Performance Analysis of Fire-Resistant RC Beams

REPORT

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Abstract

This study focuses on the development and evaluation of fire-resistant reinforced concrete (RC) beams capable of withstanding a 30-minute fire exposure. With the increasing attention on fire safety in structural design, the need for innovative solutions to enhance the fire resistance of RC structures has become paramount. In this experiment, a comprehensive approach is adopted to design RC beams with the aim of getting the observatory results on performance-based analysis of a beam on 30-minute fire rating, in accordance with industry standards and regulations. The research encompasses material grade selection, beam geometry optimization, and reinforcement detailing to enhance the beam's resistance to fire-induced disintegration. Experimental testing is conducted to assess the fire performance of the designed beams under controlled fire exposure conditions. The findings of this study provide valuable insights into the design and behaviour of fire-resistant RC beams, contributing to the advancement of fire safety in structural engineering.

INTRODUCTION

Fire resistance stands as a formidable segment within the realm of civil engineering, commanding meticulous attention due to its pivotal role in structural design. Among its manifold applications, perhaps none is as critical as its integration into the framework of reinforced concrete (RC) beams. These beams, ubiquitous in building construction, serve as the backbone of structural integrity, bearing significant moments and loads. The ability of RC beams to endure fire conditions without succumbing to substantial loss of structural integrity is paramount, ensuring the safety of occupants and safeguarding property.

The scope of this analysis encompasses the design and testing of various types of RC beams—rectangular, T-beam, and L-beam—exposed to the rigors of fire for a duration of 30 minutes. Through the strategic deployment of fire-resistant coatings and the meticulous monitoring of critical parameters such as temperature distribution, deflection, and failure modes, this study endeavours to refine and optimize the performance of RC beams under fire stressors.

The central objective of this report is to delve into the clear-cut performance of fire-resistant RC beams under R30 fire conditions. To this end, several key objectives are outlined, each serving as a focal point for investigation and analysis.

First and foremost, the study seeks to inspect the behavioural patterns exhibited by RC beams when subjected to the harsh realities of fire exposure. Through systematic observation and analysis, insights into the structural response mechanisms under such extreme conditions are sought.

Furthermore, the evaluation of existing methodologies employed for assessing fire resistance in RC beams constitutes a crucial aspect of this endeavour. By adjoining various approaches and methodologies, this report aims for better practices and identify areas ripe for refinement.

In addition to assessing current practices, this report endeavours to explore the intricacies of design considerations and standards governing the implementation of fire-resistant measures in RC beam construction. By explaining upon established norms and guidelines, as well as highlighting emerging trends, this analysis seeks to foster a comprehensive understanding of the regulatory landscape.

Moreover, the identification of challenges and prospects for future research and development represents a cornerstone of this report. By delineating potential hurdles and opportunities, this study endeavours to chart a course for continued innovation and advancement in the field of fire-resistant RC beams.

In sum, this project embarks on a multifaceted exploration into the realm of fire-resistant RC beams, delving into their performance under rigorous fire conditions, evaluating current assessment methodologies, design considerations and standards, and charting a path forward for future research and development endeavours.

PURPOSE OF THE EXPERIMENT

This analysis involves designing and testing different beam types, including rectangular, T-beam, and L-beam designs, while also considering the effects of fire-resistant coatings on their performance. By analysing parameters such as maximum moments, shear at supports, and loading conditions, the study aims to enhance the structural integrity and safety of fire-resistant RC beams. Furthermore, the study includes statistical analysis and comparative evaluation of the 30-minute fire exposure data to optimize measures for improving the overall fire resistance of the beams.

Therefore, the primary goal of the performance-based analysis is to develop a better understanding of how fire affects the material strength of RC beams, enabling the implementation of effective design modifications and optimization measures based on the obtained data. Ultimately, this analysis aims to enhance the fire resistance and safety of RC beams under fire conditions, leading to more reliable and durable structural solutions in real-world applications.

