Volume 1, No.1, pages: 32-41

# Investigation of Fire Effects on Columns of High-Rise Reinforced Concrete Buildings

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ORIGINAL ARTICLE
Received 10 Mar. 2018
Accepted 20 Oct. 2018

**ABSTRACT:**

The effects of firebreak in high-rise buildings seem essential to be investigated cautiously since world trade center towers incident. Consequently, many technological advancements were achieved and numerous researches were performed. Nevertheless, in 2017, Plasco building in Iran also was set ablaze and the consequence was the full destruction of the building, claiming lives of at least 20, injuring 70 and loss of thousands of jobs. Therefore, it is crucial to investigate the effects of fire in high-rise buildings more thoroughly in order to prevent progressive collapse, a phenomenon that caused the destruction of the two landmarks. Ordinarily, to achieve this goal, methods of analysing fire effects are developed. So by choosing a logical fire scenario, design fire is extracted from time-temperature relations of design codes. After determining the firing temperature at various times, effects of temperature increase on the material's mechanical properties are investigated. Important characteristics such as concrete compressive strength, concrete and steel modules of elasticity, tensile strength, the coefficient of thermal expansion and steel rebar yielding stress are affected by alterations of temperature. Finally, by analysing structural behaviour utilizing modelling programs and comparing results of different fire temperatures and stories in which fire occurs with the initial design of the building RCC frame, it can be concluded that axial forces increases in columns are the critical condition in fire situations and in case of fire break in distinct stories, lower floors will experience a sharper surge of axial forces.

**Key words:** RCC, High-rise, Progressive-collapse, Fire, Thermal-analysis, Column.

## 1- Introduction

There have been numerous reports of structural failure and collapses due to the effects of fire and high temperatures, influencing material and mechanical properties of structures. The devastating consequences of collapses have claimed lives of many. Nevertheless, economic, social and political penalties cannot be overlooked. Needless to mention that the scale of such catastrophe multiples in high-rise buildings, perfect examples to mention are Plasco building and WTC towers.

The twin towers were modern, technologically advanced, state of the art lightweight steel frame and a central core, assuring efficiency of the structural and architectural aspects of the design. The destruction of the WTC towers was due to progressive collapse. Although the high temperature almost halved steel frames load bearing capacity, uneven temperature load excreted to the building triggered buckling of the floors and excessive forces on the structural frame and collapses of floors one after the other [1]. Moreover, on 19 January 2017 fire was initiated on the ninth floor of Plasco commercial building in downtown Tehran, Iran, built in the 1960s and once the tallest building in the country, leading to total collapse of the beloved landmark after hours of burning. Consequently, 20 firemen were reported killed and at least 70 were injured in the collapse.[2]

Since both buildings had no significant design faults, catastrophic collapses of the two buildings indicate intensive necessities of research in the areas of progressive collapse, understanding, and prevention in case of fire breaks.

To cite this paper: Omid Aminian, Amin Aminian (2019) Investigation of Fire Effects on Columns of High-Rise Reinforced Concrete Buildings. *Advance Researches in Civil Engineering* 1(1): 32-41. www.arce.ir

Although concrete structures show a relatively better resistance in comparison with steel structures, there are still many other examples of fire, causing multi-story structures to collapse such as a 19 story concrete apartment block in St. Petersburg, Russia on June 3, 2002, resulting in a total collapse of the structure in only one hour. Table 2.1 of the Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing demonstrates a summary of multi-story building fires resulted in collapses. Ordinarily, such statistics declare the importance of a more comprehensive investigation of the effects of fire on high-rise RCC structures.

There are three performance criteria mentioned in Eurocode (EN 1991-1-2, 2002)3] regarding fire resistance of structures. Naturally, a close study of either existing or future structures regarding these criteria and compatibility of them with design codes can ensure the safety of structures, residence, and firefighters during a fire breakout. Load bearing capacity (R) is the ability of the structure to withhold stresses, moments and other structural components so it would perform well under fire conditions. Meanwhile, R criterion is critical to be investigated during fire scenarios and assumed fire types when it comes to structural elements.

