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Behaviour of Reinforced Concrete Frames under Various Load Conditions with Pre-Applied Elevated Temperature

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Abstract **-** The structural stability of reinforced concrete buildings exposed to fire is gaining very high significance in the design process, as there is increased demand and requirement for fire safe solutions. In a reinforced concrete building, the most critical section is the beam column joint and enhancing its structural behavior was found to be of great significance at ambient and elevated temperatures. This paper reports the behavior of a simple (single bay single storied) reinforced concrete frame under various loading conditions after exposure to elevated temperature (28°C to 800°C). Various loading conditions were applied on the frame specimens after exposing them to higher temperatures to stimulate the actual behavior of the frame after a real fire exposure. The specimens were cast with three different grades of concrete (M20, M45 and M60), representing the normal, standard and high strength concrete as per IS 456: 2000.Performance of the specimens are evaluated and presented in terms of load-deflection hysteresis loop. The results and observations of the study reveal that the frames made with high strength concrete are more prone to earlier failure than the frames cast with standard and normal strength concrete. At a temperature of 400^0C, the load carrying capacities of the frame cast with M20, M45 and M60 grades of concrete are 80%, 71% and 58% of the capacity at 28^0C respectively.

Keywords**:** Structural stability, Beam-to-Column Connections, Elevated temperature, Reverse Cyclic Loading, hysteresis, ductility factor, failure mode.

1. Introduction

Beam column joints are the critical components of a reinforced concrete moment resisting frame, especially when the frame is subjected to seismic loading [1]. Under earthquake induced lateral movements, beam-column joints in framed structures are generally subjected to a large shear action that leads to serious damage and stiffness degradation of the building [2]. For good seismic performance, the structural components, such as, beam-column joints, must possess enhanced deformation capability and damage tolerance [3] Several pioneers have investigated the seismic performance of RC joints under shear reversals [2,3,4]. Fire hazard is an aftermath of an earthquake. Thus the design of joints should consider the effects of elevated temperature.

Traditionally, fire safety assessment of reinforced concrete was based on a prescriptive single element analysis, neglecting static redundancies and restraints to thermal expansions [5]. For a long time, this approach was considered conservative because (1) concrete members exhibit a good performance in fire conditions when compared with other construction materials, and (2) concrete material has low thermal diffusivity (slowing down the temperature rise during fire exposure) and a considerable non-combustible property. Thus, even if a structure is labeled as safe when exposed to fire within the scope of these prescriptive rules, structural engineers were not able to assess the real level of fire hazard, because the real global structural response was unknown. The real fire events like the World Trade Centre (WTC) collapse in New York [1] and the large scale experiments, such Cardington [2] and Windsor tower's fire in Madrid [3] have shown the real impact of structural continuity in the global response of buildings subjected to fire hazard. Since then a lot of work has been carried out to understand the global fire response, especially in steel and hybrid structures. For reinforced concrete structures the global behaviour is not yet fully understood under fire exposure, mainly because of the lack of reliable data concerning material properties at high temperatures.

Much of the research literature available focuses on analytical study of the behaviour of joints under high temperature, due to the limitations and expenses incurred to conduct an experimental study. Xiao et al.[6] tested four single-span and single-story frames under low-frequency cyclic loads after being exposed to fire. The hysteretic behaviour, the stiffness degradation and energy dissipation were investigated; the post-fire seismic performances were also examined based on the fire test results. It was found that after a fire attack, the difference in stiffness degradations of beams and columns in an RC frame could transform the seismic failure mode from a strong-column-weak-beam failure into a strong-beam-weak-column one, which performs unsatisfactorily under cyclic loads. The effect of thermal variation was analytically studied and the results showed that the response of frames deviated significantly based on the temperature gradient. It was also observed that the material modeling of the specimens has a major influence on the frame behaviour. It was also concluded that the cracking contributes to the release of temperature restrain [7]. Moreover, researches [8,9] on post-fire behavior of RC frames have concluded that the overall performance of the RC frame decreased after fire exposure. From the investigation it was observed that the mode of failure, which showed ductile beam-end failure under room temperature changed to brittle column shear-bond failure after fire exposure. It was also observed that the yield displacement of the post fire specimens significantly increased but there was only limited difference in the ultimate displacements [10].

