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A Review on Optimal Fire-Resistant Architecture for Construction Industry of Developing Countries

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ABSTRACT: *Fire safety is a domain of research coupled with not only human well-being but also the design of buildings and their services. The eruption of fire disaster in a structure can cause heavy loss of property and lives, for which the investigators have emphasized on fire-resistant designs of residential and commercial buildings. Nonetheless, the densely populated developing countries have indicated the conservative, expensive and neglected approaches of building regulations and construction that have overlooked the consequences of fire behaviour, thus, degrading the fire protection. The failure of providing effective means of fire safety in the realm of buildings and structures has fuelled the current research. This paper therefore, reviews the causes of fire disaster, the proactive approaches of mitigating its effects in the construction industry, the optimal compartment designs of fire-resistant architecture and test methods of building materials. This research extends the knowledge base in identifying and recommending methods that would enable fire safety pertaining to the design of structures in fire.*

Keywords: *Fire disaster, fire safety, compartment design, proactive measures*

I. INTRODUCTION

Several countries around the world have been suffering from loss of life and property due to the incessant disasters, which are either natural or manmade. Disasters such as earthquakes, landslides, cyclones, draughts, avalanche and fires have posed threats to civilizations, structures, economic assets and habitats (Sharma, n.d.). Among the others, fire is considered as a major manmade disaster in terms of death, injury, loss of business, displacement of people and environmentally harms (Usmani, 2008). Forest fires, Urban and rural fires have caused serious implications to not only the human population but also the entire regime of fauna and flora. The biodiversity, ecology and environment of a region are vastly affected with widespread devastation due to the repercussions of human-induced fire disaster (Masellis, 1991).The fear of unrestrained fires and shirking from its penalties has been a prime human reaction against this disaster.Needless to say, the frequent encounter of fire disaster has fuelled the need of actions that can efficiently manage them and provide a safer habitat (Kenny, 2012).

The construction of buildings and their optimal architecture has played a major role in the disaster management and resilience, which has acquired the attention of various investigators. The construction industry handles the damaged and collapsed buildings after the incidence of conflagrations through procurement, design and construction of shelters (K. Papaioannou, 1991). On the other hand, buildings represent a section of places that are subjected to the fatal consequences of fire (Plastics Europe, 2015). However, if the architecture of the buildings are fire-resistant, the post-disaster reconstruction efforts will be low, also, the damage done will be less dangerous for the human civilizations. Therefore, all efforts must be incorporated into promoting and cultivating safer building construction that can with-handle the forces and loads of disasters.The prevention of fire within the building structures has led to several explorations in search for proactive methods and means for mitigating the impact of the fires. Though, the need of avoiding and preventing such a disaster is acknowledged, there is a lack of investigation regarding the development of fire-resistant structures in the construction industry of developing countries. Thedeveloping countries marked with high population density, increased settlement of high-risks areas and higher technological risks, making them more susceptible to such disasters (Wycliffe, 2015). The purpose of this paper is to explore such proactive methods pertaining to the fire-resistant architecture in the construction industry across the world through critically appraising and synthesizing information from the existing relevant literature.

II. RESEARCH OBJECTIVES

- To identify the causes of fire within the building structures and its repercussions on the surroundings
- To explore the proactive methods pertaining to the fire-resistant architecture in the construction industry
- To recommend strategies/actions for acquiring and optimal fire-resistant architecture for buildings in the construction industry

III. LITERATURE REVIEW

3.1 The Causes and Repercussions of Fire Disaster

Fires produce smokes and toxic gases that pose a fatal danger to those who are exposed to it.The causes of fire are numerous, extending from accidents and deliberate actions to malfunction in electronic devices.There are multiple reasons that may cause fires in the buildings, some of which are smoking within the premises, over heating of appliances and equipment, arson, candles, combustion through chemical and gases and faulty power distribution system (Xin and Huang, 2013).

