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Temperature Distribution in Concrete Slabs Exposed To Elevated Temperature

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ABSTRACT : *The temperature variation over a cross section of slabs can cause stresses. In some cases such kind of stresses may reach or even exceed those induced by the live loads and that temperature cracking may occur in the structure component. Calculating the change of temperature field in reinforced concrete under fire is very important for the analysis of deformation and fire resistance performance in high rise building construction. Therefore, to predict the stresses caused by temperature distribution is important for the correct design of the structures. The purpose of the present study is to present the nonlinear transient analysis over cross sections of a concrete slab. In this study, heat flow over a cross section of concrete slab is obtained using finite element computer program (ABAQUS). This finite element analysis can be used to generate the thermal loads. A two-dimensional heat transfer model is proposed to predict the temperature distribution across the slab. A prediction for variance of concrete temperature is obtained.*

KEYWORDS: *ABAQUS, Concrete slab, Fire, Thermal loads, Transient heat analysis.*

I. INTRODUCTION

The damage that fire can cause leads to loss of life and property. In the past two decades, a significant amount of research has been conducted into the performance of composite structures in fire. Concrete is specified in civil engineering projects for several reasons, sometimes cost, sometimes speed of construction or architectural appearance, but one of concrete's major inherent benefit is its performance in fire. Concrete does not require any additional protection because of its built-in resistance to fire. It is non-combustible and has a slow rate of heat transfer, which makes it a highly effective barrier to the spread of fire. Many of experimental studies are going on to determine the fire resistance of concrete. When concrete remains exposed for long time at high temperatures results in loss of mechanical and physical properties.Calculating the changes of the temperature field in the reinforced concrete members under fire is very important for the analysis on the change law of the intensity, deformation and fire resistance performance in high temperature building construction. Analyzing the bearing capability of RC slabs after sustaining fire requires the knowledge of temperature distribution in the cross sections. This is determined by the thermal properties of the material, such as the Specific heat and thermal conductivity. A simple thermal model, which is generally to all slabs with a rectangular cross section, has been assessed in a separate serious of studies.

The modeling results achieved reasonable agreement with isothermal contours obtained by Lin (1985) [16] who analyzed the temperature distribution of pure concrete according to the time-temperature curve of standard fire. The analytical stage in the modeling process is to increment the time of the model such that the temperature experienced by the slab is increased. The increase in the ambient temperature changes the temperature distribution inside of slab's cross-sections. After sustaining high temperature, the mechanical properties of reinforced steel and concrete vary according to the fire-induced temperature. It makes the stress distribution in such slab structures a nontrivial problem [19]. To determine the fire behaviour of concrete structures, there are many methods in literatures. These methods are based on tests and experiences, simplified methods and numerical methods which provide to be carried out thermal analysis by computers. In this study it is used a developed computer programmer (ABAQUS) based on finite element method for thermal analyses. Heat Transfer through Concrete Slab Heat transfer is nothing but transfer of energy between two points of different temperatures. The heat transfers continue until the two objects have reached thermal equilibrium and are at the same temperature. The heat transfer in concrete structures can be done by three modes. Those are conduction, convection and radiation. Convection is the transfer of internal energy into or out of an object by the physical movement of a surrounding fluid that transfers the internal energy along with its mass. In convection, the bulk transfer of heat energy comes from the motion of the fluid.

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. Conduction is flow of heat via collisions between atoms and molecules in the substance and the subsequent transfer of kinetic energy. In the concrete the heat transfers by the collision of particles. 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 inside the slab has to be known. In the thermal analysis of structural members under fire, the heat can be transferred by conduction within concrete structural members from point to point by collision of particles.

The thermal analysis of concrete members can be extremely complex, especially for materials that retain moisture and have a low thermal conductivity. To define the temperature profile through the cross-section is to use test data presented in tables or charts which are published in codes or design guides. These tabulated data are generally based on standard fire conditions. Simplified method, the second method of determining of temperature distributions, is presented in codes and design guides. It is possible to use simple heat transfer models based on one-dimensional heat flow. However, simple computer programs are needed to solve the heat transfer equations. Alternatively, advance finite-element heat transfer models can be used.

