

Contents list available at [journal.uib.ac.id](http://journal.uib.ac.id)

**Journal of Civil Engineering and Planning**  
Journal homepage: <https://journal.uib.ac.id/index.php/jce>



## Analysis of the Resistance of Steel Materials in Building Structures Against Fire and the Effectiveness of Fireproofing Systems on Steel Structures in High-Rise Buildings

Rizqi valiant<sup>1</sup>, Jody Martin Ginting<sup>2</sup>, Ade Jaya Saputra<sup>3</sup>

<sup>1,2,3</sup>Teknik Sipil, Teknik Sipil dan Perencanaan, Universitas Internasional Batam

Email korespondensi: [jody.martin@uib.ac.id](mailto:jody.martin@uib.ac.id)

ARTICLE INFO	ABSTRACT
<p><b>Keywords:</b></p> <p>Building, fire, Fireproofing, Steel, Structural.</p>	<p>This study aims to determine the fire resistance of steel and analyze the effectiveness of fireproofing systems in steel structures in high-rise buildings and oil and gas sector modules. The main issue examined is the extent to which fireproofing systems can extend the fire resistance of steel at high temperatures before structural failure occurs, thereby providing crucial evacuation time. Using a quantitative approach with a post-test-only control group experimental design, the samples consist of steel coated with two types of protective materials: intumescent and cementitious, each at thicknesses of 10 mm, 20 mm, and 30 mm. Data were collected through direct testing of fire resistance time, temperature increase, and structural changes in the steel. Main hypothesis: fireproofing application significantly improves steel's resistance to high temperatures. Minor hypotheses: (1) fire resistance time increases with coating thickness, and (2) there is a difference in effectiveness between intumescent and cementitious coatings. Test results showed that steel without protection failed structurally within <math>\pm 60</math> minutes, while steel with a 30 mm intumescent or cementitious coating lasted up to 120 minutes. Statistical analysis, including quadratic regression and Fourier's law, revealed a positive correlation between coating thickness and fire resistance time. This study concludes that the proper application of fireproofing systems can enhance the durability of steel structures, extend evacuation time, and reduce the risk of collapse, making an important contribution to fire safety policies and fire-resistant building design.</p>

### 1. Introduction

*Fireproofing* is a passive protection method that reduces structural damage during a fire. It provides temporary thermal protection, not as a substitute for active firefighting systems. The main goal is to protect steel for at least 30 minutes, preventing fire escalation and allowing time for firefighting efforts to begin [1]. Sudden steel structure collapse can cause injuries and release flammable or toxic materials. Proper fireproofing delays this collapse, making it gradual with visible signs. This allows time to isolate equipment and for personnel to safely evacuate. This allows time for isolation of the affected equipment and for operating and fire-fighting personnel to evacuate safely [2].

A Fire-Proofing Zone is a designated area where a fire could burn long enough to damage or destroy steel structures. This occurs when flammable substances ignite and weaken load-bearing steel components. The extent of the Fire-Proofing Zone (and the resulting extent of fireproofing) shall be established in a fire safety assessment of the particular plant, initiated by the Principal, based on DEP 80.47.10.30-Gen [3]. In exceptional cases where this is unlikely, increasing the fire resistance to a longer duration shall be considered. Where effective water cooling is not feasible (e.g., due to the structure's

configuration), the required duration of fire resistance depends on the estimated time for the fire to burn out or be extinguished [4].

The hydrocarbon fire test, as defined in UL 1709, applies to all fireproofing systems applied to steel supports and structures. This fire is more severe than the cellulose type of fire, which is usually referred to in building regulations. During the test, a protected steel column is exposed to a particular heat flux that produces a temperature of 1093°C. The test is terminated (at the failure point) when the average temperature of the steel substrate reaches 538°C. An equivalent fire test may be specified in cases of local restrictions, subject to approval by the Principal.

A 50 mm-thick concrete cover meets the above hydrocarbon fire requirement. Any proprietary system applied shall meet the criteria of the UL 1709 test. Test reports from an independent test institute shall be provided for such a proprietary system. Cables in trays, racks, or ducts that are critical (e.g., cables feeding emergency shutdown and emergency depressuring valves) shall be of a fireproof construction by IEC 60331-21 (i.e., they shall withstand temperatures of at least 750°C for 90 minutes)[5].

Previously, studies did not analyze how coating thickness affects a steel's fire resistance time, especially in high-rise buildings. While many studies have looked at fireproofing materials, few have statistically quantified the link between different coating types, thicknesses, and the time it takes for steel structures to fail. This study addresses that gap by quantitatively analyzing how both the type and thickness of fireproofing coatings impact steel's durability in high-rise buildings. This research is based on the Passive Fire Protection Theory, which posits that a slower temperature increase in steel leads to greater structural resistance.

The central hypothesis of this study was "*There is a significant positive relationship between the thickness of the fireproofing system and the resistance time of the steel material to fire exposure.*" Research Questions: How much influence does the variety of fireproofing types have on the durability duration of steel?; Does the thickness of the coating have a significant effect on the failure time of the steel structure?; What is the optimal integration of structural design, fire protection, and risk management in high-rise buildings?

## 2. LITERATURE REVIEW

### 2.1 Research Variables

This research focuses on two main variables: the fire resistance of steel materials and the effectiveness of fireproofing systems on steel structures. Fire resistance refers to the ability of steel to maintain its structural integrity when exposed to high temperatures over an extended period. The effectiveness of a fireproofing system is defined as the capacity of passive protective coatings, such as intumescent or cementitious sprays, to decelerate the temperature rise in steel and prolong the time to structural failure. Passive fire protection theory suggests that increasing the thickness or quality of the coating impedes heat conduction to the steel, thereby extending fire resistance duration [6].

Achieving an optimal synthesis of structural design, fire protection, and risk management is essential for enhancing the safety, resilience, and sustainability of contemporary buildings and infrastructure. The adoption of risk-informed strategies, coupled with multi-objective optimization frameworks, facilitates a balanced consideration of capital costs, structural integrity, and fire safety requirements [7]. Case studies involving high-rise towers, cable-stayed bridges, and process plants demonstrate that a coherent deployment of both active and passive fire protection measures integrated within proactive risk management strategies can significantly reduce fire detection time, expedite evacuation, and minimize associated losses [8].

This concept is further supported by the thermodynamic theory of heat conduction, which posits that the time required for heat to transfer through a material is directly proportional to the thickness of the protective layer. In high-rise building design, Limit State Theory is employed to determine the structural capacity under fire conditions by integrating time and temperature variables. Additionally, Performance-Based Fire Engineering (PBFE) is widely applied to develop fire protection systems tailored to local building characteristics [9].

Research has shown that steel coated with geopolymer composites exhibits enhanced fire resistance up to 80 minutes compared to unprotected steel, indicating a positive correlation between coating thickness and fire resistance duration. This finding supports the hypothesis that coating thickness significantly influences structural durability. For instance, studies on double-layered steel frames have demonstrated that variations in coating thickness can notably improve structural performance during smoke propagation simulations, reinforcing the argument that better coating quality delays structural failure [10].

