Effect of Fire Hazard on Seismic Capacity of RC Frame Building

Praveen Oggu, Swati Raman, and K. Gopikrishna

1 Introduction

Fire hazard is characterized to be one of the most disastrous events, frequently encountered in urban cities as a primary or as a secondary event. This, if not controlled at early stages, can result in a catastrophe involving huge property damages and loss of life. This disastrous nature is more pronounced in areas of high incidence, coupled with densely populated urban environments. The occurrence of fire inside a building is an unexpected phenomenon and can break out at any time due to various reasons. Conflagrations following the 1906 San Francisco and 1923 Tokyo earthquakes led to serious discussions among engineers about simultaneous safety of buildings against earthquake and fire. The CITF world statistics reported that India loses about 2500 lives annually to fire with highest rate of deaths. Even though the occurrence of building fire is more frequent in comparison with other extreme events like earthquake and hurricanes, etc., it has not been given importance during structural design and detailing. The effect of fire on material properties and on structural members are the two important parameters for proper evaluation of damage of a building due to fire. Experimental studies in literature have reported material strength degradation at higher temperature as a major cause for damages in a fire event. The study of fire and earthquake can be done in two ways—pre-fire earthquake (structure subjected to fire after earthquake) and post-fire earthquake (fire affected structure subjected to an earthquake). The present study focuses on seismic behaviour of building subjected to post-fire earthquake. In reality, the fire leads to material strength deterioration, however, the extent of reduction in strength depends on exposure time and temperature. Moreover, the reduction in overall strength of building is uncertain, and therefore, the assessment of seismic performance of such fire affected structure becomes important. Hence, post-fire behaviour of structure is necessary for determining the

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extent of structural damage post a fire event, necessary for repair and also for ensuring the safety and integrity of the structure.

Arioz (2007) studied the effect of high temperature on compressive strength of concrete with different types of aggregates and found significant reduction in compressive strength of concrete above 800 °C [1]. Topcu (2008) investigated performance of S220 and S420 reinforcing steel rebars under fire and found significant reduction in tensile strength of rebars above 950 °C [2]. Youssef and Moftah (2007) proposed stress strain model of concrete incorporating effect of temperature [3]. Jau and Hang (2007) studied the effect of non-uniform fire on strength of reinforced concrete column subjected to 2 and 4 h of fire exposure along with axial loading and biaxial bending. Kodur and Dwaikat (2008) developed the mathematical model for predicting the behaviour of reinforced concrete beams subjected to fire with the effect of spalling [4]. Tan and Yao (2004) presented simplified approach for predicting fire resistance of column subjected to different thermal boundary conditions and developed strength reduction factors for steel and concrete subjected to 1-face, 2-face, 3-face and 4-face heating by using SAFIR software tool [5–7]. Therefore, assessment of impact of fire hazard on the structural capacity of RC frame building is essential in mitigating this hazard. Hence, four-storey RC frame building perceived to be located in the city of Warangal, Telangana State has been selected to analyse thermal behaviour and post-fire seismic behaviour in this study.

2 Structural Modelling

The structural model considered consists of a regular RC building frame with G + 3, i.e. four storeys of uniform height 3.2 m having two bays with a bay width of 5 m (see Fig. 1). This represents the typical building configuration prevalent in the said location. The building frame has been designed confirming to code provisions of IS 456: 2000 and IS 1893 (Part 1) as located in seismic zone III with medium type of soil [8, 9]. The description of models and the details of loads considered for seismic analysis are given in Table 1 and Table 2, respectively. The structural design details of the model are given in Table 3. The structural modelling is performed using SAP2000, a commercial structural analysis software [10]. The structural elements (beams and columns) were modeled with concentrated plastic hinges, where the beams have only moment (M3) hinges, and the columns have an axial load and a biaxial moment (PMM) hinges as per FEMA 356 (2000) [11]. Additionally, rigid diaphragms were assigned for every storey level throughout the structure ignoring the flexibility of the floor. Mander et al. and Park et al. models were used in characterizing the stress–strain behaviour of concrete and steel rebars, as shown in Fig. 2 [10, 12]. Moreover, as per the recommendations of IS 1893 (2016), moments of inertia of beams and columns were reduced to 35% and 70% for beams and columns, respectively, while performing nonlinear structural analysis.

