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Modelling Strength Behaviour of Reinforced Concrete Beam after Fire Exposure

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ABSTRACT

Fire is considered one of the most serious potential risks for buildings and structures. Fire accidents are significant disasters that create massive damage to buildings and other concrete structures. Concrete is considered to have an acceptable fire resistance in comparison to the list of any building material such as wood or steel. Mechanical property losses take place when concrete is exposed to higher temperatures for longer periods. Standard fire tests are utilized to measure the fire resistance of the various materials used in various fields. The present study investigates the relation between the load and maximum deflection of the reinforced beam after exposing to fire for different time periods by carrying out the simulation of the experimental work carried out in referred literature using the finite element software. The variation of temperature gradient across the cross section of the reinforced concrete beam is also observed. The input parameters include the variation of thermal properties of the concrete with respect to increasing temperatures for assigning the material properties of the model. The results include the plots of the relation between the loads and the maximum deflection. The method with which the temperature propagates within the cross section of the reinforced concrete beam is also observed.

Keyword: - Reinforced Concrete Beam, Fire Exposure, Finite Element Model, Maximum Deflection, Temperature Gradient

1. INTRODUCTION

Fire is considered as one of the most severe hazards encountered by built infrastructure during its life time. The potential for an unintentional or planned fire to endanger the structural integrity and property safety of a building is known as a fire hazard. Concrete is considered to have an acceptable fire resistance in comparison to the list of any building material such as wood or steel. It is considered to have good durability against fire and hence, it protects the reinforced steel from the elevated temperatures. However, the abnormal temperature effect will force the concrete elements to lose their strength parameters and may lead to their failure [1]. The structural properties of concrete are not the same before and after fire exposure [2]. The structural strength of the concrete is reduced after exposed to higher temperatures. Cracks are also formed. Exposure to fire heats the outer surface of the concrete member. Whereas, the inner parts of the concrete member have relatively low temperature as compared to the outer exposed surface. These temperature variations within the cross section of the concrete member induce restrained stresses and hence results in cracking of the concrete.

Concrete is a composite material. It is made up of both fine and coarse particles that are bind together by a fluid cement (cement paste). When aggregate is mixed with dry Portland cement and water, the mixture forms fluid slurry that can be easily poured and mould into any desired shape. In typical structural concrete, the water-to-cement ratio plays a significant role in determining the concrete's characteristics [3]. All other factors being equal, stronger concrete is produced when the water concentration is smaller. In order to ensure that the cement paste completely encloses each aggregate particle, that the spaces between the aggregate are filled, and that the concrete is liquid enough to be poured and distributed properly, the mixture must contain just the right amount of water. Over time, the concrete hardens. Concrete's durability is influenced by a number of factors. The cement to aggregate ratio is another important factor in how long concrete will last. There will be significantly less aggregate where extra-strong concrete is required.

Reinforced concrete, commonly known as reinforced cement concrete (RCC), is a composite material in which reinforcement with better tensile strength or ductility is added to make up for the relatively low tensile strength and ductility of concrete. The reinforcement, which is often steel bars (rebar), is passively incorporated into the concrete prior to curing. Steel's tensile strength and concrete's compressive strength combine in reinforced concrete to give the member the ability to withstand these stresses over a wide range of distances.

Chemical composition and physical structure of concrete is altered as a result of exposure to high temperatures, such as those caused by fire. These alterations mostly affect the hardened cement paste and start when calcium hydroxide decomposes at 400 °C and last until the calcium-silicate-hydrate gel completely deteriorates at about 800 °C. These modifications cause the concrete to gradually deteriorate, decreasing its strength and exposing the reinforcing steel to heat while it was being heated [4]. As a result, the yield strength, ultimate strength, and elastic modulus of reinforcing steel bars all drop with rising temperatures. Typically, beams are subjected to shear and flexural loads. It is crucial to consider the residual bending and shear capacity of fire-damaged RC beams when assessing the safety of RC constructions. When exposed to high temperatures, steel and concrete both experience significant changes in their stiffness, strength, and other physical characteristics.