Integrity (E) is the ability of constructional elements to prevent the temperature conduction from the side exposed to flames to the other side. In addition, insulation (I) is the ability to limit the temperature of the unexposed side of separating elements when the other side is in contact with flames.

Moreover, some of the major issues that must not be overlooked during fire analysis or design include firstly, the consideration that applied loads during fire are less because structures are designed for a long serviceability period time during which extreme conditions of wind, snow, earthquake etc. depending on purpose of the building are considered which might not be rational to calculate the effects simultaneously with fire condition. Accordingly, structural design codes such as ASCE [4] and Eurocode introduce specific load combinations for fire condition. For instance, ASCE fire load combination is as follows:

$$U_f = 1.2D_n + 0.5\ L_n \qquad (1)$$

Where Dn and Ln are the design levels of dead and live load respectively, from the standard.

However, there are additional destabilizing effects such as reduction of concrete and steel mechanical strength and variations of other criteria. Also, there are will be a considerable amount of thermal expansion generating internal stresses in frame elements. Meanwhile, during analysis and steps leading to it, each of the structural criteria can be investigated in varying time spans (t) which are less than or equal to fire duration. Ordinarily, it is common to choose values of 25, 20, 30, 45, 60, 90, 120, 180, 240 and 360 minutes according to the suggestions of ASTM E119 [5] and ISO 834.

## 2- Design procedure under fire condition

The strategy for design under fire conditions consists of 5 major steps. Initially, considering a proper fire scenario to perform analysis under that condition is orderly according to the applied design code. A fire scenario indicates states such as how bouts of fire, the time it takes to detect a fire and how long it is needed to put out the flames, whether it is a localized or fully developed fire and etc. which is based on the characteristics, functions, and realities of the building.

Moreover, during the second step, according to the chosen fire scenario, a fire development procedure will then be taken into consideration known as 'design fire'. In addition, there are two types of design fires. Firstly is the nominal design fire which is a method based on relations of gas temperature and time without considering other effective characteristics of fire such as ventilation, therefore are easy to exploit, meanwhile effective to use. The second type of design fires is "natural fire" models which, unlike nominal design fires, take physical parameters into consideration, leading to a more accurate estimation of temperature during the realistic fire.

Moreover, Annex C of EN1991-1-2(2002) contains a notable example of the method used for fire temperature calculation.

For the next step, temperature analysis is orderly. Therefore, by using design fire and taking advantage of heat transfer calculation procedures of convection, radiation, and heat conductivity the temperature of structural materials is calculated based on the time period of design fire, chosen in accordance with standard codes and regulations. In order to perform temperature analysis, figures and charts from ACI 216.1-07 [6] are exploited to quantify temperature in varying depth of reinforced concrete sections. Also, the temperature of steel reinforcements can be assumed equal to that of concrete in the depth of the section clear cover due to considerably high heat conductivity and the relatively small area of cross-section.

The penultimate step is dedicated to the investigation of the material property of the structure by considering the effects of temperature increase on elements including both concrete and steel reinforcement material properties alterations. Concrete material property can be divided into several categories in case of final compressive strength or type of aggregate that forms the concrete. The final compressive strength of NSC (normal strength concrete) is lower than 83 Mpa; however, HSC (high strength concrete) is referred to a concrete with final compressive strength greater than 83 Mpa. Meanwhile, Utilization of varying aggregates such as carbonate, siliceous or lightweight aggregates will result in distinctive amounts of material properties in a specific temperature.