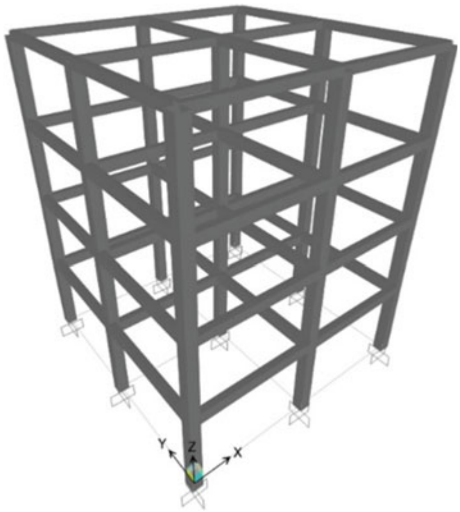


Fig. 1 3D representation of structural configuration investigated in this study

Table 1 Design details of the selected four-storey building [13]

Member	Storey	Width (mm)	Depth (mm)	Longitudinal Reinforcement		Transverse reinforcement
				Top	Bottom	
Beam	1	250	450	5–20ϕ	4–20ϕ	8ϕ @ 150c/c
	2 and 3	250	400	4–16ϕ	3–16ϕ	8ϕ @ 150c/c
	4	250	300	4–12ϕ	3–12ϕ	8ϕ @ 150c/c
Column	1–4	420	420	8–16ϕ		8ϕ @ 175c/c

Table 2 Description of the models considered

S. No	Parameter	Data
1	Height of each storey	3.2 m
2	Width of each bay	5 m
3	Grade of concrete	M 25
4	Poisson's ratio of concrete	0.2
5	Unit weight of concrete	25 kN/m^3
6	Modulus of elasticity of concrete	25 GPa
7	Grade of rebar	Fe 415
8	Modulus of elasticity of rebar	200 GPa

Table 3 Details of loads considered for seismic analysis

S. No	Particulars	Description
1	Dead load of beams and columns	Self-weight of the structure
2	Live load on slab	3 kN/m^2
3	Dead load on slab including floor finish	3.75 kN/m^2
4	Dead load of wall (230 mm thick)	14.2 kN/m
5	Seismic load	IS 1893 (Part 1): 2016
6	Type of structure	RC frame structure
7	Importance factor	1
8	Response reduction factor	3 for OMRF
9	Soil type	Medium
10	Zone factor	0.16 (Zone III)

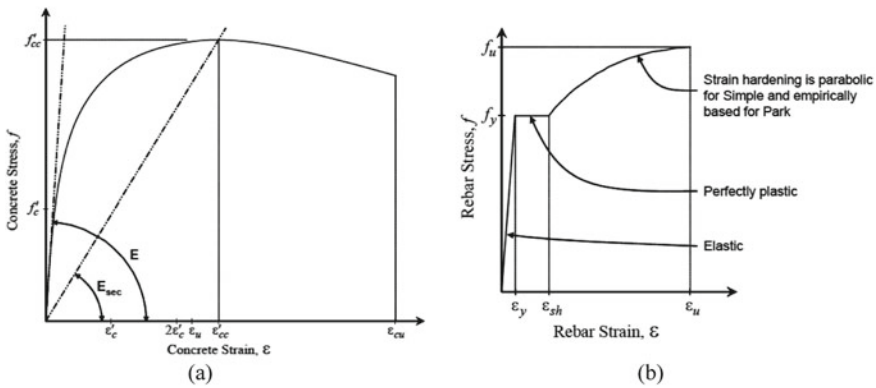


Fig. 2 **a** Mander confined concrete stress–strain curve. **b** Park stress–strain model

3 Analysis Methodology

Thermal analysis of the structural model is performed using SAFIR, a thermal analysis software to obtain evolution of temperature within structural components. In addition, modified material properties for the structural components at various elevated temperatures are considered from EUROCODE [14]. Further, section analysis for various fire exposure times (30 and 60 min) with modified material properties is performed using XTRACT software. The outcome is moment rotation and interaction curve, necessary for defining the nonlinear hinge properties of the structural components (i.e. beam and column).

