JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

Title: **FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE BEAM SUBJECTED TO FIRE**

A thesis submitted to Jimma Institute of technology, School of graduate studies in partial fulfillment of the requirements for the Degree of Masters of Science in Structural Engineering.

By:
LIDETA TEWACHEWU

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Main Advisor: ELMER C. AGON (ASSO PROF.)
Co-Advisor: HAYMANOT G/SELASE (M.SC)

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Declaration

I hereby declare that this thesis entitled "FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE BEAM SUBJECTED TO FIRE" is my original work which has not been submitted before. This thesis has not been presented in any other university and is not concurrently submitted in candidature of any other degree, and that all sources of material used for the thesis have been duly acknowledged.

Research proposal submitted by:

Lideta Tewachewu

____________________ ____________________

Signature Date

Approved by advisors:

ELMER C. AGON (ASSO PROF.) (Main adviser):

____________________ ____________________

Signature Date

HAYMANOT G/SELASE (M.SC)(Co-adviser)

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Signature Date

Approved by Faculty of Civil and Environmental Engineering research examination members.

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3. ____________________ ____________ ______________
   Name Signature Date

Acknowledgment

My first and foremost gratitude goes to Almighty God who is there for me always through the times of trouble and good times.

Completion of this thesis would not be possible without my husband Henok I wish to express my sincere gratitude.

I would like to thank my main advisor, Asso. Prof Elmer C.Agon and co-advisor, Eng.r Haymanot G/selase for their valuable advice and guidance. I would like to express my gratitude to my families and friends for their unrelenting and rigorous moral support not only on my educational careers but throughout my life. Finally, my special thanks go to Jimma Institute of Technology for facilitating this program which helps me for upgrading my profession.

Abstract

Reinforced concrete structure is the common structural system used in Ethiopia and nearly all over the world. Fire represents one of the most severe environmental conditions to which structures may be subjected, and hence, the provision of appropriate fire safety measures for structural members is an important aspect of design. Reinforced concrete (RC) structural systems are quite frequently used in high-rise buildings due to the high structural performance such as strength and durability that it can provide, compared to other materials. Much of the current knowledge on fire behavior of RC members is based on fire resistance tests under standard fire scenarios. There have been no studies under realistic (design) fire scenarios. And thus, there is limitation reliable experimental data, mathematical models or design specifications for predicting the fire performance of RC beams under design fire scenarios.

The objective of this study was to analysis the behavior of RC beam subjected to fire.in Ethiopia there is no sufficient experimental and laboratory equipment because of this ,there is no enough and detailed explanation under Ethiopian building code. Therefore, the fire resistance of RC members is an important issue that needs to be considered in the design of RC buildings.

This thesis presents investigate the behavior of reinforced concrete beam subjected to fire by using 3D finite element analysis. The first step was Simulate the structural behaviour of the same beam subjected to mechanical load and nodal temperature (as nodal temperature time history) calculated from the first step. Then, the FE models are computed with existing test data from literature to examine the accuracy of the simulations.

Values from the test and FE model are observed to be close to each other. There are three parameters to analysis the effect of RC beam subjected to fire in this paper which is concrete cover, temperature and duration of time. Results from the analysis indicated that as fire exposure time increases the material behavior degrades. Since the nodal temperature distribution increases with an increase in exposure time. When the concrete cover is zero, the stress along the center of the beam highly decrease and when the concrete cover is thirty, the stress along the center of the beam highly increases. When the temperature and duration of time increase, the vertical deflection at mid span increase.

Key Words : finite element model, reinforced concrete beam, heat transfer, fire

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Acronyms

b	Width of beam
c	Concrete cover
$\mathbf{C}_a$	Specific heat of steel
CDP	Concrete damaged plasticity
$\mathbf{C}_p$	Specific heat of concrete
$^0\mathbf{C}$	Degree centigrade
D	Overall depth
d	Effective depth
DL	Dead load
EBCS	Ethiopia building code standard
EC	European code
$\mathbf{E}_{s,\theta}$	Modulus elasticity of steel
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
RC	Reinforced concrete
t	Time (minute)
$\mathbf{T}_f$	Fire temperature measured from the standard fire curve

Chapter 1

Introduction

1.1 Background of the study

Fire accident is one of the dangerous accidents that could happen to any service structure in unexpected time. in our country, there were so many lives taken and damaging fire accident caused on Taitu Hotel, Anwar mosque and in recent time there is an accident in Bahirdar town and there was loss of human life and failure of structure .Reinforced concrete (RC) structural systems are quite frequently used in high-rise building and other built infrastructure due to a number of advantages they provide over other materials when used in building .The provision of appropriate fire safety measures for structural members is an important aspect of design. Since, fire represents one of the most severe environmental condition to which structure may be subjected in their life time. Fire is an accident which could occur in two ways, the first one is by means of human beings faults and the second is through natural disaster. Mostly fire occur in the daily activities of human being. In case of this there is loss of human life and property is occurs in Ethiopia and in the world. So the objective of fire safety is to protect human life and property. Fires occur at any time in building. Because of this the safety of occupants and maintaining the integrity of the structure are major importance, in the design of structure Building codes . requirements for fire resistance are sometimes overlooked and this may lead to costly mistake [18].code based structural fir safety requirements refers to fire resistance which is defined as the ability of structural element to maintain its load-bearing function under standard fire condition [20]. The fire resistance rating of structural member is the elapsed time it exhibits resistance with respect to structural integrity, stability, and temperature transmission while exposed to standard fire condition [3]. The measured fire resistance of a structural member or assembly is dependent on the geometry of elements, materials used in construction, load intensity fire exposure, and the characteristic of a given heater [15]. In general for safe design ,fire consideration must be part of preliminary design stage.

Figure 1.1: The Windsor Tower in Madrid after 26 hour in 2005[18]

1.2 Statement of the problem

Now a days many buildings around the world collapsed due to fire, Because of this, a loss human life and money were occurring in each of the year . But still there is no sufficient research on buildings subjected to fire. In Ethiopia building code, the previous 1995 and new building code under no detailed and enough provision existing about the performance of different kinds of construction material for fire. But due to growth of infrastructure, increasing interest of safety in this country, repetitive analysis and studies on fire resistance property determination of different construction material and structural member must be given high value. Sustainability of structures is a vital issue in the construction industry. Exposure to fire or elevated temperature is serious condition that leads to change in materials properties. Consequently, change in overall behavior is expected. Hence, building should be provided with sufficient structural fire resistance to with stands in such circumstance, or at least give occupants to scape before strength and, or stability failure occurred. In structural design of buildings in addition to normal gravity and lateral loads it is necessary to design the structure to safely resist exposure to fire. However, it is usually necessary to guard against structural collapse for a given period of fire exposure. This paper tried to consider the effect of different concrete cover with different temperature and exposure time using finite element analysis.

1.3 Objectives of the research

1.3.1 General Objective

The main objective of this research was to analyze reinforced concrete beam subjected to fire using Finite Element Analysis.

1.3.2 Specific objective

The specific objectives of this research are:

- Validate the experimental result by using finite element.
- To evaluate temperature effects at critical nodes of the beam.
- To evaluate the effect of concrete cover with different temperature and duration of time.
- To identify the effect of fire on thermal properties of reinforced concrete beam at different exposure time.

1.4 Significance of the Study

The study add knowledge on understanding the analysis of fire response of concrete beams using finite element method and the result obtained from this study is helpful for further study and coming researcher The old EBCS as well as the new EBC does not discuss about fire design of concrete structure deeply, but fire is the most severe environmental condition like earthquake and wind load subjected to building structures in their lifetime. Exposure to fire or elevated temperature is an extreme condition that leads to change in materials properties; consequently, change in overall is expected. Therefore, this study will add valuable information on the behavior of concrete beam under fire to fill this gap. This study used to design reinforced concrete beam for fire and model, to assess the capacity of the beam after fire, Generally this paper helps practical guidelines for fire resistance design of reinforced concrete beam under building code.

1.5 Scope of the thesis

This study shall cover the effect of concrete cover with different duration of time and temperature to analysis the behaviour of RC beam subjected to fire.

1.6 Organization of the Thesis

The research is organized in to five chapters. The first chapter is stated about the general background, objectives, significant of the study and scope of the study. The second chapter describes previous works done about the effect of fire on the capacity of reinforced concrete beam. The third chapter is the main body of the research, which consists of the methodology used, and the procedures followed in conducting the research. The fourth chapter consists of discussion and verification of the obtained result and finally the fifth chapter provides conclusion and recommendations of the research.

Chapter 2

Literature Review

2.1 Introduction

Reinforced concrete is one of most commonly used construction materials due to its excellent properties including good fire resistance. However, concrete resistance to fire should not be taken for granted. The measure used to assess the performance of building in structure on fire is started in the early 1918. Fire analysis applied in either in laboratory or finite element method, But experimental approach is expensive for the country like Ethiopia. the equipment to asses behavior of structural element is not available in developing country. That is why EBCS code also have not detailed explanation regarding fire design. But finite element analysis more preferable than either analytic or experimental approach analysis and finite element analysis also consider some variables which is difficult to undertake in the laboratory.

2.2 Partition work

Researchers has been working on the performance of structural building element on fire on different time. One of the paper [16] his doing in the laboratory by changing concrete cover and his research shows that spalling of failure concrete started around 100 degree Celsius and he said that the contribution of concrete cover to reinforcement in fire resistance of beam is not clearly observed .concrete surface temperature rise to higher level reduces compressive strength of concrete and residual shear strength of RCB [5]. Yet this paper the beginning concrete cover is one the protection of fire, safe transmission bond force and durability so he is not address the main objective of the paper. In [20] also do the performance of RC beam in finite element, and the model is to applied by five parametric study namely degree of axial restraint, span to depth ratio, fire scenario, load level and failure criteria on the fire response of restrained RC beam. this paper showed that the fire induced restraint has negative effect on fire resistance of slender beams having high span-to-depth ratio [16]. This paper presents a numerical procedure for predicting the mechanical behavior of RC beam exposed to fire. Using a two dimensional finite element analysis [18] also model the load-displacement behavior of RC beam of different configuration and multidimensional data analysis technique is used.

In [13] this paper is address the effect of burning by fire flame on the behavior and load carrying capacity of rectangular reinforced concrete beam. And the paper take to dependent variable which are RC beam rectangular are cast and cooled in two ways cooled in water and cooled in water and get result which is reduced in (2-5%) cooled in water than cooled in air.

In [7], the paper states that complex behavior of structure in fire. In [3], the paper also address the effect of fire induced restraint on the fire response of RC beam in finite element.

In [19] the paper use non-linear analytic methods to determine the temperature reached at a given depth of concrete and to determine the flexural strength at such elevated temperatures. In [18], the paper clarify the impact of fire on steel reinforcement in reinforced concrete structure at elevated temperature and analyzed using three dimensional(3D) finite element method.

In [17], the paper explain multi-span RC beam exposed to fire in theory and numerical form. The paper [15], study the mechanical behavior of RC continuous members after exposure to fire including 5 RC continuous slab after exposure to fire including 7 RC beams carried out content f test including loading ,heating in ISO standard and post-fire loading. The result indicates that increasing of exposure time, the loss of bending rigidity is proved larger than that of the bearing capacity because different in size the slab were subjected to more severe damage than the beams under the same heating condition.

The paper [14] shows the behavior of RC L-beam and T-beam under fire study using finite element(ANSYS) method. result shows that type of exposure and the number of sides exposed to fire is having a great effect in the fire resistance of beams.

In [13], rehabilitation effect on fire damaged high concrete beams using experimental and analytic methods. In the experiments, flexural specimens with high strength concrete are exposed to high temperatures according to ISO 834 standard time temperature curve. From four-point loading test, results show that maximum loads of the rehabilitated beams are similar to or higher than those of the non-fire damaged RC beam. In addition, structural analyses are performed using ABAQUS 6.10-3 with same conditions as experiments to provide accurate predictions on structural and mechanical behaviors of rehabilitated RC beams. The parameters are the fire cover thickness and strengths of repairing mortar. Analytic results show good rehabilitation effects, when the results predicted from the rehabilitated models are compared to structural behaviors of the non-damaged RC beams. In the paper [3] illustrated effect of loading and beam size on the structural behavior of RC beam under and after fire. Load level, cross-sectional size, temperature are parameter of the structural element and performed using experimental and analytic. The result shows that temperature. Stiffens, and ductility of the fire-damaged beams are significantly influence by the load level, cross-sectional size and time exposed under fire. The paper [2] presents the effect of different face exposures: fully and partially on the behavior of normal strength of RC beams when exposed to fire. The results shows that cooling phase is critical in attaining maximum temperature in RC beams. Different face exposure and concrete strength significant affect the load at first cracking, serviceability deflection.

2.3 Review on the method of assessment of fire

Depending of the level of complexity and accuracy, method to assess fire resistance is classified in to four experimental, perspective, analytical and simplified [3].

2.3.1 Experimental analysis

Standard fire tests involve evaluating the structural performance of an element using a furnace. The fire temperature is controlled to follow a specific standard time temperature curve. The element is considered fire resistant if it satisfies specific load capacity and/or deformation criteria. The major disadvantages of standard fire tests are the cost and needed time. However, standard fire tests are the only valid method to assess deficiencies in construction detailing and to assess fire performance of new materials [23]. Results of fire tests are also essential to validate various numerical tools.

2.3.2 Perspective method

Prescriptive methods provide guidelines and tabulated data to specify minimum cross-section size and concrete cover to maintain the resistance of an element for a predefined fire exposure duration. They are mainly developed based on standard fire tests. Their main advantage is their cease of application. On the other hand, they tend to be conservative, and do not give engineers the flexibility to use irregular shapes and innovative solutions [23].

2.3.3 Analytical method

Advanced calculation method simply conducting a complete thermal and mechanical analysis to evaluate the resistance of a structural element exposed to fire. The thermal analysis is conducted using the principles of the heat transfer, which involves considering the temperature-dependent thermal properties of concrete [23]. The Finite Element Method (FEM) is considered the most common tool to carry out advanced fire resistance analysis.

Advanced calculation methods account for the continuous alteration of the thermal and mechanical characteristics of the materials, the boundary conditions, and the non-homogeneous distribution of the temperatures within the elements. Although advanced calculation methods provide a very realistic modelling, they require thorough background knowledge and the use of sophisticated computer programs.

2.3.4 Simplified methods

Simplified methods use the ambient-temperature design methods while taking into account the effects of fire [23]. They should provide structural engineers with reliable performance-based fire design tools.

2.4 Code recommendation for fire design of concrete beams

This section gives and over reviews different standard code design for fire resistance concerning on reinforced concrete beam.

