

Fire hazard in buildings: review, assessment and strategies for improving fire safety

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buildings

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Abstract

Purpose – The current fire protection measures in buildings do not account for all contemporary fire hazard issues, which has made fire safety a growing concern. Therefore, this paper aims to present a critical review of current fire protection measures and their applicability to address current challenges relating to fire hazards in buildings.

Design/methodology/approach – To overcome fire hazards in buildings, impact of fire hazards is also reviewed to set the context for fire protection measures. Based on the review, an integrated framework for mitigation of fire hazards is proposed. The proposed framework involves enhancement of fire safety in four key areas: fire protection features in buildings, regulation and enforcement, consumer awareness and technology and resources advancement. Detailed strategies on improving fire safety in buildings in these four key areas are presented, and future research and training needs are identified.

Findings – Current fire protection measures lead to an unquantified level of fire safety in buildings, provide minimal strategies to mitigate fire hazard and do not account for contemporary fire hazard issues. Implementing key measures that include reliable fire protection systems, proper regulation and enforcement of building code provisions, enhancement of public awareness and proper use of technology and resources is key to mitigating fire hazard in buildings. Major research and training required to improve fire safety in buildings include developing cost-effective fire suppression systems and rational fire design approaches, characterizing new materials and developing performance-based codes.

Practical implications – The proposed framework encompasses both prevention and management of fire hazard. To demonstrate the applicability of this framework in improving fire safety in buildings, major limitations of current fire protection measures are identified, and detailed strategies are provided to address these limitations using proposed fire safety framework.

Social implications – Fire represents a severe hazard in both developing and developed countries and poses significant threat to life, structure, property and environment. The proposed framework has social

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implications as it addresses some of the current challenges relating to fire hazard in buildings and will enhance overall fire safety.

Originality/value – The novelty of proposed framework lies in encompassing both prevention and management of fire hazard. This is unlike current fire safety improvement strategies, which focus only on improving fire protection features in buildings (i.e. managing impact of fire hazard) using performance-based codes. To demonstrate the applicability of this framework in improving fire safety in buildings, major limitations of current fire protection measures are identified and detailed strategies are provided to address these limitations using proposed fire safety framework. Special emphasis is given to cost-effectiveness of proposed strategies, and research and training needs for further enhancing building fire safety are identified.

Keywords Fire hazard, Framework for fire design, Strategies for fire safety, Buildings, Fire protection engineering

Paper type Research paper

1. Introduction

Buildings constitute majority of built infrastructure and play a pivotal role in socio-economic development of a country. Most of the buildings are designed to last for several decades and provide residential and functional operations to large number of inhabitants throughout their design life. During this long time-span, buildings are subjected to several natural (earthquake, hurricane, tsunamis etc.) and manmade (fire, explosion etc.) hazards which can cause partial or complete collapse of the building, and incapacitation of building operations. Such destruction or incapacitation in the event of a hazard can jeopardize the life safety of inhabitants and can cause significant direct and indirect monetary losses. Hence, buildings are designed to withstand actions from numerous anticipated hazards to ensure life and structural safety during their design life, and fire represents one such extreme hazard that can occur in buildings.

Fire hazard in buildings can be defined as the potential of accidental or intentional fire to threaten life, structural, and property safety in a building. With rapid development across the globe, fire hazard in buildings have undergone significant transformation in terms of severity and versatility and have become a growing concern in recent years. In the past two decades (1993-2015), a total of 86.4 million fire incidents have caused more than one million fire deaths ([Brushlinsky et al., 2017](#)), and total annual loss from global fire hazard accounts for about 1 per cent of the world GDP ([Bulletin, 2014](#)) (approximately US\$857.9bn [[GDP, 2018](#)]). On an average, 3.8 million fires caused 44,300 fire deaths every year in both developed and developing countries across the globe ([Brushlinsky et al., 2017](#)). Between 2010-2014, maximum number of fires (600,000-1,500,000 per year) and the second highest number of fire deaths (1,000-10,000 per year) in the world occurred in a developed country such as USA ([Brushlinsky et al., 2016](#)). Whereas, developing countries such as India and Pakistan suffered highest number of fire casualties (10,000-25,000 per year) and second highest number of fires (100,000-600,000 per year) ([Brushlinsky et al., 2016](#)). Therefore, to mitigate these adverse effects of fire hazard, it is important to provide necessary fire safety in buildings.

Fire safety can be defined as the set of practices to prevent or avert occurrence of fire and manage growth and effects of accidental or intentional fires while keeping resulting losses to an acceptable level. Currently, fire safety in buildings is provided through following provisions recommended by building codes of practice. While specifications and strategies for ensuring fire safety in buildings vary from one code of practice to other, most of them are based on prescriptive based approach and are derived from similar fire safety principles. In prescriptive based approaches, fire safety in buildings is provided

using a combination of active and passive fire protection systems. Active fire protection systems (sprinklers, heat and smoke detectors etc.) are designed to detect and control or extinguish fire in its initial stage and are more important from life safety perspective. Whereas, passive fire protection systems (structural and non-structural building components) are designed to ensure structural stability during fire exposure and to contain fire spread. Their main goal is to allow ample time for firefighting and rescue operations, and to minimize monetary losses.

This traditional approach of ensuring fire safety have several limitations in addressing contemporary fire hazard challenges (discussed in detail in Section 4) and provide limited guidelines on prevention of fire hazard itself. Major limitations of active fire protection systems include poor performance and functional reliability, and high cost of installation and maintenance -which often becomes a big concern in developing countries with limited monetary resources. On the other hand, passive fire protection focusses on fire performance of individual structural members and building components instead of holistic fire safety in building; which leads to an unquantified fire safety in building. Moreover, prescriptive approach of ensuring fire safety is not well integrated with actual building design process, and often fire design is done with the main goal of obtaining approval from fire safety regulatory bodies (Maluk *et al.*, 2017). Therefore, in developing countries with poor regulation and enforcement environments, often no or inadequate fire safety provisions are provided in buildings.

To address these challenges, this study proposes a new integrated framework (see Figure 1) of fire protection features in buildings, regulation and enforcement, consumer awareness, and technology and resources advancement to improve fire safety in buildings. Unlike current fire safety improvement strategies, which focus only on improving fire protection features in buildings (i.e. managing impact of fire hazard), the novelty of proposed framework lies in encompassing both prevention and management of fire hazard. To demonstrate the applicability of this framework in improving fire safety in buildings, major limitations of current fire protection measures are identified, and detailed strategies are provided to address these limitations using proposed fire safety framework. Special emphasis is given to cost-effectiveness of proposed strategies, and research and training needs to further enhance building fire safety are identified.



