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PERFORMANCE AND DAMAGE ASSESSMENT OF REINFORCED CONCRETE SLAB EXPOSED TO ELEVATED TEMPERATURE

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ABSTRACT

Numerical investigation was carried out to study the behavior of simply supported slab using finite element method software ABAQUS. The validation of this model was based on Gordon M.E. Cooke (2). The analysis was carried out for ISO 834 standard fire curve for 90 minutes of exposure on bottom side of reinforced cement concrete. The other important parameters considered here were depth of slab, diameter of reinforcement with constant spacing, with and without live load of 1.5 kPa. The temperature distribution along the depth of the slab, temperature variation of the steel reinforcement, vertical deflection and percentage of damage were studied. A result of numerical studies indicates that the distribution of temperature along with the slab depth is nonlinear, the temperature gradients are large, the stiffness of the slab found to decrease as temperature increase with time. The increase in thickness of slab and diameter of reinforcement shows same pattern of decrease in stiffness. The stiffness was found to be decreased in higher rate when considering live load also. The slab supported on four sides was found to behave in more promising manner due to better redistribution of forces and formation of double curvature than the two side supported slab. The maximum damage percentage was found to be 68% and 94% for four sided supported slab and two sided supported slab respectively for a time period of 90 minutes.

KEYWORDS: Concrete, Damage, Elevated Temperature, Live Load, Reinforcement, Residual Strength, Slab

INTRODUCTION

Engineering structures were often subjected to extreme loads such as earthquake, fire, sabotages etc., sometimes it even leads collapse of the structure. Major structural elements in reinforced concrete structures were frames, shear walls and slabs. The accurate simulation of the nonlinear behavior of these structural elements under extreme loads is essential The study of residual strength of concrete exposed to fire has been conducted since 19th century onwards and still (as Shown in [1,2.17 & 19]). Numerous large scale experimental works had been studied on buildings subjected to fire after the terrorist attack on Twin towers of New York City in 2001. The RCC slabs have to ensure stability and functional aspect like a) Insulation and b)Integrity as specified in (22 to 29). Concrete slab is thin structural element which has to ensure functional as well as strength aspect. Concrete slab is most important because it occupies large area and it is intend to perform function of separation, compatible with the users and to ensure sufficient strength when it was exposed to elevated temperature.

Tensile membrane action of concrete slabs was studied by conducting large scale experimental test [3 to 7]. The failure was found to be double the time of load calculated by using theories available. [3 to 7]. Numerous equations were proposed to calculate the load carrying capacity by considering the effect of tensile membrane action [3 to 12]. The two main concrete failure mechanisms are cracking under tension and crushing under compression. However, concrete strength determined in simple states of stress (uni- axial compression or tension) radically differs from the strength determined in complex states of stress.

MECHANICAL PROPERTIES OF SPECIMEN

The materials properties were considered to be temperature dependent. The constitutive relationship and all the related material properties required for the analysis were based on Euro code 2[26 & 27].

Concrete Plasticity

Plasticity theory successfully treated concrete problems in which the material is subjected to primary compressive loads. In situations where tension-compression plays a significant role, plasticity theory is applied to model the compression zones while damage or fracture mechanics is used to model the tensile zones. One of the strength hypotheses most often applied to concrete is the Drucker– Prager hypothesis (1952). According to it, failure is determined by non-dilatational strain energy and the boundary surface itself in the stress space assumes the shape of energy and the boundary surface itself in the stress space assumes the shape of a cone. The advantage of the use of this criterion is surface smoothness and thereby no complications in numerical applications.

The drawback was, not fully consistent with the actual behavior of concrete. The CDP (Concrete Damaged Plasticity) model used in the ABAQUS software is a modification of the Drucker–Prager strength hypothesis. In recent years the latter has been further modified by Lubliner [15], Lee and Fenves [16]. According to the modifications, the failure surface in the deviatoric cross section needs not to be a circle and it is governed by parameter K_C.

