiveness of a sky-bridge is strictly linked to the evacuation strategy adopted and the other egress components available [Wood, 2007]. The placing of the sky-bridges should be done to ensure the maximum efficiency of the egress circulation. For this reason, it should be placed at a level where there is the lift zoning changeover [Wood, 2003]. In addition, it should be placed in a position in between of the higher and lower floors of the building, since otherwise the majority of the occupants would need to travel significant distances through vertical means of escape [Wood et al., 2005], taking into account also the expected occupant load of the different floors [Wood, 2003]. The use of a sky-bridge would also have a significant impact on the planning of the building since the connection floors would become sky-lobbies (i.e., including stair and lift lobbies) [Wood, 2003]. There is currently a lack of knowledge about the effectiveness of sky-bridges during evacuation and studies addressing their use in combination with other egress components are required.

3.4 Refuge floors

Refuge floors are an additional egress component that needs to be analysed [Ming Lo & Will, 1997]. Recent regulations, such as the Hong Kong Fire Safety Code [Hong Kong Building Department, 1996], prescribe the introduction of refuge floors in the design of the means of escape. From an evacuation perspective, refuge floors present several advantages; (1) they are a place of rest for the evacuees, (2) the possibility of having stairs or lift shafts filled with smoke is reduced, (3) they can be employed to protect people with disabilities and/or injured evacuees [Williamson & Demirbilek, 2010], (4) they can be used as a command point for rescue teams to assist evacuation, and (5) they can serve as a fire-fighting base [Wood, 2007]. In addition, the use of evacuation lifts would be made easier since refuge floors may serve as pick up floors since they could accommodate a significant number of evacuees [Wood et al., 2005]. On the other hand, there are factors which may cause the failure of the refuge floor concept, e.g., human behaviour issues (overcrowding or non-use), cost effectiveness in comparison with alternative design solutions, sustainability, etc. [Clawson & O'Connor, 2011].

3.5 Alternative means of escape

Further suggestions for alternative means of escape are available in the literature. An example is the use of helicopters to perform rescue operations. Some international regulations prescribe mandatory helipads for high-rise buildings such as the Indian Fire and Life Safety Code [Bureau of Indian Standards, 2005]. Nevertheless, helicopter rescue procedures are extremely dangerous and there are no standards in the U.S. and in most foreign countries about their implementation. The landing procedures and the rescue operations are in this case very dangerous due to the air turbulence [Biava et al., 2012] and updrafts caused by smoke and heat.

Another example of alternative means is the use of facades in emergency exiting [Romano, 2003] or the inflatable ejection modules [Khanna, 2003]. Wood [2007] pointed out that this type of systems have been met with almost universal scepticism from the practitioners due to the low technical detail of the solution proposed if compared with the use of evacuation elevators.

4 Egress strategies

The design of the egress components is only the first step towards the achievement of an adequate level of high-rise building safety. Relocation strategies play in fact a fundamental role in the safety design [Tubbs & Meacham, 2009]. Efficient evacuation is a combination of moderate speed and moderate densities [Pauls, 1994]. Few studies have investigated the issues concerning the combination of different egress components, such as occupant behaviours in the case of a combination of stairs and evacuation elevators [Nilsson & Jönsson, 2011, Heyes, 2009, Kinsey, 2011]. For this reason, there is a need to review the current findings on this topic in order to direct possible future research studies. In addition, the choice of the appropriate strategies in presence of alternative means of escape (e.g. sky-bridges) has not been investigated systematically [Lay, 2007].

During a fire emergency, the standard procedure is to evacuate downwards in a building. There could be exceptions in the case of untenable conditions in the lower floors, which may lead to evacuate to the roof. However, this strategy is not advisable if not strictly necessary because of the limited space in the building roof and difficulties in rescue the evacuees through helicopters (See Section 3.5). This strategy has been currently rarely adopted systematically for three main reasons, namely (1) air turbulence generated by the helicopters together with the smoke and heat coming from the building increase the risk of performing unsuccessful landing and rescue operations [Biava et al., 2012], (2) the number of people that can be rescued through this strategy is rather limited if compared with the population of a high-rise building, (3) mobility issues linked to fatigue, people with disabilities, etc. would be exaggerated by the process of evacuating the building upwards.

The main egress strategies can be summarised into four main solutions, namely (1) total evacuation, (2) phased evacuation, (3) defend-in-place and (4) delayed evacuation. The possible application of different strategies is mainly dependent upon the characteristics of the building in general (e.g., egress components available, compartmentation, etc.), the population involved and the staff/rescue operators.

