ANALYZING REBAR TEMPERATURE IN FIRE-DAMAGED REINFORCED CONCRETE BEAM: FINITE ELEMENT VALIDATION AND SIMPLIFIED METHOD COMPARISON.

Submitted by

Md. Hasibol Fahim

A Thesis Submitted to the Department of Civil Engineering, Daffodil International University in Partial Fulfillment of the Requirements for the Degree Of
Bachelor of Science in Civil Engineering

Department of Civil Engineering
Daffodil International University

June 2024

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June 2024

CERTIFICATION

This certifies that the student shown below completed the project and thesis titled **Analyzing Rebar Temperature in Fire-Damaged Reinforced Concrete Beams: Finite Element Validation and Simplified Method Comparison.** under my supervision. The investigation has been carried out at the labs of the Department of Civil Engineering, Faculty of Engineering, Daffodil International University, as part of the requirements for the Bachelor of Science in Civil Engineering degree. The presentation of the work was successfully held on 06 June 2024.

Signature of the candidate

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The project and thesis titled **Analyzing Rebar Temperature in Fire-Damaged Reinforced Concrete Beams: Finite Element Validation and Simplified Method Comparison.** submitted by Hasibol Fahim, ID No: 201-47-328, Session: Spring 2020, has been accepted as satisfactory. This work fulfils, in part, the requirements for the Bachelor of Science in Civil Engineering degree. The presentation of the work was held on 06 June 2024.

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DEDICATION

I dedicated my thesis to my beloved parents, whose steadfast support and generosity have been the cornerstone of my academic journey. Your support and confidence in my skills have been the primary motivation behind my actions.

I want to convey my sincere appreciation to my dear Father. Your unwavering assistance, motivation, and confidence have been the bedrock of my progress. The sacrifices and insights you have imparted to me have profoundly influenced my identity. This achievement is equally attributable to both you and me. I appreciate your role as my beacon of guidance.

I am grateful to my family, whose love, compassion, and patience have given me unwavering support. The unwavering support and confidence you have always shown in my aspirations have motivated me to achieve tremendous success.

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Abstract

This study focuses on analyzing the temperature distribution in fire-damaged reinforced concrete beams, utilizing both finite element analysis (FEA) and various simplified methods. The primary objective is to validate the temperature profiles obtained from experimental tests at different locations within the beams against FEA results and to compare these with predictions from simplified methods. The research identified that employing average conductivity values, an emissivity of 0.8, and a mesh size of 25mm in the FEA model yielded consistently accurate temperature predictions. Among the simplified methods evaluated, Wickstrom's method demonstrated the highest accuracy, with minimal error compared to FEA results, across different cover thicknesses and fire exposure durations. Kodur's method showed moderate accuracy, with errors higher than Wickstrom's but lower than those of Desai. Desai's method had the largest discrepancies, making it the least reliable. Additionally, the study confirmed that increasing the concrete cover thickness decreases the temperature at the reinforcement bars (rebars), due to enhanced insulation provided by the additional concrete, which slows heat transfer from the fire-exposed surface to the rebars. This research provides valuable insights for improving the accuracy of temperature predictions in fire-exposed reinforced concrete beams, contributing to the development of more effective fire-resistant structural designs.

CHAPTER 1
INTRODUCTION

1.1 General

Fire disasters pose significant challenges worldwide, impacting structures and infrastructure across various sectors. Understanding the dynamics of fire initiation, propagation, and the resultant heat generation is crucial for assessing structural safety and resilience. However, accurately calculating the temperature rise and heat generated during a fire event can be time-consuming and resource-intensive. To address this challenge, researchers have developed simplified methods for estimating these parameters, providing valuable insights into structural response to fire.

This thesis focuses on determining the temperature of reinforcement bars (rebars) in reinforced concrete beams subjected to fire conditions. The temperature rise of rebars is a critical factor as it directly influences their mechanical properties and, consequently, the structural integrity of reinforced concrete elements. By estimating the temperature rise of rebars, it becomes possible to assess the corresponding decrease in their strength and capacity, essential for evaluating the structural performance under fire scenarios.

The primary objective of this research is to explore and evaluate various simplified methods for estimating the temperature rise of rebars in reinforced concrete beams. These simplified methods offer a practical approach to quickly assess the impact of fire on structural elements without the need for lengthy and complex analyses. By comprehensively examining these simplified methods, this paper aims to demonstrate their effectiveness in estimating the temperature rise of rebars and their subsequent impact on structural performance.

Through detailed analysis and comparison of different simplified methods, this thesis seeks to provide valuable insights into the accuracy and reliability of these approaches. By understanding the strengths and limitations of each method, engineers and designers can make informed decisions regarding fire safety design strategies for reinforced concrete structures. Ultimately, the findings of this research contribute to advancing our understanding of fire-induced effects on structural elements and facilitate the development of efficient and effective fire safety design practices.

Figure 1-1, Presents a concerning trend in the number of fire incidents in Bangladesh over the last five years. The data shows a steady increase in occurrences, starting from 21,073 in 2019 and rising to 27,624 by 2023. This upward trajectory highlights a significant rise in fire-related emergencies, emphasizing the need for enhanced fire safety measures and awareness programs to mitigate such incidents in the future. The figure serves as a stark reminder of the growing challenges faced by fire services and the importance of proactive prevention strategies (Saad, 2020)& (Opu, 2024).

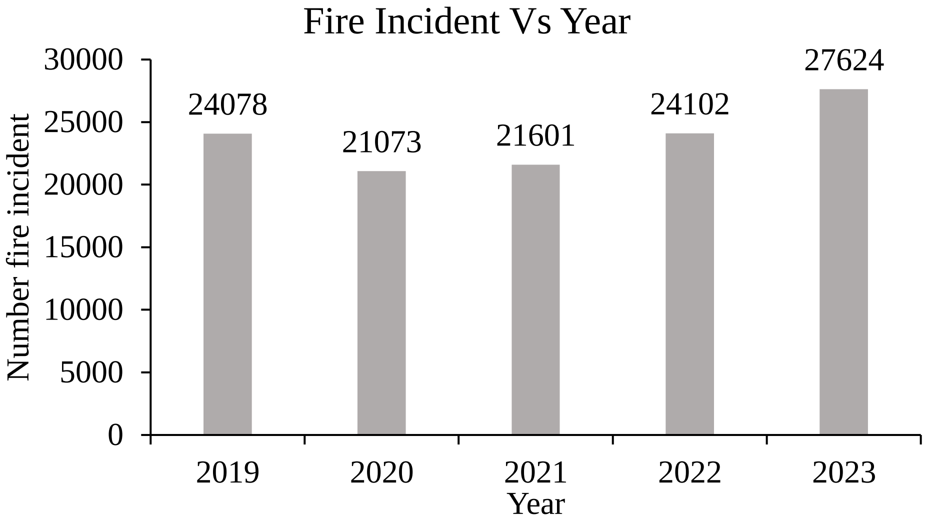


Figure 1-1: Last 5 years fire incident in Bangladesh

1.2 Scope of Study

Examining the temperature rise in reinforcement bars within concrete beams under fire conditions. Utilizing Abaqus software to simulate the thermal behavior and structural response of beams during fire exposure. Comparing simplified methods against finite element analysis for predicting temperature distribution in fire-exposed beams. Assessing the impact of cover thickness and fire duration on the temperature distribution within the beams.

1.3 Objective of this Study

The Objective of this study is to validate fire exposed beam different location temperature test result with finite element approach and compare this result with available simplified methods.

1.4 Outline of Thesis

Chapter 1. Provides a short overview of the primary goal behind the research project.

Chapter 2. A thorough analysis of previous research on the subject and the way it was conducted.

Chapter 3. How finite element model was created, what kind of material properties were used, exposed surface then unexposed surface.

Chapter 4. Following a comprehensive verification of the FEA model, the evaluation results are shown and compared with data from experiments.

Chapter 5. Provides the recommendations derived from the research and summarizes the major findings.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This literature review explores the utilization of ABAQUS (Hibbitt, 2000) in determining the temperature of rebar within reinforced concrete beams, a critical aspect of structural analysis and fire safety assessment. Through an examination of relevant research, this review aims to provide insights into the application of finite element methods (FEM) and computational techniques in analyzing the thermal behavior of concrete structures under fire conditions. By synthesizing findings from various studies, it seeks to elucidate the advancements, challenges, and opportunities in employing Abaqus (Hibbitt, 2000) software for accurately predicting rebar temperature and ensuring the structural integrity of reinforced concrete elements in fire scenarios. The literature review is discussed in detail in Section 2.2.

2.2 Literature Review

(SCHIFER, 1975) The paper discusses the use of FEM for solving contact problems, proposing a special bond element to describe energy dissipation in the contact area. It examines the compatibility conditions for contact problems, including parity of normal and shear stresses and deformations normal to the contact surface. The paper introduces an energy approach to model the energy dissipation process during contact, using the principle of virtual work. Various bond elements are proposed, with stiffness matrices derived for different engineering problems, improving the accuracy over conventional spring elements. This review focuses on the key aspects of the paper related to the finite element method and its application to contact problems in applied mechanics and engineering.

(Sherwan Albrifkani, 2016) The shift from prescriptive-based to performance-based fire resistance design, considering interactions between structural members and large deflections at high temperatures. Importance of catenary action in resisting progressive collapse and its development during large deflection behavior of RC beams in fire. Addressing challenges in simulating the non-linear response of restrained RC beams, such as instabilities, material failures, and long simulation times. Proposal of a dynamic explicit finite element simulation method to predict the response of restrained RC beams, with guidance on selecting appropriate load factoring, mass scaling, and damping values. This review highlights the transition to performance-based design, the significance of catenary action, and the proposed solutions to numerical simulation challenges in the context of fire resistance of RC beams.

(Fabrício Longhi Bolinaa, 2020) The paper discusses the relationship between concrete durability design parameters and fire resistance performance in concrete columns. An experimental evaluation was conducted on precast concrete column prototypes with varying concrete mix designs when exposed to fire. The study found that concrete cover thickness and the diameter of reinforcing steel bars have a significant impact on fire resistance. The research concludes that increased concrete durability criteria can lead to an increase in spalling and loss of cross-section in elements exposed to fire.

(Desai, 1998) Discusses the effects of fire on the structural integrity of reinforced concrete beams, including the reduction in strength of concrete and stee due to high temperatures. Proposes a method for estimating the residual flexural and shear capacities of beams after fire exposure, based on the initial strengths and the temperature-induced reductions. Validates the proposed design rules with fire tests on beams, considering practical parameters like beam dimensions, concrete strength, and reinforcement details. Compares the proposed method with current codes of practice, highlighting the need for design rules that account for shear resistance at high temperatures and offer flexibility in construction parameters.

(J.P. Firmo, 2017) The paper discusses the use of carbon fiber reinforced polymer (CFRP) strips for strengthening reinforced concrete (RC) beams, comparing externally bonded reinforcement (EBR) and near surface mounted (NSM) techniques. It presents numerical simulations to understand the fire behavior of insulated RC beams strengthened with CFRP strips, considering the temperature-dependent properties of materials. The research includes modeling of the CFRP-concrete interaction through bi-linear bond-slip laws calibrated for different temperatures, highlighting the importance of accurate bond degradation simulation at elevated temperatures. The study examines the effectiveness of fire protection systems, particularly the impact of insulation thickness in CFRP anchorage zones on the fire performance of the strengthening systems. This review encapsulates the key aspects of the research, focusing on the structural and fire resistance improvements provided by CFRP strengthening methods and the critical role of proper insulation in fire scenarios.

(Wan-Yang Gao, 2016) It emphasizes the importance of fire resistance in building design to prevent fire-induced structural failure, with typical requirements ranging from 0.5 to 4 hours based on various factors. The paper critiques the traditional prescriptive approach used in design codes for determining fire resistance of reinforced concrete (RC) beams, which is based on limited data and doesn’t consider many influential factors or the complexity of real fires. It highlights the development of numerical models and explicit equations over the past decades to predict the thermal and mechanical responses of RC beams under standard fire exposure, allowing for cost-effective analysis of fire performance. The review covers the concept of design fire scenarios that reflect real fire conditions more accurately than standard fire tests and discusses time equivalence methods to relate the severity of real fire exposure to standard fire exposure for evaluating fire resistance. These points provide a foundation for the paper's proposal of a new design approach for predicting the fire resistance of RC beams under design fire exposure. The approach aims to address the limitations of current methods and incorporate factors like concrete cover depth and compartment characteristics into the fire resistance evaluation.

(JUI-HSIANG HSU, 2028) The review discusses how fire can significantly alter the mechanical properties of concrete and stee, which are the main components of RC beams. It emphasizes the importance of combining thermal analysis with structural analysis to predict the residual mechanical properties of RC beams after fire exposure. The paper references numerous studies that have investigated the effects of fire on concrete and steel, highlighting changes in strength, stiffness, and other physical properties at high temperatures. The authors propose a novel modeling approach using the finite difference method and a lumped system concept to analyze temperature distribution and mechanical properties of RC beams during and after fire. This review serves as a foundation for understanding the complex interactions between fire damage and structural integrity in RC beams. It also underscores the need for accurate modeling to assess fire-damaged structures, especially in seismic regions.

(DWAIKAT, 2027) The paper discusses performance-based fire safety design for reinforced concrete (RC) beams, emphasizing the importance of considering realistic fire scenarios, load levels, and failure criteria in design. A computer program is presented, capable of predicting the fire resistance of RC beams under various conditions, validated against full-scale fire resistance tests. It highlights how factors like failure criterion, load level, and fire scenario significantly affect the fire resistance of RC beams. The article advocates for a shift from prescriptive-based approaches to performance-based methods, offering more cost-effective and rational fire safety solutions.

(Hitesh Lakhani P. K., 2013) The paper emphasizes the significance of understanding the performance of concrete at high temperatures, especially for safety evaluations in fire scenarios. It presents a comparative study of thermal properties using different models and boundary conditions, comparing them with experimental results. The use of ABAQUS software for numerical finite element analysis is highlighted to predict temperature distribution across structural elements. The paper discusses the impact of different boundary conditions on the thermal profile during heating and cooling phases, with a focus on prescribed temperature and convection-radiation conditions.

(Hitesh Lakhani A. S., 2017) The review highlights the importance of fire performance ratings for structural members, noting that concrete's non-combustible nature and low thermal conductivity generally provide good fire resistance. It mentions that high-temperature gradients can cause cracking in RC members, and both concrete and reinforcing steel degrade mechanically with increased temperature, potentially leading to failure. The paper references a survey of multi-storied buildings that collapsed due to fire, emphasizing the significant consequences of such events, including potential loss of life and economic loss. The review summarizes extensive experimental studies over the past decades that have investigated the effects of elevated temperatures on the stress-strain characteristics of concrete and reinforcing steel.

(Peng Liu, 2015) The paper discusses how environmental factors like temperature and humidity affect the durability and service life of concrete structures. It emphasizes temperature as a critical factor influencing concrete performance. A significant portion of the paper is dedicated to understanding concrete's thermal response to natural temperature variations. It proposes a segmented fitting method to predict temperature action spectra and introduces a novel method to determine concrete's thermal parameters. The study highlights the difference in temperature response of concrete under sheltered and unsheltered conditions, showing that sheltered conditions significantly affect the amplitude, extreme value, and arising time of the temperature response. The paper employs the Fourier heat transfer law and third-type boundary condition to model the temperature response spectrum of concrete4. It also provides a comprehensive experimental setup and methodology to measure and analyze the thermal diffusion coefficient of concrete.

(W. Y. Gao, 2012) The paper discusses the shift from prescriptive to performance-based fire safety design in RC structures, highlighting the need for accurate temperature field predictions. It reviews past attempts to create simple methods for predicting temperature profiles in RC members, noting that these methods often rely on limited test data and show significant deviations from experimental results. The authors propose a new method for predicting temperature fields in RC beams exposed to standard fire, which is simpler than finite element or finite difference analysis and is validated against experimental data and FE predictions. The paper verifies the proposed method using independent fire tests and compares it with other methods, demonstrating its accuracy and practicality for design use.

2.3 Summary

The literature review chapter provides a comprehensive overview of the utilization of Abaqus software in determining the temperature of rebar within reinforced concrete beams. It covers key topics such as the shift to performance-based fire resistance design, the relationship between concrete durability and fire resistance. Additionally, it discusses the importance of accurate temperature field predictions and proposes new methods for predicting temperature profiles in RC beams under fire exposure. Overall, the review highlights the advancements, challenges, and opportunities in using Abaqus software for enhancing fire safety in structural engineering.

CHAPTER 3
MODELING & ANALYSIS

3.1 Introduction

The chapter focuses on the detailed analysis of material properties, finite element modeling, and boundary conditions for assessing the behavior of reinforced concrete beams under fire conditions. Material details, including properties of concrete and rebar, are meticulously examined to understand their thermal behavior and structural response. Finite Element Modeling (FEM) techniques using Abaqus (Hibbitt, 2000)software. are employed to accurately simulate the thermal dynamics and structural integrity of the beams. Boundary conditions are carefully defined to replicate realistic fire exposure scenarios, with precise placement of thermocouples for temperature monitoring. This comprehensive approach facilitates a thorough investigation into the thermal behavior and structural performance of reinforced concrete beams under fire conditions.

3.2 Material Details

Material details play a crucial role in the accurate simulation of structures and components in engineering analyses. These details encompass a range of properties and characteristics that define the behavior of materials under various loading and environmental conditions. In engineering simulations, such as those conducted using Abaqus (Hibbitt, 2000) software, material details are meticulously defined to ensure the fidelity and reliability of the analysis results. From the density and elastic modulus to thermal conductivity and specific heat, each property contributes to the overall response of the material within the simulation environment. By comprehensively capturing these material details, engineers can gain valuable insights into the performance, durability, and safety of structures across diverse applications and industries.

3.2.1 Properties of the Concrete

Concrete properties encompass essential characteristics such as density, thermal conductivity, and specific heat. Density represents the material's mass per unit volume, while thermal conductivity measures its heat transfer capability. Specific heat indicates the material's ability to store thermal energy. Understanding these properties is vital for predicting concrete behavior under different conditions, aiding in structural design and analysis for various engineering applications.

This figure illustrates the variation in thermal conductivity of the material over a range of temperatures Figure 3-1, considering both the upper and lower limits. The upper limit values represent the maximum possible thermal conductivity values at different temperatures, while the lower limit values indicate the minimum possible thermal conductivity values. By visualizing this data, engineers can gain insights into how thermal conductivity changes with temperature and understand the potential range of thermal conductivities that the material may exhibit under different thermal conditions. This information is crucial for accurately modeling heat transfer processes and predicting thermal behavior in engineering simulations, such as those conducted using Abaqus software.

This Figure 3-2 depicts the relationship between specific heat and temperature for concrete material. Specific heat measures the material's ability to store thermal energy, and the graph illustrates how specific heat varies with temperature. Understanding this relationship is crucial for predicting the material's thermal response and energy absorption capacity under different temperature conditions.

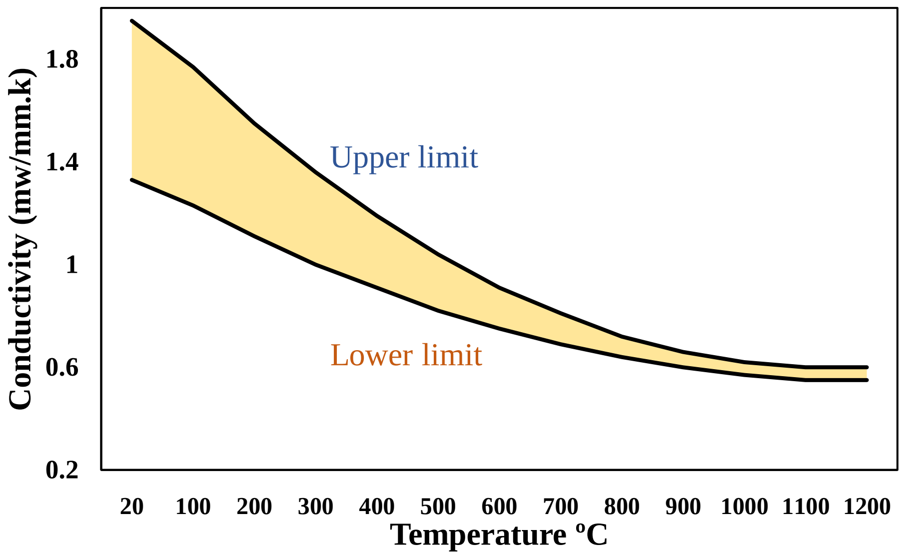


Figure 3-1: Concrete Conductivity Difference Upper limit & Lower limit

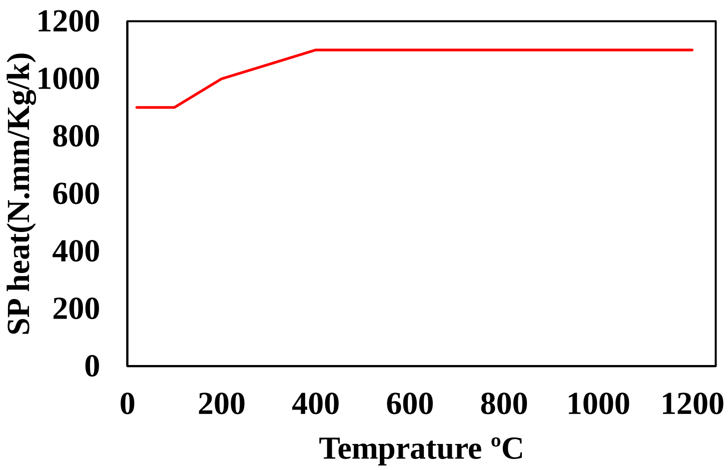


Figure 3-2: Concrete material Specific heat comparison with temperature.