With the increase in the temperature, the load carrying capacity of the reinforced concrete frames decreased and the decrease was significant for the temperatures 800°C and 1000°C [11]. The behaviour of frames was dependent on the stiffness and ductility factors. The stiffness of the frames dropped sharply at 800°C and 1000°C and caused the collapse of the frame [12]. At higher temperatures, the differential expansion of steel and concrete in the frame results in the formation of large cracks at the joint region which leads to the failure of the framework. This reduces the stiffness of the structure [13]. From discussion above, it is evident that a systematic research is needed to study the behavior of RC frames under elevated temperature since many parameters like compressive strength, tensile strength, stiffness etc. change with constituent materials, load and temperature. The influence of different grades of concrete on the behavior of RC frames at elevated temperature have not been dealt with, even though it is clear from the literature that the constituent materials of concrete has significant influence on the behaviour of concrete at elevated temperature.

This paper presents the results of experimental study of RC frames made of three different grades of concrete say M20 (ordinary), M45 (standard) and M60 (high strength), subjected to elevated temperatures and different loading conditions. The next section deals with the methodology adopted for the study. Section 3 deals with the description of the experimental program. The results obtained from the study are discussed in section 4. The final conclusions of this study are given in section 5.

2. Methodology

The frame specimens, cast with different grades of concrete were subjected to elevated temperatures of 200°C, 400°C, 600°C and 800°C. The specimens were then subjected to elevated temperature in an electric heating furnace. The maximum working temperature of the furnace is 1200°C.After cooling these specimens were subjected to reverse cyclic loading at the beam column junction along with vertical loading on the beam. The reverse cyclic loading was applied with the help of load cells and hydraulic jack attached to the loading frame. Prior to the application of the load, strain gauges and LVDT were placed at salient points for measuring the strains and displacements. These data were acquired with the help of a data acquisition system. Hysteresis loop and load deflection envelope were plotted from the recorded data. The failure modes were also analyzed from the crack patterns.

3. Experimental program

A single bay, single storied frame chosen for the study is shown in Fig.1. The RC frame specimens consisting of a beam and two columns represent a scaled down model of a conventional RC frame. The specimen has been designed for dead load (DL), live load (LL) and seismic load (SL) as per Indian standards. Since the chamber size of the available furnace is 1.1m x 1.1m x 1.1m, the size of the beam and columns were chosen to fit inside the furnace chamber. The ductile detailing was carried out for cross section according to IS 13920:2016. The beams to column connections were assumed to be semi-fixed, and the column base was assumed to be fixed (Fig.1). A total of 30 specimens were cast for all the three grades (M20, M45 and M60) of concrete under consideration. After curing the specimens were subjected to elevated temperature ranging from 28ºC to 800ºC in the electric heating furnace. After cooling, the specimens were tested under combined static vertical load and quasi-static horizontal loading conditions. The loading conditions include a static uniformly distributed load on the beam and a reverse cyclic loading on the beam column junctions. Strains in concrete, at all salient points in both the beam and columns were measured with the help of strain gauges and the deformations were captured using LVDT's. The position of the strain gauges and LVDT's are shown in Fig.1.

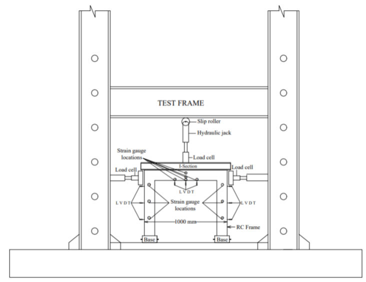


Fig.1. The experimental test setup

3.1 Details of the specimen

The details of the specimen are shown in Figure 2 and Figure 3.The frame specimen consist of beam with cross section dimensions of 200mm$\times$200mm with a span of 800mm and two columns with cross section 200mm$\times$200mm with a height of 900mm.The design of reinforcement was carried out for the ductile behavior of joints (Fig.3).