Finite Element Analysis at Elevated Temperatures

Modeling and analysis of RC Slabs was studied by using FEM Software Package ABAQUS. The analysis was carried out in two steps. Before this temperature distribution analysis was performed and checked for integrity and insulation aspect then the following was preceded

Step 1: Perform the linear structural analysis to determine the short term deflection due to loads considered.

Step 2: Perform the coupled temperature displacement analysis along with the results from previous step.

In the case of temperature analysis for concrete members, the convection is usually ignored when calculating the exposed surface temperature because convection is responsible for less than 10% of the heat transfer at the exposed surface of the concrete members [17]. On the other hand, convection is usually accounted for when calculating the unexposed surface temperature. The internal heat transfer through concrete members is typically calculated by conduction only [18]. To study the performance of reinforced concrete slab under fire, the distribution of temperature along the depth of slab was essential. The Dimensions of slab consider for the study were 4.5m x 4,5m square slab. Live load considered for the analysis was 1.50 kPa. The temperature considered for the study was ISO fire curve [28].

The analysis was performed by considering that the slab was exposed to a time period of 90 minutes, with and without live load, varying diameter of reinforcement, various thickness of slabs and for simply supported at two opposite edges and other two opposite edges Free (SSFF). Analysis was also performed for boundary condition of simply supported on all four sides (SSSS), to determine the damage and behavior of slab and to compare it with two opposite edges simply supported for a general case only

Finite Element Type and Mesh

Three-dimensional solid element and surface element were used to model the test specimen in order to achieve an accurate result from the finite element analysis. For concrete, C3D8RT- An 8-node thermally coupled brick, tri-linear displacement and temperature was used and for steel, it was 3-node truss element

Validation

For validating the existing numerical model, experimental test result of Gordon M.E. Cooke (2001), is considered[13]. RCC slab are heated from below by ISO-834 fire. In ABAQUS, the RCC slab model is heated up to 90 minutes as the slab is design to resist up to 90 minutes. The compared analysis result with experimental results was as shown in Table 1 and also given in Figure 1.

Table 1: Mid-Span Deflection Comparison of Experimental vs. Analytical Result

Time in Minutes	Mid-Span Deflection (mm)		
	Slab (ABAQUS)	BRE Slab	Error %
20	62	64	-3.2
40	104	107	-2.8
60	133	135	-1.4
80	158	159	-0.6

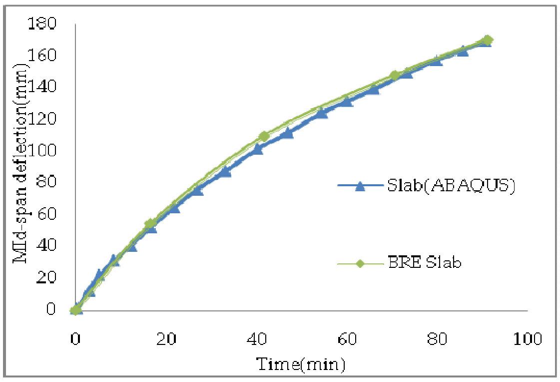

Figure 1: Comparison of ABAQUS Model with Experimental Results of Gordon M. E. Cook [13]

TEMPERATURE DISTRIBUTION IN SLAB

The temperature distribution was studied for all the thickness that was considered for the study. The results are checked for functional aspect with various codes [22 to 26 & 29]. The results of temperature distribution along the depth of slab was as shown in Figure 2, 3 & 4 for three different thickness of slab 150mm, 180mm and 250mm respectively