3.2.2 Properties of the Rebar

Rebar, a critical component in reinforced concrete structures, exhibits essential properties such as density, thermal conductivity, and specific heat, which significantly influence its behavior and performance. Density represents the mass per unit volume of the rebar material, while thermal conductivity denotes its ability to conduct heat. Specific heat measures the amount of heat energy required to raise the temperature of the material by one degree Celsius. Understanding these properties is essential for accurately predicting the thermal behavior and response of rebar in concrete structures, ensuring their structural integrity and durability under various environmental conditions.

This Figure 3-3 illustrates the variation in thermal conductivity of rebar with respect to temperature. As temperature increases, the thermal conductivity of the rebar decreases, indicating its reduced ability to conduct heat. The graph showcases how thermal conductivity changes with temperature, providing insights into the material's thermal behavior over a range of operating temperatures.

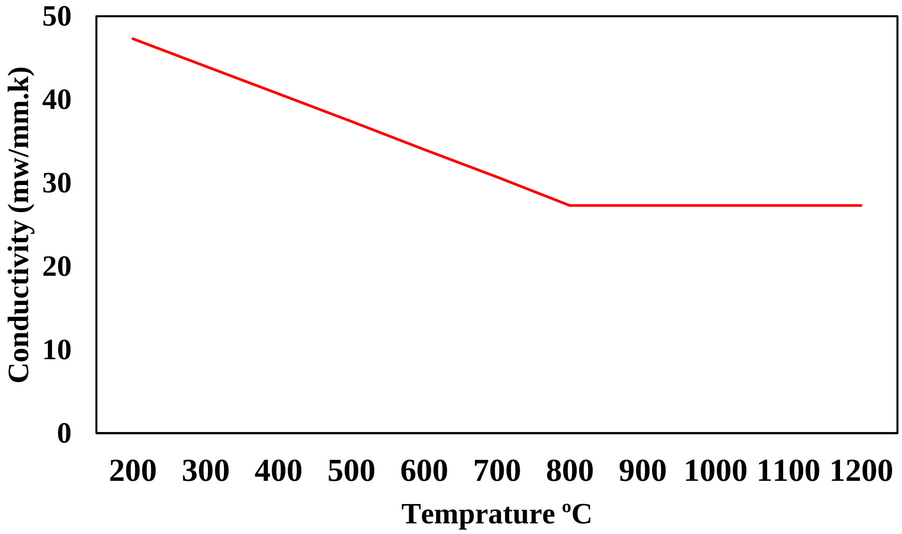


Figure 3-3: Concrete material Conductivity comparison with temperature

This Figure 3-4 depicts the relationship between specific heat and temperature for rebar material. Specific heat measures the material's ability to store thermal energy, and the figure illustrates how specific heat varies with temperature. Understanding this relationship is crucial for predicting the material's thermal response and energy absorption capacity under different temperature conditions.

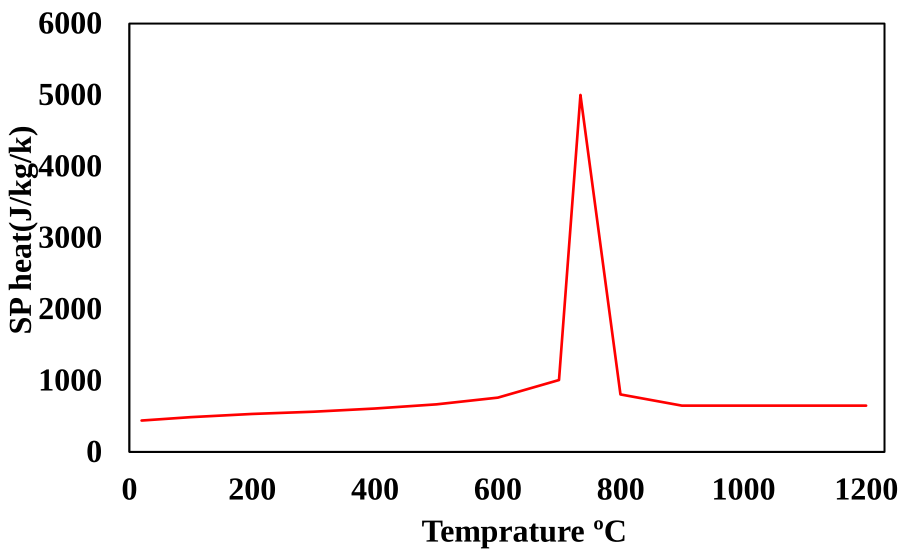


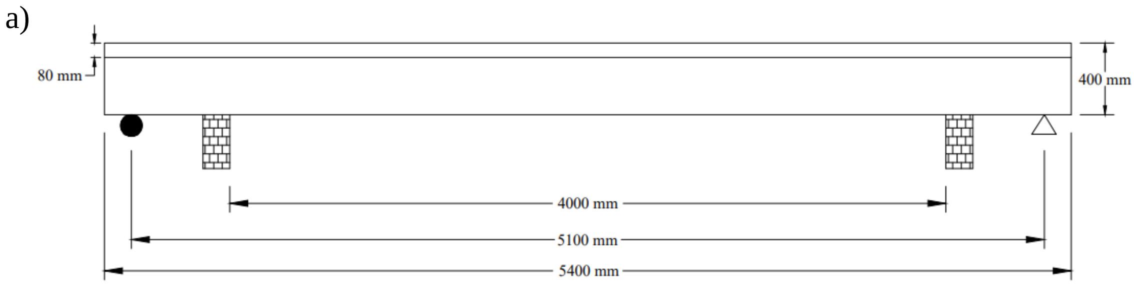
Figure 3-4: Concrete material Specific heat comparison with temperature

3.3 Finite Element Modeling

This thesis delves into the complex interplay between thermal dynamics and structural integrity in reinforced concrete beams under fire conditions, employing Finite Element Modeling (FEM) techniques with Abaqus (Hibbitt, 2000) software. It begins with precise geometry creation, detailing dimensions and rebar placements. Material properties are meticulously assigned for accurate simulation of thermal and structural behavior. Through meticulous assembly, time period establishment, and boundary condition definition, the model captures detailed responses effectively. This comprehensive approach enables a thorough analysis of temperature distribution and rebar temperatures during fire exposure, essential.

3.3.1 Geometry Creation

In creating the geometry for the reinforced concrete beam, precise dimensions of width (200 mm), depth (400 mm), and length (5400 mm) are crucial. Utilizing Abaqus CAE or other CAD software (Wu, 1993), a three-dimensional model is constructed to accurately represent the beam's shape and size Figure 3-6. Careful attention is paid to ensure that the geometry faithfully reflects the structural details, including any variations such as chamfers or fillets. By adhering closely to the specified dimensions and features, the geometry serves as the foundation upon which subsequent steps of meshing and analysis are built.



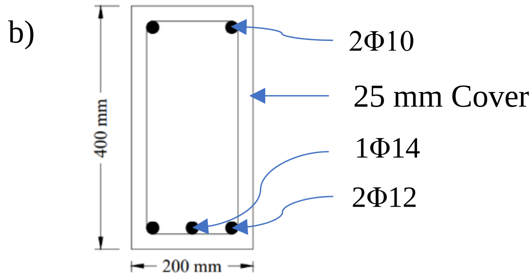


Figure 3-5: Details of specimens (200 mm   400 mm   5400 mm): (a) elevation and (b)

The placement of reinforcement bars (rebars) within the concrete beam follows a precise arrangement as specified. For instance, two 10 mm rebars are positioned at the top of the beam, providing reinforcement along its upper surface. At the bottom corners, two 12 mm rebars are placed, reinforcing the beam's lower extremities. Additionally, a single 14mm bar is positioned bottom center, augmenting its structural integrity Figure 3-7. Each rebar is carefully embedded within the concrete geometry, with interactions such as tie constraints defined to simulate the bond behavior between the rebars and the surrounding concrete matrix. This meticulous placement ensures that the resulting model accurately reflects the distribution of reinforcement within the beam, essential for assessing its strength and load-bearing capacity.

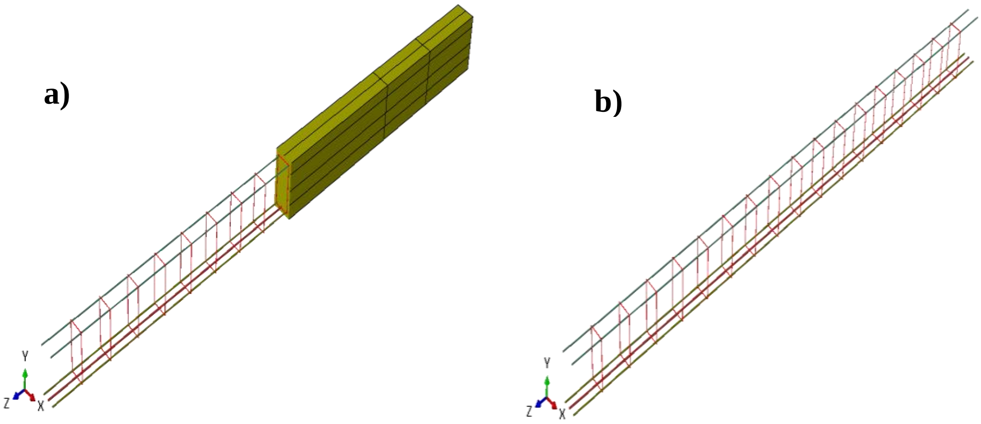


Figure 3-6: 3D View Detail of a Reinforced Concrete Beam

The shear bars, crucial for enhancing the beam's resistance to shear forces, are strategically placed at regular intervals along its length. Using wire parts representing 6 mm diameter bars, these shear reinforcement elements are positioned at a specified spacing of 300 mm. Ensuring proper embedding within the concrete geometry Figure 3-7 each shear bar is meticulously placed to optimize its effectiveness in resisting shear stresses. Interactions between the shear bars and the concrete are defined to simulate their structural integration accurately. By incorporating shear reinforcement in this manner, the model accounts for the beam's response to lateral loads and provides insights into its overall stability and performance under various loading conditions.

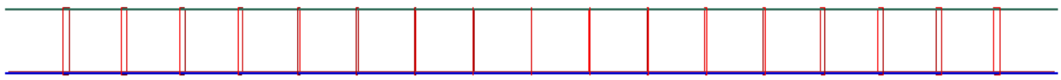


Figure 3-7: Shear bars placement

3.3.2 Material Property Assignments

Finite Element Modeling (FEM) using Abaqus software enables a comprehensive analysis of the temperature distribution and structural response of reinforced concrete beams under fire conditions. The initial phase involves meticulous geometry preparation, where the dimensions of the beam, shear bars, and rebar are precisely defined in the model. Material properties for steel and concrete are then assigned, encompassing conductivity, density, and specific heat to accurately simulate their behavior at elevated temperatures. Assembling the components follows, ensuring seamless connectivity and alignment within the model. Subsequently, time periods are established in the Step Manager, specifying initial, minimum, and maximum increments alongside allowable temperature changes per increment to ensure analysis stability.

Interaction setups are then established, embedding the model and defining interaction properties to simulate heat transfer accurately. Fire surface radiation properties are meticulously defined using the Fire module, incorporating emissivity variations and ambient temperature parameters for comprehensive simulation Figure 3-8.

Surface Manager aids in identifying exposed and unexposed surfaces crucial for boundary condition definition. Meshing follows suit, where appropriate mesh sizes ranging from 35 to 15 are assigned to capture detailed thermal and structural responses effectively Figure 3-9.This systematic approach in Finite Element Modeling facilitates a comprehensive understanding of the thermal behavior and structural integrity of reinforced concrete beams under fire scenarios.

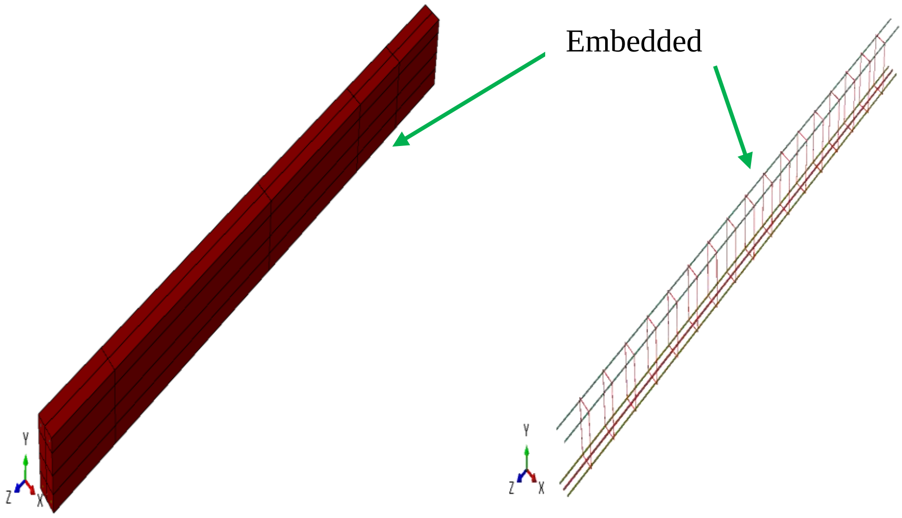


Figure 3-8: Interaction of RC Beams in FEA

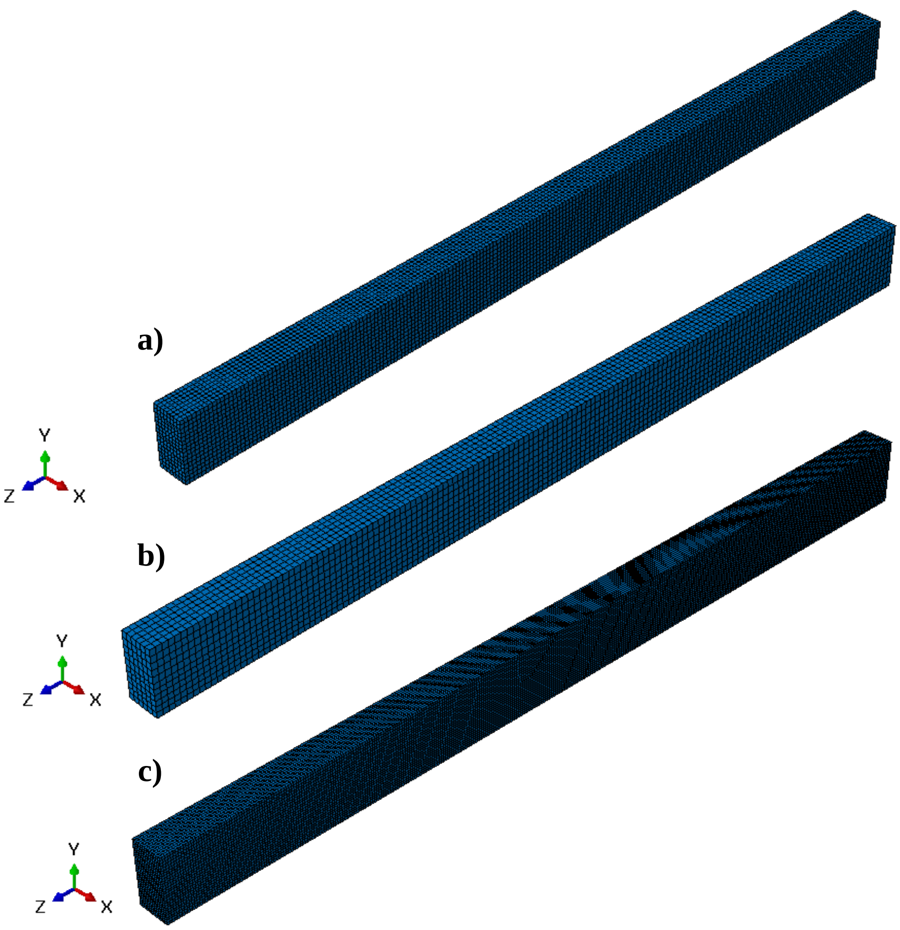


Figure 3-9: Meshing a) 25mm, b) 35mm, c) 15mm using of Beam

3.3.3 Boundary Conditions

In the Abaqus (Hibbitt, 2000) finite element model designed for assessing the temperature distribution and rebar temperature in a reinforced concrete beam under fire conditions, meticulous boundary conditions are imperative to simulate the scenario accurately. Specifically tailored for the given model, the thermal boundary conditions dictate that the top surface remains unfired up to a depth of 80 mm, with an additional 700 mm unfired along the depth from both sides. Fire exposure is simulated on three sides of the model, excluding areas 700 mm from two sides and 80 mm along the depth from the top surface. Figure 3-10 Moreover, to monitor temperature variations, two thermocouples, labeled T1 and T2, are strategically positioned within the model. T1 is situated at a width of 37 mm, a depth of 37 mm, and a length of 2700 mm, while T2 resides at a width of 100 mm, a depth of 38 mm, and a length of 2700 mm. These precise boundary conditions facilitate an accurate simulation of the thermal response of the reinforced concrete beam, enabling a comprehensive analysis of temperature distribution and rebar temperatures during fire exposure.

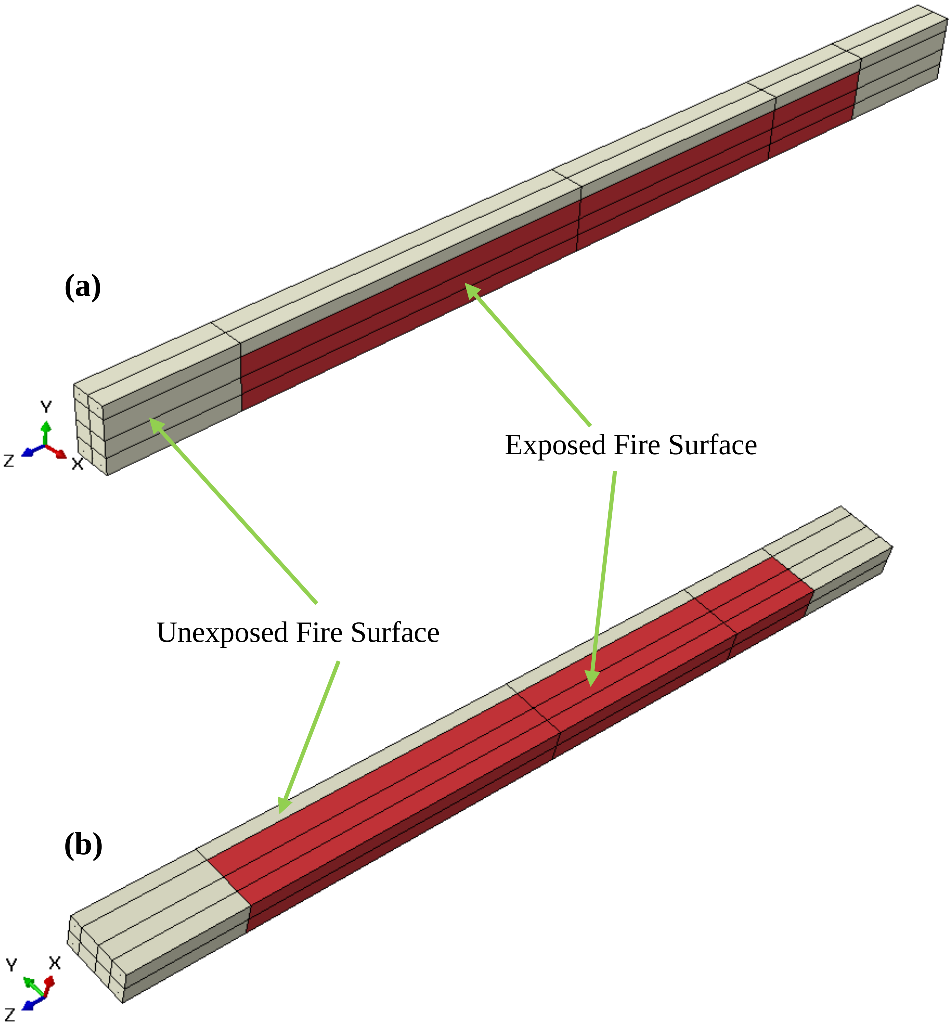


Figure 3-10: (a) & (b) Exposed and Unexposed Surface of the Beam

3.4 Summary

The thesis utilizes Finite Element Modeling (FEM) through Abaqus software to assess the behavior of reinforced concrete beams under fire conditions. It starts with meticulous geometry creation and material property assignments to ensure accurate simulation. Boundary conditions are precisely defined to replicate fire exposure scenarios, with embedded thermocouples for temperature monitoring. This methodical approach provides valuable insights into thermal dynamics and structural integrity, contributing to more effective fire safety design strategies.

CHAPTER 4
RESULT & DISCUSSIONS

4.1 Introduction

This paper presents a detailed study of the thermal response of reinforced concrete beams exposed to fire conditions. Utilizing finite element analysis (FEA) validated against experimental data, the study investigates the temperature distribution within the beams. The study compares FEA results with simplified methods proposed by Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021), and Desai assessing their accuracy in predicting temperature rise. A parametric study further examines the influence of various factors such as cover thickness and fire duration on temperature distribution. The findings offer valuable insights for fire safety engineering practices, highlighting the effectiveness of different predictive methods.

4.2 Finite Element Validation

Initially, establish a validation model as outlined in Chapter 3. This model is thoroughly explained in the chapter before it. Extracted the finite element analysis (FEA) value from the model and compared it with experimental data obtained from (Wu, 1993) The dimensions of the model were detailed to precisely match the prescribed measurements: a width of 200 mm, height of 400 mm, and a length of 5400 mm. The reinforcement layout adhered meticulously to the stipulated configuration, comprising two 10 mm bars at the top, two 12 mm bars at the bottom corners and a single 14 mm bar positioned bottom center, each span the entire length of 5400 mm. In addition, a 6 mm shear bar was appropriately placed with a spacing of 300 mm center to center.