Temperature-dependent properties are divided into two categories: Thermal properties and mechanical properties. Ordinarily, the former consists of specifications such as thermal conductivity, specific heat, and density. Thermal conductivity and specific heat can be calculated from relations and figures respectively presented by Schineider and Harmathy [7]. Also, the density of the materials does not significantly change in relation with temperature. Meanwhile, mechanical properties include compressive strength, modulus of elasticity, shear modulus, and tensile strength, constrained thermal expansion, thermal expansion of adjacent members, internal cross-sectional thermal expansion and other possible mechanical influences for materials. The concrete compressive strength of NSC and HSC concrete can be calculated by figures recommended by Phan [8] for different aggregate types also, Phan reveals that the compressive strength of concrete generally decreases when exposed to high temperatures. Nevertheless, for temperatures below 450 degrees Celsius, compressive strength experiences an increase as temperature surges. Furthermore, modules of elasticity are also one of the most critical properties used while modeling any structure, for which of concrete, Cruz [9] has suggested charts and relations to calculate. Besides, effects of temperature on tensile strength and coefficient of thermal expansion of concrete have been investigated by ACI 216. Similarly, ACI 216.1-07 contains figures of yielding strength-temperature relationships of steel reinforcements. Weigler & Fischer [9] also investigated the relationship of modules of elasticity of steel reinforcements and temperature. Finally, during the final step in order to investigate the current load-bearing capacity of the structure, a comparison between design resistance of the building and the effects of the imposed design fire will be made and in case that the latter is greater than the former, the structure can withstand the fire.

## 3- Modelling

In order to investigate the implications of fire in a high-rise building, a 20 story RCC building is simulated. The model is a rectangular (35m*23m) plan and consists of 8 grids along the x-direction, in addition to 6 grids along the y-direction. The number of shear walls along either direction is 4. Also, Concrete materials, longitudinal and shear steel reinforcement are defined separately. After all the sections are defined, assigned and loads are acknowledged, the building is analysed and finally designed in accordance with ACI 318-14.

