Behaviour of RC Frame Subjected to Fire Following Earthquake

Haveri Manish, M. Swathi, and S. D. Anitha Kumari

Abstract Natural disasters are the second largest enemy of human kind after devastating wars. Natural disasters such as floods, earthquakes, tornadoes, volcanic eruptions, hurricanes, tsunami and landslides have significant effect on a building leading to partial damage or complete collapse. Earthquake effect on a building triggers fire which can completely damage the strength of the building. Post-Earthquake fire can lead to collapse of the building which is partially damaged due to the prior ground-motion. This in turn accounts to the decrease of stability of the structure to withstand the superimposed loads. Fiber Reinforced concrete (FRC) has good resistance to fire and can withstand more loads when compared to nominal concrete. Polypropylene fibers have great resistance to fire and are widely used as fire proofing material. Hence this work is an approach to strengthen the Reinforced concrete (RC) frame with FRC to reduce the damage caused by fire loads imposed on the frame after the occurrence of earthquake. FRC has good resistance to fire and can withstand more loads when compared to nominal concrete. The analysis of RC frame for earthquake loads, fire loads and fire following earthquake are done in ANSYS software and the same is compared with the experimental results of FRC frame. It was found that the cyclic loading deformation of FRC frame reduces by 44.33%, fire loading deformation reduces by 80% and Fire Following Earthquake (FFE) loading deformation by 60%.

Keywords Fire following earthquake · Fiber reinforced concrete · Fire loads

1 Introduction

Over the centuries, some towns and cities have repeatedly been struck and sometimes devastated by major earthquakes. The difference between damage and devastation depends not only on the magnitude of the earthquake, but also on local geology and on building techniques. Earthquakes do not cause fires directly. It is the damage to

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structures containing flammables like wooden walls and ignition sources. The effects of post-earthquake fire on buildings are of two kinds, one is the damage due to the burning of non-structural material, which possesses material value and the other is the damage caused due to the additional loads (fire) on the building. These extra loads are normally loads that the structures are not designed for, and when combined with the earthquake damage can lead to the collapse of buildings. The structural strength of concrete is enhanced with the addition of fibers which increases the tensile property of concrete making it stronger to take more loads when subjected to unexpected severe loading conditions. Different fibers available in the market perform differently to fire with regard to the thermal conductivity and bonding with concrete. Fibers such as steel fibers, carbon fibers, polypropylene fibers are generally used in concrete to enhance its properties. Experiments have proved that polypropylene fibers are more resistant to fire when compared to steel fibers and vinyl fibers. This study focusses on the effect of fibers as major strengthening materials in buildings with RC frame which are subjected to earthquake followed by fire.

Yoshitake et al. [1] presented the behavior of fiber reinforced concrete under elevated temperatures. The study compares the performance of plain concrete and different Fiber Reinforced Concrete viz., Steel FRC, Polypropylene FRC and Vinyl FRC to the effect of fire in a tunnel lining. It is reported that polypropylene fiber reinforced concrete exhibited high resistance to fire compared to steel fiber reinforced concrete and plain concrete. Zhang et al. [2] explains the results of experimental setup of an RC frame that has exposed to different temperatures and static load. It was concluded that fire load and higher temperature of the specimen had large influence on the mechanical properties of the frame reducing its strength and stiffness. Ye et al. [3] explains the non-linear analysis of a RC frame subjected to fire adopting finite element method. The structural deformation and post fire ultimate loadings were investigated. It was suggested to increase the beam and column rotation in order to increase the ductility of the structure so as to resist the changes of the deformation and internal forces. Mostafaei and Kabeyasawa [4] conducted shake table experiments on a six-story RC frame subjected to Kobe earthquake. The same frame was subjected to fire following earthquake loading and its performance was evaluated using numerical methods. It was concluded that fire on the damaged structure had considerable effects on the material properties due to degradation and rapid heat penetration. This reduced the load carrying capacity of the frame. Kumar [5] reported experimental studies of a single story sub-assemblage of a G + 3 RC frame subjected to Post-Earthquake Fire (PEF). It was observed that despite spalling of concrete, the roof slab remained structurally stable to carry the superimposed loads whereas the roof beam suffered maximum degradation of concrete which was confirmed through visual inspection also. Behnam et al. [6] reported results of PEF based on FEMA356 sequential analysis where the structure is subjected to different magnitude of earthquake followed by 4 h fire analysis. It was noticed that fire resistance of structure was initially 240 min which reduced to 90mins after exposed to earthquake of magnitude 0.35 g. Similarly, fire resistance of structure was initially 210 min which reduced to 60 min after exposed to earthquake of magnitude 0.25 g. Raouffard and Nishiyama [7] describes the results of fire test carried out to evaluate the performance of moment-resisting RC frame at elevated temperatures. From the experiment it was observed that the thermal gradient within the frame was non-linear where the end sections of the beam attain lower temperature compared to the mid sections due to which there were flexural cracks in mid-section.