2.4.1 Design of Rc beam according to ES and EN 1992:2015

Concrete cover is the distance between the surface of the reinforcement closest to the nearest concrete surface (including links and stirrups and surface reinforcement where relevant) and the nearest concrete surface. And it is essentials for four primary reasons (slab or beam).

- To bond the reinforcement to the concrete so that the two elements act together. The efficiency of the bond increases as the cover increases.
- To protect the reinforcement against corrosion.
- To protect the reinforcement from strength loss die to overheating in the case of fire.

Additional cover sometimes is provided on the top of slabs, particularly in garages and factories, so that abrasion and wear due to traffic will not reduce the cover below that required for structural and other purposes.

Rather than giving the minimum cover, the tabular method is based on nominal axis distance, see fig.5 this is the distance from the center of the main reinforcing bar to the surface of the member. The designer should ensure that,

Concrete cover according to EN 1992-1-1 and EN 1992-1-2 The nominal cover is defined as a minimum cover C_{min} plus an allowance in design for deviation ΔC_{dev},

$$\mathbf{C_{nom} = C_{min} + \Delta C_{dev}} \tag{2.1}$$

Where C_{min} should be set to satisfy the requirements below:

- Safe transmission of bond forces
- Durability
- Fire resistance

And ΔC_{dev} is an allowance which should be made in the design for derivation from the minimum cover. It should be taken as 10 mm, unless fabrication (construction) is subjected to a quality assurance system, in which case it is permitted to reduce ΔC_{dev} to 5 mm.

2.4.2 Minimum cover for fire resistance

Rather than giving the minimum cover, the tabular method is based on nominal axis distance. This is the distance from the center of the main reinforcing bar to the surface of the member.

The designer should ensure that,

$$\mathbf{a \geq C_{nom} + \hat{O}_{link} + \hat{O}/2} \tag{2.2}$$

Table 2.1. Minimum dimensions and axis distances for simply supported beams made with reinforced and pre- stressed concrete [12].

Standard fire resistance	Minimum dimensions (mm)						
	Possible combinations of *a* and b_{min} where *a* is the average axis distance and b_{min} is the width of beam				Web thickness b_w		
					Class WA	Class WB	Class WC
1	2	3	4	5	6	7	8
R 30	b_{min} = 80 *a* = 25	120 20	160 15*	200 15*	80	80	80
R 60	b_{min} = 120 *a* = 40	160 35	200 30	300 25	100	80	100
R 90	b_{min} = 150 *a* = 55	200 45	300 40	400 35	110	100	100
R 120	b_{min} = 200 *a* = 65	240 60	300 55	500 50	130	120	120
R 180	b_{min} = 240 *a* = 80	300 70	400 65	600 60	150	150	140
R 240	b_{min} = 280 *a* = 90	350 80	500 75	700 70	170	170	160
a_{sd} = *a* + 10mm (see note below)							

2.4.3 Euro Code

Euro code 1 Part 1-2: "Actions on structures exposed to fire" [9] regulates calculation models for the determination of load effects and temperature. The fire scenario is treated as "exceptional action" and does not need to be superimposed with other load, Independent exceptional actions. For the fire design, different time-temperature curves are provided for the determination of hot gas temperature.

Euro Code 2 Part 1-2: "Design of Concrete Structures – Structural Fire Design" [10] deals with the design of concrete structures for the case of fire. It states the design values for material properties and combination factors for actions and treats methods of the passive and structural fire precautions; active fire protection methods are not included. For the determination of a sufficient fire rating, Euro code 2 gives three alternatives of design methods.

2.4.4 ACI 216.1-07/ TMS 0216-07

Code requirements for determining the fire resistance of concrete and masonry assemblies For concrete structures, fire resistance can be achieved by providing the appropriate depth of structural element and thickness of concrete cover depending on their function. ACI 216.1 and AC1 318 provide tables with various assemblies of building materials and finishes providing specific fire endurance.

Fire resistance rating is measured in terms of hours of exposure to the standard fire defined by ASTM E119 (2012), e.g., the fire rating for siliceous aggregate concrete with a minimum equivalent thickness of five inches (127 mm) is two hours. Formulas are provided to calculate the equivalent thickness of non-uniform sections, such as ribbed or undulating panels, and sections consisting of multiple layers. The code also gives minimum cover thickness to protect pre-stressed or passive steel reinforcement against fire. Distinction is made between restrained and non-restrained members. Most cast-in-place or precast construction is restrained, whereas single spans and simply-supported end spans of multiple bays are unrestrained [2].

2.4.5 Behavior of concrete at elevated temperature

Based on the compressive strength; concrete is normally classified as,

- normal strength concrete,
- Ultra-strength concrete.
- high strength concrete

Fire represents one of the most severe risks to buildings and structures. While normal concrete is typically considered to be resistant against fire and high temperatures, the low permeability of high performance fiber reinforced concrete (HPFRC) may result in failure by explosive spalling at high temperatures. Explosive spalling is the process of concrete explosively breaking away as a result of elevated temperatures. Spalling reduces the cross section area of critical sections and may expose conventional steel reinforcement to high temperatures.

2.5 Heat and Temperature

All matter is made up of molecules and atoms which are always in different types of motion. The motion can be translating, rotating or vibrating which creates thermal energy. Therefore all matters have thermal energy and the level of motion defines heat of a matter. The more motion the atoms or molecules have the more heat they will have.

All movement of atoms and molecules are not similar to each other, some move faster than others. Temperature is a definition to cope with this variety and unified it in theory. Temperature is an average value of energy for all the atoms and molecules in a given system and it is independent of how much matter there is in the system. It is simply an average of the energy in the system.

2.6 Heat transfer

Heat transfer takes place in three ways: Conduction, Convection and Radiation. Both conduction and convection require matter to transfer heat [17].

2.6.1 Conduction

Takes place in matter. Conduction is one way to transfer heat between substances that are in direct contact with each other. It is transmission of kinetic energy among the molecules without matter transport. It is possible to classify matters according to the rate of heat transfer by conduction and define matters to be a good conductor or less conductor. The better the conductor, the faster heat will be transferred. For example metal is defined as a good conductor because heat transfer faster. Conduction occurs when a substance is heated, particles will gain more energy, and vibrate more. These molecules then bump into nearby particles and transfer some of their energy to them. This then continues and passes the energy from the hot end (more energetic particles) down to the colder end (less energetic particles) of the substance due to energy gradient. Conduction takes place in solids, liquids and gases.

2.6.2 Convection

One other way for heat transmission is Convection. Thermal energy can be transferred from hot places to cold places in fluids or gases due to bulk or macroscopic motion. Convection occurs when warmer areas of a liquid or gas rise to cooler areas in the liquid or gas. Cooler liquid or gas then takes the place of the warmer areas which have risen higher. This results in a continuous circulation pattern. Water boiling in a pan is a good example of these convection currents. Another good example of convection is in the atmosphere.

2.6.3 Radiation

Radiation is a method of heat transfer that does not rely upon any contact between the heat source and the heated object as is the case with conduction and convection. Heat can be transmitted through empty space by thermal radiation often called infrared radiation. Energy emitted by matter due to changes in electron configuration that results in changes in energy via electromagnetic waves or photons. No mass is exchanged and no medium is required for its propagation. Radiation is propagation of electro-magnetic waves in vacuum or in transparent matters. Examples of radiation is the heat from the sun, or heat released from the filament of a light bul.

2.7 Fire modeling as temperature

The time-temperature curve used in fire resistance tests is called the standard fire. Several models of time-temperature relationships are available for the simulation of fires for design purposes: The standard time–temperature curves from ASTM E119 and ISO 834 are compared in the figure below. They are seen to be rather similar. All other international fire resistance test standards specify similar time–temperature curves.

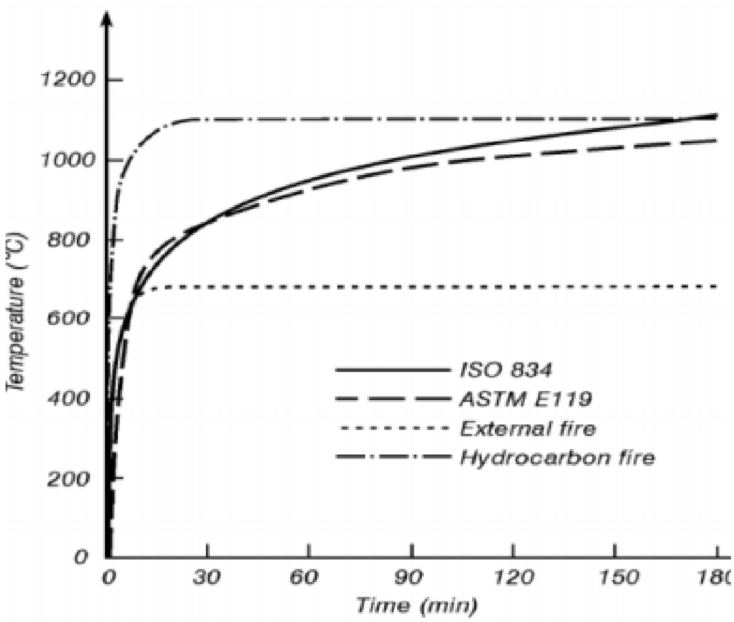


Figure 2.1: standard time–temperature curves from ASTM E119 and ISO 834 are compared [14]

Chapter 3

Research Methodology

3.1 Research design

The primary goal of this paper analysis the behavior of reinforced concrete beam subjected to fire. It focused on modeling of material properties at elevated temperature for both thermal and mechanical, for concrete, rebar and geometrical modeling of beam and finite element modeling of material in abacus.

3.2 Thermal Properties of Materials

Thermal properties of materials are those affect the temperature distribution or define the rate of heat transfer. Specific heat, Conductivity and density are the parameters required to determine diffusivity. These parameters also vary with temperature and duration of time for both materials, steel and concrete these parameters and its variation with respect to temperature are presented.

3.2.1 Thermal Properties of Concrete

Specific heat: The specific heat of concrete measures the energy required to raise one degree of temperature of one unit volume of concrete. According to EN 1992 1-2 the variation of specific heat of dry concrete (u= 0%) as function of temperature (valid for both siliceous and calcareous aggregates concrete).

$$(\theta) = 900 \qquad for\ 20°C \le \theta \le 100°C$$

$$Cp(\theta) = 900 + (\theta - 100) \qquad for\ 100°C \le \theta \le 200°C$$

$$Cp(\theta) = 1000 + (\theta - 200)/2 \qquad for\ 200°C \le \theta \le 400°C$$

$$Cp(\theta) = 1100 \qquad for\ 400°C \le \theta \le 1200°C$$

Peak values of specific heat for different moisture contents are: $C_{ppeak} = 900$

For moisture content of 0% of concrete weight

$C_{ppeak} = 1470$, for moisture content of 1.5% of concrete weight

$C_{ppeak} = 2020$, for moisture content of 3% of concrete weight

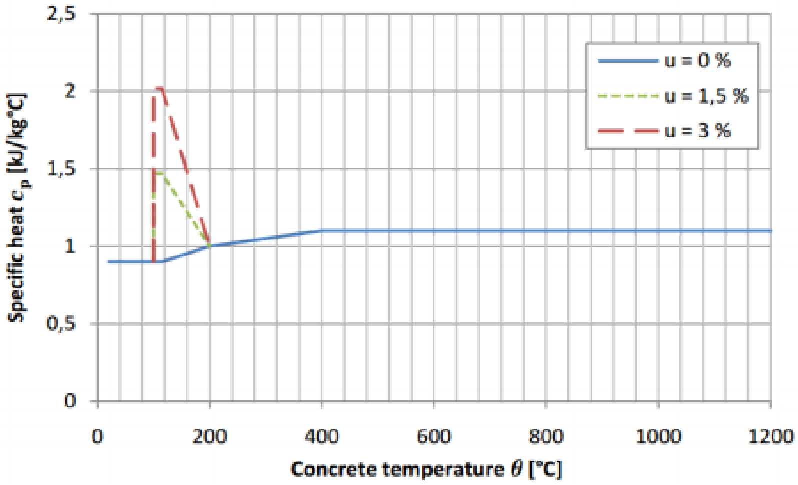


Figure 3.1: Specific heat of concrete as function of temperature for three different moisture contents [10]

3.2.2 Thermal conductivity

Thermal conductivity is the ability of a material to conduct heat. It is defined as the ratio of the heat flux to temperature gradient. The EN 1992 1-2 defines the concrete's thermal conductivity (λ) between two boundary limits. The upper limit as function of temperature is given by:

$$\lambda_c = \mathbf{2 - 0.2451} * (\mathbf{100}\theta) + \mathbf{0.0107} * (\theta/\mathbf{100})^{\mathbf{2}} \quad \textbf{for} \quad \mathbf{20^0C} \leq \theta \leq \mathbf{1200^0C} \tag{3.1}$$

$$\lambda_c = \mathbf{1.36 - 0.136} * (\mathbf{100}\theta) + \mathbf{0.0057} * (\theta/\mathbf{100})^{\mathbf{2}} \quad \textbf{for} \quad \mathbf{20^0C} \leq \theta \leq \mathbf{1200^0C} \tag{3.2}$$

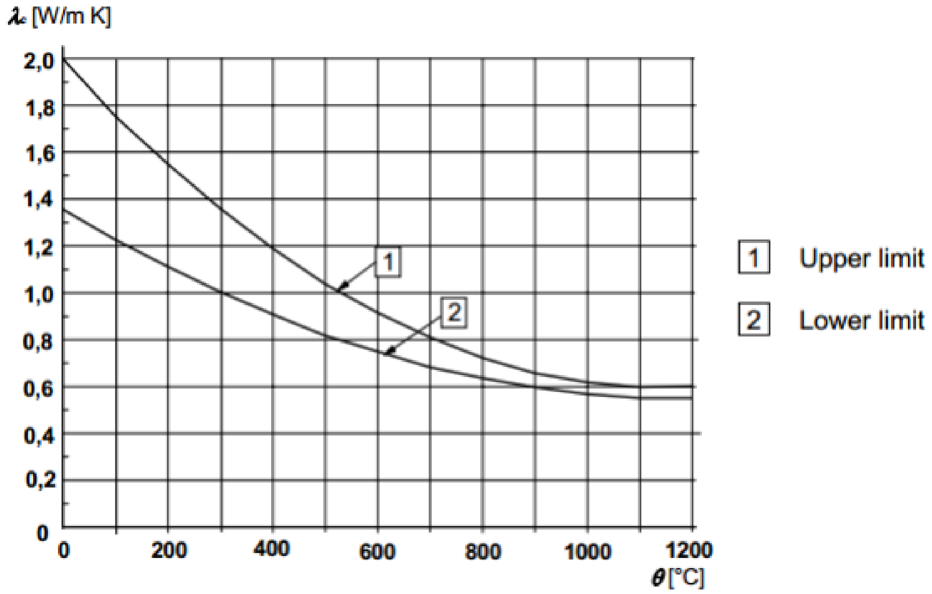


Figure 3.2: Thermal conductivity of concrete[10]

