Performance of Steel Beams reinforced by CFRP Sheets with Fire-Retardant Coating

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ABSTRACT

The objective of this study was to determine the physical, mechanical, and chemical aspects of bonding and priming Fire-Retardant Coatings (FRCs) to steel surfaces before and after fire testing. Carbon Fiber Reinforced Polymers (CFRP) have been used to strengthen steel components. Certain types of polymer systems have demonstrated high fire retardancy without additives, while others require additives to achieve optimum fire resistance. A wide range of compounds are available to enhance the fire retardant properties of these materials, characterized by their chemical nature and behavior (such as halogenated, metal complex, silicon-based, and phosphorus additives) and mode of action (either condensed or gas-phase active systems).This article provides a comprehensive overview of fire retardant additives for CFRP used in various large-scale applications, including the aerospace, automotive, railway, electronics, and civil engineering industries, as well as their fire retardant mechanisms at the microscopic, macroscopic, and nanoscale levels. In addition to fire retardant properties, this study also discusses the effects of additives on other material parameters and coatings, such as glass transition temperature, mechanical performance, and FRP processability. The primary focus is on thermoset systems, with a brief mention of thermoplastics according to the matrix compounds relevant to the FRP market size. Test results show that the direct velocity ultrasonic value varied between 3.016 and 3.618 km/s, giving an estimated compressive strength of 15.974 MPa. The standard deviation was 0.533 km/s with a relative standard deviation of 16.407%.

Keywords-steel coating; Carbon Fiber Reinforced Polymers (CFRP); fire-retardant; epoxy bond

I. INTRODUCTION

The numerous benefits of CFRP, including a high strength-to-weight ratio, corrosion resistance, high material stiffness, and effectiveness in strengthening or repairing, have led to a growing acceptance of CFRP as a reinforcement material for deteriorated steel beams in the construction sector. CFRP is a composite material comprising longitudinal Carbon Fibers (CF) embedded in an adhesive matrix. Recent studies have demonstrated the efficacy of CFRP in reinforcing steel tube coatings susceptible to post-buckling failure. The application of CFRP to Short Hollow Structural sections (SHS) has resulted in an increase in axial load capacity by up to 2.6 times, as evidenced by authors in [1–3]. The reinforcement of structural steel coatings with CFRP results in enhanced composite stiffness and thickness, which in turn leads to an increased critical buckling stress and consequently a higher axial load capacity [2]. Nevertheless, concerns pertaining to CFRP's fire resistance, including smoke generation, strength loss, fire spread, and reduced steel stiffness at elevated temperatures, in conjunction with the paucity of research in this domain, have constrained its deployment in steel coatings that are required to adhere to specific fire safety standards [4, 5]. In principle, steel coatings should maintain a Fire-Resistance Level (FRL) of at least 30 minutes, with requirements increasing up to 240 minutes depending on the building type [7, 8]. CF demonstrate high heat resistance, retaining tensile stiffness and strength even at elevated temperatures. For instance, authors in [6] found that at 600 °C, CF retains nearly all its room-temperature stiffness and strength. However, the adhesives commonly used in CFRP are temperature-sensitive and begin to lose significant mechanical and bonding strength near their glass transition temperature, which typically ranges from 65 °C to 120 °C. When the composite CFRP is exposed to high temperatures, this results in degradation that affects critical properties, including elastic stiffness and tensile strength [9]. Consequently, the adhesive's capacity to transfer stress between fibers is diminished, which markedly reduces the CFRP composite's overall strength. Tensile testing of CFRP samples by authors in [10, 11], at temperatures up to 250 °C revealed a significant decline in tensile strength and elastic modulus, with a reduction of 68% and 29%, respectively, at 100 °C [9]. Similarly, authors in [11] observed a reduction in tensile and stiffness strengths by 23% and 56%, respectively, at 200 °C. In related experiments on steel/CFRP double strap joints, authors in [11] evaluated the bond fatigue strength of CFRP-enhanced samples at varying temperatures. The adhesive demonstrated a glass transition temperature (T_g) of 42 °C, exhibiting an initial decrease of approximately 18% in bonding stiffness at T_g, followed by a precipitous decline to only 10% at 60 °C. The bond strength exhibited a gradual decline with increasing temperature until reaching the glass transition temperature (T_g), after which it demonstrated a rapid decrease, reaching only 5% of the ambient bonding strength at 60 °C. From this analysis, it is evident that the effectiveness of CFRP can be significantly reduced at relatively low temperatures (below 100 °C), which may compromise the structural stability of CFRP-enhanced steel coatings.