Figure 1.
Integrated framework to implement strategies for improving fire safety in buildings

2. Impact of fire hazard

Buildings contain several direct and indirect sources that contribute to fire hazard; and in the event of a fire there is significant risk to life, structure, property and environment from the initial development stages of fire itself.

2.1 Sources of fire hazard

Fire hazard constitute of all factors present in a building that can cause ignition (start fire), aggravate fire severity, incapacitate building fire safety provisions, and hinder escape or firefighting operations. Based on available statistics it is suggested that cooking is the leading cause of fire in both residential and non-residential buildings (USFA, 2016). Other sources of ignition in buildings include all live flames, heaters and hot surfaces, electrical malfunction, fireworks, and arson and vandalism. After ignition, fire severity can be aggravated by several factors such as large quantity of combustible household materials; improper storage of tools, rubbish, equipment, and volatile flammable materials (liquid petroleum gas, paints, ammunition etc.); materials producing toxic smoke on combustion; and combustible building components such as composite panels and timber. Also, use of open architecture (glass partitions, false ceiling etc.), large windows, and poor fire compartmentation design can cause rapid fire growth and spread by providing constant supply of oxygen to fire. All of the factors discussed above have a direct impact on starting fire or increasing its severity, and a comprehensive review of all such factors can be found in the literature (Buchanan and Abu, 2017; Drysdale, 2011).

On the other hand, fire safety in building can be threatened by indirect factors as well, which can incapacitate building fire protection measures, and hinder fire escape and firefighting operations. Some of these factors include poor regulation and enforcement of building codes (no or inadequate fire safety provisions in buildings), lack of common and civic sense (disabling or not using smoke detectors, ignoring fire alarm, vandalism etc.), lack of resources for maintenance of active fire systems (insufficient water for sprinklers, expired fire extinguishers etc.), and damage to fire safety provisions from other hazards (earthquakes, hurricanes etc.). These factors can lead to insufficient fire safety provisions within a building and significantly increase risk to life, structural, and property safety in the event of a fire; thus, contribute to fire hazard.

Another source of fire hazard, especially in populated areas close to wildlands, is one arising from forest fires (wildfires). Due to increase in human encroachment on the wildland urban interface, number of buildings and people living in the fire prone wildland is increasing significantly in recent years. This has made wildfires (resulting primarily from arson and lightning) a major source of fire hazard in wildland urban areas across the globe. In USA alone, an average of 66,903 wildfires occurred every between 2009-2018 which burned an average of 6.9 million acres and caused an average of US\$1.8bn for firefighting costs (NICC, 2018; Cost, 2018). In 2018, a total of 25,790 structures were destroyed by wildfires including 18,137 residences, 6,927 minor structures, and 229 commercial/mixed residential structures; which is highest number of structures lost to wildfires since 1999, and almost double of previous highest of 12,306 in 2017 (NICC, 2018). In Canada, about 8,000 wildfires occur every year and are responsible for burning of 6.1 million acres per year (CWFIS, 2018). Similar trends in building fire hazard from wildfires can be found across the globe as well.

2.2 Development of building fire

The full uninterrupted development process of a building fire inside a typical room is illustrated in Figure 2 through temperature-time evolution. The temperature-time evolution

depends on a wide range of variables (fuel load, ventilation, compartmentation characteristics etc.), therefore, there is significant variation in fire dynamics of each fire. A comprehensive discussion on fire development and its characterization can be found elsewhere in the literature (Buchanan and Abu, 2017). In general, growth of fire in a compartment is categorized into two distinct phases; namely pre-flashover fires and post-flashover fires (Figure 2). In pre-flashover phase, the duration from smoldering (flameless combustion) to ignition (combustion with flames) is defined as incipient stage, and duration from ignition to flashover (rapid increase in temperatures) is defined as growth stage of fire. Whereas, in post flashover phase, duration for which temperatures keep increasing from combustion is defined as burning stage, and subsequent cooling is defined as decay stage of fire. Pre-flashover phase is important from life safety perspective, and post-flashover phase is important from structural safety perspective. Detailed impact of fire hazard in pre and post-flashover phases is discussed below.

2.3 Impact on life safety

There is significant risk to life safety in both pre and post-flashover phases of building fires, and on an average about 44,300 fire deaths have occurred every year between 1993 and 2015 (Brushlinsky *et al.*, 2017). During pre-flashover phase of fire, combustion generates several toxic gases which are extremely deleterious to humans and inhalation (even in small quantities) can be fatal within minutes (Nelson, 1998; Alarie, 2002). Most common among these are carbon monoxide (generated from incomplete combustion), hydrogen cyanide (generated from burning plastics), and phosgene gas (generated from burning vinyl-based household materials). The smoke generated from combustion also contains small soot particles and toxic vapor which can cause irritation to eyes and digestive system. It is due to this high toxicity of smoke (toxic gases, soot particles and vapor) that more fire deaths occur from smoke than burning itself (NFPA, 2018). Also, smoke and hot gases obscure and hinder escape routes from building during fire, which further increases risk to life safety from inhalation of toxic gases and burning.

Other threats to life safety are from reducing oxygen levels in room from combustion and inhaling hot air. Humans undergo impaired judgement and coordination when oxygen levels in room fall to 17 per cent from normal 21 per cent; headache, dizziness, nausea, and fatigue at 12 per cent; unconsciousness at 9 per cent; and respiratory arrest, cardiac arrest, and even death when oxygen levels fall to 6 per cent (NFPA, 2018). Also, inhaling hot gases can burn respiratory tract, and one breath of hot air can even lead to death. During post-

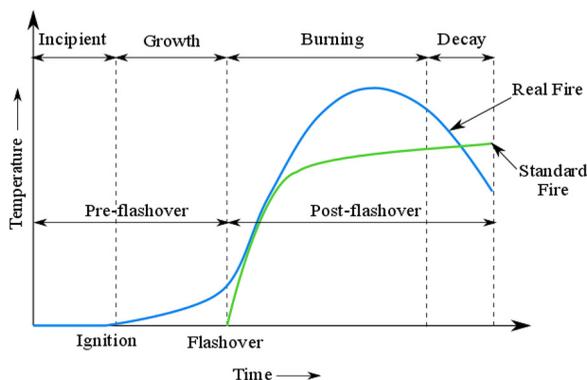


Figure 2. Uninterrupted building fire development process inside a typical room

flashover phase, the concentration of toxic smoke is very high and fire temperatures are untenable for humans and can lead to certain death, thus, all life safety operations are usually targeted towards pre-flashover phase of fire. Apart from toxic smoke and burning, biggest risk to life safety during post-flashover phase is partial or complete collapse of structure which can inhibit firefighting operations and kill trapped inhabitants under collapsed debris. Therefore, fire represents significant threat to life safety even when it is not fully developed, and every minute is critical in evacuating inhabitants during building fires.