3.2.3 Thermal Elongation

The thermal strain of heated concrete (at temperature θ) is defined in relation to its initial length at ambient temperature (20^0C) by equation 3.4 for siliceous aggregates concrete:

$$\epsilon_{\mathbf{c}}(\theta) = \mathbf{-1.8*10-4+9*10-6}\theta\mathbf{+2.3*10-11}\theta^{\mathbf{3}} \quad \mathbf{for} \quad \mathbf{20^0C} \leq \theta \leq \mathbf{700^0C} \tag{3.3}$$

$$\epsilon_{\mathbf{c}}(\theta) = \mathbf{14*10-3} \quad \mathbf{for} \quad \mathbf{700^0C} \leq \theta \leq \mathbf{1200^0C} \tag{3.4}$$

Equation 3.6 defines the thermal strain for calcareous aggregates,

$$\epsilon_{\mathbf{c}}(\theta) = \mathbf{-1.2*10-4+6*10-6}\theta\mathbf{+1.4*10-11}\theta^{\mathbf{3}} \quad \mathbf{for} \quad \mathbf{20^0C} \leq \theta \leq \mathbf{805^0C} \tag{3.5}$$

$$\epsilon_{\mathbf{c}}(\theta) = \mathbf{12*10-3} \quad \mathbf{for} \quad \mathbf{805^0C} \leq \theta \leq \mathbf{1200^0C} \tag{3.6}$$

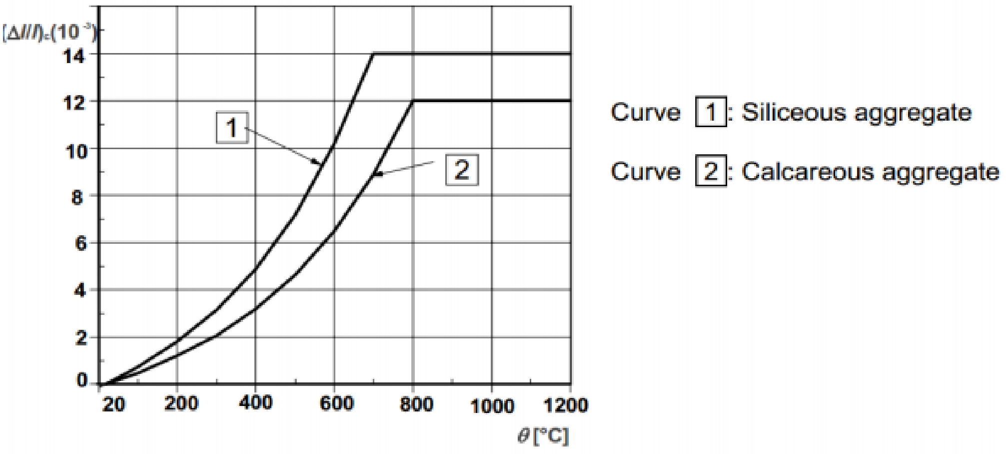


Figure 3.3: Thermal elongation of concrete with temperature [10]

3.3 Thermal Properties of reinforcing

3.3.1 Thermal elongation of reinforcing

Reinforcing steel:

$$\epsilon_s(\theta) = -2.416 * 10^{-4} + 1.2 * 10^{-5}\theta + 0.4 * 10^{-8}\theta^2 \quad \text{for} \quad 20^0C \leq \theta \leq 750^0C \tag{3.7}$$

$$\epsilon_s(\theta) = 11 * 10^{-3} \quad \text{for} \quad 750^0C \leq \theta \leq 860^0C \tag{3.8}$$

$$\epsilon_s(\theta) = -6.2 * 10^{-3} + 2 * 10^{-5}\theta \quad \text{for} \quad 860^0C \leq \theta \leq 1200^0C \tag{3.9}$$

3.3.2 Specific heat

$$C_a = 425 + 7.73 * 10^{-1}\theta - 1.69 * 10^{-3}\theta^2 + 2.22 * 10^{-6}\theta^3 \quad \text{for} \quad 20^0C \leq \theta \leq 600^0C \tag{3.10}$$

$$C_a = 666 + 13002(738 - \theta) \quad \text{for} \quad 600^0C \leq \theta \leq 735^0C \tag{3.11}$$

$$C_a = 545 + 17820(-731 + \theta) \quad \text{for} \quad 735^0C \leq \theta \leq 900^0C \tag{3.12}$$

$$\mathbf{C_a = 650 \quad for \quad 900^0C \leq \theta \leq 1200^0C} \tag{3.13}$$

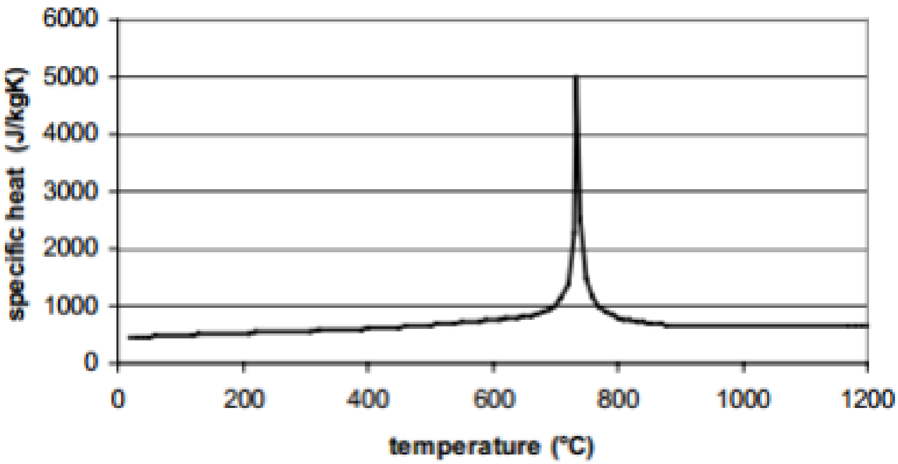


Figure 3.4: Variation of the specific heat of steel with temperature [10]

3.3.3 Thermal conductivity

The thermal conductivity of steel depends mainly on the composition of the material and decreases with increasing temperature. The thermal conductivity of steel is assumed to be high enough to allow the assumption that normal size sections have a uniform temperature throughout [14].

$$\lambda_\mathbf{a} = \mathbf{54 - 3.33 * 10^{-2}}\theta \quad \mathbf{for} \quad \mathbf{20^0C} \leq \theta \leq \mathbf{800^0C} \tag{3.14}$$

$$\lambda_\mathbf{a} = \mathbf{27.3} \quad \mathbf{for} \quad \mathbf{800^0C} \leq \theta \leq \mathbf{1200^0C} \tag{3.15}$$

3.4 Mechanical properties of Concrete

At elevated temperatures, the mechanical behavior of concrete is complex, involving strong non-linearity, different failure mechanisms under compression and tension (crushing or cracking), and other temperature-dependent effects such as thermal expansion and . Concrete temperature-dependent mechanical properties, including compressive and tensile strength, modulus

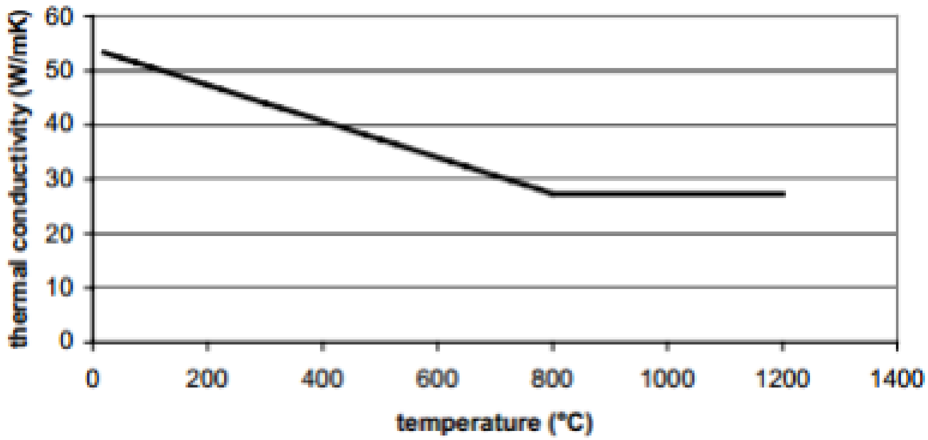


Figure 3.5: thermal conductivity of steel with different temperature [10]

of elasticity, Poisson's ratio and component of strain are discussed in this section.

3.4.1 Compressive strength of concrete

Compressive strength of concrete decreases with increasing of temperature. It can be seen that concrete with siliceous aggregates undergoes a rapid loss in strength at a temperature around 450^0C, where temperature around 700^0C[17] The strength-temperature relationship defined in Euro code [16] for concretes with siliceous and calcareous aggregates is plotted in figure below.

3.4.2 Tensile strength of concrete

The tensile strength of concrete also decreases with increasing temperatures. Compared to the compressive strength, the tensile strength shows a greater relative decrease and thus, is more responsive to the effects of temperature. The tensile strength is affected by the mix portions and significantly by the type of aggregate.

3.4.3 Poisson's ratio

Based on the test data, the Poisson's ratio of concrete is taken as 0.20 at 20^0C and to remain constant until 150^0C. Beyond the latter temperature, the Poisson's ratio is assumed to decrease linearly to 0.1 at 400^0C and to

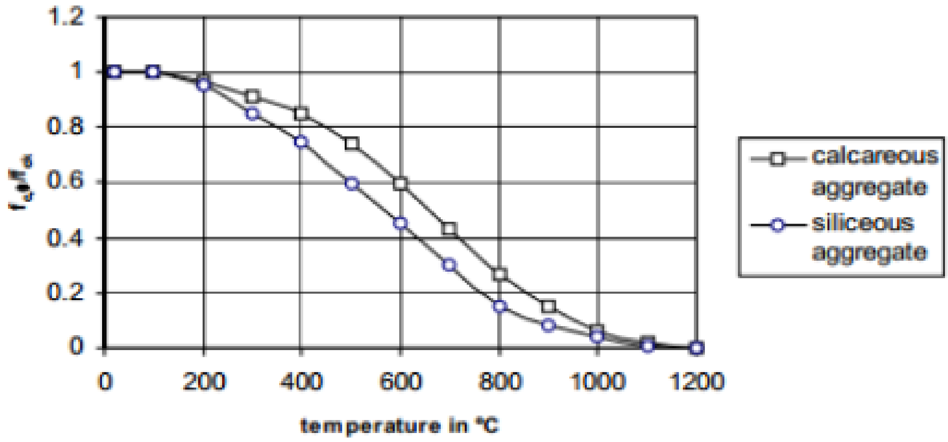


Figure 3.6: Ratio of compressive strength according to euro code2 [10]

further decrease linearly down to zero at 1200^0C. In this paper constant Poisson's ratio 0.2 has been used.

3.4.4 Concrete density

The density of concrete is taken to have constant value of 2400 Kg/m^3 for all temperature change.

3.4.5 Components of strain

$$\epsilon = \epsilon_{\mathbf{th}}(\mathbf{T}) + \epsilon\sigma(\tilde{\sigma}, \sigma, \mathbf{T}) + \epsilon_{\mathbf{cr}}(\sigma, \mathbf{T}, \mathbf{t}) + \epsilon_{\mathbf{tr}}(\sigma, \mathbf{T}) \quad (3.16)$$

Where ϵ = total strain, ϵ_{tr} = transient strain
ϵ_{th} = thermal strain, $\mathbf{T}$ = temperature
$\epsilon\sigma$ = stress related strain, σ = stress
ϵ_{cr} = creep strain, $\tilde{\sigma}$ = Stress history

3.4.6 Modulus of elasticity

During heating the modulus of elasticity decreases. This is due to the breakage of bonds in the microstructure of cement paste as well as to the increase of short-time creep at increasing temperature.

$$\mathbf{E_{cT} = 1.0 * E_c \quad for \quad 20^0C \leq \theta \leq 100^0C} \quad (3.17)$$

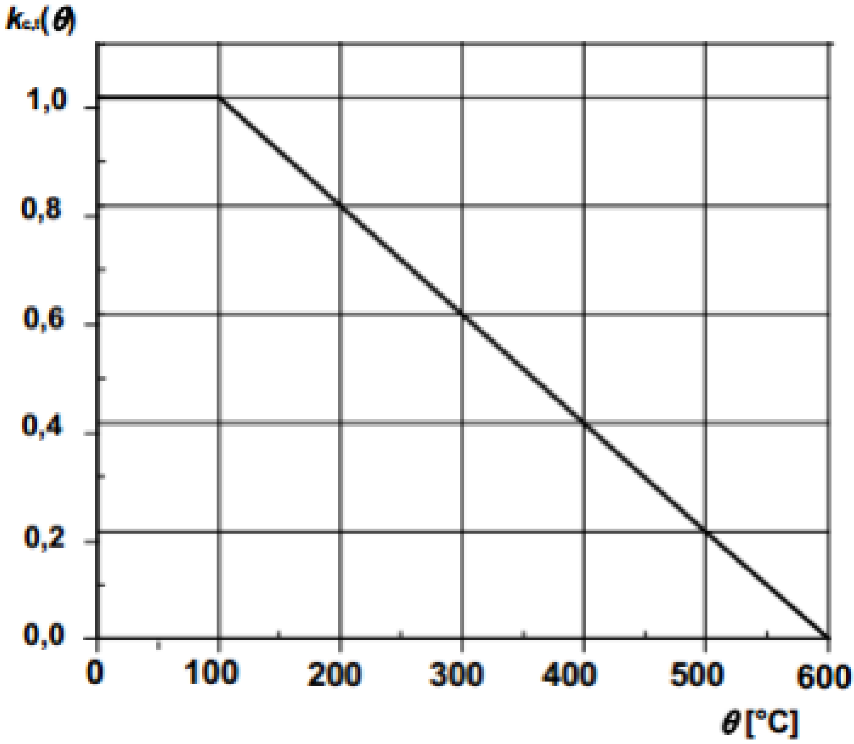


Figure 3.7: Reduction in tensile strength according to euro code [10]

$$\mathbf{E_{cT} = (1.015 - 0.00154\theta + 2 * 10^{-7}\theta^2 + 3 * 10^{-10}\theta^3)E_c \quad for \quad 100^0C \leq \theta \leq 1000^0C} \tag{3.18}$$

$$\mathbf{E_{cT} = 0 \quad for \quad \theta \geq 1000^0C} \tag{3.19}$$

3.5 Mechanical properties of steel

3.5.1 Strain component

The total strain of steel can be calculated as the sum of three strain components similar to the total strain of concrete according the following formula,

$$\epsilon = \epsilon_{\mathbf{th}}(\mathbf{T}) + \epsilon\sigma(\sigma, \mathbf{T}) + \epsilon_{\mathbf{cr}}(\sigma, \mathbf{T}, \mathbf{t}) \tag{3.20}$$

Where

ϵ =total strain,	ϵ_{cr} =creep strain
ϵ_{th} =thermal strain,	T =temperature
$\epsilon\sigma$ = stress related strain,	σ = stress

3.5.2 Steel density

The density of steel is remaining essentially constant with temperature and therefore is assumed to be 7850 kg/m^{3}k.