Finally, the pre-fire seismic inelastic capacity of the structure is assessed using nonlinear static analysis (NLS) for various fire scenarios described in terms of exposure times (30 and 60 min) on the structural models considered. The moment rotation and P-M interaction curves obtained from XTRACT software for various fire scenarios are considered as input for seismic behaviour assessment. Nonlinear static (or pushover) analysis is then performed, using the response spectrum specified in IS code for the specified site conditions (Zone III, Medium soil profile) at Warangal city, Telangana state. Pushover analysis is a static, nonlinear procedure in which the magnitude of the structural loading or displacement is incrementally increased in accordance with a certain predefined pattern. The loading is monotonic. With increase in magnitude of loading, weak links of the structures can be obtained. Pushover analysis estimates force and displacement capacity of structure along with sequential formation of hinges in the structure under analysis. The outcome of pushover analysis is usually represented in the form of base force (or base shear) versus roof displacement. This is popularly referred as capacity curve of structure. The outcome of the pre-fire nonlinear seismic analysis is a capacity curve defined in terms of base shear with roof. The overall methodology of the study is depicted as a flowchart in Fig. 3. In general, the seismic behaviour of RC building in terms of typical capacity curves representing original (or stronger) capacity and reduced (or weaker) capacity are shown in Fig. 4.

4 Results and Discussion

4.1 Thermal Analysis

The structural components, i.e. beams and column are first modelled, and their thermal capacities were estimated using SAFIR software. SAFIR performs the transient thermal analysis to determine the temperature distribution in the structure. The thermal profiles of the cross-sections of the structural components are shown in Fig. 5.

The sectional analysis results for the beam and column structural components in terms of moment curvature and interaction diagrams for fire scenarios of 30 min and 60 min duration were performed in XTRACT program. The reduced sectional capacities of the structural components are shown in Figs. 6 and 7.

4.2 Seismic Analysis

The reduced sectional properties of beams and columns obtained from thermal analysis are considered for defining hinge properties at elevated temperatures in the NLS of the structural model as discussed. The outcome of NLS analysis, the capacity curve developed in accordance with FEMA regulations for no fire, 30 min fire exposure

