Study into the Behavior of Reinforced-Concrete Short Column under Fire Exposure Using ANSYS

Aejaz Mushtaq Dar, M.Tech Scholar Structural Engg,Civil Engg Deptt. DBU Punjab
Dr. Rajesh Goyel ,Supervisor & Professor
Dr. Pooja Sharma ,HOD Civil Deptt. DBU Punjab
Er. Mudasir Hussain Dar, Co-Guide & Junier Engineer.

Abstract: Fire is a significant threat to the structural integrity of buildings. Depending on the architecture of the structure and the intensity and duration of the fire event, structural members may lose strength and stiffness eventually leading to collapse whether by crushing or flexural buckling. The focus of my project is on the behaviour and fire performance of reinforced-concrete short column under fire conditions. Finite element software ANSYS is used to perform the thermal analysis. The residual strength or axial load carrying capacity of columns under varying time-temperature curve is determined. The study is performed on columns of different cross-sections to investigate the effect of five parameters, namely the grade of concrete, grade of steel, percentage of reinforcement in column, concrete cover (clear) and column size. The residual strength based on various failure criteria is determined, and minimum strength is selected for a given fire rating. Four-sided fire exposure along with the ISO 834-1 standard fire curve is used to carry out the thermal analysis in ANSYS.

It has been found that concrete cover is the most important factor effecting residual strength of columns. Increasing grade of concrete, grade of steel, or percentage reinforcement is effective in enhancing fire strength only for low temperatures of about 400OC. Increasing column size increases strength, however more concrete area is exposed to fore, and hence not effective at high temperatures.

1. Introduction

Fire safety in buildings has evolved as one of the objectives in concrete design after incidents such as World Trade Centre attack on September 11, 2001 (U.S.A.) and the terrorist attack in Taj Hotel on November 26, 2011 (INDIA). This has generated a renewed interest in fire resistant analysis and design of structures worldwide. The popularity of numerical techniques such as finite element analysis has facilitated to simulate the fire conditions that have reduced the number of expensive fire tests and made fire analysis easier and well accepted [1-3]. Usually, concrete structures are designed to perform at room temperature, and the safety at high temperatures is checked using code provisions.

However, some structures such as the chimney, nuclear reactors, and furnaces, are always subjected to high temperatures (100 – 500ºC) and due to unpredicted fire accidents, buildings and bridges are exposed to a temperature of about 1000ºC [4].

Columns are the primary structural elements that transfer the loads of a building vertically to the foundation and reinforced concrete is one of the two main material types used for columns. The high-temperature exposure of an RC column leads to significant variation in material properties and reduction in strength of reinforcement as well as concrete. Moreover, the temperature propagation inside the structure is non-uniform, and it results in the degradation of strength unevenly and finally the failure of the structure [5, 6].

Relatively lesser studies were done on evaluating the fire performance of reinforced concrete (RC) columns compared to flexural members such as slab and beam. Further, much of the current knowledge on the fire behaviour of RC columns is based on fire tests under standard fire exposure. Studies have demonstrated that parameters such as load level, amount of steel reinforcement, effective length of column, concrete strength, moisture content, area and shape of cross section and aggregate type have significant influence on fire resistance [4, 7-10].

When concrete columns are exposed to fire, the material properties of concrete and the reinforcing steel change as the temperature increases. The decreases in yield strength and modulus of elasticity reduce the overall strength of the column. Once the column strength decreases lower than the applied load, the column will fail either by crushing or by flexural buckling. In structural fire performance testing, a column is placed in a furnace and subjected to a controlled fire while being loaded with a prescribed force. The length of time from the beginning of fire exposure to failure is the fire resistance rating of a column.

Achieving code-specified fire resistance ratings is the goal in prescriptive-based design fire protection [11]. Fire and structural code books such as the International Building Code list types of occupancies and the fire resistance ratings various structural members should have. For reinforced-concrete columns, minimum dimensions for concrete cover and column dimensions are listed for specific fire resistance ratings. However, in the fire protection and structural engineering industries, prescriptive-based design is slowly being replaced with performance-based design. The major difference between the two types of design is that performance-based requires the demonstration of fire safety. Numerous methods are available for assessing the fire safety of a design.