According to James (2013), several causes of fire can be related to open flamesoccurring due to carelessness in dealing with candles and combustible substances, electrical flamesoccurring due to faulty electrical devices and equipment, cooking and unprompted ignition and the ignition of waste materials.The unattended cooking appliances, keeping combustible products in kitchen and careless mistakes while cooking can lead to unwanted accidents related to fire. When the wasted materials are disposed in an improper manner within a combustible environment, then the unprompted ignition might result into a fire hazard. According to Mural (2011), destructive fires can be raised form the careless disposal of lighted cigarette ends and matches, inappropriate storage of combustible materials,negligence to electrical installations, lack of inspection and patrols of construction sites, negligence towards fire safety regulations and general indifference to cleanliness.

In buildings, the spreading of fire, if encountered, is dependent on the area and height of the compartment, presence, type and quantity of combustible material in the compartment, ventilation provisions and installations of fire sprinkler system (Drysdale, 1990).At construction sites, the combination of heat, oxygen and fuel in appropriate proportions causes the fire, which is commonly termed as the fire triangle. Out of these three elements, oxygen is present in the atmosphere or can be increased through additional oxidizers; fuel comprises of combustible waste materials, flammable gases and packaged resources; heat results from smoking materials, electrical appliances, cutting of metals and light fixtures (Shin, Kwon, Lee, 2014). Based on the sources of fuel, fire is distinguished into the following classes (Queensland Government, 2004):

- **Class A:** Fires arising from combustible materials such as wood, paper, rubber etc.
- **Class B:** Fires arising from combustible liquids and gases
- **Class C:** Fires arising from metals and chemical compounds such as potassium, sodium etc.
- **Class D:** Electrical fires
- **Class E:** Fires arising from cooking oils

A fire disaster may not extent to a disastrous magnitude, but it however, results into high proportions of destruction with substantial number of victims. Apart from death, the victims who survive are seriously afflicted with burn injuries so extensive that the local resources are unable to provide immediate treatment or effective cure (Masellis, Ferrara and Gunn, 1999). The emanation of heat and toxic gases from the fire disaster can cause grave implications to the surrounding environment.Fire can lead to fatal burns and collapse of houses and properties, leading to higher losses of life and environment, therefore, a reliable fire-resistant system for a building should be built (Hopkins, 2016).

3.2 Proactive Methods For Resisting Fire In construction Industry

Protection and safety from fire is not only concerned with shielding the human lives, but also designing the buildings with fire-resistant attributes and measures.The degree of damages done to buildings and structures (houses, schools, hospitals, cinemas, offices, factories, warehouses, treatment plants, airports, bridges etc.) due to fire are primarily due to their unsafe design and construction from the loads and effects of conflagrations (James, 2013).

Primordially, there were two approaches for building fire-safety architecture for buildings. According to Harmathy (1974), there can be either defensive approach or offensive approach to build a preventive design of buildings for fire disasters. Whereas the defensive approach considers the aspect of ventilation and selection of lining materials during the architectural stage of designing the building, the offensive approach utilizes certain equipment and facilities for detecting and supressing fires. In the recent times, these measures are rendered as the traditionalapproaches of commencing fire protection within the structures comprised of enforcing construction restrictionsrelated with zoning and occupancy restrictions. For controlling the fire spread, the traditional approaches are active (fire sprinkler system, deluge system etc.) and passive approaches (fire resistant concrete lining, fighting explosive thermal spalling in concrete, additional reinforcement layer etc.)(Khoury, 2008).

According to Bilow and Kamara (2008), the use of the building material is the most crucial aspect during the construction of structures, where the appropriate building components which can resist the forces of fire must be utilized in lining the floors, walls and other structures. Concrete is considered to be acquainted with fire-resistive properties. Such properties of structural assemblies and construction components are identified through fire test methods. The standard fire tests determine the load bearing capacity of the component before it collapses, its integrity and insulation against high temperatures. Such measurements and requirements are incorporated in the building codes of the construction industry, as the fire-resistant design and construction of a building is dependable on the material properties (load-bearing capacity) and its reaction towards high temperatures (Lane, 2000).