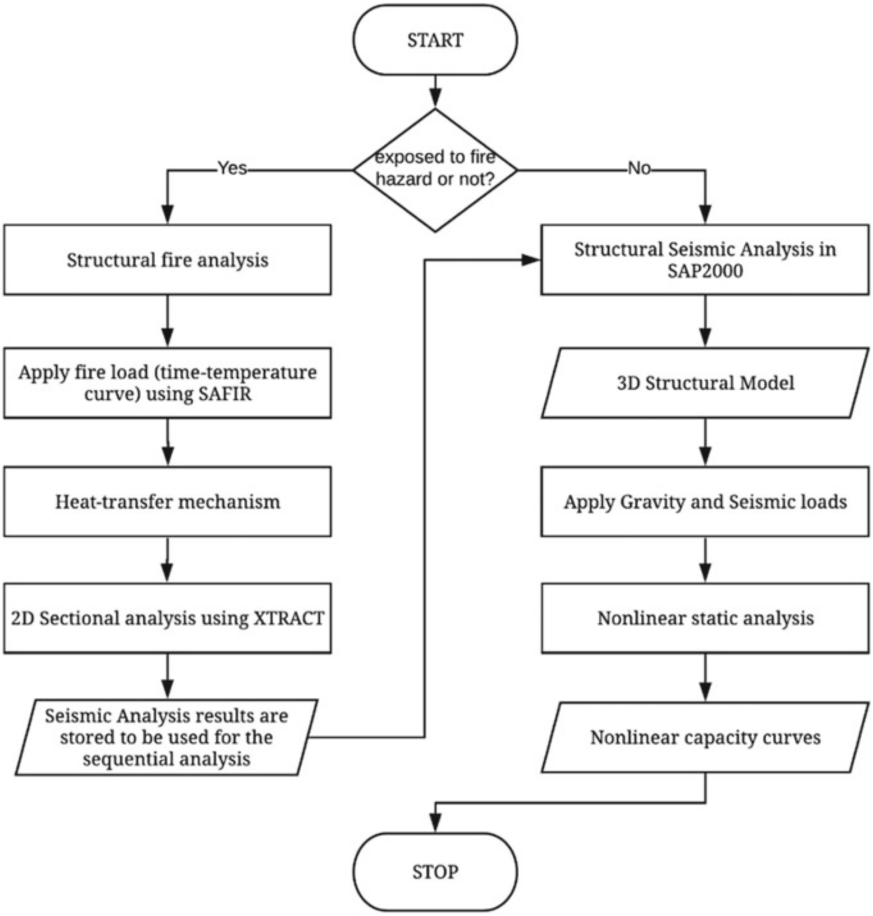


Fig. 3 Flowchart of the methodology used in this study

and 60 min fire exposure durations is shown in Fig. 8. It can be observed that there is substantial reduction in base shear for the structural model due to fire hazard. This suggests reduction in capacity of the structure due to degradation in exposed material due to fire. Hence, there is an imminent need to assess the structural behaviour considering the effects of fire as it proves detrimental for the survival and functionality of the structure. Therefore, assessment of impact of fire hazard on the structural capacity of RC frame building is essential in mitigating this hazard.

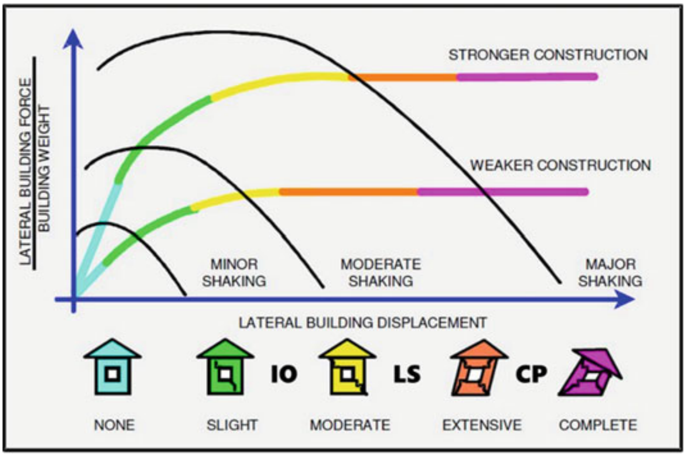
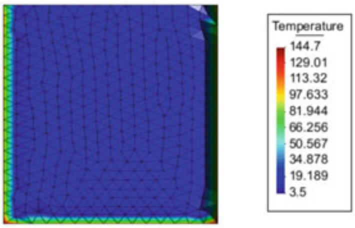
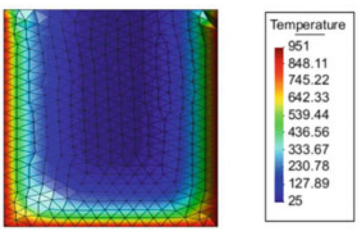


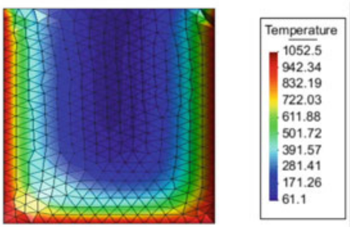
Fig. 4 Seismic behaviour of RC building for different performance levels



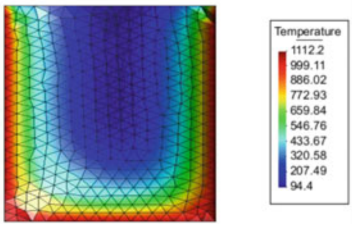
(a) Beam section exposed for 2 min



(b) Beam section exposed for 60 min



(c) Beam section exposed for 120 min

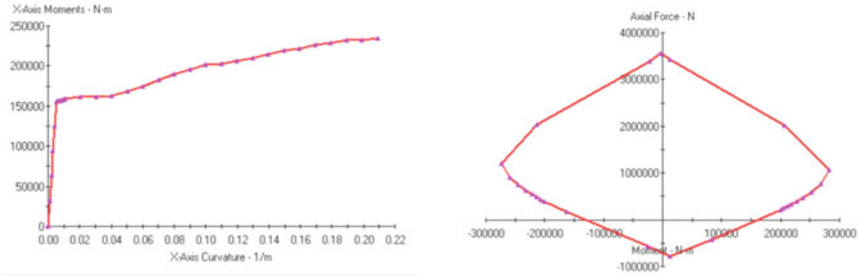


(d) Beam section exposed for 180 min

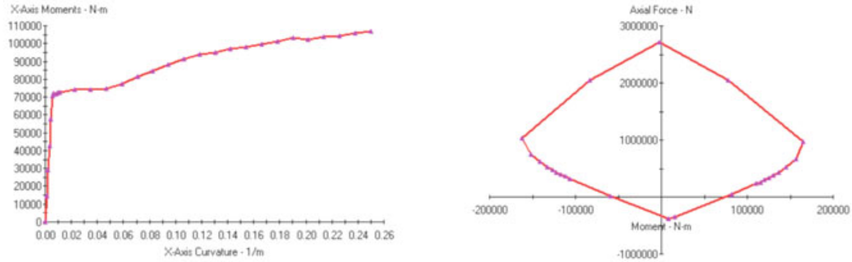
Fig. 5 Beam section exposed to ISO 834 fire for various durations