2. Methodology & Materials

This chapter outlines the methodology used in this project. The methodology includes the thermal analysis, calculation of residual strength based on strength and buckling effects and determining the effect of various parameters on the residual strength of column.

Column and parameters used

The column used in this study is a 3m long RCC column. It is an interior column of a structure which can be subjected to high temperatures on all faces and is critical in fire scenarios. The column is assumed to be fixed at the ends by rigid slabs. The parameters used are:

a) *Column Size*: Columns with square cross-section of 300mm x 300mm, 400mm x 400mm and 500mm x 500mm are used.
b) *Grade of Concrete*: The grades of concrete used in this study are M30, M40, M50 and M60.
c) *Grade of Steel Reinforcement:* The reinforcement used is steel of grade Fe-415, Fe-500 and Fe-550.
d) *Clear Cover to The Reinforcement:* The clear covers provided to the reinforcement are 40mm, 45mm, 50mm, 55mmm and 60mm.
e) *Percentage Reinforcement:* The main reinforcement used is steel bars, 8 in number. The bar diameters used are 16mm, 20mm and 24mm.

A shear reinforcement of 10mm stirrups of Fe-415 at a spacing of 100mm has been provided in all cases.

3. The Material Model

The finite element code ANSYS, version 16.2, has been used. Its reinforced concrete model consists of a material model to predict the failure of brittle materials, applied to a three-dimensional solid element in which reinforcing bars may be included. The material is capable of cracking in tension and crushing in compression. Plastic behaviour has been considered for both concrete and reinforcing bars. However, strain hardening has not been considered for steel.

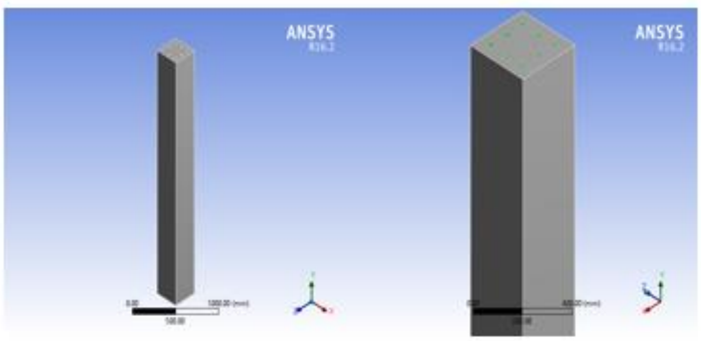

Figure 1: Column used in ANSYS

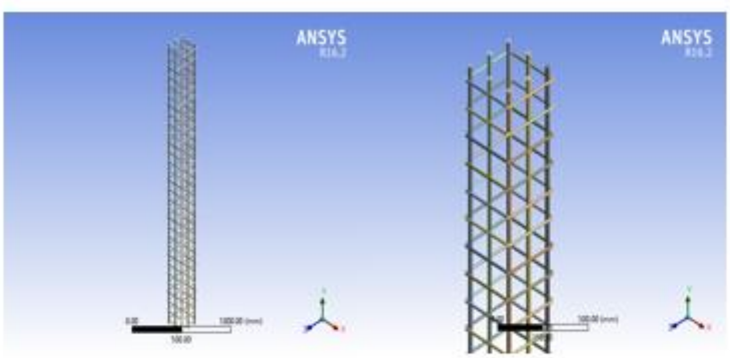

Figure 2: Column reinforcement used in ANSYS

4. Results & Discussion

The following section describes the results for the column behavior study:

To study the effect of these parameters, a detailed study is performed on columns of various cross-sections such as 300x300 mm, 400x400 mm and 500x500 mm with column length of 3 m. All the parametric studies are done for concrete cover, grade of concrete and grade of steel of 40 mm, 30 MPa and 415 MPa respectively, except for the varying parameter and subjected to four side fire exposures.