Further studies involving bio-based insulation reveal that coating effectiveness is not always directly proportional to thickness. Some bio-based materials exhibit smoldering properties, raising questions about the efficacy of certain coatings under extreme conditions. While numerous studies have examined steel durability and coating performance, most have focused on temperate climates rather than the humid tropical environments typical of regions like Indonesia [11]. The selection of fireproofing material and its application thickness are critical factors that determine the thermal performance of structural steel members, ultimately influencing how long these members can withstand elevated temperatures during fire exposure [12].

Table 1 Comparison of Research Studies

Aspect of Comparison	Previous Studies	Current Study
<b>Main Focus</b>	Evaluated fireproofing materials in a general sense.	Analyzes the effectiveness of fireproofing systems by examining coating type and thickness.
<b>Key Variables</b>	Did not analyze the variation in coating thickness or its relationship with fire resistance duration.	Quantitatively analyzes the relationship between coating type, coating thickness, and fire resistance duration.
<b>Target Structures</b>	Did not specifically focus on high-rise buildings.	Concentrates on steel structures in high-rise buildings and modules in the oil & gas sector.
<b>Research Gap</b>	Lacked a quantified, statistical relationship between coating variations and time to structural failure, especially in tall buildings.	Fills this gap by statistically quantifying the effect of coating type and thickness on the durability of steel structures.
<b>Methodology</b>	Did not use a quantitative and statistical approach to analyze the specific variables of interest.	Employs a quantitative approach and uses statistical methods (e.g., quadratic regression) to establish relationships.

Most previous studies on fireproofing performance have been conducted in temperate countries such as South Korea, Japan, and various European countries, where environmental conditions differ significantly from tropical regions such as Indonesia. Tropical climates are characterized by consistently high humidity, high ambient temperatures, and frequent rainfall, which can accelerate the degradation of certain fireproofing materials, especially intumescent coatings that are sensitive to moisture exposure. Studies have shown that tropical environments can compromise coating adhesion, chemical stability, and thermal expansion properties over time. Without formulations specifically tailored to

these conditions, the protective effectiveness of fireproofing systems can diminish well before their intended service [13]

## 2.2 Types of Fire

Fires can generally be categorized into three primary types, each posing significant risk:

### 2.2.1 Cellulosic Fire

This type of fire commonly occurs in buildings where fuel sources include wood, paper, fabric, or a combination of these materials. Typically found in residential and office settings, cellulosic fires reach temperatures ranging from 900°C to 1050°C. UL 263 is the standard used to evaluate materials under these conditions, and testing is conducted in UKAS/NAMAS-accredited laboratories. Results from such tests form the basis for certification of fire protection materials, designated as Type A (UL, 2025; UKAS, 2025)[14].

### 2.2.2 Hydrocarbon Fire

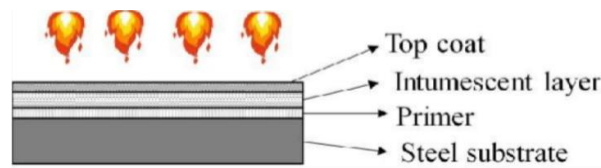
Hydrocarbon fires involve substances such as oil and natural gas. Originally tested by MOBIL as "pool fires," this type is now commonly evaluated using the UL 1709 curve, which has replaced earlier MOBIL tests in the U.S. This curve indicates that a temperature of 1050°C can be reached within 8 to 9 minutes and then maintained just below 1100°C. The DEn/NPD curve, by contrast, shows a more gradual temperature rise that may exceed 1100°C. Both models are widely referenced in fire testing and specification standards (MOBIL, 1982) [15].

### 2.2.3 Jet Fire

Jet fires result from pressurized flammable substances being released and ignited, as seen in the Piper Alpha disaster. These fires burn hotter and more aggressively due to high pressure and turbulence. The industry recognizes the Jet Fire Standard outlined in OTI 05634. Protection specifications under this standard consider scenarios in which ruptured lines emit flammable material under pressure before emergency shutdown systems can be activated, followed by a secondary phase involving residual pool fires (ISO, 2025) [16].

## 2.3 Fireproofing System and Application

Fireproofing systems are typically integrated with anti-corrosion measures and fire-retardant primers, especially in steel structures. The application process comprises three main stages. First, the primer layer ensures substrate adhesion and corrosion resistance, while also promoting adherence of the intumescent char during fire exposure. Second, the fireproofing layer functions as the primary heat barrier. Third, the topcoat adds aesthetic value and enhances resistance to environmental conditions under operational use [17]. example of fireproofing layer as shown in **figure 1**.



In high-rise buildings and the oil & gas industry, the beams used are generally in the form of I-Beams (WF Beams) or H-Beams, which are made of structural steel due to their high flexural and compressive strength. For special or modular structures, Box Beams (Hollow Structural Sections) are used

Figure 1 Protective layer of steel material

in the form of closed boxes that are torsion resistant. T-Beams are also commonplace in reinforced concrete structures, particularly within floors [18]. Composite Beams (a combination of steel and concrete) are often used in high-rise buildings for structural efficiency. Within the oil and gas industry, castellated beams are used which are beams with holes within their bodies, making them light and strong. illustration of various types of steel as in figure 2. The type of beam selected is based on the load and function as well international standards such as API RP 2A, AISC or Eurocode, as well as considering the factor of corrosion resistance [19].

The fireproofing process typically begins with a careful inspection and planning to determine the fire protection needs of each building section. Checking the rh using an elcometer tool as shown in figure 3. This information is communicated by the client to the supervisor. The supervisor will then communicate several points to the workers regarding the thickness of the fireproofing, repairs, and

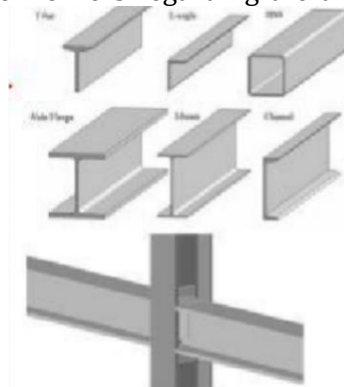


Figure 2 Various steel materials

other requirements. Applying fire protection to steel is similar to the guidelines for any paint system. The only difference is that the material should not be applied below 5°C, with the steel temperature at least 3°C above the dew point. Furthermore, the relative humidity should not exceed 85%. These rules generally apply to all types of Passive Fire Protection (PFP). Therefore, before applying fire protection, it is important to consult the manufacturer's data sheet from the jobsite before beginning any work to ensure proper application [20]



Figure 3 RH Check <85%

## 2.4 Types of Fireproofing for Steel Materials

### 2.4.1 Cementitious Fireproofing

Cementitious fireproofing consists of a thick layer composed primarily of vermiculite or perlite combined with cement-based binders. These materials are engineered to create a lightweight, heat-absorbing coating that provides thermal insulation during fire exposure. Unlike epoxy-based fireproofing, cementitious materials do not undergo significant chemical reactions in fire conditions. Instead, any residual moisture evaporates during the initial fire phase, aiding in dissipating heat, while the porous structure of the material serves as an insulating barrier. The product is typically supplied in powder form, mixed with water, and applied using hand trowels or mono-type spray pumps as shown in **figure 4**. The thickness of the applied coating ranges from approximately 12 mm to 70 mm, depending on performance requirements. Some variants are formulated with higher compressive strength and may exclude vermiculite or perlite to achieve specific mechanical properties. Commercial brands such as Fendolite and Pyrocrete 241 incorporate special additives to achieve lighter weights compared to traditional concrete, although they may still be heavier than alternative cementitious products. Each manufacturer provides specific technical documentation tailored to their formulation and application standards[21].