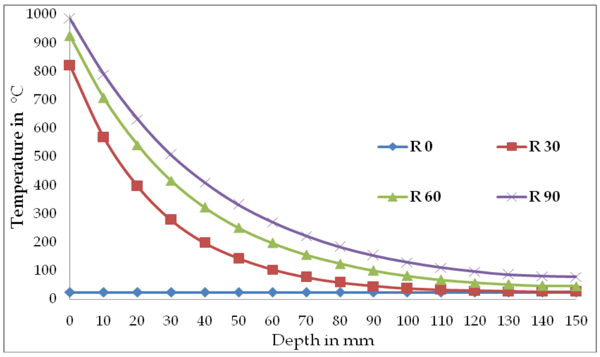

Figure 2: Variation of Temperature for 150mm Thick Slab

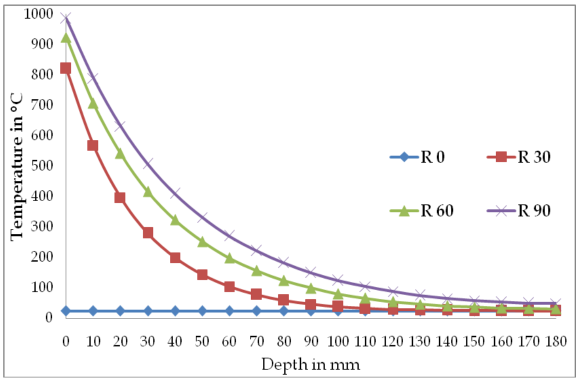

Figure 3: Variation of Temperature for 180mm Thick Slab

From Figure 2 to 4 it was inferred that the temperature varies nonlinearly along the depth of slab. The magnitude of the temperature was found to be high in the regions which were close to the exposed surface and it found to be diminishing as the distance increases from the exposed surface. The following table 2 to 4 shows the temperature at the various positions along the depth of slab. The temperature was measured in °C.

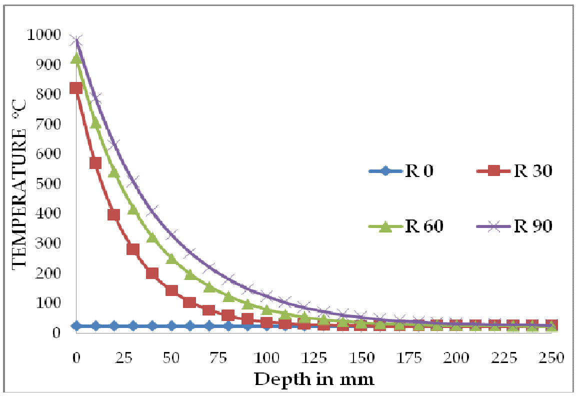

Figure 4: Variation of Temperature for 250mm Thick Slab

Table 2: Temperature Distribution at Reinforcement Zone and Top of Slab for 150 mm Thick Slab

Temperature in °C, Depth in mm					
Exposed Duration	Depth from Exposed Surface to Fire in mm				
	20	25	30	35	150
R30	397	338	279	239	27
R60	542	480	418	371	46
R90	633	570	508	459	79

Table 3: Temperature Distribution at Reinforcement Zone and Top of Slab for 180 mm Thick Slab

Temperature in °C, Depth in mm					
Exposed Duration	Depth from Exposed Surface to Fire in mm				
	20	25	30	35	180
R30	398	339	281	241	25
R60	542	480	418	371	32
R90	633	570	508	459	49

Table 4: Temperature Distribution at Reinforcement Zone and Top of Slab for 250 mm Thick Slab

Temperature in °C, Depth in mm					
Exposed Duration	**Depth from Exposed Surface to Fire**				
	20	**25**	**30**	**35**	**180**
R30	398	339	281	241	25
R60	542	480	418	371	26
R90	633	570	508	459	28

From the Table 2 to 4 it was inferred that the temperature was found to have same magnitude for same duration of exposure and it found to vary only at the unexposed surface it is due to increase in thickness of slab. At the depth of 20 mm from the exposed surface the temperature exceeds the limit of 593°C as specified in ASTM E119 (22) for reinforcement. The unexposed surface temperature was well within the limits specified by ASTM E119, Euro Code, and BS476part (20 to 22) for all the thickness. From the above temperature analysis it was found out that the minimum clear cover of 25 mm is required for 90 minutes of exposure to ISO fire curve.