The residual strength is determined based on two failure criteria i.e., strength and buckling criteria. In strength criteria, the crushing load is calculated; and in buckling criteria, the Euler's buckling load is calculated; and the minimum of the two is the residual strength of column. Tables below show the influence of various parameters on axial load capacity of column for various time intervals and the residual strength based on these studies are discussed in successive sections.

1. *Column size*: From Table 1, it can be witnessed that the percentage reduction in strength increases with increase in size of column and is more predominant in columns of larger size. This is because in a large sized column, more of the concrete area is exposed to fire and hence it is more severely affected. The percentage reduction in load carrying capacity of column with fire on four sides is initially about 10-15% but as the time of exposure increases the percentage reduction is more prominent. At very high temperatures, most of the strength from concrete is lost due to extensive cracking, and all of the three columns tend to have the same strength. At high temperatures, spalling of concrete can also take place, thus reducing the effective resisting section. Corners are the critical regions under fire, and when two adjacent sides are exposed to fire the corner bars are severely affected.

Table 1: Comparison of load carrying capacity based on column size.

Column Size mm^2	Load carrying capacity (Pu in kN) with time of exposure							
	0h	0.5h	1h	2h	3h	4h	5h	6h
300x300	1748.3	1538.2	1428.9	1239.4	762.2	380.5	143.9	72.6
400x400	2588.3	2304.4	2153.1	1883	1292.8	788.2	151.4	74.2
500x500	3668.3	3310.6	3117.4	2766.6	2033.3	1405.8	331.4	81.5

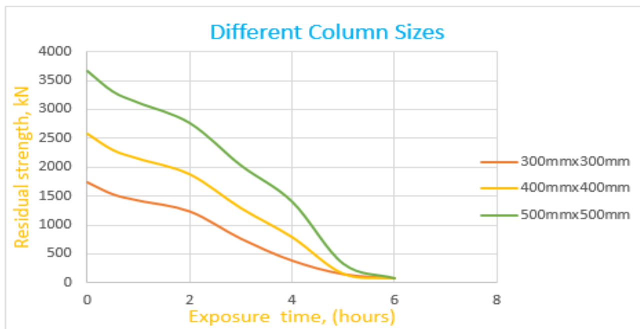

Figure 3: Residual strength vs exposure time for different column sizes

2. *Effect of concrete cover*: The tabulated fire ratings given in various codes are based on concrete cover. As the cover reduces the temperature of reinforcement increases which in turn causes the degradation of reinforcement strength, thereby decreasing the capacity of column.

During the initial hours of fire exposure, increase in cover does not have much effect in increasing the capacity as the degradation of strength in reinforcement is less. But as the time passes, the degradation of both concrete and steel takes place and causes sufficient reduction of strength. The effect of concrete cover on axial capacity of column is shown in Table 2. This is owing to the decrease in reinforcement temperature with increase in cover and hence increase in capacity and fire rating of column.

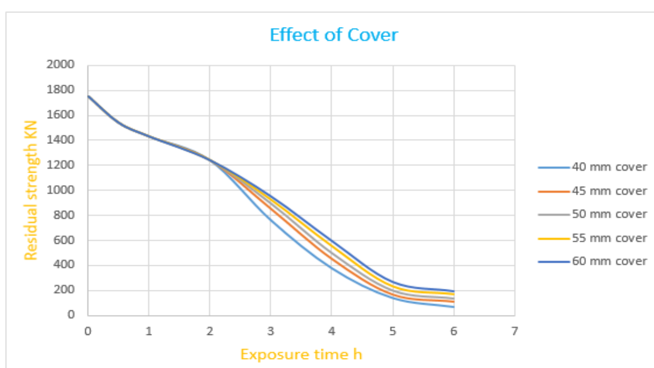

Figure 4 : Comparison of load carrying capacity based on clear cover

Table 2: Comparison of load carrying capacity based on clear cover.

