Redefining fire safety in Swedish high-rise buildings

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ABSTRACT

Current Swedish regulations on high-rise building fire safety lack a clear definition on the design challenges of tall buildings. There are no special high-rise provisions, except from some requirements on means of escape from tall buildings. As external rescue no longer is an option for building with more than seven stories, there is a need to redefine key elements of fire safety in Swedish high-rise structures. This paper identifies challenges to the tall buildings in terms of evacuation, containment of fire and fire service intervention. It proposes a risk-informed design approach by specifying key safety objectives and it introduces the barrier concept to provide a holistic view on high-rise fire safety. The proposed barrier concept follows the “defend in depth” principle and establishes three lines of defence, i.e. the containment of the fire within the fire compartment, the possibility to escape as well as perform rescue operations safely and finally, reducing the risk of a catastrophic outcome.

INTRODUCTION

Background

In the early 1970s the U.S. started to develop specific high-rise building criteria in the national codes. The original intent of the high-rise building provisions was to require more fire safety features in buildings where external rescue operations no longer was possible. The codes required sprinklers, voice communication, pressurised stairs and emergency power. The stack effect and delayed evacuation was considered two major challenges that the codes would face. The World Trade Center events and the recent fires in Madrid, Chicago and Venezuela have again put emphasis back on high-rise fire safety [1].

Regulations on high-rise fire safety in Sweden are still immature. There are very few details in the building regulations that are specific for high-rise buildings. The requirements on load-bearing structures are the same for a 5 story building and a 55 story building. By means of escape, there is no difference between a 16 story building and a 166 story building. This lack of guidance and control is although acknowledged by the authorities, as they state that it could be necessary to use an analytic design approach for buildings taller than 16 stories. However, there are no guiding principles on how to carry out a design based on such an approach. By tradition, design teams focus on performing comparative analysis of one sub-system, mostly escape, when verifying fire safety in high-rises. A holistic approach, treating all essential technical requirements on buildings in case of fire is extremely seldom.

Objectives and limitations

This paper gives an introduction to the current Swedish code requirements on high-rise buildings and compares them briefly to other countries with similar regulatory structure as Sweden. It goes in to detail on the design approach and the fire safety design solutions adopted in two recently built Swedish high-rises. Finally, the paper identifies the fire safety challenges of high-rise buildings and outlines a risk-informed design approach to meet these challenges and show code compliance. The paper is focused on high-rise residential buildings. It does only cover safety aspects related to building fires. Other threats to iconic high-rise buildings are beyond the scope of this paper.

Swedish high-rise experience

The Swedish building code has been performance-based since 1994 and Sweden has a relative large number of fire protection engineers employed both at regulatory bodies and in fire safety consulting businesses. Therefore, one could assume that high-rise fire safety issues are extensively dealt with in the building code. This is not the case and one reason could be that Sweden only has app. 100 buildings with more than 16 stories compared to 11,000 in the U.S.

There is no definition of a high-rise in the building code. However, there is a significant difference between buildings lower than eight stories and those higher. The fire service can perform external rescue operations with ladders reaching buildings that are no more than seven stories high. As a consequence of this, higher buildings should be able to evacuate without fire service assistance. To solve this requirement, such buildings need certain fire and smoke safe stairwells. Such stairwells were allowed to serve as single means of escape from tall buildings, prior a code change in 2002. The fire and smoke safe staircase originally had a protected lobby which was open to the external air. Now days these stairwells, most commonly, are provided with arrangements (i.e. pressurisation) which prevent the spread of fire gases to the stairwell.