EFFECT OF AREA OF REINFORCEMENT

The reinforcement was provided based on the normal design. The required reinforcement was Main reinforcement - 8mm diameter at 100 mm c/c. Distributor -8 mm diameter at 150 mm c/c. In this the main reinforcement diameter was varied from 8mm to 10mm and 12mm. The effect of rebar was analyzed by considering only Dead load (DL) and also by considering both dead load and live load (LL). The allowable deflection for members exposed to elevated temperature is about span /20 as per BS 476. The deflections were obtained for the different diameter of main reinforcement and for various loading effects were plotted as shown in Figure 5 and Figure 6.

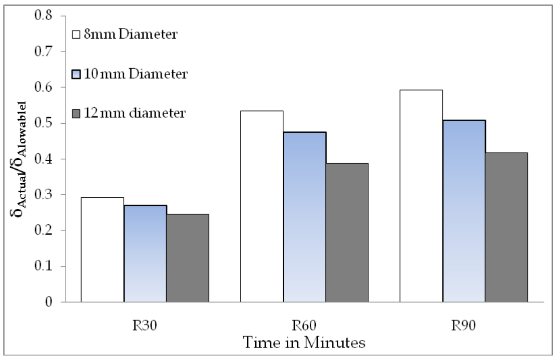

Figure 5: Comparison of Finite Element Slab Deflection with BS 476 Code Provision, Subjected to Dead Load Only

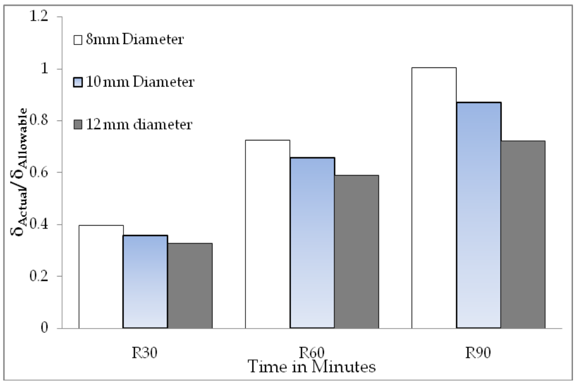

Figure 6: Comparison of Finite Element Slab Deflection with BS 476 Code Provision, Subjected to Dead Load and Live Load

From figure 5 and figure 6 it was inferred that under elevated temperature there was loss of material property which results in increase in deflection even for a constant load. As the exposed time was increased, the deflection found to be increased. In addition to dead load presence of live load leads to increase in deflection by 10%, 9% and 8% for 8mm diameter, 10mm diameter and 12mm diameter specimen for 30 minutes of exposure respectively. In case of 90 minutes of exposure the deflection was found to be increased by 40%, 36 % and 31% respectively. For 8mm diameter specimen under combined DL and LL for duration of 90 minutes of exposed condition it exceeds the strength criteria as specified in BS 467(). So the member with 8 mm diameter as main reinforcement had failed for the exposure of 90 minutes under ISO fire curve. From the values obtained it is clear that by increasing percentage of reinforcement by 20% and 42% than the required amount results in increase in stiffness of the member by 14% and 28% respectively for 10mm diameter and 12 mm diameter specimen.

EFFECT OF INCREASE IN DEPTH OF MEMBER

The analysis was performed for three various depth (150mm, 180mm and 250mm), the reinforcement provided was 10mm diameter of 100mm center to center as main reinforcement and 8mm diameter at 100 mm center to center as distributor, B.C. considered SSFF. The deflections was obtained for above conditions were plotted as shown in Figure 7 and Figure 8

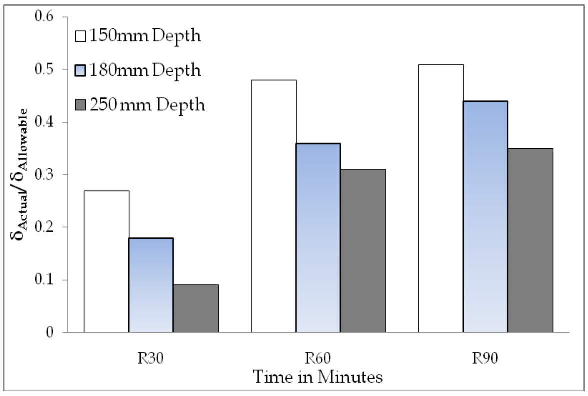

Figure 7: Comparison of Finite Element Slab Deflection with BS 476 Code Provision, Subjected to Dead Load Only

