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Risk and Reliability Assessment of Smoke Control Systems in the Buildings

Kuldeep Kumar[1], Virendra Kumar Paul[2]
[1]Ph.D. Scholar; [2]Professor, Department of Building Engineering and management, School of Planning and Architecture, New Delhi

Abstract: During building fires, the most lethal factor affecting the occupants is the spread of smoke and toxic gases in the compartment, adjacent spaces, evacuation routes, and locations that are remote from the fire origin threatening life and damage to the property of the facility. Smoke and heat control in building fires is a major challenge for the egress of occupants as well as the fire-fighting operations. This paper provides an insight into risks due to the failure of smoke control and ventilation systems. Life and fire safety in and outside the building must also be analyzed in order to limit the spread of fire and control the spread of smoke thereby, offering adequate time and structural stability for the evacuation process as well as firefighting operations. This paper focuses on the identification of factors to establish the critical risk and reliability of the smoke control and exhaust systems in the buildings in an event of a fire.
Keywords: Risk assessment; Reliability, Smoke Exhaust, Smoke Management, Risk Factors

I. INTRODUCTION / BACKGROUND

As a primary requirement of all fire safety codes, the provision of smoke control systems (including exhaust and ventilation systems) is required wherein the evacuation process of egress may take a substantial amount of time or involves the potential of hazard (greater than normal) such as for basements, high-rise buildings, etc. In addition, smoke control systems play an important role in building with large volume multi-story spaces like malls, atriums, or theatres. In such buildings, the high ceilings may lead to the lack of effectiveness of sprinkler operation to control or dowse a fire (Paul, et al., 2021).

Also, smoke control systems are invariably complex in their design and contain components such as the building's HVAC system, electrical equipment, fire alarm system, architectural components (e.g., operable doors), etc. Hence, the involvement of numerous components and their interlinkages may lead to many potential failure points which can cause the overall system to fail to operate and perform suitably due to the lack of monitoring and control of the component, commissioning procedures, automatic self-testing, or periodic testing and maintenance as per the requirements and condition of the system and its components.

This study outlines the following overarching principles of fire safety during the design, construction as well as in use phase of the buildings (IFSS, 2020):

1) *Prevention* – Safeguarding against the outbreak of fire and/or limiting its effects.
2) *Detection and Communication* – Investigating and discovering of fire followed by informing occupants and the fire service.
3) *Occupant Protection* – Facilitating occupant avoidance of and escape from the effects of fire.
4) *Containment* – Limiting fire and all its consequences to as small an area as possible.
5) *Extinguishment* – Suppressing fire and protecting surrounding

The above-mentioned principles are relevant to all building typologies and regions as well as nations regardless of the differing political, economic, social, technological, legal, or environmental differences between jurisdictions

II. RISK AND RELIABILITY ASSESSMENT AT THE DESIGN AND OPERATIONAL PHASE OF THE BUILDING

Depending upon the complexity of the project, the concept design for smoke and heat control and ventilation systems are generally conceived and finalized several years prior to the final occupancy of the building. In addition, the performance criteria are frozen / established in the design phase that enables other disciplines to work towards providing integrated design conforming to these performance criteria. Hence, a proper and effective coordination among the stake holders, especially the design team is crucial so as ensure that any design change do not impact the design and intended performance smoke control system during the occupancy stage. While the building is the in-use or operational phase it is vital to analyze and assess the performance of the system to be analyzed or assessed.

The smoke control systems installed in a building plays an important role in life and fire safety of the occupants from the fire risks, especially pertaining to the smoke and heat spread in the building from the fire origin through various compartments impacting and imposing hazards the occupants as well as the property. Typically, the smoke control systems rely on an exhaust or natural/ mechanical system to operate when a fire is detected. It is imperative to note that the smoke control systems are designed and implemented in the buildings to limit or prevent smoke spread along with maintaining the tenable conditions and to assist with post fire operations.

III. RELEVANT CODAL PROVISIONS IN NBC

The National Building Code of India (NBC, 2016), also recognizes the guidelines for fire drill and evacuation procedures for high-rise buildings in annexure D-9.7 wherein there is a mention of periodic formal inspections of each floor area, including exit facilities, fire extinguishers, and the monthly testing of communication and alarm systems. Besides, annexure E-7 of NBC 2016 also highlights having a fire and life safety audit for all buildings with heights more than 15 m. Such audits should preferably be conducted by a third-party agency with relevant experience. Also, the frequency of such audits is recommended as once in two years (NBC, 2016). Also, annexure G-5.4 in the commercial kitchens mentions about inspection of sprinklers at least twice a year and cleaning due to the probability of coating of grease on sprinklers in such areas.