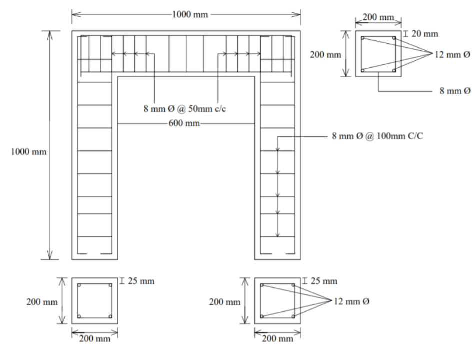


Fig. 2. Frame Specimen Fig. 3. Reinforcement details of the single bay single storied frame specimen

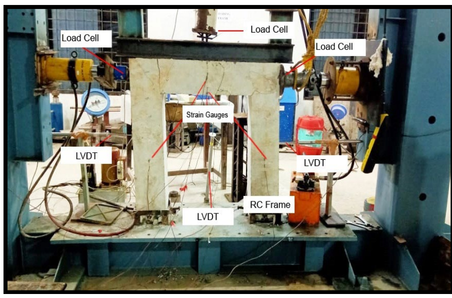
3.2 Exposure to elevated temperatures

After curing, the frame specimens were exposed to elevated temperatures of 200ºC, 400ºC, 600ºC and 800ºC, in the electric heating furnace (Fig. 4). The furnace has a heating chamber and a controlling unit. The maximum working temperature of the furnace is 1200ºC. The specimens were kept inside the chamber and then heated gradually to the target temperature. Then that target temperature was maintained for two hours (excluding the ramp up time). After the temperature exposure the specimens were taken out and allowed to cool. The cooled specimens were then mechanically tested.

Fig.4. Frame specimen inside the furnace

3.3 Experimental set-up

Experimental setup is shown in Fig. 5. The frame specimens were loaded on the test frame of capacity, 1500kN. The fixity at the ends of the two columns were obtained by inserting the column bases vertically in a box made of cast iron, which was welded to the base frame and by keeping rubber pads in between the specimens and the walls of the box (Fig. 5). The uniformly distributed flexural load of magnitude 10T was applied on the beam with the help of a hydraulic jack and an I-Section. This was done to stimulate the load from the slab. Reverse cyclic loading was applied by placing two hydraulic jacks at the level of the beam on both sides of the specimen, and the applied loads were measured using two load cells (Fig. 5). The reverse cyclic loading was given in the form of positive and negative cycles. The loading pattern is shown in Fig. 6. The test was conducted in a load controlled manner with an increment of 2kN, in both positive and negative cycles. Nine Linear Voltage Displacement Transducers (LVDT's) were used to measure the deformations at various points of the frame (see Fig. 5). The strain gauge readings could not be captured throughout the test as the strain gauges were de-bonded due to cracking of concrete during the course of the test.



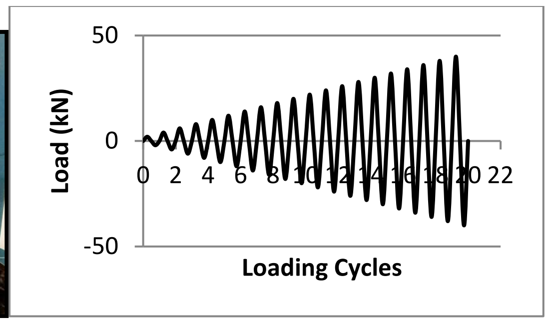


Fig. 5. Experimental set up of test frame   Fig. 6. Reverse Cyclic Loading Pattern applied on the test frame

4. Results and Discussion

The results are presented below in the form of load-deflection hysteresis loop plots, load-deflection envelopes, discussions on displacement ductility factor, the crack pattern and different failure modes of the RC frame specimens.

4.1 Load – deflection hysteresis loop

Structures are expected to enter the elasto-plastic range during strong earthquakes. The hysteresis loops can be used for understanding of the sesmic elasto-plastic response of structures [14,15]. From the current study also, the load deflection hysteresis loops were generated to evaluate the structural seismic performance. The energy dissipation capacity of the structure can be evaluated by considering the area enclosed by the hysteresis loops. Load-deflection hysteresis loops for the RC frame specimens, cast with different grades of concrete and pre-loaded with different temperatures under consideration are shown in Figures 8-10.The discussion of the results under each category are given below.