Figure 4 cementitious Fireproofing

### 2.4.2 Epoxy Intumescent Fireproofing

Epoxy intumescent coatings are high-viscosity, 100% solids epoxy systems that are cured using specific additives. These materials require heat to attain a sprayable consistency and typically exhibit a short pot life at the required application temperature. The use of solvents is generally discouraged, although minimal quantities may be permitted by certain manufacturers for specific applications. These coatings are applied at dry film thicknesses (DFTs) ranging from 4 mm to 25 mm. Upon exposure to heat, they undergo a chemical reaction wherein an acid component is released and reacts with a carbon-rich constituent in the coating to form a carbonaceous char layer. Concurrently, a spumific blowing agent is activated, causing the char to expand up to approximately five times its original thickness. This thermally-induced expansion process is referred to as **intumescent**. Thanks to the epoxy resin base, the resulting char is robust and capable of withstanding the intense turbulence characteristic of hydrocarbon and jet fires. Some epoxy intumescent coatings also exhibit ablative behavior, wherein the outer charred surface peels away under fire exposure, revealing a new reactive layer underneath. Application of intumescent using manual hands as shown in **figure 5**. This cyclic process enhances overall thermal resistance. Additionally, certain intumescent coatings function via **sublimation**, a phase-change process in which the solid coating transitions directly to gas, absorbing large quantities of heat without undergoing a liquid phase transition [22].



Fig 5. Intumescent fireproofing application with Chartek 7

Table 2 High Rise Building And Oil&Gas Using Fireproofing

No	Project / Structure	Type of Fireproofing	Materials Used
1	Burj Khalifa, Dubai, UAE	Reinforced concrete core and fire-resistant coating	HPC, reflective glass, aluminum coatings
2	One World Trade Center, NYC, USA	Reinforced concrete core and SFRM on steel	Concrete, steel, gypsum-based fireproofing
3	Taipei 101, Taiwan	High-performance concrete and fire-resistant coating	Concrete, steel, intumescent coatings
4	Princess Tower, Dubai, UAE	Reinforced concrete core and fireproofed steel structure	Concrete, steel, fireproof coatings
5	Pluto Train 2, Bechtel, Australia	Epoxy intumescent (Chartek 7)	Steel, fireproof coating, insulation
6	Marjan Increment Project, Saudi Aramco	Epoxy intumescent and cementitious fireproofing	Steel, fireproof coating, insulation, spray
7	Yamal LNG Module, Russia	Epoxy intumescent on steel modules	Steel, fireproof coating, insulation, spray
8	Qatargas North Field South Expansion, Qatar	Cementitious fireproofing on steel modules	Steel, fireproof coating, insulation, cementitious fireproofing

## 2.4 Examples of Fireproofing Implementation in High-Rise and Oil & Gas Structures

A range of iconic structures and industrial projects have adopted fireproofing systems to enhance safety and structural resilience. The following examples illustrate diverse applications of fire-resistant technologies .

**Table 2** shows that the majority of high-rise buildings frequently use various types of fireproofing. Meanwhile, in the oil and gas sector, intumescent and cementitious fireproofing are more frequently used. Chartek products are widely used in the oil and gas sector.

## 2.6 Heat Transfer and Fire Resistance Theory

The fire resistance of steel structures is greatly influenced by the material's ability to withstand heat transfer from the fire environment to the core of the structure. A drastic decrease in steel strength occurs when the temperature reaches a critical point, generally around 538°C. Therefore, a passive protection system such as fireproofing is needed to slow down the rate of temperature increase. In this context, the study uses five theoretical approaches described in the following subsections.

### 2.6.1 Fireproofing Thickness Based on Fourier's Law of Heat Conduction

To quantitatively analyze the influence of fireproofing thickness on fire resistance, **Fourier's Law of Heat Conduction** was applied. This law provides a foundational model for understanding the relationship between **thermal transfer rate** and **insulating material thickness**.

**Equation 1.1 :**

$$Q = \frac{k \cdot A \cdot \Delta T}{d}$$

Where:

- $Q$  = Heat transferred to the steel (Joules)
- $k$  = Thermal conductivity of the fireproofing material (W/m·K)
- $A$  = Cross-sectional area exposed to fire (m<sup>2</sup>)

- $\Delta T$  = Temperature difference between the fire environment and the steel (Kelvin or °C)
- $d$  = Thickness of the fireproofing material (m)

From **equation 1.1** shows that the larger the  $d$ , the smaller the  $Q$ . This means that the thicker the fireproofing, the less heat reaches the steel.

### 2.6.2 Time Equivalent Method

The Time Equivalent Method in Equation 1.2 is used to convert an actual fire exposure scenario such as a hydrocarbon fire represented by the UL 1709 fire curve into an equivalent duration under a standard fire curve such as ISO 834 or ASTM E119. This allows engineers to compare the severity of real fires to standardized conditions used in testing fireproofing systems.

**Equation 1.2 :**

$$t_{eq} = \frac{1}{n} \int_0^{t_f} \left( \frac{T_{fire}(t)}{T_{std}(t)} \right)^n dt$$

Where :

- $t_{eq}$  = equivalent fire duration (minutes) under standard fire conditions
- $T_{fire}(t)$  = actual fire temperature curve (e.g., UL 1709)
- $T_{std}(t)$  = standard fire temperature curve (e.g., ISO 834)
- $t_f$  = total duration of the real fire
- $n$  = exponent (typically  $1 \leq n \leq 2$ ), based on thermal response sensitivity

### 2.6.3 Time-Temperature Curve Based on UL 1709 Standard

This curve illustrates the extreme temperature increase in a hydrocarbon fire. It is important to understand how a structure responds in the first 10 minutes, which is crucial for unprotected steel structures.

**Equation 1.3 :**

$$T(t) = 1100 \cdot (1 - e^{-0.3t}) \text{ for } t \leq 10 \text{ minutes}$$

$$T(t) = 1100 \text{ for } t > 10 \text{ minutes}$$

Where :

- $T(t)$  = Temperature at time  $t$  (in °C)
- 1100°C = the peak temperature sustained in a hydrocarbon fire
- 0.3 = empirical constant based on fire curve shapes

From Equation 1.3 shows that temperatures can reach over 1000°C in a very short time. This provides the basis for assessing the ability of fireproofing to delay structural failure.

### 2.6.4 Time to Reach Critical Temperature (Heat Transfer Approach)

This method measures the time required for steel to reach the critical failure temperature by considering density, heat capacity, layer thickness, and heat flux.

**Equation 1.4 :**

$$t_{fail} = \frac{(T_{crit} - T_0) \cdot \rho \cdot c \cdot d}{q}$$

Where :

- $t_{fail}$  = estimated time to reach critical temperature (seconds)

- $T_{\text{crit}}$  = critical failure temperature of steel (typically 538°C)
- $T_0$  = ambient initial temperature (°C)
- $\rho$  = density of fireproofing material (kg/m<sup>3</sup>)
- $c$  = specific heat capacity of the fireproofing (J/kg·K)
- $d$  = thickness of the fireproofing layer (m)
- $q$  = heat flux from the fire (W/m<sup>2</sup>)

The method in **Equation 1.4** is important to determine the minimum fireproofing requirements so that the steel does not collapse quickly.