A code change in 2002 stated that it is necessary to have two staircases in buildings taller than 16 stories. But, the demands on load-bearing and separating structures are still the same. Using Swedish prescriptive rules it is possible to build a high-rise, with only the following safety measures; two fire and smoke safe staircases, fire hydrants for fire service intervention, fire compartments with 60 min fire resistance and load-bearing structures with 90 min fire resistance. There are no requirements on sprinklers, fire alarms, firemen's lifts etc. However, there was another important code change in 2002 that affects high-rise buildings. The authorities has recognised the incompleteness of the prescriptive solutions to certain buildings associated with a very high risk due to fire, stating that "analytic design and, where relevant, an associated risk analysis shall verify the fire safety and the evacuation safety in buildings where fire may cause great risk of human injury". Some examples of buildings where the fire risk could be considered "very high" are high-rises with more than 16 stories, underground structures, and large multiple occupancy buildings. Most high-rise buildings in Sweden are built prior to the code change in 2002, allowing them to be design with one single staircase. Two examples of recently built high-rises in Sweden are the "Turning Torso" a 54 story office and residential building and the "Kista Science Tower" a 31 story office building.

Turning Torso – 54 story office and residential building

The Turning Torso was designed by the renowned architect Santiago Calatrava, built with a height of 190 metres in Malmoe, Sweden. The building which was completed in 2005 has a concrete core that is surrounded by nine cubes with apartments and offices. Each cube consists of five stories. Technical rooms are situated in the basement and on intermediate floors between every second cube. A maximum of 900 people are expected to be within the building at the same time. The fire safety design of Turning Torso was carried out with a prescriptive approach allowing a single fire and smoke safe staircase. However, additional extensive fire protection has been added. The overall fire safety strategy is to provide sufficient safety barriers to effectively minimise the likelihood of a severe fire.

The building is protected by a fire alarm and a redundant sprinkler system. Door shutters are required on all apartment doors and the door between the pressurised stairwell and the protected lobby. The building and the stairwell is divided into six fire sections, with a fire-rating of 2 hours and independent active safety measures. Literally speaking the Turning Torso consists of six buildings on top of each other. There is a protected firemen's elevator and fire hydrants throughout the building. The fire service has a specially design control station at the ground floor, where they can communicate with the occupants, as well as monitor and control the fire safety features of the building. A phased evacuation concept is used and several systems are redundant and equipped with standby power. A two hour rating on load-bearing structures is used. The overall fire safety strategy was adopted by applying a simple "what-if analysis?" to the problem. Questions like what if the sprinkler system fails, what if the pressurisation fails, etc. were asked.

If the fire alarm system fails the sprinkler system has a high probability to prevent the conditions in the room of fire of becoming lethal. If the sprinkler system fails, the pressurised stairwell provides a safe environment for escape. If the pressurisation is unsuccessful the occupants have a safe area only a few stories away, in the next fire section. Passive fire protection measures should make it almost impossible for the fire and smoke to spread to another fire section. The fire service is able to enter the cube where the fire occurs through a protected firemen's elevator. Their main task is to ensure that people are evacuated to safe areas and that the fire is readily put out.

The sprinkler system allowed the design team to make some trade-offs compared to the prescriptive requirements. E.g. there is no vertical separation distance between windows in different fire compartments, a limited amount of combustible surface finishes is allowed in protected lobbies and the HVAC-system has some features that were considered unnecessary in the presence of sprinklers.

It the Turning Torso would have been designed after the code change in 2002, it is most likely that it still would have a single staircase for evacuation. The demands on verification would ultimately have been higher. The risk analysis approach used to develop the fire safety strategy of the building should require more structure and more discussions on risk levels and redundancy. It is the overall holistic risk-informed approach that is missing, where the trade-offs must be evaluated to the overall fire safety strategy.

Kista Science Tower – 31 story office building

The Kista Science Tower is a triangular 31 story office building in the outskirts of Stockholm, Sweden, completed in 2002. It was designed with the same regulatory prerequisites as the Turning Torso, i.e. single means of escape was allowed without any verification. The building is fully equipped with sprinklers and a fire alarm. The protected lobbies, the stairwell and the firemen's elevator shaft is pressurised to protect them from smoke spread. The most important active safety system in Kista Science Tower is the sprinkler, as it limits fire spread within the fire compartment, it protects the separating and load-bearing structure and prevents fire spread through walls, floors, façade and HVAC-system. The design team of the building recognised the importance of the system and made additional precautions to prevent fire spread.