Despite considerable concern regarding the fire resistance of CFRP-strengthened steel coatings, no study has yet examined the extent of degradation that CFRP reinforced steel coatings undergo in fire conditions or explored effective methods to enhance steel performance in such scenarios. The existing literature on the behavior of CFRP-reinforced beams with fire-retardant coatings is limited [4, 12–15]. Authors in [15], evaluated the effects of temperature and fire exposure duration on the axial compression capacity of CFRP-enhanced RC cylinder columns. At elevated temperatures, CFRP demonstrated remarkable resilience, exhibiting an increase in the strength of the steel coating of up to 2.46 times when CFRP was applied. Following a three-hour exposure at 100 °C and 200 °C, a 5.1% and 27.1% reduction in axial load capacity was observed, respectively. The CFRP-strengthened coating retained twice the load capacity of the unstrengthened coating when exposed to 200 °C. Furthermore, authors in [16] demonstrated that a CFRP-strengthened coating maintained a 31.5% higher load capacity than an unstrengthened coating at 400 °C, indicating a substantial strengthening effect even at high temperatures. Authors in [17] conducted two full-scale experiments to investigate the fire resistance of FRP-enhanced RC circular coatings with and without insulation. An epoxy-coated mortar-based fire-retardant system with an average thickness of 53 mm was applied to insulate one of the circular coatings. The columns and coatings were tested in accordance with the ASTM E119 fire standard, with the same coating ratio (0.56) applied to both. The unprotected coating was able to withstand the load for 210 minutes before failing. It was observed that when exposed to fire, the FRP layers ignited rapidly, resulting in a significant increase in temperature within the FRP coating. This finding underscores the flammability of FRP and highlights the necessity for a fire suppression system in FRP composites. In contrast, the insulated steel coating demonstrated remarkable resilience, withstanding fire exposure for over five hours. However, the insulation was only able to maintain the FRP surface below the adhesive's glass transition temperature (71 °C) for 34 minutes. Nevertheless, it was effective in maintaining lower temperatures in the steel coating and reinforced steel bars, thereby enhancing the FRL. Additionally, a single sheet of galvanized steel plaster lath was mechanically fastened to the outer surface of the steel beams to ensure the coating remained intact with the FRP surface during fire exposure. Both steel beams were subjected to a loading rate of 0.73 and tested under standard fire conditions, as outlined by authors in [18], and exhibited FRLs exceeding 300 minutes in both cases. In comparison, the FRL of the circular unstrengthened RC coatings was 245 minutes. The integrated coating system demonstrated efficacy in maintaining surface FRP temperatures on both steel beam coatings below 100 °C for an extended period (over 240 minutes). A non-intumescent hardening surface coating was applied to FRP-strengthened square steel bars, which were coated with a 38 mm layer of Tyfo VG. The FRL of the strengthened square was 256 minutes, compared to 262 minutes for the unstrengthened square steel coating. Following this interval, the temperature of the FRP surface exceeded 100 °C within 30 minutes, and the testing revealed visible cracks in the coating system, which may have contributed to the lower FRL. This outcome highlights the importance of securing the steel coating with the FRP surface in order to enhance fire resistance. Nevertheless, the FRP-reinforced square steel coating demonstrated comparable fire resistance to the unstrengthened steel, while exhibiting an enhanced load-bearing capacity.

Nevertheless, the insulation maintained lower temperatures in the reinforced steel, thus enabling the prolongation of protection. A comparison of these results with those reported by authors in [5] for unstrengthened steel and by authors in [17] for CFRP-enhanced uninsulated steel, reveals an intriguing insight. The unstrengthened steel exhibited a higher CFRL under a larger load ratio than the FRP-reinforced unprotected steel, as evidenced by the test data. These findings give rise to concerns regarding the fire performance of CFRP-strengthened steel, as its FRL was found to be significantly lower than that of unstrengthened steel. This underscores the significance of fire-resistant insulation in safeguarding CFRP-strengthened steel. In consequence, the CFRP temperature surface surpassed the glass temperature transition within a period of 30 to 60 minutes during the course of the fire tests, thereby indicating that steel coatings will lose strength at a rapid rate. It is also noteworthy that previous studies on FRP-unstrengthened/strengthened steel, with and without insulation, have demonstrated a FRL of approximately 240 minutes [5, 14, 15]. While the test settings, geometry, and materials employed in these studies influence the behavior of the coated steel, the low thermal conductivity and slow rate of mechanical degradation in steel are major factors contributing to the elevated CFRLs observed. However, the outcomes for steel coatings will be entirely different due to the greater strength and conductivity loss at extremely high temperatures, with the exception of findings presented by authors in [5]. The majority of existing studies have focused on examining the performance of RC columns and slabs that have been strengthened with CFRP and coated with fire-retardant materials [12-16]. The objective of this study is to experimentally investigate the flexural performance of a steel beam that has been strengthened with CFRP sheets and applied with a fire-retardant coating. In order to present the methodology, it is essential to adhere to a structured approach that conveys the study's rigor and reproducibility.