This model is validated by determining the FEM values from the Abaqus (Hibbitt, 2000) model concerning the thermocouple positions T1 and T2 and comparing the FEM values with the test results. 2D and 3D View thermocouple locations are shown in the Abaqus (Hibbitt, 2000) model image Figure 4-1 & Figure 4-2. Numerous trials were conducted to refine the Abaqus (Hibbitt, 2000) model parameters and ensure accurate predictions of the temperature distribution within the reinforced concrete beam under fire conditions. These trials encompassed variations in material properties, interaction settings, and mesh sizes to evaluate their impact on the simulation results. Initially, the material properties of concrete were explored across a spectrum, utilizing upper limit, lower limit, and average values. This allowed for a comprehensive understanding of how variations in thermal conductivity and specific heat influenced the simulated temperature distribution. Additionally, different combinations of interaction settings were tested to accurately model the interaction with the fire surface.

This involved fine-tuning parameters such as emissivity, which ranged from 0.6 to 0.8, to accurately represent the surface's ability to emit thermal radiation. Additionally, various mesh sizes ranging from 15 to 35 were assessed to evaluate their impact on simulation accuracy. Through systematic analysis, the optimal mesh size was determined, striking a balance between computational efficiency and solution accuracy. After numerous iterations, it became evident that trials employing average conductivity values, an emissivity of 0.8, and a mesh size of 25 consistently delivered satisfactory results. These parameters yielded high R^2 values, indicating strong correlation between Finite Element Analysis (FEA) results and experimental data ($R^2 = 0.990$ for T1 and $R^2 = 0.985$ for T2). Comparison between FEA and experimental results across various conditions further validated the accuracy of these parameters Figure 4-3 & Figure 4-4.Hence, these optimized parameters strike an effective balance between computational efficiency and accuracy in predicting temperature distribution within the reinforced concrete beam.

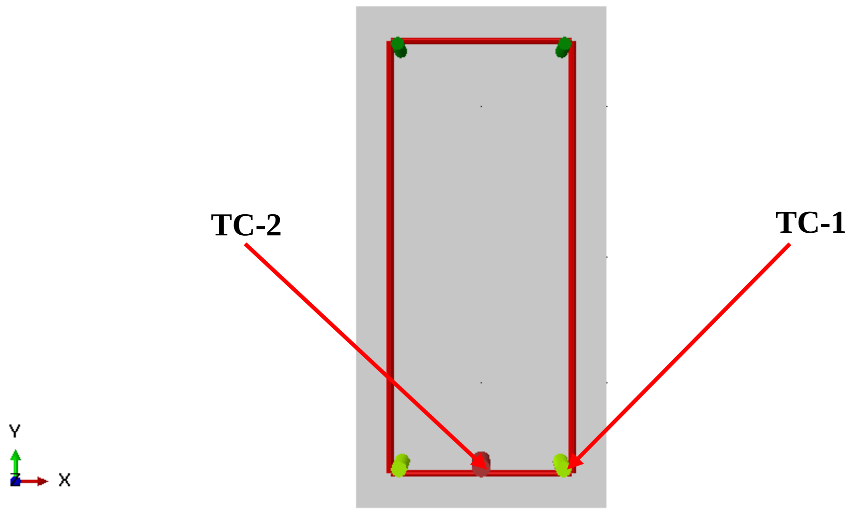


Figure 4-1: 2D View Thermocouples Locations in Beams (200 x 400 x 5400 mm)

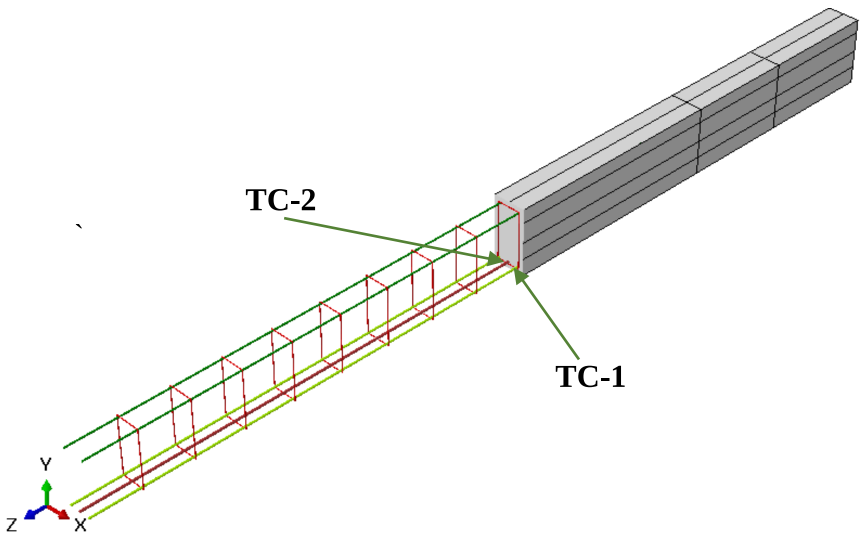


Figure 4-2: 3DView Thermocouples Locations in Beams (200 x 400 x 5400 mm)

The validation of the Abaqus (Hibbitt, 2000) model's accuracy is demonstrated through comparison figure between experimental data (Test-T1 & Test-T2) and Finite Element Method results (Thermocouples T1&T2). The validation of the Abaqus model's accuracy is demonstrated through comparison graphs between experimental data and Finite Element Method (FEM) results Figure 4-5 & Figure 4-6. The graphs depict the measured data points or curves alongside the simulated values obtained from the Abaqus model. Each graph is meticulously labeled with clear axes and titles, facilitating easy interpretation of the results. Through a detailed analysis of the comparison graphs, insights are gained into the agreement between the experimental and FEM results.

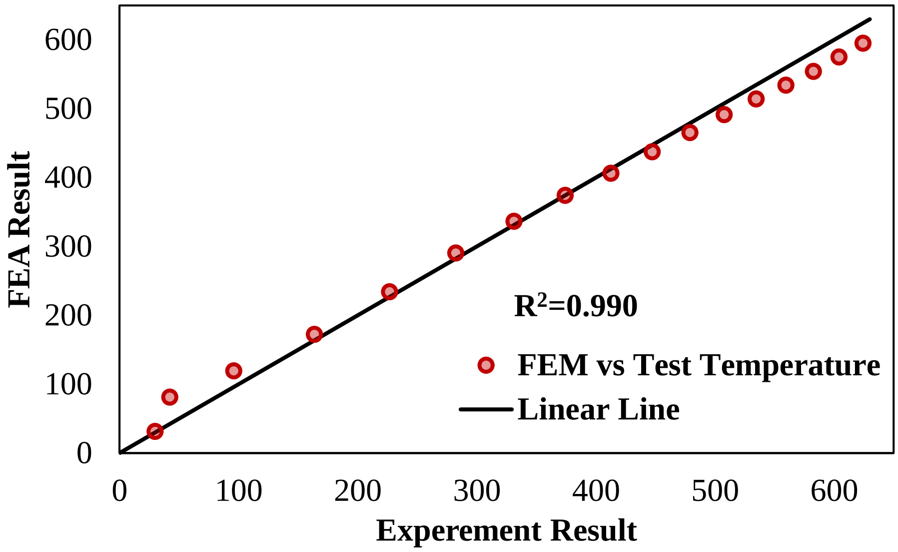


Figure 4-3: Compression between FEA and Experimental result for TC-1

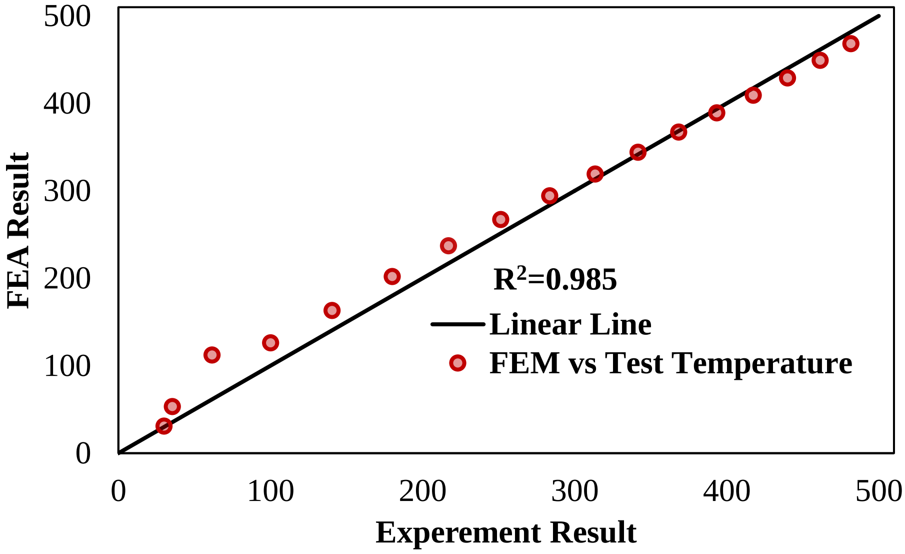


Figure 4-4: Compression between FEA and Experimental result for TC-2

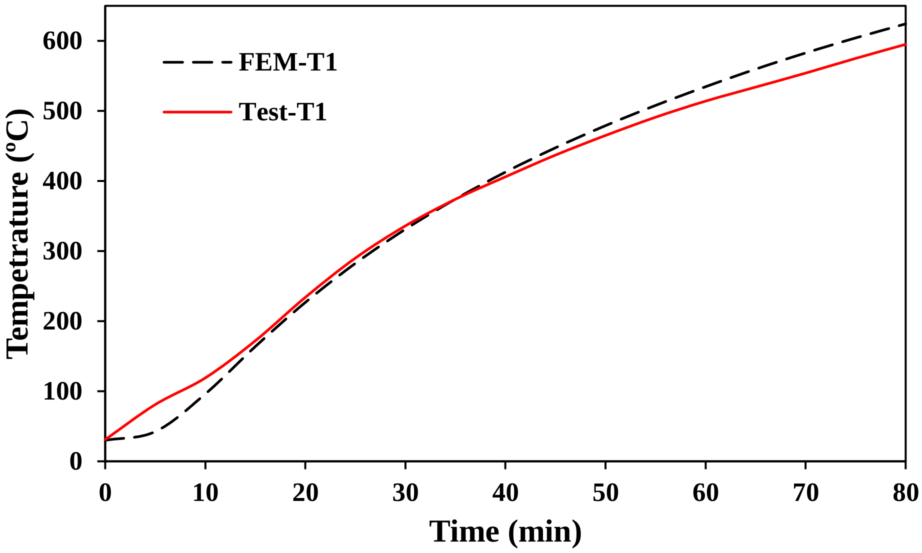


Figure 4-5: Compression between FEA-T-1 and Test- T-1

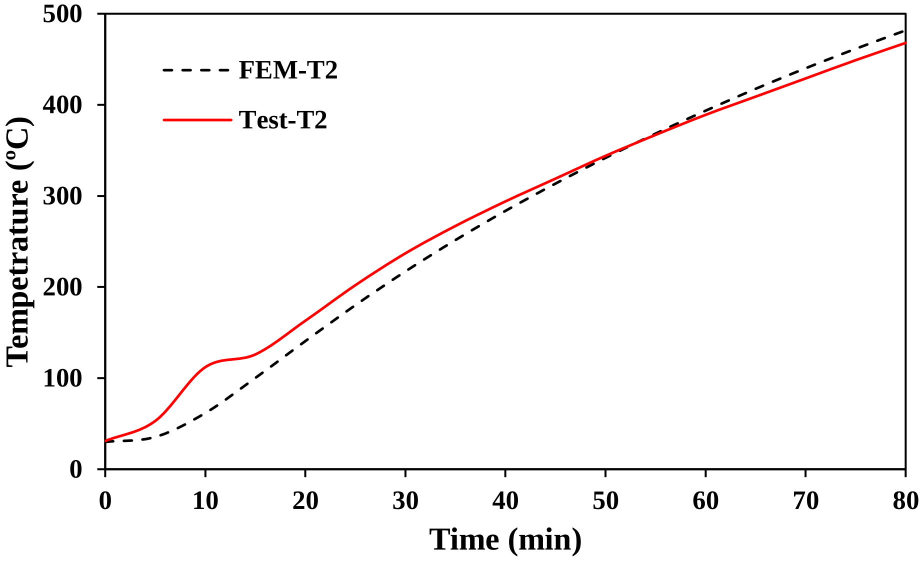


Figure 4-6: Compression between FEA-T-2 and Test-T-2

4.3 Simplified Methods

In this section, the focus is on comparing Finite Element Method (FEM) and experimental results with simplified methods proposed by Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021), and Desai (Desai, 1998). These simplified methods offer alternative approaches to estimate the temperature rise in reinforced concrete beams under fire conditions. The results obtained from the FEM analysis and experimental tests are juxtaposed with the outcomes derived from analytical calculations based on the equations provided by Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021), and Desai (Desai, 1998). Through graphical representations, the accuracy and reliability of these simplified methods are evaluated against the more computationally intensive FEM approach and the empirical data obtained from experimental tests. There are many simplified methods for determining Tc, among them the equation of Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021), and Desai (Desai, 1998) is used in this paper. Then each equation is described.

According to Wickstrom (A.Gedam, 2021) method, the temperature (Tc) in an RC member exposed to the heat conduction occurring in two directions (x and y) at a given depth x and y (in meters) and time t (in hours) can be calculated as

$$T_c = \left[\eta_w\left(\eta_x + \eta_y - 2\eta_x\eta_y\right) + \eta_x\eta_y\right]T_f \quad (4.1)$$

$$\eta_w = 1 - 0.0616(t^{-0.88}) \quad (4.2)$$

$$\eta_x = 0.18 \ln\left({}^{t}/_{x^2}\right) - 0.81 \quad (4.3)$$

$$\eta_y = 0.18 \ln\left({}^{t}/_{y^2}\right) - 0.81 \quad (4.4)$$

In Eqs. (4.2)– (4.4), η_w is the ratio between concrete surface temperature and the fire temperature, η_x and η_y are the heat transfer factors induced by each side of fire exposure, and T_f is the fire temperature.

According to Kodur (A.Gedam, 2021) method, the equation for temperatures controlled by 2-D heat transfer can be expressed as

$$T_c = \left[-1.481\left(\eta_z\eta_y\right) + 0.985\left(\eta_z + \eta_y\right) + 0.017\right](at^n) \quad (4.5)$$

$$\eta_z = 0.155 \ln\left(\frac{t}{z^{1.5}}\right) - 0.348\sqrt{z} - 0.371 \quad (4.6)$$

$$\eta_y = 0.155 \ln\left(\frac{t}{y^{1.5}}\right) - 0.348\sqrt{y} - 0.371 \quad (4.7)$$

In Eqs. [4.6, 4.7], η_z and η_y are the heat transfer factors resulting from y and z side fire exposure, t is the fire exposure time in hours, z and y is the distance from the point in the concrete section to fire exposure surface in meters. For ISO 834 fire, a=935, n=0.168 and ASTM E119 fire, a=910, n=0.148.

According to Desai (Desai, 1998) method, the temperature (T ºC) inside a beam that is exposed to fire on three sides is determined by the following factors along a contour x mm distant from these sides, as a function of time spent in the fire (t, in minutes), b the cross-sectional width (in millimeters) and r which is the overall height to width ratio. The cubic equation that follows is provided in Eqs, [4.8].

$$T = \frac{\left(D - Ax + Bx^2 - Cx^3\right)}{r^{0.25}} \quad (4.8)$$

$$D = 475r^{\frac{7}{12}} - \left(b - 105t^{\frac{1}{3}}\right) \quad (4.9)$$

$$A = 3.33\left[3 + 0.033t + \frac{(100 - t)}{b}\right] \quad (4.10)$$

Eqs. [4.9, 4.10], For the purpose of determining the values of D, A, B, and C, several simultaneous equations are meant to represent and here B= 0.085, C=0.000221.

This method's applicability should be confined to rectangular beams with widths (mm) 300 > b > 100 and values of ‘r’ within the range 1< r < 3.

The value of Tc is determined for Thermocouple T1 and Thermocouple T2 using Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021) and Desai's (Desai, 1998) equation and compared with this value through FEM results and test result. It can be seen in the plot that the FEM results and the experimental results match very well for the thermocouple T1 and thermocouple T2 values. FEM result is compared with simplified methods (Fig 4.7 & fig 4.8).

Here see Figure 4-7 &Figure 4-8. The Desai equation isn't producing accurate results for Thermocouples T.C.1 and T.C.2. To address this, we've adjusted the starting point of Desai (Desai, 1998) graph from 0 to 5 minutes. This change reflects the fact that the Desai (Desai, 1998) equation may not accurately predict temperatures at 0 minutes, as unrealistic temperatures are observed in that initial timeframe. By starting the plot at 5 minutes instead, we aim to improve the accuracy of temperature predictions and ensure more reliable simulation results.

From the graph Figure 4-7 it can be seen that the Kodur equation (A.Gedam, 2021) gives fairly good values for thermocouple T1. The graph shows that the Kodur (A.Gedam, 2021) result is very similar to the FEM result. The Kodur (A.Gedam, 2021) result was in good agreement with the FEM result in the beginning but not in the end. Here Kodur (A.Gedam, 2021) result is started from 10 minutes for thermocouple T1 instead of starting from 0 because the value obtained by Kodur (A.Gedam, 2021) equation shows that negative temperature comes at 0 and 5 minutes which value is not possible. For this it is started from 10 minutes instead of 0. From Figure 4-8 it can be seen that Kodur (A.Gedam, 2021) equation does not give good results for thermocouple T2. From the figure it can be seen that Kodur (A.Gedam, 2021) result forms a line with a short distance from FEM result. Kodur (A.Gedam, 2021) result is started from 20 minutes for thermocouple T2 instead of starting from 0 because the value obtained by Kodur (A.Gedam, 2021) equation shows that negative temperature comes at 0 to 15 minutes which value is not possible. For this it is started from 20 center instead of 0.

The figure also shows Figure 4-7 that the Wickstrom equation (A.Gedam, 2021) gives a much better value for thermocouple T1. The graph shows that the FEM result is very similar to the Wickstrom (A.Gedam, 2021) result. Here Wickstrom (A.Gedam, 2021) result is started from 10 minutes instead of starting from 0 because the value obtained by Wickstrom equation shows that negative temperature comes at 0 and 5 minutes which value is not possible. For this it is started from 10 minutes instead of 0. Figure 4-7 It can be seen that the Wickstrom (A.Gedam, 2021) equation for thermocouple T2 also does not give good results. The figure shows a much lower temperature than the actual temperature by creating a line with one distance. Wickstrom (A.Gedam, 2021) result is started from 20 minutes for thermocouple T2 instead of starting from 0 because the value obtained by Wickstrom (A.Gedam, 2021) equation shows that negative temperature comes at 0 to 15 minutes which value is not possible. For this it is started from 20 minutes instead of 0. Finally, Figure 4-7 & Figure 4-8 it is understood that the simplified method gives good results for corner reinforcement but cannot give good results for middle reinforcement. It is seen that Wickstrom (A.Gedam, 2021) and Koidur (A.Gedam, 2021) equation gives very close results for thermocouple T1, the location of thermocouple T1 is in the corner. But the same equation gives much lower temperature for thermocouple T1 whose location is bottom middle.

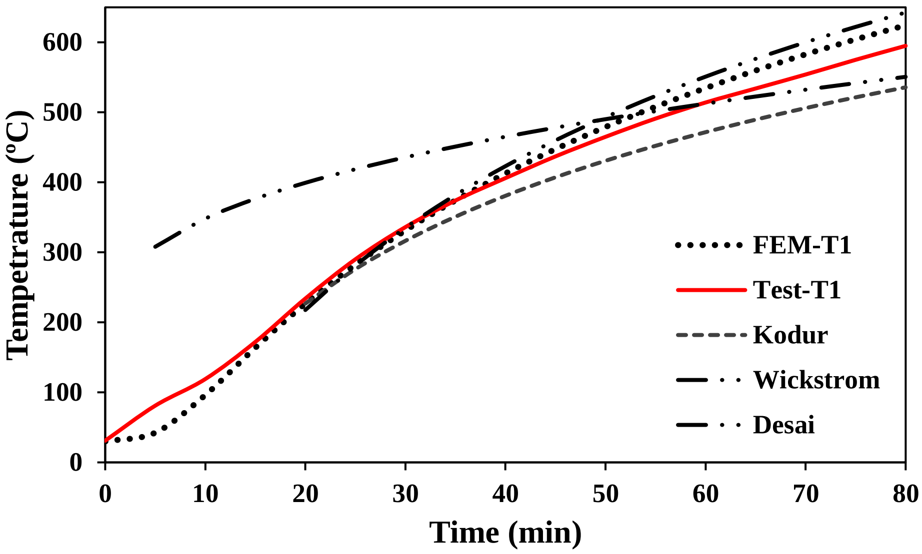


Figure 4-7: Validation of Heat Transfer Model at T1

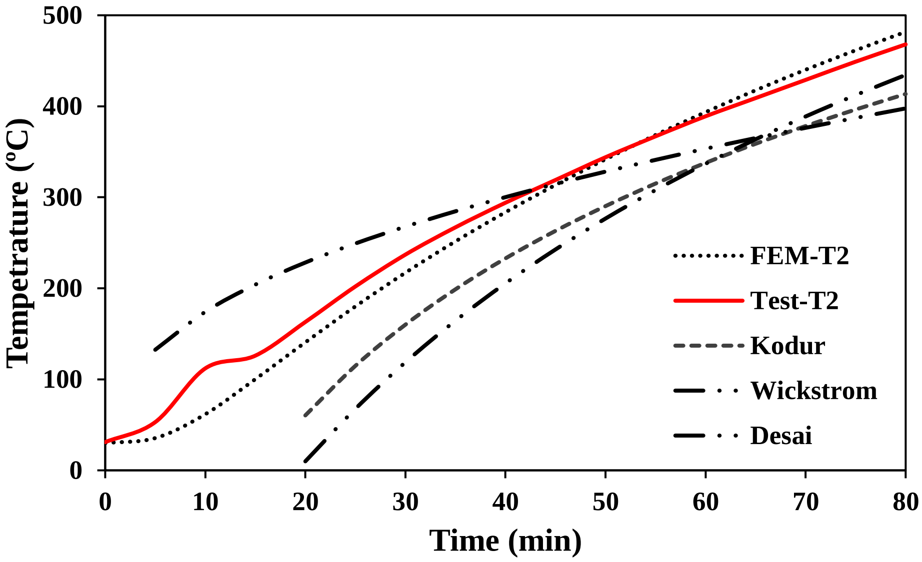


Figure 4-8: Validation of Heat Transfer Model at T2.