LITRATURE REVIEW

Analysing and calculating of fire resistance is a critical consideration in the design of concrete structures to ensure structural integrity and occupant safety under fire conditions. This literature review examines key design standards, including Eurocodes 1-1 and 1-2, as well as IS 456, and some fire-based effects on concrete relevant to structural design.

1. **Eurocodes 1-1:**

Eurocode 1-1, "Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings," provides guidelines for determining the design loads on structures, including those induced by fire. It outlines methods for calculating fire actions, considering factors such as fire severity, duration, and spatial distribution.

2. Eurocodes 1-2:

Eurocode 1-2, "Actions on structures exposed to fire," specifically addresses the effects of fire on structural elements and provides design procedures for ensuring fire resistance. It defines fire scenarios, thermal actions, and material properties for use in fire design calculations. The code emphasizes the importance of fire protection measures, including passive fire protection and structural fire resistance, to mitigate the effects of fire on concrete structures.

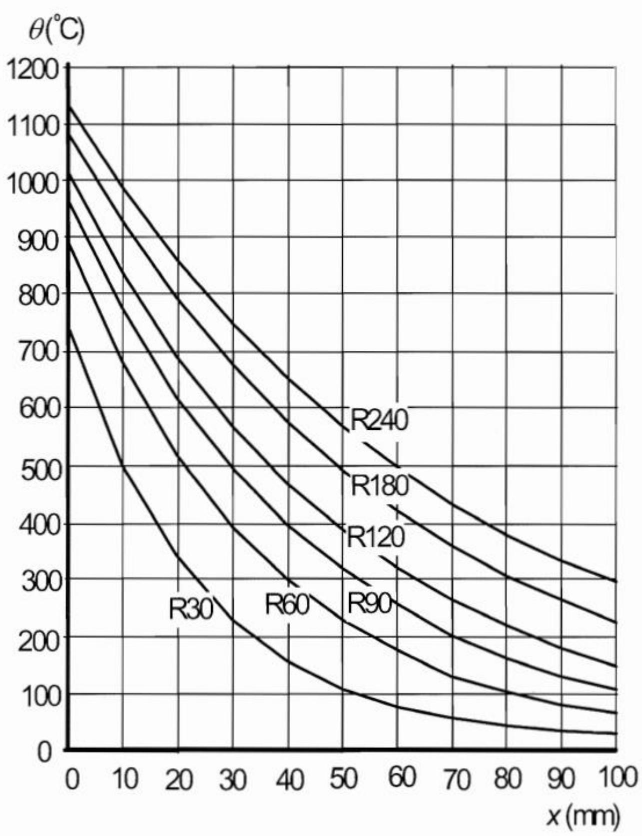
Table 3.1 gives the stress-strain relationship of normal weight concrete at elevated temperatures. While table 3.2a gives the stress-strain relationship in steel at elevated temperatures.

Table 3.1: Values for the main parameters of the stress-strain relationships of normal weight concrete with siliceous or calcareous aggregates concrete at elevated temperatures.

Concrete temp. θ	Siliceous aggregates			Calcareous aggregates		
	$f_{c,\theta} / f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$	$f_{c,\theta} / f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$
[°C]	[-]	[-]	[-]	[-]	[-]	[-]
1	2	3	4	5	6	7
20	1,00	0,0025	0,0200	1,00	0,0025	0,0200
100	1,00	0,0040	0,0225	1,00	0,0040	0,0225
200	0,95	0,0055	0,0250	0,97	0,0055	0,0250
300	0,85	0,0070	0,0275	0,91	0,0070	0,0275
400	0,75	0,0100	0,0300	0,85	0,0100	0,0300
500	0,60	0,0150	0,0325	0,74	0,0150	0,0325
600	0,45	0,0250	0,0350	0,60	0,0250	0,0350
700	0,30	0,0250	0,0375	0,43	0,0250	0,0375
800	0,15	0,0250	0,0400	0,27	0,0250	0,0400
900	0,08	0,0250	0,0425	0,15	0,0250	0,0425
1000	0,04	0,0250	0,0450	0,06	0,0250	0,0450
1100	0,01	0,0250	0,0475	0,02	0,0250	0,0475
1200	0,00	-	-	0,00	-	-

