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ONE- OR TWO-WAYS OUT OF A HIGH-RISE BUILDING?

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ABSTRACT

This paper presents a simplified reliability assessment of vertical egress provisions in high-rise residential buildings (height >25 m). The assessment evaluates the impact of the building's height, floor area and external assistance on the resulting fire risk to occupants and relates the required egress reliability to the tolerable societal risk from fire in buildings. The applied assessment puts the problem of egress reliability into perspective by developing relationships on which performance-based alternative design solutions in residential high-rise buildings can be formulated. This paper also assesses some frequently used precautions and evaluates them in the format that permits their comparison against the risk-based acceptance criteria, or alternatively – if such are not practical - against the prescriptive solutions. The potential difficulties are discussed with some such precautions and advice is provided on how to avoid them. The paper aims at improving understanding of the egress problem in high-rise buildings to facilitate performance-based building design.

INTRODUCTION

The rational control of life safety from fires in high-rise buildings remains a continuous challenge for building regulators, building designers and fire safety engineers. In particular, the number of required egress provisions and the level of their protection against fire and smoke are frequent topics for discussion. Furthermore, in today's 'performance-based' environment the interest of many fire safety practitioners is strongly focused on the interrelationships of parameters on which the cost-effective 'alternative solutions' could be formulated.

This study tries to put the problem of the egress provisions in high-rise residential buildings into perspective by considering a selection of parameters and relationships. A risk-based (or risk-informed) model is presented with the aim to assess the required reliability of the vertical egress provisions against the tolerable societal risk acceptance criteria, or – if such are not established - against the prescriptive solutions. The model uses a high level 'top-down' approach in which probabilities are attached to abstract functional elements representing the fire development and the egress provisions. The probabilistic nature is necessary because the parameters are not simply numbers but distributions. The abstract functional elements are themselves models of reality.

By applying the ‘bottom-up’ approach the study evaluates some common design solutions for their reliability in the format that permits them to be compared against the risk-based acceptance criteria. It also highlights the potential pitfalls when selecting fire precautions for protecting the vertical egress provisions from smoke and fire penetration.

Definition of the problem

Aslaksen[1] argues that problems are usually approached in a stepwise fashion:

(a) Definition of the problem.

(b) Definition of the decision criteria.

(c) Identification of the possible options.

(d) Selection of the preferred option.

In this stepwise approach the ‘definition of the decision criteria’ is the most critical step. It is both vital and challenging. Challenging, because it is time consuming and often controversial. Vital, because if it is not carried out the process loses its claim of being a rational process.

To define the problem in relation to the number of means of escape from a high-rise building, it is useful to recall the fire safety goals and objectives, which the society considers important for buildings. The Building Code of Australia (BCA) as well as many other building codes stipulate two main fire safety related goals, namely (i) protection of lives, and (ii) protection of adjoining property. Considering that the second goal is not relevant in the current context, attention will be concentrated on the first goal only, i.e. the protection of lives. Intuitively, the acceptability of the number of means of escape must be related to the level of safety the building can provide to its occupants.

Tanaka[2] reports that two or more means of escape are required in most national building codes when the number of stories or height of the building, or number of occupants of a room or a storey, exceeds a certain number. On average, 50 occupants seem to be the threshold number of occupants allowed in a room or a floor having only one exit. Two exits are supposed to be sufficient if all occupants are able to escape through the other exit when one exit is blocked by fire, as long as the two exits are adequately separated so that both exits are unlikely to be simultaneously involved in one fire. Means of escape can consequently be modeled as a single fire protection feature i.e. functional element, with its capacity and reliability criteria. This feature will be referred to as the ‘way-out’ provision.

In this study, quantitative criteria are sought to logically decide which egress conditions in high-rise buildings are socially acceptable and which are not. For simplicity it is assumed that each single stair provision has the capacity to handle the total required number of occupants (capacity = 1). That assumption allows focus on the reliability component of the vertical egress provisions only (efficiency = capacity x reliability).