4.1 Total Evacuation

This strategy involves the evacuation of all building occupants at once from a building to the designated area of safety [Hassanain, 2009]. The possible large population involved in the evacuation of a high-rise building may cause significantly high densities in the means of escape. As it is described in Section 2, this is strongly dependent on the building use that will be a determinant factor in the occupant load of the building as well as the natural behaviours of the occupants. This type of evacuation strategy is generally ordered by the fire department or it could be the result of a self-evacuate decision of the population of the building. The instinctive behaviour of leaving a hostile environment has been observed first by Wood [1972], who studied more than 950 fires to understand evacuees' behaviour. However, this instinctive behaviour may be frustrated by the high-rise building layout which often requires long travel distances to reach a safe area. Since the 70ies [GSA, 1971], total evacuation strategies have been in fact questioned, since occupants may in fact need to cross areas where there is smoke and therefore be exposed to increasing risk. The possible high level of congestion in the means of egress may also lead to an increase of the time to evacuate the building.

4.2 Phased Evacuation

There are cases in which the single staged total evacuation is not practical. Occupants might not appreciate that they should not rush in order to optimize the flows during an evacuation [Pauls, 1994]. The phased evacuation strategy is instead based on the concept that occupants on the most critical floors such as the fire floor and floors nearby will be prioritised. The scope is to decrease the queuing time in the egress components and reduce people densities in the means of escape. The fire compartmentation plays a key role in this strategy [The Building Regulation, 2006]. In fact, occupants in the compartment of the fire need to be evacuated, whilst the remaining occupants need to be evacuated only if it is necessary. The effectiveness of this strategy relies also on the fire safety installations available in the building, the level of training of the staff and adequate means of communication within the building [Wong & Luo, 2005].

An example of such strategy is the procedure employed in the Petronas Towers [Ariff, 2003]. In the case of an emergency contained on only one floor, occupant in three floors need to be relocated, namely the fire floor, the floor above and the floor below the fire. Occupants will empty that floor and they need to re-enter the building three floors below their floor in what is called a "temporary refuge floor". These occupants will wait for instructions in relation of the development of the situation (e.g. whether a total evacuation is needed, etc.). Similar procedures are employed in other high-rise buildings all around the world, such as the Prudential Tower in Boston [Boston Properties, 2012].

4.3 Defend-in-place

A possible solution to be adopted in the case of a high-rise building fire is the defend-in-place strategy. Occupants should close the door of their room and seal the cracks and wait for the rescuers. This strategy has been largely employed in the past for people with disabilities since they could not be able to perform the evacuation on their own. Several case studies are in support of this strategy, such as the MGM fire in Las Vegas [Best R & Demers D, 1982], where over 50% of victims died trying to use the escape routes. Many of these fatalities may have been avoided if this strategy would have been adopted [Proulx, 2001].

Proulx [2001] stated that the defend-in-place strategy is the most appropriate behaviour during high-rise building fires in the case of residential buildings (e.g., dormitory, hotels, apartments, etc.) if they have the following main characteristics from both the occupants and the design point of view (See also Section 2.2); (1) the building should be above 6 floors in height since evacuation of low-rise building is faster in that case, (2) the building should be residential, including enclosed compartments where tools for defend-in-place activities are available, (3) the building should be made of non-combustible construction, (4) an alarm system should inform occupants of the occurring fire, and (5) a voice communication system should provide occupants with information about the evolution of the fire and advice occupants on the defend-in-place activities to perform. The effectiveness of this strategy is in fact strongly affected by the communications between the occupants and the rescue operators. Actual incidents such as the recent fire at the Kuddbygränd 12 in Stockholm [Swedish Accident Investigation Board, 2010] resulting in 7 fatalities showed that a lack of information about the actions to be performed by the occupants could be one of the main causes of the failing of this strategy (i.e. occupants did not remain in their apartments and they eventually died in the staircase).

4.4 Delayed evacuation

A delayed evacuation takes place when evacuees are temporarily waiting in dedicated areas of refuge/rescue assistance (e.g., refuge areas, refuge floors, etc.) in order to be reached by rescuers. This type of strategy is generally employed to rescue occupants with temporary (i.e. injured) or permanent disabilities. These occupants may not be able to perform self-rescue activities and may need an external aid to reach a safe place. In particular, most of the disabled occupants may not be able to use stairs, with a subsequent need of help in the case this egress component represent the only mean of escape available. For this reason, this strategy seems to be particularly effective for high-rise buildings with a significant percentage of this type of users, e.g., health care facilities.

Different examples are available in the literature, such as the compulsory introduction of refuge floors in the Hong Kong legislation context [Hong Kong Building Department, 1996] in order to provide a safe area for people with disabilities, injured evacuees, etc. and perform delayed evacuations or the Swedish Legislation [BBR, 2012] where temporary evacuation locations, i.e., refuge areas, are required for specific building uses and conditions.

4.5 Use of egress components

Egress strategies may include the use of one or more egress components. The traditional evacuation strategy relies on the use of stairs. As pointed out in previous Section 3.1, several issues have been investigated with regards of the stair design. The basic concept is to ensure that the evacuation strategy should be able to evacuate safely the population of the building trying to avoid overcrowding. Current legislations provide several prescriptions on the design of stair layout, e.g. the NFPA 101 in the US or the Approved Document B in the UK.