Behrouz et al. [6] describes the numerical and experimental studies on the structural resistance of two RC beam-column joints with similar geometry configuration, reinforcement and concrete strength. The second is strengthened by means of carbon fibre-reinforced polymer (CFRP) at the vicinity of the joint in order to relocate the plastic hinge away from the column extremity towards the beam. Both specimens are subjected to a cyclic load. The post-earthquake fire (PEF) resistance of the specimens subjected to various damage levels such as immediate occupancy (IO), life safety (LS) and collapse prevention (CP) is then evaluated based on finite element analysis. The resistances of frame to different damage levels were noticed and were observed that the resistance of frame is 25% greater at the life-safety and 35% more in collapse prevention levels of damage. Poorna and Prasad [8] explain the behavior of RCC slabs for different grades and different concrete cover. The results showed that deflection of slab decreases as the grade of concrete increases and decreases as the concrete cover increases. Kadir [9] explains about the structural damage that is caused by fires occurring after the earthquake on a Roorkee frame test. The analysis of these two sequential events i.e., fire and earthquake loads was done using Finite element methods. The studies indicate that the structural behavior during a FFE is very damaging and hence more insight is required into the performance of structures and the ways to improve the mechanical behavior of such structures. This study focusses on a G + 2 structure subjected to earthquake followed by fire loading condition with and without fiber reinforcement.

2 Validation and Methodology

Kadir [9] has reported experimental results using Roorkee frame. These results are used for the validation of the numerical model developed in this study. The experimental set up consists of a frame subjected to cyclic loading at the slab level at the height of 4.3 m using hydraulic jack system. The frame is later subjected to temperature loads. Figure 1 shows the experimental setup of the frame. Cyclic loading was achieved by applying a lateral load to the frame using a hydraulic jack at the slab level in load control mode. The temperatures in the different structural elements are recorded in the frame using different Thermocouples at different locations after exposing it to fire in furnace. The sectional details of the frame are shown in Table 1. The displacement history values used for the study are shown in Table 2. The maximum base shear obtained from the experiment is 315 kN.

To simulate the mechanical behavior and validation, a G + 1 frame is modeled using solid 365 element and is shown in Fig. 2. The total height of the single bay frame is 5.8 m and width 3 m and the grade of concrete used is M-30. The description of loads and dimensions are same as used in the experiment. The frame was analyzed

Fig. 1 Roorkee frame experimental set up [9]

Table 1 Description of the experimental setup [9]

Building elements (mm)	Material	Load details
Column—300 × 300	Grade of concretes—M30	Floor finish—1 kN/m^2
Beam—230 × 230	Density of concrete—25 kN/m^2	Live load—2 kN/m^2
Thickness of slab—120		

Table 2 Displacement history for cyclic loading

Time (s)	Displacement (mm)
0	−19
100	19
200	−30
300	35
400	−39
500	49.8
600	−61
700	68.8
800	−79.6
900	95

using numerical software for both 3D and 2D models to compare the results. Cyclic loading was given which was obtained from the test. The frame was subjected to equivalent cyclic lateral displacements in displacement control mode. Figure 3 shows the capacity curves for the displacement history obtained from experimental test results and 3D simulation. The results show that the maximum base shear obtained