Table 3.2a: Class N values for the parameters of the stress-strain relationship of hot rolled and cold worked reinforcing steel at elevated temperatures

Steel Temperature θ[°C]	$f_{sy,\theta} / f_{yk}$ hot rolled	$f_{sy,\theta} / f_{yk}$ cold worked	$f_{sp,\theta} / f_{yk}$ hot rolled	$f_{sp,\theta} / f_{yk}$ cold worked	$E_{s,\theta} / E_s$ hot rolled	$E_{s,\theta} / E_s$ cold worked
1	2	3	4	5	6	7
20	1,00	1,00	1,00	1,00	1,00	1,00
100	1,00	1,00	1,00	0,96	1,00	1,00
200	1,00	1,00	0,81	0,92	0,90	0,87
300	1,00	1,00	0,61	0,81	0,80	0,72
400	1,00	0,94	0,42	0,63	0,70	0,56
500	0,78	0,67	0,36	0,44	0,60	0,40
600	0,47	0,40	0,18	0,26	0,31	0,24
700	0,23	0,12	0,07	0,08	0,13	0,08
800	0,11	0,11	0,05	0,06	0,09	0,06
900	0,06	0,08	0,04	0,05	0,07	0,05
1000	0,04	0,05	0,02	0,03	0,04	0,03
1100	0,02	0,03	0,01	0,02	0,02	0,02
1200	0,00	0,00	0,00	0,00	0,00	0,00



x is the distance from the exposed surface

The above image shows the temperature variation at different difference exposed in specified fire conditions.

3. **IS 456:**

IS 456, "Code of Practice for Plain and Reinforced Concrete," is an Indian standard that provides guidelines for the design and construction of concrete structures. While IS 456 primarily focuses on general design considerations for concrete elements, it also includes provisions for fire resistance design.

Section 8.9 of IS 456 discusses the requirements for fire resistance of structural elements, including concrete beams, columns, and slabs. The standard specifies minimum cover requirements, concrete quality, and reinforcement detailing to enhance the fire resistance of concrete elements. We considered the fire impact but since this is a performance-based analysis we can avoid abiding this standard. Additionally, IS 456 recommends testing methods and fire rating criteria for evaluating the fire performance of concrete structures.

4. **Other Fire-Based case studies on Concrete:**

In addition to design standards, various fire-based effects can impact the performance of concrete structures. These effects include thermal expansion, moisture evaporation, and strength reduction.

Thermal expansion of concrete during fire exposure can lead to internal stresses and cracking, compromising structural integrity. Moisture evaporation from concrete pores at high temperatures can accelerate degradation and reduce concrete strength.

Spalling, the sudden ejection of concrete fragments, occurs due to the buildup of internal pressure from trapped moisture and thermal gradients. Spalling can expose reinforcement and further weaken the structure.

Strength reduction in concrete and reinforcing steel at elevated temperatures affects load-carrying capacity and structural stability during fire events. Understanding these fire-based effects is essential for designing robust fire-resistant concrete structures and implementing effective fire protection measures.

EFFECT OF FIRE ON REINFORCED CONCRETE BEAM

The effect of fire on reinforced concrete beams can be significant and can compromise their structural integrity. Concrete is a non-combustible material, but its mechanical properties can degrade when subjected to high temperatures. Here's how fire affects reinforced concrete beams:

1. **Loss of Strength:**

   High temperatures can cause the concrete in the beams to lose strength. The heat can lead to dehydration of the cement paste, which weakens the bond between the aggregate and the cement paste. This loss of strength can significantly reduce the load-bearing capacity of the beams.