Being a high-rise building ultimately means that some safety measures employed by the fire service as a redundant option to passive and active system no longer are available. Therefore the Kista Science Tower is divided into fire sections on every fourth floor. The prevention of fire spread between fire sections do not rely upon any active safety measure. Separating and load-bearing structures have at least 60 min fire resistance. The double-glazing façade was of particular interest to the design team as it could act as a chimney and easily spread fire to the floor above. Fire tests were conducted in order to find an optimal solution for the fire protection of the façade.

The fire safety design strategy for the Kista Science Tower would probably have been the same, if the building would have been designed today, with improved requirements on verification. The design ideas of the building are robust, and barrier orientated. As with Turning Torso a holistic risk-informed analysis would have been necessary to determine performance requirement for the active and passive fire safety measures.

Fire safety requirements in other countries

Specific code requirements on fire safety in tall buildings in countries where high-rises are more frequently built show far more extensive fire protection than what could be found in the Swedish regulations. The NFPA Life Safety Code [2] defines a high-rise as a building taller than 23 m. In such buildings the code requires fire alarm, sprinklers, two independent escape routes (i.e. two stairwells), at least one firemen's elevator and the possibility for the fire service to communicate with the occupants.

The building code of Australia has similar requirements. The Australian code requires smoke detector, sprinkler systems, two pressurised stairwells, and firemen's elevator in buildings taller than 25 m. The British Approved Document B does not require sprinklers in residential buildings. A single staircase could be acceptable if an extensive fire compartmentation is employed. Fire alarm and a firemen's elevator are fundamental requirements. The code requirements in Hong Kong are similar to those in the U.S., except that the stairwells in high structures should be divided into fire sections, with safe refuge areas in between [3].

DESIGN CHALLENGES

Fire safety in high-rise buildings is related to a number of design challenges that normally don't exist in buildings where the fire service could intervene from the outside. The prerequisites changes as buildings become higher and some of these challenges are:

1. Escape is only possible through internal stairwells, or from the roof with rescue helicopters. There is a necessity for phased evacuation in order not to clog the stairs.
2. External fire service intervention is not possible and internal fire fighting operations is therefore the only option. All rescue operations will be delayed and take longer times. Significant difficulties for fire service command and communication are recognised.
3. Stack effects opposes a serious problem to control smoke spread.
4. There is a potential for an extreme catastrophe in the event of a structural collapse.

Building cost considerations

Most building codes require two separate means of escape. This is not a preferable option for the property owner, who finances the construction work. Minimising non-rentable space is of great importance and therefore it is very attractive to have as few stairwells as possible. If the building code allows for a performance-based approach, a fire safety design solution with single means of escape will most likely be adopted. In a residential building, the use of a single staircase results in increased revenues of app. $ 150,000 per year. However, single means of escape requires additional fire protection and a cost-benefit analysis could show which fire safety design solutions that has the lowest life cycle cost. Regardless the outcome of such an exercise, property owners wishes to maximise rentable space.

Escape

There are a number of variables that influences the possibility of safe escape from high-rise buildings. As the building increases in height, the travel distance within the building to the outside gets longer. Studies on occupants ability to self escape from high-rises shows that elderly and mobility-impaired people will have great difficulties walking down long stairs. Due to a generally less-fit population, the egress performance in stairs has diminished drastically, app. by one half in recent decades. A conservative assumption of the walking speed is one minute per floor. Some research indicated that the minimum exit stair width should be at least 1.2 m between rails, i.e. a nominal width of app. 1.4 m. stairs, to allow two people to walk side by side [4].

Due to changed population characteristic there is a decrease in traditional reliance on self evacuation by stairs as the default response to an emergency. Some research indicated that around 5-10 % of the population is not able to uses stairs for escape, a fact which emphasises the use of elevators. However, using elevators for escape in the event of fire is a controversial approach in conflict with the perception of many occupants. Extensive research is needed to design communication systems, including signage, for making elevator systems functional for occupant evacuation [4].