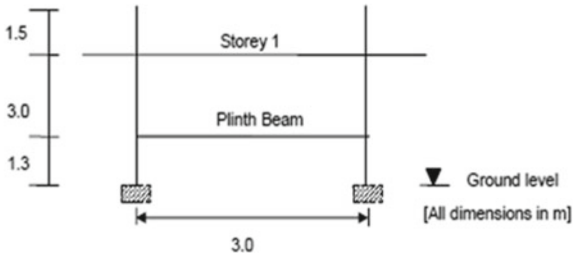


Fig. 2 Details of the RC frame

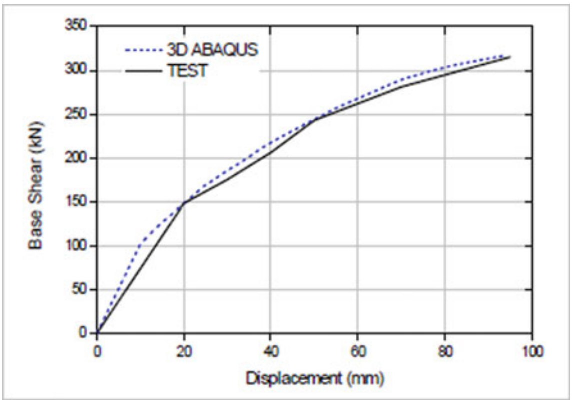


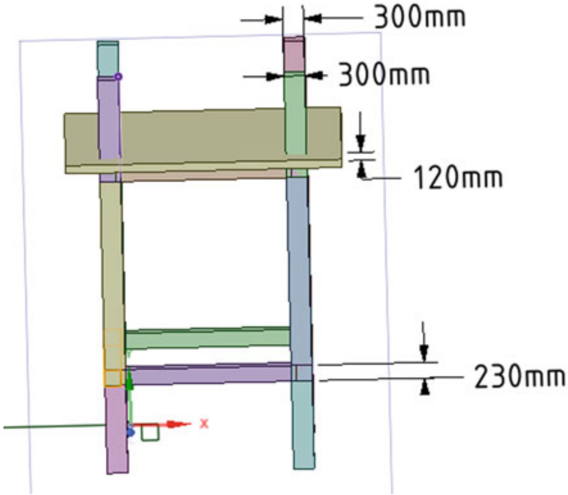
Fig. 3 Comparison of test results and numerical results

for the frame was 317 kN. Following the application of earthquake loads, fire loads are applied to the frame. The temperatures recorded from the thermocouples for different structural elements are input in software to see the deformations. The model in ANSYS is shown in Fig. 4.

M-30 grade concrete is used for the frame and its behavior is simulated by multi-linear isotropic hardening properties. Stress-strain values for the concrete are assigned for M-30 concrete. Fixed supports can resist vertical, horizontal forces and moment as they restrain both rotation and translation. The structure only needs one fixed support in order to be stable and is used in this study. Connection between the elements should be defined to ensure the connectivity of the members and their load transfer.

The accuracy that can be obtained from any FEA model is directly related to the finite element mesh that is used. Types of meshes considered here are Quadrilateral meshing, tetrahedral meshing and Quad-dominant meshing. It was observed that quad-dominant meshing gave the most accurate results compared to the other two methods but took excess time for the simulation. Quadrilateral meshing showed approximate results and consumed the least time of all the three methods. Tetrahedral meshing showed considerably accurate results but less accurate than quad-dominant method. However, tetrahedral meshing was considered since it consumed lesser time and provided satisfactory results.

Fig. 4 3D ANSYS model (All Dimensions in mm)



Once the model is defined and the boundary conditions are given, the structure is subjected to cyclic loading. In experiment, cyclic loading was achieved by applying a lateral load to the frame using a hydraulic jack at the slab level in load control mode. In the numerical simulation, the frame was subjected to equivalent cyclic lateral displacements in displacement control mode.

The results of base shear and displacement are shown in Table 3.

Figure 5 shows the comparison of capacity curves obtained from ANSYS and experiment. The graph is plotted for force reactions (Base shear) and the displacement input. The base shear obtained for the RC frame is 364 kN from the Numerical analysis. The graph indicates that the numerical evaluation is almost convergent with the test results.

The comparison of the numerical results (ANSYS and ABAQUS) with that of experimental results for cyclic loading is shown in Table 3.

A G + 2 Frame with the same section properties is considered for further study. The frame was subjected to same boundary conditions and loading conditions which was considered in validation. The total deformation observed is 103.35 mm is shown in Fig. 6 and the capacity curve for cyclic loading of G + 2 frame is shown in Fig. 7.