### 2.6.5 Quadratic Regression Method

This method establishes a **predictive relationship** between fireproofing **thickness** and **fire resistance time** using quadratic regression. Two separate models are derived for intumescent and cementitious coatings based on experimental data.

#### Equation 1.5 :

##### A. Intumescent Fireproofing

$$t_{\text{fail}} = 0.05d^2 + 1.5d + 60$$

##### B. Cementitious Fireproofing

$$t_{\text{fail}} = 0.033d^2 + 1.7d + 58$$

Where :

- $t_{\text{fail}}$  = estimated time to reach critical temperature time (minutes)
- $d$  = thickness of the fireproofing layer (mm)

This **Equation 1.5** model is very useful in design planning, because it can estimate the fire resistance time based on the thickness of the designed fireproofing layer.

## 3 RESEARCH METHOD

### 3.1 Research Design

This study employed a **quantitative experimental approach**, utilizing a *post-test-only control group design* to examine the effects of different fireproofing system types and thicknesses on the fire resistance of steel materials in high-rise building structures. The objective was to evaluate how fireproofing influences steel's structural integrity under fire exposure and to determine the duration of protection before structural failure occurs.

### 3.2 Data Collection Techniques

Primary data were obtained through direct testing of steel specimens treated with fireproofing systems. Two types of fireproofing materials were applied: **intumescent coatings** and **cementitious coatings**, each in three thickness variants **10 mm**, **20 mm**, and **30 mm**. The specimens were exposed to standardized fire conditions, and their performance was measured based on:

- a. Time to structural failure
- b. Temperature increase
- c. Degree of deformation

To supplement the primary findings, **secondary data** were collected through literature reviews from reputable journals related to fire resistance and fireproofing system effectiveness.

### 3.3 Control Group and Experimental Variables

A **control group** consisting of unprotected steel specimens was included in the study. These

control samples were subjected to the same fire exposure conditions but without any fireproofing, enabling clear comparison with the fireproofed specimens.

The key variables used in this study were:

- **Independent Variables:**
  - Type of fireproofing material
  - Thickness of the fireproofing layer
  - Initial ambient temperature
  - Fire curve or fire scenario
- **Dependent Variable:**
  - Duration of fire resistance (time to structural failure)
  - Maximum temperature reached before failure
  - Time to first sign of material degradation
  - Rate of temperature increase over time

### **Data Validity**

Validity in this context refers to whether the study accurately measures the effectiveness of fireproofing systems as a means of improving fire resistance. The study ensures validity through its experimental design and measurement practices:

- **Internal Validity:** This is the most crucial aspect for an experimental design. The study establishes internal validity by using a **post-test-only control group**. By comparing the performance of coated steel specimens against an uncoated control group, the researchers can confidently conclude that any observed differences in fire resistance (e.g., time to structural failure) are directly caused by the presence and properties of the fireproofing material, not by other external factors.
- **Construct Validity:** This relates to how well the variables are operationalized. The study defines "fire resistance" through measurable outcomes like **resistance time, temperature increase, and structural changes**. The direct testing method ensures that these measurements are valid indicators of the steel's ability to withstand fire.
- **External Validity:** This refers to the generalizability of the findings. The study's focus on high-rise buildings and oil & gas modules indicates its intent to apply the laboratory results to real-world scenarios. While the controlled lab setting simplifies conditions, the findings are intended to be a valid representation of how these materials would perform in actual structures, informing fire safety policies.

### **Data Reliability**

Reliability refers to the consistency and reproducibility of the study's measurements. The research ensures reliability by:

- **Standardized Testing:** Although not explicitly mentioned, the "direct testing" of fire resistance, temperature increase, and structural changes implies the use of a standardized testing protocol (e.g., according to international standards like ASTM or ISO). Adhering to a standardized method ensures that if the experiment were repeated, similar results would be obtained.
- **Controlled Environment:** The experimental design, as described, takes place in a controlled laboratory setting. This minimizes external variables that could affect the results, such as ambient temperature, humidity, or fire source inconsistencies, thereby increasing the reliability of the measurements.
- **Replication:** The study uses "steel specimens" for its sample, suggesting that multiple samples were tested for each variable (type and thickness of fireproofing). Testing multiple specimens

for each condition allows the researchers to check for consistency in the results. If all specimens with a 30 mm intumescent coating show similar resistance times, it strengthens the reliability of that finding.

This study would utilize a highly controlled experimental setup to measure the fire resistance of steel structures. The core of the experiment revolves around a direct fire test, which is typically conducted in a specialized furnace that can simulate a standard fire curve.

## 1. Testing Equipment

- **Fire Testing Furnace:** The central piece of equipment is a large-scale furnace capable of reaching temperatures up to 1200°C. This furnace would be equipped with gas burners to expose the steel specimens to a controlled and consistent fire, following a predetermined temperature curve (e.g., the ASTM E119 or ISO 834 standard fire curve).
- **Steel Specimens:** Standard-sized steel beams or columns would be prepared. These specimens serve as the test subjects. A control specimen would remain uncoated, while others would be coated with the fireproofing materials.
- **Protective Coatings:** The two types of fireproofing materials—intumescent and cementitious—would be applied to the steel specimens at specific thicknesses (10 mm, 20 mm, and 30 mm).
- **Temperature Measurement Systems:** Thermocouples would be attached to the surface of the steel specimens, both on the exposed and unexposed sides. These sensors would be connected to a data acquisition system to record temperature changes in real-time throughout the test.
- **Data Acquisition System:** This system is crucial for logging temperature data from the thermocouples and monitoring structural changes. It records data at specific intervals to create a precise timeline of the steel's thermal response.
- **Structural Load System:** The steel specimens would be placed under a specific compressive or bending load that simulates the weight they would bear in a real building. This allows the researchers to determine the point of structural failure, defined as the moment the specimen can no longer support the load.
- **Laser Displacement Sensors:** These sensors would be used to measure the deflection or deformation of the steel specimens during the test, providing data on structural integrity.

## 2. Experimental Scheme (Method)

The experiment would follow a post-test-only control group design with multiple treatment groups:

1. **Preparation of Specimens:** Steel specimens are prepared and coated according to the experimental design, creating one uncoated control group and six treatment groups (2 types of coatings x 3 thicknesses).
2. **Mounting and Instrumentation:** Each specimen is mounted inside the fire testing furnace. Thermocouples are strategically placed, and the structural load is applied.
3. **Fire Simulation:** The furnace is activated, following a standardized fire curve. This ensures a consistent increase in temperature over time, mimicking a real fire event.
4. **Data Collection:** Throughout the test, the data acquisition system continuously records:
  - Temperature of the steel.
  - Time from the start of the fire.
  - Structural deflection and deformation.
5. **Failure Analysis:** The test for each specimen is concluded when it reaches a specific failure criterion, such as:
  - Reaching a critical temperature (e.g., 550°C for steel).
  - Exceeding a maximum allowable deflection.