3.2.1 Current Testing Methods of Fire-Resistant Materials

Though, the need to measure fire was acknowledges in the 16^{th} and 18^{th} century, the technology to measure the dynamics of fire such as the temperatures and heat flux has emerged in the recent times that has enabled the development of fire safety standards. The computational tools and technology have enabled the testing of structural fire endurance of materials needed for fire-resistant structural designs (Lawson, 2009). The fire-tests determine the ability of a building material or component to withstand the duration of fire and provide protection against it. Currently, the following are few of such testing methods:

- ASTM E119 (standard test method)
- DIN 4102
- UL 2221
- UL 1479
- UL 2085
- EN 16035

3.3 Fire-Resistant Architecture For Buildings

3.3.1optimal Compartment Designs In Buildings

The size and nature of the compartment in a building is one of the most crucial aspect that needs strong consideration by the designer (McGuire, 1962). Depending on the location of the buildings, the probability of a fire outbreak and its duration, the decision about designing the compartments can be made. The elementary rules for designing compartments in a way that causes least amount of structural damage during the duration of fire are as follows (Harmathy, 1974):

1. The compartment must comprise of appropriate windows (high or low) to provide sufficient ventilation. The purpose of ventilation is to ensure that the fire can be controlled before it spreads outside the compartment or the fire temperatures increases.
2. Lining the compartment walls and ceilings with additional layers of building materials
3. Building low ceilings inside the compartments. It will force the fire to burn outside the compartment. Such type of rule should be implemented in the storage building design.
4. The doors in the compartment walls must also be fire-resistant.

Also, there are special kinds of compartments, which have direct access to the exterior of the building with escape-stairwells. Bricks and stones are usually used for providing resistance from fire due to their inherent properties. However, in the recent times, specialized fire-stopping materials have evolved that are used by the designers in building the compartments. Fire-rated glazing is one such material that is applied with fire dampers and sealants for supporting the compartments (Razwick, 2009).

3.3.2 Engineering Design for Fire Protection In Buildings

As professed by Harmathy (1974), the design of building elements for fire resistance was instigated by the specialized engineers who were responsible for:

1. Estimation of fire severity parameters for the buildings. Such calculation is related to the area and other dimensions of compartments, ventilation properties, layering of building materials and fire load capacity
2. Investigation of heat flows and stress-strain research of the building components by utilizing the fire severity parameters
3. Decision-making for the appropriate fire protection systems

In the engineering-based design (one of the early approaches), there are no constraints of the building code and the engineer is accountable for taking the decisions pertaining to the fire protection and load-supporting components (usually steel) in the specific circumstances. The three factors that are considered to make the decisions about the structure are: how much heat the fire produces, how much the building materials are affected by the high temperature and how steady the structure is after the loads of fire (Bastings, 1988).The structural design for fire are built without considering the demand and capacity calculations.

3.3.3 Performance-Based Design (PBD) For Fire-Resisting Structures

Irrespective of the traditional approaches, there are instances of uncontrolled fires that have caused severe damage to the buildings, portraying the lack of knowledge pertaining to engineered structural fire protection design. Performance-based approach for fire-resisting structures merges the accurate demand requirements with the desired system performance and extends from the traditional approaches.It therefore considers the current demand and capacity calculations for structural design of the building (Grosshandler, 2003).Performance-based design comprises of both designing and analysing the components, where the analysis covers the thermal and mechanical response of the components towards the heat and the structural response towards fire exposure. Such a designis used in estimating the thermal effects of a fire on the structural component of the system, its depletion regarding the mechanical properties, its performance regarding the resistivity towards fire load, along with the characterization of building fires (Salminen & Hietaniemi, 2016).