Evacuation sequencing or phased evacuation should preferable be used in high-rises. Some general rules for prioritising escape is to begin with the floor of immediate danger and adjacent floors above and below, depending on where the fire is located in relation to fire sections, etc. Next, start evacuation of floors above the area in danger. Experimental results shows people are quite defensive, e.g. they hesitate to enter a stairwell until there is a gap in the flow of people in the stairwell [4].

The concept of safe refuge areas is adopted in many codes, among those the Hong Kong building regulations. Refuge floors should act as a safe place for rest before occupants continue to escape downwards. They could also act as safe places when staircases below are obstructed by smoke. Refuge floors are required in residential buildings taller than 40 stories. An option to evacuate people from the roof should be present in building with a height of 25-40 stories [5].

Preventing the spread of smoke and fire and assuring structural integrity

The stack effect caused by temperature differences between the outside and the inside, is a delicate problem to solve in order to maintain control of smoke spread. When the outside is colder than the inside, i.e. during the winter, there is an upward movement of air within the shafts. This upward flow causes an inflow of air from the lower floors and an outflow of air to the upper floors. If smoke enters the shaft below the neutral plane it will spread to the upper floors with the driving force of the stack effect. In the summer time there is a reverse stack effect with identical, but opposite prerequisites [6].

In high-rises there is a potential risk of vertical fire spread from window to window as the fire service response will be delayed. The prescriptive separating distance between windows of 1.2 m in the Swedish building code, requires a rapid fire service intervention in order to contain the fire. The necessary vertical separating distance should therefore be derived through calculations based on window configuration and the size of the fire compartment, assuming a fully developed fire. As an example, the Japanese building regulation requires a separating distance of 1.9 m in high-rises.

The structural integrity of load-bearing constructions is crucial to assure complete escape and the safety of the rescue personnel. The Swedish building code requires a fire rating on load-bearing structures of 90 minutes for buildings taller than four stories. The prescriptive approach should not be valid for high-rise buildings. Instead, the required fire rating should be based on the time of complete evacuation and the time for full burnout of a fire compartment or fire section. The Eurocode [7] gives a fuel load distribution for apartments, which could be used with the time equivalence concept to assess the necessary fire resistance rating. If an apartment fire is not intervened there is a probability of 82 % that it will last longer than 60 min. Corresponding probabilities for 90, 120, 180 and 240 min are 31 %, 7 %, 0.33 % and 0.01 % respectively.

Fire service intervention

The response of the fire service in high-rise buildings is complicated. Special attention is needed to assure that the fire service has sufficient ability to carry out an attack. It is also of great importance to guarantee the safety of the rescue personnel. The major challenges in of high-rise fire service operations are related to command and tactics, the vertical movement of personnel and equipment and the delayed, long response time. One important key to success is a properly design control station where the fire service command can supervise the attack, as well as control and monitor the performance of the safety systems within the building. It is also important that there is at least one firemen's elevator and that there are an appropriate number of fire hydrants.

If the building has single means of escape, the fire hydrants must be placed so that the integrity of the stairwell is kept intact. In these buildings the firemen's elevator is of utterly importance as the only stairwell otherwise would be used both for attack (fire fighters moving upward) and for escape (occupants moving downwards). As fire-fighters ascend, 50 % of the egress capacity will be lost [8].

A RISK-INFORMED DESIGN APPROACH

The Swedish building code currently considers buildings with more than 16 stories as high-rises that require special attention by the design team. This is not in line with the design challenges, identified in the previous sections as external rescue operations is considered unavailable in buildings higher than seven stories. In Sweden a reasonable definition of a high-rise building would be a tall building with eight or more stories.