Recent studies have investigated the importance of an appropriate egress strategy when using evacuation elevators. Actual evacuation scenarios showed that elevators can be used to assist the evacuation of a high-rise building [Averill, et al., 2001, Sekizawa, et al., 1999]. Unfortunately, few studies are available on the human factors associated to the use of this egress component [Nilsson & Jönsson, 2011]. Current best practices include the requirement to have a management system able to dispatch an elevator trip aimed at emptying the complete height of the shaft [Weismantle et al., 2007]. The number of the elevator stops is another key factor to be considered. Any attempt to counteract the delay due to the increased number of floors served by the evacuation elevators is currently not considered acceptable [Barney, 2002]. The main solution generally employed is to serve a maximum of approximately 15 floors with one elevator or a group of elevators [Noordermeer, 2010]. The concept of zoning is therefore necessary to optimize the design solution employed. The building is therefore divided into zones of a certain number of floors where elevators have been assigned. High-rise buildings are also generally provided with shuttle elevators that are usually larger and faster, whose aim is to link sky-lobbies. The concept of "lifeboats" has been proposed by Pauls [1978] in the 70ies. He made a comparison to a ship evacuation where occupants are gathered before leaving the ship using lifeboats. He suggested that occupants could initially evacuate to the sky-lobbies and then wait there for further instructions.

A few studies have investigated the combination of different egress components. First studies about the combined use of these egress components are already available in the 70ies [Pauls 1978]. Pauls provided predictions of evacuation times in high-rise building by using different types of means of egress (either stairs or elevators) and different layout of the egress components employed (essentially varying the width of the stairs).

During the 90ies, the studies made by Klote et al. [1992] were focused on investigating the feasibility of using evacuation elevators by comparing the evacuation times obtained employing different egress components. The combined use of stairs and elevators were also investigated and the conclusions stated that evacuation elevators may represent a substantial improvement in the safety design of high-rise buildings. In particular, taller buildings are subjected to an increased reduction in the evacuation times in the case of use of evacuation elevators [Klote et al., 1992].

Three recent studies are available in the literature with regards of the human factors associated with the use of elevators. They are either based on an online survey [Kinsey, 2011] or on-site questionnaires [Jönsson et al., 2012] or simulation questionnaires and an online survey [Heyes, 2009]. They investigated the risk perception of the evacuees in terms of their choice of using a certain egress components (i.e., elevators or stairs) in relation to their position respect to the fire.

All studies confirmed that an increasing number of occupants are likely to use elevators to evacuation from a high-rise building with increasing floor height. Results found by Heyes [2009] and Jönsson et al. [2011] substantially agree in a linear correlation for floors from 5 to 60. The online survey made by Kinsey [2011] showed instead a stepwise correlation with a progressive increase in the elevator usage every 10 floors. All research studies reveal that building occupants would be prepared to use evacuation elevators if they are given sufficient training. Nevertheless, Heyes [2009] stated that a number of participants were reluctant to use elevators even from the 60^{th} floor of a high-rise building.

Another key aspect to be considered is the waiting time. This consists of the likelihood of the occupants in waiting for an emergency elevator before deciding to use the stairs. This is a crucial factor in the vertical evacuation process of a high-rise building but unfortunately there are no studies that specifically address this issue [Nilsson & Jönsson, 2011]. The difficulties of collecting this type of information derive from the need to have data that actually reflect the real behaviour of people in a fire event. The specific layout of the infrastructure under consideration together with the warning messaging strategies employed to encourage the use of the elevators play a fundamental role [Kuligowski & Hoskins, 2011].

Modelling studies and relocation strategies should therefore take into account that a 50:50 split of occupants using the two different egress components is not representative of the choices that people would make naturally in a real situation. Real-time information, e.g. the elevator waiting time, etc., should therefore be provided to the occupants in order to influence the evacuation performance of a high-rise building. Occupants could in this manner perform an informed decision on the egress component to use and become more likely to choose to use the elevators. The importance of a correct messaging strategy has also been highlighted by the recent studies made by Kuligowski & Hoskins [2012]. They pointed out that there are no standard requirements or widely recognized guidance for the messages about the use of emergency elevators, both for building occupants and emergency responders.

The greater challenge of a joint use of stairs and elevators relies on the strategic planning, interface design and operator training [Groner, 2002]. The prediction of the natural people performance is made even more difficult in the case of additional alternative means of escape. They could turn out to be inadequate if not accompanied by detailed evacuation plans. An example is the evacuation of the Petronas Towers due to the bomb scare on the day after the WTC terrorist attack in 2001 [Ariff, 2003]. This building consists of two towers, three stairwells and thirty-nine elevators using a double-decker design. Elevators are designed in a manner that if one lift got stuck, another elevator can move along and the occupants can move to the other one. The towers have also a sky-bridge at floors 41 and 42 as an additional egress component. In the case of a single tower evacuation, occupants on the upper floors can evacuate one of the two towers by using the stairs until they reach the floor of the sky-bridge. They can eventually use the elevators to reach the ground floor from the other tower. Occupants below the sky-bridge would instead use the stairs. Since there was no information about the tower where the bomb was situated, the occupants of both towers tried to cross the sky-bridge at the same time, causing heavy congestion and counter-flows which resulted in a jam [Ariff, 2003] which caused a significant delay in the evacuation time. The same building was evacuated in October 2002 using a new and more effective strategy that employs shuttle elevators servicing the sky-lobbies in both towers [Bukowski, 2010b]. The outcome was a substantial reduction in the evacuation times, which highlighted the importance of an efficient evacuation plan.