4.4 Parametric Study

In the parametric study section of the thesis, a detailed analysis was conducted to investigate the impact of various parameters on the temperature distribution within a reinforced concrete beam model under fire conditions, utilizing Abaqus (Hibbitt, 2000) software. This new model has been created in the same approach as the model that was created for validation. The study encompassed a range of parameters, including dimensions, reinforcement configuration, cover thickness (covering from strip's face), and fire duration. A new model was developed with specific dimensions, featuring a unique reinforcement layout comprising two 10mm bars at the top corners, two 25mm bars at the bottom corners, and a single 25mm bar positioned at the bottom center, spanning the entire length. Additionally, 10mm shear bars were utilized with a spacing of 150mm center to center. Multiple analysis scenarios were executed, varying cover thicknesses (25mm, 38mm, 50mm, 63mm, 75mm) and fire durations (60 minutes, 90 minutes, 120 minutes, 150 minutes, 180 minutes). Temperature distributions at designated nodes (T1 and T2) were monitored and recorded for each scenario. Results from the parametric study were compared with predictions from established simplified methods proposed by Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021), and Desai (Desai, 1998), along with Finite Element Method (FEM) results. Particularly, Wickstrom (A.Gedam, 2021), Kodur (A.Gedam, 2021), and Desai (Desai, 1998) method was scrutinized, and errors between its predictions and FEM results were determined to evaluate its accuracy. Time (60 minutes, 90 minutes, 120 minutes, 150 minutes, 180 minutes) and cover (25mm, 38mm, 50mm, 63mm, 75mm) by comparing FEM temperature with simplified method temperature and determining the error which is shown Table 4-1 to Table 4-5. Shows Figure to Figure 4-30the difference between FEM temperature and simplified method temperature. In some plots it is seen that negative temperature is coming and, in some tables, it is seen that the error is more than 100% that the values are not possible. Through systematic analysis and comparison, the study aims to provide valuable insights into the behavior of reinforced concrete beams under fire and assess the reliability of simplified methods in predicting temperature distribution, thereby contributing to the advancement of fire safety engineering practices.

Table 4-1 presents a comparison of finite element analysis (FEA) results with a simplified method of a reinforced concrete (RC) beam with a 25 mm cover at different time intervals. The tables and Figure display temperatures measured by thermocouples T1 and T2 during a fire test, comparing FEA results with Kodur (A.Gedam, 2021), Wickstrom (A.Gedam, 2021), and Desai (Desai, 1998) simplified methods. Figure 4-9 to Figure 4-13provide visual comparisons of the FEA and simplified results for the 25 mm cover at various time intervals. Kodur (A.Gedam, 2021) method shows the least error compared to FEA, indicating it provides the most accurate results. In contrast, Desai (Desai, 1998) method exhibits the highest error, suggesting it is the least accurate. Wickstrom (A.Gedam, 2021) method shows a decreasing error with increasing time, which may indicate better performance in longer-duration fire exposure. For a 25 mm cover, Kodur (A.Gedam, 2021) method is the most reliable, as it consistently shows the lowest error across all time intervals. This table seems to be focused on evaluating the accuracy of different simplified methods in estimating the behavior of an RC Beam when compared to detailed FEA results. The error percentages and graphical figures help in understanding the effectiveness of each method.

Table 4-1: Comparison of FEA and Simplified results (RC Beam with 25 mm)

Cover 25 mm								
T.C	Time (min)	FEA	Kodur	Error %	Wickstrom	Error %	Desai	Error %
T1	60	487.84	402.97	17.40	440.83	9.64	345.10	29.26
	90	604.54	500.71	17.18	573.26	5.17	397.60	34.23
	120	690.71	569.67	17.52	668.11	3.27	439.42	36.38
	150	758.13	622.58	17.88	741.49	2.20	474.75	37.38
	180	812.41	665.23	18.12	801.02	1.40	505.66	37.76
T2	60	458.81	220.66	51.91	172.05	62.50	172.05	62.50
	90	565.88	335.94	40.63	311.88	44.89	275.97	51.23
	120	647.41	419.38	35.22	415.32	35.85	318.09	50.87
	150	713.96	484.78	32.10	497.14	30.37	353.72	50.46
	180	768.77	538.49	29.95	564.64	26.55	384.93	49.93

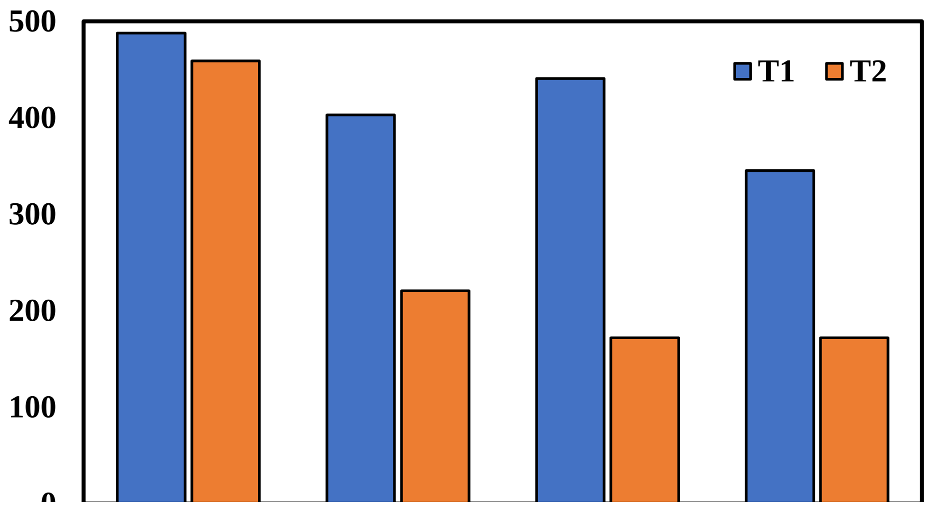


Figure 4-9: FEA and simplified results compared for 25mm cover and time 60min.

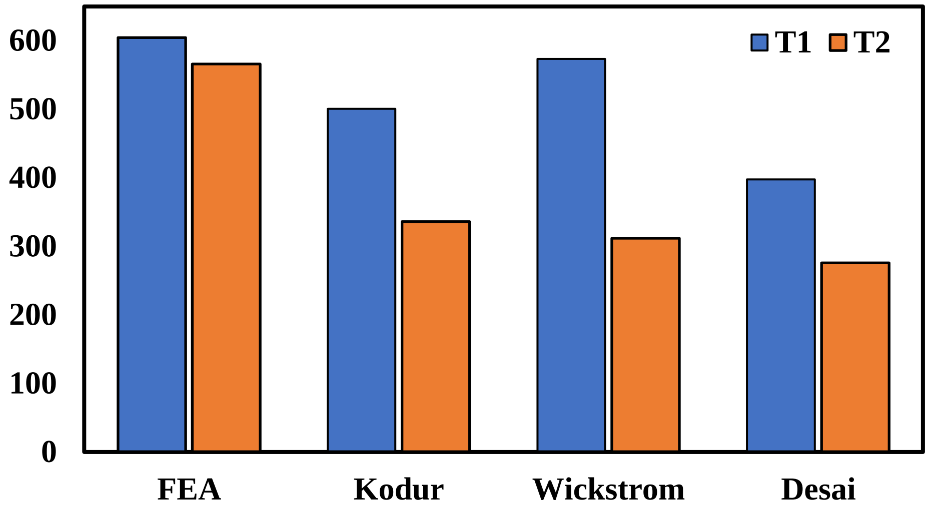


Figure 4-10: FEA and simplified results compared for 25mm cover and time 90min.

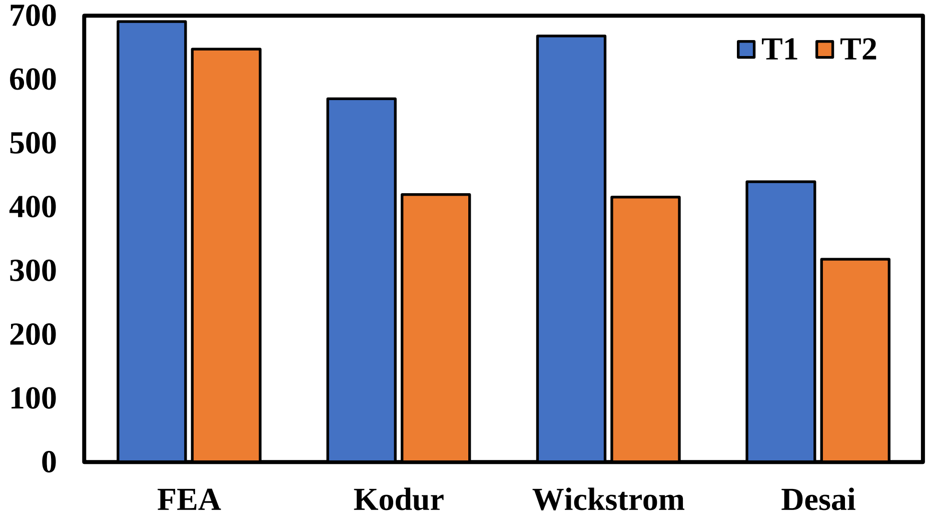


Figure 4-11: FEA and simplified results compared for 25mm cover and time 120min

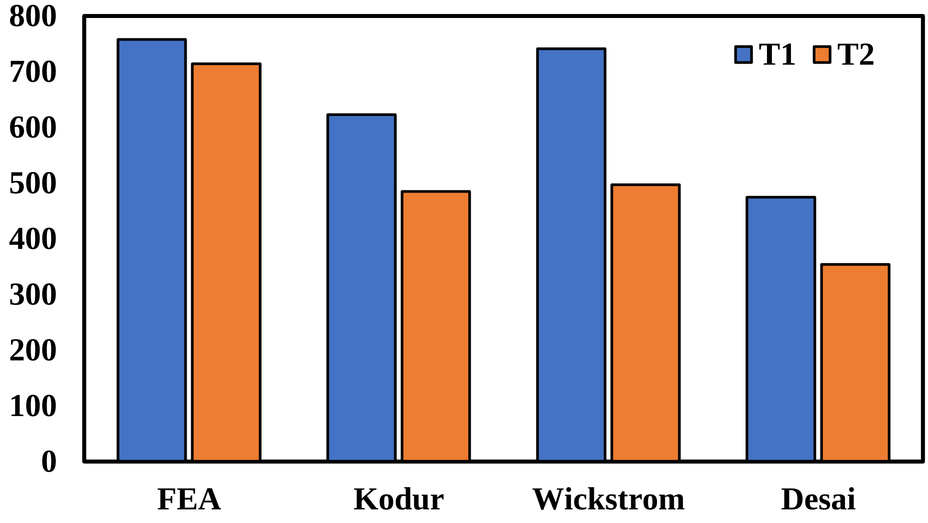


Figure 4-12: FEA and simplified results compared for 25mm cover and time 150min.

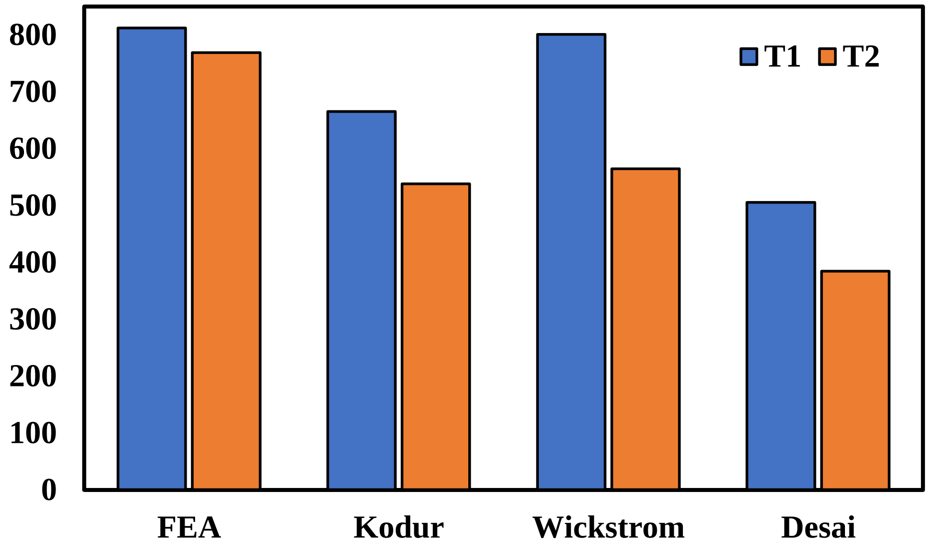


Figure 4-13: FEA and simplified results compared for 25mm cover and time 180min

Table 4-2 presents a comparison of finite element analysis (FEA) results with a simplified method of a reinforced concrete (RC) beam with a 38 mm cover at different time intervals. Figure 4-14 to Figure 4-18 provide visual comparisons of the FEA and simplified results for the 38 mm cover at various time intervals. The tables and Figure display temperatures measured by thermocouples T1 and T2 during a fire test, comparing FEA results with Kodur (A.Gedam, 2021), Wickstrom (A.Gedam, 2021), and Desai (Desai, 1998) simplified methods. The tables and graphs show the temperature readings at thermocouples T1 and T2 over time intervals of 60, 90, 120, 150, and 180 minutes, comparing FEA results with Kodur (A.Gedam, 2021), Wickstrom (A.Gedam, 2021), and Desai (Desai, 1998) simplified methods. Kodur (A.Gedam, 2021) method consistently shows the least error compared to FEA, making it the most accurate among the simplified methods. In contrast, Desai (Desai, 1998) method often has the highest error rates, indicating it is the least accurate. For thermocouple T1, Kodur (A.Gedam, 2021) method provides the best results, while for T2, it varies depending on the time interval. However, Kodur (A.Gedam, 2021) method generally offers better values for both T1 and T2. Kodur's method shows a decreasing error trend with increasing time, suggesting improved accuracy over longer durations. Wickstrom (A.Gedam, 2021) and Desai (Desai, 1998) methods exhibit increasing error rates as time progresses. Kodur (A.Gedam, 2021) method is optimal for a 38 mm cover because it minimizes the error and provides the closest approximation to the FEA results. This table focuses on assessing the accuracy of various simplified methods in estimating the behavior of an RC beam compared to detailed FEA results. The error percentages and graphs illustrate the effectiveness of each method.

Table 4-2: Comparison of FEA and Simplified results (RC Beam with 38 mm)

Cover 38 mm									
T.C	Time (min)	FEA	Kodur	Error %	Wickstrom	Error %	Desai	Error %
T1	60	292.17	323.19	10.62	321.46	10.02	300.99	3.02
	90	405.91	427.60	5.34	456.33	12.42	353.52	12.91
	120	494.64	502.10	1.51	554.35	12.07	395.37	20.07
	150	567.28	559.80	1.32	630.95	11.22	430.75	24.07
	180	627.50	606.70	3.31	693.57	10.53	461.69	26.42
T2	60	190.28	153.97	19.08	85.63	55.00	223.17	17.29
	90	282.49	270.69	4.18	223.84	20.76	275.97	2.31
	120	361.57	355.48	1.68	326.98	9.57	318.09	12.03
	150	430.55	422.12	1.96	409.00	5.01	353.72	17.84
	180	490.87	477.00	2.83	476.93	2.84	384.93	21.58

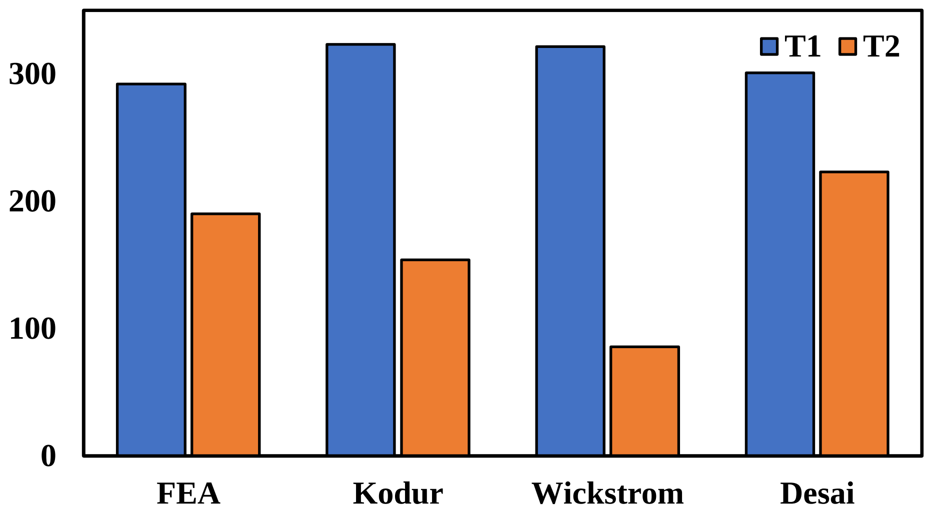


Figure 4-14: FEA and simplified results compared for 38mm cover and time 60min.

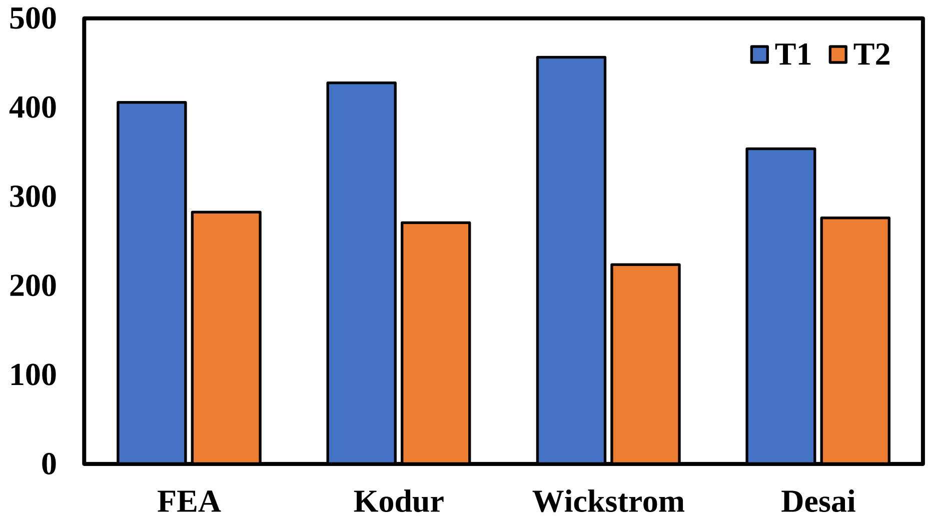


Figure 4-15: FEA and simplified results compared for 38mm cover and time 90min.

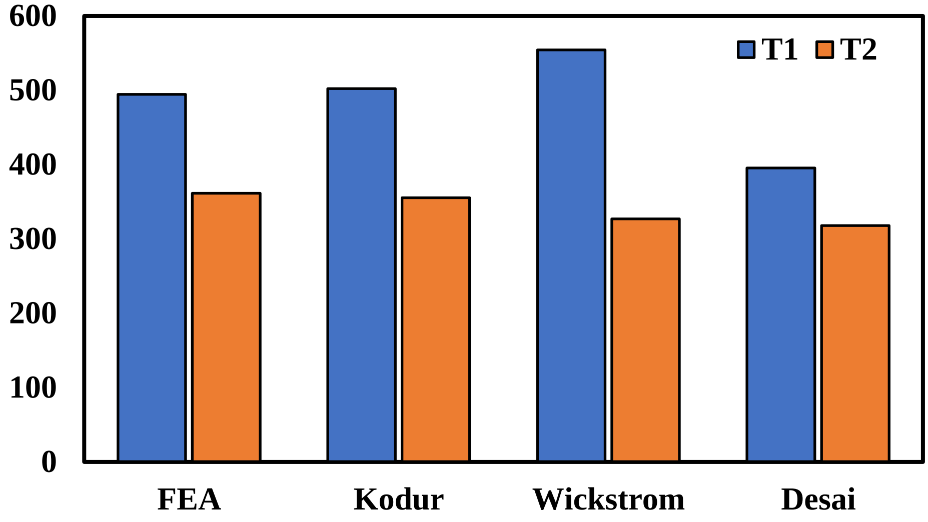


Figure 4-16: FEA and simplified results compared for 38mm cover and time 120min

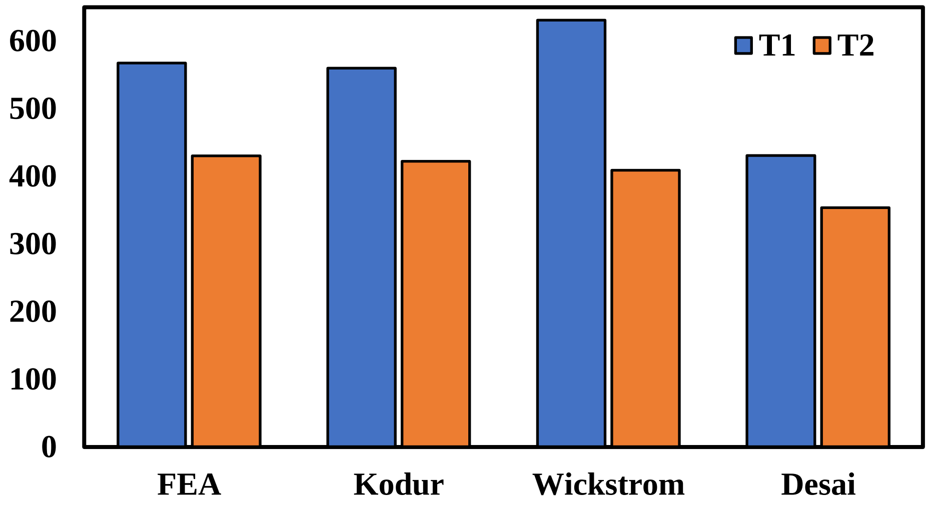


Figure 4-17: FEA and simplified results compared for 38mm cover and time 150min

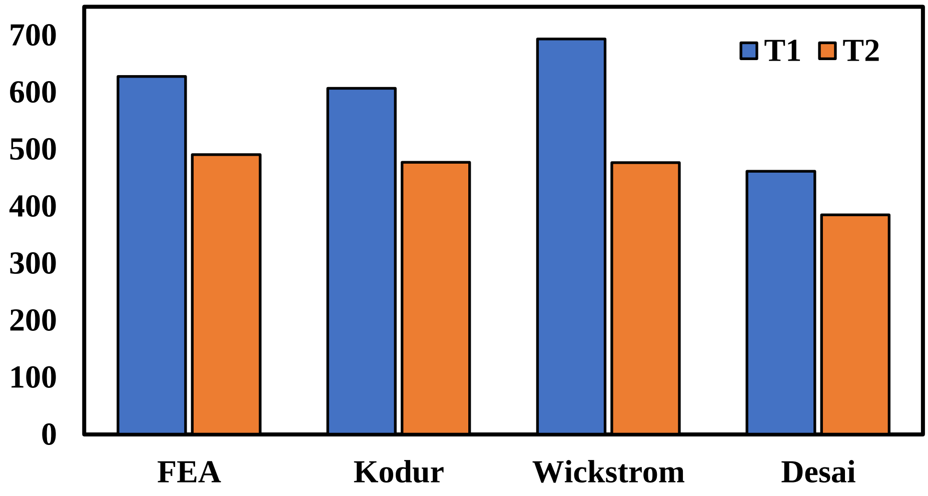


Figure 4-18: FEA and simplified results compared for 38mm cover and time 180min.