IV. IDENTIFICATION OF RISK AND RELIABILITY ASSESSMENT FACTORS

An exhaustive and in-depth literature review has been carried out, wherein various relevant published and non-published articles and journals were studied to identify the key risk factors and their associated reliability issues pertaining to the failure of smoke control systems in the building in case of a fire emergency.

The identified factors are listed below:

1) Exhaust systems
2) Natural Ventilation
3) Smoke barriers (Smoke / water curtains)
4) Dampers
5) Pressurization
6) Stack effect
7) piston effect (in lift/elevator shafts)
8) evacuation effect – loss of effective pressurization
9) Airflow (efficiency for dilution and purging) **-** Inlet and exhaust point locations (adequacy and efficiency)
10) Fire-rated Fans (fire rating, capacity-CFD, speed, etc.)
11) Duct insulation
12) Smoke reservoir (provision and size)
13) Compartment components **-** leakages, openings
14) Wind effect (including the design considerations for wind)
15) Awareness and training of staff and good practices

It is imperative to note that the above factors play an important role in controlling or reducing the spread of smoke in different areas of the building including the control of fire ignition and development in the early stage, control of flame spread, control of smoke and toxic, facilitate of means to allow occupants avoidance and provision of sufficient structural stability. In addition, (Ferreira, 2016), in his study revealed that the problem of reliability of smoke control systems is often identified at the point where additions/alterations are made to the building spaces, wherein re-investigation of the systems has been done and found that:

a) The system "never operated properly" or "no one really understood how it functioned" and the system was disconnected at some point;
b) It was found to be improperly working due to a loss of function of one or more critical components; or
c) It was found to be operating, but the operation of the system either fails to meet the intended design criteria or exceeds those criteria in such a way as to create an unsafe condition in the building, typically by creating unacceptably high door-opening forces (Ferreira, 2016).

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V. CRITICALITY OF THE FACTORS

Relative Importance Index (RII) method

The previous sections provide the factors to assess the risk and reliability of the smoke control systems in the buildings. The criticality of factors pertaining to the risk and reliability assessment of the smoke exhaust and control systems has been established through a survey. The survey was conducted through the rating system with the aim to gather expert opinions regarding the importance in terms of the probability (i.e. leading to risk) of failure of each factor. The rating system was comprised of the Likert scale (from 1 to 5), where: 1-Low probability, 3 – Medium/ average probability, and 5 – Very High probability of the failure of a particular factor. The respondents for this survey include various industry experts with relevant experience in fire and life safety, including fire safety officers and engineering, design consultants, facility managers, and experts from the fire service department.

The Relative Importance Index (RII) method is used to prioritize the factors through ranking. The relative Importance Index is the mean for a factor that gives it weightage in the opinions of respondents. The calculation of RII is shown below:

$$RII = \Sigma W / (A*N)$$

where,

W is the weighting given to each factor by the respondents (ranging from 1 to 5),
A is the highest weight (i.e. 5 in this case), and
N is the total number of respondents.

Higher the value of RII, more the probability of failure of that assessment factor in an event of a building fire. The RII has been computed for each factor to establish the relative importance of the identified factors as per Table 1 below:

VI. SURVEY ANALYSIS AND RESULTS

Table 1: Ranking of Risk and reliability assessment factors

S. No.	Risk factors (R)	RII
1	Exhaust systems	0.87
2	Natural Ventilation	0.65
3	Smoke barriers (Smoke/water curtains)	0.55
4	Dampers	0.78
5	Pressurization	0.74
6	Stack effect	0.59
7	Piston effect (in lift/elevator shafts)	0.68
8	Evacuation effect – loss of effective pressurization	0.64
9	Airflow (efficiency for dilution and purging) - Inlet and exhaust point locations (adequacy and efficiency)	0.58
10	Fire-rated Fans (fire rating, capacity-CFD, speed, etc.)	0.67
11	Duct insulation	0.68
12	Smoke reservoir (provision and size)	0.61
13	Compartment components – leakages, openings	0.69
14	Wind effect (including the design considerations for wind)	0.65
15	Awareness and training of staff and good practices	0.78

As a process of prioritizing, the risk factors with a Relative Importance Index (RII) of more than 0.70 are selected as the important factors for ranking purposes. The decision of selecting the benchmark of 0.70 has been taken in concurrence with the fire safety experts with experience of over 15 years.