Column Size mm2	Clear cover mm	Load carrying capacity (Pu in kN) with time of exposure							
		0h	0.5h	1h	2h	3h	4h	5h	6h
300x300	40	1748.3	1538.2	1428.9	1239.4	762.2	380.5	143.9	72.6
	45	1748.3	1538.2	1428.9	1239.4	851.3	452.5	167.6	111
	50	1748.3	1538.2	1428.9	1239.4	895.3	501.4	202.6	139
	55	1748.3	1538.2	1428.9	1239.4	923.3	553.1	230.5	167.8
	60	1748.3	1538.2	1428.9	1239.4	951.2	596.5	269	195

3. Effect of grade of concrete: The effect of concrete strength is studied by varying the characteristic compressive strength of concrete from 30 to 60 MPa. Studies show that effect of spalling is not a major issue in normal strength concrete [8] and is not accounted in the present work. From Table 3, it is visualized that axial capacity of column increases with increase in concrete strength and with increase in cross-section. The percentage increase in capacity is more pronounced in columns with larger cross-section. Using a higher grade of concrete in column against fire is more effective when the exposure time is less than 2 hours. After 2 hours the curves in Fig 5, tend to each other indicating that the higher grade of concrete is not effective now.

Table 3: Comparison of load carrying capacity based on grade of concrete.

Column size	Grade of concrete	Load carrying capacity (Pu in kN) with time of exposure							
		0h	0.5h	1h	2h	3h	4h	5h	6h
300x300	30	1748.3	1538.2	1428.9	1239.4	762.2	380.5	143.9	72.6
	40	2108.3	1829.8	1682.9	1429.5	862	427.2	156	75
	50	2468.3	2121.4	1937	1619.6	961.9	473.8	168	78.5
	60	2828.3	2413	2191	1809.7	1062	520.5	180.6	81

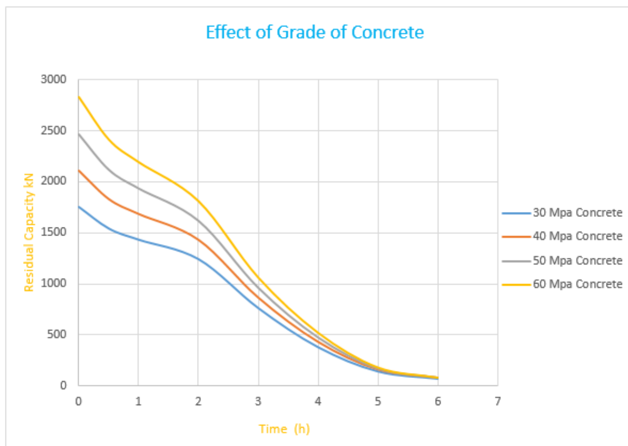

Figure 5: Effect of Grade of Concrete on residual strength

4. Effect of grade of steel: To study the effect of grade of steel, different types of steel reinforcement normally used for construction having yield strength 415, 500 and 550 MPa are used in this work [22]. The axial load capacity of column increases with increase in grade of steel initially. But it decreases as the time of exposure is more as shown in Table 4. The grade of steel has less effect on both buckling and strength failure criteria. This can be attributed to the decrease in strength of reinforcement irrespective of grade of steel. In Fig.6, it can be seen that the three curves are nearly parallel, thus showing that the grade of steel has not much effect on the fire strength of column. All the three grades of steel are highly affected after a temperature of about 500^{O}C.