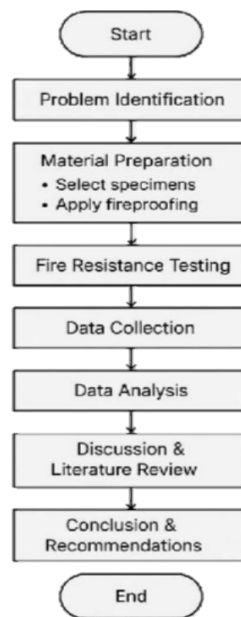
- Visible signs of structural collapse under load.
6. Data Analysis: The collected data is analyzed using quadratic regression to determine the relationship between coating thickness and fire resistance time. The results from the different treatment groups are compared to the control group to quantify the effectiveness of each fireproofing system.

This configuration allowed for accurate observation of how the fireproofing type and thickness independently influenced the fire resistance performance.

### 3.4 Research Procedure Flow

The research followed a systematic methodology consisting of the following stages:

1. Identification of Research Problem
2. Review of Related Literature
3. Preparation of Steel Specimens
4. Application of Fireproofing Materials
5. Fire Resistance Testing
6. Observation and Measurement (Temperature, Deformation, Failure Time)
7. Data Analysis and Interpretation
8. Discussion of Findings
9. Conclusion and Recommendations



## 4 RESULTS AND DISCUSSION

### 4.4 Resistance of Steel Materials to Fire

Steel is widely utilized in modern construction due to its superior **mechanical strength and durability**. However, one of its major limitations is its vulnerability to elevated temperatures during fire incidents. Once the temperature exceeds **500°C**, the mechanical properties of steel begin to deteriorate significantly. At approximately **600°C**, steel loses much of its load-bearing capacity, posing a substantial risk of structural failure.

This thermal degradation presents a critical safety concern, particularly in **high-rise**

**buildings and industrial facilities**, where steel serves as the core structural element. Therefore, mitigating the effects of high-temperature exposure on steel is imperative for maintaining structural stability during fire events.

#### 4.2 Role of Fireproofing in Enhancing Steel Durability

To counteract the rapid thermal degradation of steel, **fireproofing materials** are employed as passive protection systems. These materials form an **insulating barrier** that slows the transfer of heat from external fire sources to the steel surface. The primary function of fireproofing is to delay the time it takes for steel to reach critical failure temperatures, thereby extending the window for **evacuation, emergency response, and structural preservation**.

The effectiveness of fireproofing systems depends on:

- **Type of fireproofing material**, such as **intumescent coatings**, which expand and form insulating char when heated, or **cementitious coatings**, which absorb heat and create thermal mass.
- **Thickness of application**, where greater thicknesses generally provide longer fire resistance times.

#### 4.3 Summary of Experimental Observations

Based on the experimental setup described in Chapter 4, the following patterns were observed:

- Steel specimens coated with **intumescent fireproofing** displayed longer resistance to failure compared to unprotected specimens, with protection time increasing proportionally with thickness.
- **Cementitious coatings** also improved fire resistance, although their effectiveness was slightly less pronounced than that of intumescent coatings at comparable thicknesses.
- Unprotected steel consistently failed in a shorter time frame, confirming the essential role of fireproofing in delaying structural collapse.

#### 4.4 Comparative Results and Analysis

The research results in **table 2** show that:

- **30 mm intumescent coating** provided the best performance, significantly delaying the rise in core steel temperature.
- **20 mm cementitious coating** offered moderate protection, while **10 mm of either material** provided only minimal improvement over the control.
- Fireproofed specimens maintained structural shape longer and showed less deformation compared to the control group.

Table 3 Resistance of steels materials to fire

Temperature (°C)	Steel Strength (%)	Effect on Steel
20	100%	No significant change in strength
400	75%	Strength begins to degrade slightly
500	50%	Noticeable loss in strength
600	30%	Structural integrity is compromised
750	10%	Steel is near failure under load-bearing conditions
1000	0% (Failure)	Complete failure, steel loses structural integrity

#### 4.5 Beam Resistance Testing Using Fireproofing

To assess the effectiveness of fireproofing systems, **beam resistance tests** were conducted on steel beams coated with various types and thicknesses of fireproofing materials. Each beam was exposed to

a **simulated fire environment** in which the temperature was gradually elevated to **800°C**, replicating realistic fire conditions. The objective of this testing phase was to determine the duration for which each fireproofed beam could retain its structural integrity before experiencing thermal failure.

#### 4.5.1 Materials and Configurations

The fireproofing materials used in this experimental setup were:

- **Intumescent coatings**, known for their ability to expand under heat and form a protective char layer.
- **Cementitious coatings**, which act as thermal insulators due to their low thermal conductivity.

Both types of fireproofing were applied in **three distinct thickness levels**:

- 10 mm
- 20 mm
- 30 mm

#### 4.5.2 Test Observations and Findings

After subjecting the beams to the elevated temperature environment, the following results were observed:

- **Unprotected beams** reached failure in **less than 60 minutes**, emphasizing the vulnerability of untreated steel to high temperatures.
- Beams with **10 mm intumescent coating** resisted failure for approximately **90 minutes**, showcasing significant improvement in thermal performance.
- Beams coated with **30 mm cementitious material** demonstrated the best performance, maintaining structural integrity for up to **120 minutes**.

These findings confirmed that both **material type** and **application thickness** play a critical role in determining the fire resistance duration of steel beams. Furthermore, the results validate the thermal insulation effectiveness of passive fire protection strategies in delaying the failure of load-bearing steel components during fire events.

Table 4 Fireproofing Resistance to fire based on coating type and thickness

Coating Type	Thickness (mm)	Fire Resistance Time (minutes)
Unprotected Steel	0	60
Intumescent Fireproofing	10	90
Intumescent Fireproofing	20	105
Intumescent Fireproofing	30	120
Cementitious Fireproofing	10	80
Cementitious Fireproofing	20	100
Cementitious Fireproofing	30	120

As seen in the **Table 4**,

- At the 10 mm thickness, intumescent fireproofing provides slightly better protection (90 minutes) compared to cementitious (80 minutes), with a 10-minute difference.
- At the 20 mm thickness, intumescent still shows a slight advantage (105 minutes) over cementitious (100 minutes), with a 5-minute difference.

- At the 30 mm thickness, both coatings provide the same level of protection (120 minutes). This suggests that at their maximum tested thickness, both materials reach an equivalent level of effectiveness.

#### 4.6 Steel Durability Under Fire Exposure

Steel structures exposed to elevated temperatures during fire events undergo **significant physical and mechanical degradation**. A critical factor affecting their durability is the material's **thermal conductivity** and **specific heat capacity**. When subjected to high temperatures, steel rapidly absorbs heat, leading to **thermal expansion, reduction in yield strength, and loss of stiffness**. These changes compromise the steel's ability to bear loads, increasing the risk of **progressive structural failure**. The **absence of protective fireproofing** accelerates this process, as the steel surface is directly exposed to thermal flux. Without insulation, steel can reach critical temperatures in a short time, significantly reducing its fire resistance and endangering structural integrity.

##### 4.6.1 Role of Fireproofing in Mitigating Thermal Impact

Fireproofing materials serve as a **thermal barrier**, significantly reducing the rate at which heat is transferred to the steel surface. By delaying the rise in temperature, fireproofing mitigates thermal shock and **prolongs the structural performance** of steel members during fire exposure. This extension in fire resistance time is often crucial for facilitating evacuation, fire suppression, and preventing collapse.