2. **Spalling:**

Spalling occurs when the surface of the concrete bursts and breaks off due to the rapid expansion of water vapor trapped within the concrete pores. This phenomenon can expose the reinforcement bars to higher temperatures and further weaken the structure.

3. **Reinforcement Behaviour:**

The behaviours of steel reinforcement in concrete under fire conditions depends on the temperature and duration of exposure. Steel loses its strength at high temperatures, and prolonged exposure to fire can cause it to soften and eventually lose its load-carrying capacity.

4. **Creep and Shrinkage:**

High temperatures can induce creep and shrinkage in both concrete and steel, leading to additional deformations and stresses in the beams.

5. **Cracking:**

Thermal gradients induced by fire can lead to cracking in the concrete, which can further compromise the structural integrity of the beams.

6. **Post-fire Behaviour:**

After the fire is extinguished, the beams may undergo additional changes in properties due to the cooling process. Rapid cooling can induce thermal stresses, leading to additional cracking and weakening.

To mitigate the effects of fire on reinforced concrete beams, fire-resistant materials such as intumescent coatings or fireproofing sprays can be applied to the surface of the beams. Additionally, fire protection measures such as fire barriers and sprinkler systems can be installed to prevent or delay the spread of fire in a building, reducing the exposure of structural elements to high temperatures. Regular inspection and maintenance of fire protection systems are also crucial to ensure their effectiveness in the event of a fire.

BEAM DESIGN

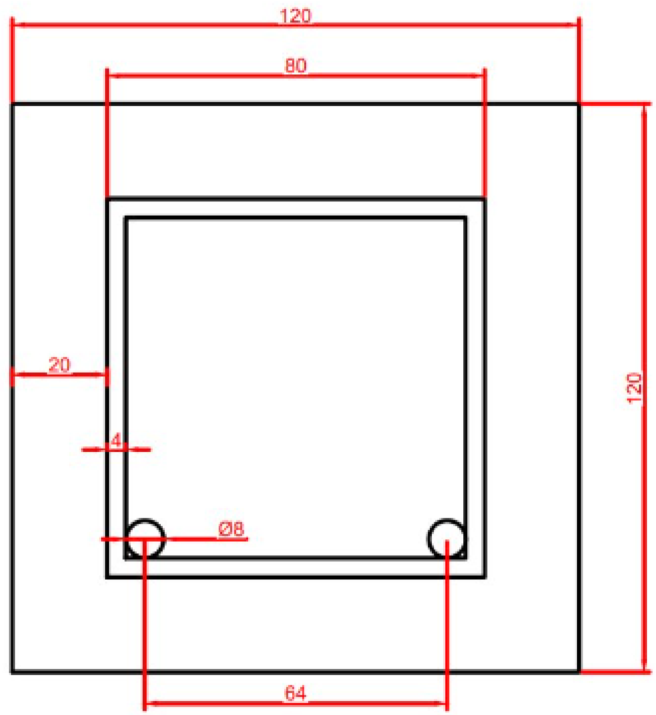
1. Design Parameters of the Rectangle Beam

Parameter	Value
Dead Load (w2) (N/mm)	0.36
Live Load (w1) (N/mm)	3.00
Factored Dead Load (N/mm)	0.54
Factored Live Load (N/mm)	4.50
Maximum Factored Design Moment (Mu) (N-mm)	2.37E+06
Maximum Factored Shear Force (Vu) (N)	5.04E+03

Effective Length (L) (mm)	2000
Total Length (mm)	3500
Width (b) (mm)	120
Depth (D) (mm)	120
Effective Depth (d) (mm)	92
Characteristic Strength (fck) (N/mm^2)	20
Clear Cover (cc) (mm)	20
Diameter of Steel (mm)	8
Yield Strength (fy) (N/mm^2)	415
Modulus of Elasticity (Es) (N/mm^2)	200000
Number of Steel bars	2
Area of Steel (Ast) (mm^2)	100
Minimum Reinforcement (As min.) (mm^2)	22.6
Maximum Reinforcement (As max.) (mm^2)	576