II. MATERIALS AND METHODS

A. CFRP Sheets

Table I presents the results of tensile testing on CFRP samples [17], while Table II presents the ultrasound readings. The CFRP specimens exhibited a linear relationship between the applied tensile displacement and load until reaching their ultimate tensile strength, a phenomenon that was observed in the GFRP specimens as well. A slight non-linear phase was observed in the vicinity of the specimens' maximum tensile strength, which was followed by a sharp decline. Furthermore, at temperatures exceeding 400 °C, the previously linear force-displacement curves exhibited slight nonlinearity. The retention of tensile strength and ultimate tensile strength versus temperature curves for CFRP specimens were evaluated across three temperature ranges: 60 °C–150 °C, 150 °C–400 °C, and 400 °C–600 °C. In the initial temperature range, the adhesive material reached its glass transition temperature (T_g), resulting in a notable decline in its mechanical properties and capacity to transfer shear stresses between fibers. Due to the heat resistance of the carbon fibers, the decline in tensile strength of CFRP sheets was less rapid in the second temperature range than in the first. However, the degradation of the adhesive accelerated the rate of strength loss in the third temperature range. The tensile strength of CFRP sheets coated with thermochromic paint was observed to exceed that of uncoated CFRP sheets, with tensile performance gains varying from 19% at lower temperatures (approximately 350 °C) to 38% at higher temperatures (approximately 500 °C). Therefore, the application of an intumescent paint coating on CFRP sheets has been an effective technique for fire protection. Similar patterns of strength degradation have been observed in other studies [18, 19]. Authors in [18] observed two significant instances of strength reduction in pultruded CFRP sheets between 150 °C and 450 °C, whereas in this temperature range, strength reduction was relatively minor. Additionally, the samples were observed to lose approximately 50% and 93% of their initial strength at temperatures of 300 °C and 700 °C, respectively. Four discrete CFRP failure modes are presented in [17]. The initial failure mode occurred at lower temperatures (25 °C–100 °C), manifesting as brittle failure. In the second failure mode (100 °C–200 °C), a change in color of the epoxy coating to brown was observed, accompanied by an acceleration of the degradation observed in the first failure type. At temperatures between 200 °C and 300 °C, the epoxy coating was unable to maintain the integrity of the CFRP fibers, resulting in the loss of its ability to transmit shear stresses between them. This led to the samples fracturing into smaller pieces. In the fourth and final failure mode (300 °C–600 °C), the resin adhesive began to burn, producing a black char and smoke. Two distinct failure modes were observed in CFRP sheets coated with thermochromic paint, as shown in [17]. In the initial failure mode, the thermochromic paint did not undergo sufficient activation, resulting in minimal swelling. As a result, the coated CFRP sheets fractured into smaller pieces at the site of failure. In the second failure mode (350 °C–600 °C), the thermochromic paint underwent a significant expansion, resulting in the formation of a substantial thermal barrier, as shown in [17].

TABLE I. CARBON FABRICS TENSILE EXPERIMENT IMPREGNATED WITH EPOXY RESIN

Temperature (°C)	**CFRP without intumescent paint**			**F-T**	**CFRP with intumescent paint**			**F-T**
	σ_u (MPa)	COV (%)	S-R (%)		σ_u (MPa)	COV (%)	S-R (%)	
25	2,665.2	3.5	100	1	-	-	-	-
60	1,867.8	3.7	70.1	1	-	-	-	-
100	1,662.0	5.3	60.8	1	-	-	-	-
150	1,422.9	3.1	53.3	1-2	-	-	-	-
200	1,441.9	2.5	54	2	-	-	-	-
250	1,430.4	3.4	53.6	2-3	-	-	-	-
300	1,339.1	4.3	50.2	3	1,648.7	2.2	61.8	1
350	1,340.7	2.1	50.3	3-4	1,591.4	3.3	59.7	1-2
400	1,307.4	6.3	49	4	1,574.2	2.5	59.0	2
450	1,199.1	5.5	44.9	4	1,513.7	3.9	56.7	2
500	1,092.9	4.2	41	4	1,512.8	4.1	56.7	2
600	874.4	4.9	32.8	4	1,065.0	6.9	39.9	2