Table 3 Comparison of results: Experimental, ABAQUS and ANSYS simulations

Analysis type	Base shear (kN)	Displacement (mm)	Percentage error of base shear	Percentage error of displacement
Experimental results	315	80		
ABAQUS 3D	317	80	0.6	
ANSYS Workbench	330	79.566	4.5	0.54

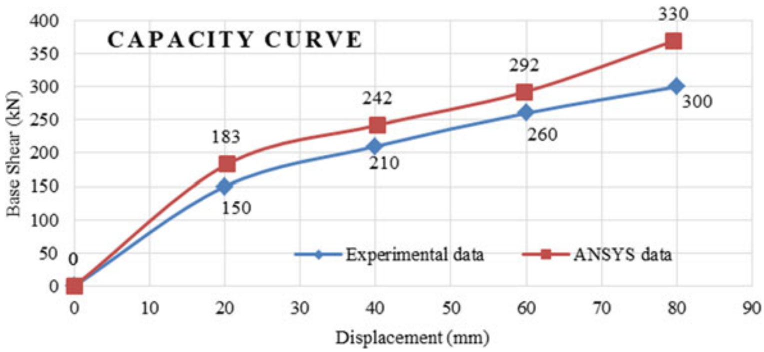


Fig. 5 Capacity curves from experiment and ANSYS simulations

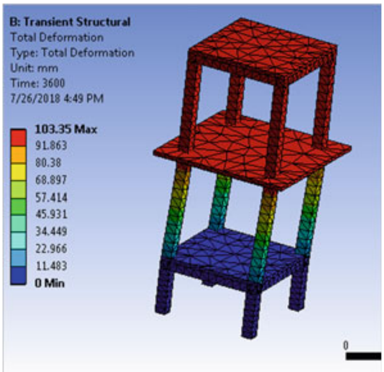


Fig. 6 Total deformation of G + 2 frame for cyclic loading

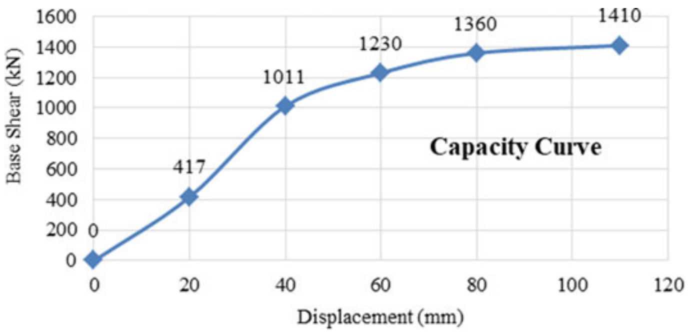


Fig. 7 Capacity curve for cyclic loading for G + 2 frame

Table 4 Temperature load of the slab

Sl. No	Time (s)	Temperature (°C)
1	0	0
2	600	310
3	1200	600
4	1800	800
5	2400	950
6	3000	1000
7	3600	900

The temperatures in various structural elements are recorded in the frame using different Thermocouples at different locations. The temperature variation in the slab as obtained from the experiment [9] is input in ANSYS. The temperatures recorded in the slab are shown in Table 4.

Transient thermal is used for the fire analysis in ANSYS. The results from transient structural are linked to the transient thermal for the input of loads for post-earthquake fire. The deformation of the G + 2 slab due to fire in the RC slab is shown in Fig. 8. A comparison between the experimental and numerical simulation indicates around 30% variation in the fire deformation. This may be due to the disparity in the distribution of the temperature across the experimental and numerical sections. The effect of temperature and slow cooling in real situations lead to more deformations compared to FEM modeling.

The total deformation of the slab due to the temperature variation and is already subjected to earthquake load is shown in Fig. 9. Due to the effect of earthquake, the structure already underwent considerable damage. The same structure when subjected to further extreme loading of fire deforms considerably and the maximum deformation observed in this case was 182.18 mm.