Due to its constituent materials' lower thermal conductivity, high heat capacity, and slower rate of strength deterioration with temperature when chemically mixed, concrete is one of the best fire-resistant building materials. Due to its low thermal conductivity, concrete acts both as a fire barrier between neighbouring spaces and as a self-protective material, slowing the rate at which heat is transferred through it [5]. The behaviour of a concrete structural part exposed to fire is controlled by the combined action of all three qualities of concrete, namely its thermal, mechanical, and deformation properties [6]. These parameters are dependent on the features and composition of concrete and change with temperature.

Determining the reduction of the strength properties of an RC structure exposed to a high temperature becomes one of the key steps of the analysis. Beyond physical (thermodynamic) changes, high-temperature concrete also undergoes various chemical transformations, and mechanical damage that makes the process more complicated and unpredictable. These complexities could be of variable range, because of which the results could be on a trajectory very different from conventionally established guidelines and should not be fully consistent with estimates based on these standard guidelines. When the study of high temperature concrete is the concern, there is virtually no chance that the RC structure behaves as it should behave at ambient temperature (20 ° C) which amplifies the complication and therefore the Simple changes applied to the models available for concrete at normal temperature will not be satisfactory.

2. METHODOLOGY

The material properties of concrete and reinforcement steel varies with respect to the increasing temperatures. These variations of material properties can be taken from the previous research papers. The reinforced concrete beam is modelled using the finite element software. The variation of material properties with respect to temperatures are taken into consideration. Temperature load will be applied in Transient Thermal Analysis. The results will be imported in Transient Structural Analysis and further studies will be carried out by applying the loads in increments at uniform rate. The relation between the applied load and the maximum deflection will be studied. The variation of temperature across the cross section of the reinforced concrete beam is also observed.

2.1 Input Parameters

2.1.1 Properties of Concrete

In typical structural design, the effect of fire is generally not considered. The properties that vary with respect to the increasing temperature includes density, thermal conductivity and specific heat of the concrete. These variations will cause the surrounding structure to respond against these effects.

2.1.1.1 Compressive Strength

The ability of a material or structure to support loads without cracking or deflecting is known as compressive strength. For typical construction projects, the concrete's compressive strength ranges from 15 MPa to 30 MPa and beyond in commercial and industrial constructions. The compressive strength of 25MPa is adopted in the present study.

2.1.1.2 Tensile Strength

The equation $f_{cr} = 0.7\sqrt{f_{ck}}$ N/mm^2 yield an estimate of the concrete's flexural tensile strength, also called as modulus of rupture. The tensile strength of M25 concrete grade is estimated to be 3.5 N/mm^2.

2.1.1.3 Modulus of Elasticity

The slope of an object's stress-strain curve in the elastic deformation area is referred to as its elastic modulus. A material's elastic modulus will be higher when it is stiffer. Concrete has an elasticity modulus of $5000\sqrt{f_{ck}}$ MPa which is calculated to be 25000 N/mm^2 for M25 grade of concrete.

2.1.1.4 Density

The mass or weight of concrete needed to fill a container with a given unit volume is known as the bulk density or unit weight of concrete. The density of normal concrete and reinforced concrete at room temperature is 2400 kg/m3 and 2500 kg/m3 respectively. But the density of concrete decreases with respect to increasing temperature due to the loss of moisture as shown in Fig 1.

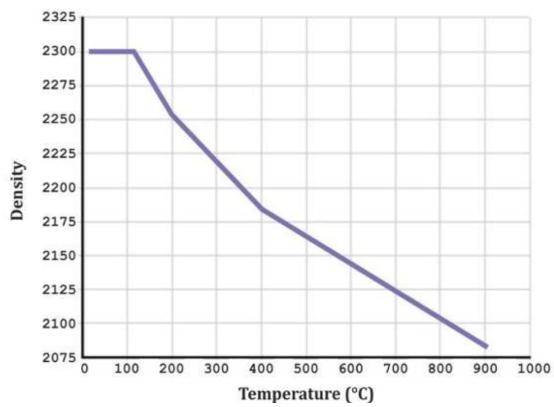

Fig -1: Variation of Density of Concrete

2.1.1.5 Thermal Conductivity

Thermal Conductivity, k (or λ), is the property of a material to measure the heat transfer characteristics. Thermal conductivity is measured in W/m.K. It is the ability of a substance to transfer heat through a material by conduction. The variation of thermal conductivity of concrete is shown in Fig 2.