Reinforcement Ratio (Pt)	0.91
Xu (mm)	42
Xu, limit (mm)	44.1
Moment Capacity (MuR) (N-mm)	2.70E+06
Shear Force due to Design Load (Vu) (N)	5.04E+03
Nominal Shear Stress (τv) (N/mm^2)	0.457
Design Shear Stress of Concrete (τc) (N/mm^2)	0.595
Shear Diameter (mm)	4
Maximum Stirrup Spacing (Sv max) (mm)	69
Shear Stirrup Spacing (Sv) (mm)	60
Minimum Shear Reinforcement (Asv) (mm^2)	7.98
Steel Bars in Shear Cross-section	2
Asv (mm^2)	25.1
Nominal Max. size of Coarse Aggregates (mm)	20

Distance between the Bars (mm)	64



Cross-Section Dimension of the Rectangle Beam

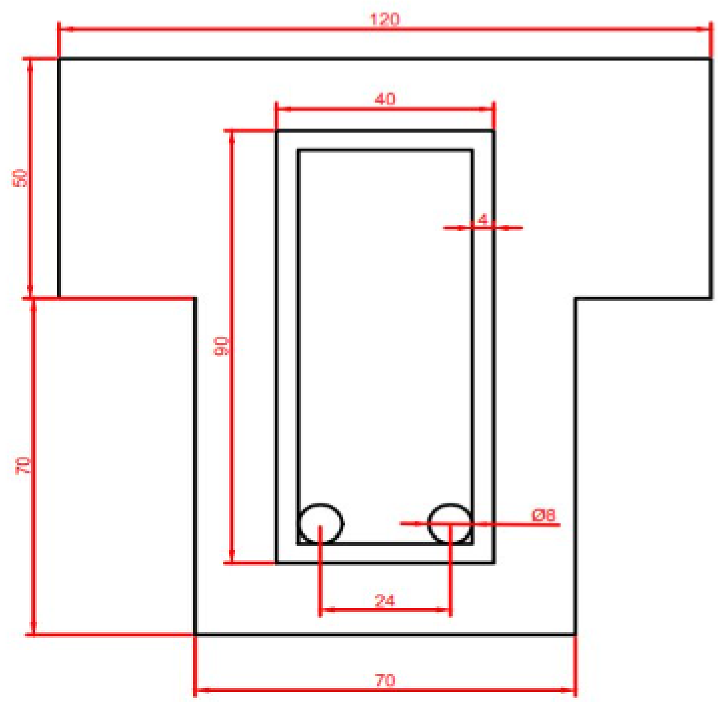
2. Design Parameters of the T-Beam

Parameter	**Value**
Dead Load (N/mm)	0.2725
Live Load (N/mm)	3

Factored Dead Load (N/mm)	0.40875
Factored Live Load (N/mm)	4.5
Effective Length, Leff (mm)	2000
Total Length, L (mm)	3500
Width of the Flange, b (mm)	120
Effective Width of the Flange, bf (mm)	120
Depth of the Beam, D (mm)	120
Depth of the Flange, Df (mm)	50
Effective Depth, d (mm)	97
Width of the Web, bw (mm)	70
Area of T beam (mm^2)	10900
Characteristic Strength of Concrete, fck (N/mm^2)	20
Clear cover in the web, cc (mm)	15
Diameter of Steel (mm)	8

Yield Strength of Steel, fy (N/mm^2)	334.075
Modulus of Elasticity, Es (N/mm^2)	200000
Number of Steel bars	2
Area of Steel (Ast), mm^2	100.5309649
Minimum Reinforcement, As min. (mm^2)	17.27606076
Maximum Reinforcement, As max. (mm^2)	436
Reinforcement Ratio, Pt	0.8636680835
Xu (mm)	33.81811045
Xu, limit (mm)	51.41
Moment Capacity, MuR (N-mm)	2419215.193
Shear Force due to Design Load (Vu)	4908.75
Nominal Shear Stress (τv), N/mm^2	0.7229381443
Design Shear Stress of Concrete (τc)	0.58728034
Shear Diameter (mm)	4