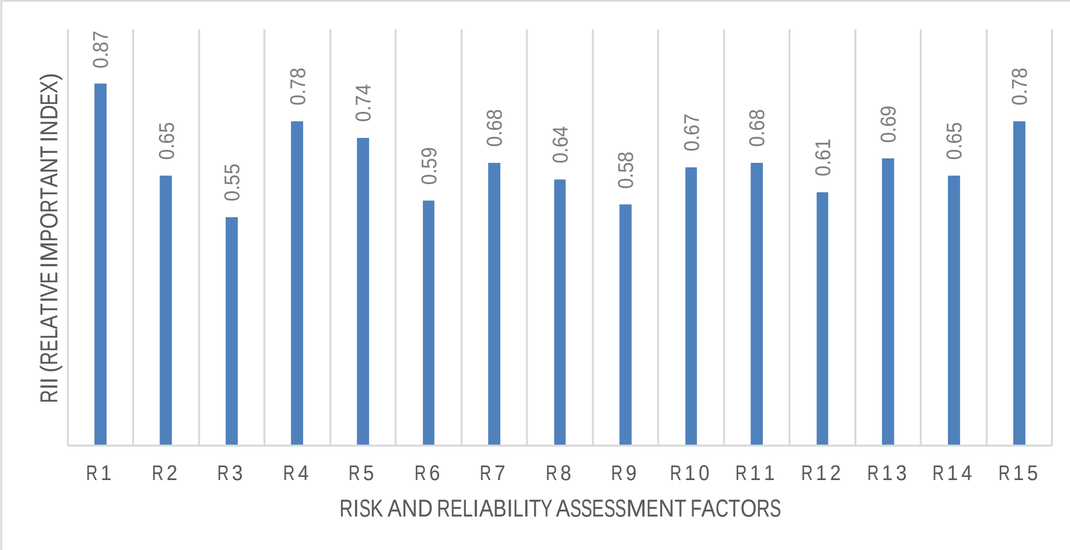

Figure 1 Risk and reliability assessment factors with respect to the RII

It is evident from the survey results that there is a variation in the importance of the factors in terms of their probability of failure. Though all the risk and reliability assessment factors are important as far as fire and life safety is concerned but for the study purpose recommendations and mitigation measures are provided for top-ranked factors with an RII of more than 0.70. These factors are listed below:

Table 2: Critical factors w.r.t smoke control systems in the buildings

S. No.	Risk factors (R)	RII
1	Exhaust systems	0.87
2	Dampers	0.78
3	Pressurization	0.74
4	Awareness and training of staff and good practices	0.78

VII. PROPOSED MITIGATION MEASURES AND RECOMMENDATIONS

A. Risk of Failure of Exhaust Ventilation

Exhaust ventilation systems, being a vital part of smoke and heat removal and control in buildings, especially with large open areas and high ceilings such as atria, shopping malls, etc. through venting the hot smoke collected high level in space by means of powered exhausting fans. It is important to note that exhaust ventilation can only protect property by permitting active intervention of the fire services to be quicker and more effective (Paul, et al., 2021). The application of exhaust systems is of particular importance for high-rise buildings (Kunhua, 2020). The method of exhaust ventilation plays a significant role in achieving fire and life safety objectives of the building occupants wherein the failure or inappropriate performance of it may impose hazards of the spread of smoke and heat leading to compromising the tenability conditions required for occupants as well as firefighting operations.

In an event of a fire, to prevent the smoke spread to the adjacent compartmentation via exhaust ventilation systems, the following solutions may be recommended:

1) Shutting down the fan(s),
2) Increasing (by double) the speed of rotation of the fan(s),
3) Converting the supply fan into an exhaust fan, and
4) Bypassing the support plenum to the exhaust plenum.

The various problems of the failure of exhaust systems can also be addressed by assessing the design and calculations of smoke exhaust systems along with the proper inspection and following an adequate maintenance protocol. It may be noted that the design of the exhaust systems and their installation must be done in compliance with the prevailing fire safety codes and standards along with the provision of any upgradation if required in the future.