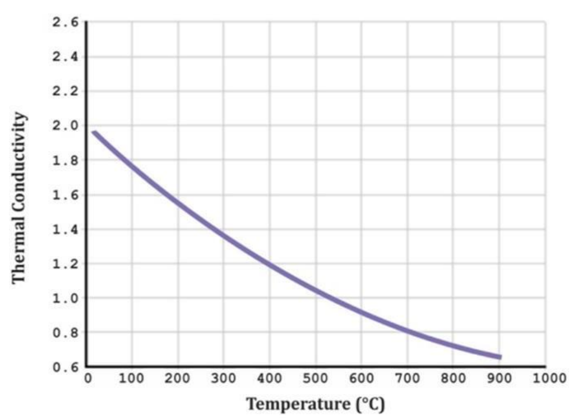

Fig -2: Variation of Thermal Conductivity of Concrete

2.1.1.6 Specific Heat

Specific Heat is defined as the quantity of heat required to raise the temperature of one unit of a substance by one degree Celsius. Calories or joules per gram per Celsius degree are typically used as the units of specific heat. The variation of Specific Heat of concrete is shown in Fig 3.

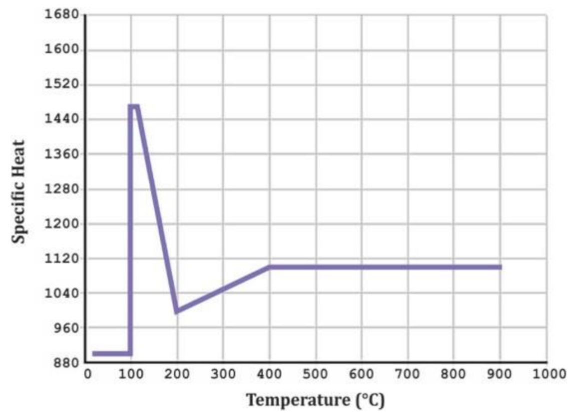

Fig -3: Variation of Specific Heat of Concrete

2.1.2 Properties of Steel

Steel reinforcement are steel bars that are provided in combination with plain cement concrete to make it reinforced concrete. Hence these structures form steel reinforced cement concrete structure (R.C.C). The material properties of the reinforcing bars also change with respect to increasing temperature.

2.1.2.1 Tensile Strength

Steel's tensile strength refers to its resistance to breaking under tension. Tensile strength of steel is the maximum strength of steel to resist or withstand against tension stress prior to failure at the end of the plastic stage when two equal and opposite pulling forces are applied over a steel specimen. The tensile strength of 360 MPa is adopted in the present study.

2.1.2.2 Density

The density of the reinforcing bars does not vary with respect to temperature. It remains constant even at higher temperatures. The value of density of reinforcing bars is taken as 7850 kg/m^3 and it remains constant even at elevated temperatures.

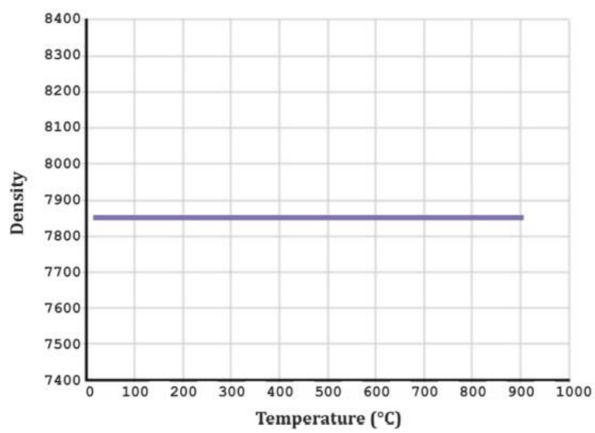

Fig -4: Variation of Density of Steel

2.1.2.3 Modulus of Elasticity

The slope of an object's stress-strain curve in the elastic deformation area is referred to as its elastic modulus. Reinforcing steel bars having an elasticity modulus of 210000 N/mm^2 are used.

2.1.2.4 Thermal Conductivity

The variation of thermal conductivity of reinforcing steel with respect to temperature variation is shown in Fig 5.