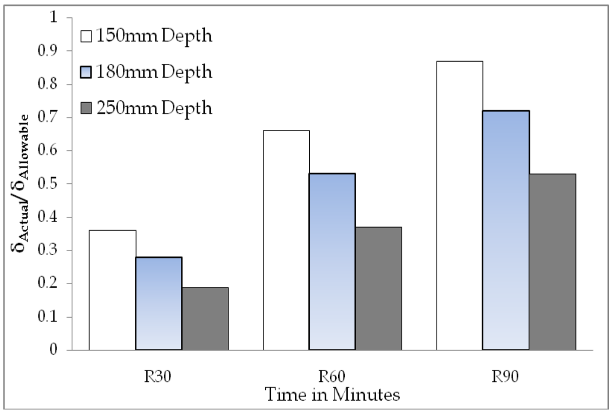

Figure 8: Comparison of Finite Element Slab Deflection with BS 476 Code Provision, Subjected to Dead Load and Live Load

From figure 7 it was observed that under elevated temperature with increase in thickness of member the deflection was reduced of about 4% and 9% for exposure of 30 minutes of duration. It was about 7% and 16% for exposure of 90 minutes of duration. From the results it is clear that the smaller depth of slab faster the deterioration of the section when it is subjected to fire.

From figure 8 it was observed that under elevated temperature, with increase in thickness of member the stiffness of the member increases which results in decrease in the deflection rate when compared with the 150mm thick specimen. The following figure 9 explains the percentage of damage the slab was subjected due to fire.

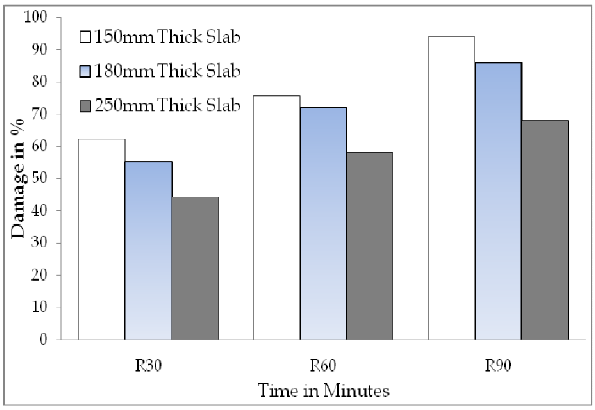

Figure 9: Percentage of Damage versus Time for Various Thicknesses of Concrete Slabs

From figure 9 it was predicted that under elevated temperature with increase in thickness of member the percentage of damage decresased. The maximum damage was occurred in 150mm slab and least damage was found in 250mm slab for any time. The percentage of damage is ranging from 62% to 94% for 150mm slab for 30 minutes to 90 minutes of exposure. In case of 180 mm slab it was about 56 % to 86% and for 250 mm slab it was 44% to 68 %. The main reason for the above variation is mainly due to the temperature distribution across the depth of the specimen and also the loading effects add in addition to the former one.

EFFECT OF DIFFERENT BOUNDARY CONDITION

The supports conditions considered for the analysis were Simply supported (SSSS) on all sides and simply supported on two opposite edges and other two opposite edges free (SSFF). The effect of boundary condition on deflection and percentage of damage was obtained were plotted as shown in Figure 10 and Figure 11 respectively.