B. Risk of failure of Fire / Smoke Dampers

A fire damper is a device, that closes automatically upon the detection of heat and a smoke damper is a device installed to control the movement of smoke in accordance with the prescribed standards and codes. The combination fire/smoke dampers can fulfill the function with override controls to pressurize individual spaces (Paul & Kumar, 2021). Both active and passive fire safety measures are employed in the buildings to eliminate and mitigate building fire risks. The active measures are not able to avoid the spread of smoke and toxic gases efficiently which leads to fatalities among the building occupants whereas, on the other hand, the passive fire protection methods are designed to prevent smoke, toxic gases, and fire from spreading from one zone to another majorly through compartmentation (Paul, et al., 2021).

To ensure the reliability of the dampers, the installation should always be accomplished in accordance with the manufacturer's instructions (i.e., through the installation manual) and prevailing life and fire safety standards. Like other fire protection systems in the buildings, the inspection, as well as maintenance of dampers is essential for the proper operation of the dampers which also helps in assessing the reliability of these systems. It is pertinent to note that the operation of dampers must be interlinked with the BMS system for a prompt response to the smoke spread and thereby addressing the issue from the BMS room only. It is recommended that the operation (opening and closing) of dampers should always be in automatic mode to ensure the effective performance of the dampers to mitigate the risk of the spread of smoke in the building areas.

C. Pressurization

A pressurization system in the building is provided to restrict smoke leaking passed closed doors into protected escape routes, such as the staircase through injecting clean air so that the pressure in the stairwell is greater than the adjacent compartment and such pressure difference must be maintained (Paul, et al., 2021). The air leakage in these escape routes can include stairway doors, windows, gaps in walls, natural leakage through wall materials, elevator doors, service shafts, facades, and raised floor systems (Lay, 2014).

The pressurization system mainly depends on the peak flow rate which is determined by the number of doors open at any point of time. It is to be noted that any doors being opened beyond the small number assumed in the design case will definitely cause a loss of air which will definitely affect the performance of the pressurization system as intended during the design.

The purpose of the provision of pressurization systems is to ensure the protection of building occupants as well as fire-fighting personnel during building fires. Normally, in high-rise buildings evacuation is planned in a phased manner such that all occupants do not enter the escape stairs simultaneously, instead the occupants at the highest risk evacuating first. The main issue which is to be highlighted here is that instead of the door opening (i.e. one floor at a time), it is likely that most of the fire doors would be partially open (i.e. either fully open or closed). Since pressurization in the buildings is not designed for such circumstances, the consequence is that increased air pressure may be required to retain the desired pressure difference from adjacent areas. This balance of air pressure is a fairly complex task, especially in the case of high-rise buildings (Paul, et al., 2021). To address this issue, building code such as the ASHRAE Design Manual for Smoke Control has suggested different shafts parallel to one another to service different sections of the stairwell.

A pressurization system thus claimed to be the primary line of protection for building cores and protection of life, would tend to fail or underperform, unless all aspects considered. Failure of the pressurization system can thus expose occupants as well as firefighters to serious conditions leading to their incapacitation or death.

D. Awareness /Training and Good Practices

Ironical though, there is still a dearth of formal education opportunities, especially for building professionals as far as fire and life safety is concerned.

At any stage of the project, the life safety of the building occupants should be taken into serious consideration. It is prudent to impart fire safety training and awareness to construction workers, including on issues such as handling combustible materials in a safe manner and handling emergency situations.

Several studies and research also reveal that during site inspections or fire audits, it was established that there is a lack of awareness among the staff or building users, or visitors regarding the provision and operation of installed fire safety equipment such as portable fire extinguishers, Fire Hose Cabinets, Fire Alarm call point, etc. Hence it is imperative to impart knowledge about fire and life safety and develop a program for conducting regular mock drills and training to all building users, especially the staff members so that they can act as the first respondent in case of any fire emergency.

VIII. CONCLUSION

Various risk and reliability assessment factors affecting the smoke control and exhaust systems have been identified and subsequently the criticality of the factors through RII method has been established. It is pertinent to note that the reliability of the smoke exhaust system necessitates risk assessment and analysis with backup redundancies. The production of smoke and its properties is influenced by many factors. For example, during a building fire, a material may have a substantial smoke production due to a rapid surface spread of flames even though it is producing rather small amounts of smoke.

The main purpose to implement smoke control systems using physical mechanisms is to avoid the building occupants from encountering smoke and heat as far as possible. These mechanisms include pressurization, compartmentation, dilution, airflow, and buoyancy which are the key determinants of the management of smoke, and thus, smoke management strategies are essential in the building, wherein pressurization and smoke extraction and systems are sub-sets of this strategy.

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