Fire scenarios and design fires

It is necessary to have a clear understanding of possible residential fire scenarios that could oppose a threat to the building and its occupants. Statistics from the Swedish Rescue Service Agency on app. 33,000 apartment fires over the last ten years show that two thirds of the fires start in apartments and one third start in other areas as stairwells, basements, refuse storage rooms, attics, etc. Three possible general fire scenarios are considered; fires in apartments, fires in escape routes and fires in service areas. Fires in apartments are those who are most likely to occur. The initiating events of these fires and the initial fire spread is difficult to control. The risk behaviour of the occupants and the high and uncontrolled fire load in an apartment require active fire safety measure to suppress or control the fire. Apartment fires have a high probability on becoming fully developed, imposing a potential threat to the building as a whole.

Fires in escape routes could occur either in the protected lobbies or in the stairwells. The major causes of these fires are either arson or electrical fault. As the fire load in these premises is limited due to the use of strict regulations on claddings and surface finishes, it is not likely that this scenario will oppose a threat to the occupants. Arson could be prevented by not having combustible items in escape routes and by security measures as restricted access, camera surveillance etc. If the fire service is promptly notified of the fire and if the stairwell is equipped with smoke ventilation, the availability of the escape route will rapidly be restored.

Fires in service areas as basements, attics, refuse storage rooms, mechanical rooms could oppose a serious threat to the occupants if the fire risks are not properly controlled. Again, arson is a common fire cause in these locations. The above proposed security measures to prevent arson will be effective for these fires as well. But, since the fire load in service areas could be significant, it is of great importance that both passive and active safety measures are adopted to control the fire risk. Basements are not allowed to be connected to the stairwell and refuse storage areas should preferably be placed outside, away from the building. To conclude, the design fire in residential high-rise buildings is considered to be a fully developed apartment fire. The risk-informed approach should focus on this fire and measures necessary to protect the buildings and its occupant. Other fire risks should be limited with prescriptive measures, which keep the fire load low enough and potential arsonists away from the building.

Fire safety objectives in high-rise buildings

The main fire safety objectives in buildings are; limiting the probability of outbreak of fire, ensuring safe evacuation of occupants, preventing large property losses and to protect the environment. These objectives are translated to technical requirements, covered within the Swedish Ordinance on Technical Requirements for Construction. These technical requirements, i.e. the essential performance of the building in the event of fire are as follows (in suggested order of priority):

1. The generation and spread of fire and smoke within the construction is limited.
2. The load-bearing capacity of the construction can be assured for a specific period of time.
3. The safety of fire service is taken into consideration.
4. People in the building on fire can leave it or be rescued by other means.
5. The spread of fire to neighbouring buildings is limited.

There is no actually difference between high-rise buildings and other lower buildings considering the objectives and the technical requirements. The major difference is that the role of the fire service as an active part in fulfilling the objectives is diminished in high structures. A suitable alteration of the objectives and the requirements on high-rise buildings is to add that all relevant requirements should be accomplished without taking an extensive fire service intervention into account. High-rise structures need the fire service in order to check that the safety systems operates as intended and to launch small scale attacks to verify that the fire is readily put out.

The complete evacuation of a tall building is, as mentioned in a previous section, extremely difficult and should by all means be avoided. Therefore the fire service will play an extremely important role in monitoring and controlling the fire safety features. Measures must be in place allowing for the fire service to quickly reach the fire floor in a safe manner. Extensive fire service intervention should only be necessary in case of a extreme and unlikely event, e.g. when there are multiple failures of major fire safety systems within the building.

An introduction to the barrier concept

Traditional fire safety regulations could be considered being built up by a number of barriers, being either preventive or protective. Barriers that are intended to work before a specific initiating event takes place (e.g. a fire), serve as a means of prevention. Such barriers are supposed to ensure that the accident does not happen, or at least to slow down the developments that may result in a severe accident. Barriers that are intended to work after a specific initiating event has taken place serve as means of protection. These barriers are supposed to shield the environment and the people in it, from the consequences of the accident.