Maximum Stirrup Spacing, Sv max (mm)	72.75
Shear Stirrup Spacing (Sv) (mm)	60
Minimum Shear Reinforcement (Asv)	5.780242409
Steel Bars in Shear Cross-section	2
Asv (mm^2)	25.12



Cross-Section Dimension of the T-Beam

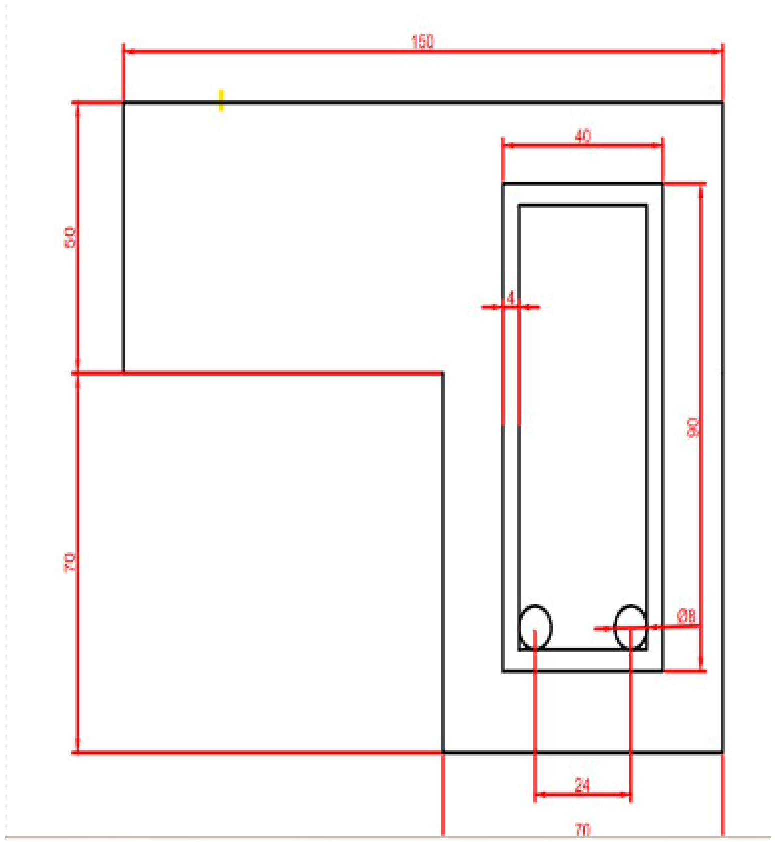
3. Design Parameters of the L-Beam

Parameter	Value
Dead Load (N/mm)	0.31
Live Load (N/mm)	3
Factored Dead Load (N/mm)	0.465
Factored Live Load (N/mm)	4.5
Maximum Factored Design Moment (Mu) (N-mm)	2351718.75
Maximum Factored Shear Force (Vu) (N)	4965
Effective Length (Leff) (mm)	2000
Total Length (L) (mm)	3500
Width of the Flange (b) (mm)	150
Effective Width of the Flange (bf) (mm)	127.6923077
Depth of the Beam (D) (mm)	120
Depth of the Flange (Df) (mm)	50

Effective Depth (d) (mm)	97
Width of Web (mm)	70
Area of L Beam (mm^2)	12400
Characteristic Strength of Concrete (fck) (N/mm^2)	20
Clear Cover in the Web (cc) (mm)	15
Diameter of Steel (mm)	8
Yield Strength of Steel (fy) (N/mm^2)	334.075
Modulus of Elasticity (Es) (N/mm^2)	200000
Number of Steel Bars	2
Area of Steel (Ast) (mm^2)	100.5309649
Minimum Reinforcement (As min.) (mm^2)	17.27606076
Maximum Reinforcement (As max.) (mm^2)	496
Reinforcement Ratio (Pt)	0.8116398857
Xu (mm)	31.78087488