**Fig.1. Plan view of the designed building**

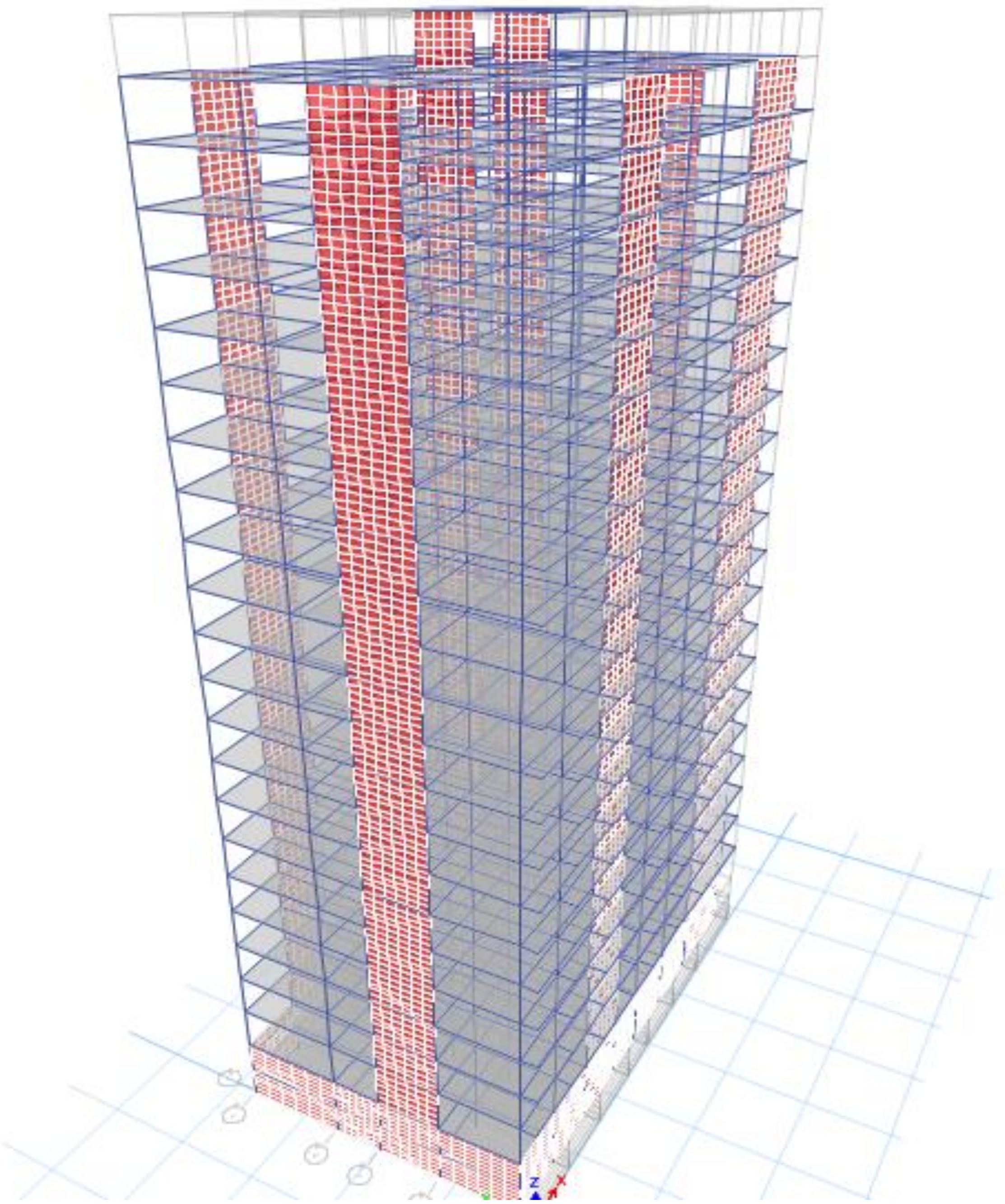

**Fig. 2. 3D view of the designed building**

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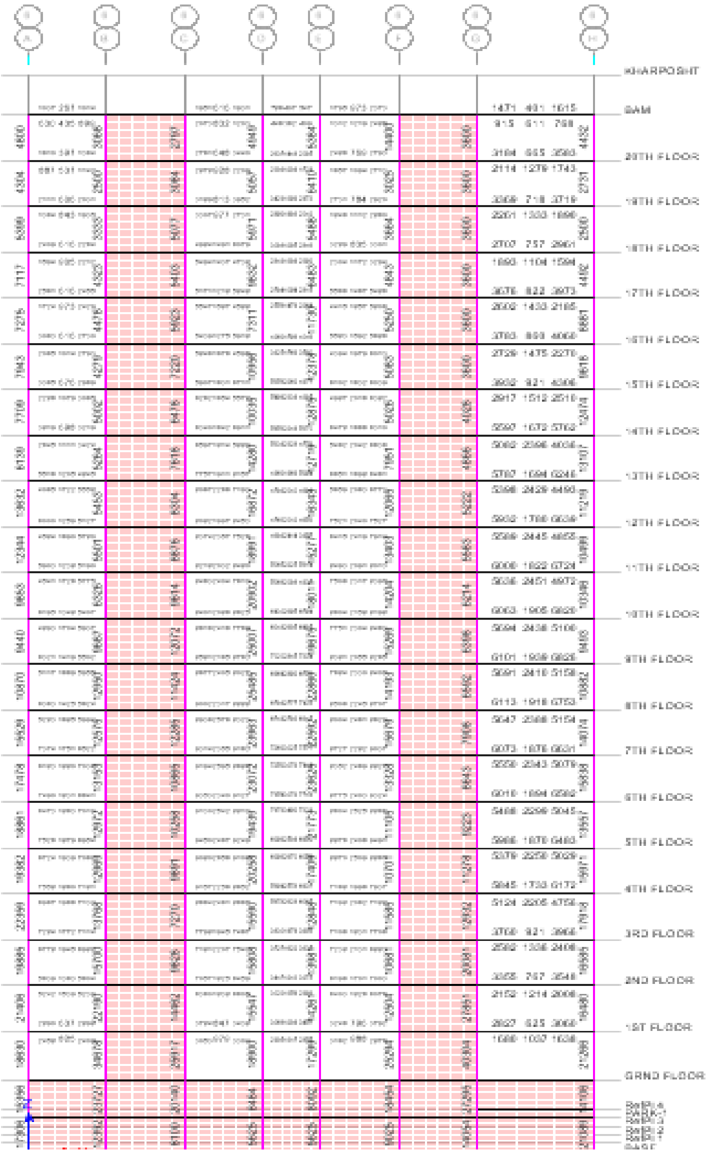

**Fig.3. Elevation view of the designed building**

In order to analyse fire effects, a scenario needs to be considered. The assumed scenario involves a major fire break out in a specific story. Meanwhile, the conditions of nominal fire are presumably satisfied, so the firing temperature in each specific time is extracted from the time-temperature curve recommended by ASTME 119E. Temperature analyses are then performed by utilizing ACI 216.1-07 in selected times, in this case, 5, 10, 30, 60, 120 and 180 minutes.