3.5.3 Deformation properties of materials

Thermal expansion, creep strain are deformation properties of materials are dependent on the chemical composition, aggregate type and chemical reactions during heating in the concrete and for steel the thermal expansion depends on the molecule composition of the steel bars.

3.5.4 Thermal expansion of concrete

When concreted exposed to fire it goes under expansion. The thermal expansion varies with temperature. The thermal expansion of concrete increases from zero at room temperature to about 1.3% at 700^{0}C and then generally remains constant through 1000^{0}C. This increase is substantial in the 20 – 700^{0}C temperature range and is mainly due to high thermal expansion resulting from constituent aggregates and cement paste in concrete. Thermal expansion of concrete is complicated by other contributing factors such as additional volume changes caused by variation in moisture content, by chemical reactions (dehydration, change of composition), and by creep and micro-cracking resulting from non-uniform thermal stresses. In some cases, thermal shrinkage can also result from loss of water due to heating, along with thermal expansion, and this might lead to the overall volume change to be negative, that is, shrinkage rather than expansion.

3.5.5 Thermal expansion of steel

Steel rebar show elongation behavior under elevated temperatures. If the grades of rebar were higher it shows less elongation and it depends on ductile behavior of the steel. At high temperatures the steel reinforcement show ductile behavior and it causes increase in deflection of the structural members. The elongation ratios were increased up to 300^{0}C, while the material becomes brittle with decrease of the elongation values.

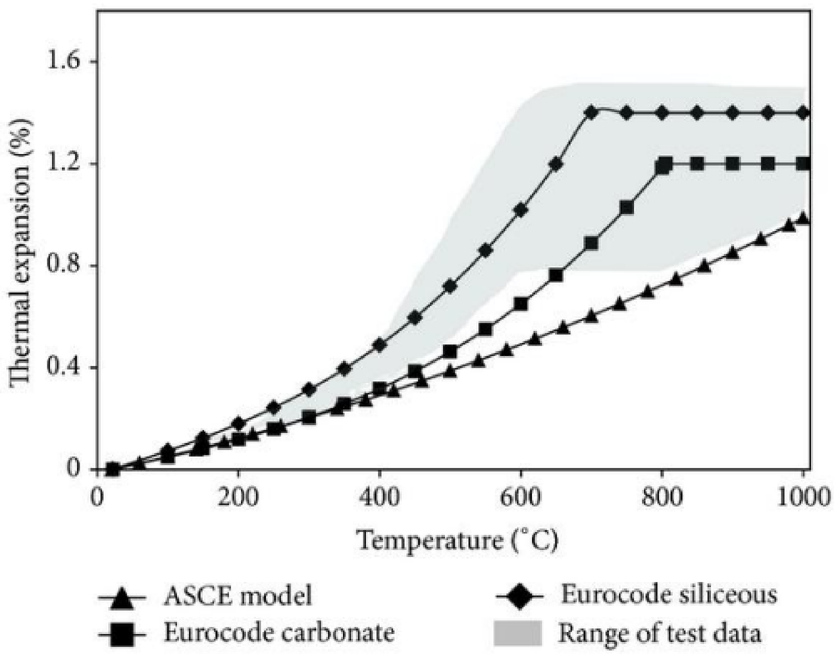


Figure 3.8: Thermal expansion of concrete [10]

3.6 Finite Element Modeling

3.6.1 Abacus software

The commercial finite element software Abaqus[]is the most widely used software in the academic research of material and geometric nonlinear analysis due to the flexibility that it provides for the users with numerous options for materials models, analysis and solutions techniques.

Material modeling in ABAQUS

The 3D BEAM reinforced concrete was modeling using ABAQUS 6.1 software version. The concrete beam modeled using solid element, for heat transfer analyses. There are three type of modeling in abacus. The smeared crack model,The brittle cracking model, The concrete damaged plasticity model. concrete damage plasticity used for this study.

Concrete damage plasticity

The CDP model needs a complete stress-strain curve of concrete under compression to define the compressive behaviour. The stress-strain curve can be defined beyond the ultimate stress into the strain softening region. Two parameters are required to be defined in the tabular format, namely compressive stress σ_c(i.e., yield stress) and the inelastic strain ϵ_{cin}.

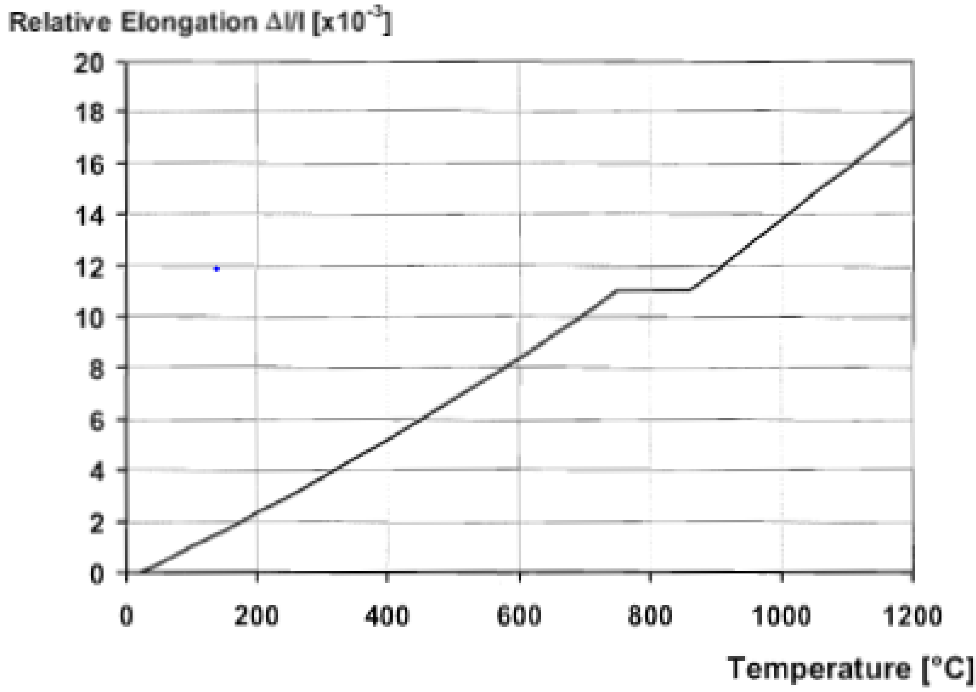


Figure 3.9: Thermal elongation of steel [10]

Creating numerical model

The section was modeled in Abaqus CEA software in order to find the temperature distribution over the cross section in different times of exposure. The software program requires number of parameters and characteristics inputs to analyze the problem. The following steps have been used to produce the model and read the results.

Part In Abaqus there is a section which called "Part". In this section model can be drawn by knowing the geometry of the beam. The coordinates of the points were determined in millimeter unit, therefore in all other sections, if it is referred to length, the unit is considered to be in millimeter.

Property

In this part both steel and concrete property is fill based on euro code and previous research. Density conductivity, specific heat, concrete damaged plasticity, expansion coefficient, modulus of elasticity poisons ratio was based on euro code, and geometrical model based on the previous experimental research.

Reinforcement steel

Steel is a homogeneous material and the stress-strain behavior can be

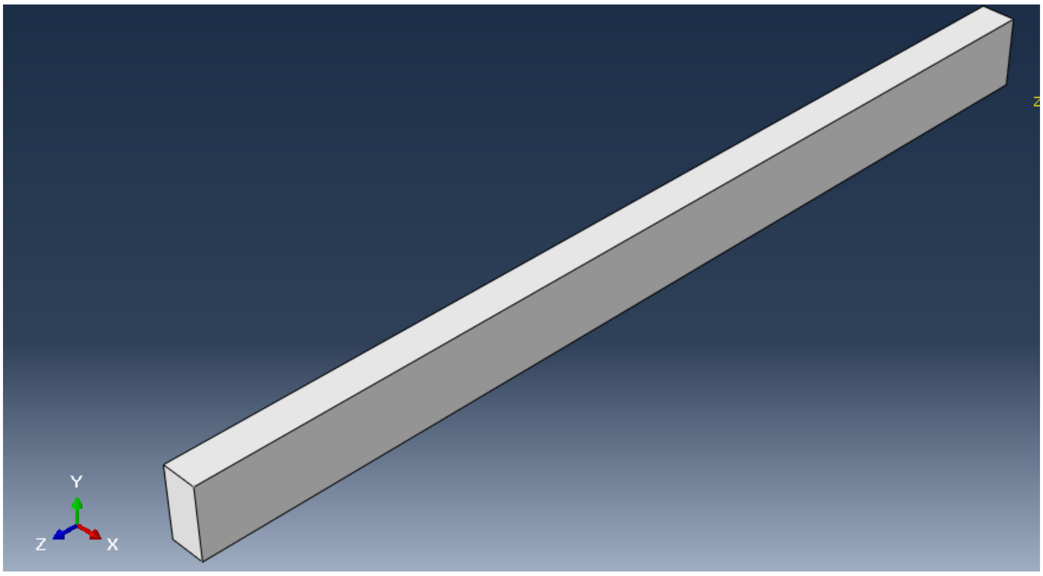


Figure 3.10: Concrete beam layer FEM model

assumed to be identical in tension and compression. Steel bars in reinforced concrete members are normally long and relatively slender and, therefore, they can be generally assumed to be capable of transmitting axial forces only.in this study three different bar diameter are used to investigate the effect of bar diameter on different temperature.

Assembly Modeling between Concrete and Reinforcing

The concrete plate and beams are constrained by the 'assembly' module 'create instance and translate instance' command. The translate instance command in abaqus is used to bind two types of element. this section, beam (part 1) and Steel bars (part 2) are assembled together. In order to assemble these two parts, firstly it is needed to extract holes corresponding to steel bars from the beam. Then, by adding steel bars to part 1 in the positions of holes the model become complete and new part will be created (Part 3). At the end, it is better to make part 3 dependent in order to have better meshing.

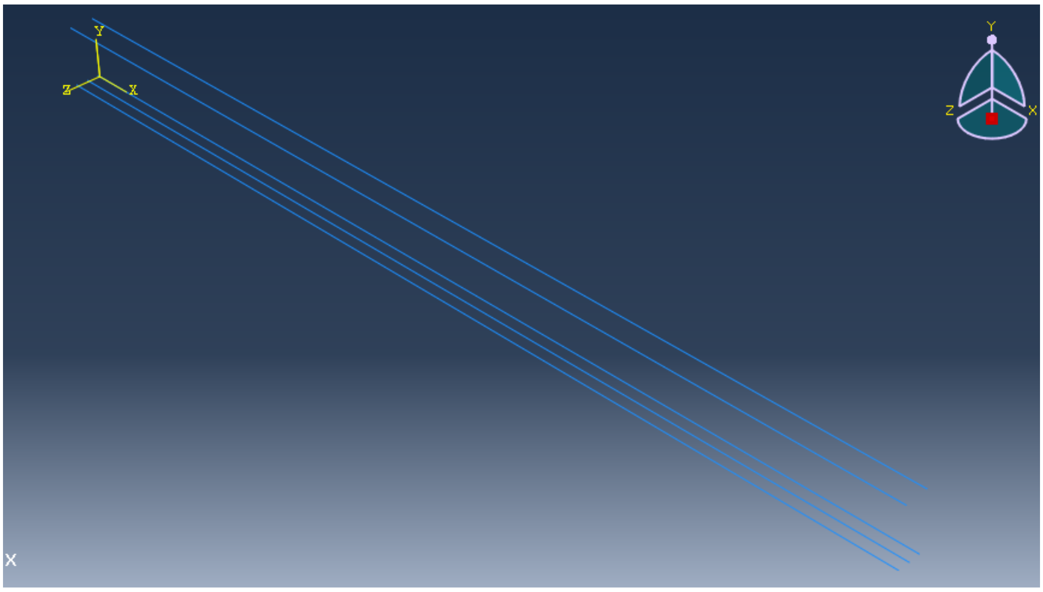


Figure 3.11: Steel layer FEM model

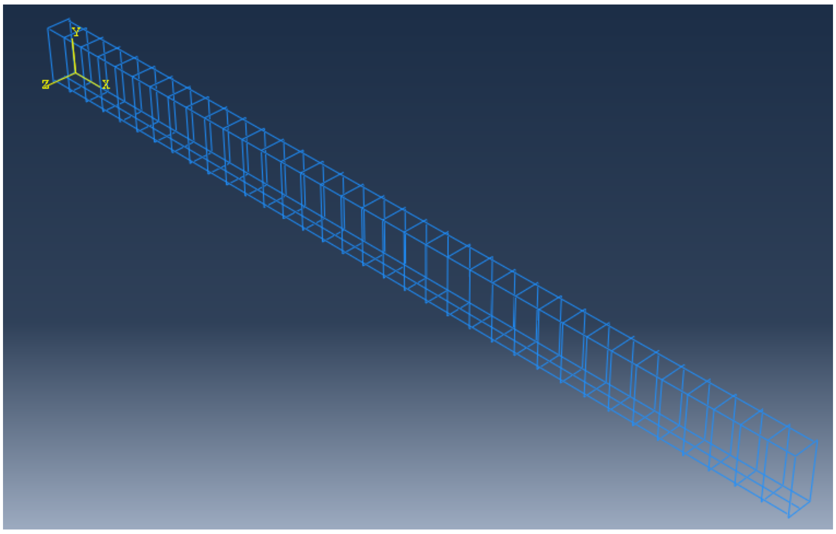


Figure 3.12: Stirrup and steel layer FEM modell

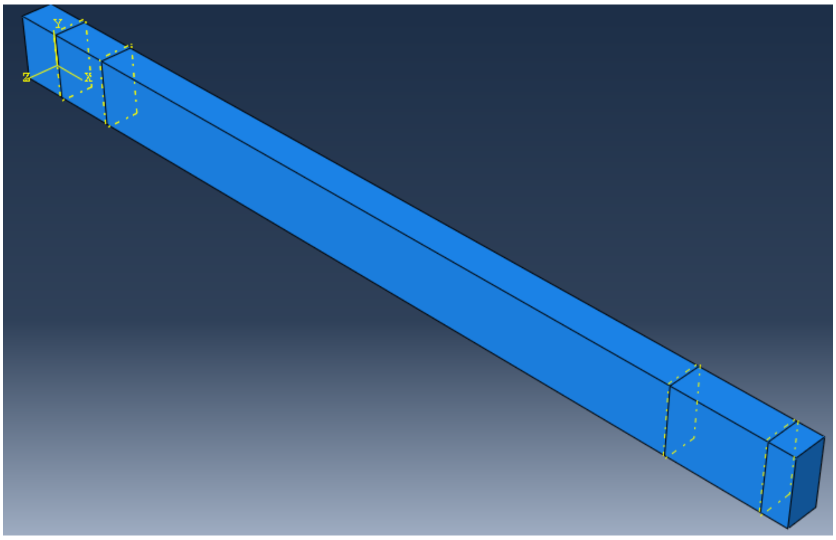


Figure 3.13: Reinforced concrete beam layer FEM model

Interaction

Interaction is the part that the property and characteristic of fire will be defined. Surface radiation and surface film condition has been defined.