Qualitative assessment

A preliminary qualitative assessment is useful to better understand the problem. Consider a BCA complying high-rise building slightly higher than 25 m, which is served by a generic 'way out' provision, defined at this stage simply as a functional 'egress element' with a failure probability P_{fail}. 25 m is the height above which the BCA requires all buildings to have sprinklers installed and to have at least two pressurised fire isolated stairs serving all floors. However, if these two stairs are replaced with a functional 'way-out' element, which is simply described by its failure probability P_{fail}, defining the likelihood that the 'egress provision' will become blocked due to a single fire in the building.

Now assume a single accidental fire in one of the apartments, i.e. sole occupancy units (SOU) on one of the floors. For simplicity consider only severe fires, i.e. fire situations where sprinklers have failed. For the single stair building the following fire situations can be predicted:

A. Fire starts and remains contained in the SOU.

B. Fire starts and spreads (fire or smoke) beyond the SOU but remains contained on the floor of fire origin.

C. Fire starts and spreads (fire or smoke) to the 'way-out' provision;

D. Fire starts and spreads to the 'way-out' and other floors (either internally through installation shafts or externally by façade windows).

A qualitative measure of fire hazard can be attributed to each of the these situations as follows:

A. All occupants can leave their SOU; external assistance can be provided; life safety threat minimal.

B. Only occupants on the fire floor must remain in their SOU; external assistance is still possible (can reach the floor on fire by internal means); life safety threat increased.

C. All occupants above the 'fire-floor' must remain in their SOU, external assistance restricted (cannot reach the floor on fire by internal means); life safety threat high.

D. All occupants above the 'fire floor' are potentially exposed; external assistance very restricted; life safety threat very high.

It can be seen that in situations A and B the stair remains smoke and fire free. The situation can therefore be rated as not overly critical: even if the horizontal egress route becomes smoke logged, the external help can still reach the 'fire floor' and operate from the smoke free fire isolated stair. The occupants will meanwhile remain protected in their SOU, which are all fire compartments. In contrast, situations C and D are clearly 'high life-risk' situations with a high potential for a multi-fatality outcome. They arise due to the vertical part of the 'way-out' provision becoming smoke logged. As a consequence, neither the occupants can move out, nor the external assistance can move into the building.

Based on this qualitative assessment the problem can be simplified further by focusing on the fire situations C and D, where only the **vertical** part of the 'way-out' provision becomes unusable.

Quantitative assessment

For a sensible quantitative assessment both the severity and the likelihood of the possible fire situations must be taken into account, as both the expected number of occupants and the likelihood of fire development and spread are important. This however, constitutes the concept of risk.

In performance, environment risk now appears to be becoming the dominant decision criteria. Lund University in Sweden[3], Home Office in the UK[4], and the US NUREG[5] are only some of many reputable institutions worldwide who strongly argue for the acceptance of risk as the most informative decision criteria for problems in public domain. They all argue that the ‘risk-based’ methods are more rational than the alternate ‘rule-based’ methods. The issue of risk is a complex one, not least because it is a composite concept. It is the product of the probability that an event will take place and the negative effect it will have if it does take place. Aslaksen[1] argues that risk abatement within engineering is concerned with minimizing both components, within the balance of effort being determined by cost-effectiveness.

Risk-based acceptance criteria

Risk is not always simply the multiplication of two quantities, as there are differences in how people perceive the same or similar risks. For instance, society generally perceives more strongly ‘single multi-fatality’ events than ‘multiple single-fatality’ accidents. The first, usually referred to as the ‘acceptable’ or ‘tolerable’ societal risk, is often described by the exceedance curve, which relates the probability of the event with its consequences in terms of number of fatalities. This curve is known as the frequency-number curve or ‘FN-curve’. Simplified, it can be said that the societal risk is the product of individual risk for the specific location with the number of persons on that location, multiplied with a ‘societal’ weighting factor. According to Vrijling and Frantzich[5] the individual risk of dying in an accident per year P_{ai} should not exceed:

$$P_{ai} = C_{vol} \text{ x } 10^{-4} \tag{1}$$

where C_{vol} is the factor expressing the degree of volunteering in an activity or exposure, ranging from up to 10 for activities like mountain climbing to 0.01 for imposed ‘exposures’, like living or working in a hazardous environment.

In this study, however, risk will be expressed as a relative risk only, giving an indication of the likelihood of a number of building occupants being exposed to critical conditions, with a potential of becoming victims. The simplified risk calculations presented here cannot predict the exact number of persons not able to evacuate, nor can the methodology be argued to be fully comprehensive.