Then, temperature-dependent concrete and steel reinforcement materials are defined. Therefore, by using detailed outputs of temperature analysis, material properties such as concrete compressive strength, concrete modulus of elasticity, the thermal expansion coefficient of concrete, modules of elasticity of steel reinforcements, yielding strength of longitudinal and shear steel reinforcements are set. In addition, assigning a temperature to varying elements and sections of the burning floor, according to temperature analysis results, is vital. The analysis is then performed by exploiting fire temperature effects resulted from the previous steps to 20th, 10th, and 2nd story components one after the other. Then, the results of the analysis are gathered and comprehensively compared.

## 4- Results

According to ASTME 119 E, design fire temperatures for varying time intervals are as the following table. However, these temperatures cannot be used for design procedures because they do not represent the whole element's temperature at different depths. So temperatures at specific depths of the sections are chosen as the details were previously elaborated.

Table 1: Thermal analysis results

| Time (minute) | Design fire temperature (Celsius) | Concrete Temperature (Celsius) | Rebar Temperature (Celsius) |
|---|---|---|---|
| 5 | 538 | 86.47 | 150.89 |
| 10 | 704 | 113.15 | 197.45 |
| 30 | 843 | 135 | 236 |
| 60 | 927 | 149 | 260 |
| 120 | 1010 | 315 | 426 |
| 180 | 1060 | 426.5 | 537.5 |

The sources mentioned prior in this article have suggested methods to determine material properties as functions of temperature. So by utilizing the relations, equations and charts, required input details of the structural analysis are calculated and shown in the following table.

Table 2: mechanical properties of materials

| Time (minute) | Fc (MPa) | Ec (Mpa) | Thermal expansion Coefficient | Fy longitude steel reinforcement (Mpa) | Fy shear steel reinforcement (Mpa) | Es (Mpa) |
|---|---|---|---|---|---|---|
| 5 | 30.9 | 25561.42 | 6.6918E-06 | 392.27 | 326.7614 | 189950.6 |
| 10 | 31.5 | 23912.29 | 6.90525E-06 | 392.27 | 313.4242 | 189950.6 |
| 30 | 31.5 | 23362.59 | 0.00000708 | 392.27 | 300.087 | 189950.6 |
| 60 | 31.5 | 22538.03 | 0.000007192 | 392.27 | 286.7498 | 187951.1 |
| 120 | 33 | 18415.22 | 0.00000852 | 313.816 | 253.4068 | 159958.4 |
| 180 | 30 | 13742.7 | 0.000009412 | 219.6712 | 220.0638 | 83978.15 |

The results of mechanical property investigations are used to calibrate computer models of the building for different time intervals, temperatures and fire effects being applied to either 20th, 10th and 2nd stories in each model. An example of a comparison between fire analysis results and design results is hereby presented for one of the columns in the 20th story.

**Table 3: Analysis and design results of C19 for 20th floor**

| Time | Story | Column | P (Kg f) | V2 (Kg f) | V3 ( Kg f) | M2 (kgf-m) | M3 (kgf -m) |
|---|---|---|---|---|---|---|---|
| t=5 min | 20TH FLOOR | C19 | 36422.8 | 849.3707 | 535.7052 | 1236.711 | 1056.194 |
| t=10 min | 20TH FLOOR | C19 | 33184.12 | 618.5705 | 840.462 | 1285.244 | 984.0036 |
| t=30 min | 20TH FLOOR | C19 | 32940.8 | 560.0457 | 868.1517 | 1350.035 | 993.9746 |
| t=60min | 20TH FLOOR | C19 | 32855.65 | 511.7095 | 870.6125 | 1364.275 | 986.3789 |
| t=120min | 20TH FLOOR | C19 | 35386.04 | 55.5147 | 809.9584 | 1342.819 | 844.0688 |
| t=180min | 20TH FLOOR | C19 | 40432.05 | 224.3941 | 616.7846 | 1011.614 | 653.7042 |
| Design | 20TH FLOOR | C19 | 35974.05 | 8848.21 | 7672.86 | 9078.22 | 8312.63 |