2.4 Impact on structural safety

During fully developed stage, fire temperatures can reach above 1,000°C which can cause significant degradation in strength and stiffness properties of structural materials (concrete, steel, wood, etc.) (Kodur, 2014). This material degradation can incapacitate structural members to carry designed structural loads, and lead to partial or complete collapse of building during or after fire. Also, material degradation has strong potential to cause permanent structural damage which can cause premature failure of building under other natural hazards for which it was originally designed for; thus, endangering structural safety. A detailed review on impact of fire on structural safety can be referred to literature (Buchanan and Abu, 2017).

2.5 Impact on property safety

One of the biggest impact of fire hazard is on property safety and it causes direct and indirect losses of billions of dollars in both developed and developing countries across the globe (Brushlinsky *et al.*, 2017). Even if building withstands fire without life losses, aftermath of almost every fire involves monetary losses magnitude of which depends on severity of fire. Direct losses from fire hazard include loss of property from burning, sprinkler operation, firefighting operations (damage to property from water of fire brigade, breaking of doors and windows etc.), falling debris from partial or complete collapse of structure; and structural damage and cost of repair. Whereas, indirect losses include loss of use during time required for repairs, loss from temporary or permanent relocation, loss from demolishing structure, increase in insurance costs, environmental contamination etc.

2.6 Impact on environmental safety

Fire hazard generates several environmental pollutants from combustion, firefighting operations, and spillage from containers of hazardous materials due to damage from fire. Most common fire pollutants include metals, particulates, polycyclic aromatic hydrocarbons, chlorinated dioxins and furans, and brominated dioxins and furans, polychlorinated biphenyls and polyfluorinated compounds (Martin *et al.*, 2016). During fire, transmission of these pollutants occurs to environment through fire plume (air contamination), from firefighting water runoff (water contamination), and deposited air and water contaminants (land contamination); thus, causing environmental pollution. The magnitude of environmental pollution depends on the exposure duration, transmission medium, and susceptibility of receiving atmospheric, aquatic and terrestrial environments; and a detailed study on effect of fire on environment can be referred to the literature (Martin *et al.*, 2016).

3. Review of current fire protection measures

Most of the current fire protection measures are prescriptive and based on similar fire safety principles. Therefore, these provisions can be grouped under four generic categories as:

general strategy for fire safety, building codes and standards, safety provisions within building, and firefighting operations.

3.1 General strategy for fire safety

The first line and foremost strategy to tackle fire hazards is prevention of fire occurrence. Because it is not always possible to prevent fire, impact of fire should be managed by either managing fire itself or by managing exposed persons and the property. The usual strategy for managing persons is to evacuate exposed persons from the building by causing movement of people through a safe fire escape route. For people to evacuate safely, it is important that these requirements are met simultaneously: fire is detected in incipient or growth stage (earlier the better), occupants are notified using fire alarm and a safe fire escape route exists in the building. However, in case of high rise buildings, it is not possible to evacuate people through a safe fire escape passage in the time bound. Therefore, defend-in-place strategy is adopted by providing safe refuge on certain levels of building, which are then evacuated by firefighting department. This allows firefighters to target evacuation operations to these specific refuge areas only and save precious time which can be a factor of life and death in fire situations.

To manage fire and its impact, general strategy is to control the available fuel for combustion and use suppression by using various fire protection features installed in a building. Many building codes and standards specify a permissible limit of the available fuel load in a building (given as energy floor density in MJ/m^2), so that in case of ignition, fire growth is controlled by limited fuel supply. The fire severity corresponding to this limited fuel load is taken into consideration in the building design to withstand this certain level of fire severity. Therefore, the limit on the available combustible fuel load inside a building is dependent on the fire resistance requirement of the building and vice versa.

The other effective method of controlling fire is through suppression using automated or manual fire protection provisions. In case of automatic fire suppression systems, it is essential that both fire detection equipment and fire suppression equipment work simultaneously. The automatic provisions for fire suppression include automated sprinklers, condensed aerosol fire suppression systems, and gaseous fire suppression systems. On the other hand, manual fire suppression refers to manual fire extinguisher systems or standpipe systems. The suppression of fire depends upon early detection, functional reliability, and performance reliability of fire protection measures.

The last defense (for controlling fire and to manage its impact) is through compartmentation and structural stability. The structural stability is important as it helps in localizing fire, allows the firefighting operations to continue safely and prevent property losses arising from total collapse of structure. To ensure structural stability, it is important to control the fire spread inside building and to keep it to a localized zone only. This can be achieved by using fire compartmentation which contains the fire to a local area only and does not allow further movement of fire inside the building. Another possibility for controlling fire movement is by using fire venting which provides increased ventilation to fire affected zone only and exhausts the available fuel.

3.2 Building codes and standards

Detailed provisions in building codes are specified to avert the occurrence of fire, manage its impact, and to ensure life and structural safety while keeping property and life losses to a minimum. Building codes and standards provide guidelines for both design and assessment of fire resistance of structural members and assemblies. In case of building fire design, codes specify function of building elements under fire exposure, permissible limit of fuel load

density, required fire ratings for building elements, recommendations on type of materials, minimum member dimensions to achieve required fire rating, and guidelines for evacuation strategies. These recommendations vary with type of occupancy such as hospital, commercial buildings, and residential buildings etc. Generally, for public buildings such as hospitals and nursing homes (where risk to life safety is higher and indirect monetary losses are very high), building codes and standards recommend much conservative solutions with high factor of safety.

To assess fire safety of a structural member or assembly, building codes and standards use three main fire safety criteria as per function of a building member. These include: stability criterion (R) which is the ability to withstand applied loads during fire exposure; integrity criterion (E) which is the ability to prevent fire propagation due to formation of cracks and fissures; and insulation criterion (I) which is the ability to insulate the unexposed faces during fire exposure. Considering these fire safety criteria, the fire resistance assessment can be carried out by prescriptive approach or advanced analysis (Buchanan and Abu, 2017). In prescriptive based approach, fire resistance assessment is carried out by correlating member specifications (dimensions, clear cover, aggregate type) to fire safety criteria using data from standard fire tests. Whereas, in case of advanced analysis methods, building codes and standards provide parametric fire curves to be used in the fire resistance assessment, and recommend material properties at elevated temperatures to be used in the analysis while fire safety criteria remains same (Eurocode 2, 2004).

3.3 Fire safety provisions within a building

The fire safety provisions provided within a building are grouped under two main categories as active and passive fire protection systems. The active fire protection systems (sprinklers, smoke detectors, fire extinguishers etc.) refer to the control of fire by taking some action using an automated device or by a person. On the other hand, passive fire protection systems refer to the fire protection measures which are built in within the building itself, and do not require any operation by people or automated controls (for example fire ratings of structural and non-structural members or assemblies).