Svenson [9] showed how the barrier concept has been applied by practitioners of risk analysis. A barrier was defined as “equipment, constructions, or rules that can stop the development of an accident”. Svenson provided a distinction between three types of barriers; passive, active, and procedural. Passive barriers, such as fire-rated structures, would always be ready to use. Active barriers, such as fire extinguishing equipment, would require some kind of activation before they could be used. Finally, procedural barriers, such as instructions for use of equipment, would require a mediating agent in order to be effective. A distinction must be made between barrier functions and barrier systems. A barrier function represents a function that could stop the development of an accident, and barrier systems are those systems that are maintaining the barrier functions. Such systems, in case of fire, could be a well-trained fire warden, a fire compartment, an automatic sprinkler system, the firemen’s elevator, etc. The use of the barrier concept should be based on a systematic description of various types of barrier systems and barrier functions. The NFPA “Fire Safety Concepts Tree” [10] is a good example on the use of the barrier concept to deal with fire risks.

The barrier concept in high-rise buildings

As stated in the previous section, fire safety regulations are normally based on a barrier concept. This section will provide some insights on how the barrier concept could be applied on fire safety in high-rise buildings, outlining key barrier functions and some suitable systems to maintain these functions. Only protective barriers are considered in this example, as it has its starting point after the outbreak of the design fire, described earlier. The preventive barriers to limit the probability of outbreak of fire should be the same, no matter the building height.

The fire service would normally be able to be an effective barrier to contain a fire within a compartment. Rescue units could simultaneously perform both outside and internal attempts to intervene with the fire. Statistics from the Swedish Rescue Service Agency on app. 33,000 apartment fires over the last ten years, show that there is a likelihood of 97 % that the fire will be contained within the fire compartment. A flexible and well-trained rescue service has the possibility to improvise, adapt and overcome the large variety of building fires that they meet. The fire safety objectives of high-rise buildings should not rely upon a massive fire service intervention. However, the fire service must be operational to meet the challenges of apartment fires in high-rises as a complement to the active, passive and procedural safety systems.

There will always be scenarios that are beyond the design parameters of the safety systems. Therefore, a quick response of the fire service with small tactical units that are guaranteed a safety attack route is a must in high-rise structures. In order to avoid unnecessary escape, extensive measures must be taken to contain the fire within the apartment of origin.

Fire safety measures have failure probabilities in the range of 5-30 %. A common success rate for sprinklers is app. 95 %, therefore sprinklers by them self are not able to contain the fire within a compartment with an equal or higher probability than the fire service. Additional safety systems are needed to back-up the sprinkler system. Alternatively, the sprinkler system needs to be designed with a proved reliability that outnumbers the fire service. Unfortunately, there are some scenarios and human actions that an inflexible system cannot meet. Therefore the 1st line of defence, i.e. maintaining the fire within the compartment must have at least two independent barriers in addition to fire service intervention. One of these barriers is naturally the sprinkler system and the other is the fire-rated structures surrounding the compartment. Attention is needed to assure that vertical fire spread from window to window is controlled with a high degree of probability. The prescriptive rule on vertical separating distances between windows is generally very weak and indirectly demands the fire service intervention in order stop fire spread.

Naturally, there is a probability that the fire will burn longer than the fire resistance time. If this happens or if there is another failure in the 1st line of defence, the 2nd line of defence must ensure that the escape routes are available to the occupants for the time period required to evacuate the building. Again, two redundant systems are necessary. Here protected lobbies with door shutters and very low fuel load in combination with pressurised stairwells are suitable measures. The concept of barriers is also used in the 3rd line of defence which has the primary objective of limiting the consequences if the two first defence lines fail. The use of vertical fire sections, safe refuge areas etc. are measures involved in this line of defence. The employed measures follow the same redundancy principle as outlined above.

If each barrier is assumed to have a probability of failure of 10 %, the 1st line of defence will contain 99 out of 100 fires, the escape routes in the entire building will be available in 9,999 of 10,000 fire outbreaks and the fire will not spread beyond the vertical fire sections in 999,999 of 1,000,000 fires. The proposed “defend in depth” principle and the corresponding lines of defence for fire safety in high-rise buildings are summarised below.