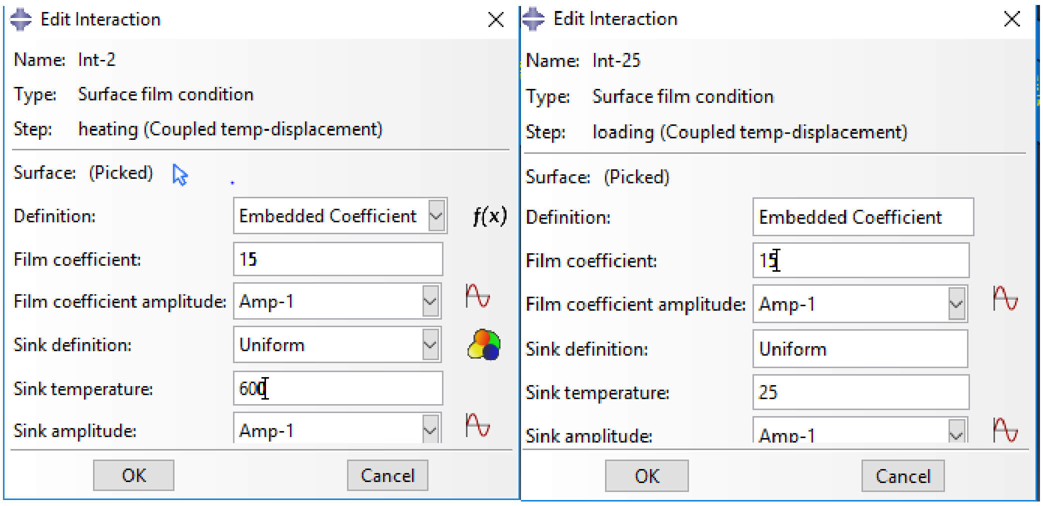


Figure 3.14: Interactions input to FEM model

Mesh size and Element type

As an initial step, the finite element analysis requires meshing of the model. Hence, the model is divided into number of small elements. After the application of the load, the stress and the strain are calculated at integration points of these elements. The approximate mesh size used in this study is 50. The element types used for thermal analysis were 3D eight-node continuum (DC3D8).The stress element used were C3D8R. This is defined as a three-dimensional (3D), continuum (C), hexahedral and an eight-node brick element with reduced integration (R).

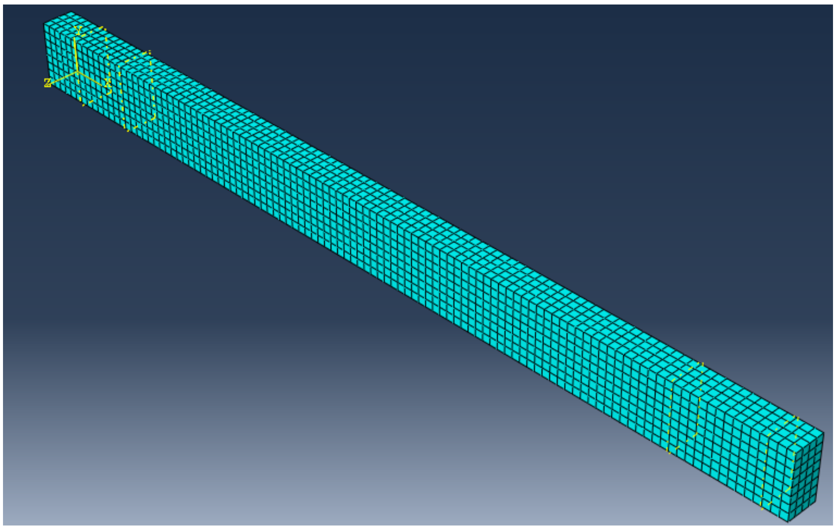


Figure 3.15: Mesh of RC beam layer

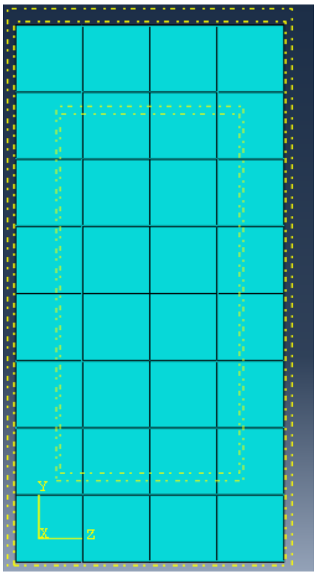


Figure 3.16: Side view of RC beam

Load, Boundary condition and predefined field

The heat transfer analysis was carried out by applying the ISO834 temperature time curve into node of the bottom and two side of beam as amplitude tabulated data and for unexposed side Heat transfer analysis is independent of support boundary condition since no displacement is involved. Three loading steps were used for structural analysis. The first step is initial loading, $25C_0$ magnitude were applied on beam.The second steps were the output of thermal analysis which is applied as predefined load on beam. The third steps were mechanical loading; mechanical load was applied on beams at magnitude of 24.688 KN/mm^2 in the negative Y-direction. Boundary condition used were, U_x=U_y=U_z=0 on left support and U_y =0 for right support. Rotation at both support and U_x, U_z at right support is non-zero.

Distributed load on beam=24.688 KN/mm^2 pressure = 24688/0.2 = 123440/ 0.2 is width of the beam.

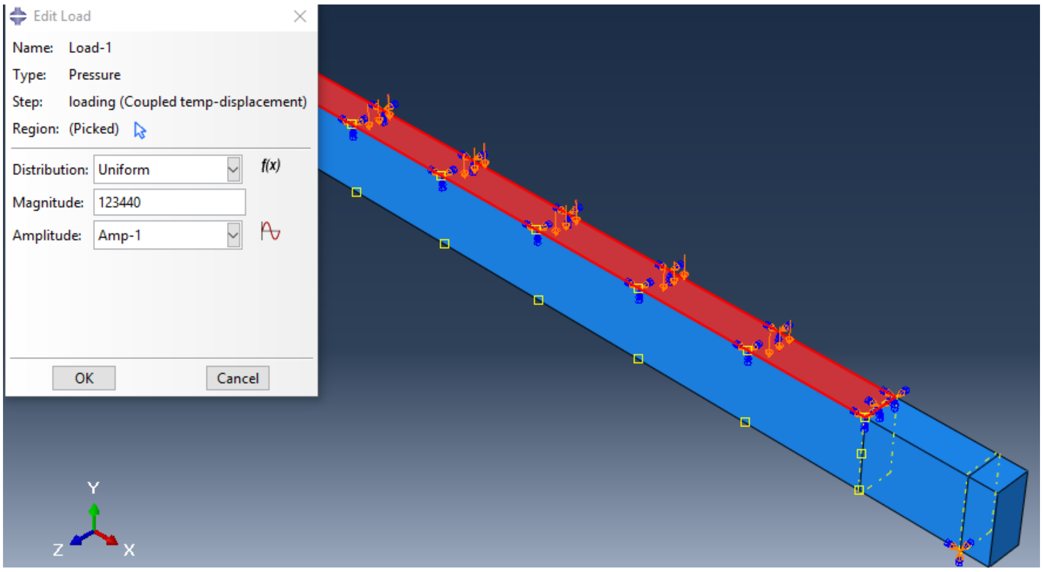


Figure 3.17: Loading and boundary condition RC beam

Steps of analysis in ABAQUS

In this part, the method of analyzing and its required parameters were defined. Since the model is carrying load and also exposed to fire, the method has been chosen is "coupled temp-displacement". Time period is 7200 seconds and was used transient response. The outputs are "stresses", "stress misses", "deflection","Nodal temperature (NT)", for every increments.

The tensile strength of concrete also decreases with increasing temperatures. Compared to the compressive strength, the tensile strength shows a greater relative decrease and thus, is more responsive to the effects of temperature. The tensile strength is affected by the mix portions and significantly by the type of aggregate.

Thermal analysis: The Euro code temperature-dependent thermal properties (thermal conductivity, specific heat, density) of concrete and reinforcing steel are built into the program.

Mechanical analysis: Mechanical analysis is the second step of analysis conducted in this study to determine structural response of concrete beam exposed to fire. Finite Element software Abaqus is used to predict the structural response to the temperature increase. The nodal temperatures from the time varying nodal temperature data from the heat transfer analysis is applied as a boundary condition on the structural response model analysis. Nonlinear temperature-dependent material property (Poisson's ratio, compressive strength, tensile strength, Young's modulus, and yield strength) in accordance with Euro code 2 [15] and is constant along the length of the beam element.

Geometrical modeling: The structural system modeled in this study is simply supported beam. The dimensions were length 5 meter, depth 400 mm and width 200 mm.RC beam reinforced bar used were 16 .diameter and top and bottom of beam respectively for validation. But for other analysis 12, 14 16 mm diameter was used in different temperature and duration of time.

Beam geometry
Span, L: 5.0 m
Depth, h: 400 mm
Width, b: 200 mm

Concrete properties
Compressive strength (ambient temperatures): 30 N/mm^2
Elastic modulus (ambient temperatures): 32000 N/mm^2
Tensile strength: 3 N/mm^2
Concrete model (thermal and mechanical): Siliceous aggregate

Axis distance of reinforcing bar to concrete surface:
Bottom, top and both side: 25 mm

Reinforcing steel properties
Yield strength (ambient temperatures): 347.826 N/mm
Elastic modulus (ambient temperatures): 210000 N/mm^2
Steel model: cold worked steel Bar diameter: 16 mm for bottom and top.
Number of bars at the top: 2 Number of bars at the bottom: 3
Stirrups: 8mm diameter c/c 180 mm

Loads Total load: 24.688kN/mm^2
Fire exposure: ISO 834 standard fire (30, 60, 90 and 120 minute)

Chapter 4

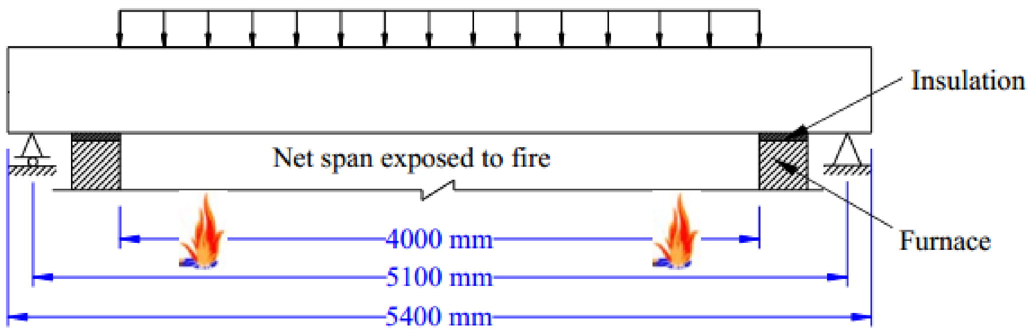
Result and Discussion

4.1 Overview of the FEA result

In this chapter, the result and the model is displayed in the figure and diagram. From the mechanical analysis, the results focus on mid-span deflections, stress along x (s11) in concrete for RC beam. Each model was considered in a heat transfer analysis and mechanical analysis. All results that represent temperature data origins from the heat transfer analyses, while all other data is taken from the mechanical analyses. Finite element validations are discussed to check the accuracy of present FE model.

4.2 Validation of the FE model

The dimensions and reinforcement details of the beam are in the shown in the Figure below The reinforcing steel had 240 MPa and 380 MPa of yield stress and tensile strength, respectively and 210000 MPa modulus of elasticity. The concrete cube strength is 23.1 MPa and 29000 MPa modulus elasticity of concrete. During the test slab with thickness 80 mm was placed over the beam and distributed load of 300 kg/m^2 was applied on the top slab. The total load acting on the beam consisted. The distributed load and self-weight of the slab. During heat transfer the beam is subjected to ISO834 on two side and bottom of beam. And for unexposed surface and initial load step 27^{0}C was applied. All material input and models was done with the procedure according to the present FE model. Temperature verses deflection and temperature versus exposure time of the beam selected for validation.