TABLE II. RESULTS OF ULTRASOUND READING

No.	**Member Type**	**Time (μs)**	**Indirect Velocity (Km/s)**	**Avg. Indirect Velocity (Km/s)**	**Direct Velocity (Km/s)**	F_{cu} **(Mpa)**	**Avg.** F_{cu} **(MPa)**
1	BLR-1	82.9	2.413	2.699	3.016	12.688	15.974
2	BLR-2	71.7	2.784		3.487	16.912	
3	BLR-3	69.1	2.894		3.618	18.321	
	Min. of V(D)				1.667		
	Max. of V(D)				4.664		
	Avg. of V(D)				3.250		
	Compressive strength (MPa)				20.165		
	Standard Division (SD) of V(D)				0.533		
	Relative standard deviation				16.407		

As a consequence of the epoxy bond weakening that occurs around the glass transition temperature (T_g), there was a notable decline in the tensile strength of CFRP sheets when the temperature was in the range of 25 °C to 150 °C. As the fibers bear the majority of the applied load in this temperature range and are resistant to these temperatures, the strength reduction in CFRP sheets was found to be minimal between 150 °C and 400 °C. In this temperature range, the tensile strength of CFRP sheets was approximately 50% of their benchmark strength at 25 °C. At temperatures exceeding 400 °C, the rate of tensile strength reduction increased due to the thermal degradation and decomposition of epoxy adhesives, CFRP and GFRP fibers.

However, the strength reduction in GFRP sheets was greater than that in CFRP sheets at these temperatures, as glass fibers have lower melting points than carbon fibers. CFRP and GFRP sheets coated with thermochromic paint exhibited increased tensile strength compared to similar untreated specimens at the same temperatures. The increase in tensile strength for GFRP sheets ranged from 26% at 350 °C to 193% at 600 °C, while for CFRP sheets, ranged from 19% at 350 °C to 38% at 500 °C. Both CFRP and GFRP sheets exhibited failure along a line perpendicular to the loading direction at low temperatures (20 °C–100 °C), with no notable changes in color or texture. At higher temperatures (above 300 °C), the adhesive in GFRP and CFRP samples ignited, resulting in the production of toxic fumes and black char. This was followed by oxidation and fiber rupture. Scanning Electron Microscopy (SEM) examination revealed that the adhesive surfaces of samples tested at 200 °C–350 °C became rough and fractured. Additionally, delamination of the resin and fibers was observed in the failure regions at these temperatures. The SEM analysis of intumescent paint-coated samples indicated that the numerous large and small pores in the activated thermochromic paint formed a thermal barrier. The barrier prevented the transfer of heat and oxygen to the FRP sheets, enabling them to demonstrate superior tensile performance at elevated temperatures (i.e., above 300 °C). Diagnostic plots of Bayesian models developed to predict the tensile strength of both coated and uncoated CFRP and GFRP sheets at various temperatures demonstrated the models' appropriateness, as shown in [17].

B. Fire Coating

A series of fire experiments were conducted on CFRP-strengthened steel beams using the ISO-834 standard fire. The effects of adhesives, load levels, fire insulation, and reinforcement technology were all considered. Additionally, this study provides insight into the development of fire-retardant properties in Near-Surface Mounted (NSM)-CFRP systems. The testing analysis and data lead to the following conclusions:

- The fire resistance of NSM-CFRP-enhanced RC beams can be markedly improved with the application of fire coatings. The NSM-CFRP-enhanced beam, which was adequately protected, demonstrated resilience to standard fire exposure for a duration exceeding three hours at a high load level. In contrast, beams that lacked sufficient shielding exhibited performance characteristics comparable to those of unstrengthened beams.
- The fire protection coating demonstrated superior performance to both bottom-side coverage and local patch protection for thermal insulation. During fire exposure, full coating coverage exhibited enhanced performance compared to organic polymer coatings.
- NSM-CFRP-strengthened beams demonstrate superior performance compared to EB-CFRP-strengthened beams under similar conditions. The strengthening contribution of NSM-CFRP systems remains effective even when CFRP experiences slippage or bonding temperatures exceed T_g.
- It is possible to estimate the fire resistance of NSM-CFRP strengthening systems using the glass transition temperature (T_g), although this may be an overly conservative approach. Further systematic research is required on the thermal and structural responses of NSM-CFRP strengthening systems in order to establish a rational design criterion and failure philosophy.