Table 4-3 presents a comparison of finite element analysis (FEA) results with a simplified method of a reinforced concrete (RC) beam with a 50 mm cover at different time intervals Figure 4-19 to Figure 4-23 provide visual comparisons of the FEA and simplified results for the 50 mm cover at various time intervals. The tables and graphs compare the temperature readings from FEA with those from the simplified methods at thermocouples T1 and T2 over various durations. Kodur (A.Gedam, 2021) method generally has the least error compared to FEA, especially at longer durations, indicating better accuracy. Desai (Desai, 1998) method shows the most error at the 60-minute mark for T2. Kodur method exhibits a decreasing error trend with time, suggesting improved accuracy with longer durations. For T1, Kodur method provides the best results, while for T2, the best method varies depending on the time. Wickstrom (A.Gedam, 2021) and Desai (Desai, 1998) method tends to give the worst results for short time duration, particularly at the 60-minute duration, due to its higher error percentage. The figures visually compare the FEA and simplified results over time for two different temperature conditions (T1 and T2).

Table 4-3: Comparison of FEA and Simplified results (RC Beam with 50 mm)

Cover 50 mm								
T.C	Time (min)	FEA	Kodur	Error %	Wickstrom	Error %	Desai	Error %
T1	60	205.69	254.46	23.71	223.95	8.88	272.17	32.32
	90	308.91	363.37	17.63	359.78	16.47	324.74	5.13
	120	394.31	441.66	12.01	459.59	16.56	366.63	7.02
	150	466.17	502.65	7.83	538.17	15.44	402.04	13.76
	180	527.94	552.51	4.65	602.75	14.17	433.02	17.98
T2	60	137.28	103.26	24.78	20.98	84.72	223.17	62.57
	90	220.04	221.09	0.48	157.99	28.20	275.97	25.42
	120	294.82	306.90	4.10	260.90	11.50	318.09	7.89
	150	361.85	374.49	3.49	343.07	5.19	353.72	2.25
	180	421.82	430.24	2.00	411.32	2.49	384.93	8.75

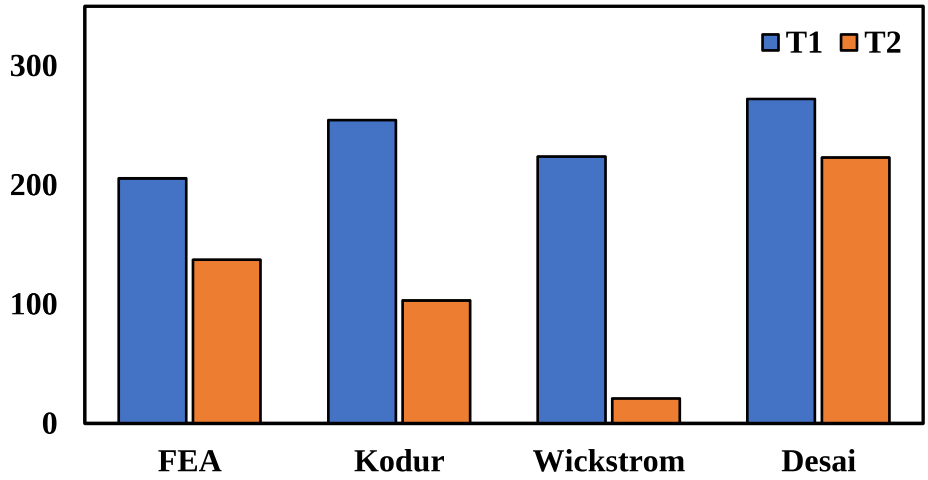


Figure 4-19: FEA and simplified results compared for 50mm cover and time min.

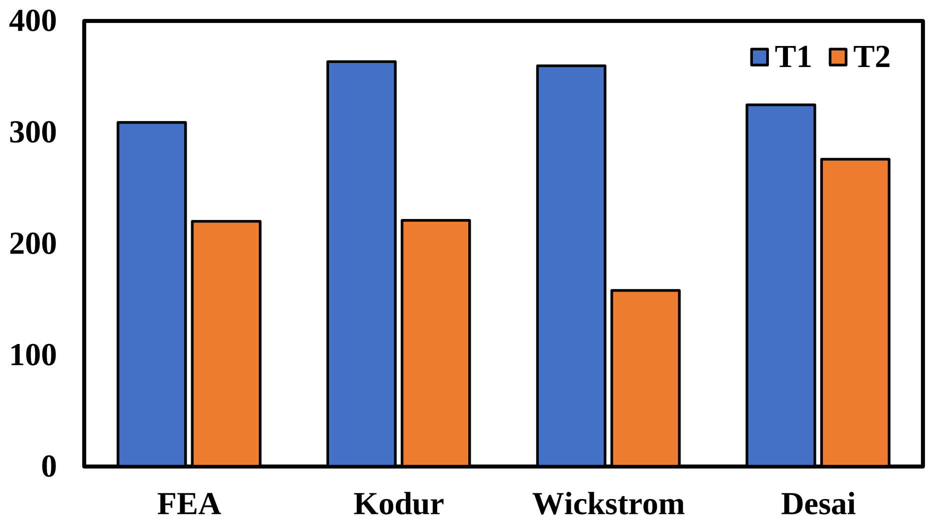


Figure 4-20: FEA and simplified results compared for 50mm cover and time 90min.

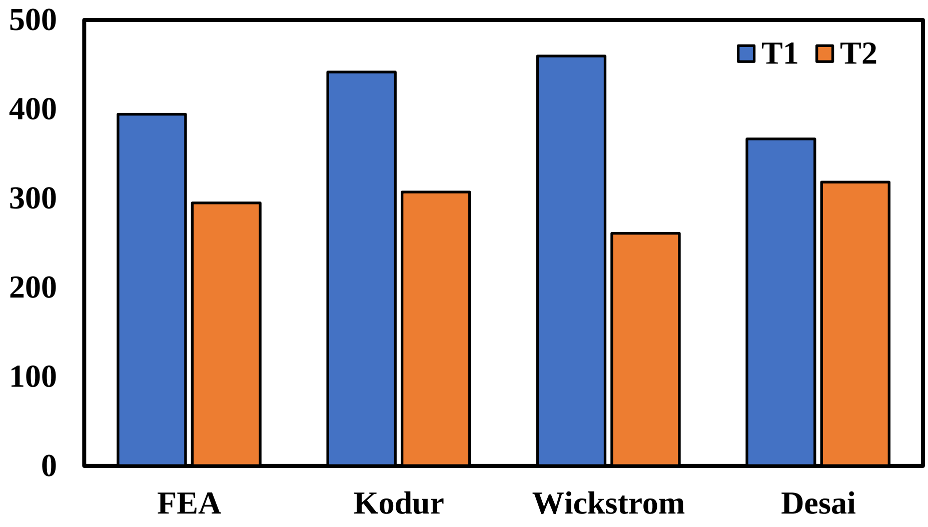


Figure 4-21: FEA and simplified results compared for 50mm cover and time 120min

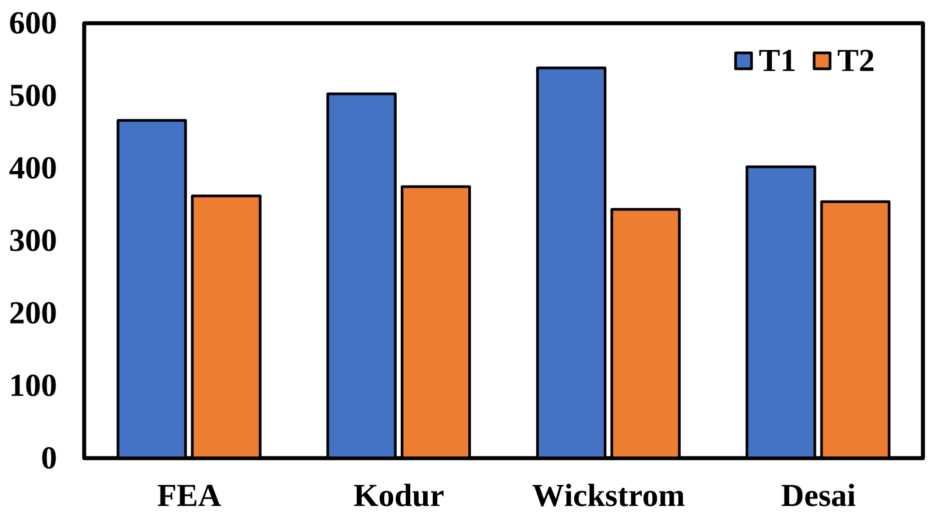


Figure 4-22: FEA and simplified results compared for 50mm cover and time 150min.

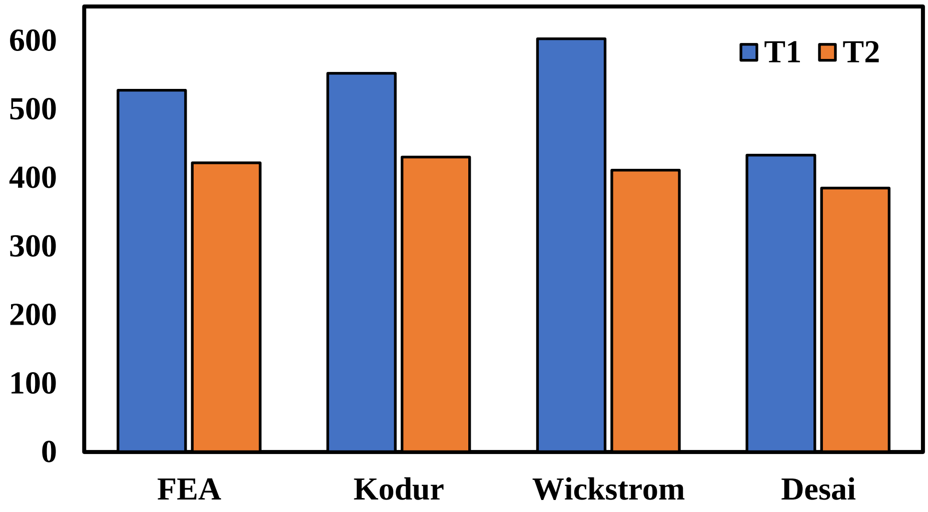


Figure 4-23: FEA and simplified results compared for 50mm cover and time 180min.

The Table 4-4 compares Finite Element Analysis (FEA) results with simplified methods Kodur (A.Gedam, 2021), Wickstrom (A.Gedam, 2021), Desai (Desai, 1998) for an RC Beam with a 63 mm cover. It presents a temperature-time analysis for two scenarios (T1 and T2) over periods of 60, 90, 120, 150, and 180 minutes. The comparison shows varying error percentages between FEA and the simplified methods, indicating the accuracy of each method. Kodur (A.Gedam, 2021) method generally shows less error compared to FEA, while Wickstrom (A.Gedam, 2021) method has varying accuracy, and Desai (Desai, 1998) method exhibits the highest error rates at certain times. Wickstrom (A.Gedam, 2021) and Desai (Desai, 1998) method tends to give the worst results for short time duration, particularly at the 60-minute duration. For thermocouple T1, Kodur (A.Gedam, 2021) method provides the best results, while for T2, the best method varies depending on the time. Figure 4-25 to Figure 4-28 illustrate the comparative results graphically for better visualization of the differences at different time intervals.

Table 4-4: Comparison of FEA and Simplified results (RC Beam with 63 mm)

Cover 63 mm								
T.C	Time (min)	FEA	Kodur	Error %	Wickstrom	Error %	Desai	Error %
T1	60	166.52	184.70	10.92	128.94	22.57	251.46	51.00
	90	257.22	297.34	15.60	265.00	3.02	304.06	18.21
	120	335.32	378.79	12.96	366.01	9.15	345.99	3.18
	150	403.33	442.57	9.73	446.06	10.60	381.44	5.43
	180	463.45	494.92	6.79	512.19	10.52	412.46	11.00
T2	60	114.30	56.37	50.68	-37.94	133.20	223.17	95.26
	90	190.58	175.21	8.06	97.96	48.60	275.97	44.81
	120	261.63	261.97	0.13	200.67	23.30	318.09	21.58
	150	326.25	330.44	1.29	282.98	13.26	353.72	8.42
	180	384.96	387.01	0.53	351.52	8.69	384.93	0.01

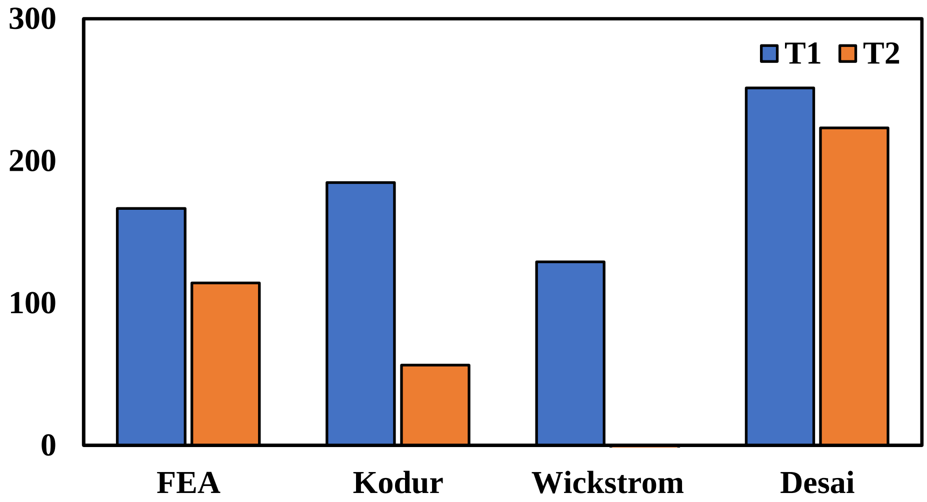


Figure 4-24: FEA and simplified results compared for 63mm cover and time 120min.

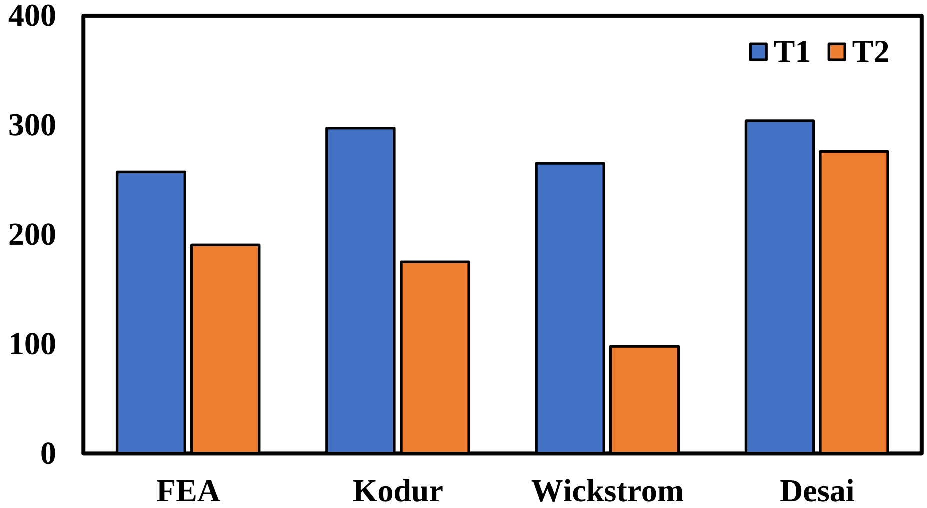


Figure 4-25: FEA and simplified results compared for 63mm cover and time 60min.

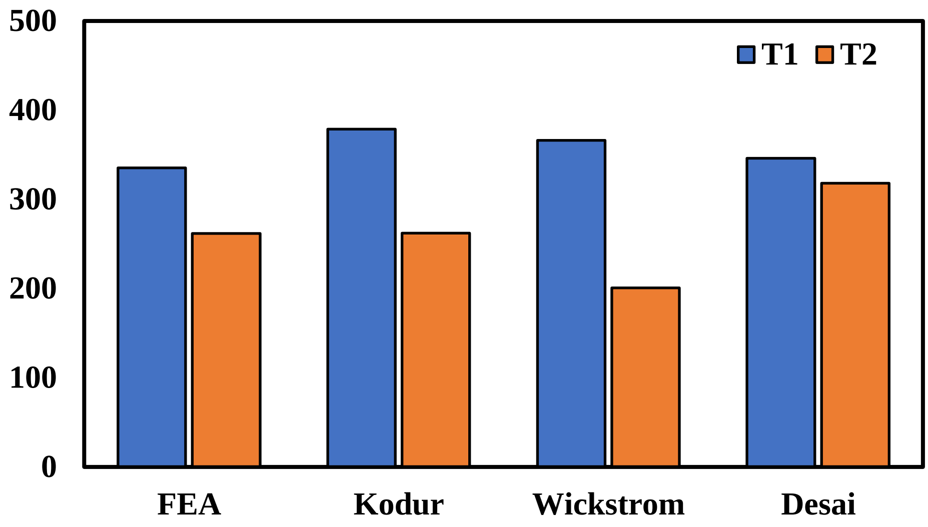


Figure 4-26: FEA and simplified results compared for 63mm cover and time 120min.

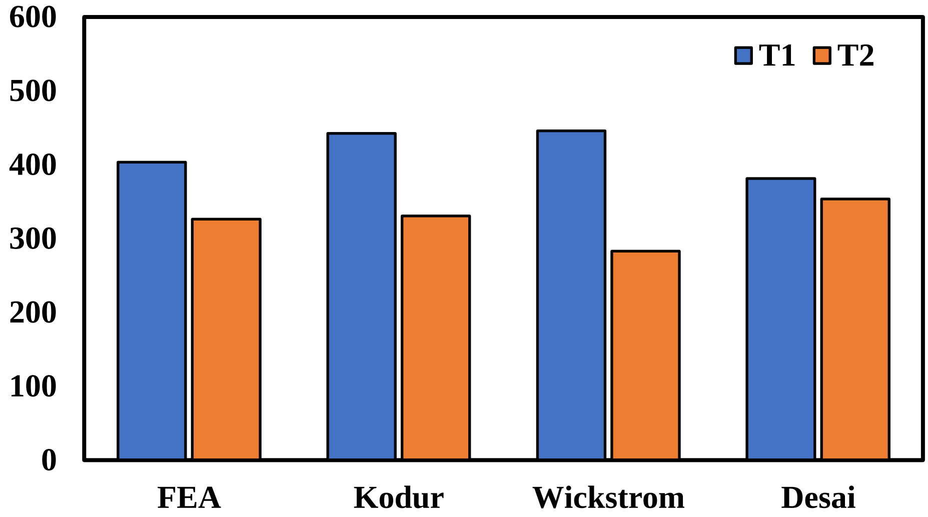


Figure 4-27: FEA and simplified results compared for 63mm cover and time 150min.

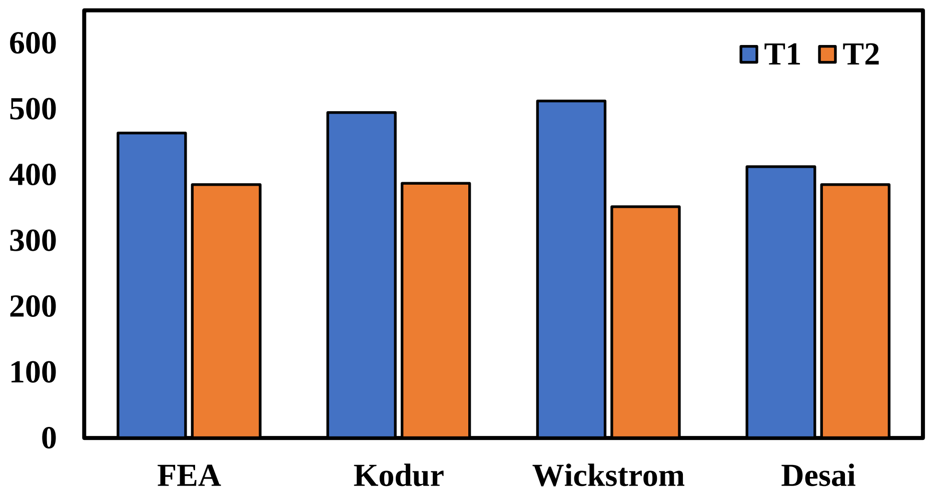


Figure 4-28: FEA and simplified results compared for 63mm cover and time 180min.