In the incipient stage of fire, fire extinguishers are used to contain the fire while they still can. If the fire goes into growth phase, the priority is to evacuate people out of the building as inhalation of toxic gases from fire can be fatal within minutes (Nelson, 1998; Alarie, 2002). In this stage, the fire management falls to automated or manual active fire protection systems. It should be noted that the timing for onset of all automated fire protection systems is crucial as any delay in fire alarm directly endangers life safety and reduces chances of containing fire once it grows in intensity. Therefore, ideally all evacuation process should be completed before fire gets out of control of active fire protection systems. Time available for escape can be related to the fire growth period as:

$$t_d + t_s + t_{rs} \leq t_u \quad (1)$$

where t_d is the time elapsed from ignition to fire detection, t_s is the delay between detection and start of escape activity, t_{rs} is the time to move to a place of relative safety and t_u is the time (from ignition) for the fire to produce untenable conditions.

After flashover, the fire temperatures can reach as high as 1,000°C and the resulting thermal expansion and degradation in material properties pose a serious threat to structural safety. During this phase of fire, the main target of passive fire protection systems is to contain the spread of fire while ensuring structural stability. To do so, it is important that all structural and non-structural members satisfy the fire safety criterion of Section 3.2 for the

required duration of fire exposure. These passive fire protection systems allow safe firefighting operations, safe evacuation operations, and mitigate property losses.

3.4 Firefighting

If the fire is not extinguished through active fire protection systems, extinguishing or controlling fire as well as ensuring life safety comes down to the role of firefighting department. The time required by the firefighting department to reach the site and begin firefighting operations play a key role in firefighting and is known as response time. The firefighting department is equipped with specialized equipment to provide alternate entries into a building, and to perform rescue operations even in most inaccessible places. In some countries, firefighting department also has the legal powers to inspect and enforce building owners to comply with building fire safety provisions as specified in codes and standards. This allows for better enforcement of the fire safety provisions, and a continuous monitoring of the same helps in improving fire safety.

4. Assessment of current fire protection measures

Current fire protection measures have several limitations in addressing contemporary fire hazard challenges.

4.1 Adverse conditions/features in modern buildings

Urbanization and increasing population density are leading to increased number of high rise buildings in the cities for both commercial as well as residential purposes. Despite fire safety provisions specified in building codes, implementing fire safety has become a serious challenge. These challenges arise because of:

- modern buildings having high fuel (fire) load which is hard to limit;
- highly combustible nature of room contents – due to more plastic and cellulose based materials in modern houses;
- open space architecture and use of too much glass (which is poor for fire compartmentation);
- use of new construction materials with poor fire performance; and
- longer response times for firefighting – due to adverse traffic conditions, narrow lanes and irregularly planned cities.

Due to enhanced standard of living, there is abundant carbon rich fuel (for example wood furniture, stationary, clothes, and other flammable items) in most of the modern buildings. Such high intensity of fuel load plays a key role in faster fire propagation, shorter flashover time, and rapid changes in fire dynamics. A full scale experimental study aimed at characterizing fire development in modern and legacy rooms concluded that flashover point can occur as fast as within 5 min of fire in modern rooms, and after 29 min in case of legacy rooms (Kerber, 2012). The development of room temperatures in case of legacy and modern rooms of this study is shown in Figure 3. It can be clearly observed from Figure 3 that temperature rises rapidly for relatively shorter duration in case of all modern room fires, thus, represent increased fire severity.

Further, modern buildings are designed with open architecture glazing with transparent glass windows and false ceilings to facilitate larger open office spaces for comfort and aesthetics. These open spaces, false ceilings, and large openings do not provide required compartmentation for fire safety. Thus, the probability of fire spread from one floor to

another via large openings increases as compared to normal buildings, as glass windows and false ceiling are prone to failure at high temperatures. Breaking of such large sized windows can provide immense supply of oxygen to fire, thus, aggravating the fire severity as well. Therefore, combination of high fuel load density and open architecture create ideal conditions for intense and rapid-fire spread in modern buildings.

In recent years, new construction materials are being developed to achieve high performance in terms of strength, stiffness, ductility and cost. Examples include, ultra-high-performance concrete with 6-8 times greater compressive strength than that of conventional concrete; high performance steel; and fiber reinforced polymers (FRP) which are non-corrosive, extremely lightweight, and stronger than steel. These new materials are often used in high rise buildings and have better strength and stiffness than conventional construction materials at normal temperatures. However, most of these materials undergo rapid degradation in structural properties (usually faster than conventional materials) at elevated temperatures which leads to lower fire resistance (Kodur, 2014; Firmo *et al.*, 2015). Also, modern buildings consist of large quantities of plastic and vinyl-based materials which have high combustion toxicity, and therefore, increase risk to life safety.

Further, due to narrow streets, high traffic volume, and irregularly planned cities the response time for firefighting operations is significantly longer in most of the developing countries. This longer response time along with extreme reduction in flashover time in modern buildings [5 min vs 29 min (Kerber, 2012)] provides insufficient time for evacuation and firefighting operations, and significantly exacerbates the risk to life and structural safety. However, the current adopted fire safety provisions based on prescriptive based approach do not account for these factors.

4.2 Limitations of current building code provisions

In case of defining structural fires, most of the building codes and standards use standard fire curves (Figure 2) (ISO 834-1, 2012; Eurocode 1, 2004; ASTM E119-18, 2018). These standard fires are highly conservative and do not represent realistic fire scenario in building. No consideration is provided to fuel loads, ventilation openings, progressive burning, or localized fires; which play a key role in characterizing temperatures in post-flashover stage.

In case of active fire protection systems, prescriptive codes have limited guidelines on providing acceptable limits for functional and performance reliability of new/existing fire protection systems, and they lack a framework to assess the same. Further, there is a lack of rational provisions to standardize the qualitative and quantitative requirements of fire

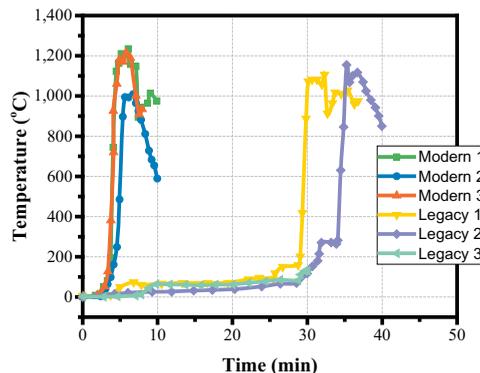


Figure 3.
Development of room temperatures in legacy and modern building fires

protection systems such as sprinklers, smoke detectors, fire extinguishers, fire safety escape routes etc. For example, Figure 4 (Hagiwara and Tanaka, 1994) illustrates that for a similar number of inhabitants, the required width for fire escape stairway is significantly different in building codes of different countries. Due to these factors, most of the building codes and standards have significant differences in terms of the active fire safety provisions in buildings.