An efficient use of combined egress components is not trivial and requires high efforts from the management point of view and a deep knowledge of the specific characteristics of the building under consideration. In this context, the use of evacuation modelling tools may be appropriate in order to evaluate the effectiveness of possible evacuation strategies. The review of the previous studies available on the topic has therefore been presented in next Section 5.

5 Model capabilities and modelling studies

Evacuation models are often employed in engineering analyses within the context of performance based design. The flexibility of this type of tools and the relatively easiness of their use led to use them to perform fire safety design assessments and analyse different relocation strategies. The characteristics of evacuation models are gradually evolving since the model developers are continuously including new features and sophisticated sub-models. This is mainly made to encourage model users to apply evacuation models in different fields and increase the number of model users.

There are currently six main evacuation model reviews useful for the definition and characterisation of the evacuation model capabilities [Friedman, 1992, Gwynne et al., 1999, Kuligowski et al., 2010, Olenick & Carpenter, 2003, Santos et al., 2004, Watts, 1987]. The most important and recent review of evacuation models has been provided by Kuligowski et al. [2010] in which 26 models are included. The review includes a detailed categorisation of the model features as well as the definition of the modelling methods to represent model agents, sub-algorithms, validation methods, etc.

As pointed out by Kuligowski et al. [2010], there are different problems concerning this type of evacuation model reviews. The key problem is related to the rapid advances in the evacuation model capabilities which make it difficult to provide up-to-date information. The framework of Kuligowski's review has been recently employed by Ronchi & Kinsey [2011] to create an online platform (http://www.evacmod.net/?q=node/5) in which model developers provide up to date information about models on the site themselves. The information about evacuation models included in this study was therefore retrieved from this model directory.

As discussed in the previous sections, the characteristics of different models need to be reviewed in order to check their suitability for simulating high-rise building evacuations. In this context, two type of analyses have been provided, namely 1) to review the main characteristics of a set of the most common evacuation models in order to identify the features that need to be embedded within them for simulating high-rise building evacuation scenarios, (2) to analyse the literature about the main studies available about the use of evacuation models for high-rise buildings.

5.1 Review of model capabilities for high-rise building evacuations

The first categorisation that needs to be discussed when studying evacuation model capabilities is the method employed to represent the movement of the occupants. According to Kuligowski et al. [2010], models can be divided into three groups, namely 1) coarse network models, 2) fine network models, and 3) continuous models. These three types of methods represent a different level of resolution in the representation of the behaviours of the agent.

In the coarse network models, the space is represented as a network of nodes and arcs, representing different parts of the infrastructure (e.g., rooms, stairs, etc.). This is the simplest method to simulate an evacuation scenario and it presents advantages and limitations. The main advantage is the possibility to rapidly represent complex infrastructures such as a high-rise building. They also have fast computational time even in the case of the simulation of very complex evacuation scenarios such as the evacuation of a high-rise building. The main limitations are related to the simple representation of the evacuation which does not permit to represent many of the behaviours that may occur during an evacuation. A recent survey about the model users performed by Ronchi & Kinsey [2011] showed that this approach has been abandoned by a significant part of model developers and model users.

The fine network approach represents the space as a grid of uniform cells. Each cell can be occupied by one occupant at a time. The movement of the agents is simulated within those models through a series of steps in the cells of the network. A common feature of this type of models is an improved tracking of the location of the occupants during the evacuation process based on a fine network representation of the space. Agents are modelled as individual entities with the possibility to simulate complex local and global behavioural factors. This type of models is currently largely employed and examples of their applicability for high-rise buildings will be provided in next Section 5.2.

Continuous models simulate the agents through a system of coordinates within the environment. They offer the flexibility to simulate occupant behaviours which may be sensitive to occupant location, orientation and inter-distance among the agents. These features are important to simulate high-rise building evacuations, in particular for the case where high densities arise, since continuous models are not sensitive to the dimensions of the network employed [Nilsson, 2007]. The main disadvantage of these tools is the computational time needed to simulate complex scenarios, i.e. generally higher than the time needed with the other two types of models. Continuous models need in fact to re-calculate the coordinates of the agents at every time-step.