Risk calculations

By accepting risk as a decision criterion the main parameters influencing the risk in a building can now be indicated. Tanaka has shown in a similar exercise[6] that by expressing the probability of a fire loss occurrence with P_L (per building and year) and the potential size or severity of the fire loss by S_L, and with R_a indicating the acceptable level of fire risk (per building and year), the risk value can be written as follows:

$$R = P_L\, S_L <= R_a \tag{2}$$

Equation 2 can be used to address a number of issues in a rational manner. It shall be used to calculate the acceptable failure probability P_{fail} of the 'way out' provision in a high-rise building. This acceptable failure probability can be measured and expressed either in absolute terms or in relative terms.

The fire loss occurrence probability P_L can then be written as:

$$P_L = P_{fire}\, P_{sev}\, P_{spr}\, P_{fail} \tag{3}$$

where P_{fire} is the fire occurrence probability per year, P_{sev} is the probability that fire has the potential to become a severe fire (i.e. fully developed), P_{spr} is the probability that the fire sprinkler will fail, and P_{fail} is the failure probability of the relevant safety measure, i.e. the 'way out' provisions in this case.

The fire loss severity in terms of exposed number of occupants can be expressed as:

$$S_L = d\, n\, A_f \tag{4}$$

where 'd' is the occupant density in persons per m^2, 'n' is the number of floors, and 'A_f' is the typical floor area in m^2.

By writing:

$$P_{fire} = f\, n\, A_f \tag{5}$$

where 'f' is the likelihood of fire ignition per m^2 per year, the resulting risk R can be rewritten as:

$$R = d\, f\, n^2 A_f^2\, P_{sev}\, P_{spr}\, P_{fail} \tag{6}$$

As stipulated, P_{fail} denotes the required value of the failure probability of the 'way out' provision to maintain the risk R at a specified value. If $R_a \geq R$ there is the option to select the P_{fail} in such a way to satisfy the following relationship:

$$R_a \geq d\, f\, n^2 A_f^2\, P_{sev}\, P_{spr}\, P_{fail} \tag{7}$$

Comparative approach

In a comparative approach the following relationship holds for two different buildings with the same R_a:

$$d\, f\, n^2 A_f^2\, P_{sev}\, P_{spr}\, P_{fail} = d\, f\, n^2 A_f^2\, P_{sev}\, P_{spr}\, P_{fail} \tag{8}$$

If the conditions on the right hand side of Equation 8 specify a reference building meeting the code requirements (indicating an acceptable solution), then the acceptable failure probability of an arbitrary building P_{fail} can be determined as a function of the P_{fail} conditions of the reference buildings from the following equation:

$$P_{fail} = (d\, f\, n^2 A_f^2\, P_{sev}\, P_{spr} \,/\, d\, f\, n^2 A_f^2\, P_{sev}\, P_{spr})\, P_{fail} \tag{9}$$

By assuming the parameters d, f, P_{fd} and P_s to be equal for both buildings, the failure probability P_{fail} for a given acceptable risk value can be express as follows:

$$P_{fail} / P_{fail} = (n / n)^2 (Af/Af)^2 \tag{10}$$

If the reference building is just above 25 m high and the typical floor areas in both buildings are equal ($Af = Af$), then Equation 10 can be expressed in the form $P_{fail}/P_{fail} = (h/25)^2$.

Importance of external assistance

Thus far the fact that increasing the height of the building makes it increasingly more difficult for the external assistance to be deployed has been ignored. External assistance may be important for two obvious reasons (i) to attack and control the fire and (ii) to assist the people exposed to move away from the fire. Without external assistance the likelihood of fire spreading beyond the RFO and into the floors above will increase. Equally, the exposed people on the floor of fire origin and above are more likely to become early victims of fire and smoke if they have no assistance. The more vulnerable the occupants are and the higher the likelihood of fire spread the more important is the external help. Fraser-Mitchell[7] argued in his paper that the number of dependent persons present has a significant impact on the risk of death. Often the number of dependents is quite high, mainly due to young children and to a degree the elderly or sick.

Based on the preliminary qualitative analysis it has been concluded that in high rise buildings the most severe fire situations will arise – not so much when the horizontal egress provisions become unusable - but when the vertical 'way-out' provisions become compromised due to smoke or fire penetration. Under such scenarios, the occupants cannot move out of the building and the external assistance by internal means becomes impossible.