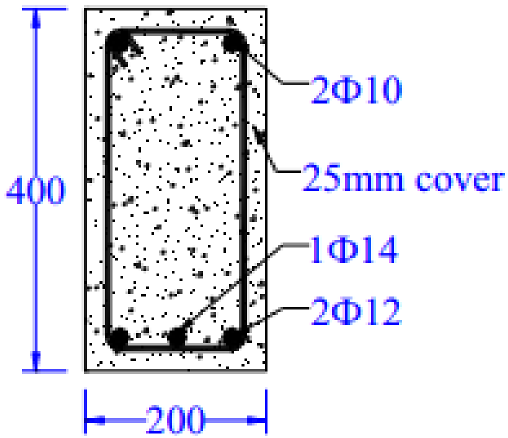


Figure 4.1: Detail of specimens (200 mm * 400 mm * 5400 mm): elevation and cross section [23]

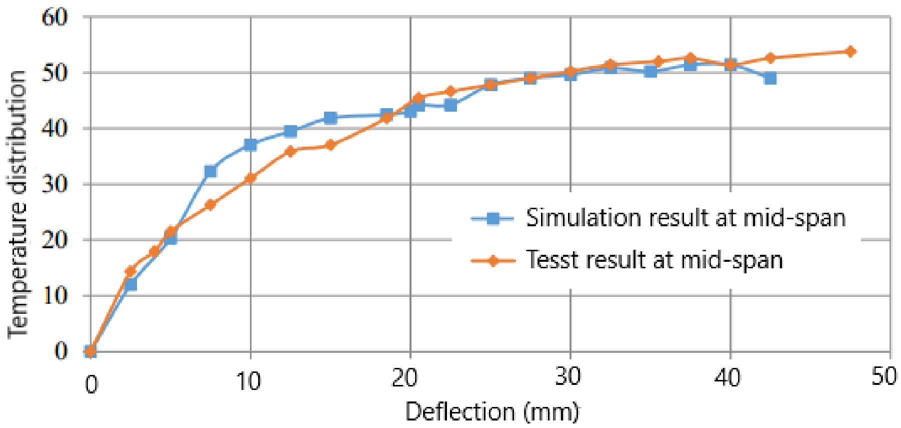


Figure 4.2: Comparisons of the RC beams tested by Wu et al: The predicted and measured deflection at mid-point of b

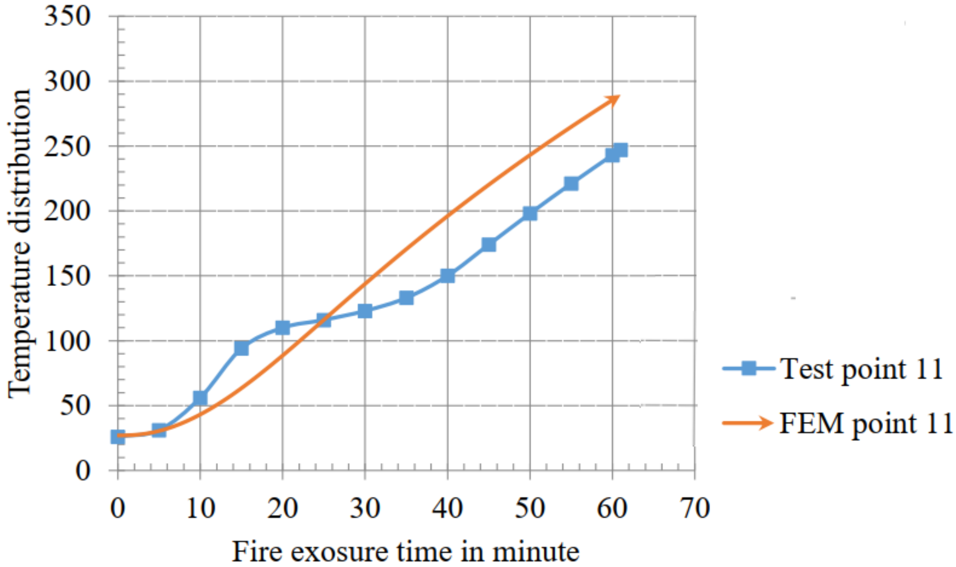


Figure 4.3: Comparisons of the RC beams tested by Wu et al: temperature Vs duration of time

4.3 Results of RC beam

Thermal analysis is used for the determination of nodal temperature distribution along the cross section of the beam. The Geometrical modeling type of beam with the same dimension is selected. and the same thermal analysis was conducted for the beam. The value of nodal temperature is uniform longitudinally and different along center of the beam. because of concrete cover. The results from ABAQUS are presented in table 4.1 at different point of the beam along cover and diameter of bar for fire exposure of 30, 60, 90, 120 minutes. However the concrete cover and bar diameter are used simultaneously for modeling of RC beam. Because euro code recommend concrete cover for different diameter of bar, but not specify the effect of concrete cover on different temperature and duration of time.

Table 4.1: Summary of values of nodal temperatures for different time of exposure

Node	Time in minute	Temperature
2717	30	830.127
	60	930.801
	90	994.857
	120	1010.01
2730	30	218.954
	60	376.205
	90	499.681
	120	569.682
3632	30	187.822
	60	322.777
	90	423.914
	120	514.058
2627	30	86.055
	60	159.276
	90	206.76
	120	287.124

Thermal analysis nodal temperature-time curves were obtained. As expected the result indicated that as time of fire exposure increased temperature distribution value also increased. As shown on Table 4.1 above at different node different temperature is obtained for different time of exposure.

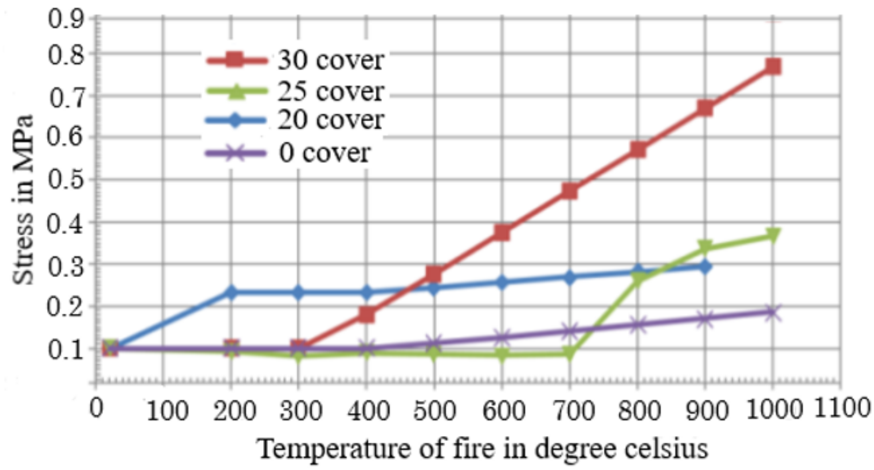


Figure 4.4: Varation of stress with temperature and concrete cover

From thermal analysis nodal as concrete cover increased the value of nodal temperature decreased along the center of the beam, for different fire exposure duration different values of nodal temperature obtained at the same node. As can be seen, temperature is maximum at exposed surface of temperature of beam and minimum at unexposed side. As time increased nodal temperature also increased As the time of exposure increased nodal temperature also increased and maximum temperature occurred at the surface exposed to fire whereas minimum temperature at internal section of beam. As shown in the Figure 4-3 concrete cover increased the value of stress increased, When the concrete cover 30 the stress along the center of the beam is highly increase and the concrete cover is 25 the stress along the center of the beam is decrease half of 30 concrete cover.

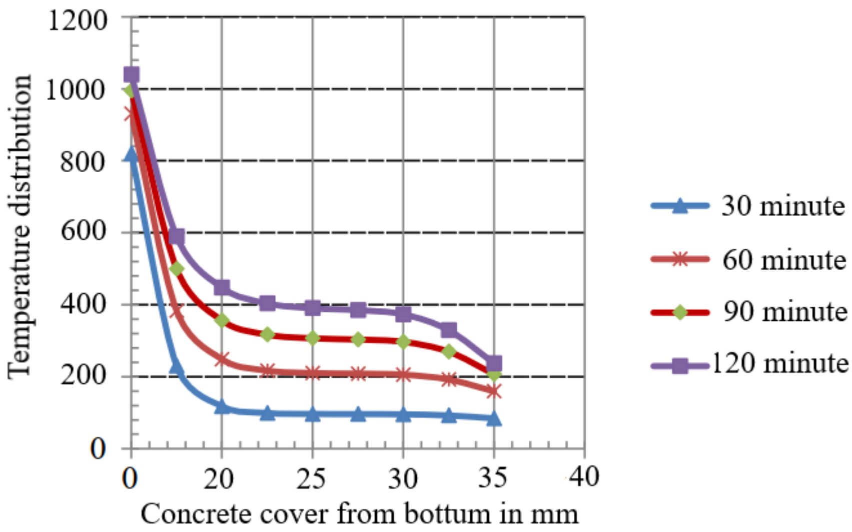


Figure 4.5: Temperature variation along concrete cover

As concrete cover increased the value of nodal temperature decreased along the center of beam. For different fire exposure duration, different values of nodal temperature obtained at the same node. As its seen temperature is maximum at exposed surfaces of beam and minimum at unexposed side. As time increased nodal temperature also increased. Numerical value is set in appendix D.

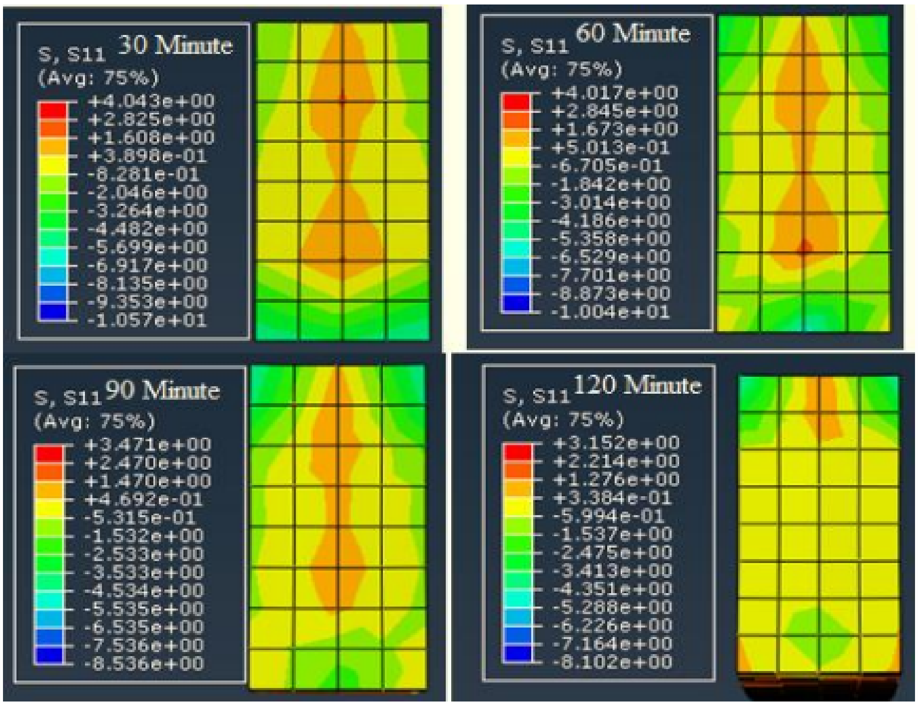


Figure 4.6: stress distribution result from abacus

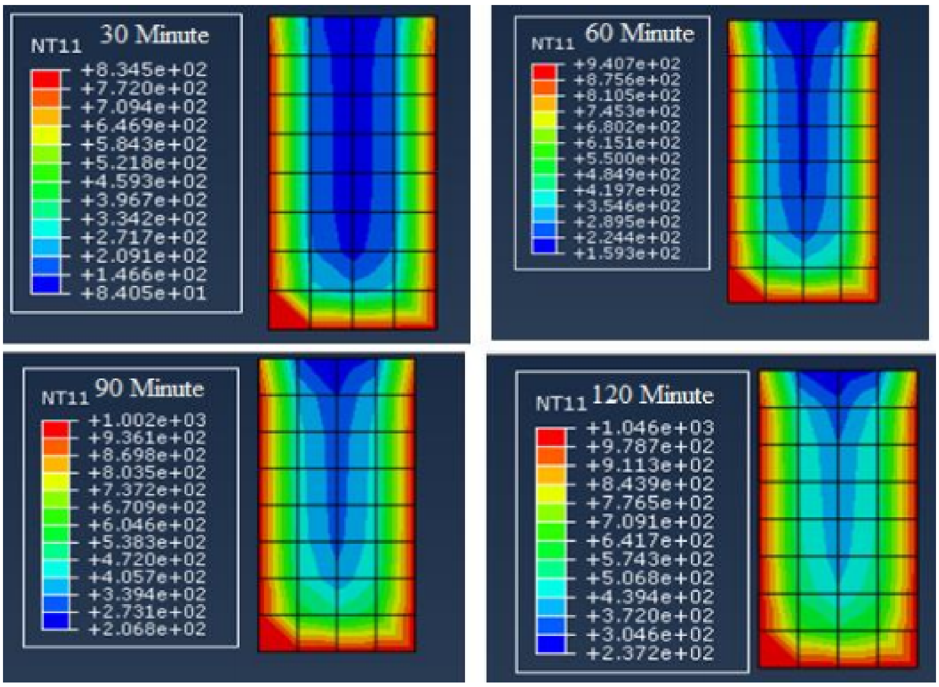


Figure 4.7: Screen shot of thermal analysis result

Vertical deflection of RC beam

The vertical deflection of the RC beam at mid span is increased as the time of exposure to fire increased. At exposure of 60 minute vertical deflection of beam increased highly by more than half of deflection at 30 minute. As exposure time increased to 90 and 120 minute the value of deflection added, but not increased with the rate at 30 and 60 minute. And as temperature increase vertical deflection at mid span increased. See appendix D-2.

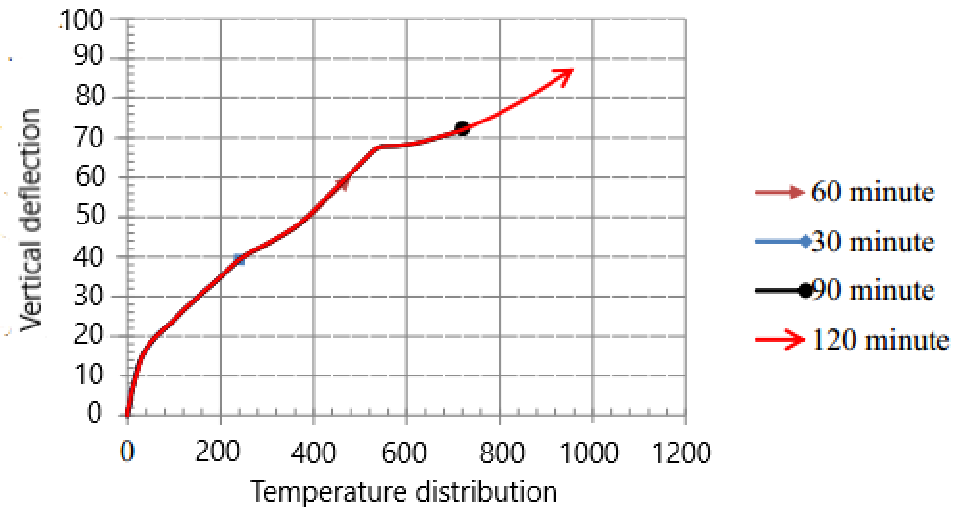


Figure 4.8: Variation of vertical deflection with temperature and duration of time

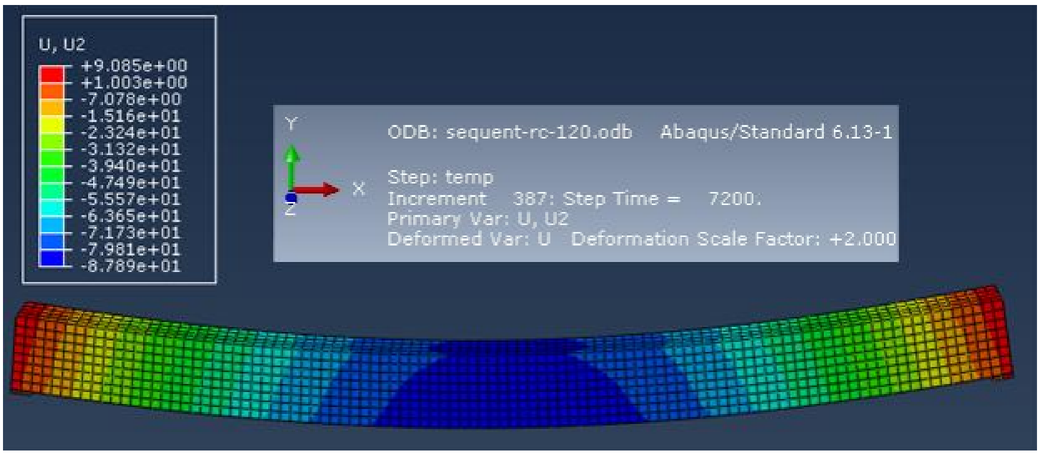


Figure 4.9: Variation of vertical deflection with temperature and duration of time

Stress Misses in RC beam

Along the concrete cover as exposure time increased at bottom of the beam stress misses distribution decreased. At 120 minute stress misses increased at 25 mm concrete cover and From bottom 30,60,90 minute stress misses decreased at 25 mm concrete cover. see appendix D-4.