A key factor for assessing the suitability of different evacuation models for the simulation of tall building evacuations is their ability to represent different egress components. According to the discussion made in Section 3, models should be able to simulate both horizontal and vertical egress components. In this context, the new trends of the use of emergency elevators need to pay attention to the possibility to simulate this component within a model. The complex decision making process associated to the use of elevators in the case of multiple egress components available should also be addressed by the models.

A set of evacuation models is described in this section in order to provide an analysis of their characteristics and their suitability for simulating high-rise evacuation scenarios including multiple egress components. These models are all listed in the top 7 most used models in the recent survey performed by Ronchi & Kinsey [2011], namely STEPS [Mott Macdonald, 2011], Pathfinder [Thunderhead Engineering, 2012], buildingEXODUS [Galea et al., 2011], FDS+Evac [Korhonen & Hostikka, 2010] and one model that was selected since it was specifically designed for high-rise building evacuations, i.e., EXIT89 [Fahy, 1996]. In addition, simulation tools with specific features have also been reviewed, such as ELVAC [Klote & Alvord, 1992b], ELEVATE [Peters, 2002], Building Traffic Simulator (BTS) [Siikonen, 1993] (developed for modelling vertical evacuations) and BUMMPEE [Christensen & Sasaki, 2008] (developed for modelling mixed-ability populations).

The selection of the models is based on their scope (i.e. if they are designed for simulating high-rise buildings, the population that can be simulated, etc.), and the egress components that they can represent (e.g., stairs, elevators, etc.). The focus of this section is on their degree of sophistication in representing vertical egress components. In particular, the models are reviewed in terms of their capabilities in simulating emergency elevators and the interactions with other egress components. The simulation of emergency elevators is analysed in terms of kinematic (e.g., acceleration, speed, etc.), physical (e.g., maximum load, number of doors, etc.), operational (e.g., opening and closing times, floor range specification, etc.) and behavioural (e.g., implicit or explicit representation of waiting times, choice of the egress components, etc.) features.

EXIT89 [Fahy, 1996] is a freeware coarse network model available from the model developer. EXIT89 has been reviewed since it has been specifically designed for modelling high-rise building evacuations and it has been recently successfully applied for the analysis of the World Trade Center evacuation [Kuligowski et al., 2011]. The limitations and advantages associated to coarse network models make EXIT89 a model that can be relatively fast to set up and able to rapidly produce results in a short computational time. On the other hand, since the model has been developed when the use of emergency elevators was not common, it does not allow the simulation of this egress component. It is therefore considered not suitable for simulating high-rise building evacuations including elevators.

STEPS (Simulation of Transient and Pedestrian movementS) [Mott Macdonald, 2011] is a fine network model developed by the Mott MacDonald simulation group. The model is a commercial tool freely available for educational purposes. The movement towards the exits is calculated through the use of a potential map. STEPS also allows the user to define specific routes through the use of checkpoints. The agents are represented through a list of factors which include unimpeded walking speeds, awareness, patience, and pre-evacuation time. The exit route of the agents is based on the agent's patience coefficients in order to represent their likelihood to wait in a queue. Evacuation elevators can be represented within the model through a series of attributes concerning the kinematic, physical, and operational aspects of the vertical evacuation. Behavioural performance is represented automatically by the model with no explicit user control of how many agents will use an elevator on a given floor or their waiting time for the elevators. Nevertheless, these behaviours can be represented implicitly, e.g., through the use of waiting zones, patience coefficients, etc. The main advantage of the model is the possibility to represent the interactions between horizontal and vertical components. The limitations are associated with the implicit representation of the behavioural factors associated to vertical egress components and the problems deriving from the use of a fine network approach (e.g., case studies with high densities may be dependent on the grid employed).

Pathfinder 2011 [Thunderhead Engineering, 2011] is a continuous model. The model is a commercial tool developed by Thunderhead Engineering freely available for educational purposes. The model uses two different methods to simulate people movement. The first is a hydraulic model, the SFPE method by Gwynne & Rosenbaum [2008], based on the calculation of the means of the capacity of the considered environment. The second methodology is an agent-based model, i.e. the Reynolds [1999] steering behaviour model refined by Amor et al. [2006]. The steering system moves passengers along their paths and allows each occupant to interact with the environment and the other occupants. Emergency elevators include user-defined kinematic, physical, and operational features. The latest version of the model includes a way-scripting function that enables to direct the occupants by performing "*go-to*" or "*wait*" actions.