The Table 4-5 compares Finite Element Analysis (FEA) results with simplified methods for an RC Beam with a 75 mm cover. It examines the temperature changes over time at intervals of 60, 90, 120, 150, and 180 minutes. The table presents the percentage error between FEA and simplified methods named Kodur (A.Gedam, 2021), Wickstrom (A.Gedam, 2021), and Desai (Desai, 1998). The tables and figure compare the temperature readings from FEA with those predicted by Kodur (A.Gedam, 2021), Wickstrom (A.Gedam, 2021), and Desai (Desai, 1998) methods at different times for thermocouples T1 and T2. Kodur (A.Gedam, 2021) method generally shows the least error, suggesting it may provide the best approximation to FEA results, while Desai (Desai, 1998) method often has the highest error. For thermocouple T1, Wickstrom (A.Gedam, 2021) method seems to yield the best results, while for T2, the data suggests Kodur (A.Gedam, 2021) that method might be more accurate at certain times. Wickstrom (A.Gedam, 2021) and Desai (Desai, 1998) method tends to give the worst results for short time duration, particularly at the 60-minute duration. Figure 4-29 to Figure 4-33 illustrate the comparative results graphically for better visualization of the differences at different time intervals.

Table 4-5: Comparison of FEA and Simplified results (RC Beam with 75 mm)

Cover 75 mm								
T.C	Time (min)	FEA	Kodur	Error %	Wickstrom	Error %	Desai	Error %
T1	60	117.29	124.06	5.77	49.11	58.13	239.87	104.51
	90	196.21	239.40	22.01	184.89	5.77	292.51	49.08
	120	268.21	323.18	20.49	286.57	6.85	334.48	24.71
	150	333.15	389.02	16.77	367.58	10.33	369.96	11.05
	180	391.62	443.23	13.18	434.75	11.01	401.01	2.40
T2	60	84.83	18.53	78.15	-84.86	200.04	223.17	163.09
	90	151.83	138.20	8.98	50.17	66.96	275.97	81.77
	120	217.68	225.72	3.69	152.71	29.85	318.09	46.13
	150	279.37	294.89	5.56	235.13	15.84	353.72	26.62
	180	336.15	352.12	4.75	303.90	9.59	384.93	14.51

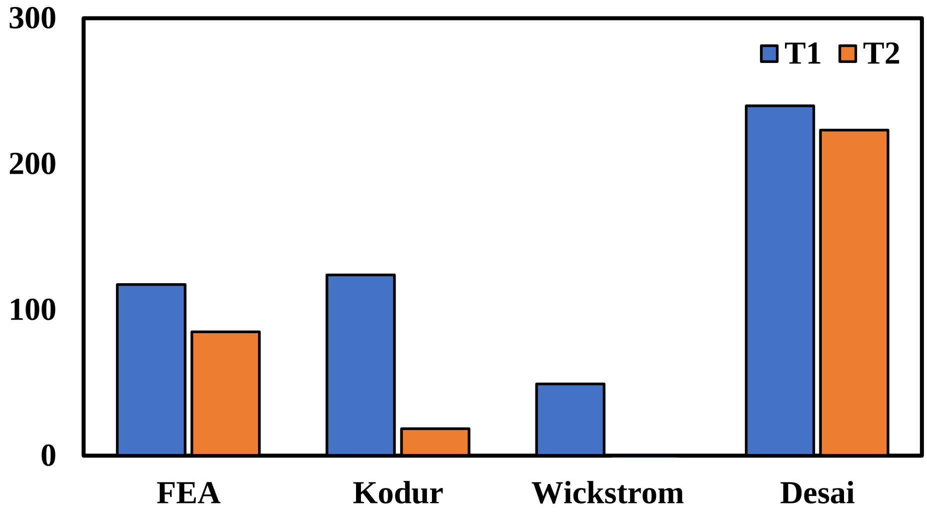


Figure 4-29: FEA and simplified results compared for 75mm cover and time 60min.

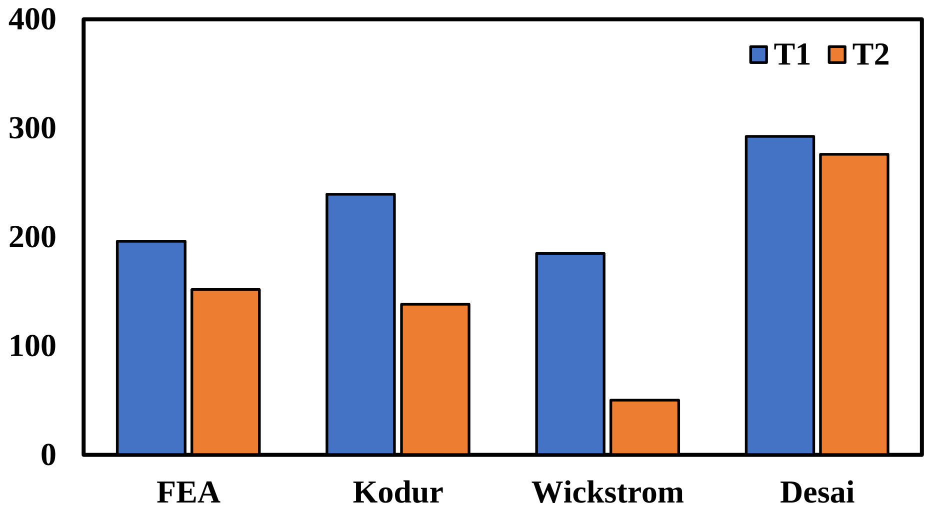


Figure 4-30: FEA and simplified results compared for 75mm cover and time 90min

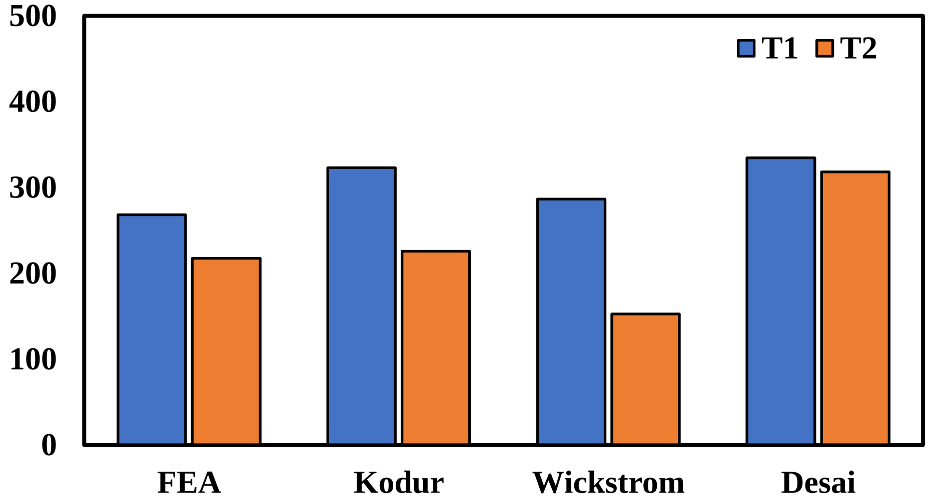


Figure 4-31: FEA and simplified results compared for 75mm cover and time 120min

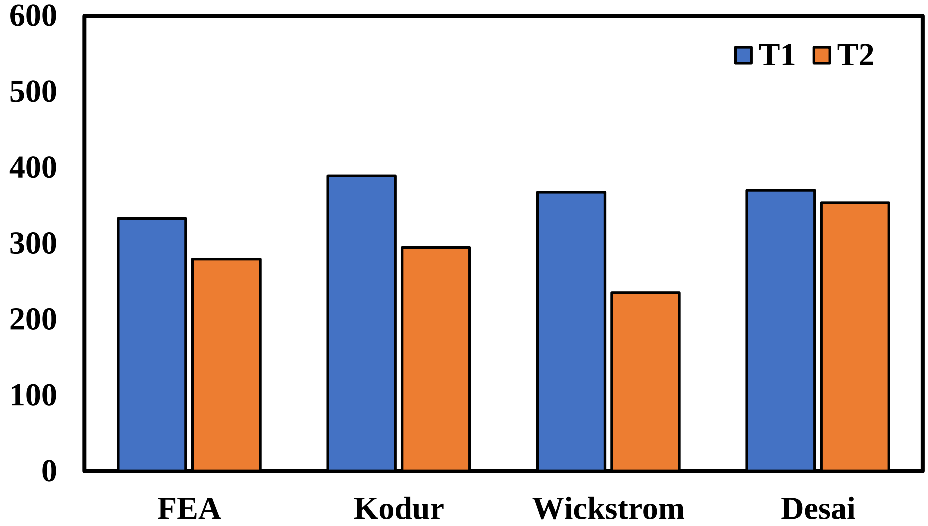


Figure 4-32: FEA and simplified results compared for 75mm cover and time 150min

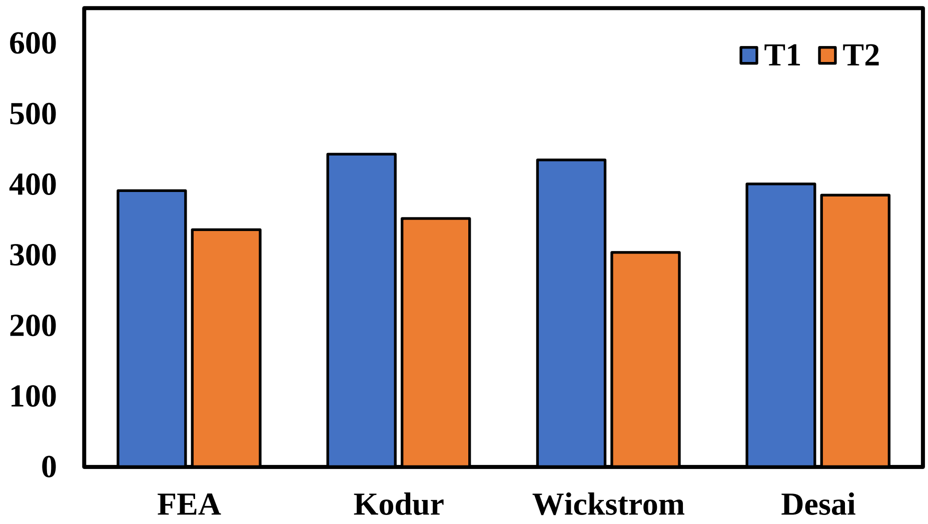


Figure 4-33: FEA and simplified results compared for 75mm cover and time 180min

The Figure 4-34 from the current page compare the temperature differences between Finite Element Analysis (FEA) and simplified methods for thermocouples T1 across various beam cover sizes and time intervals.

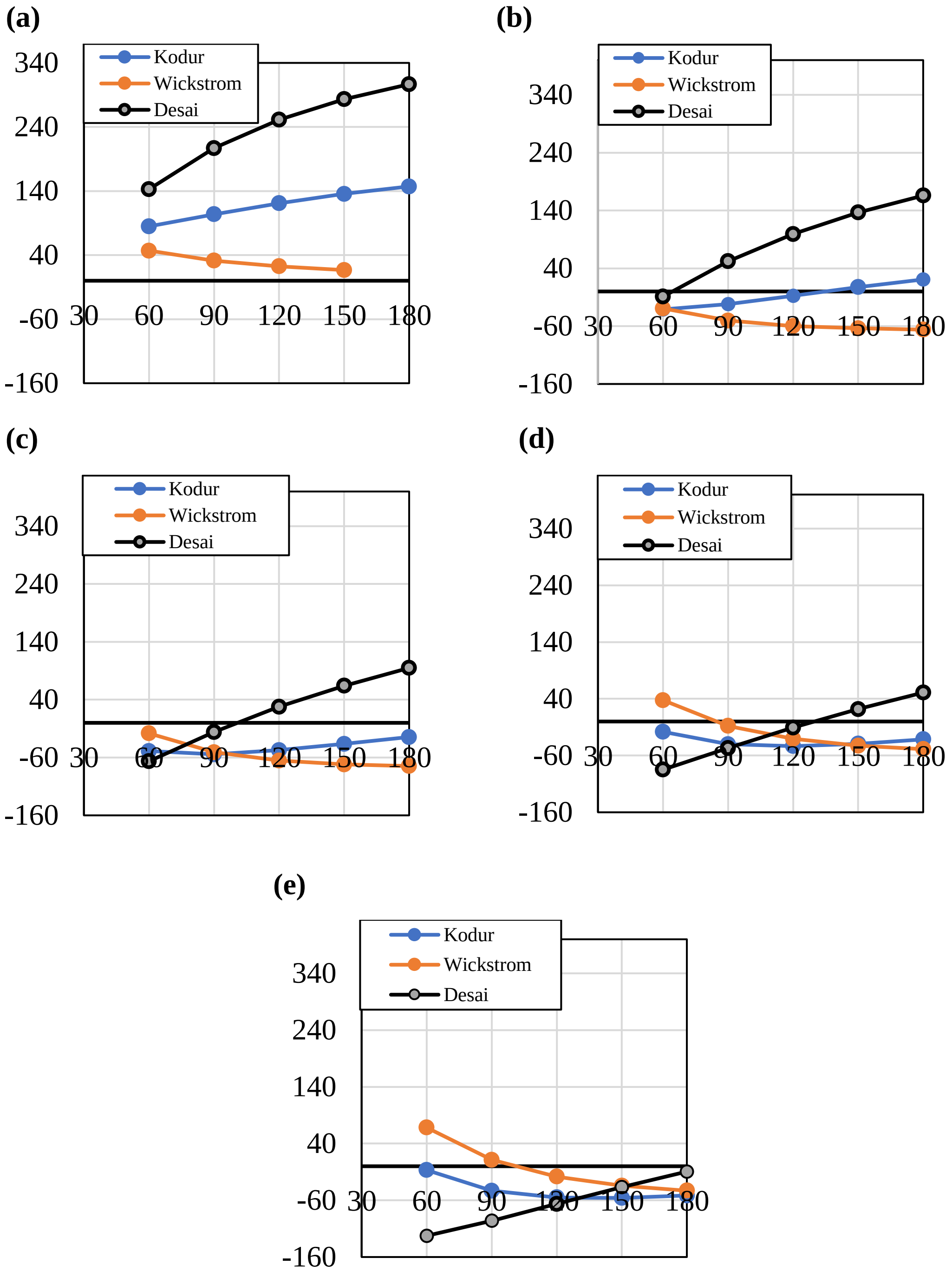


Figure 4-34: For Thermocouples T1 Temperature difference among FEA and simplified method (a) 25mm (b) 38mm (c) 50mm (d) 63mm (e) 75mm beam cover

The Figure *4-35* from the current page compare the temperature differences between Finite Element Analysis (FEA) and simplified methods for thermocouples T2 across various beam cover sizes and time intervals.

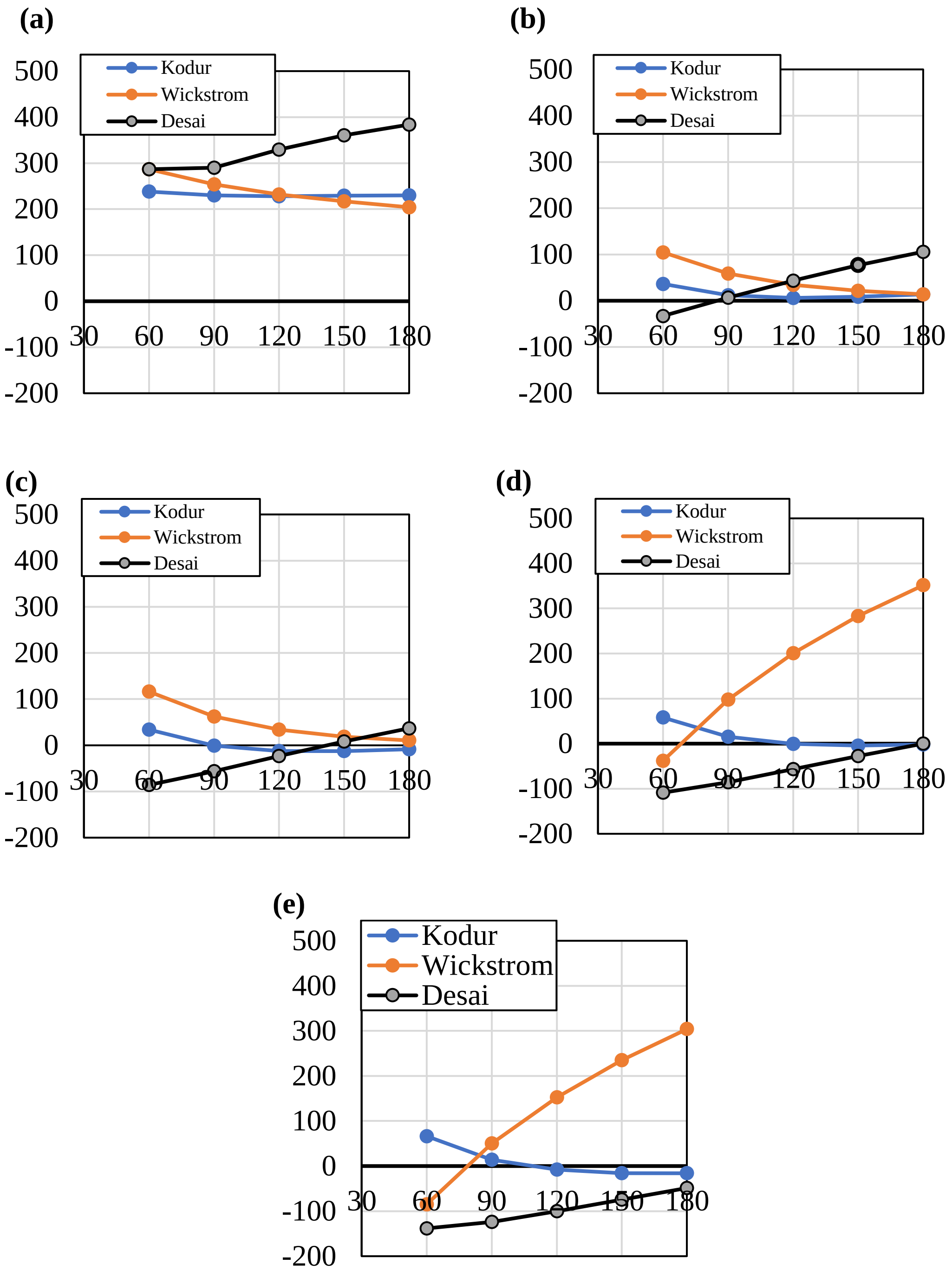


Figure 4-35: For Thermocouples T2 Temperature difference among FEA and simplified method (a) 25mm (b) 38mm (c) 50mm (d) 63mm (e) 75mm beam cover.

4.5 Summary

The study validates a finite element model against experimental data, focusing on temperature distribution in reinforced concrete beams under fire conditions. It compares the results from the finite element model with simplified methods proposed by Wickstrom, Kodur, and Desai for estimating temperature rise in fire-exposed beams. A detailed parametric study is conducted to assess the impact of various factors like cover thickness and fire duration on the temperature distribution within the beam. The paper demonstrates the accuracy of the finite element model through comparison graphs and discusses the effectiveness of simplified methods in predicting temperature distribution. The paper provides valuable insights into the behavior of reinforced concrete beams under fire and evaluates the reliability of different methods for fire safety engineering practices.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

The following are notable findings that resulted from this analysis

1. It became evident that employing average conductivity values, an emissivity of 0.8, and a mesh size of 25mm consistently delivered satisfactory results. These parameters were crucial in ensuring accurate temperature predictions and reliable outcomes across various scenarios.
2. Among the simplified methods evaluated, the method proposed by Wickstrom demonstrated the highest accuracy with the least error when compared to FEA results. This method consistently showed close agreement with FEA across various cover thicknesses and fire exposure durations.
3. The Kodur method exhibited moderate accuracy, with errors higher than those of Wickstrom but lower than those of Desai. Desai's method showed the largest discrepancies, making it the least reliable among the three simplified methods evaluated.
4. The results consistently showed that as the cover thickness increases, the temperature at the reinforcement bars (rebars) decreases. This is due to the increased insulation provided by the additional concrete cover, which slows the heat transfer from the fire-exposed surface to the rebars.

5.2 Recommendations

In future studies using reinforced concrete beams, it is advised that similar viscosity and dilation angle values be used. This recommendation is based on the ideal parameters that have been determined. Researchers should consider the following aspects for future investigation

1. Further research should focus on refining the finite element modeling techniques to improve the accuracy of temperature predictions in reinforced concrete beams exposed to fire.
2. Investigate the applicability of advanced materials, such as CFRP strips, for enhancing the fire resistance of reinforced concrete structures.
3. Conduct experimental studies to validate the findings of this research and enhance the understanding of the thermal behavior of reinforced concrete elements under fire conditions.
4. Collaborate with industry professionals to implement the research findings into

practical design guidelines for improving the fire safety of structural systems.

5. Explore the potential of incorporating performance-based fire resistance design approaches into structural engineering practices to optimize fire protection strategies.

By following these recommendations, future research endeavors can contribute to the advancement of fire safety measures in structural engineering and promote the development of resilient and sustainable infrastructure.