Xu, limit (mm)	51.41
Moment Capacity (MuR) (N-mm)	2444215.976
Shear Force due to Design Load (Vu) (N)	4965
Nominal Shear Stress (τv) (N/mm^2)	0.7312223859
Design Shear Stress of Concrete (τc) (N/mm^2)	0.5747935726
Shear Diameter (mm)	4
Maximum Stirrup Spacing (Sv max) (mm)	72.75
Shear Stirrup Spacing (Sv) (mm)	60
Minimum Shear Reinforcement (Asv) (mm^2)	5.780242409
Steel Bars in Shear Cross-section	2
Asv (mm^2)	25.12

1. RC beam specimen



Cross-Section Dimension of the L-Beam

PROPOSED EXPERIMANTAL SETUP

This experiment aims to investigate the structural response of a reinforced concrete (RC) beam under pool fire conditions fuelled by heptane or Petron. Understanding the behaviour of RC beams under fire conditions is crucial for assessing their fire resistance and ensuring structural safety in buildings and other constructions.

1. Materials:

1. RC beam specimen

2. Ignition source (e.g., propane torch)
3. Fuel tank (2m x 0.5m size)
4. Heptane or Petron fuel
5. Support stand (2 meters in height)
6. Thermal cameras
7. Thermocouples (with connections at the top and bottom of the beam)
8. DSLR camera
9. Safety equipment (gloves, goggles, fire extinguisher)
10. Go pro

2. Experimental Setup:

1. Preparation of RC Beam:

- Prepare the RC beam specimen according to standard dimensions and reinforcement specifications.

Depth of the Rectangle Beam

Width of the Rectangle Beam

Depth of the T- Beam

Depth of the Web of the T-Beam

Width of the Web of the T-Beam

Depth of the L-Beam

Width of the Web of the L-Beam

2. **Setting up the Support Stand:**

- Securely fix the support stand at a height of 1 meter to simulate fire exposure from the bottom.

3. **Fuel Preparation:**

- Fill the fuel tank with heptane or Petron fuel to create the pool fire that will produce temperature of maximum 800C in beam.

4. **Ignition System:**

- Use an ignition source (e.g., propane torch) to ignite the fuel surface in the pool.

5. **Placement of RC Beam:**

- Position the RC beam horizontally on the support stand, ensuring it is centred above the pool fire.

6. **Temperature Measurement:**

- Install thermocouples with connections at the top and bottom of the RC beam to measure temperature gradients.
- Place thermal cameras at strategic positions to capture temperature distribution along the beam.

7. **Experimental Procedure:**

- Ignite the fuel surface in the pool using the ignition source.
- Start recording data from thermal cameras and thermocouples once the fire is established.

- Monitor the temperature evolution along the beam and at different depths using thermocouples.
- Record any visible changes, such as spalling, cracking, or deformation of the beam.
- Continuously capture visual data using the DSLR camera to document the fire progression and beam response.

8. **Data Collection:**

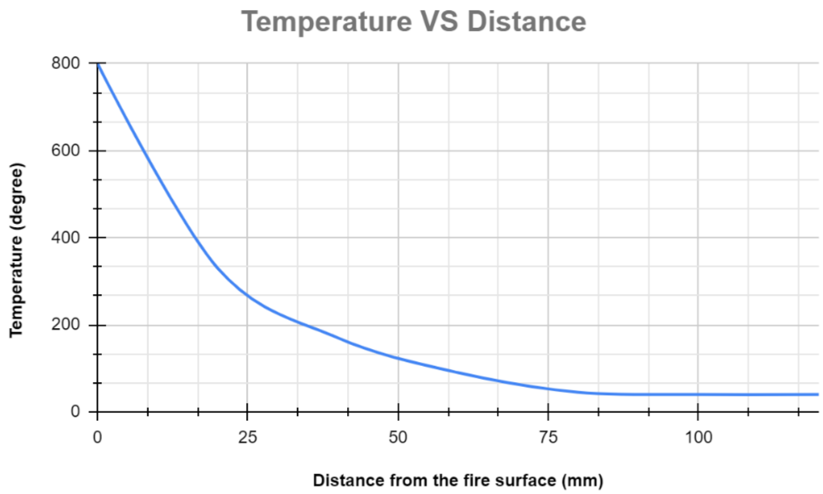
- Measure the temperature profiles along the RC beam at various time intervals.
- Record any structural changes observed during the fire exposure.
- Document the duration of the fire exposure and the behaviour of the pool fire.