5 Conclusions

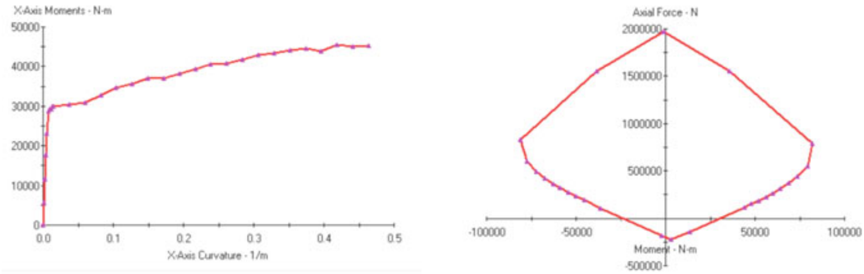
Four-storeyed RC building frame is modelled using SAP2000 commercial structural software. The modified material and cross-sectional properties necessary for defining the hinge properties of the structural components due to various fire exposure times (i.e. 30 and 60 min duration) are developed using XTRACT software. Further, the pre-fire seismic behaviour is assessed by performing NLS analysis with modified



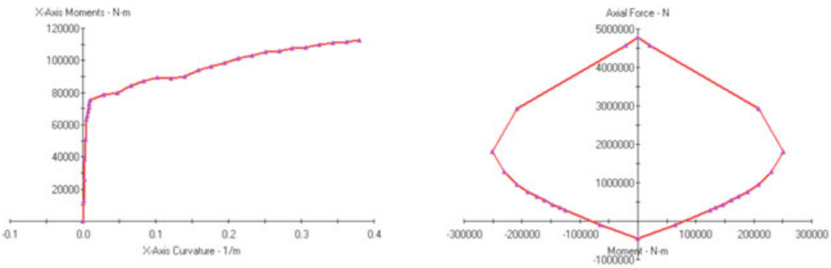
Beam 1



Beam 2 & 3

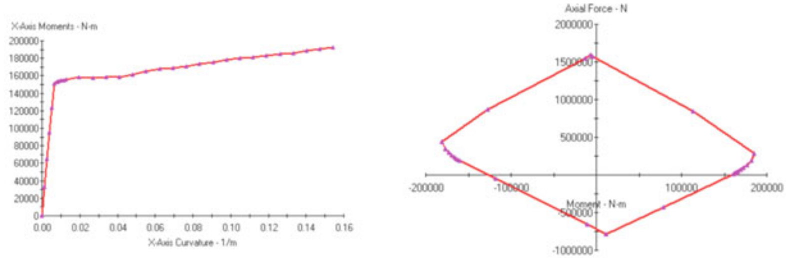


Beam 4

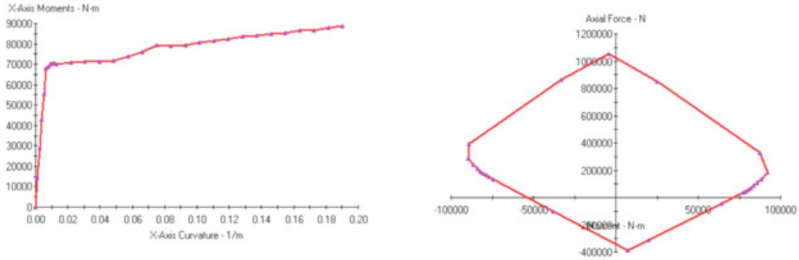


Column

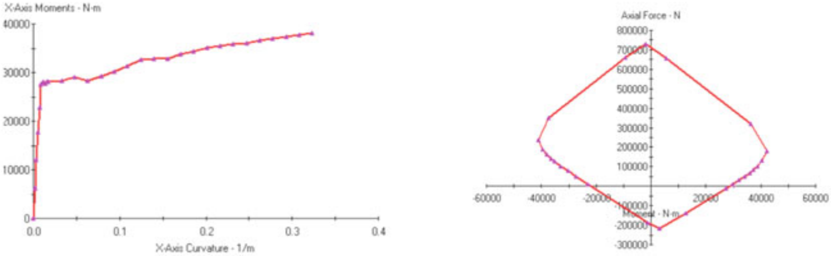
Fig. 6 Moment curvature and P-M interaction diagrams of beams and column, exposed for a duration of 30 min