II. MATERIAL PROPERTIES

General

Computer packages (ABAQUS) are heavily dependent upon the material definitions provided as an input. Therefore in order to assess the adequacy of thermal analysis to determine the temperature distribution of concrete structures at elevated temperatures, a thorough investigation of the material models available also required.

Thermal Properties of Concrete

In this section the mechanical behaviour of concrete elevated temperatures is described. In a fully developed fire, the thermal properties of concrete such as thermal conductivity, specific heat and high thermal expansion varies with the effect of temperature.

Thermal Conductivity

Thermal conductivity is the capability of a material to conduct heat. It represents the uniform flow of heat through concrete of unit thickness over a unit area subjected to a unit temperature difference between the two opposite faces. The thermal conductivity of siliceous aggregate concrete as represented in Eurocode 2, in section 3.3.3 is shown in Fig.1 (a).

Specific Heat

The specific heat of a material is the amount of heat per unit mass which is required to change the temperature of the material by a degree. The specific heat of concrete with siliceous aggregates as a function of temperature according to Eurocode 2, in section 3.3.2 is shown in Fig.1 (a).

Mechanical Properties of Concrete

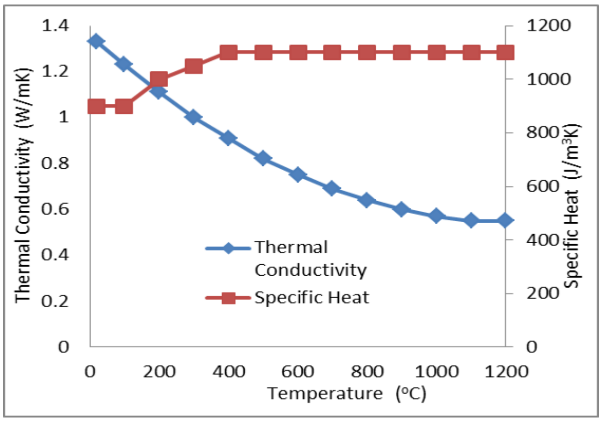
In this section the mechanical behaviour of concrete elevated temperatures is described. The material models devised to characterize this behavior are described.

Modulus of Elasticity

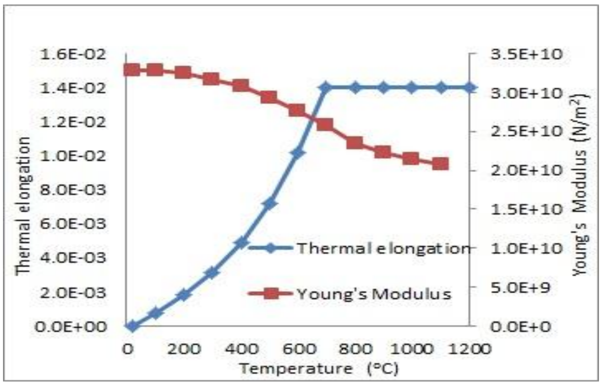
The modulus of elasticity of the concrete in Fig.1 (b) decreases with an increment in temperature. The reduction of the modulus of elasticity is due to the rupture of bonds in the microstructure of the cement paste when the temperature increases.

Thermal expansion

Due to its isotropic nature, concrete exhibits thermal expansion when it is subjected to a temperature change. The thermal expansion of concrete with siliceous aggregates expressed as a function of temperature according to Eurocode 2, in section 3.3.1 is shown in Fig.1 (b).



(a)



(b)

Fig.1 Thermal and Mechanical properties of concrete as represented in Eurocode
Finite Element Analysis at Elevated Temperatures

Finite element package ABAQUS was used to model and analyze the concrete slabs. A non-linear heat transfer analysis was performed to predict the temperature distribution from thermal analysis.

