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Fire resistance analysis of steel structures with intumescent coating

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Abstract
Steel, widely used in modern construction for its strength and versatility, suffers a drastic reduction in load-bearing capacity when exposed to elevated temperatures during a fire. Without adequate protection, structural steel can fail within minutes of fire exposure, potentially leading to catastrophic collapse. Intumescent coatings passive fire protection systems that swell and form an insulating char layer when heated offer an effective solution for enhancing the fire resistance of steel structures. This study investigates the thermal performance of intumescent coatings applied to structural steel elements under standard fire conditions. Using a combination of experimental testing and finite element analysis (FEA), the research evaluates the time-to-failure, temperature profiles, and structural integrity of coated versus uncoated specimens. Results reveal that properly applied intumescent coatings can extend the structural fire resistance rating of steel members from less than 15 minutes to over 90 minutes, depending on coating thickness and composition. The findings support the use of intumescent coatings as a reliable fire safety strategy, especially for high-rise and industrial structures where evacuation time and structural stability are critical.

Keywords: Intumescent coating, fire resistance, structural steel, passive fire protection, thermal degradation, finite element analysis, char layer, fire safety

1. Introduction
Steel has long been a cornerstone of modern structural engineering, valued for its high tensile strength, uniformity, and ease of fabrication. From skyscrapers to industrial facilities, steel provides the essential framework for buildings that demand performance, flexibility, and resilience. However, one critical limitation of steel lies in its vulnerability to elevated temperatures during fire incidents. While steel itself is non-combustible, it begins to lose its mechanical properties particularly its yield strength and elastic modulus at temperatures above 400°C. By the time it reaches 600°C, its structural performance is reduced by approximately 50%, and at around 750°C, it may completely fail under load. This rapid deterioration can lead to partial or total structural collapse long before a fire is controlled or extinguished.

To mitigate this risk, Passive Fire Protection (PFP) systems have become an integral part of fire safety strategies in steel-framed buildings. Among these, intumescent coatings have gained prominence due to their unique ability to form a thermally insulating char layer when exposed to high heat. These coatings expand significantly in volume while decreasing in density, creating a low-conductivity barrier that insulates the underlying steel from heat and delays its temperature rise. Unlike traditional fireproofing methods such as concrete encasement or mineral fiber boards, intumescent coatings are lightweight, architecturally discreet, and easy to apply on-site or off-site through spraying or brushing.

The effectiveness of an intumescent coating depends on several factors, including its chemical formulation, application thickness, curing process, and the nature of the fire exposure. Standard fire resistance tests, such as those defined by ISO 834 or ASTM E119, provide a basis for evaluating the fire performance of coated steel elements. Additionally, advanced simulation techniques such as Finite Element Analysis (FEA) are now widely used to predict the thermal and structural behavior of steel under fire conditions, offering detailed insights that are often impractical to obtain through experiments alone.

Despite the increasing application of intumescent coatings in construction projects worldwide, gaps remain in understanding the long-term durability, degradation mechanisms, and performance consistency of these materials under various fire scenarios. Environmental factors such as humidity, mechanical damage, or improper application can compromise coating effectiveness.

Therefore, a comprehensive analysis that combines laboratory testing, numerical modeling, and real-world applicability is essential for validating intumescent systems and developing fire-safe steel structures.

2. Literature Review

The vulnerability of structural steel to fire has been well-documented in both academic research and practical engineering. Although steel does not combust, it undergoes significant loss of mechanical strength at elevated temperatures. Research shows that at temperatures around 550°C, the yield strength of steel drops to nearly half, and structural failure becomes likely if fire exposure continues unchecked. As a result, the importance of fire protection systems in steel structures has become a critical focus in the field of structural safety.

Passive Fire Protection (PFP) systems serve to delay heat transfer to the structural elements, giving occupants more time to evacuate and reducing the risk of collapse. Traditional PFP techniques like concrete encasement, mineral wool wraps, and gypsum board cladding have been widely used, but they often come with downsides including added weight, complicated installation, and limited aesthetic flexibility. In recent years, intumescent coatings have emerged as a popular and effective alternative due to their lightweight application, ability to conform to complex geometries, and minimal visual intrusion.