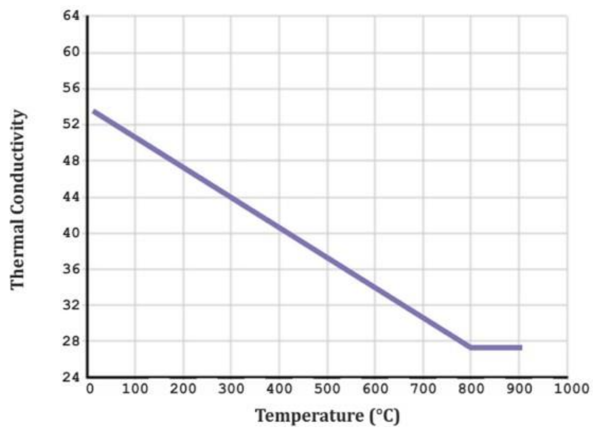

Fig -5: Variation of Thermal Conductivity of Steel

2.1.2.5 Specific Heat

Specific Heat refers to the quantity of heat that is required to raise the temperature of a body by one degree Celsius. The variation of Specific Heat Capacity of reinforcing steel with respect to the increasing temperature is shown by Fig 6.

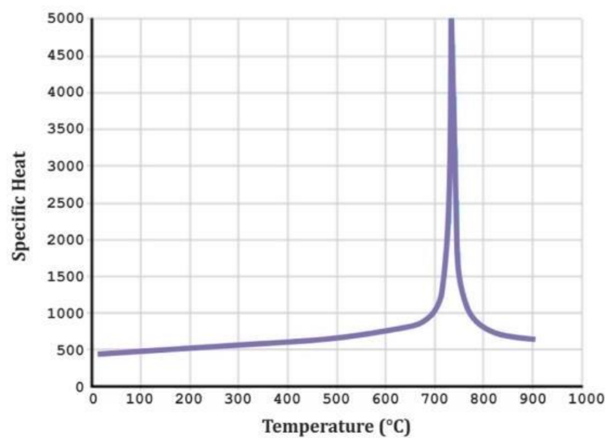

Fig -6: Variation of Specific Heat of Steel

2.1.3 Fire Curve

Fire curves that show the temperature dependence over time can be created for each building space. Building fire safety can be designed with the use of such curves. The standard fire curve is used to calculate the heat load that will be applied to the building components during testing. The time-temperature curve adopted to study the relation between load and maximum deflection is shown in Fig 7.

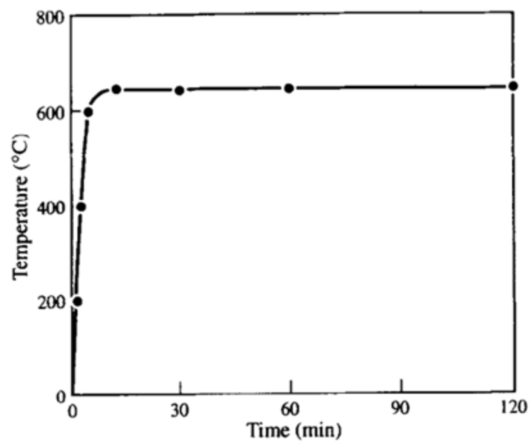

Fig -7: Fire Curve

2.1.4 Test Specimen

Cross section of the concrete beam modelled is 120mm wide and 200mm deep. Total length of 1800mm is adopted. The crushing strength of the concrete of 25MPa is adopted. Reinforcement is provided in the form of longitudinal bars of 10mm diameter with the effective cover of 25mm. The minimum yield stress of the reinforcement is taken to be 360MPa. The fire (temperature) load was applied to the bottom surface of the beam to study the maximum deformation as well as heat propagation along the cross section of the beam. During the thermal analysis, the beams are not loaded. The thermal analysis is carried out for 30, 60 and 120 minutes for beams B1, B2 and B3 respectively. Temperature load is not applied on beam B. After the thermal analysis, the beams are loaded using two point loads acting on the top surface at the distance of 675mm each from both the ends. The load is applied at the rate of 500N per minute and the maximum deflection is noted. The temperature variation across the cross section of the beam is also observed.

3. RESULTS

The temperature gradient across the cross section of the reinforced concrete (RC) beam was found out for 30, 60 and 120 minutes. Transient Thermal Analysis of concrete beams was carried out using the finite element software in order to model the temperature distribution in concrete element exposed to fire. Material and thermal properties such as thermal conductivity, specific heat, and density are given as inputs to determine the temperature distribution. Temperature distribution profiles generated from the finite element software are shown after exposure to different durations of heating. The deflections were noted by carrying out Transient Structural Analysis on the same beams. The results of thermal analysis were imported to study the relation between the applied loads and the maximum deflection.