4.1.1. Frames cast with M20 grade concrete

The load-deflection hysteresis loops for the RC frame specimens of M20 grade concrete subject to reverse cyclic loading and pre-applied temperature are shown in Figure 7(a–e). From the hysteresis plots, it can be inferred that as the temperature increases, the load carrying capacity of the frames decreases.

The hysteretic loops for the post-temperature RC frames were not able to take the full cycles of reverse cyclic loading as corresponding to the frames at ambient temperature. The loops showed remarkable pinching with increase in temperature, which indicates that the seismic performances of the specimens are decreased after exposure to elevated temperatures.

From Figure 7, it can be observed that as the pre-applied temperature increases from 28ºC to 600ºC, the load carrying capacity of the frame decreases from 30kN to 20kN with a corresponding increase in displacement from 13.50mm to 17mm. The load carrying capacity further reduces to 14kN at a temperature of 800°C

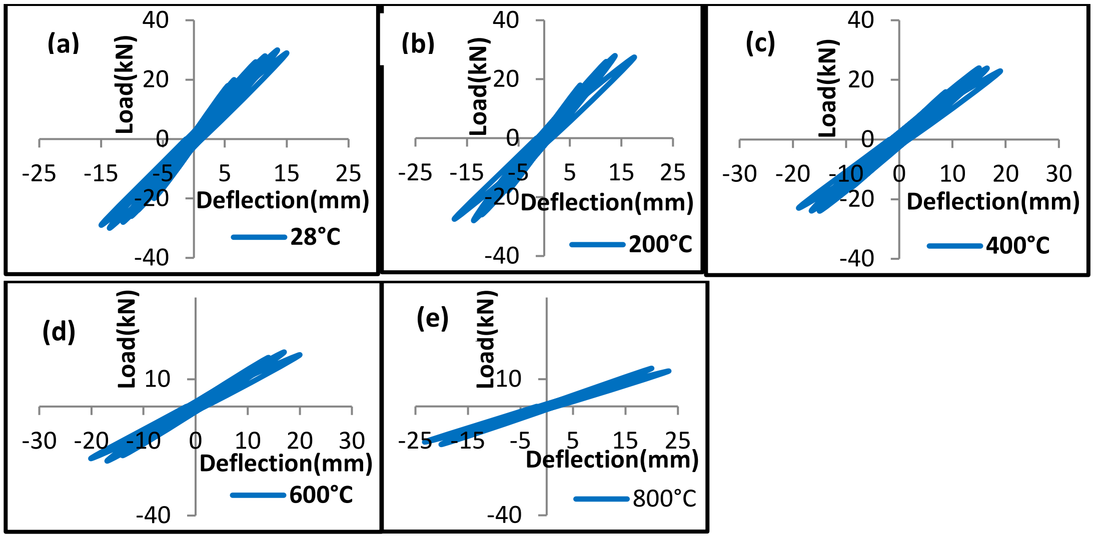


Fig. 7 Load-deflection hysteresis loops for frames (M20 grade concrete) with pre-applied temperatures of (a) 28^{0}C, (b) 200^{0}C, (c) 400^{0}C, (d) 600^{0}C and (e) 800^{0}C

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It can be observed from the above results that a temperature increase of 28°C to 800°C results in a reduction in load carrying capacity of 53%, of which 30% of deterioration was observed when the temperature was raised from 600°C to 800°C. Hence it can be concluded that the rate of deterioration in the load carrying capacity of the frame is very high after 600°C.The rate of increase in deflection in both the forward and reverse cycle is also very high after 600°C.

4.1.2 Frames made with M45 grade concrete

The load-deflection hysteresis loops of the RC frame specimens of M45 grade concrete subjected to the same loading conditions as before are shown in Figure 8(a-e).