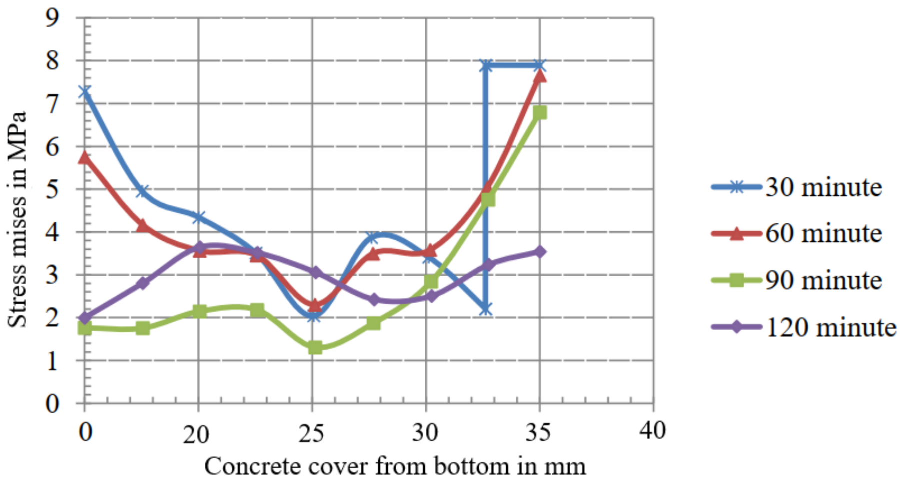


Figure 4.10: Stress misses distribution variations along concrete cover

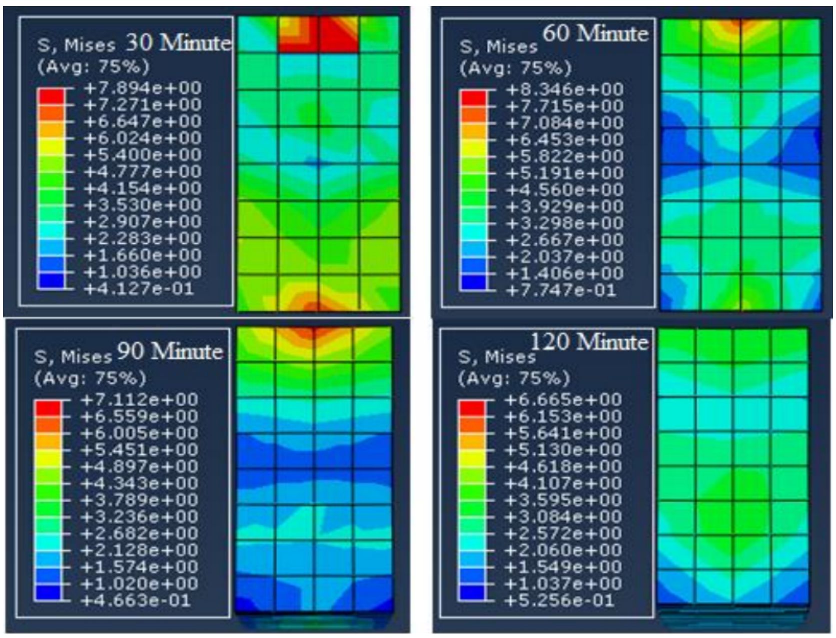


Figure 4.11: Screen shot of Stress mises result from abaqus

Chapter 5

Conclusions and Recommendation

5.1 Conclusion

Anon linear 3D FE model was developed in this study and validated the experimental program conducted by [10] as can be seen from the previous section. And it is good agreement between the measure experimental and predicted FE model. ABAQUS different steps of modeling has been conducted such as geometry, Material properties, mesh generation, and element selection, creating boundary condition, and step of analysis.Both thermal and mechanical properties of material are defined according to euro code and previous researches based on this researches the following conclusion are follow:

- When the concrete cover becomes 30, the stress along the center of the beam increase; when it becomes 25 and 20, the stress along the center of the beam will be much lower than that of the above cover.
- The result indicates that, as time of fire exposure increase nodal temperature value of RC beam also increases.
- Thickness of Concrete cover is increase the stress at the middle of the beam is increase. The diameter of the bar is direct relationship to concrete cover if the diameter of the bar is increase the thickness of concrete cover also increase.
- Deflection in RC beam at 60 minute increased by 1.49 times the deflection at 30 minute and slowly increased at 90 and 120 minute.
- 3D sequential fully coupled thermal stress analysis simulation is capable of determine the response of concrete beam exposed to fire

5.2 Recommendation

As seen from this research, Exposure to fire or elevated temperature of structural element is an extreme condition that leads to change of structural behavior so, The following recommendations are presented in order to develop and improve current findings.

- The beams were tested under the effect of concrete cover and bar diameter with different period of time with different nodal temperature. More research is needed to determine the effect of boundary condition and different loading.
- More variable should be considered to achieve more specified result. such as boundary condition, type of loading.
- Fire resistance rating of structural elements and/or whole structure of different type of structure should be consider such as RC, composite structure and steel structures.

Bibliography

[1] ABAQUS/Standard and ABAQUS/Explicit 6.13.1Analysis User's Guide.

[2] ACI Committee 2161. "Standard method for determining fire resistance of concrete and masonry construction assemblies", Detroit: American Concrete Institute; 1997.

[3] Arioz,O "Effects of Elevated Temperatures on Properties of Concrete." Fire Safety Journal, 2007,(42(8), 516-522.

[4] A.S. Usmani, J.M. Rotter, S. Lamont, A.M. Sanad, M. Gilli "Fundamental principles of structural behavior under thermal effects" Fire Safety Journal 36 (2001) 721–744, 22 March 2001.

[5] Bruce Ellingwood, T.D Lin "Flexural And Shear Behavior of concrete beams during fire", pg:440-458, 1991.

[6] Buchanan Andrew H., Structural Design for Fire Safety, New York, Wiley, 2001.

[7] Dwaikat, M.B.M "Flexural response of reinforced concrete beam exposed fire," (2009).

[8] EBCS(new Ethiopian building code)2005.

[9] Eurocode 1: Actions on structures – Part 1-2: "General actions – Actions on structures exposed to fire", November 2002, 59 pp.

[10] Eurocode 2: Design of concrete structures. ENV 1992-1-2 part 1.2: "General Rules Structural fire design, European Committee for Standardization", Brussels, 1995.

[11] Eurocode 3: Design of steel structures. Draft pr EN 1993-1-2 part 1.2: General rules Structural fire design, European Committee for Standardization, Brussels, 2002.

[12] European committee for standardization, Design of steel structures: General rules: - Structural Fire Design, EN 1993-1-2, Eurocode 3, and Part 1-2: Brussels, 2005.

[13] Hsu, H.J, and Lin,C.S, "Residual Bearing Capabilities of Fire-Exposed Reinforced Concrete Beams", International Journal of Applied Science and Engineering, Chaoyang University of Technology,2006, ISSN 1727-239.

[14] ISO 834-1975. Fire resistance tests elements of building construction. International Organization for Standardization; 1975.

[15] Kodur, V.K.R., Phan, L., "Factors governing the fire performance of high strength concrete systems, in Proceedings of the fourth international workshop Structures in Fire," Aveiro. p. 573-586 (2006).

[16] Kodur, V. and Dwaikat, M. (2009), "Macroscopic FE model for tracing the fire response of reinforced concrete structures," Engineering Structures, vol. 31, pp. 2368-3279.

[17] Lie, T.T., "Fire Temperature-Time Relations," Hdbk Fire Protection Eng'g, 3rd. ed. Chapter 4.8, SFPE, Bethesda, MD 2002.

[18] Lin, T. and Ellingwood, B. "Flexural and shear behavior of reinforced concrete beams during fire tests",(1987) .NBS-GCR-87-536, Portland Cement Association, IL, USA.

[19] Malholtra, H.L.: "Design of fire-resisting structures", Surrey University Press, London, 1982.

[20] Purkiss JA. "Fire safety engineering design of structures", 2nd ed. Butterworth Heineman: Oxford; 2007.

[21] Shettey MS (1988). "Concrete technology theory and practice", Third edition, p.361

[22] Wang WY, Liu B, Kodur VKR (2013) "Effect of Temperature on Strength and Elastic Modulus of High-Strength Steel", J Mater CivEng. 25(2):174–182.

[23] Wu HJ, Lie TT, Hu JY. Fire resistance of beam-slab specimens-experimental studies. Internal Report No. 641, Institute for Research in Construction, National Research Council Canada, Canada; 1993.

Appendix

Appendix-A

Mechanical properties of material used as input

Table A-1: Concrete Damage Plasticity parameter

Dilation angle $\psi(^0)$	31
flow potential eccentricity e $\psi(^0)$	0.1
Ratio of initial equibiaxial $\psi(^0)$ compressive yield stress to initial uniaxial compressive yield stress	1.16
Ratio of the second stress invariant on the tensile meridian. K_c	0.667
viscosity parameter μ	0

Table A-2: young's modulus of concrete (MPa)

Young's modulus elasticity E (MPa)	Poisson's ratio	Temperature (^{0}C)
32000	0.2	20
32000	0.2	100
22956.8	0.2	200
18531.2	0.2	300
14406.4	0.2	400
10640	0.2	500
7289.6	0.2	600
4412.8	0.2	700
2067.2	0.2	800
310.4	0.2	900

Table A-3: Expansion Coefficients of Concrete

Expansion Coefficient, α $(^0)$C	Temperature ^{0}C
0	20
$9.29*10^{-6}$	100
10^{-5}	200
$1.12*10^{-5}$	300
$1.29*10^{-5}$	400
$1.5*10^{-5}$	500
$1.76*10^{-5}$	600
$2.06*10^{-5}$	700
$1.79*10^{-5}$	800
$1.59*10^{-5}$	900

Table A-4: compression hardening of concrete

Yield stress (MPa)	Inelastic strain	Temperature(°C)
8.964143	0	20
15.8307	0.0004	20
24.36823	0.001	20
30	0.002	20
20.68437	0.004	20
11.95341	0.006	20
7.408483	0.008	20
4.967932	0.01	20

2.477064	0.0145	20
1.400778	0.0195	100
8.964143	0	100
11.16279	0.0002	100
25.06527	0.0017	100
30	0.0032	100
26.90446	0.0047	100
21.40127	0.0062	100
16.49318	0.0077	100
12.76596	0.0092	100
6.166143	0.0142	100
3.543307	0.0192	100
2.812836	0.0217	200
8.515936	0	200
15.18048	0.0009	200
26.07561	0.0029	200
28.5	0.0044	200
24.49364	0.0069	200
18.22155	0.0094	200
10.46339	0.0139	200
6.207735	0.0189	200
4.051911	0.0239	300
7.619522	0	300
15.77209	0.0016	300
23.11036	0.0036	300

25.5	0.0056	300
23.84205	0.0076	300
8.631131	0.0186	300
4.798415	0.0261	400
6.723108	0	400
13.0814	0.002	400
18.27617	0.004	400
21.49682	0.006	400
22.5	0.008	400
18.83721	0.013	400
9.574468	0.023	400
6.982759	0.028	500
5.732173	0	500
9.169002	0.002	500
12.28091	0.004	500
14.84721	0.006	500
18	0.0118	500
13.57542	0.0218	500
9.612781	0.0293	600
4.033865	0	600
6.375543	0.0036	600
7.848837	0.0056	600
13.5	0.0206	600
13.03648	0.0256	600
11.95194	0.0306	700

2.689243	0	700
4.250362	0.003	700
5.232558	0.005	700
9	0.02	700
8.690987	0.025	700
7.534884	0.0325	800
1.344622	0	800
2.125181	0.008	800
2.616279	0.01	800
4.5	0.025	800
3.98398	0.035	800
3.543307	0.04	900
0.717131	0	900
1.13343	0.003	900
1.395349	0.005	900
2.4	0.02	900
2.317597	0.025	900
1.770577	0.0375	900

Table A-5: Compression damage properties of concrete

Compression damage, dc	Inelastic strain	Temperature(°C)
0	0	20
0.018888	0.0004	20
0.093863	0.001	20
0.330667	0.002	20
0.743616	0.004	20
0.897425	0.006	20
0.951385	0.008	20
0.97361	0.01	20
0.990789	0.0145	20
0.996093	0.0195	20
0	0	100
0.003783	0.0002	100
0.105225	0.0017	100
0.330668	0.0032	100
0.563441	0.0047	100
0.727151	0.0062	100
0.826832	0.0077	100
0.886071	0.0092	100
0.963313	0.0142	100
0.984189	0.0192	100
0.988843	0.0217	100
0	0	200

0.019572	0.0029	200
0.157956	0.0044	200
0.330667	0.0069	200
0.604521	0.0094	200
0.775841	0.0139	200
0.909897	0.0189	200
0.959907	0.0239	200
0	0	300
0.03402	0.0016	300
0.150747	0.0036	300
0.330667	0.0056	300
0.513255	0.0076	300
0.920706	0.0186	300
0.96794	0.0261	300
0	0	400
0.027132	0.002	400
0.093863	0.004	400
0.200637	0.006	400
0.330667	0.008	400