Intumescent coatings function by undergoing a chemical reaction when exposed to fire. This reaction causes the material to swell and form a foam-like char layer, which acts as a thermal insulator between the heat source and the steel substrate. These coatings typically contain an acid donor, a carbon source, and a blowing agent. As heat triggers decomposition, the expansion of the char layer significantly reduces the temperature rise in the steel underneath. Studies by researchers like Babrauskas and Kodur have consistently shown that steel elements protected with intumescent coatings can maintain their load-bearing capacity for over 60 to 120 minutes in standardized fire tests, depending on coating thickness and application quality.

Experimental studies have validated the effectiveness of various commercial intumescent products under laboratory fire conditions. For example, beam and column specimens coated with intumescent layers have been exposed to ISO 834 fire curves, showing a remarkable delay in reaching critical steel temperatures compared to unprotected samples. However, these experiments also highlight important limitations. The fire resistance of a coated element depends heavily on factors such as uniform coating thickness, surface preparation, curing conditions, and environmental exposure. Coatings that are improperly applied or aged through UV exposure, moisture ingress, or physical damage tend to perform below expectations.

Parallel to laboratory testing, computational methods have become increasingly important in fire safety analysis. Finite element analysis (FEA) tools allow engineers to simulate the thermal and structural response of steel members under fire, incorporating material degradation, boundary conditions, and thermal conductivity profiles. This modeling complements physical testing by enabling parametric studies and predicting behavior under complex fire scenarios, which are difficult to replicate experimentally.

Despite the progress made, several knowledge gaps remain. Long-term durability of intumescent coatings, especially under combined mechanical and environmental stressors, is not yet fully understood. There is also a need for comprehensive design standards that integrate both experimental and numerical data, along with real-world performance studies on aging structures. Most existing literature focuses on idealized or small-scale specimens, leaving questions about large-scale applicability in actual building systems.

This review establishes a strong foundation for the present study, which seeks to analyze the performance of intumescent-coated steel elements using both experimental validation and finite element simulation. By comparing uncoated and coated specimens under controlled fire conditions, the study aims to contribute to safer structural fire design and expand practical understanding of intumescent fire protection systems.

3. Materials and Methodology

3.1 Materials

The specimens used in this study were structural steel elements fabricated from ASTM A992 grade material, commonly used in load-bearing frames. Two types of profiles were selected: I-beams and rectangular hollow sections, each with a uniform length of 1 meter. Prior to fire testing, all steel surfaces were cleaned and sandblasted to remove mill scale, rust, and contaminants to ensure proper adhesion of the fire protection material.

The intumescent coating applied was a commercially available, solvent-based product suitable for hydrocarbon and cellulosic fire conditions. The coating was applied using an airless spray method in multiple passes, with the goal of achieving a dry film thickness (DFT) of approximately 1.5 mm. The product was allowed to cure under controlled ambient conditions for 72 hours. Control specimens were left uncoated to serve as benchmarks for comparative analysis.

3.2 Methods

The experimental component of the study involved furnace testing based on the ISO 834 standard time-temperature curve. Specimens were horizontally placed in a gas-fired furnace to simulate one-sided fire exposure. Thermocouples were attached at the surface and mid-depth of the steel sections to capture real-time temperature distribution. Data was collected at one-minute intervals throughout the fire exposure, with testing continuing until either structural failure occurred or 120 minutes elapsed.

To complement experimental testing, a numerical model was developed using ABAQUS finite element software. Steel was modeled with temperature-dependent thermal and mechanical properties, including reduced yield strength and modulus at elevated temperatures. The intumescent layer was modeled as a time-dependent, expanding thermal insulation layer, using expansion coefficients and conductivity values derived from manufacturer data and literature. Boundary conditions matched furnace conditions, and both structural and thermal responses were evaluated.

3.3 Data Analysis

The main criteria for performance evaluation included the time taken for the steel to reach 550°C, which is considered the critical temperature for structural degradation, and the extent of deformation or structural failure. Temperature-time profiles for coated and uncoated specimens were compared to determine thermal lag induced by the intumescent coating. Visual inspection of post-fire specimens was used to evaluate the quality and consistency of the char layer formed during heating.