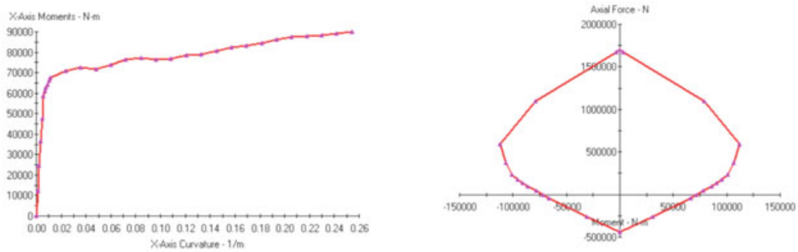
Beam 1



Beam 2 & 3

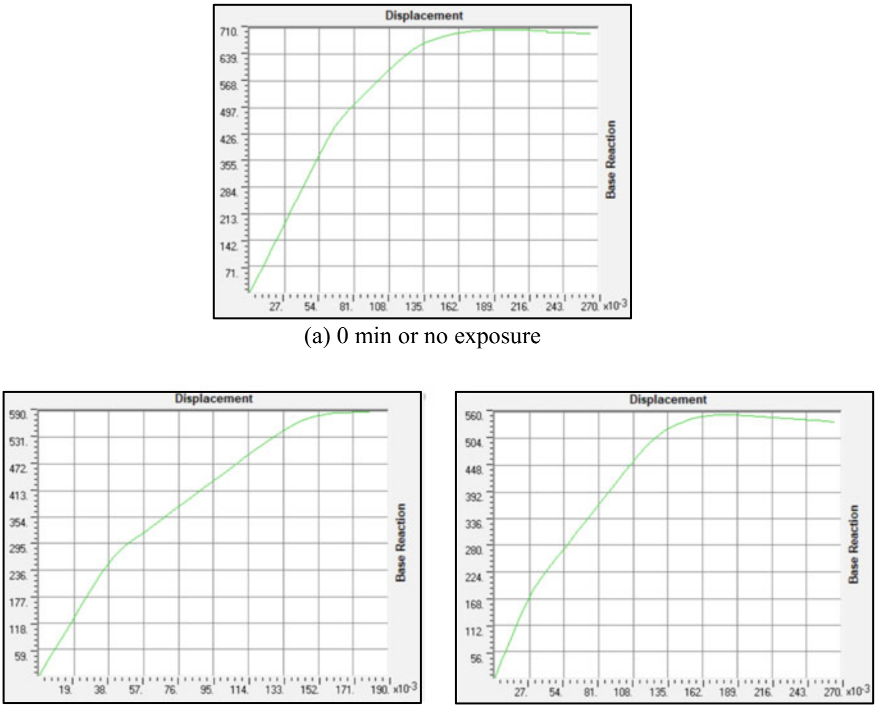


Beam 4



Column

Fig. 7 Moment curvature and P-M interaction diagrams of beams and column, exposed for a duration of 60 min



(a) 0 min or no exposure

(b) 30 min

(c) 60 min

Fig. 8 Capacity curves of the model exposed to different durations

hinge properties at elevated temperatures. The RC frame buildings are reported to be vulnerable to fire hazard in literature, this observation can be clearly envisaged in the study presented. From the capacity curves developed during nonlinear static analysis for the hypothetical structural model, it can be observed that certain structural components might have incurred damages contributing to reduced seismic capacity.

From this preliminary analysis, it can be concluded that fire hazard has significant effect on reducing the capacity of the structure and proves detrimental for the survival in case of existence of fire for prolonged duration. Hence, structural analysis, post a fire hazard is imminent for appropriate design of repair/rehabilitation measures to restore the functionality of the structure. This aids in building a safe and functional built environment.

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