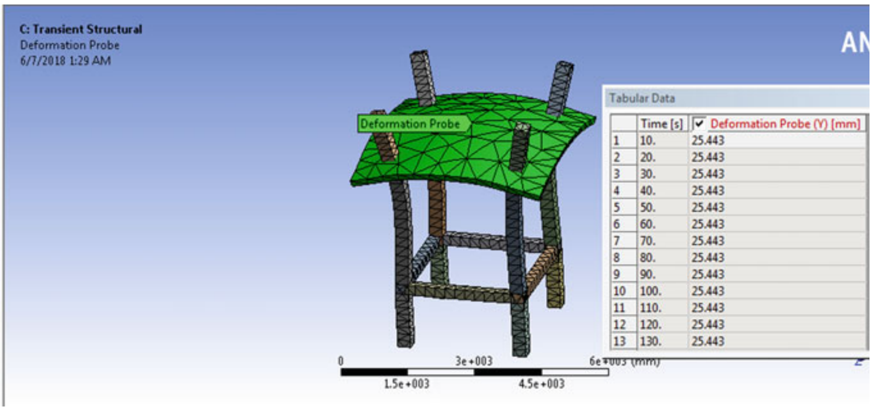


Fig. 8 Deformation due to temperature on the slab

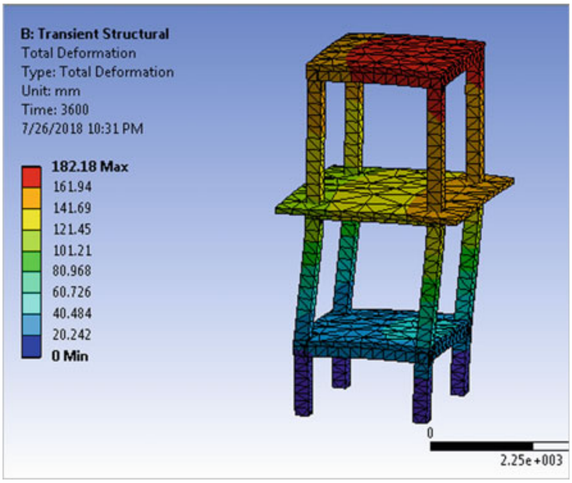


Fig. 9 Total deformation of RC frame subjected to FFE loading

The same model was exposed to ISO 834 standard fire curve using the nominal fire curve equation given by:

$$T = 345 \log_{10}(8t + 1) + 2 \quad (1)$$

where T is the temperature in °C and t is the time in minutes. Figure 10 shows the deformation on the RC frame when loaded with temperature according to ISO 834.

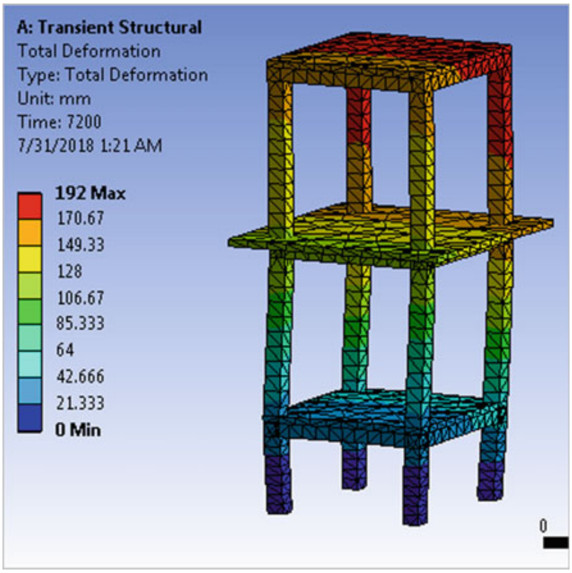


Fig. 10 Total deformation of RC frame subjected to FFE loading (As per ISO curve)

Table 5 Temperature loading for the structural components

Time (s)	Beam (°C)	Column (°C)	Slab (°C)
0	0	0	0
600	100	130	310
1200	270	350	600
1800	400	500	800
2400	480	650	950
3000	550	780	1000
3600	550	830	900

The maximum deformation observed in this case is 192 mm and closely matches with the behavior predicted by experimental temperature values which is around 182 mm.

Table 5 shows the temperature loading for the various structural components in the frame.

3 Analysis of FRC Frame

Fibers when added to concrete make the concrete more tough and improve the ductility and its resistance to thermal shock, fatigue and impact loads to a greater extent. Widely used fibers in concreting are steel fibers, polypropylene fibers, glass fibers, organic and carbon fibers. Polypropylene fibers are found to have excellent resistance for fire and help reduce the spalling of concrete in cases of severe fire. They have high density and melting point is as high as 165 °C.