For passive fire protection systems, fire resistance of desired structural member or assembly is assessed under standard fire exposure at service load levels, simplified end restrains, and simplified failure criterion. The resulting fire resistance is extended to other members of different dimensions based on simplified correlations of experimental fire resistance with member dimensions, concrete cover to reinforcement, type of aggregate etc. These provisions are provided in the form of prescriptive guidelines to obtain desired fire resistance of structural or non-structural members. Most of these prescriptive guidelines offer very limited to no commentary on the accepted fire safety provisions which makes the comparison between such codal fire safety provisions very difficult. Also, there is significant variation in the predicted fire ratings of different codes for same member (Kodur and Hatinger, 2011).

Further, this traditional approach of evaluating fire resistance is often overly conservative and do not account for specific conditions in buildings such as varying fuel load, realistic fire and loading scenarios, compartmentation characteristics, member interactions, continuity, restraint conditions etc. Therefore, the experimental studies based on this conventional approach provide unrealistic response of the structural systems under fire scenario and should not be used to predict actual response of structures under fire. Also, no consideration is provided to the adverse effect of performance specific problems of new constituent materials (for e.g. spalling in high strength concrete), toxicity, and degradation in their corresponding material properties at elevated temperatures in fire resistance predictions.

4.3 Reliability of fire protection systems

Reliability of active fire protection systems is not 100 per cent and this inhibits fire detection in its growth stage, risks safe evacuation of inhabitants, and decreases the chances of extinguishing or controlling fire in its growth phase. On the other hand, improper functioning of active fire protection systems such as false alarms can cause disbelief in the

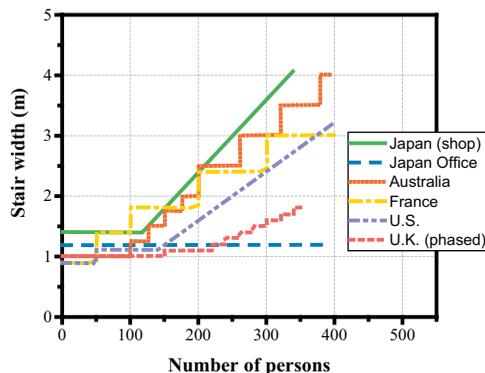


Figure 4. Required stair width for fire escape as per various building codes

fire alarm, unnecessary panic, and valuable property damage (for e.g. water damage to sensitive furniture and paintings due to sprinklers).

Between 2012 and 2016, smoke alarms failed to operate for an average of 25,700 home fires per year which caused an average of 440 deaths and 1,440 injuries annually (Ahrens, 2019). Whereas, a comprehensive review on effectiveness of sprinklers indicate that general sprinkler system effectiveness in controlling fire ranges from 70.1 to 99.5 per cent (Frank *et al.*, 2013). These variations can be different in different countries; however, there is significant lack of reliable statistical data, experimental, and analytical studies. Therefore, it can be argued that there is significant amount of uncertainty associated with the functioning of active fire protection systems.

In case of passive fire protection systems, the major reliability constrains lie in the holistic fire performance of the structure. Passive fire protection is often focused on individual elements, and it is assumed that if individual elements satisfy required fire resistance criteria, these elements will satisfy fire safety criteria in building assembly as well. However, it may not be the case always, as restrains to thermal expansion, continuity, load transfer mechanisms and redundancy in structural system inside building may enhance or aggravate fire resistance of the building components; which makes it difficult to assess passive fire resistance of the building assembly.

Other reliability constrains with passive fire protection systems lie in the use of thermal insulation materials. These insulation materials are used to enhance the fire resistance of new or existing structural elements, and there is significant variation associated with the performance of the same. This variation is primarily due to uncertainty in the adhesion of insulation material with structural element, varying thickness (in case of spray applied insulation systems), and due to lack of reliable high temperature material properties. It has been demonstrated by experimental and numerical studies that fire insulation undergoes significant delamination under dynamic loading, and it can significantly accelerate failure of the structural element under subsequent fire exposure in post-earthquake fire scenario (Arablouei and Kodur, 2016).

4.4 Limitations of firefighting

The available resources for firefighting vary from country to country and play a key role in minimizing fire deaths and fire losses. The effectiveness of firefighting depends mainly on three factors:

- (1) average response time;
- (2) quality and quantity of available resources (including firefighters) for firefighting; and
- (3) compliance effectiveness of fire safety regulations.

The response time is defined as the minimum time taken by the firefighting department to reach the fire site and start firefighting operation, after receiving the notification of fire incident. Shorter response time provide many advantages to life safety, as the chances of complete evacuation and quenching or controlling fire are higher in the initial stages of the fire. However, the average response time vary from few minutes to few hours in different countries. This high variation in average response time from country to country can be attributed to its dependence on high number of factors such as topology of area, firefighting equipment, traffic conditions, civic sense etc.

The second influencing factor on firefighting is the quality and quantity of available firefighting resources. For example, the fire brigade has a limit to the maximum height up to

which firefighting operations can be performed, amount of water it can carry etc. Therefore, even if the response time of fire brigade is short, firefighting may not be effective. Moreover, the standards of training for firefighters vary significantly from one country to another, and some countries do not even have trained firefighters at all (Brushlinsky *et al.*, 2017). It should be noted that firefighting involves working in intense stress environments with high risk to life safety, and therefore, lack of proper training has direct impact on firefighting effectiveness.

Another important role of firefighting department is to inspect the compliance efficacy of fire safety regulations in buildings. However, many developing countries have no such provisions in firefighting department at all. Moreover, due to high initial setup and maintenance costs, firefighting department in many developing countries of the world struggle with quality and quantity of firefighting resources (Rafi *et al.*, 2012), and sometimes firefighting department is not present at all.

4.5 Excessive cost of installation and maintenance

One of the major drawbacks of the fire protection measures is the high cost of installation and maintenance. Based on average percentage cost distribution of fire hazard for 16 countries from 2008 to 2010, it is observed that providing fire protection measures in buildings is the most expensive measure with a huge 39.6 per cent contribution to total fire hazard costs (Brushlinsky *et al.*, 2016). Also, it should be noted that the direct and indirect costs contribute to only 22.4 per cent of the total fire hazard costs, and the rest 77.6 per cent of costs come from the cost of fire protection measures, fire insurance, and cost of fire service. It means that the cost of fire protection measures is significantly higher than the actual direct or indirect losses resulting from fire hazard, which clearly demonstrate the need for economically effective fire protection systems. The active fire protection systems such as sprinklers require constant maintenance and water resources as well, both of which may not be feasible in developing countries with limited water resources. This high cost of fire protection is the primary reason for moderate to no fire protection measures within buildings in developing countries.