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Appendix

Table A.1: List of Trial

ID	Conductivity	Mesh	Emissivity
J-1	High	25	0.8
J-2	Average	25	0.8
J-3	Low	25	0.8
J-4	High	25	0.7
J-5	Average	25	0.7
J-6	Low	25	0.7
J-7	High	25	0.65
J-8	Average	25	0.65
J-9	Low	25	0.65
J-10	High	25	0.6
J-11	Average	25	0.6
J-12	Low	25	0.6
J-13	High	35	0.8
J-14	Average	35	0.8
J-15	Low	35	0.8
J-16	High	35	0.7
J-17	Average	35	0.7
J-18	Low	35	0.7
J-19	High	35	0.65
J-20	Average	35	0.65
J-21	Low	35	0.65
J-22	High	35	0.6
J-23	Average	35	0.6
J-24	Low	35	0.6
J-25	High	15	0.8
J-26	Average	15	0.8
J-27	Low	15	0.8
J-28	High	15	0.7
J-29	Average	15	0.7
J-30	Low	15	0.7
J-31	High	15	0.65
J-32	Average	15	0.65
J-33	Low	15	0.65
J-34	High	15	0.6
J-35	Average	15	0.6
J-36	Low	15	0.6

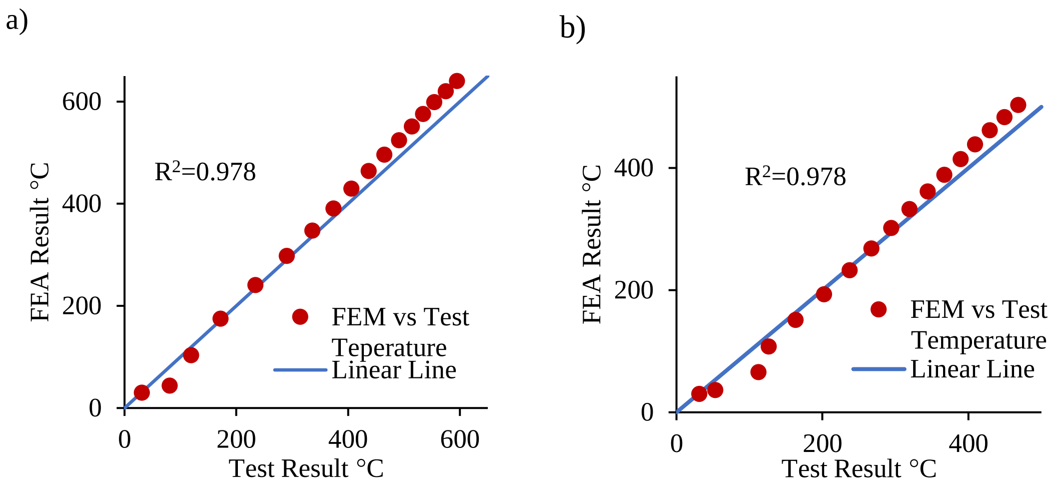

Figure A.1: Comparison of FEM vs Test Results for J-1 (a) TC-1 (b) TC-2

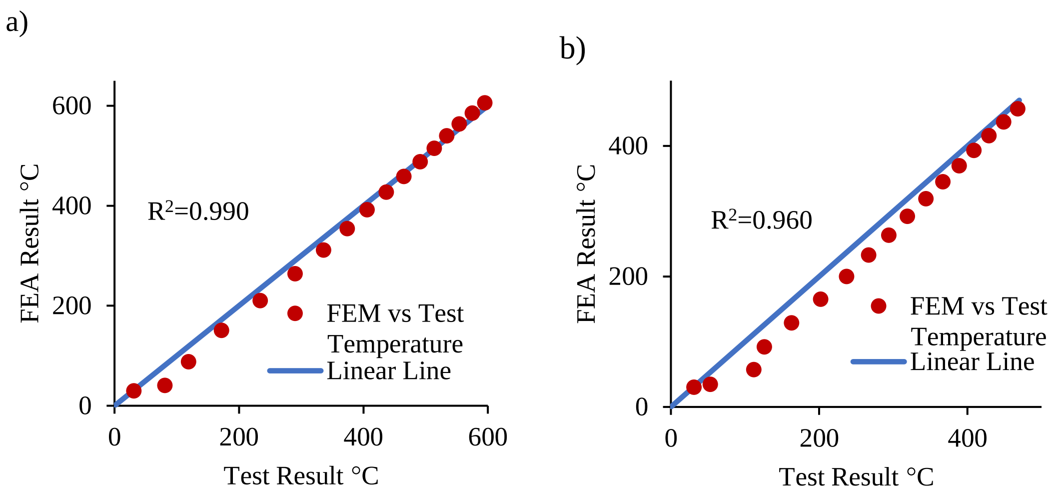

Figure A.2 Comparison of FEM vs Test Results for J-2 (a) TC-1 (b) TC-2

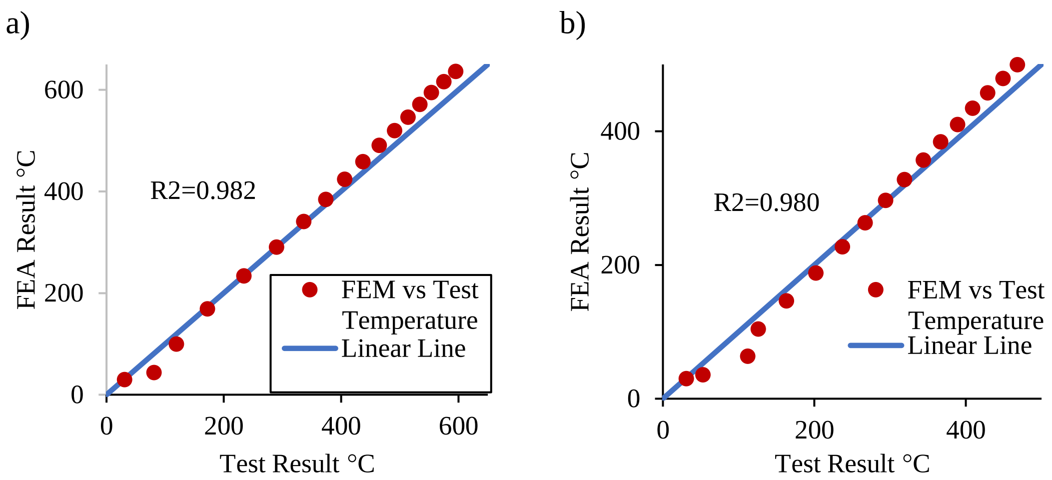

Figure A 3: Comparison of FEM vs Test Results for J-3 (a) TC-1 (b) TC-2

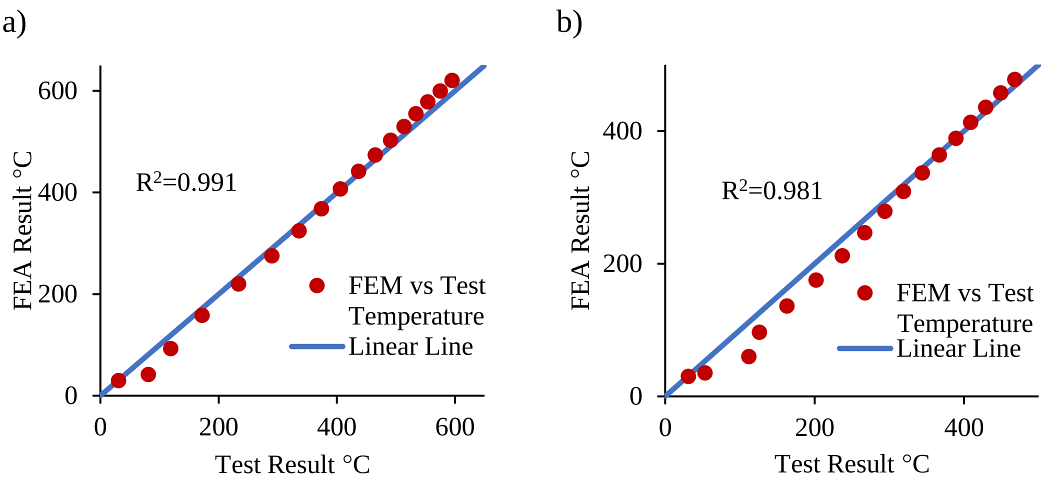

Figure A.4: Comparison of FEM vs Test Results for J-4 (a) TC-1 (b) TC-2

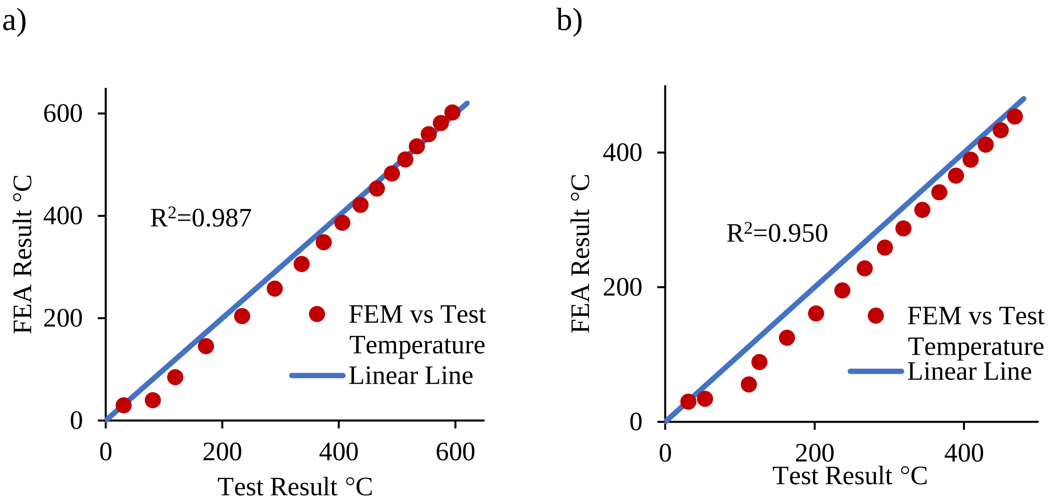

Figure A.5: Comparison of FEM vs Test Results for J-5 (a) TC-1 (b) TC-2

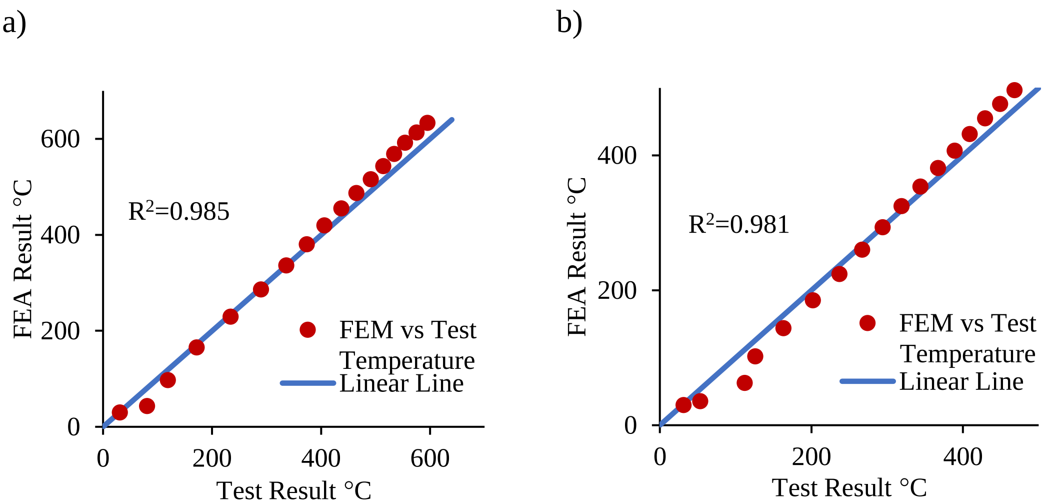

Figure A.6: Comparison of FEM vs Test Results for J-6 (a) TC-1 (b) TC-2

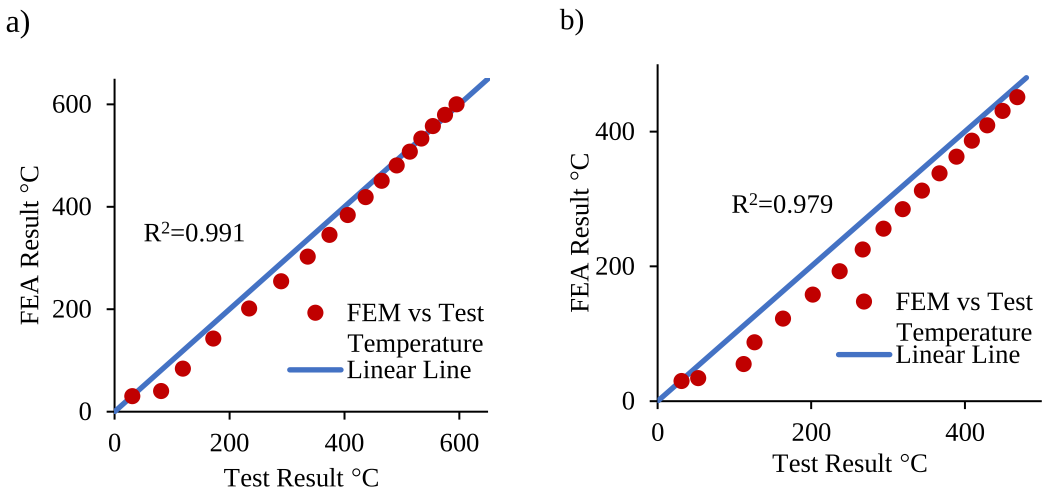

Figure A.7: Comparison of FEM vs Test Results for J-7 (a) TC-1 (b) TC-2

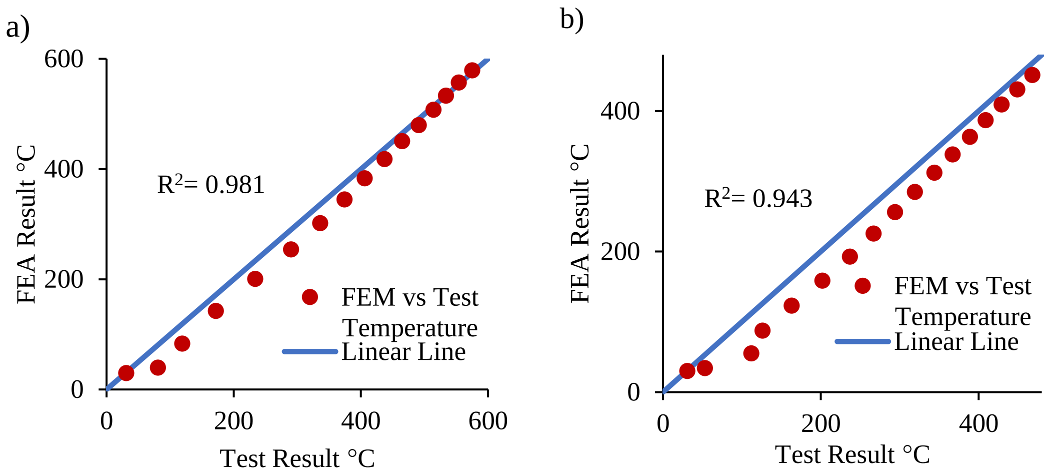

Figure A.8: Comparison of FEM vs Test Results for J-8 (a) TC-1 (b) TC-2

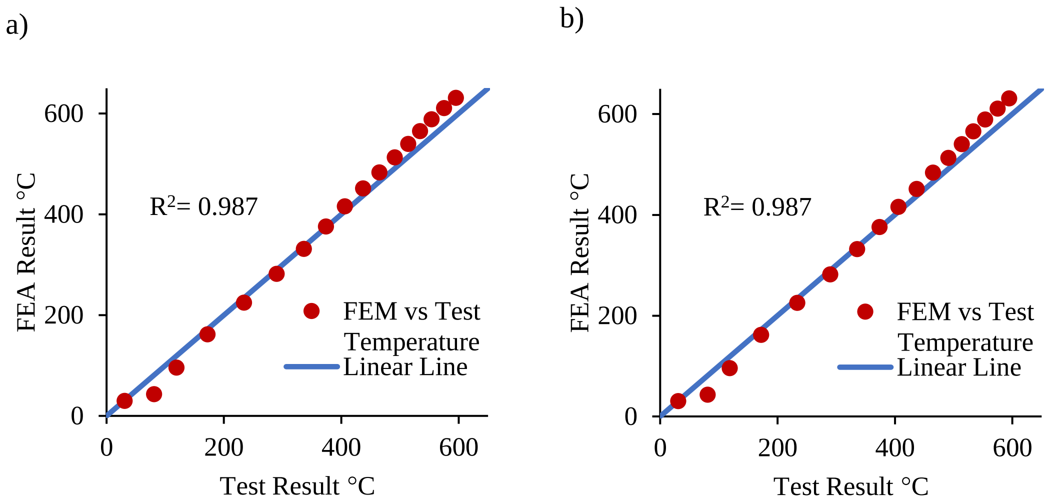

Figure A.9: Comparison of FEM vs Test Results for J-9 (a) TC-1 (b) TC-2

a) b)

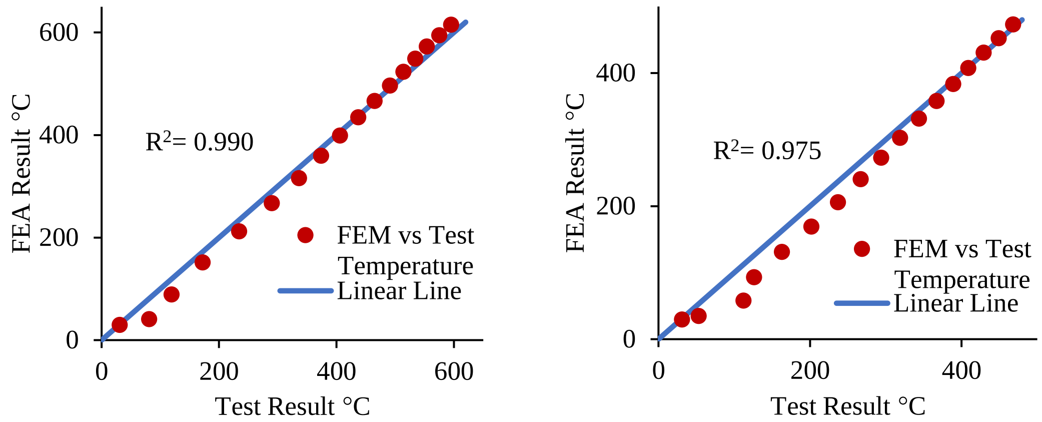

Figure A.10: Comparison of FEM vs Test Results for J-10 (a) TC-1 (b) TC-2

a) b)

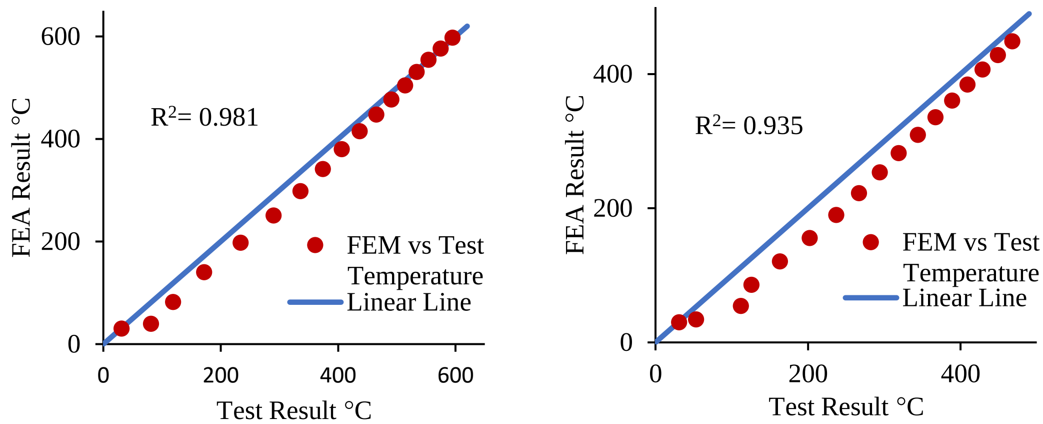

Figure A.11: Comparison of FEM vs Test Results for J-11 (a) TC-1 (b) TC-2

a) b)