The impact of the reduced chance of external help in high-rise buildings relative to the building's 'vulnerability' to vertical fire spread can be addressed by including a parameter '*e*' which increases with the building's height. The value of this parameter is not known, however if it is assumed to be of the form $e = n^x$, where x indicates the importance of external help relative to the likelihood of the vertical fire spread and the occupants vulnerability on the n^{th} floor, then the resulting societal risk due to the restricted access and the resulting consequences can be expressed for a n storey building as follows:

$$R \propto R_0 \; n^x \, dn \tag{11}$$

where R_0 ($= d\, f\, n^2 A_f^2 P_{sev} P_{spr} P_{fail}$) is the original risk as derived previously.

For the stipulated acceptance criteria $R_a \geq R$ the resulting increase in risk R means that the failure probability P_{fail} of the 'way out' provision would have to be further reduced accordingly.

The floor-area influence

It has been shown before that the risk to life in high-rise buildings is not only dependent on the number of floors but also on the size of the 'typical floor area'. The increasing floor area increases the number of exposed occupants and - at the same time - also the likelihood of fire ignition. The linear increase in floor area size increases the resulting risk for a power of two.

The prescriptive BCA controls the size of the floor area served by a single stair in residential buildings by permitting that only one door from a SOU may connect to the stair on any floor without a lobby.

However, where lobbies are provided the maximum limit between the SOU and the single stair must not exceed 6 m. A similar effect is achieved in other occupancy buildings by the requirement that a single stair must not serve more than 50 occupants per floor. Consequently, where an increase of the floor area in high rise buildings is proposed, then the additional adjustment (reduction) of the failure probability P_{fail} of the 'way-out' provision becomes necessary. A parameter could be also be introduced to consider the increased difficulties of external help due to the increase in floor area or horizontal access route lengths.

Identification of possible precautions

So far the 'way-out' provision in functional terms has been treated as if it were a single 'black-box' fire protection feature. Its 'failure probability' P_{fail} has been determined to match the societal risk acceptance criteria. However, a real-world egress solution must now be found whose failure probability will match the derived 'way-out' failure probability as closely as possible. A stipulation is that the real-world egress solution must consist of at least one fire-isolated stair. Then, by assessing the failure probability of such a single stair, some informed judgment about the failure probability of a combination of stairs can now be made. Generally, the failure probability of an egress solution can be adjusted by a number of fire precautions. Self-closing fire or smoke doors and stair /lobby pressurisation are most commonly used precautions.

Self-closing doors

The provision of a series of self-closing doors is the most common approach to prevent smoke spread from the room of fire origin via the corridor into the fire-isolated stair. The problem can now be formulated in terms of a number of doors that need to be kept open simultaneously to meet the failure probability P_{fail}:

$$P_{fail} = (P_d)^{\mathrm{I}} \qquad (12)$$

where 'P_d' is the probability that a self-closing door will remain open, and 'i' is the number of doors in series between the SOU on fire and the 'way out' provision.

Now assume that a 'standard' single stair egress solution includes a series of three doors: one from the SOU to the corridor, one from the corridor to the lobby, and one from the lobby into the stair. The cumulative failure probability is then $P_{fail} = (P_d)^3$.

If the number of independent (redundant) stairs serving a building is increased to 2 or 3, then the number of doors that must be kept open simultaneously due to a single fire becomes 5 or 7, respectively. This is based on the following consideration: 1door from the SOU on fire, and additional two doors for each 'lobby-stair' combination. Note that only the scenarios C and D, as discussed in the qualitative assessment, are being addressed, i.e. the situations in which the vertical 'way-out' provision are smoke logged and cannot be used either by occupants or external assistance.

By assuming the Pd = 0.1 for a door with a self-closing device, the P_{fail} then becomes 10^{-3}, 10^{-5}, and 10^{-7} for the one-, two- and a three-stair 'way-out' provision, respectively. It can be concluded that each addition of an independent stair reduces the cumulative failure probability of the 'way-out' provision for a factor of 0.01, and that each addition of a self-closing door reduces the total failure probability for a factor of 0.1. However, the problem of over-reliance on one single measure and the potential for the common cause failure must be seriously considered in this context (explained further below).