4.6 Poor compliance of fire safety regulations

Even though number of fires in developed countries is significantly high than developing countries, still the death rate in developed countries is much lower than developing countries with lower number of fire incidents (Brushlinsky *et al.*, 2016). One of the main attributes for this anomaly is the variation with respect to compliance effectiveness, degree to which fire safety provisions are implemented, of fire safety regulations in specified building codes and standards of each country. This is very important from fire safety perspective as the level of fire safety prescribed in codes and standards will not matter if it is not followed and implemented properly in the buildings. In developed countries (such as USA and Canada), specific provisions for measuring the code compliance effectiveness exist (Park, 2008). However, this may not be the case in many developing countries where fire safety regulations are always a major challenge due to lack of enforcing mechanism/awareness, resources and poor regulating environments. Such lack of effective measures of enforcing fire safety regulations can lead to inadequate fire safety provisions in buildings which results in high life and property losses.

4.7 Lack of consumer education and awareness

To identify major source of structure fires, the leading causes of fire in residential and non-residential buildings of USA has been analyzed (USFA, 2016), as maximum number of fires

in the world occur in USA and there is a scarcity of reliable global statistical data on fire hazard. Trends in leading causes of fires in residential and non-residential buildings are shown in Figure 5. It can be observed from Figure 5 that cooking is the leading cause of fire in both residential and non-residential building fires. Further, as cooking is more frequent in residential buildings, numbers of fires from cooking in residential buildings (about 160,000) are higher as compared to non-residential buildings (about 25,000). Apart from cooking, the other leading causes of fire include heating, electrical malfunction, carelessness, open flame and arson. However, it can be clearly observed from Figure 5 that relative to cooking, these leading causes contribute much smaller portion in fire hazard for both residential and non-residential buildings. These leading causes of fires can be addressed by increasing the consumer awareness about the fire hazards. Nevertheless, the current scenario clearly represents a lack of the same. It should be noted that these leading causes of fire in USA may not necessarily represent global fire scenario, however, it certainly illustrates the impact of consumer awareness on fire hazard.

5. Strategies for improved fire safety

One of the biggest limitations of existing fire protection strategies lies in not providing a holistic framework to mitigate fire hazard. Most of the building codes focus on management of fire hazard using active and passive fire protection features in buildings together with some emphasis on prevention, regulation, and enforcement. These protection strategies were

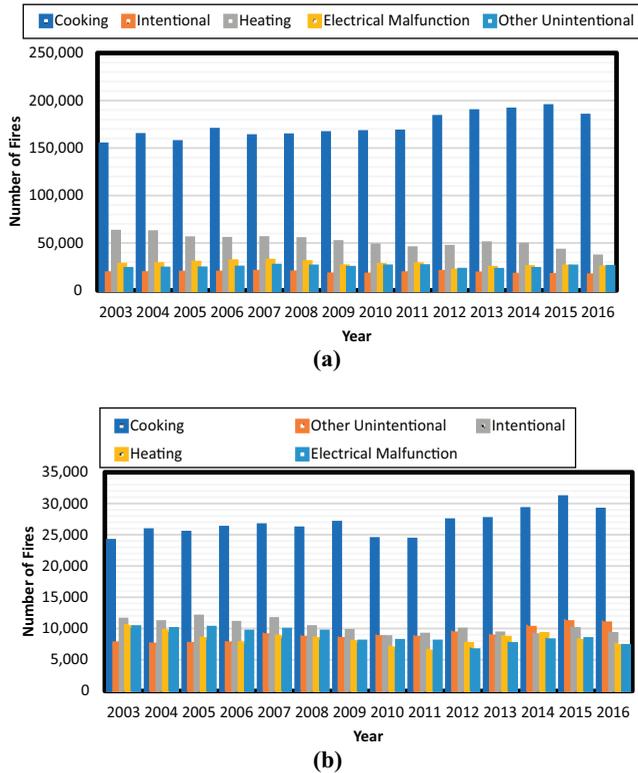


Figure 5. Leading causes of fire in buildings from 2003 to 2016 in USA in (a) residential and (b) non-residential buildings

mainly developed for fire scenarios and construction practices of the 1960s and 1970s and do not take into consideration contemporary fire hazard challenges discussed in Section 4.

Similar trend is followed by recent strategies on improving fire safety in buildings as they lack a holistic framework and only focus on one aspect of fire safety in buildings such as: fire safety design, research needs, or the human behavior. [Maluk *et al.* \(2017\)](#) presented a study on exploring the potential benefits of integrating fire safety with building design process, as fire safety is perceived as an additional constraint in the current design practice rather than a design parameter. [Gehandler \(2017\)](#) proposed a theoretical framework to change traditional linear decision based fire safety design to an iterative deterministic decision based process. [Kobes *et al.* \(2010\)](#) studied the impact of human behavior on evacuation response under fire conditions, and concluded that more studies are required to properly understand the psychonomics related to fire safety. While these studies present an excellent case for improving one aspect of fire safety, they do not provide a comprehensive strategy to mitigate fire hazard itself.

Also, most of the newly developed strategies to improve fire safety are specific to type of building, location, and socio-economic conditions for which they are originally developed ([Chien and Wu, 2008](#); [Chen *et al.*, 2012](#); [Cowlard *et al.*, 2013](#); [Navitas, 2014](#); [Nimlyat *et al.*, 2017](#)); which makes it difficult to extrapolate their results to global fire hazard. Therefore, an integrated framework encompassing prevention and management of fire hazard is proposed (illustrated in [Figure 1](#)), and its applicability in improving above limitations of existing fire safety strategies is demonstrated below. Further, special emphasis is given to the applicability of these strategies specific to place of application in both developing and developed countries.

5.1 Improving fire protection features in buildings

As discussed in Section 4, several adverse conditions exist in modern structures from fire safety perspective and this is not fully addressed in current fire protection provisions laid out in building codes. Due to several socio-economic differences, addressing these limitations require different strategies for developed and developing countries. In developing countries, cost is a major criterion for incorporating fire safety provisions; therefore, in place of costly fire safety strategies, alternate strategies should be developed to provide similar level of fire safety. Therefore, to avoid rapid growth of fire and to localize its impact in developing countries, it is proposed to use fire compartment concept (less use of glass and open spaces, limiting fuel load etc.) in building design. In case it is not possible to change building architecture, additional exit paths should be strategically located in building to improve egress timing, and thus, improve life safety. In all existing buildings, where it is not possible to provide additional fire exits, illuminating paint and additional exit signs can be provided along with temporary exit paths in terms of emergency ladders and staircases. Also, in all irregularly planned cities, reserved parking spots should be provided for firefighting vehicles in building sites along with maintaining active water mains, fire extinguishers, and a separate water tank to reduce initial start time of firefighting operations.