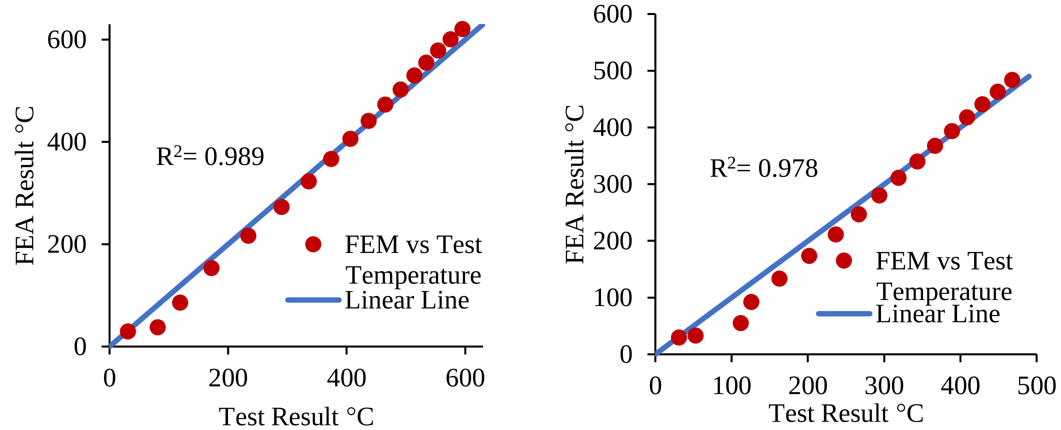

Figure A.12: Comparison of FEM vs Test Results for J-12 (a) TC-1 (b) TC-2

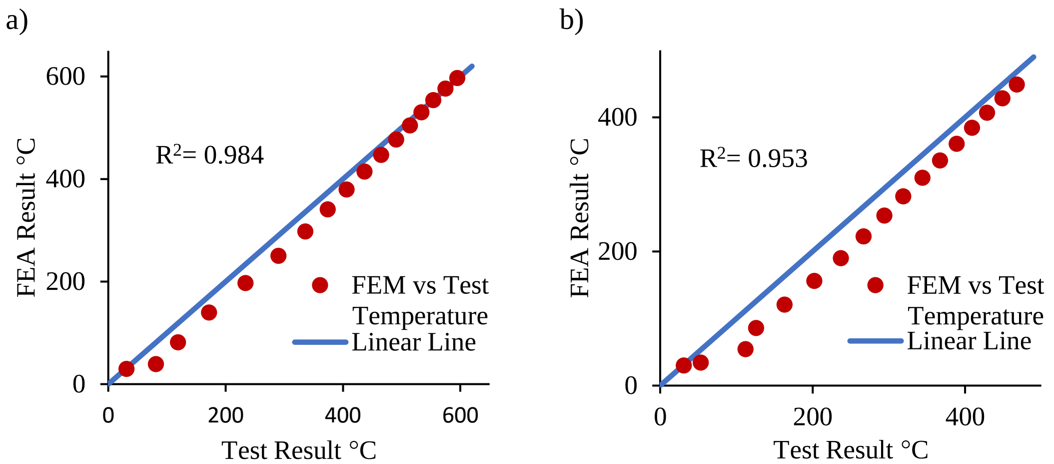

Figure A.13: Comparison of FEM vs Test Results for J-13 (a) TC-1 (b) TC-2

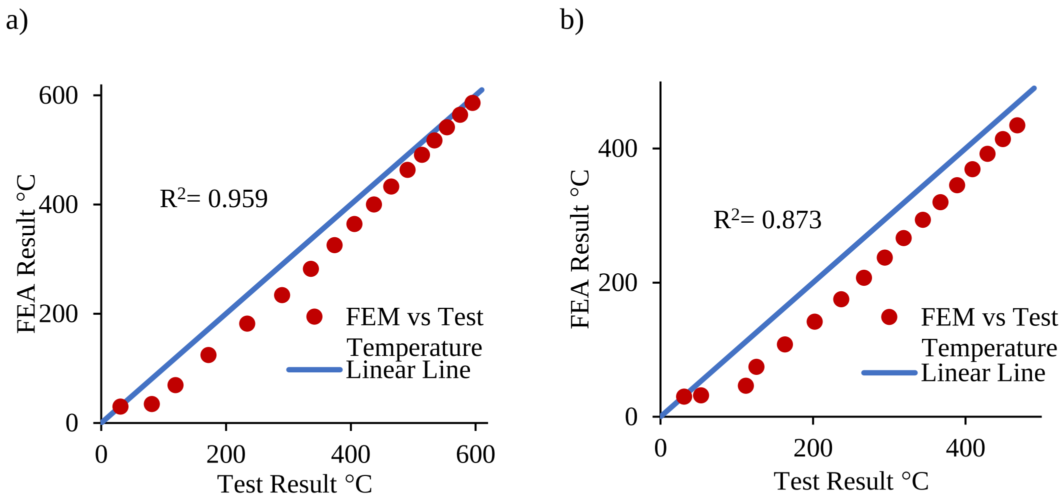

Figure A.14: Comparison of FEM vs Test Results for J-14 (a) TC-1 (b) TC-2

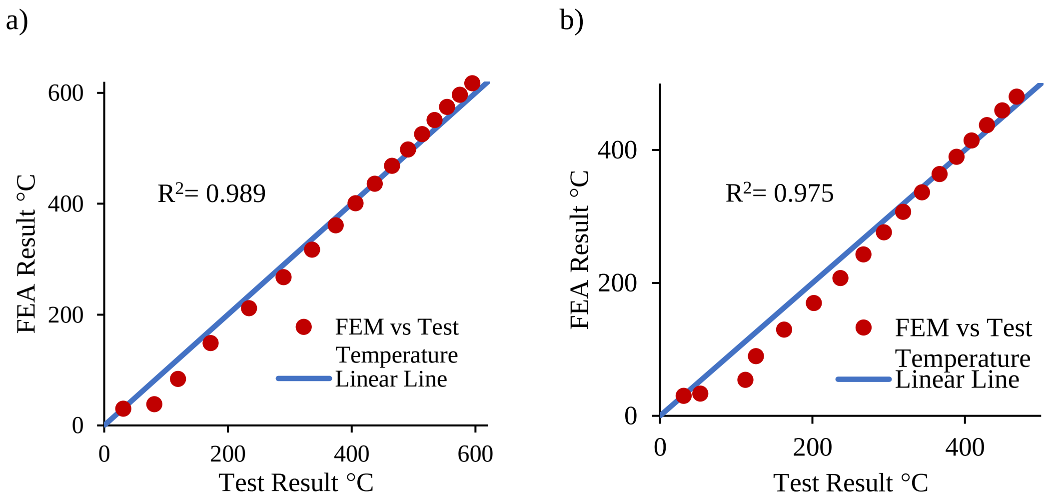

Figure A.15: Comparison of FEM vs Test Results for J-15 (a) TC-1 (b) TC-2:

a) b)

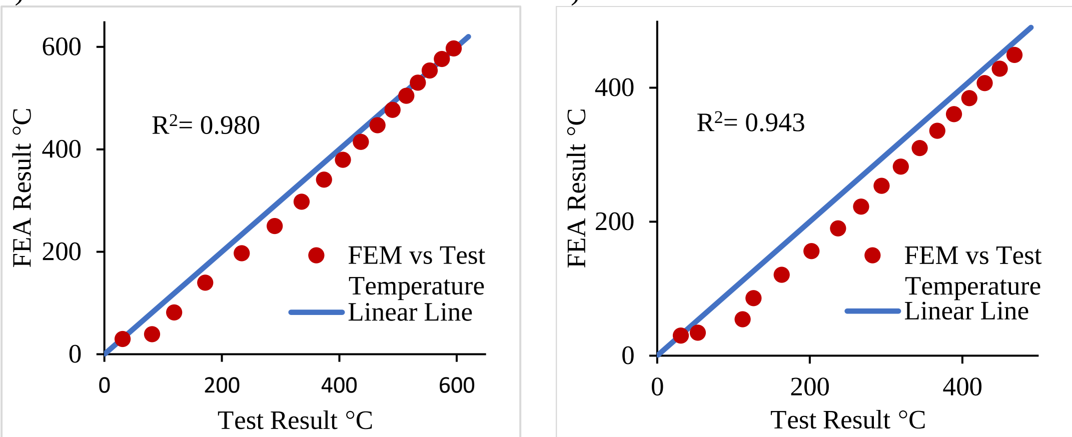

Figure A.16: Comparison of FEM vs Test Results for J-16 (a) TC-1 (b) TC-2

a) b)

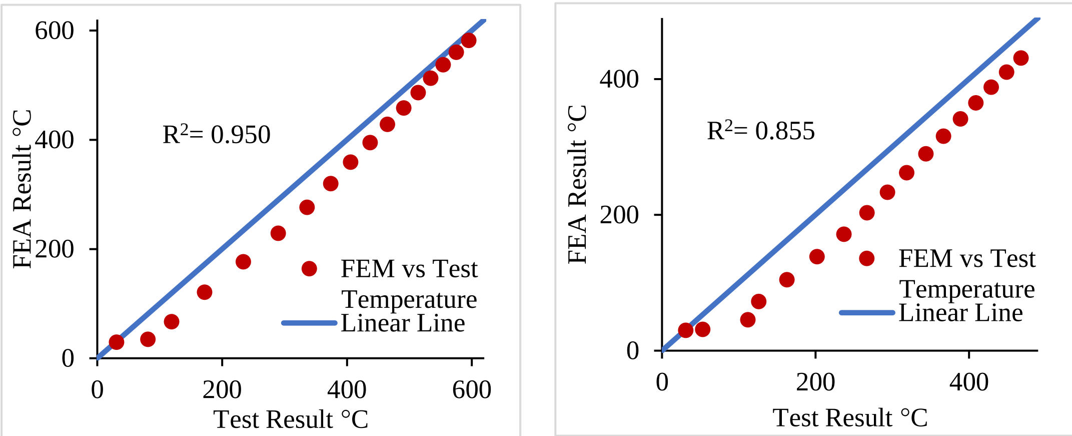

Figure A.17: Comparison of FEM vs Test Results for J-17 (a) TC-1 (b) TC-2

a) b)

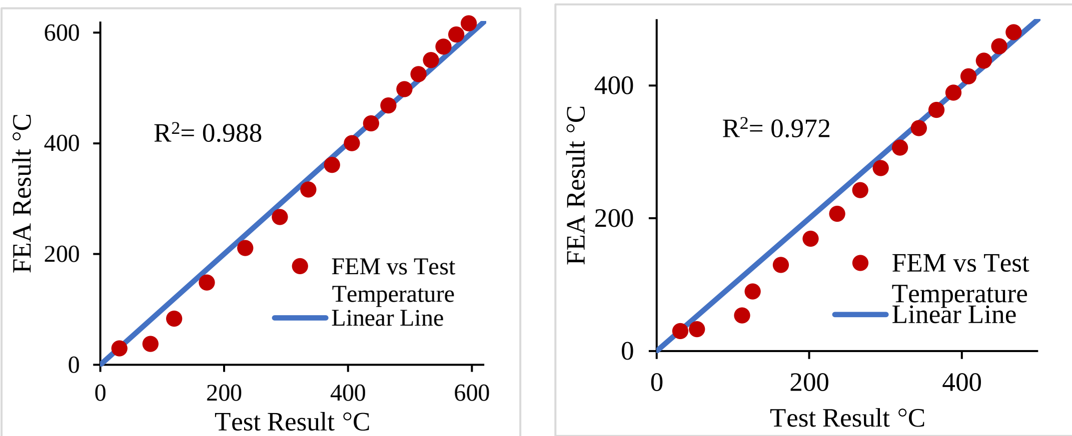

Figure A.18: Comparison of FEM vs Test Results for J-18 (a) TC-1 (b) TC-2

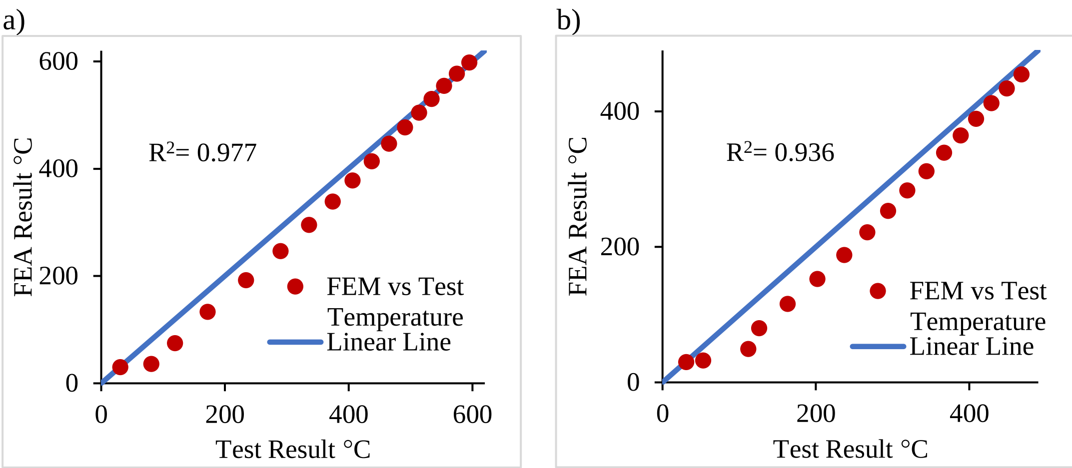

Figure A.19: Comparison of FEM vs Test Results for J-19 (a) TC-1 (b) TC-2

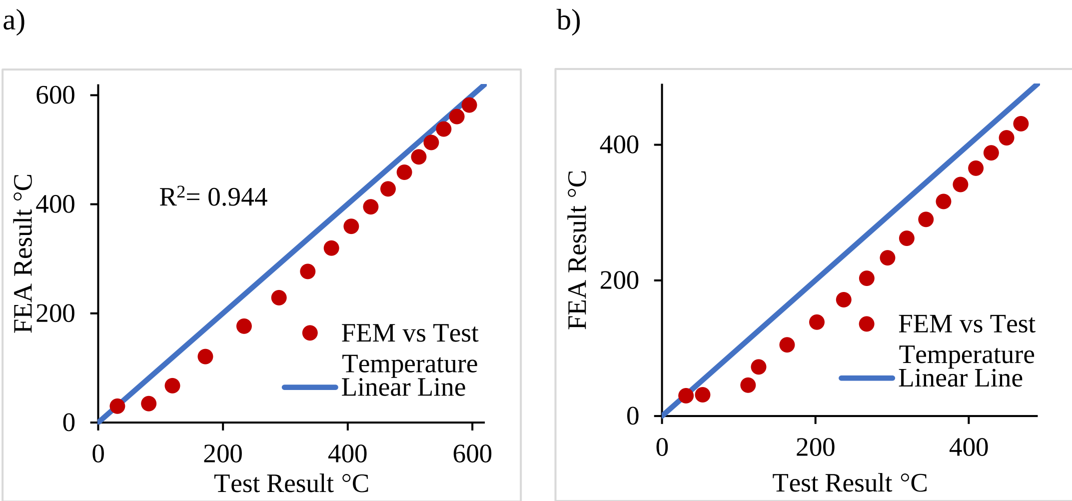

Figure A.20: Comparison of FEM vs Test Results for J-20 (a) TC-1 (b) TC-2

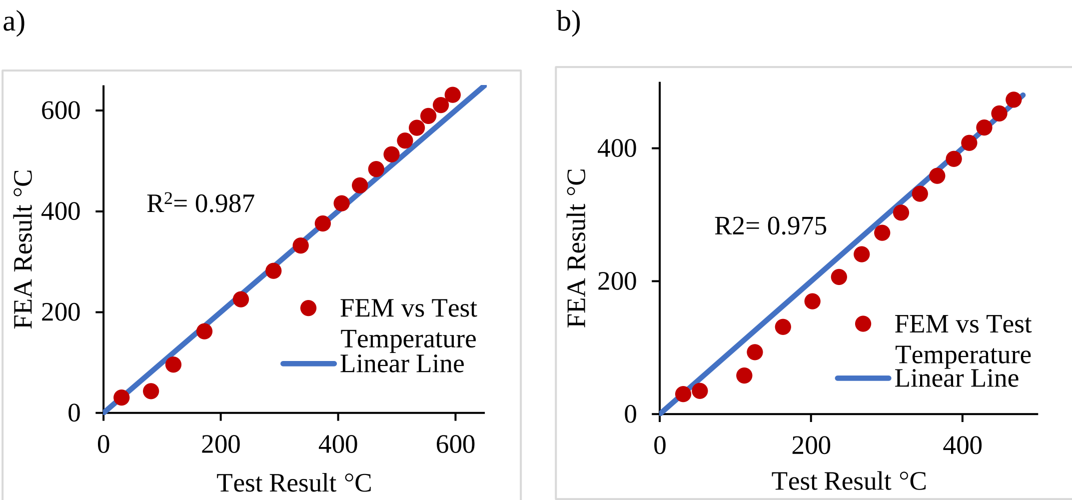

Figure A.21: Comparison of FEM vs Test Results for J-21 (a) TC-1 (b) TC-2

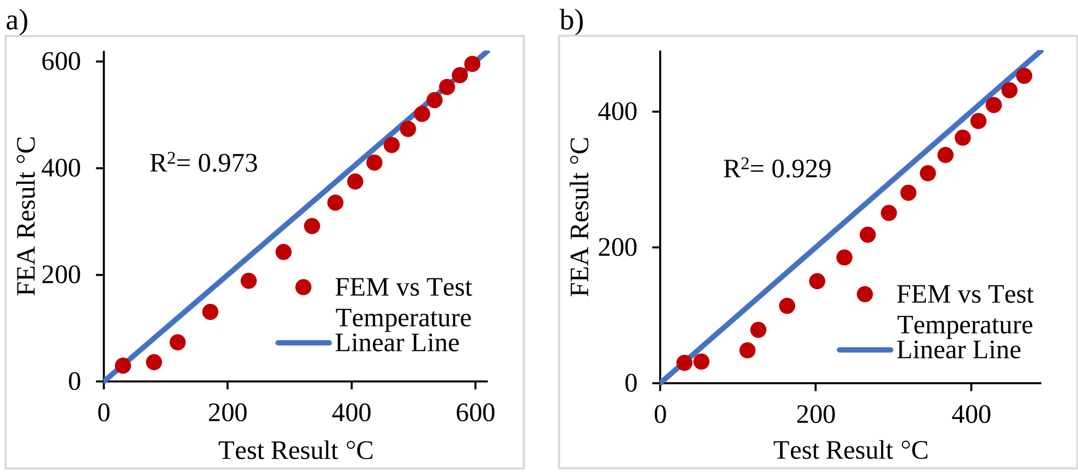

Figure A.22: Comparison of FEM vs Test Results for J-22(a) TC-1 (b) TC-2

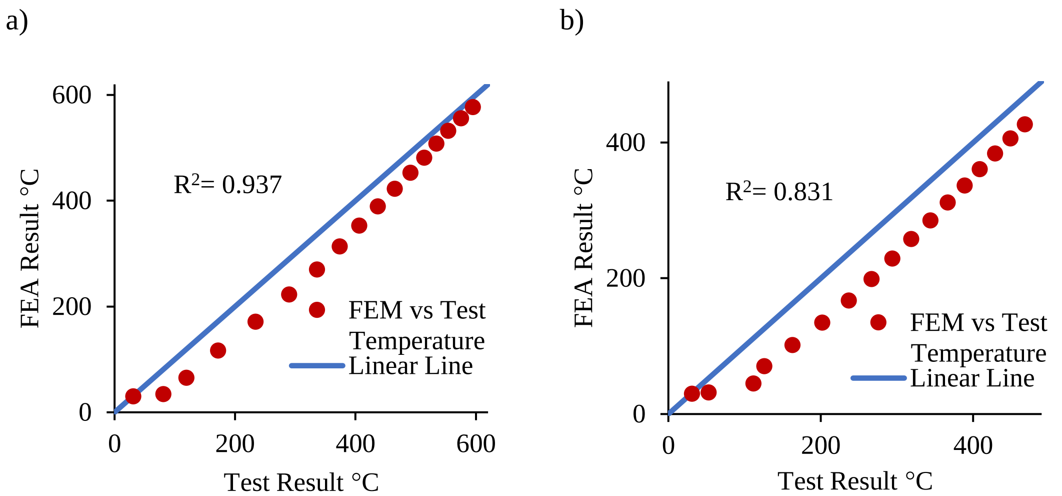

Figure A.23: Comparison of FEM vs Test Results for J-23(a) TC-1 (b) TC-2

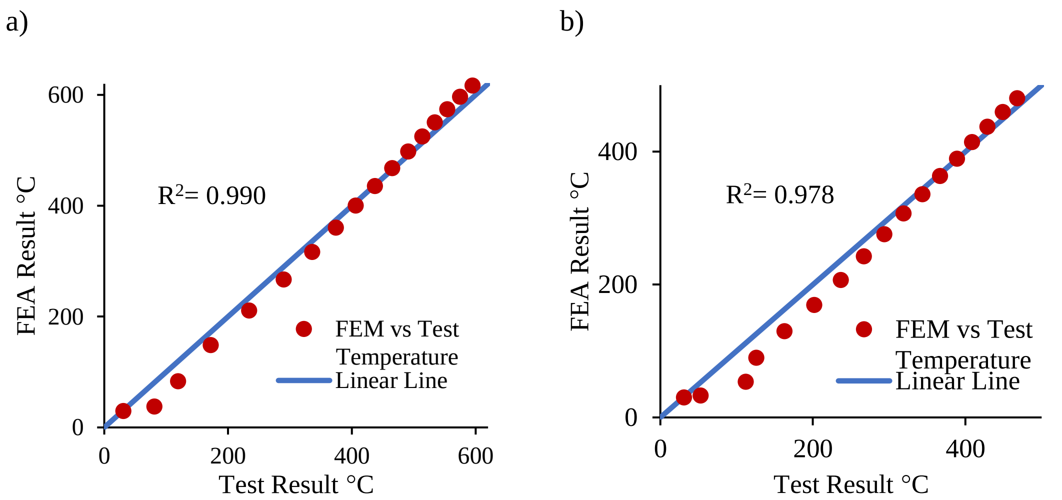

Figure A.24: Comparison of FEM vs Test Results for J-24 (a) TC-1 (b) TC-2

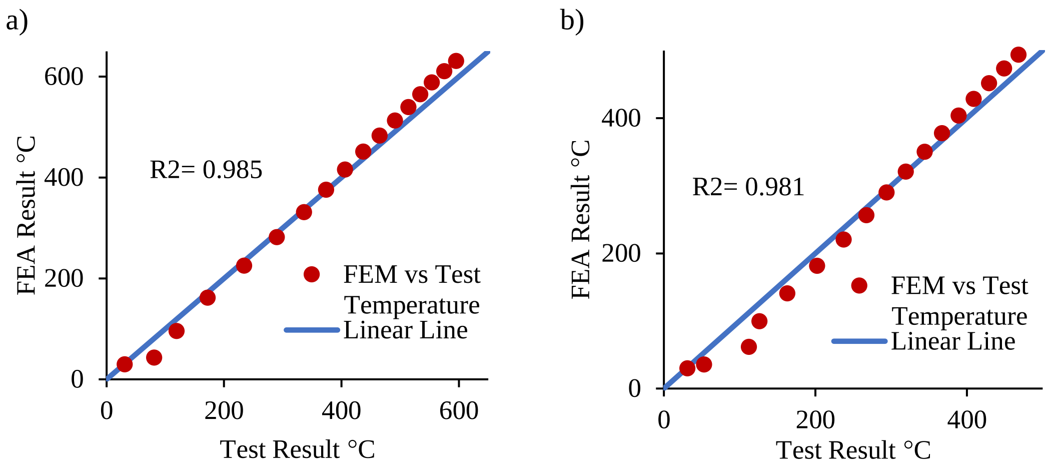

Figure A.25: Comparison of FEM vs Test Results for J-25 (a) TC-1 (b) TC-2