3.1 Temperature Variation across the Cross Section

With the help of researched data, temperature distribution within the concrete beam was successfully simulated using the finite element software. Temperature was found to be maximum at the exposed surface and progressed inwards with time. Following exposure to various heating durations, temperature distribution profiles can be produced. Temperature contours across the cross section of the reinforced concrete members exposed to fire for different time intervals were recorded and plotted as shown in the figures below. The minimum temperature is recorded at the opposite surface where the fire is applied, while the maximum temperature is recorded at the surface where the fire is applied.

3.1.1 The temperature variation across the cross section of the beam B1 (30 minutes of fire exposure)

It is represented by Fig 8. The rise in the minimum temperature across the cross section is very less. The temperature in the reinforcement is raised to 325.52 ºC after 30 minutes of fire exposure.

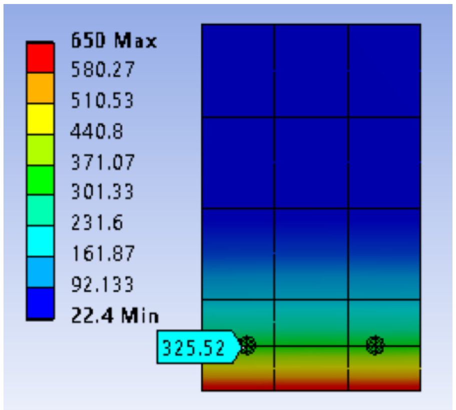

Fig -8: Temperature Contours after 30 minutes of fire exposure

3.1.2 The temperature variation across the cross section of the beam B2 (60 minutes of fire exposure)

It is shown in Fig 9. The minimum temperature across the cross section rises to 30.7 ºC after exposing to fire for 60 minutes. The temperature in the reinforcement is raised to 405.23 ºC after 60 minutes of fire exposure.

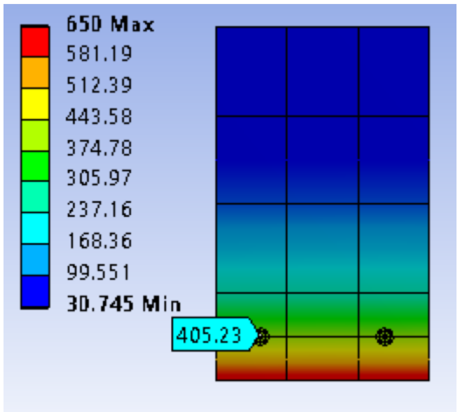

Fig -9: Temperature Contours after 60 minutes of fire exposure

3.1.3 The temperature variation across the cross section of the beam B3 (120 minutes of fire exposure)

The temperature variation across the cross section of the beam B3 (120 minutes of fire exposure) is shown in Fig 10. The minimum temperature across the cross section rises to 78.12 ºC after exposing to fire for 120 minutes. The temperature in the reinforcement is raised to 469.28 ºC after 120 minutes of fire exposure.

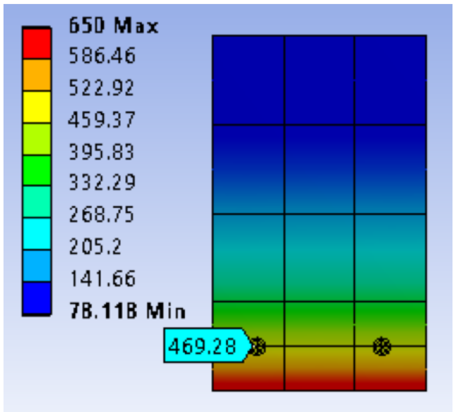

Fig -10: Temperature Contours after 120 minutes of fire exposure

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3.2 Relation between Load and Maximum Deflection

Previous works have detailed all the thermal properties of concrete in order to build up a numerical model of fire exposed concrete structure. The relations between the load and the maximum deflections are shown in the below figures. The plot shows that the relation is linear for all the beams (before and after exposing to fire). It can also be noted that the slope of the plot decreases with increasing durations of fire exposure. The maximum deflection noted for the beam B3 (120 minutes of fire exposure), B2 (60 minutes of fire exposure) and B1 (30 minutes of fire exposure) is almost 5.4, 5.2 and 4.8, respectively, times the maximum deflection of the beam B (not exposed to fire). The deflection is higher for the beams exposed to fire for longer duration. The slope of the plot decreases as the time of exposure to fire increases. Hence, deflection occurs at faster rates for the applied loads for the beams exposed to fire.