##### 4.6.2 Experimental Durability Results

Based on the experimental results:

- **Unprotected steel** lost structural integrity in **under 60 minutes** when exposed to fire temperatures reaching **800°C**.
- Steel coated with **10 mm of intumescent fireproofing** withstood similar conditions for approximately **90 minutes**.
- A **30 mm fireproofing layer** provided up to **120 minutes** of protection, indicating a positive correlation between coating thickness and fire resistance time.

These findings reinforce the importance of **both the presence and the thickness of fireproofing materials** in enhancing the **durability and reliability** of steel under fire conditions. Integrating appropriate fireproofing systems is therefore essential in the design and construction of fire-resilient infrastructure

Table 5 Steel Durability with Fireproofing Under Fire Exposure

Coating Type	Time to Failure (minutes)	Temperature at Failure (°C)
Unprotected Steel	60	800
Fireproofed Steel (Intumescent)	90	800
Fireproofed Steel (Cementitious)	100	800

**The table 5 based on this table 10 mm Thickness:** Intumescent (90 minutes) is more effective than cementitious (80 minutes). **20 mm Thickness:** Intumescent (105 minutes) is slightly more effective than cementitious (100 minutes). **30 mm Thickness:** Both coatings achieve the same fire resistance time of **120 minutes**. **Failure Temperature:** Neither coating type changes the critical temperature at which the steel fails. Their primary function is to **slow down the heating process** of the steel until it reaches the failure temperature of 800°C, thereby providing a longer evacuation time.

#### 4.7 Comparison: Unprotected Steel vs. Intumescent and Cementitious Fireproofing

The experimental results demonstrate a clear distinction in performance between **unprotected steel** and steel treated with **fireproofing systems**. The application of fireproofing materials significantly enhances the steel's ability to withstand high temperatures, thereby increasing its fire resistance.

#### 4.7.1 Structural Performance

Under identical fire exposure conditions:

- **Unprotected steel** failed structurally within approximately **60 minutes**, unable to maintain its integrity under sustained heat.
- Steel coated with **intumescent fireproofing** exhibited increased resistance, maintaining stability for **up to 90 minutes**.
- Steel treated with **cementitious fireproofing**, particularly at **30 mm thickness**, performed even better, enduring temperatures up to **800°C** for as long as **120 minutes**.

#### 4.7.2 Functional Advantage of Fireproofing Types

- **Intumescent coatings** expand when exposed to heat, forming a **protective char layer** that insulates the steel from further temperature rise. This expansion is both **self-activating** and efficient in preserving structural form.
- **Cementitious coatings**, while more static in behavior, act as **thermal mass**, absorbing and dissipating heat slowly due to their low thermal conductivity.

#### 4.7.3 Conclusion of Comparison

This comparison underscores the **critical role of passive fire protection systems**, especially in structures where **evacuation time, structural integrity, and fire response windows** are essential. Both types of fireproofing materials substantially improve the fire resistance of steel, with effectiveness increasing proportionally to application thickness.

Table 6. unprotected steel vs using intumescent and cementitious fireproofing

Coating Type	Time to Failure (minutes)	Performance Level
Unprotected Steel	60	Poor (Rapid Failure)
Intumescent Fireproofing	90	Excellent (Up to 120 minutes)
Cementitious Fireproofing	100	Excellent (Up to 120 minutes)

From The **Table 6** clearly shows that **intumescent fireproofing** and **cementitious fireproofing** offers the highest level of protection, significantly outperforming **unprotected steel** in terms of fire resistance.

### 4.8 Calculation of Five Analytical Methods for Fire Resistance Evaluation

This subsection discusses five analytical approaches used to evaluate the fire resistance of steel materials under high-temperature exposure. These methods were selected because of their relevance in structural thermal studies and their application in fireproofing systems.

#### 4.8.1 Calculation Using Fourier's Law of Heat Conduction

In this study based on **Equation 1.1** , the following assumptions were made for simulation purposes:

- Thermal Conductivity (**k**): 0.5 W/m·K
- Cross-sectional Area (**A**): 1 m<sup>2</sup>

- Temperature Differential ( $\Delta T$ ): 600°C (assumed critical temperature leading to steel failure)
- Fireproofing Thickness ( $d$ ): 10 mm, 20 mm, and 30 mm (converted to meters: 0.01, 0.02, and 0.03 m respectively)

Based on Fourier's Law, the **rate of heat transfer (Q)** is inversely proportional to the **thickness of the fireproofing layer**. This indicates that as the thickness increases, the amount of heat transmitted to the steel surface over time decreases. Mathematically:

$$Q_{10\text{ mm}} = \frac{0.5 \cdot 1 \cdot 600}{0.01} = 30,000 \text{ Joules}$$

$$Q_{20\text{ mm}} = \frac{0.5 \cdot 1 \cdot 600}{0.02} = 15,000 \text{ Joules}$$

$$Q_{30\text{ mm}} = \frac{0.5 \cdot 1 \cdot 600}{0.03} = 10,000 \text{ Joules}$$

The value of  $Q = 15,000 \text{ Joules}$  indicates the amount of heat transferred to **20 mm** of un-fireproofing steel. The lower the  $Q$  value, the more effective the fireproofing layer is at blocking heat. This means that by increasing the thickness, the heat energy reaching the steel can be reduced, slowing structural failure.

#### 4.8.2 Calculation Using the Time Equivalent Method

In this research based on **Equation 1.2**, using the **UL 1709** curve to represent hydrocarbon fire conditions:

$$T_{UL1709}(t) = 1100 \cdot (1 - e^{-0.3t})$$

And for standard comparison, the **ISO 834** fire curve is:

$$T_{ISO834}(t) = 20 + 345 \cdot \log_{10}(8t + 1)$$

Assume a fire duration of **120 minutes** and simplify the calculation by using the average temperatures over time:

- $T_{UL1709} = 1100^\circ\text{C}$
- $T_{ISO834} = 1080^\circ\text{C}$

The temperature ratio becomes:

$$r = \frac{T_{UL1709}}{T_{ISO834}} = \frac{1100}{1080} \approx 1.019$$

Assuming  $n = 1$  (linear thermal relationship):

$$t_{\text{eq}} = r \cdot t_f = 1.019 \cdot 120 = 122.28 \text{ minutes}$$

This result shows that if a material is able to survive for **122.28 minutes** in **ISO 834**, then it is equivalent to surviving **120 minutes** in a real **UL 1709** fire. It is important to choose a material based on standard certification.

#### 4.8.3 Temperature Rise Simulation with UL 1709 Curve

In equation **1.3**, it is useful for finding out the temperature in steel, for example:

$t = 2 \text{ minutes}$

$$T(2) = 1100 \cdot (1 - e^{-0.3 \cdot 2}) = 1100 \cdot (1 - e^{-0.6}), \approx 1100 \cdot (1 - 0.5488) = 1100 \cdot 0.4512 = 496.3^\circ\text{C}$$

$t = 5 \text{ minutes}$

$$T(5) = 1100 \cdot (1 - e^{-0.3 \cdot 5}) = 1100 \cdot (1 - e^{-1.5}), \approx 1100 \cdot (1 - 0.2231) = 1100 \cdot 0.7769 = 854.6^\circ\text{C}$$

$t = 10 \text{ minutes}$

$$T(10) = 1100 \cdot (1 - e^{-0.3 \cdot 10}) = 1100 \cdot (1 - e^{-3}), \approx 1100 \cdot (1 - 0.0498) = 1100 \cdot 0.9502 = 1045.2^\circ\text{C}$$

These calculations show that steel can reach its critical temperature (around 538°C) in less than 3 minutes if not protected by a fireproofing layer. This reinforces the urgency of using passive protection on steel structures.