In developed countries, use of open architecture with high content of combustible fuel load should be justified using installation of reliable active fire protection systems, or realistic simulation of egress and fire resistance using advanced analysis procedures. Instead of relying on standardized prescriptive procedure to assess fire safety in buildings, it is preferable to use performance based fire design. Also, before using any new construction materials in buildings, it should be made mandatory to assess its performance under fire exposure.

On the other hand, one of the biggest limitations of building codes in practice is lack of uniform criteria for classification of structures. This can be fixed in both developing and developed countries by classifying buildings for fire hazard based on building design characteristics, potential of fire hazard, significance of building, and impact of fire hazard. [Kodur and Naser \(2013\)](#) have developed a framework to assess the importance and risk factor for design of bridges against fire hazard by assigning weightage factors to key characteristics of bridges. Similar approach can be applied to classify buildings into four categories as critical, high-risk, moderate-risk and low-risk. Other researchers have developed risk based analysis models to quantify fire risk in buildings as well ([Xin and Huang, 2013](#)), and a set of guidelines to identify critical structures can be defined in the national codes as per common consensus. This will promote uniform fire safety throughout country, and ease of classification as well.

Further, this risk-based classification should be integrated with building design using performance-based codes and standards to make building codes more effective in evaluating realistic fire performance of building. The provision of fire safety in each risk-based category should be justified on the account of classified risk, and special emphasis should be given to the use of cost-effective alternate strategies to attain desired level of fire performance. For example, only critical structures should be designed with highest factor of safety for worse possible fire scenarios. In high to low risk buildings, designers should be allowed to benefit from realistic fire scenario, loading, continuity, and actual restraint conditions which can lead to a less conservative and more integrated design.

5.2 Regulation and enforcement

Regulation and enforcement are one of the leading problems in developing countries which is often overlooked by current fire safety strategies. There should be a legal provision of severe fines/penalties which can be implemented using an appropriate mechanism. Such provisions do not exist in several developing countries, and according to authors is one of the leading causes of fire hazard in developing countries. For example, often the offset distances between buildings are not followed in most of the developing countries, and that leads to easy migration of fire from one building to other. Required active and passive fire protection measures are often compromised in building due to monetary constrains or from reluctance due to unawareness. In all such cases, the regulatory guidelines should be more stringent with higher fines in all such cases when occupants endanger the safety of others in the vicinity. Fire warden should be assigned to carry out annual inspections in all residential and commercial buildings for up keeping of fire protection features. Inspections should aim at ensuring fire loads to be below permissible limits, performance and functional reliability of fire protection features such as active water mains, functional fire extinguishers, unobstructed fire escape etc.

Also, in developed countries, regulation authorities should benefit from newly developed cognitive infrastructure, where active and passive fire safety measures in building are monitored continuously using automated sensors, to check for fire safety regulation and enforcement automatically ([Naser and Kodur, 2018](#)). This concept can be of great importance in high rise buildings, where all fire safety provisions can be monitored using automated sensors instead of doing it manually. Not only this will save significant time but will also increase safety through continuous monitoring of fire safety provisions instead of annual inspections.

5.3 Common and civic sense

Common/civic sense and public awareness is one of the most neglected cause of fire hazard and is the leading cause of fires in both developing and developed countries across the globe. Common sense includes keeping ignition source and fuel source away from each other, keeping household items with high potential of ignition away from the reach of children, proper dispose of inflammables, use of fire extinguishers, or taking other necessary precautions to avoid accidental fires. Civic sense or public awareness includes knowledge of fire escape routes and extinguishers, giving right of way to firefighter or other emergency vehicles, proper use of inflammatory substances (lighters, cigarettes, candles, etc.) in buildings, and understanding impact of fire hazard and individual responsibility in mitigating it.

Most of the fires can be easily prevented using common sense and public awareness in day to day life if properly implemented. Also, people can play a key role in reducing response time of firefighting operations by giving right of way to firefighters on roads, which can significantly improve firefighting operations. This common and civic sense among public can be greatly influenced in both developed and developing countries using consumer education for improving fire safety in buildings. Occupants should be provided basic knowledge of available fire escape routes, fire safety symbols, location of fire extinguishers, places of assembly in case of fire, and fire alarm. To ensure new occupants are familiar with emergency fire response, regular evacuation drills should be organized. In case of high rise/critical buildings where there is high risk to life safety, refuge floors (places of assembly in case of fire) should be provided and fire wardens should be designated on selected floors to prevent fire hazard. This awareness about fire safety in buildings should be disseminated using media, and mandatory fire safety curriculum in educational system.

5.4 Technology and resources

This section is applicable to both developing and developed countries. Technology and resources should focus on four main components:

- (1) reduction of response time;
- (2) developing new firefighting resources;
- (3) proper design and planning; and
- (4) learning from experience to update building codes.

Shorter response time is key to controlling fires as it is easier to control fire in its incipient or growth stage. In addition, shorter response time increases the chances of safe evacuation from building. Therefore, firefighters should be provided with adequate equipment and training to execute emergency fire drill with high efficiency. In developing countries, where number of professional firefighters is very less and it is not possible to provide required firefighting equipment due to monetary constrains, volunteer firefighters should be trained to ensure ample workforce for firefighting operations. These volunteers can further disseminate information about fire hazards to increase public awareness.

In developed countries, research should focus on developing new fire resistant materials and harnessing emerging technological advances for mitigation of fire hazard. For example, recent study by [Olawoyin \(2018\)](#) argued that nanotechnology, can be the future of developing fire resistant materials if it is tested and applied properly. However, there are several knowledge gaps in this field that need to be addressed. [Çakiroğlu and Gököğlu \(2019\)](#) used virtual-reality to teach basic fire safety behavioral skills to a group of ten primary school students, and concluded that virtual reality significantly enhanced the fire

safety behavioral skills of students in real life. Similar studies should be pursued by developed countries to further enhance the field of fire safety. Whereas, in case of developing countries, research focus should be on finding new cost-effective alternatives to traditional automated and manual firefighting equipment.

Other important resource allocation in both developing and developed countries should be in proper design and planning. Firefighting department should maintain the building plan records of critical buildings classified in very high-risk category to properly assess the evacuation and firefighting operations in case of a fire. To further reduce response time in developing countries with irregularly planned cities, special emphasis should be given to the strategic location of firefighting department to ensure similar response time for all covered areas.