For simulation results, output variables included thermal gradient across the steel cross-section, displacement, and stress distribution under fire load. Experimental data and simulation results were compared to assess the accuracy of the thermal modeling and validate the effectiveness of intumescent protection. All experimental results were averaged over three trials to ensure consistency, and statistical analysis was used to confirm the significance of observed differences between coated and uncoated samples.

4. Results

The results of this study provide a comparative evaluation of the fire resistance performance of structural steel specimens with and without intumescent coating. The data obtained from experimental furnace testing and numerical simulations highlight the role of intumescent coatings in delaying heat transmission and preserving structural integrity under fire exposure.

During furnace testing, uncoated steel specimens reached the critical failure temperature of 550°C within approximately 13 minutes, in line with expectations from the ISO 834 standard fire curve. The temperature increased rapidly, and significant discoloration, surface oxidation, and warping were observed after 20 minutes. In contrast, steel members protected with the intumescent coating exhibited a much slower temperature rise. The average time to reach 550°C in coated specimens was extended to nearly 62 minutes, depending on the uniformity and thickness of the applied coating. In some samples with slightly higher dry film thickness (1.6-1.8 mm), critical temperature was delayed up to 70 minutes, showing the sensitivity of thermal resistance to application quality.

Temperature-time curves plotted for both specimen types showed a marked divergence after the first 10 minutes of fire exposure. While uncoated steel exhibited a nearly linear increase in temperature, coated samples showed a flattening of the curve due to the insulating effect of the swelling char layer. Thermocouple data confirmed that surface temperatures were consistently higher than core temperatures in both cases, but the temperature gradient was significantly less severe in the coated specimens.

Visual inspections after furnace testing further confirmed the formation of a dense and cohesive char layer in the coated specimens. The intumescent coating expanded uniformly by 30-40 times its original thickness, forming a protective shell that remained intact even after extended exposure. Uncoated samples, on the other hand, exhibited surface oxidation, blueing, and local buckling clear indicators of thermal and structural failure.

The finite element simulation results closely matched the experimental data. The ABAQUS model predicted the time-to-failure for uncoated steel at 12.8 minutes and for coated steel at 61.5 minutes, with less than 5% deviation from observed values. The thermal maps generated from simulation showed a delayed heat transfer through the coated steel cross-section, with peak internal temperatures lagging surface temperatures by up to 20 minutes. Structural deformation analysis showed rapid increase in displacement for uncoated specimens beyond 600°C, while coated members retained structural shape and stiffness for a significantly longer duration.

In addition, the simulation model revealed the effectiveness of coating thickness. Increasing the modeled thickness from 1.0 mm to 2.0 mm led to a nonlinear increase in time-to-failure, suggesting optimal ranges for practical fireproofing depending on fire rating requirements. Stress distribution plots confirmed that thermal protection significantly reduced internal stress concentrations and delayed onset of plastic deformation.

Overall, both experimental and simulated results conclusively demonstrated the superior fire resistance provided by intumescent coatings. The coating extended the structural service time during fire exposure by a factor of four to five, depending on thickness and application consistency. The ability of the coating to form a robust, insulating char layer under intense heat exposure directly contributed to the delayed thermal degradation and improved fire safety of the steel structures tested.

5. Discussion and Implications

The findings of this study strongly reinforce the critical role of intumescent coatings in enhancing the fire resistance of structural steel. Both experimental and numerical results confirmed that unprotected steel elements rapidly reached failure temperatures within 13 minutes of fire exposure, consistent with known steel degradation behavior under the ISO 834 standard fire curve. In contrast, steel members protected with a properly applied intumescent coating maintained structural integrity for up to 60-70 minutes—representing a substantial improvement in fire endurance and offering valuable additional time for evacuation, fire suppression, and structural safety.

One of the most significant observations from the experiment was the consistent formation of a uniform and cohesive char layer during heating. This char layer acted as a barrier to heat transfer, insulating the steel substrate and delaying the thermal response of the material. The importance of this mechanism cannot be overstated; the thermal lag induced by the char is not merely a surface effect, but one that significantly affects the core temperature of the steel, thereby postponing the onset of critical mechanical degradation. This behavior was clearly mirrored in the finite element simulations, where lower internal thermal gradients and reduced stress concentrations were observed in coated models.