This command can be used to implicitly represent the decision making process of the occupants choosing between different vertical components. The main advantage of this model derives from the possibility to represent the interactions between vertical and horizontal egress components. Limitations are associated with the limited number of input parameters in the elevator kinematic sub-model (e.g., it does not include motor delay, deceleration rate, deceleration jerk, etc.).

buildingEXODUS 5.0 [Galea et al., 2004] is a commercial tool developed by the Fire Safety Engineering Group at the University of Greenwich. It is a fine network model using a two-dimensional grid of nodes with the motion and behaviours determined by an individual set of heuristics of rules. The emergency elevator sub-model is currently under development and it is still not officially released. It includes kinematic, physical, operational and behavioural features. The elevator sub-model embeds a detailed mechanism to control the floor dispatching process during the simulation. The model embeds a set of agents attributes to be assigned in order to simulate the behaviours of the agents, namely (1) choice of the egress component (i.e., elevator or stairs), (2) assessment of the initial elevator area, (3) elevator wait behaviour, and (4) elevator redirection (i.e. use stairs instead of elevators). Default settings are mainly derived from an online survey performed by the model developers [Kinsey, 2011]. The main advantage of this model is its flexibility in representing complex relocation strategies and the behavioural variables embedded. Limitations are associated with the general problems of fine network models (e.g. results may be dependent on the grid size employed in the case of high-densities).

FDS+Evac [Korhonen & Hostikka, 2010] is an open source continuous model developed by VTT in Finland. FDS+Evac treats each agent as an individual entity, using stochastic properties for assigning their main characteristics, such as unimpeded walking speed, pre-evacuation times, familiarity with the exits, etc. The models present a multiplicity of functions and variables that could permit to simulate artificially elevators although the current version of the model (2.3.1) does not embed an elevator sub-model. Nevertheless, an elevator sub-model is currently under development (being already embedded in the source code) and it will be released together with the next version of the corresponding fire model FDS, the Fire Dynamics Simulator by the National Institute of Standards and Technology [McGrattan et al., 2010]. Unfortunately, to date there is no documentation available on the elevator sub-model. The main advantage associated with FDS+Evac is its great flexibility in simulating complex agents’ behaviours. The main limitations are linked to the high computational time required to simulate a complex high-rise building and the considerably high time required for the input set-up. For all these reasons, the current version of the model is not considered as suitable to simulate complex high-rise building evacuations including multiple egress components.

A set of dedicated tools to perform vertical transport evacuation modelling is also available, e.g., ELVAC [Klote and Alvord, 1992b], ELEVATE [Peters, 2002], Building Traffic Simulator (BTS) [Siikonen, 1993]. The main limitation of these tools is that the simulated human factors are generally homogeneous and simplified [Kinsey, 2011]. In addition, since the models are specifically designed for vertical evacuation modelling, the interactions between horizontal and vertical egress components are represented implicitly. For example, ELVAC includes a “trip inefficiency” component in order to represent additional and/or sub-optimal elevator time components (i.e. time needed to empty floors and trips to pick up latecomers). ELEVATE and BTS assume that the bottlenecks are placed around the vertical components and exits, i.e., behaviours outside these areas are represented implicitly through varying arrival rates to the vertical components. For all these reasons these models are not considered suitable for analysing scenarios involving both horizontal and vertical components.

It is also worthy to mention that there is a recent study aiming at developing an evacuation model entirely dedicated to the simulation of the impact of disabled people on evacuation, namely the BUMMPEE (Bottomup Modeling of Mass Pedestrian flows - implications for the Effective Egress of individuals with disabilities) model [Christensen & Sasaki, 2008]. The focus of this model is to simulate behaviours which represent the diversity and prevalence of disabilities in the population and their interaction with the infrastructure and the environment. Research activities on the validation of this model are currently being conducted but initial studies applying the model for high-rise buildings are already available in the literature [Jeongin Koo et al., 2012].

5.2 Modelling case studies

This section reviews a set of relevant studies performed to analyse high-rise building evacuation scenarios through computer modelling.

The most important case study available in the literature involving the evacuation of a high-rise building is without any doubt the evacuation of the World Trade Centre in 2001. Evacuation models have been employed to reconstruct the evacuation process and assess the key variables affecting the egress performance of the building.

Galea et al. [2008b] used buildingEXODUS to approximate the evacuation of the North Tower of the WTC. The study used the response data obtained by the survivor accounts [Blake et al., 2004] and the population of the building is derived from the formal investigation made by the National Institute of Standards and Technology [Averill et al., 2005]. The model results suggested that the impact of fire-fighters entering the building on the overall evacuation efficiency was minimal. Different hypothetical scenarios were also simulated, permitting to draw conclusions on, (1) the importance of having dispersed staircases within buildings, (2) the importance of having a balanced distribution of occupants in the staircases in the case of high-rise building evacuations, (3) in high-rise buildings, the average floor evacuation efficiency decreases with height. The simulation work also highlighted three fundamental components of high-rise building evacuations that are not currently fully represented in evacuation models, namely (1) the impact of fatigue, (2) the impact of group dynamics and (3) the impact on evacuation dynamics of disabled people. The importance of the behaviours of this type of occupants in the WTC and the subsequent effects on the evacuation process has been fully discussed by Shields et al. [2009]. Evacuation models need to take into account the possibility to simulate not only mixed-population but also the global impact they may have on the evacuation process, e.g., their need for assistance, the formation of emerging groups with their assistors or others, etc. Johnson [2005] performed a study when he reviewed existing computer models with a critical point of view deriving from the WTC evacuation. He pointed out several aspects that need to be addressed in evacuation models, such as (1) the impact of the ingress/egress of emergency personnel, (2) the representation of more complex group dynamics, and (3) the impact of building information and management systems on the evacuees' ability to evacuate.