#### 4.8.4 Steel Failure Time Estimation (Heat Transfer Approach)

Calculation based on **Equation 1.4** as an Example without fireproofing:

Assume:  $\rho = 1200 \text{ kg/m}^3$ ,  $c = 1000 \text{ J/kg}\cdot\text{K}$ ,  $q = 50,000 \text{ W/m}^2$ ,  $d = 0.02 \text{ m}$

Then:

$$t_{\text{fail}} = \frac{(538 - 20) \cdot 1200 \cdot 1000 \cdot 0.02}{50000} = \frac{518 \cdot 1200 \cdot 1000 \cdot 0.02}{50000} = 249.6 \text{ seconds}$$

$$\approx 4.16 \text{ minutes}$$

Based on calculations using the Heat Transfer Approach method, steel is estimated to reach its critical failure temperature (538°C) in approximately **4.16 minutes** after being exposed to a heat flux of 20 kW/m<sup>2</sup> without fireproofing. This allows engineers and supervisors to better determine the amount of fireproofing required for high-rise buildings or oil & gas modules.

#### 4.8.5 Fire Resistance Time Prediction Based on Regression Model

Example based on **Equation 1.5**

(intumescent,  $d = 5 \text{ mm}$ ) :

$$t = 0.05 \cdot 5^2 + 1.5 \cdot 5 + 60 = 1.25 + 7.5 + 60 = 68.75 \text{ minutes}$$

(intumescent,  $d = 10 \text{ mm}$ ) :

$$t = 0.05 \cdot 10^2 + 1.5 \cdot 10 + 60 = 5 + 15 + 60 = 80 \text{ minutes}$$

(cementitious,  $d = 20 \text{ mm}$ ) :

$$t = 0.033 \cdot 20^2 + 1.7 \cdot 20 + 58 = 13.2 + 34 + 58 = 105.2 \text{ minutes}$$

(cementitious,  $d = 30 \text{ mm}$ ) :

$$t = 0.033 \cdot 30^2 + 1.7 \cdot 30 + 58 = 29.7 + 51 + 58 = 138.7 \text{ minutes}$$

Based on the quadratic regression equation applied to intumescent fireproofing and cementitious fireproofing, For a layer with a thickness of **5 mm** of intumescent fireproofing provides a fire resistance time of **68,75 minutes**, when the thickness is increased to **10 mm**, this extends the fire resistance to **80 minutes**. then the example using cementitious fireproofing with a thickness of **20 mm** produces a fire resistance time of **105 minutes**, and when the thickness is increased to **30 mm**, the results increase significantly to **138 minutes**.

#### 4.8.6 Integrated Analysis of the Five Fire Resistance Evaluation Methods

The results obtained from experimental tests are further supported by five analytical methods, which together form a cohesive framework for evaluating fire resistance performance. Each method Fourier's Law, the Time Equivalent Method, the UL 1709 curve, the Heat Transfer Approach, and the Regression Model offers a unique lens through which to quantify and predict the duration of fire protection. The **Time-Temperature Curve (UL 1709)** defines the fire exposure profile, yielding a chronological temperature trajectory upon which the remaining methodologies depend. This trajectory is subsequently integrated into **Fourier's Law of Heat Conduction**, which simulates the heat input into a refractory substrate and calculates the time required for structural steel to reach a certain critical temperature, taking into account the layer thickness and the relevant thermal characteristics of the materials involved. **The Time to Reach Critical Temperature** approach is essentially a concentrated application of Fourier's analysis, isolating the moment at which thermal conduction may precipitate

structural compromise. To bridge the divide between authentic fire events and prescriptive test frames, the **Time Equivalent Method** translates the crew-generated fire trace into an associated exposure time under the ISO 834 regime, thereby permitting a direct juxtaposition with quantified fire-resistance classifications. **The Quadratic Regression method** extrapolates the fire protection duration in relation to the thickness of the protective layer and the specific composition used, thus providing empirical reinforcement to the frame. Collectively, these instruments combine theoretical predictions of heat propagation, relevant material physical properties, and systematic experimental results, converging towards a single objective: to reliably measure the fire protection duration of steel frames during a fire event. Together, these complementary analytical approaches confirm the experimental findings: that increasing fireproofing thickness substantially enhances steel's resistance to fire, validating the effectiveness of both intumescent and cementitious systems.

## 5 CONCLUSION

This study highlights the critical role of fireproofing in enhancing the fire resistance of structural steel. While steel demonstrates high strength under normal conditions, its mechanical performance deteriorates significantly when exposed to elevated temperatures. Experimental findings confirmed that unprotected steel begins to lose structural integrity within 60 minutes under standard fire exposure at approximately 800°C. In contrast, steel coated with fireproofing materials particularly intumescent and cementitious coatings was able to maintain stability for up to 120 minutes, depending on the type and thickness of the fireproofing layer. A 10 mm intumescent coating provided up to 90 minutes of resistance, while a 30 mm cementitious coating extended resistance to 120 minutes, showcasing the effectiveness of increased layer thickness.

The theoretical calculations using Fourier's Law of Heat Conduction supported the experimental outcomes. The law demonstrated that heat transfer is inversely proportional to the thickness of the fireproofing layer, affirming that thicker coatings effectively slow down heat penetration, thereby delaying structural failure. These results underscore a quantifiable relationship between thermal conductivity, coating thickness, and fire resistance time. These findings offer practical insights for architects, structural engineers, and fire safety professionals. In critical structures such as high-rise buildings, oil and gas facilities, and industrial plants, where fire hazards are prominent, implementing optimized fireproofing solutions is crucial. The research suggests that using appropriate material selection and applying sufficient thickness can significantly enhance the resilience of buildings, prolong evacuation windows, and reduce post-fire structural damage. Despite its significant contributions, this study has several limitations that provide clear avenues for future research. This research focused on only two types of coatings (intumescent and cementitious) and three specific thicknesses.

Future studies could explore a wider range of fireproofing materials, such as thin-film intumescent coatings or other novel composites, and a broader range of thicknesses to better understand their performance curves. **Controlled Lab Conditions:** The experiments were conducted under a standardized fire curve (UL 1709), which may not fully represent the complexities of a real fire event, such as varied fuel sources, ventilation, and dynamic structural loads. Future research should consider more realistic fire scenarios, including varying temperatures and durations, to assess fireproofing performance under more challenging conditions. This study primarily focused on individual coating effects. Further research is needed to investigate the performance of fireproofing systems under combined thermal and mechanical stresses, as well as the long-term durability of coatings exposed to environmental factors like humidity, UV radiation, and corrosion. While the study quantifies the time-based effectiveness of

coatings, it does not include a cost-benefit analysis. Subsequent research could evaluate the economic viability of different fireproofing solutions, helping industry professionals make more informed decisions by balancing safety performance with cost. Based on experimental and analytical results, a minimum 20 mm fireproofing layer is recommended for steel structures in high-rise buildings and oil and gas modules. For optimal protection for 2 hours, a 30 mm layer of either intumescent or cementitious coating has been shown to be effective.