Description of Model

Geometric modeling of slab cross-section has been done using part module. The thermal conductivity of the steel was too high when compared with concrete. If we considered the cross-section of reinforcement, the temperature was almost equal at all points. Therefore, we neglected the effect of steel reinforcement in the concrete cross-section for temperature distribution.

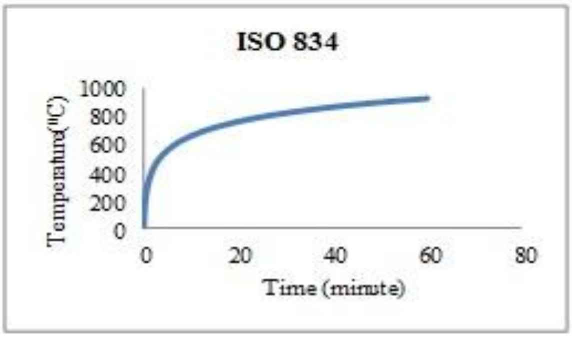


Fig.2 ISO-834 Fire standard curve (BS 456 part 20)

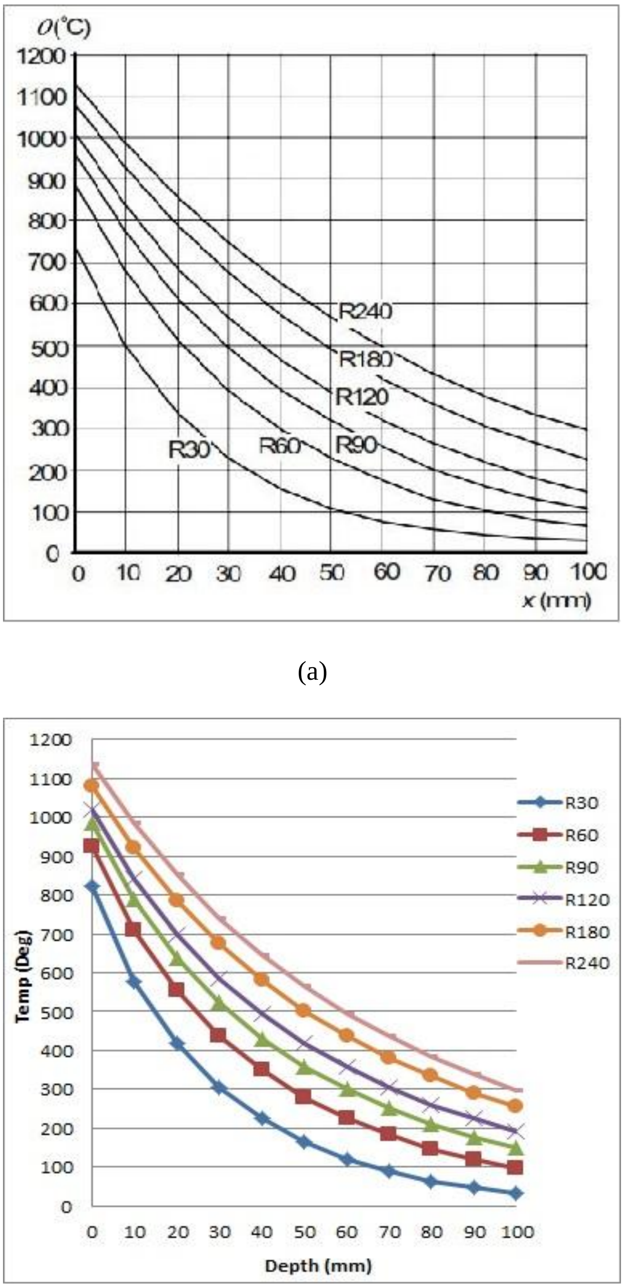
Finite Element Type and Mesh

All the parts of the FE slab model were modeled using a 4-node linear heat transfer quadrilateral (DC2D4). In order to find out the suitable mesh size a mesh convergence study has been carried out. The distribution of temperature was found out for various mesh sizes and compared the results. There is no much variation in the results beyond the increase of 20 layers along the depth. Hence, the slab model was meshed into 20 divisions along the depth.