Kuligowski et al. [2011] used 4 evacuation models, namely EXIT89 [Fahy, 1996], Simulex [IES, 2001], ELVAC [Klote and Alvord, 1992b] and buildingEXODUS [Galea et al., 2004] to simulate a variety of hypothetical evacuation scenarios the evacuation in the WTC. The scope of the study was to provide additional context with which to understand the WTC evacuation process and compare the capabilities of different models. The authors successfully employed EXIT89 and buildingEXODUS to model scenarios of the entire WTC towers since both can simulate an evacuation including more than 25000 people and 110 floors. Simulex has a limited maximum number of floors and exits, so it was employed only to simulate phased evacuation scenarios. The ELVAC model was instead successfully employed to calculate how many occupants could have reached the ground floor of WTC2 in 16 minutes using shuttle elevators.

Few additional studies are available in the literature using evacuation models to approximate the egress process in high-rise buildings. Pelechano & Malkawi [2008] reviewed the suitability of fine network models in representing the evacuation of a high-rise building. The models selected as case study were STEPS and buildingEXODUS. Main findings focused on the lack of predicting capabilities in terms of human behaviour, with particular emphasis on the need for simulating the communication between agents.

Wong et al. [2005] performed a study in which they used STEPS to demonstrate the increased evacuation efficiency of a 100 floors high-rise building when applying a combined strategy of stairs and elevators. In particular, the strategy employed included the use of sky-lobbies and shuttle elevators. The total number of occupants in the evacuation was approximately 21,000. The geometry of the building was very complex, including three stairs, four refuge floors and 14 shuttle elevators linking the refuge floors and the ground level. The proportion of evacuees waiting for the evacuation elevator on the refuge floors was calibrated through the use of patience coefficients and the estimation of queuing time. The study showed that the total evacuation time can be significantly reduced without complicated procedures, but using an efficient and simple relocation strategy. Wong et al. [2005] pointed out that there is still a need of investigating building of different heights, elevator capacity and go into more depth into the possible behavioural factors. An evacuation model was therefore employed in this case to optimize the egress strategy of a high-rise building, showing the impact of an adequate plan on the total evacuation time.

Shen-Wen Chien & Wei-Jou Wen [2011] used buildingEXODUS to investigate the use of evacuation elevators in Taipei 101, the second tallest building in the world. In their study, the simulation results showed that the use of elevators as a method of evacuation can help to reduce the evacuation time in a non-fire emergency. Nevertheless, in the case of fire events, elevator evacuation is less effective due to the particular layout of the building. In this case, the use of an evacuation model was useful to determine the appropriate egress components to employ in relation to the specific characteristics of the building under consideration.

5.3 Findings on model capabilities for high-rise buildings

The models described in this chapter present different level of sophistication in the representation of the evacuation through different egress components. In addition, model users should also be aware of the intrinsic limitations of the models associated with the method employed to represent people movement (i.e. coarse network, fine network or continuous). Since few studies are currently available with regards of the behavioural issues associated with the use of different egress components [Jönsson & Nilsson, 2011], evacuation models should be able to provide enough flexibility in representing people behaviours to test different relocation strategies. STEPS, Pathfinder and buildingEXODUS all embed implicit or explicit variables to simulate the behavioural factors associated with the evacuation of a high-rise building evacuation (although the elevator sub-model is still not officially released). They can therefore all be used to simulate high-rise building evacuation with different egress components. EXIT89 does not present an elevator sub-model and it is therefore not suitable in presence of this egress component. The current version of FDS+Evac (2.3.1) can be used to simulate complex behavioural aspects concerning the evacuation of high-rise buildings; nevertheless its use is not recommended for these scenarios because of the high times required by the model (both for setting up the scenarios as well as the computational times to run the simulations). In addition, the elevator sub-model is still not officially released and to date it is only available in the source code. The review of the characteristics of ELVAC, ELEVATE, and the Building Traffic Simulator (BTS) shows that they may be employed to simulate vertical evacuation scenarios in high-rise buildings. In contrast, they present limitations in the representation of the behavioural aspects associated with the use of different egress components (they are mostly represented implicitly). They are therefore not considered suitable to analyse scenarios where there is a need of directly studying the interaction between vertical and horizontal egress components (e.g., evacuation elevators and a sky-bridge).

6 Discussion

This study contains information from a significant amount of literature related to human behaviour and modelling studies for high-rise building evacuations. The work includes the analysis of the main factors associated with different building uses, egress components and egress strategies. A review of the capabilities of a set of relevant egress models to perform the simulation of high-rise buildings has been performed and a series of previous examples of their application have been presented. The most important observations and results of these studies have been summarised. This section presents a brief discussion to sum up these observations and resume the results of the review performed.