Table -1: Maximum Deflection found by Research Paper and as obtained from FE Software

Beam	B	B1	B2	B3
Fire Exposure time (minutes)	0	30	60	120
Ultimate Load (by research paper) (N)	59500	52500	48000	36500
Maximum Deflection found by research paper (mm)	6.75	9.6	10.22	11.9
Maximum Deflection obtained from FE software (mm)	3.0835	14.801	16.173	16.572
Difference	-3.665	5.201	5.953	4.672

It can be observed from Figure 11 and Figure 12 that the maximum deflection for Beam B (not exposed to fire) is 3.08mm. The deflection pattern is symmetric about the beam centre.

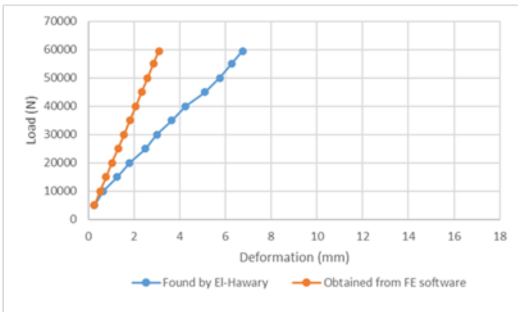

Fig -11: Load-Maximum Deflection of Beam B

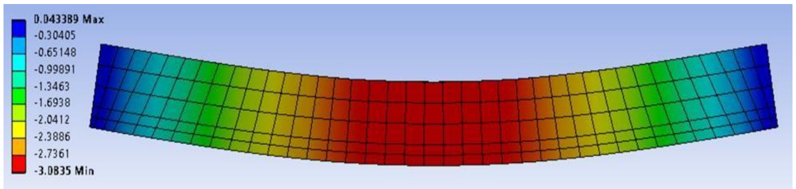

Fig -12: Maximum Deflection of Beam B

From Figure 13 and Figure 14, it can be seen that the maximum deflection for Beam B1 (30minutes fire exposure) increases to 14.80mm. When the load of 50kN is applied, the deflection of the beam B1 increases almost 5.7 times the deflection occurred in beam B.

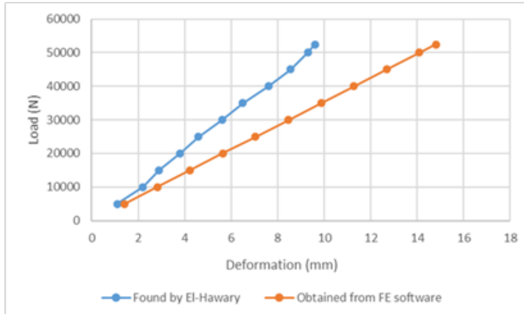

Fig -13: Load-Maximum Deflection of Beam B1 (30 min)

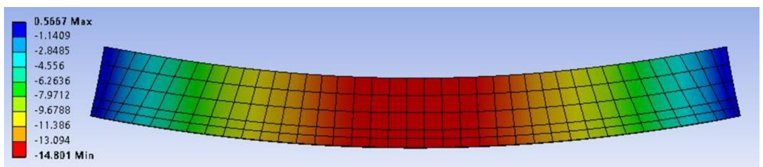

Fig -14: Maximum Deflection of Beam B1 (30 min)

The maximum deflection for Beam B2 (60minutes fire exposure) increases to 16.17mm as can be observed from Figure15 and Figure 16. The deflection pattern is symmetric about the centre of the beam for all the beams (with and without fire exposure).