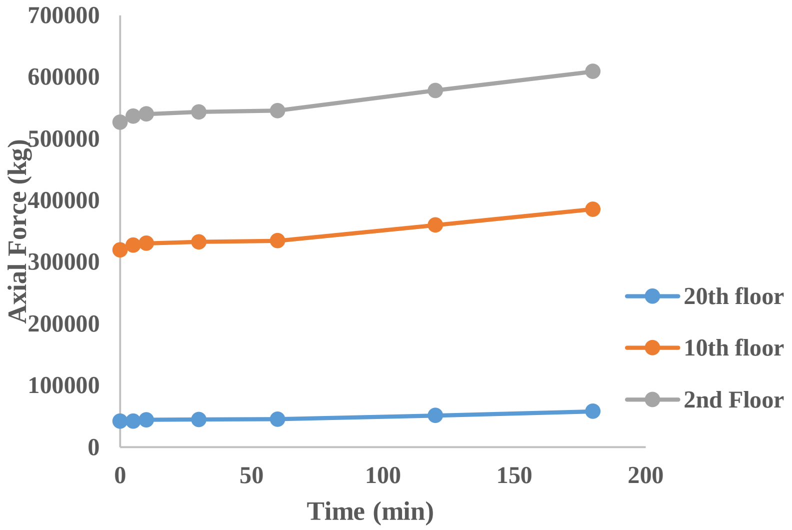

**Fig.4. Axial forces of the C3 column for different floors**

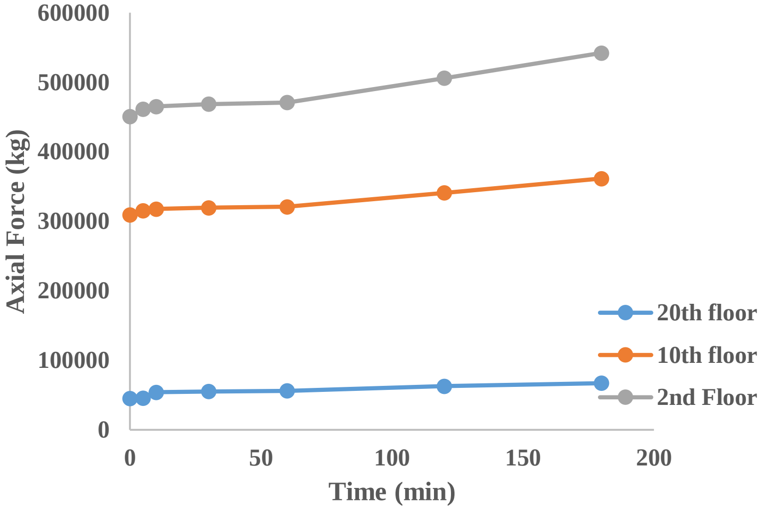

**Fig.5. Axial forces of the C34 column for different floors**

The rate of axial forces increase is an indicator of fire influence on different stories and demonstrates forces growth over time.