The review showed that the first question designers should address when approaching the conceptual fire safety design of a high-rise building is the purpose of the building. Three main building uses were considered in this study, namely office buildings, residential buildings (e.g. hotels, apartments, etc.) and health care facilities. The review showed that the compartmentation and the design (either it is traditional or an open space concept) can strongly affect the choice of the adequate egress strategy. The defend-in-place strategy was generally found adequate for residential buildings which present specific characteristics, such as the presence of tools to perform defend-in-place activities (e.g. sheets, towels, etc.), compartmentation, etc. Delayed evacuation strategy is appropriate for buildings including a relevant number of people that is not able to perform self-rescue activities without external aid, e.g., health care facilities. From a behavioural perspective, the building use affects several relevant factor of the evacuation process such as the familiarity with the building, the degree of alertness, and level of training of the evacuees. Fire safety systems (e.g. voice communication systems) and the availability of staff are other key factors of the evacuation process.

The main characteristics of the egress components available in high-rise buildings have been discussed with particular attention on the means of evacuation that have been recently introduced in the fire safety designs, e.g. emergency elevators, sky-bridges, refuge floors, etc. The review highlighted that research has so far focused more on the design aspects of the egress components, while few research studies have been carried out on the behavioural processes that take place during a high-rise building evacuation. In particular, there is a need to further investigate the behaviours of the occupants in the case of the choice between multiple egress components. There is also a need to analyse the impact that specific variables may have on the evacuation process, such as the use of different messaging strategies, the level of training and the availability of staff.

The capabilities of a set of evacuation models among the most used by practitioners have been reviewed in order to analyse their suitability to simulate high-rise building evacuations. Models included in this review are STEPS [Mott Macdonald, 2011], Pathfinder [Thunderhead Engineering, 2012], buildingEXODUS [Galea et al., 2011], FDS+Evac [Korhonen & Hostikka, 2010], EXIT89 [Fahy, 1996], ELVAC [Klote & Alvord, 1992b], ELEVATE [Peters, 2002], Building Traffic Simulator (BTS) [Siikonen, 1993], and BUMMPEE [Christensen & Sasaki, 2008].

Models specifically designed for simulated vertical evacuations are not fully suitable for simulating evacuation scenarios which involve both horizontal and vertical egress components since horizontal components are generally represented implicitly. Models that do not include sub-models for emergency elevators are not considered as adequate to simulate high-rise building evacuations because this component is becoming an integral part of the fire safety design for this type of buildings. A set of evacuation models embedding sub-models to simulate emergency elevators has been reviewed with particular attention on the interaction between this egress component and other egress components (e.g. stairs, refuge floors, sky-bridges). The reliability of the results produced by these models is strongly user-dependent since modellers need to perform a significant calibration effort in order to simulate the possible behaviours of the occupants that may take place in the case of multiple egress components. Another important aspect to be taken into consideration is the time required to set up and run the scenarios. The complexity of high-rise building evacuations require models able to simulate significant number of occupants and for this reason computational time plays a key role in the suitability of the models. Models which present slow computational times and set-up times are therefore not recommended. Given the differences in the characteristics of evacuation models, their predictive capabilities may be enhanced if different models are employed to study specific aspects of the evacuation process. The application of a multi-model approach allows the modeller to use the strengths of each model and apply the most suitable algorithms to simulate each specific behavioural variable.

The review shows that evacuation models have been found as useful tools for simulating egress strategies and test the effectiveness of different fire safety designs. Nevertheless, few case studies are available in the literature for the case of high-rise building evacuations and few comparisons of different strategies have been performed. In addition, few validation studies have been performed, mainly because of the lack of real world data available. The main set of actual data available in the Literature comes from the World Trade Centre terrorist attack. The application of evacuation models to simulate the WTC evacuation process shows the benefits of the use of evacuation models from both a design and a procedural perspective.

7 Future Research

Specific factors of the evacuation process in high-rise buildings need further studies. The first important factor is the effect of fatigue on the evacuation process. Given the increasing height of buildings and the gradual reduction in the physical ability of the population, this appears as a key variable that has been so far mainly ignored in evacuation models. An important factor that also needs investigation is the effect of group dynamics in the evacuation process. In this context, the studies of the WTC evacuation showed the relevance of the impact of the formation of groups during the evacuation through stairs. An important variable that needs to be enhanced in evacuation models is the possibility to explicitly implement the impact of the actions of staff on the evacuation process. In particular, there is a need of developing algorithms able to represent the effects of communications between agents. A final factor that needs further investigations is the impact of the presence of people with disabilities. Evacuation models permits to study and review different egress strategies that can be specifically designed for this type of occupants. Nevertheless, the current capabilities of evacuation models are not enhanced to take into consideration the variability of the impairments that can affect the evacuation process and the subsequent group dynamics that may take place. Further studies on this topic are therefore required.

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