Model validation

To validate modeling, boundary conditions and loading procedures, a nonlinear heat transfer analysis performed on the slab. By applying initial ISO-834 temperature curve shown in Fig.2 and the analysis is performed using 'Heat transfer' analysis. And the ABAQUS result was compared with the temperature profiles given in EN1992-1-2. Temperature distribution curve of the FE Model was plotted using the resulting values.

Slab Validation



(a)

(b)

Fig.3 Temperature profiles for slab (a) EN1992-1-2 (b) ABAQUS MODEL

From the comparison of Fig.3 (a) and Fig.3 (b), the slab model was validated. After the finite element thermal analysis, the slab model gives the temperature distribution history same as given in the EN1992-1-2.

III. RESULT AND DISCUSSION

General

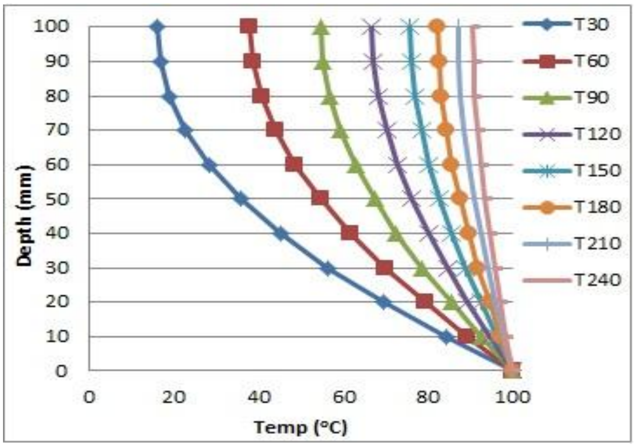
The thermal analysis with finite element method was carried out in order to obtain temperature distribution history of cross-sections of a slab in the buildings subjected to fire. A non-linear heat transfer analysis carried out for different slab thickness, elevated temperatures and the results were discussed below.

Transient Heat Transfer Analysis – Parametric Study

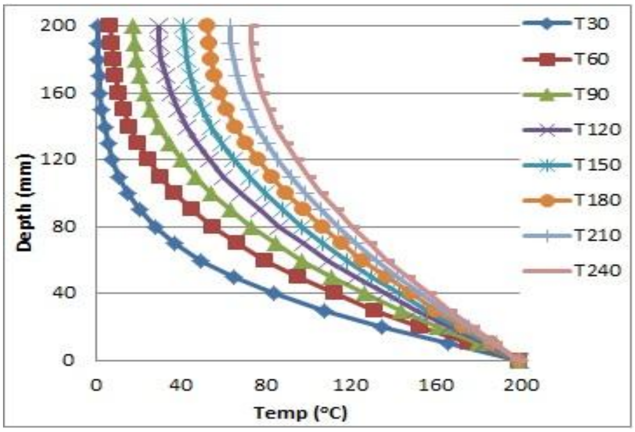
In this study, a slab of meter width was considered from infinite width. According to EN 1992-1-2-2004, we considered the sides of the slab ware insulated and the bottom surface was exposed to the temperature. For conservation purpose, the top surface was at room temperature. The temperature distribution of 2D finite element model of slab across cross-section was found out by changing various parameters.

Those are,
[1] Varying thickness of slab from 100mm to 500mm.
[2] Fire of varying temperatures from 100 °C to 400 °C.
[3] Varying exposure time of 30min to 240 min.

After running the aforementioned finite element thermal analyzing program, the temperatures of all elements of slab cross-section were determined according to each time steps. Some temperature distributions obtained from the analysis were given in Fig.4 for 30, 60, 90, 120, 150, 180, 210 and 240 min. As it is seen, the temperatures increase with time increment through inside the cross-section.