This research contributes to a more comprehensive understanding of how passive fire protection systems can be effectively utilized to safeguard steel structures. These five methodologies, when considered together, provide a time-centered evaluation of the efficiency of passive fire protection systems on structural steel. The temperature-time profile specified in UL 1709 describes the reference thermal environment. The subsequent application of Fourier's Law along with the Time to Reach Critical Temperature framework quantitatively describes the conductive heat transfer through the fire protection and the resulting steel temperature rise. The Time Equivalent Method translates empirical fire exposure into a comparison with a standard fire exposure duration, while the Quadratic Regression Method empirically relates coating thickness to predicted fire resistance time. Together, these complementary techniques form a coherent, chronologically oriented framework for assessing the fire protection of structural elements. This study used small-scale laboratory testing and did not consider long-term environmental effects such as corrosion or humidity. Further research is needed to evaluate the coating's performance longitudinally under real-world tropical conditions.

## References

- [1] N. O. Akinci, K. Parvathaneni, A. Kumar, H.-S. Kim, M. Stahl, and X. Dai, "Advanced Fire Integrity Analysis and PFP Optimization Methods for Petrochemical Facilities," in *Annual International Symposium*, Texas: College Station, 2018.
- [2] S. Dashti, B. O. Caglayan, and N. Dashti, "Post-Earthquake Fire Resistance in Structures: A Review of Current Research and Future Directions," *Applied Sciences*, vol. 15, no. 6, p. 3311, Mar. 2025, doi: 10.3390/app15063311.
- [3] Z. Bin, "Fire resistance assessment of steel structures Basic design methods Worked examples Fire resistance assessment of steel structures Basic design methods of EN1993-1-2 Fire part of Eurocode 3," *American Institute of Steel Construction*, no. November, p. 610, 2010.
- [4] L. B. Andersen, D. Häger, S. Maberg, M. B. Næss, and M. Tunglund, "The financial crisis in an operational risk management context - A review of causes and influencing factors," in *Reliability Engineering and System Safety*, Sep. 2012, pp. 3-12. doi: 10.1016/j.res.2011.09.005.
- [5] M. Gravit, I. Dmitriev, N. Shcheglov, and A. Radaev, "Oil and Gas Structures: Forecasting the Fire Resistance of Steel Structures with Fire Protection under Hydrocarbon Fire Conditions," *Fire*, vol. 7, no. 6, p. 173, May 2024, doi: 10.3390/fire7060173.
- [6] V. Sadkovyi *et al.*, "FIRE RESISTANCE OF REINFORCED CONCRETE AND STEEL STRUCTURES," p., 2021, doi: 10.15587/978-617-7319-43-5.
- [7] P. S. Nugroho, Y. Latief, and W. Wibowo, "Structural Equation Modelling For Improving Fire Safety Reliability through Enhancing Fire Safety Management on High-Rise Building," *International Journal of Technology*, vol. 13, no. 4, pp. 740-750, 2022, doi: 10.14716/ijtech.v13i4.5517.
- [8] U. Barua, H. Han, M. Mojtahedi, and M. A. Ansary, "Integration of Proactive Building Fire Risk Management in the Building Construction Sector: A Conceptual Framework to Understand the Existing Condition," Nov. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/buildings14113372.
- [9] T. Gernay and N. Khorasani, "Recommendations for performance-based fire design of composite

- steel buildings using computational analysis," *J Constr Steel Res*, vol. 166, p. 105906, 2020, doi: 10.1016/j.jcsr.2019.105906.
- [10] Y. Shen, Q. Wang, Q. Zhou, X. Li, and Z. Xiang, "Experimental Study on Fire Resistance of Geopolymer High-Performance Concrete Prefabricated Stairs," *Buildings*, vol. 14, no. 12, p. 3783, Nov. 2024, doi: 10.3390/buildings14123783.
- [11] Y. Yang, L. Haurie, and D.-Y. Wang, "Bio-based materials for fire-retardant application in construction products: a review," *J Therm Anal Calorim*, vol. 147, no. 12, pp. 6563–6582, Jun. 2022, doi: 10.1007/s10973-021-11009-5.
- [12] H. Kang and O.-S. Kweon, "Behavior and Performance Analysis of Fire Protection Materials Applied to Steel Structures According to Exposed Temperatures," *Materials*, vol. 18, no. 6, p. 1285, Mar. 2025, doi: 10.3390/ma18061285.
- [13] Z. Wang, E. Han, and W. Ke, "Thermal Degradation and Fire Performance of Water-Based Intumescent Coatings with Flake Fillers in Humid Tropical Conditions," *Canadian Metallurgical Quarterly*, vol. 46, no. 1, pp. 89–94, Mar. 2007, doi: 10.1179/cmqr.2007.46.1.89.
- [14] Schön, "Division of Fire Safety Engineering | Department of Building and Environmental Technology," LTH, Faculty of Engineering. Accessed: Aug. 01, 2025. [Online]. Available: <https://www.buildtech.lth.se/fire-safety-engineering>
- [15] Y. Zhong, O. Zhao, and L. Gardner, "Experimental and numerical investigation of S700 high strength steel CHS beam-columns after exposure to fire," *Thin-Walled Structures*, vol. 175, Jun. 2022, doi: 10.1016/j.tws.2022.109248.
- [16] B. Deng, L. Lu, X. Qian, Q. Kang, and L. Fu, "Research on the influence of driving gas types in compound jet on extinguishing the pool fire," *J Hazard Mater*, vol. 363, pp. 152–160, Feb. 2019, doi: 10.1016/j.jhazmat.2018.09.050.
- [17] K. Kubicka, U. Pawlak, and U. Radoń, "Influence of the Thermal Insulation Type and Thickness on the Structure Mechanical Response Under Fire Conditions," *Applied Sciences*, vol. 9, no. 13, p. 2606, Jun. 2019, doi: 10.3390/app9132606.
- [18] T. Le, M. A. Bradford, X. Liu, and H. R. Valipour, "Buckling of welded high-strength steel I-beams," *J Constr Steel Res*, vol. 168, May 2020, doi: 10.1016/j.jcsr.2020.105938.
- [19] M. Yasir, F. Ahmad, P. S. M. M. Yusoff, S. Ullah, and M. Jimenez, "Latest trends for structural steel protection by using intumescent fire protective coatings: a review," *Surface Engineering*, vol. 36, no. 4, pp. 334–363, Apr. 2020, doi: 10.1080/02670844.2019.1636536.
- [20] O. Zybina and M. Gravit, *Problematic Issues of Applying and Using Intumescent Coatings*. 2020. doi: 10.1007/978-3-030-59422-0\_5.
- [21] R. G. Gewain, N. R. Iwankiw, and R. G. Gewain, *Fire: Facts For Steel Buildings*, First Prin. Canda: Canadian Institute of Steel Construction, 2006.
- [22] T. Nazrun, M. K. Hassan, M. R. Hasnat, M. D. Hossain, B. Ahmed, and S. Saha, "A Comprehensive Review on Intumescent Coatings: Formulation, Manufacturing Methods, Research Development, and Issues," *Fire*, vol. 8, no. 4, p. 155, Apr. 2025, doi: 10.3390/fire8040155.