The analysis of the G + 2 frame was done for the performance in cyclic loading, fire loading and fire following earthquake loading. The results of total deformation for the respective loading were found to be 57.529, 21.253 and 72.05 mm. Figure 11 shows the total deformation of the G + 2 frame for FFE loading.

Table 6 shows the comparison of deformation values of the G + 2 frame when subjected to different loading conditions.

Fig. 11 Total deformation of the FRC frame

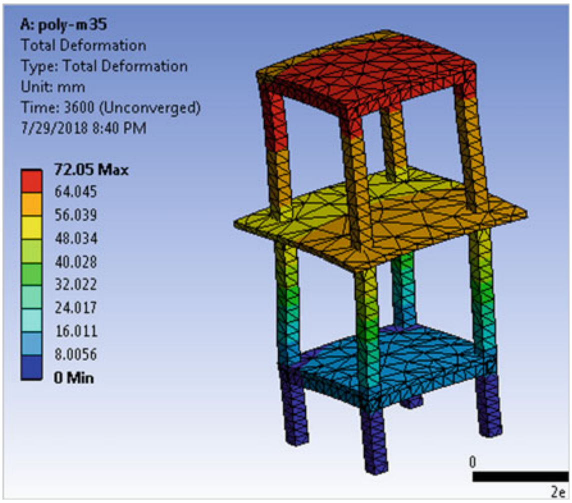


Table 6 Comparison of deformation for cyclic, fire and FFE loading in FRC frame

Loading type	RC frame (mm)	FRC frame (mm)	% decrease
Cyclic loading	103.35	57.529	44.33
Fire loading	106.29	21.253	80
Fire Following Earthquake(FFE)	182.18	72.05	60

4 Conclusion

The building when exposed to fire after suffering from earthquake loads have a greater effect on the stability of the structure since the structural elements already undergo degradation due to dynamic loading. The results from the analysis of the frame clearly show that the vulnerability of the frame to fire after the exposure to earthquake loading is greater. The deformation of frame for FFE loading was found to be 42% more than only fire loading [10]. The polypropylene fibers in the FRC frame help concrete withstand the fire loads to a greater extent. The decrease in total deformation of the FRC frame was found to be 44.3% in cyclic loading, 80% in fire loading and 60% in FFE loading. The results conclude that the addition of polypropylene fibers can make the concrete hard against the fire following earthquake loading.

References

1. Yoshitake I, Baba K, Ito T, Nakagawa K (2005) Behavior of fiber reinforced concrete under fire temperature, Yamaguchi University

2. Zhang X, Qing-Qing S, Zhong-Yi Li, Song-Hua T,Ying-She L (2014) Experimental study on fire resistance of reinforced concrete frame structure. International Conference on Mechanics and Civil Engineering
3. Ye Z, Huang R, Jiang Y, Lv L (2015) Nonlinear anal-ysis of reinforced concrete frame subjected to fire. International Conference on Mechatronics, Electronic, Industrial and Control Engineering, pp 1148–1152
4. Mostafaei H, Kabeyasawa T (2010) Performance of a six-story reinforcement concrete structure in post-earthquake fire. In: Proceedings of the 9th U.S. national and 10th Canadian conference on earthquake engineering, pp 01–10, Canada
5. Kumar V (2012) Behaviour of full scale reinforced concrete frame under stimulated post-erathquake fire. World conference on earthquake engineering, Lisboa
6. Behnam Behrouz, Ronagh H, Lim PJ (2015) Numerical evaluation of the post-earthquake fire resistance of CFRP strengthened reinforced concrete joints based on experimental observations. Eur J Environ Civil Eng 1(1–19). https://doi.org/10.1080/19648189.2015.1018448
7. Raouffard MM, Nishiyama M (2015) Fire resistance of reinforced concrete frames subjected to service load: part 1. Experimental study. J Adv Concr Technol 13:554–563
8. Poorna S, Prasad R (2016) Effect of fire on RC slab. Int J Innov Res Sci Technol 3(4):179–183
9. Kadir MA (2013) Fire resistance of earthquake damaged reinforced concrete frames. The University of Edinburgh
10. Samir S (2011) Effect of polypropylene fibers on concrete fire resistance. J Civ Eng Manage 17:259–264