(a)



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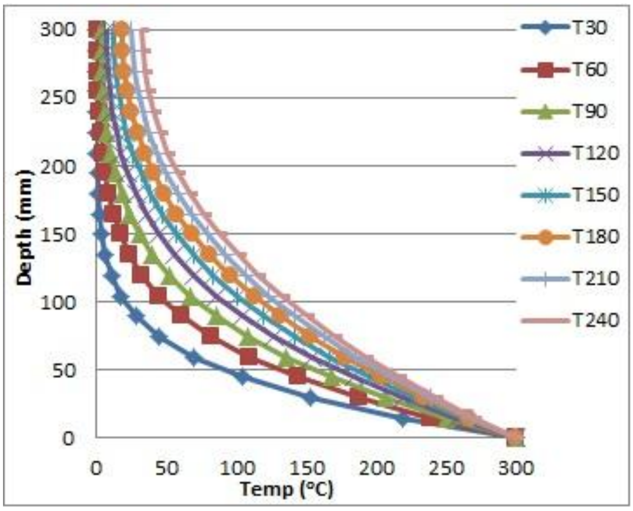
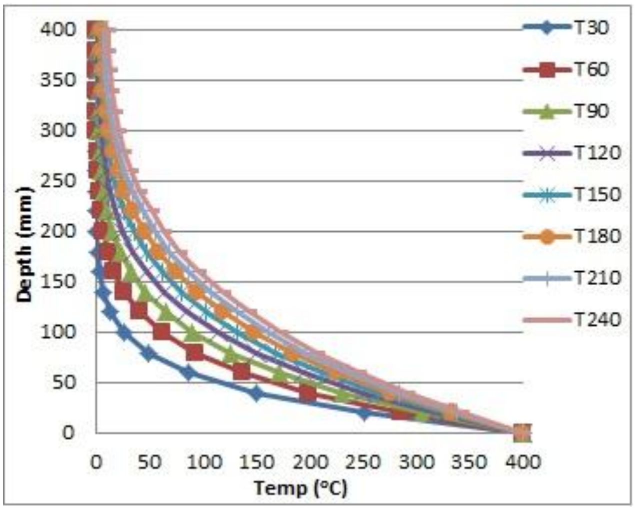


(c)



(d)

Fig.4 Temperature profiles for a slab

(a) h=100mm &T=100°C (b) h=200mm &T=200°C

(c) h=300mm &T=300°C (d) h=400mm &T=400°C

From the results obtained from FEA software (ABAQUS), we observed that the distribution through the cross-section of slab was nonlinear. From EN1992-1-2, thermal property, conductivity of concrete decreases with increase of temperature. Due to this decrease in conductivity, the temperature of elements of slab decreases with increase of exposed temperature.

Role of Slab Thickness

The thickness of the slab varies for different structures and it has a significant effect on temperature distribution. To understand the role of slab thickness on temperature distributions, we considered a section at 100mm distance from exposed surface with varying slab thickness. The temperature at that point can be compared for every 30 min of reaction time and with different exposed temperatures.

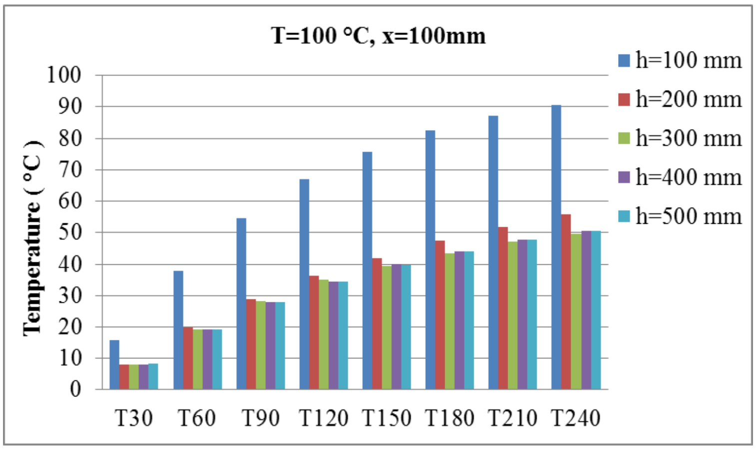


Fig.5 Comparision of temperature with slab thickness (T=100 °C, x=100mm)

When a slab of 100mm thick is considered and it is subjected to 100°C, the element at 100mm from exposed surface is reached around 90°C after 4hrs of exposure. Similarly, for 200mm thick slab, element at 100mm from exposed surface is reached around 56°C. As the depth of the slab increases beyond 200mm, the temperature of the elements at respective points is constant.