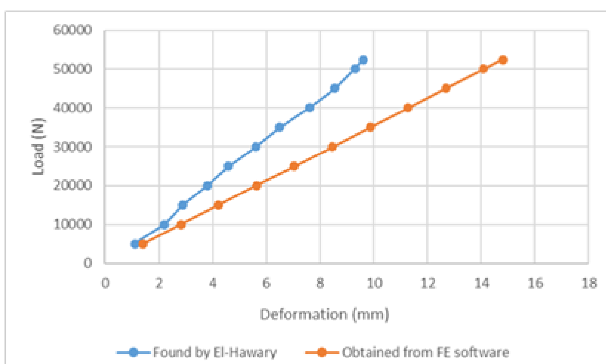

Fig -15: Load-Maximum Deflection of Beam B2 (60 min)

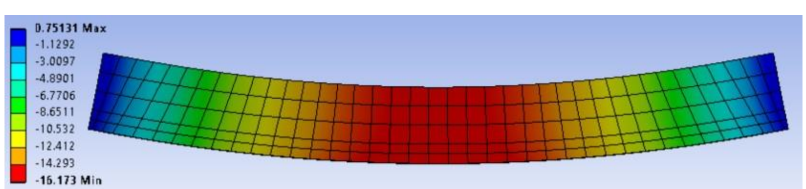

Fig -16: Maximum Deflection of Beam B2 (60 min)

It can be observed from Figure 17 and Figure 18 that the maximum deflection for Beam B3 (120minutes fire exposure) increases to 16.57mm. The deflection increases linearly for the applied loads. It can be observed that the deflection increases as the time of fire exposure is increased.

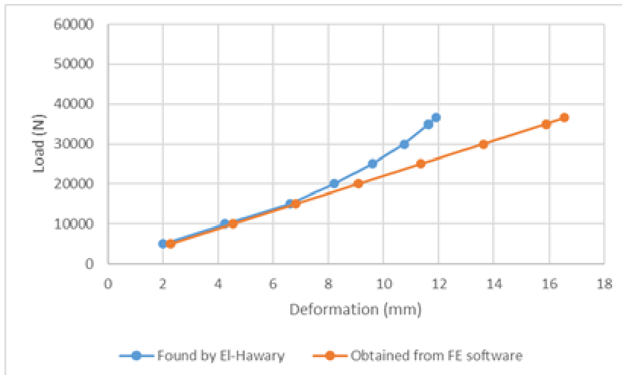

Fig -17: Load-Maximum Deflection of Beam B3 (120 min)

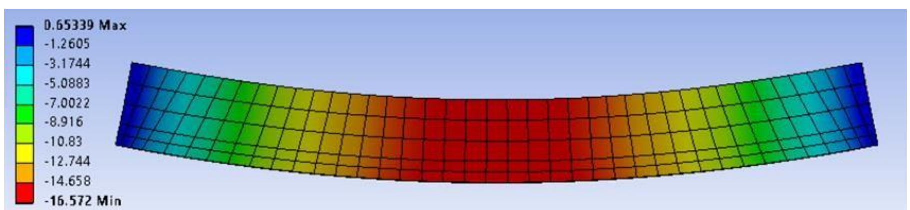

Fig -18: Maximum Deflection of Beam B3 (120 min)

4. CONCLUSION

The finite element method makes it easier for researchers to study various structural problems and achieve a solution in a shorter time compared to experimental investigation. Within the scope of this study, simulation of experimental work from the referred research paper was carried out on finite element software. The concrete beam was modelled taking into account the different fire duration times and temperatures. The variation of thermal properties of the concrete with respect to increasing temperatures were also considered as the input parameters for the material properties of the model. The thermal and mechanical properties at elevated temperatures will successfully facilitate modelling the concrete under fire exposure. Simulation was carried out to study the relation between the loads and the maximum deflection. The temperature variation across the cross section was also observed by applying the fire (temperature) load to the bottom surface of the reinforced concrete beam.

From the present study it can be concluded that:

- The relation between the load and the maximum deflection is linear as observed from the plots shown in Figure 11, 13, 15, 17.
- The deflection increases as the time period of fire exposure is increased as can be observed from the slope of the plots which decreases with the increasing the time periods of fire exposure.
- The maximum deflection noted for the beam B3, B2 and B1 is almost 5.4, 5.2 and 4.8, respectively, times the maximum deflection of the beam B (not exposed to fire).
- The maximum temperature occurs at the surface at which the temperature load is applied.
- The temperature progresses inwards with time as can be observed from the temperature contours obtained from the finite element software.

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