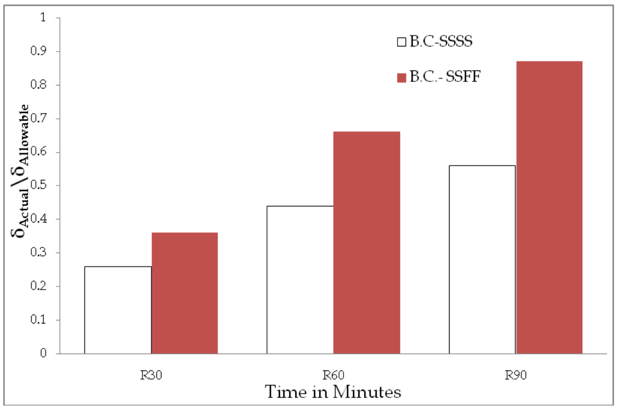

Figure 10: Comparison of Finite Element Slab Deflection with BS 476 Code Provision

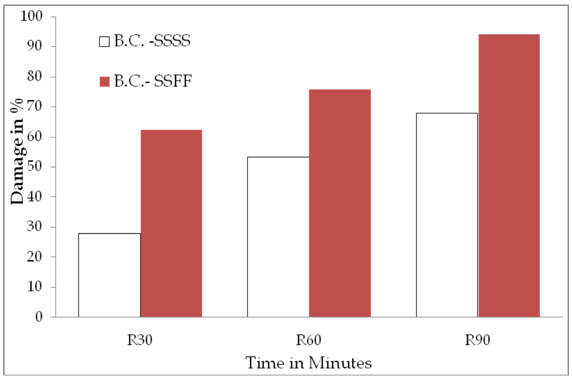

Figure 11: Percentage of Damage versus Time for Various Boundary Conditions of Concrete Slabs

Form the Figure 10 it was inferred that the deflection of the slab was found to decreases as the support condition varies. The four side supported slabs behaves in a better way than the two sided supported slab. This is mainly due to the effect of boundary condition and which enchases the stiffness of the member by reducing the deflection. Similarly percentage of damage is less for the four side supported specimen than the two side supported slab

CONCLUSIONS

Non-linear analysis of concrete slabs was carried out with ISO-834 fire curve. Due to increase in temperature some portion of the members gets deflected, as thermal expansion play an important role and for some condition in some edges results in thermal bowing which plays an important role at the initial stage of heating.

- Temperature distribution in all layers increases as the temperature increase and also as the duration of exposure was increased
- Formation tension ring is found to be evident for fixed and pinned condition for slabs supported on two opposite sides.
- For Roller supported the initial stage of deterioration is due to axial tension then followed by thermal bowing in addition to this material effect is also to be considered
- Formation of tension ring is found to be evident for slabs supported on all four sides than the slabs supported only at two opposite sides.
- The failure is due to both material degradation and also due to excessive deflection for two side SSFF B.C.
- The Slab supported on four sides had deflection lesser than slabs supported on two sides. Indicates the better performance in slabs that is supported on all four sides.

REFERENCES

1. Abrams. M. S. “Compressive Strength of Concrete at Temperatures to 1600 F.” ACI Publications SP25, paper SP25-2, Detroit 1971.
2. Anand N 1, Ahmad, Prince Arulraj. G “The effect of elevated temperature on concrete materials A literature review”, International Journal of Civil and Structural Engineering Volume 1, No. 4, 2009.