Also, it is important to periodically update the building codes based on experiences from previous disasters, new innovations in materials, design changes, and contemporary fire hazard issues. For example, if the recent trends in fire hazard represent a decay or increase in its severity, fire safety in buildings should be adjusted accordingly. The fire performance of new construction materials should be characterized and used in the fire design process. The impact of change in building design, due to modernization, should be assessed on fire safety, and contemporary fire hazard issues resulting from design, socio-economic growth and other factors should be identified. Updating building codes regularly for all these factors will allow them to evolve and improve along with fire hazard, and thus, increase their effectiveness.

6. Research and training needs

Major research and training needs to improve fire safety in buildings can be identified as: cost-effective active fire protection systems, rational fire design approaches, characterization of new materials, performance-based design guidelines, and fire hazard from wildfires.

6.1 Cost-effective fire suppression systems

Currently, most of the fire suppression systems (sprinklers, active mains, automated aerosol fire suppression systems etc.) have high installation and maintenance costs. For example, according to an NFPA estimate sprinklers cost about \$14.5 per m² (\$1.35 per ft² mean cost) in new construction (NFPA, 2013). Therefore, for a standard house with 204.3 m² (2,200 ft²) area total cost of installation alone is US\$2,962 (approximately INR 200,000). This cost of installation is too high for developing countries with limited financial resources and low household incomes. Also, sprinklers incur additional costs in terms of maintenance as they require water main supply which is not easy to provide in developing countries with limited water resources. Therefore, there is a strong need to come with alternative cost-effective fire suppression systems.

6.2 Rational fire design approaches

Rational fire design approaches use advanced numerical models and focus on tracing realistic behavior of structural components under fire exposure. While some validated numerical models exist in literature (Kodur and Kumar, 2018; Kumar and Kodur, 2017; Kumar and Srivastava, 2017; Kumar and Srivastava, 2018), still, there is a lack of a framework for undertaking rational fire design of structures. The absence of well-defined rational design framework and validated numerical models for fire resistance assessment is constraining designers to create cost effective and rational designs. This is limiting the versatility of structural products and creating a hindrance in using their full potential in building applications. Therefore, research efforts should be focused on developing a generic

framework for undertaking rational fire design of structures. The availability of such framework will lead to innovative and cost-effective design of structures while ensuring better degree of fire safety as compared to current prescriptive approaches. Also, such an approach will allow fabricators to assess the fire resistance of structural members and assemblies before undertaking expensive and time-consuming fire tests in laboratories.

6.3 Characterization of new materials for fire performance

With new advancement in construction materials, there is a strong need to characterize and establish their fire performance under various fire design scenarios. Often, new materials bring new challenges to fire design process, which are widely overlooked by current prescriptive based approaches such as spalling of concrete, rapid strength degradation of FRP composites etc. Therefore, to ensure good fire performance of new construction materials, their behavior under fire conditions should be characterized prior to use in buildings. Most of the current research efforts are focused on characterizing strength degradation of new materials, however, there are limited studies on determining toxicity and combustibility of material. High toxicity can increase risk to life safety, whereas, high combustibility aggravates fire severity by causing rapid fire growth and spread. Therefore, research efforts should characterize all three fire safety aspects viz. toxicity, combustibility, and strength degradation; and then make informed decisions on the use of new materials in buildings.

6.4 Development of performance-based codes

While prescriptive based codes state how to construct a building, performance-based codes state how a building should perform under a wide range of conditions. Therefore, to develop performance-based codes for fire design it is important to define acceptable levels of performance for life, structural, property, and environmental safety. For life safety, code should provide acceptable limits for toxicity, combustibility, and egress parameters to ensure life safety during fire exposure. For structural safety, the performance parameters include structural response parameters under fire exposure such as deflection, integrity, insulation and residual strength. Performance-based codes should also provide guidelines to limit or minimize property losses under fire exposure by providing guidelines on detection and evaluation of residual strength of fire exposed structures (i.e. whether structure is repairable or not). Also, to minimize impact of fire hazard on environment, performance-based codes should provide acceptable limits for firefighting operations, and other factors

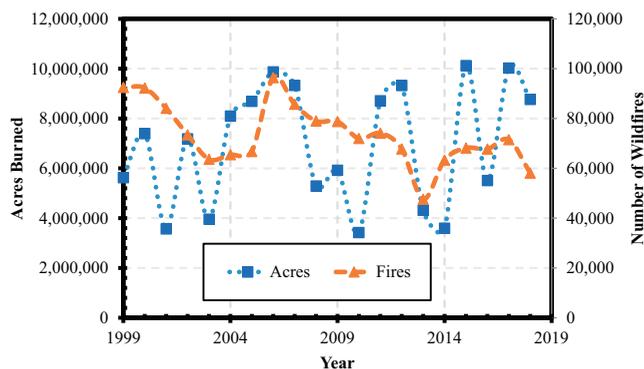


Figure 6. Annual wildfires and acres of land burned in USA from 1999 to 2018

influencing pollution. The availability of performance-based codes will not only allow a better understanding of fire design but will also lead to uniform fire safety provisions.

6.5 Fire hazard from wildfires

With the continuously changing habitat for humans it is important to account for all new factors that can contribute to the fire hazard. Wildfires represent one such example which have resulted from recent excessive human encroachment in wildlands. Recent trends in the number of wildfires occurred and burned area is illustrated in [Figure 6](#). It can be observed from [Figure 6](#) that higher number of wildfires in a particular year do not necessarily mean higher area burned as the impact of wildfire depends on available fuel and weather conditions. Therefore, even small number of wildfires can be very dangerous to built infrastructure if they transform into conflagrations. Also, there is currently very limited data in the literature on key differences in fire response of structure subjected to wildfires and building fires from within. As buildings are usually designed for a fire resistance of 2-4 h only, it is not possible or economical to design buildings to withstand wildfires which can last as long as few days to few weeks. Therefore, more focus should be on rapid evacuation instead of providing passive fire resistance. Also, there is a strong need to study the behavior of buildings subjected to wildfires as there is a scarcity of studies on the same in literature.

7. Conclusions

Based on the information presented above, the following conclusions can be drawn:

- Fire represents a severe hazard in both developing and developed countries and poses significant threat to life, structure, property, and environmental safety.
- Current fire protection measures lead to an unquantified level of fire safety in buildings, provide minimal strategies to mitigate fire hazard, and do not account for contemporary fire hazard issues.
- Implementing key measures that include improving fire protection features in buildings, proper regulation and enforcement of building code provisions, enhancing public awareness, and proper use of technology and resources are key to mitigating fire hazard in buildings.
- Major research and training needs required to improve fire safety in buildings include developing cost-effective fire suppression systems, rational fire design approaches, characterizing new materials, developing performance-based codes, and understanding fire hazard from wildfires.

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