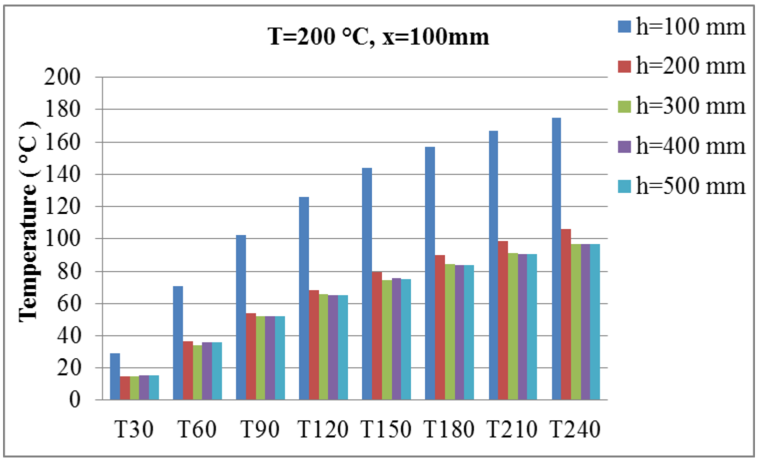


Fig.6 Comparision of temperature with slab thickness (T=200 °C, x=100mm)

When a slab of 100mm thick is considered and it is subjected to 200°C, the element at 100mm from exposed surface is reached around 175°C after 4hrs of exposure. Similarly, for 200mm thick slab, element at 100mm from exposed surface is reached around 107°C. As the depth of the slab increases beyond 200mm, the temperature of the elements at respective points is constant.

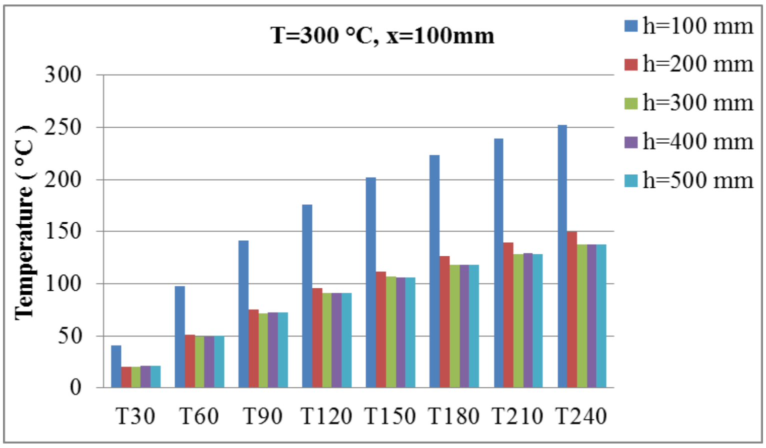


Fig.7 Comparision of temperature with slab thickness (T=300 °C, x=100mm)

When a slab of 100mm thick is considered and it is subjected to 300°C, the element at 100mm from exposed surface is reached around 255°C after 4hrs of exposure. Similarly, for 200mm thick slab, element at 100mm from exposed surface is reached around 150°C. As the depth of the slab increases beyond 200mm, the temperature of the elements at respective points is constant.