Stair pressurisation

Apart from the use of self-closing doors, an effective control of fire and smoke spread from a SOU via the corridor into the fire-isolated stair can be achieved by the use of the stair pressurisation approach. Unfortunately, the failure probability of such systems is difficult to assess, in particularly where the pressurisation system is not part of a continuously operating air handling system (AHS). Cautious should be taken when contemplating such systems for residential high-rise buildings. The air pressurisation system requires continuous pressure differences between the barriers that can only be achieved if a continuous airflow is maintained from the pressurised stair towards the perimeter of the building. If such flow is not sustained then the pressure inside the building will build up and the pressure differences controlling the smoke spread are reduced.

It is also important to bear in mind that an airflow of 1 m/s against the door opening from the ‘room of fire origin’ is generally required to prevent the flow of smoke. However, such flow can only be maintained in large volume rooms with a high leakage rate to the outside, or where dedicated return-air shafts are provided, as in ‘sandwich’ pressurisation systems. However, these conditions are usually not met in residential buildings. Unless such airflow can be maintained, the pressure in the ‘room of fire origin’ and in the pressurised stair will equalize and the positive effect of pressurisation will cease. As a consequence the smoke will spread as if there were no pressurisation.

Common cause failure

The over-reliance on a ‘single measure’ used repeatedly within a system may make the protection concept vulnerable to the ‘common cause failure’, which can significantly contribute to overall risk of failure. A common cause failure represents the failure of components caused by common influences such as design, manufacturing, installation, or management deficiencies. A common cause failure can fail more than one component at the same time and can occur with greater probability than would be predicted by the product of the individual component failure probability[4]. The influence of the quality of ‘management’ is a most obvious example. For instance, if the strategy relies too much on the use of the self-closing doors, the risk can be run that by selecting a poor product, or due to an omission in management or maintenance procedures, they may fail with a higher rate than expected.

The potential for the common cause failure can be seen also in the application of stair pressurisation systems. If the pressurisation units for each stair are not independent, then the failure of the common elements in the pressurisation system can put the whole pressurisation system out of operation simultaneously.

A practical way to prevent or reduce the vulnerability to the common cause failure is to apply the ‘defence in depth’ protection principle[4]. The defense-in-depth principle is based on applying redundancy, diversity, and independence of fire precautions for critical life safety components and should include defenses against human errors. By providing diversity the common cause failure can be reduced.

DISCUSSION

The derived quantitative relationships and results in this paper are only informative. They indicate high complexity of the problem and a considerable lack of information and data. However, they show the way in which the issue could be studied and developed further. The diversity of opinions about the level of required reliability of the vertical egress provisions in high rise buildings is therefore likely to continue until more research is done and at least a basic consensus derived.

Due to the complexity of the issue on one side and its high life-risk potential on the other, it appears to be important that the alternative solutions in this area are conservative and based on the 'defense in depth' principle. This means that the performance-based design solutions addressing alternative solutions for the egress from high rise buildings should strictly apply redundancy, diversity and independence when considering the selection of candidate fire precautions.

To effectively control the potentially dangerous 'common cause failure' of the complex egress provisions in high rise buildings it appears unavoidable, at least at present, to rely on multiple redundant stairs supported by a combination of self-closing doors and active smoke controls, possibly stair-pressurisation. In addition, the position of the stair inside the building, i.e. whether in the centre or at the perimeter of the building, with the potential for natural smoke control, should also be considered. And, as a matter of high importance, the reliability and limitations of all these systems should always be considered.

CONCLUSIONS

In the current 'performance' environment the interest of many fire safety practitioners is strongly focused on the interrelationships of parameters on which the decision criteria for cost-effective 'alternative solutions' in high rise buildings could be formulated. This paper provides some perspective on the required reliability of the 'way-out' provisions in high-rise buildings and highlights concepts such as how such reliability could be assessed. A simplified risk-based (or risk-informed) model is presented with the aim to assess the required reliability of the vertical egress provisions against the tolerable societal risk acceptance criteria or against the existing prescriptive solutions. The purpose of this paper was not to develop a precise relationship for risk assessment, but rather to develop an approach to gain some understanding of the problem.

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