1st line of defence: The fire should be contained within the fire compartment and is not allowed to spread. Suitable barriers are sprinklers, fire-rated structures and fire service intervention.

2nd line of defence: Complete escape and rescue operations should be possible even if the 1st line falls. Proposed barriers are fire-rated structures, pressurisation and protected elevators.

3rd line of defence: The consequence if both the 1st and 2nd line fall should be limited allowing for a complete burn-out. Suitable barriers are fire sections, safe refuge areas and load-bearing capacity.

Developing fire safety design solutions

The barrier concept outlines three important lines of defence that the adopted fire safety design solutions must comply with. The primary role of the design team is to choose appropriate safety systems to meet relevant hazards and the architectural ideas of the building. The team must establish evacuation strategies, suitable fire ratings on structures and preferable tactics of fire service intervention. Further on, the design team must ensure that external vertical fire spread is limited and that the stairwells and elevator shafts are properly protected from smoke. Finally, the need for the 3rd line of defence, depending on the building height and occupant load, must be evaluated. Special attention is needed when deciding on the load-bearing capacity in the event of fire. This capacity must at least allow for complete evacuation of the building and give the fire service additional time to intervene with the fire, in order to rescue those that could be trapped above the fire floor.

It is preferable if only systems designed according to a well-established standard would be used in high-rise buildings. System performance and maintenance requirements must be well known, as the secondary role of the design team is to evaluate the reliability of the fire safety systems in order to ensure that they operate according to the requirements on availability. In reliability analyses it is of crucial importance to identify any failures that have a common cause, as they drastically could lower the grade of redundancy. E.g., if there is one single computer controlling all safety functions, a hard-drive error could simultaneously make all functions unavailable. The design team must conduct extensive fault tree analyses for all lines of defence, and later combine them for the entire building. This exercise aims at deriving the minimum set of events necessary and sufficient to cause the top event, e.g. a failure of the one of the defence lines. The by far largest contributions to error and uncertainty in fault tree analysis result from qualitative aspects and arise from lack of understanding of the system, incorrect fault tree logic describing the system failures and improper accounting for common cause failures [11]. The design team must include a well-trained risk analyst in order to cope with this challenge.

CONCLUSIONS

The fire safety design of high-rise buildings should not follow a traditional prescriptive approach as the Swedish building regulations are very poor on the details specific to high-rise fire safety. An analytical design approach is already required in the building code, if there is a great risk of human injury in case of fire in the building. The authority considers high-rises with more than 16 stories as building where the risk to life could be great. If the fire safety design solution is derived on basis of an analytical approach, the design team must verify, document and assure that the quality of the design is satisfactory. Some requirements on the verification of the fire safety in high-rises are outlined below:

1. A comparative analysis is not appropriate as the building code lacks too much information on the specific needs for high-rises. Instead, the risk analysis must be holistic and focus on the essential performance of the building in the event of fire, in relation to all the technical requirements covered within the building act.

2. The verification should have its base in the “defend in depth” principle describing the necessary barrier functions and associated barrier systems to fulfil the safety objectives. A thorough description on expected outcomes related to the failure of different safety systems must be presented.

3. Human behaviour must be taken into account, both in deciding the evacuation strategy, as well as when outlining maintenance instructions and analysing human response to fire.

4. It must be assured that the reliability of the fire safety systems meets the necessary requirements on availability. A fault tree analysis of the various lines of defence shall show that common causes of failure have been identified and that actions have been taken to eliminate those. The design team must specify the control and maintenance requirements necessary to meet the demands on availability.

5. The evacuation strategy as well as the tactics of the fire service must be well documented and verified. The design team must assure that the proposed escape strategy is functional and meets the safety objectives. Special attention must be given to mobility-impaired people. Intended modes of fire service operation related to the “defend in depth” principle with associated lines of defence must be clarified.

6. The design team must show that fire resistance ratings on separating structure as well as load-bearing members meets the safety requirements i.e. complete evacuation of the building and allowing for a complete burnout of a fire section.

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