9. **Safety Measures:**

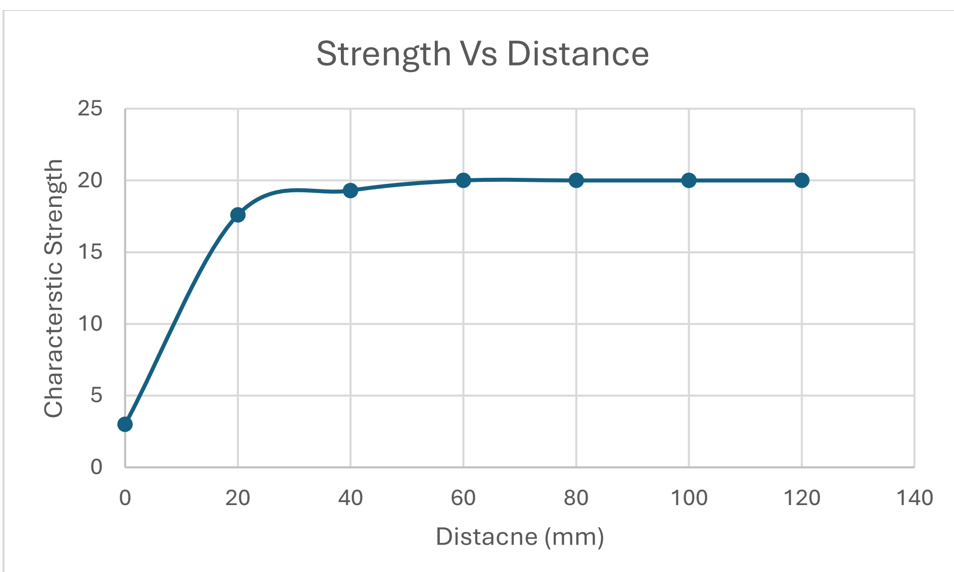
- Wear appropriate safety gear throughout the experiment.
- Have a fire extinguisher nearby in case of any accidents.
- Ensure proper ventilation to prevent the buildup of combustible gases.

RESULT AND DISCUSSION

Distance (mm)	T (°C)	fc,θ/fck	fck (MPa)
0	35.00	0.15	3
20	35.00	0.88	17.6
40	35.00	0.965	19.3
60	35.00	1	20
80	35.00	1	20
100	35.00	1	20
120	35.00	1	20



This curve displays variation of temperature along cross section of beam with This curve displays the variation of temperature along the cross-section of the beam with This curve displays the variations of temperature along the beam's cross-section with changes in distance from the exposed surface. This graph is helpful in extracting information regarding changes in the characteristics and strength of concrete.



This graph depicts the fck variation along cross-sectional area along the distance from exposed surface which we utilise to find weighted average fck of whole beam in terms of area.We have found overall characteristics strength of concrete by dividing whole beam into elements then finding percentage change in fck from Euro code. We have fck of whole beam 16.5N/mm^2 after 30 min fire with exposed temperature 800C.

CHALLENGES

The study on fire-resistant RC beams faces challenges like defining clear research objectives and scope. Understanding structural responses to fire is crucial, but with limited time, experimental testing becomes challenging. Additionally, lack of clarity on material behaviour and absence of testing time hinder comprehensive analysis and validation.

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