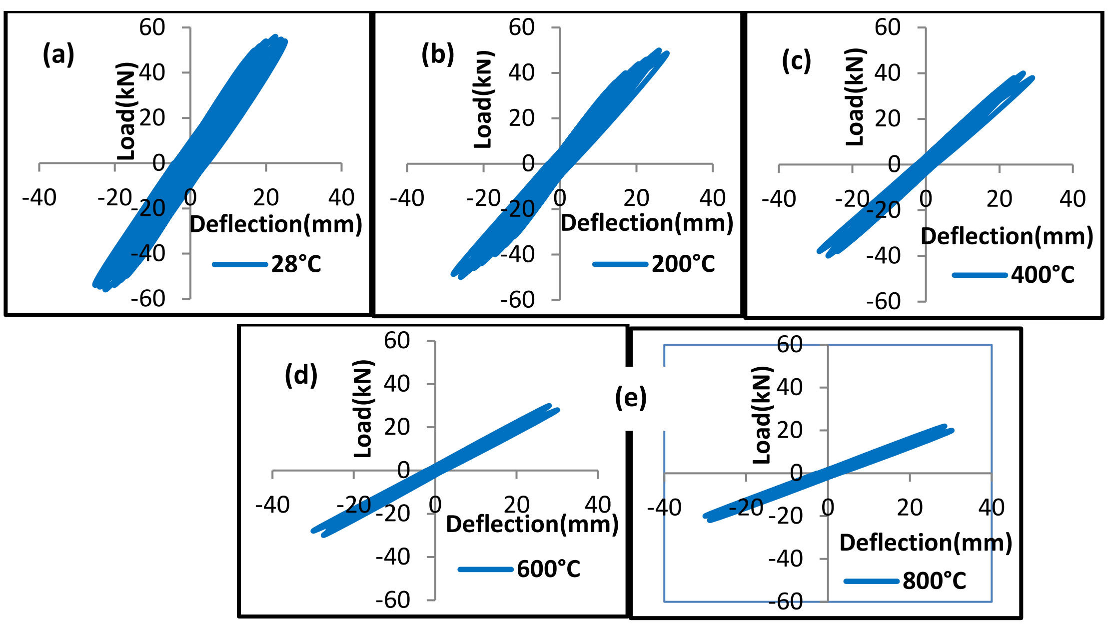

Fig. 8. Load-deflection hysteresis loop for frames of M45 grade at (a) 28^{0}C (b) 200^{0}C (c) 400^{0}C (d) 600^{0}C and (e) 800^{0}C

The hysteresis loops showed remarkable pinching even at 400ºC pre-applied temperature, compared to the hysteresis loop at 28°C unlike in the case of M20 grade concrete frames. From Figure 9(a), obtained for the frame subjected to loading at 28ºC, the maximum load carrying capacity is 56 kN with an average maximum displacement of 22.50mm Whereas after a pre-applied temperature of 800°C the load carrying capacity of the frame reduces to 22kN (percentage reduction is 60%) with an average displacement of 28.50mm (percentage increase is 20%) (Fig. 8. (d)). The Fig.9 shows a shift of maximum values from left towards the right side from Fig. 8 (a-e), which implies that the load carrying capacity decreases and deflection value increases as temperature increases. The numbers of cycles of load taken by the specimen are also getting reduced as temperature increases.

4.1.3 Frames made with M60 grade concrete

The load-deflection hysteresis loops of the RC frame specimens of M60 grade concrete with pre-applied temperature are shown in Figure 9.