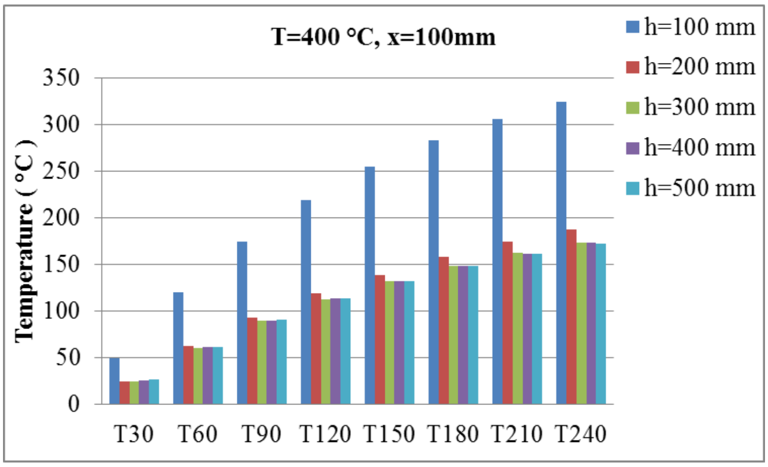


Fig.8 Comparision of temperature with slab thickness (T=400 °C, x=100mm)

When a slab of 100mm thick is considered and it is subjected to 400°C, the element at 100mm from exposed surface is reached around 320°C after 4hrs of exposure. Similarly, for 200mm thick slab, element at 100mm from exposed surface is reached around 190°C. As the depth of the slab increases beyond 200mm, the temperature of the elements at respective points is constant.

From the Fig.4, we can conclude that the variation of the temperature is more in near to the exposed surface up to 100mm depth. Beyond 100mm depth, the variation of temperature is small. Therefore, the remaining depth of the slab is at constant temperature irrespective of exposed time and exposed temperature.

IV. CONCLUSIONS

In this study behavior of concrete slabs subjected to temperatures starting from 100 degrees to 400 degrees were studied using a FEM model in ABAQUS. ISO834 was used initially to obtain the temperature profiles for developing the model, as shown in fig 3 the temperature profiles are very close to the EN 1992-1-2-2004. The various temperature to which the slab was subjected was principally obtained by following the ISO standard fire curve i.e., ISO834. The obtained temperature profiles have been observed to be in accordance with the available literature, having validated the present FEM model the slab was taken up for further parametric study. Five concrete slab models were considered to study three different parameters namely: the concrete slab thickness; the exposed surface temperature; and reaction time.

Slab thickness:

Concrete slab thickness has been taken up for studying the variation of temperature profiles, five different thicknesses have been modeled using ABAQUS. From the graphs obtained it is very clear that the temperature variation is significant up to 100 mm thickness later as the slab thickness is increased there is no much variation in the temperature profiles as the time increases for which the slab is exposed to temperature. Also, while keeping the depth at which the temperature is calculated and studying the temperature from 100 degrees to 400 degrees for the subjected reaction times, the slab having 100mm depth was taken up as the critical depth for study, from the fig 5 – 8 it is observed that only 100mm depth slab is having higher temperatures when compared to other slabs. Probably this is due to the fact that other slabs having more thickness absorb the excess temperature compared to 100mm depth slab.

Exposed temperature:

In this study a slab is subjected to two different temperatures to study the variation of exposed surface temperature , having studied this parameter the following conclusions were made , for example let us consider a 100mm slab subjected to 100 degrees and 200 degrees. The temperature for a particular reaction time was on the higher side for the slab when subjected to higher temperature. Also, there was a general trend followed in the temperature profiles which suggests that the initial starting point was only high whereas the shapes of the curves were similar. This parametric study mainly suggests there was very less variation in shape profiles when slab were subjected to increasing order of temperatures.

From the above parametric study the major conclusions drawn out are as follows:

- From the thorough investigation of temperature of slab throughout the exposure, the distribution of temperature through the depth of the slab is non-linear irrespective of exposed temperature and exposed time.
- As increasing the time of exposure, the differential temperature in the slab near to exposed surface decreases due to low conductivity at higher temperatures. But, still it is more than far end of slab.
- The results obtained from this study clearly suggest that the effect of fire is more on the region near to exposed surface. As the depth of slab increases, there is no significant effect of fire on the region far to the exposed surface of slab due to low thermal conductivity of the concrete.
- Whenever the temperature of exposed surface increases, the differential temperature in the slab near to exposed surface of slab increases.

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