0.626419	0.013	400
0.886071	0.023	400
0.930759	0.028	400
0	0	500
0.01565	0.002	500
0.047798	0.004	500
0.099077	0.006	500
0.330097	0.0118	500
0.69686	0.0218	500
0.834881	0.0293	500
0	0	600
0.012184	0.0036	600
0.027132	0.0056	600
0.330667	0.0206	600
0.461373	0.0256	600
0.576728	0.0306	600
0	0	700
0.012184	0.003	700
0.027132	0.005	700
0.330667	0.02	700
0.461373	0.025	700
0.626419	0.0325	700
0	0	800
0.012184	0.008	800
0.027132	0.01	800
0.330667	0.025	800
0.576728	0.035	800
0.670604	0.04	800
0	0	900
0.012184	0.003	900
0.027132	0.005	900
0.330667	0.02	900
0.461373	0.025	900
0.709533	0.02	900

Appendix-B

Thermal properties of material used as input (Euro code)

Table B-1: Thermal conductivity of concrete

Thermal Conductivity upper bound (W/m k)	Temperature(°C)
1.951408	20
1.7656	100
1.5526	200
1.361	300
1.1908	400
1.042	500
0.9146	600
0.8086	700
0.724	800
0.6608	900

Table B-2: Specific heat of concrete

Specific heat capacity (J/kg k)	Temperature(°C)
900	20
900	100
1000	200
1100	300
1100	400
1150	500
1200	600
1100	700
1100	800
1100	900

Mechanical properties of steel

Table B-3: young's modulus of reinforcing steel

Young's modulus of steel Es (MPa)	Poisson's ratio	Temperature(°C)
210000	0.3	20
210000	0.3	100
182700	0.3	200
151200	0.3	300
117600	0.3	400
84000	0.3	500
50400	0.3	600
16800	0.3	700
12600	0.3	800
10500	0.3	900

Table B-4: Expansion Coefficients of Reinforcing Steel

Expansion Coefficient, α (/°C)	Temperature(°C)
0	0
1.25E-005	100
1.29E-005	200
1.33E-005	300
1.37E-005	400
1.41E-005	500
1.45E-005	600
1.51E-005	700
1.31E-005	800
1.34E-005	900

Table B-5: compression hardening of reinforced steel

Yield stress (MPa)	Plastic strain	Temperature(°C)
339.99	0	20
351.4209	0.0004	20
362.2377	0.0014	20
374.2805	0.0024	20
378.5468	0.0034	20
382.141	0.0044	20
385.2202	0.0054	20

387.8819	0.0064	20
	0.0074	20
390.1914	0.0084	20
392.1945	0.0094	20
393.9248	0.0104	20
395.4075	0.0114	20
396.6616	0.0124	20
397.7019	0.0134	20
398.5394	0.0144	20
399.1828	0.0154	20
399.6382	0.0164	20
399.9098	0.0174	20
400	0.0184	100
326.34	0	100
341.407	0.0005	100
354.1044	0.0015	100
362.3139	0.0025	100
368.6427	0.0035	100
373.8269	0.0045	100
378.2019	0.0055	100
381.9542	0.0065	100
385.2003	0.0075	100
388.0184	0.0085	100
390.4637	0.0095	100
392.5767	0.0105	

394.3878	0.0115	100
395.92	0.0125	100
397.1911	0.0135	100
398.2147	0.0145	100
399.0011	0.0155	100
399.5577	0.0165	100
399.8897	0.0175	100
400	0.0185	100
312.7824	0	200
326.4106	0.0003	200
343.5039	0.0013	200
353.8446	0.0023	200
361.6936	0.0033	200
368.0772	0.0043	200
373.4422	0.0053	200
378.0313	0.0063	200
381.994	0.0073	200
385.4295	0.0083	200
388.4076	0.0093	200
390.979	0.0103	200
393.1815	0.0113	200
395.0441	0.0123	200
396.5886	0.0133	200
397.832	0.0143	200
398.7871	0.0153	200

399.463	0.0163	200
399.866	0.0173	200
400	0.0183	200
275.3877	0	200
287.1596	0.0002	300
315.3745	0.0012	300
331.1739	0.0022	300
343.0011	0.0032	300
352.5618	0.0042	300
360.5693	0.0052	300
367.404	0.0062	300
373.2967	0.0072	300
378.4	0.0082	300
400	0.0182	300
214.1496	0	300
228.2535	0.0002	400
263.6338	0.0012	400
284.3818	0.0022	400
300.0349	0.0032	400
312.7311	0.0042	400
323.3851	0.0052	400
332.4895	0.0062	400
340.3458	0.0072	400
347.1536	0.0082	400
376	0.0182	

149.604	0	400
161.4311	0.0003	400
186.3297	0.0013	500
201.3042	0.0023	500
212.6568	0.0033	500
221.8849	0.0043	500
229.6381	0.0053	500
236.2688	0.0063	500
241.9936	0.0073	500
246.9563	0.0083	500
268	0.0183	500
88.42176	0	500
96.1584	0.0003	500
110.8593	0.0013	600
119.83	0.0023	600
126.6514	0.0033	600
132.2039	0.0043	600
136.8725	0.0053	600
140.8672	0.0063	600
144.3173	0.0073	600
147.3088	0.0083	600
167	0.0183	600
27.1992	0	600
30.39043	0.002	600
34.23697	0.003	600

36.70582	0.004	700
38.60551	0.005	700
40.16024	0.006	700
41.4716	0.007	700
42.59594	0.008	700
43.56837	0.009	700
44.41244	0.01	700
48	0.02	700
20.3994	0	700
23.52925	0.002	700
27.88123	0.003	700
30.74407	0.004	800
32.96143	0.005	800
34.7818	0.006	800
36.32	0.007	800
37.6404	0.008	800
38.78335	0.009	800
39.77603	0.01	800
44	0.02	800
16.9995	0	800
19.35308	0.002	800
22.42422	0.003	800
24.41942	0.004	900
25.95952	0.005	900
27.22185	0.006	

28.28749	0.007	900
29.20168	0.008	900
29.99266	0.009	900
30.67943	0.01	900
33.6	0.02	900
32.4		

Appendix-C

Thermal properties of material used as input

Table C-1: Thermal conductivity of steel

Thermal conductivity(W/m k)	Temperature(°C)
53.334	20
50.67	100
47.34	200
44.01	300
44.01	400
40.68	500
34.02	600
30.69	700
27.36	800
27.3	900

Table C-2: Specific heat of steel

Specific heat capacity(J/kg k)	Temperature(°C)
439.8018	20
487.62	100
529.76	200
564.74	300
605.88	400
666.5	500
759.92	600
1008.158	700
5000	800
803.2609	900

Table C-3: Density of concrete

DENSITY((Kg/m3)	TEMPERATURE(°C)
2400	20
2400	100
2400	200
2400	300
2400	400
2400	500
2400	600
2400	700
2400	800
2400	900

Table C-4: Density of steel

DENSITY((Kg/m3)	TEMPERATURE(°C)
7850	20
7850	100
7850	200
7850	300
7850	400
7850	500
7850	600
7850	700
7850	800
7850	900

Appendix-D

Output from FE model analysis of concrete beam

Table D-1: temperature distribution variation along concrete cover from bottom to top

30 minute		60 minute		90 minute		120 minute	
Concrete cover	temp	Concrete cover	temp	Concrete cover	temp	Concrete cover	Temp
0	820.127	0	930.801	0	994.857	0	1040.01
20	229.954	20	383.205	20	499.681	20	589.688
25	117.654	25	248.48	25	356.019	25	447.306
30	96.3429	30	216.811	30	316.684	30	403.35

Table D-2: Result from Reinforced concrete beam analysis unit used for dimension millimeter, time: second temperature degree centigrade. Deflection in mm.

	30 minute	60 minute		60 minute		90 minute	
time	Deflection	Time	Deflection	Time	Deflection	Time	Deflection
0	0	0	0	1720.02	37.9933	0	0
1	0.9947	1	0.99437	1740.02	38.2709	1	0.99437
1.1	0.99471	1.1	0.99437	1760.02	38.5503	1.35	0.99441
1.2	0.99472	3.17812	0.99629	1940.02	40.5811	1.575	0.99449
4.31719	0.99877	26.8493	1.42188	1960.02	40.7366	39.8239	2.81622
39.8239	2.81608	39.8239	2.81622	2140.02	42.153	43.0676	3.41342
53.215	5.89874	43.0676	3.41342	2160.02	42.3173	77.3667	6.53787
59.8668	6.39426	43.8785	3.58952	2180.02	42.4832	78.2327	6.57753
63.972	6.5421	45.0948	3.86624	2360.02	42.4832	180.022	12.8852
68.1299	6.60238	46.9194	4.294	2380.02	44.0537	260.022	15.6831
77.3667	6.53243	53.7615	5.90126	2400.02	44.2355	280.022	16.2107
79.5316	6.57199	79.5316	6.64939	2420.02	44.4196	300.022	16.704
140.022	6.64368	81.48	6.76764	2680.02	44.5856	320.022	17.2043
160.022	10.7167	84.4026	6.94825	2700.02	47.0506	340.022	17.6715
180.22	11.8431	220.022	14.4553	2720.02	47.2603	480.022	20.2399
200.22	12.881	360.022	18.1145	2980.02	47.4716	500.022	20.8103
220.22	13.7328	380.022	18.5678	3000.02	50.8051	520.022	21.0822
240.22	14.4592	380.022	18.9584	3260.02	51.1213	540.022	21.3616
460.022	15.1077	420.022	19.3019	3280.02	55.2038	680.022	23.0405
480.022	19.9767	440.022	19.6269	3420.02	55.5097	700.022	23.3048
600.02	21.9895	460.022	19.9388	3440.02	57.6411	860.022	25.8589
740.022	23.8842	660.022	22.7613	3600.0	57.9472	880.022	26.1814
880.022	26.2638	680.022	23.0288			900.022	26.4979
1060.02	28.865	860.022	25.8241			920.022	26.8071
1220.02	31.196	880.022	26.1436			940.022	27.1038
1440.02	34.1029	900.022	26.457			960.022	27.3863
1660.02	37.3042	1100.02	29.2546			1100.02	29.3196
1680.02	37.5984	1120.02	29.5688			1120.02	29.6351
1700.02	37.8815	1140.02	29.9027			1140.2	29.9701

1720.02	38.1555	1300.02	32.0583			1340.02	32.3951
1740.02	38.4314	1320.02	32.3214			1360.02	32.6568
1760.02	38.7093	1500.02	34.8198			1580.02	32.9178
1780.02	38.989	1520.02	35.113			1600.02	36.0984
1800.02	39.2708	1540.02	35.4038			1620.02	36.3898

90 minute				120minute			
Time	Deflection	Time	Deflection	Time	deflection	Time	deflection
1780.02	38.9896	3700.02	62.5776	0	0	1700.02	38.2408
1800.02	39.2766	3720.02	62.9019	1	0.9947	1740.02	38.5219
1820.02	39.5649	3740.02	63.2251	1.9125	0.9951	1780.02	39.0892
1940.02	40.7666	3920.02	66.1149	2.41875	0.99549	2000.02	41.3392
1960.02	40.9247	3940.02	66.4367	43.8785	3.58918	2040.02	41.6517
1980.02	41.0847	3960.02	66.7589	45.0948	3.8658	2060.02	41.963
2120.02	42.1947	4100.02	67.825	46.9194	4.29338	2200.02	42.9438
2140.02	42.3578	4120.02	67.8222	49.6562	4.97698	2220.02	43.1132
2160.02	42.5225	4120.02	67.839	84.4026	6.94195	2440.02	45.0235
2280.02	43.5494	4240.02	67.8489	88.7865	7.21356	2460.02	45.346
2300.02	43.7276	4260.02	67.8605	95.3623	7.65642	2500.02	45.5205
2320.02	43.9036	4280.02	67.8737	220.022	14.459	2660.02	47.3496
2460.02	45.0908	4300.02	67.8884	240.022	15.1075	2700.02	47.7824
2480.02	45.2619	4320.02	67.9047	360.022	18.1396	2900.02	50.3129
2500.02	45.4359	4340.02	68.2529	380.022	18.5956	2920.02	50.6146
2660.02	47.0518	4540.02	68.3048	540.022	21.1278	2960.02	52.9133
2680.02	47.2651	4560.02	68.9312	680.022	23.1017	3080.02	53.2369
2700.0	47.4804	4740.02	69.0194	700.022	23.368	3100.02	61.0439
2820.02	48.8511	4760.02	69.68	840.022	25.6124	3120.02	61.3657
3040.02	52.1597	4920.02	69.7693	860.022	25.9381	3320.02	64.589
3060.02	52.4957	4940.02	70.8186	940.022	27.19	3360.02	64.9104
3280.02	55.9972	5160.02	70.9042	1000.02	27.7518	3600.02	67.3107
3300.02	56.3056	5180.02	70.9864	1120.02	29.7355	3620.02	67.4274
3320.02	56.6131	5200.02	71.6858	1240.02	31.4487	3800.02	67.9016
3480.02	59.08	5360.02	71.8145	1260.02	31.7102	3840.02	67.9053
3500.02	59.3892	5380.02	71.9435	1440.02	34.1164	4020.02	68.0034
3520.02	59.6985	5400.02	72.34	1460.02	37.9616	4180.02	68.0272

120 minute			
Time	Deflection		
4360.02	68.381	5920.02	75.4074
4380.02	68.436	5940.02	75.5636
4560.02	68.9213	6080.02	75.7231
4720.02	69.0046	6100.02	76.8764
4920.02	69.7501	6120.02	77.0463
5060.02	70.4323	6260.02	77.2173
5220.02	70.5191	6400.02	78.4186
5240.02	71.1304	6420.02	78.5898
5360.02	71.2084	6540.02	79.6469
5380.02	71.7495	6660.02	79.8328
5400.02	71.878	6680.02	80.9774
5540.02	72.0067	6840.02	82.145
5560.02	72.96	6860.02	82.3491
5720.02	73.1006	6880.02	83.958
5740.02	74.1334	7100.02	86.571
5760.02	74.2668	7120.02	86.7709
5900.02	74.401	7200.02	87.5747

Table D-3: stress distribution variation along concrete cover in Reinforced concrete beam

30 minute		60 minute		90 minute		120 minute	
cover	stress	cover	stress	cover	stress	Cover	Stress
0	-9.5062	0	-12.533	0	-6.7317	0	-1.5755
20	-3.9007	20	-8.6554	20	-10.531	20	-2.3808
25	0.52382	25	-4.0815	25	-11.86	25	-13.229
30	-0.2406	30	-1.6879	30	-8.0602	30	-10.106

Table D-4: Stress misses distribution along concrete cover in Reinforced concrete beam

30 minute		60 minute		90 minute		120 minute	
cover	S, misses	cover	S, misses	cover	S, misses	Cover	S, misses
0	7.27645	0	5.75323	0	1.76136	0	1.99747
20	4.95433	20	4.16636	20	1.75481	20	2.80367
25	4.34116	25	3.56292	25	2.14787	25	3.64693
30	3.50905	30	3.45657	30	2.18204	30	3.51364