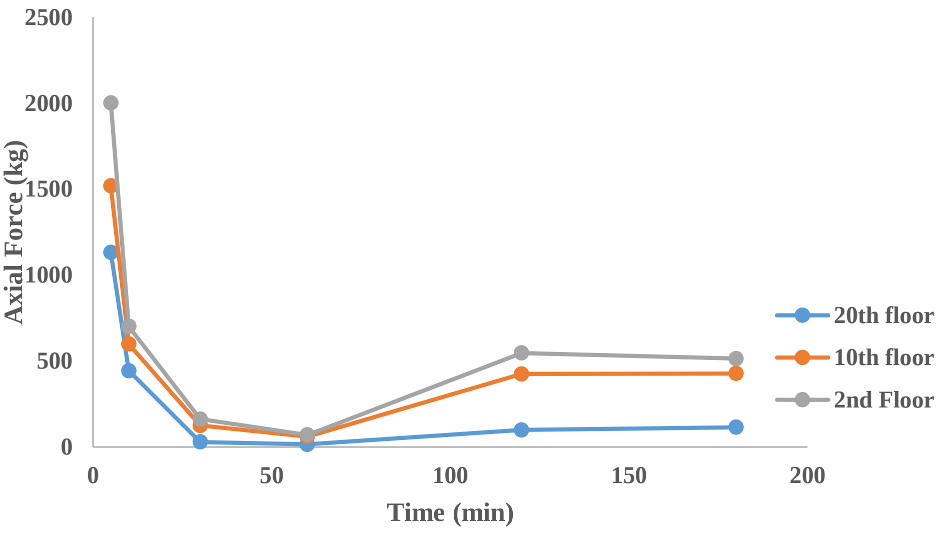

**Fig.6. the rate of axial forces increase for  thenC34 column on different floors**

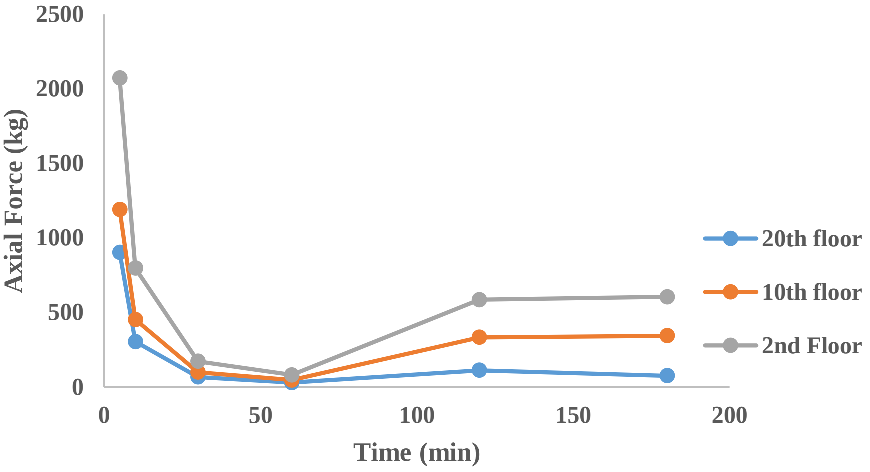

**Fig.7. The rate of axial forces increase for  the C34 column on different floors**

## 5- Conclusion

From the charts and tables of the results section, it is deduced that:

1-By comparing initial design results of the structure, before temperature influences being applied, and results of structural analysis, it can be concluded that axial forces are the critical modules and collapse of the structure is mostly due to surges of that force in columns.

2-As time progresses and temperature intensifies, it results in an increase of the axial forces amount in each column.

3-The growth of axial forces in columns follows trends in different stories.

4-The lower the stories are, the higher changes of their axial forces are.

5-If any enhancement, in case of fire resistance, is to be applied, it should be in lower stories.

6-After a certain point, which in case of this research is 60 minutes, changes in axial forces will be accelerated so the longer it takes to extinguish the fire, the higher will be the risk of structural collapse.

7-Since columns stability and existence is crucial for the existence of the whole building and avoidance of progressive collapse, designers should take fire safety procedures more seriously and as shown in this article, consider the possibility of axial forces increase in columns.

As mentioned, high-rise building collapses due to fire can have catastrophic results so in order to prevent such disaster it is crucial to continue researches in this field and develop a thorough, performance-based design code for buildings, considering fire state more seriously. It is also recommended to investigate the effects of localized fire, around one or several columns to examine effects of unbalanced forces exertion. Also, any possible differences between the behaviour of side columns and columns positioned in the middle of the building should be checked.

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