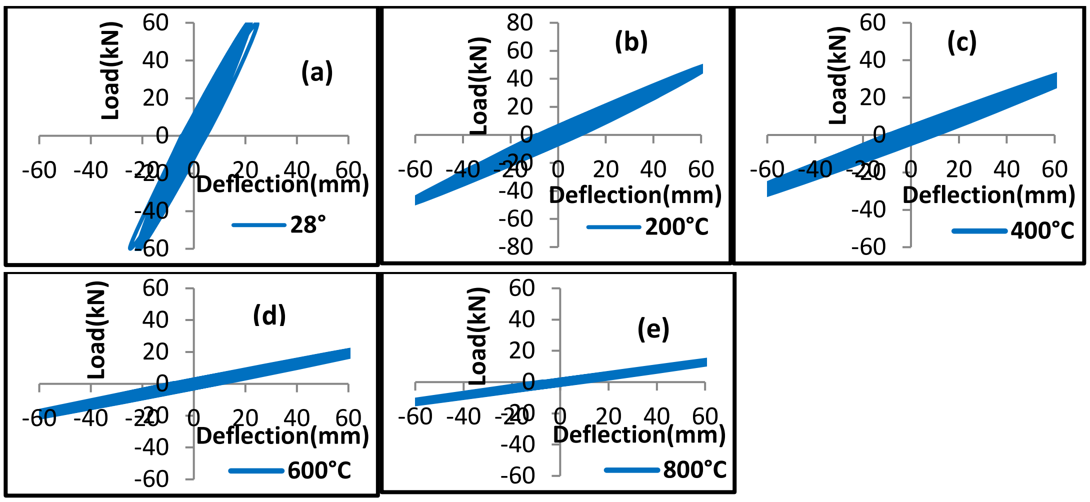

Fig. 9. Load-deflection hysteresis loop for frames of M60 grade at (a) 28ºC, (b) 200ºC, (c) 400ºC, (d) 600ºC and (e) 800ºC

The hysteresis loop was very stiff at 28ºC (Fig. 10(a)), with the maximum load carrying capacity of 62kN and with an average maximum displacement of 22mm.Remarkable pinching of the loops were seen at pre- applied temperature of 200ºC, which reveals the vulnerability of the frames cast with high strength concrete at early temperatures. At a pre-applied temperature of 200ºC, the load carrying capacity reduced to 38%. At 600ºC, the maximum load carrying capacity was reduced to 24 kN (percentage reduction 61%) with an average displacement of 48mm in both the cycles. At 800ºC, the maximum load carrying capacity further reduced to 16kN (percentage reduction 74%) with a displacement of 52mm. Table 1 shows the maximum load and maximum deflection values in the hysteresis loops of different specimens at the corresponding pre-applied temperature.

Table 1. Maximum load and maximum deflection values in the hysteresis loops different specimens at the corresponding pre-applied temperature.

Temperature	M20 grade frames			M45grade frames			M60 grade frames		
	Load (kN)	% decrease	Displacement (mm)	Load (kN)	% decrease	Displacement (mm)	Load (kN)	% decrease	Displacement (mm)
28ºC	30	0	13	56	0	22	62	0	22

200ºC	28	7	13	50	11	25	50	19	38
400ºC	24	20	15	40	29	26	36	42	44
600ºC	20	34	17	30	46	28	24	61	48
800ºC	14	53	20	22	60	28	16	74	52

It can be observed from the Table 1, that the percentage reduction in strength of the frames increases as grade of concrete increases for a particular pre-applied temperature. At a temperature of 400^0C, the load carrying capacities of the frame cast with M20, M45 and M60 grades of concrete are 80%, 71% and 58% of the capacity at 28^0C respectively.

5. Summary and Conclusion

A single bay, single storied frame representing a simple conventional RC frame was chosen in the present work to study the behavior of beam-column connections with pre-applied temperatures, followed by mechanical loading. The behavior of frames subjected to different pre-applied temperatures of 200°C, 400°C, 600°C and 800 were compared with that at ambient temperature. From the study, the following conclusions were made:

- The hysteresis loops for RC frames subjected to pre-applied temperature followed by combined flexural and cyclic loading were not as full as the corresponding frames tested at ambient temperatures and they showed remarkable pinching, which indicates that the seismic performance of the specimens decreases after exposure to elevated temperature.
- From the hysteresis loops, it can also be noticed that, the slopes of the loops are decreasing for increased temperatures, irrespective of grade of concrete. This implies that, the load carrying capacities of the frames decrease with increase in temperature together with increase in deflection.
- From the Table 1, it can be seen that the load carrying capacity decreases with increase in pre-applied temperatures. Hence it can be concluded that the frames made with high strength concrete are more vulnerable to temperature effects than the frames cast with ordinary and standard concrete.

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