PBD is a unified approach to structural fire protection and design of buildings as it is able to compute the attributes of building fires (temperature, heat influx and flow), thermal effects of building components (fire load, ventilation), furnace testing, and architectural and structural design of the building and the structural performance of the building. Upon the comprehension of the knowledge pertaining to the materials, the passive fire protection design is developed through the selection of fire-resistive assembly of compartments (walls, columns and floor), which are able to survive the heat exposure and also provide cost-efficiency. Several conceptual designs are constructed and tested with the thermal models and heat-transfer analyses, with further exposure to higher temperatures. On this basis, changes are made via additional preventive layers of thickness as per the thermal failure criteria and structural performance regarding load-bearing capability (Beyler, Beitel, Iwankiw, Lattimer, 2007). The aforementioned testing methods are utilized for this purpose, and the required changes are then incorporated for the redesigning of the structure.

IV. RELATED WORK

Cowlard, Bittern, Abecassis-Empis and Torero (2013) conducted their survey on the evaluation of fire protection measures in the design of tall buildings. The researchers have identifies a knowledge gap related with the design of compartments of tall buildings for achieving structural efficiency during the occurrence of fire disaster. For this purpose, the performance-based design is an essential requirement that considers the dynamic requirement of compartmentation of the area. The researchers have recommended the use of prescriptive fire safety tools on the basis of fire-spread in a modern compartment.

Usmani (2008) has professed that the fire protection and the maintenance of the structural fire resistance is a neglected area. The researcher has investigated the impact of fires emerging after earthquakes on the buildings. It is revealed that there are no current regulations that require the buildings to consider the disasters of fire and earthquake. The traditional or conventional structural fire engineering needs faster development.

Wycliffe(2015) have observed that the destruction of fire disasters have increased over time to the lack of enforcement of building codes, insufficient proactive measurements, lack of awareness and increased settlements. The researcher has conducted the study on evaluating the fire preparedness in the hospitality business in the Kisumu City. With the deployment of questionnaires, the researcher revealed that the hotels, restaurants, shopping complexes etc. are highly susceptible to fire disasters, and have inadequate fire-fighting measures and requires fire safety approaches within the building premises.

Hung and Chow (2002) conducted their research on fire resisting construction requirements of the buildings in Hong Kong. The researchers have recommended the utilization and incorporation of engineering performance-based fire codes, since the existing codes have ambiguous objectives. The construction industry is inefficient at incorporating the fire-resistant codes, which requires further investigation, along with the testing methods.

V. RESULTS AND CONCLUSION

In the recent times, several structural failures of buildings due to fires have been noted, which has fuelled the need for fire-resistant construction and design of buildings and structures. Therefore, this review paper has delved into the causes and repercussions of fire disaster, the proactive measures taken in the construction of buildings for acquiring fire safety and the design approaches for fire-resistant architecture.It is revealed from this study that the design should be based on the nature of fire, which can be determined through the compartment size, ventilation and lining materials.On the basis of this exploration, the study recommends the following to be incorporated in the existingfire structural designs for sustainable construction:

1. The increase in the implementation of active approaches (fire-resistant systems such as sprinklers)
2. The use fire stopping and penetration seals on the joints of building elements/materials
3. Increasing thickness of insulation
4. Use of concreteand specialized materials in compartment designing with additional layering
5. Increased airtightnessof buildings
6. Three-dimensional testing of heat-transfer analysis of the building materials
7. Alternative load carrying mechanisms can be implemented for fire protection

The current research concludes that due to the persistence of fire disasters and its disastrous repercussions, the performance-based approach of designing structures and buildings requires modifications and enhancement to further its efficiency during the times of fire eruption. More attention should be given on the optimal compartment designs with access to exterior of the building. Also, most of the attention is on the testing of the materials used for building and not on the overall performance of the structure. The geometrical changes of the buildings due to heat exposure may result in the degradation of the complete building, which is highly ignored by the researchers in this field. Therefore, these aspects should be considered for further research in the fire-resistant architecture of the buildings or structures.

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