Table 4: Effect of Grade of steel

Column size	Grade of steel	Load carrying capacity (Pu in kN) with time of exposure							
		0h	0.5h	1h	2h	3h	4h	5h	6h
300x300	415	1748.3	1538.2	1428.9	1239.4	762.2	380.5	143.9	72.6
	500	1891.4	1681.2	1572	1382.5	863.4	436.3	173.4	87.7
	550	1975.5	1765.4	1656.1	1466.6	922.5	469.1	190.7	96.5

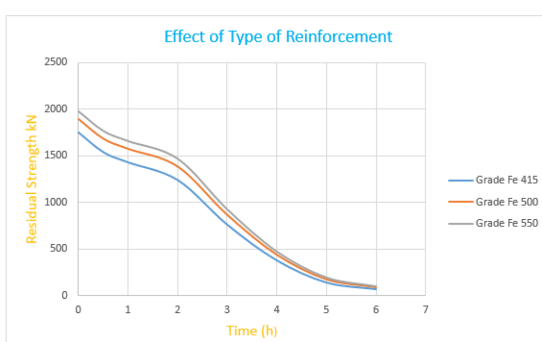

Figure 6: Effect of type of reinforcement

5. Effect of %age reinforcement: A higher percentage of reinforcement clearly gives higher strength to the column. However, this effect is prominent only up to a temperature of about 500^{O}C. Afterwards steel strength degrades quickly. Therefore, columns with higher percentage of steel have higher percentage reduction in strength. This effect can be seen from Fig.7.

Table 5: Effect of %age reinforcement on residual strength

Column size	%age reinf.	Load carrying capacity (Pu in kN) with time of exposure							
		0h	0.5h	1h	2h	3h	4h	5h	6h
300x300	1.787	1496.9	1286.7	1177.5	988	585.9	282.4	92.1	46.2
	2.793	1748.3	1538.2	1428.9	1239.4	762.2	380.5	143.9	72.6
	4.021	2055.6	1845.5	1736.2	1546.7	978.1	500.4	207.2	104.9

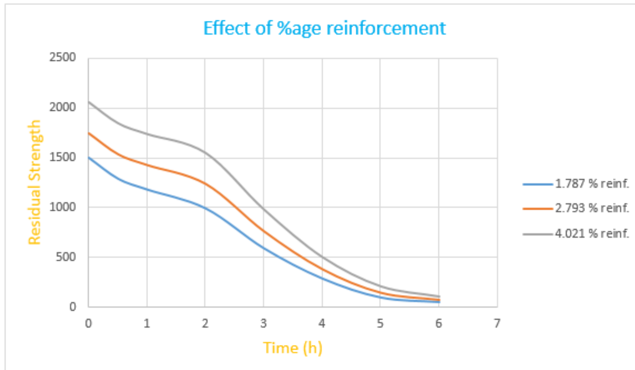

Figure 7: Effect of %age reinforcement

Conclusion & Future Scope

To provide a proper design method for determining the axial capacity of column subjected to fire, 500 C isotherm method is used and the influence of various parameters on fire rating is discussed. The following conclusions are drawn from the present study:

- The fire provisions that are given in IS 456:2000 are based on the minimum cover and cross-section size for different structural members. It can be noted that the maximum reinforcement temperature depends only on concrete cover and cross-section size has no significant influence, for a particular exposure condition. Concrete cover has considerable influence in fire rating based on strength criteria.
- Grade of concrete and steel has less effect on fire strength at high temperature but has a significant effect at low temperature. Contradictory to normal strength design at ambient temperature, increasing the grade of concrete and steel is not effective for fire strength.
- For the same surface area of exposure, two adjacent sides exposed to fire have a higher reduction in strength compared to two opposite sides exposed. Constructing columns as part of partition walls prevents half of cross-section getting exposed to fire that results in increasing the axial capacity significantly and hence fire rating can be enhanced.
- The variation in fire strength is more pronounced for smaller cover thickness. The reduction in axial capacity is higher for siliceous concrete, and hence the concrete made of carbonate aggregate has more fire resistance compared to that of siliceous aggregate.
- The bars distribution on four faces of the column cross-section can provide some improvement in capacity. Reinforcement bars should be placed away from the corners
- Hence, it can be concluded that further studies have to be conducted, and proper methodology has to be developed for analyzing RC columns subjected to fire.

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