3. A. S. Usmani. “Limit Capacity of Laterally Restrained Reinforced Concrete Floor Slabs in Fire.” Cement & Concrete Composite Structures, 26, pp. 127-140., 2013.
4. C. G. Bailey, D. S. White and D. B. Moore. “The Tensile Membrane Action of Unrestrained Composite Slabs Simulated Under Fire Conditions.” Engineers Structures, 22, pp. 199-212., 2000.
5. C. G. Bailey. “Membrane Action of Unrestrained Lightly Reinforced Concrete Slabs at large Displacements.” Engineers Structures, 23, pp. 470-483, 2000.
6. C. G. Bailey,” Holistic behavior of concrete buildings in fire.” Proceedings of the Institution of Civil Engineers, Structures and Buildings, pp. 199-212., 2002.
7. C. G. Bailey Foster S. J, Durgess I. W, Plank R. J. (2004). “Experimental Behavior of concrete Floor Slab at Large Displacement.” Engineers Structures, 26, pp. 1231-1247., 2004.
8. C. G. Bailey and W. S. Toh. “Small Scale Concrete Slab Tests at Ambient and Elevated Temperature.” Engineers Structures, 29, pp. 2775-2791., 2007.
9. C. G. Bailey W. S. Toh. “Behavior of Concrete Slab Tests at Ambient and Elevated Temperature.” Engineers Structures, 32, pp. 2975-2992., 2007.
10. C. G. Bailey and Ellah Elloboy. “Fire Test on Bonded Post – Tensioned Concrete Slabs.” Engineers Structures, 31, pp. 686-696., 2009.
11. C. G. Bailey and Ellah Elloboy “Structural Performance of a Post – Tensioned Concrete Floors during Horizontally Travelling Fires.” Engineers Structures, 33, pp. 1908-1917., 2011.
12. C. G. Bailey and S. Guo “Experimental Behavior of Composite slab during the heating and cooling regime.” Engineers Structures, 33, pp. 563-571, 2011.
13. Gordon M.E. Cooke. “Behavior of precast concrete floor slabs exposed to standardized fires”. Fire Safety Journal, 34, pp.459-475., 2001.
14. Ian A. Fletcher, S. Welch -& A. S. Usmani. (2007). “Behavior of Concrete Structures in Fire.” By BIBLID: 0354-9836, 112, 37-52, 2007.
15. Lee J., Fenves G. L: “Plastic-damage model for cyclic loading of concrete structures”, Journal of Engineering Mechanics, Vol. 124, No. 8, pp. 892–900., 1989.
16. Lubliner J. J, Oliver S.O, Oñate E, “A plastic-damage model for concrete”, International Journal of Solids and Structures, 25, 3, 229-326., 1989
17. Li L, Purkiss J. “Stress-Strain Constitutive Equations of Concrete Material at Elevated Temperatures”. Fire Safety Journal, 40, 449-484., 2005.
18. Majewski S: “The mechanics of structural concrete in terms of elastic-plasticity”, Silesian Polytechnic Publishing House, Gliwice, 2003.
19. Schiender U. “Concrete at High Temperature – A General Review.” Fire Safety Journal, 13, pp 55 -68, 1988.
20. Terro, M. J “Numerical Modeling of the Behavior of Concrete Structures”. ACI Struct Journal, 95, 183-93, 1998.

21. Usmani, A. S, Rotter, J. M, Lamont, S, Sanad, A. M, Gillie M. "Fundamental Principles of Structural Behavior under Thermal Effects". Fire Safety Journal, 34, 721-744., 2001.

22. ASTM Standards. Standard Test Methods for Fire Tests of Building Construction and Materials, in Annual Book of ASTM Standards. Vol. 04, Designation: E 119-88, ASTM, 922–942, 1988

23. BS 476: Part 20: 1987, Fire tests on building materials and structures, Method for determination of the fire resistance of elements of construction (general principles), British Standards Institution, London, UK (1987).

24. BS 476: Part 21: 1987, Fire tests on building materials and structures, Method for determination of the fire resistance of load bearing elements of construction, British Standards Institution, London, UK (1987).

25. BS 476: Part 22: 1987, Fire tests on building materials and structures, Method for determination of the fire resistance of non-load bearing elements of construction, British Standards Institution, London, UK (1987

26. Eurocode 2, Design of concrete structures-part 1.1: General rules- rules for buildings, Commission of the European communities, Brussels, Belgium (2004).

27. Eurocode 2, Design of concrete structures-part 1.2: General rules- structural fire design, Commission of the European communities, Brussels, Belgium (2004).

28. ISO Fire Resistance Tests. Elements of Building Construction, ISO 834, "International Organization for Standardization." Geneva, 1975

29. SP-24 "Explanatory Handbook on Indian Standard Code of Practice for Plain and Reinforced Concrete", IS – 456 – 1978, Bureau of Indian