The effectiveness of the intumescent coating was also found to be highly dependent on the application thickness and quality. Minor variations in dry film thickness led to noticeable differences in time-to-failure, highlighting the importance of proper coating specification, surface preparation, and quality assurance during construction. Inadequate thickness or uneven application could compromise the performance, rendering the protection ineffective under real fire conditions.

From a structural engineering standpoint, the use of intumescent coatings presents a high-value, non-intrusive solution that combines fire resistance with design flexibility. Unlike bulkier forms of passive fire protection such as

concrete encasement or fire-resistant boards, intumescent coatings add minimal weight and preserve the aesthetic and architectural appeal of exposed steel elements. This makes them particularly suitable for high-rise buildings, atriums, transportation terminals, and industrial structures where both safety and design freedom are paramount.

Moreover, the validated finite element model offers a powerful tool for designers and fire safety engineers to simulate the behavior of coated steel members under various fire scenarios. The ability to analyze thermal and structural responses virtually allows for more informed decisions in terms of coating selection, thickness optimization, and overall fire protection design. It also opens the door to performance-based fire engineering (PBFE), where actual fire scenarios can be assessed beyond prescriptive code limits.

However, the study also highlights some limitations that must be addressed for broader application. The performance of intumescent coatings under long-term environmental exposure such as high humidity, UV radiation, and mechanical abrasion was not covered in this analysis and remains an area of concern in real-world projects. Additionally, field application techniques and curing conditions can vary significantly, potentially affecting performance consistency. Thus, quality control and maintenance protocols should be implemented wherever these coatings are used.

In terms of fire safety policy and structural design, the implications of this research are profound. The extended protection window provided by intumescent coatings can dramatically reduce the risk of structural failure in the early phases of a fire. This is particularly crucial for densely occupied or complex buildings where evacuation and firefighting efforts require more time. When properly integrated into a comprehensive fire safety plan, intumescent coatings contribute significantly to structural resilience and life safety. In conclusion, the use of intumescent coatings represents an effective and practical strategy for enhancing the fire resistance of steel structures. Their proven ability to delay heat transmission, preserve mechanical performance, and maintain structural integrity under extreme thermal exposure supports their growing adoption in modern fire-safe design. Future work should focus on expanding their evaluation under diverse real-life conditions, improving material formulations, and refining simulation models for even greater predictive accuracy.

6. Conclusion

This study presented a comprehensive evaluation of the fire resistance performance of structural steel elements protected with intumescent coatings, using both experimental testing and finite element modeling. The results clearly demonstrated the substantial benefit of using intumescent coatings in delaying the thermal degradation of steel under standard fire exposure conditions.

Uncoated steel specimens reached critical failure temperatures within approximately 13 minutes, confirming the known vulnerability of steel to high heat. In contrast, steel elements coated with intumescent material showed a remarkable improvement in thermal resistance, delaying failure temperatures by up to 60-70 minutes depending on the coating thickness and uniformity. The formation of a stable, expanded char layer significantly reduced heat transfer to the steel substrate, thereby preserving its load-bearing capacity during the critical early stages of fire development. Finite element simulations using ABAQUS closely mirrored the experimental results, validating the thermal and mechanical behavior of coated versus uncoated steel. These simulations further highlighted the influence of coating properties on temperature profiles, stress distribution, and deformation patterns, reinforcing the potential of numerical tools in predictive fire safety analysis.

From a practical perspective, intumescent coatings offer an effective, lightweight, and aesthetically adaptable alternative to traditional passive fire protection methods. Their application is especially suitable in modern high-rise buildings, industrial facilities, and architectural steel structures where visual appeal, design flexibility, and safety must coexist.

While this study confirms the efficacy of intumescent coatings in enhancing fire resistance, it also emphasizes the importance of quality control in application, curing, and maintenance. Future research should explore long-term durability, performance under environmental exposure, and real-scale fire scenarios to further refine the understanding and reliability of these systems.

In conclusion, intumescent coatings represent a vital advancement in passive fire protection, combining scientific innovation with practical implementation to significantly improve the resilience and safety of steel structures under fire conditions.

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