Samples TB1, TB2, and TA6 exhibited lower temperatures than samples TA5, TA7, and TA1 (local patch protection), yet demonstrated a faster loss of fire retardant than the unprotected specimens, T0 and TA0, as shown in [20]. This is predominantly attributable to the elevated load level observed in the second fire test. An increase in load level results in a corresponding rise in reinforcing stress. It has been demonstrated that CFRP subjected to elevated stress levels is highly susceptible to delamination when the glass transition temperature (T_g) is exceeded during the heating process [21].

C. Fire Test

In a furnace, intumescent-coated steel substrates and uncoated steel (10 mm thickness) were subjected to fire testing for durations of 30, 45, 90, and 120 minutes. The sample surfaces were exposed to a 10 mm layer of LPG butane gas for the specified time intervals. The mean flame temperature was approximately 950 °C. Consequently, during the fire test, the temperature at the rear of the steel gradually increased, as the coating did not have sufficient time to fully insulate it. The thermochromic coating component on the surface formed a carbonaceous layer. After the 120-minute fire test, the maximum temperature remained below 70 °C, as presented in [22]. During the course of the test, the charring coating demonstrated its efficacy in providing effective protection for the laboratory setup. The behavior of the coated steel specimen during the furnace fire test, can be seen in [22]. Upon reaching a critical temperature, the coated surface began to melt and form a thick liquid layer when exposed to flame heat. As a result of the chemical changes that occurred, inert gases were emitted simultaneously. The gases became trapped within the thick liquid, thereby assisting in the expansion of the char. This resulted in the coating expanding to a thickness that was many times greater than its original measurement (2 mm to 10 mm), forming a protective carbonaceous char layer [22], that acted as a barrier, isolating the surface from the fire [23-31]. he resulting char was observed to be four times thicker than the initially applied intumescent coating. Prior to complete combustion, the substantial char exhibited a markedly diminished heat capacity in comparison to the initial intumescent coating. The two-hour fire test yielded the formation of multiple carbon-containing layers, thereby substantiating the coating's capacity to serve as a protective barrier for the underlying surface. Furthermore, the reduced hardness of the intumescent coating may suggest the presence of diverse additives within the char. The cross-section of the thermochromic-coated steel following the 30-minute fire test is provided in [22]. A minor fissure in the sample indicated a reduction in the adhesive bonding between the steel substrate and the thermochromic coating in comparison to the pre-test sample. The bond between the priming and thermochromic coatings remained intact and stable. The adhesive demonstrated sufficient strength to withstand the applied heat without any issues. The presence of a gap along the steel surface substrate and priming coating is observed in [22], which is likely attributable to temperature variations and differing adhesion capabilities [24].

Consequently, as the temperature increases, the intumescent coating undergoes a greater expansion than the steel. The rough surface of the steel prevented the thermochromic coating from delaminating. The CF within the intumescent coating at the instant of the fire test can be seen in [22], as their melting point exceeds that of the chemicals comprising the coatings. The micrographs of thermochromic-coated steel following a 45-minute fire test are presented in [22], as well as the formation of the large pores in the thermochromic coating, which can be attributed to the escape of the blowing agent. The adhesive bonding between the priming coating and intumescent coating remained intact and uncompromised following the 45-minute fire test. This revealed that the interface between the priming and steel surface layers remained intact, demonstrating the coating's exceptional heat endurance at the top layers. Nevertheless, a notable gap is apparent at the juncture between the priming coating and the steel surface, as presented in [22]. It is possible that the space between the priming coating and the steel surface may serve as a trap for gases. The char is porous, thereby facilitating the generation and entrapment of gases resulting from a multitude of chemical reactions involving acid, blowing agents, and carbon sources, which ultimately lead to char expansion (25). Following a 45-minute fire testing period, the formation of a charred layer of thermochromic coating on the surface, is obvious. The fissures in the carbonized layer indicate that the temperature reached the melting point of the intumescent coating at this location. The condition of the thermochromic-coated steel following a 90-minute fire test is illustrated in [22]. At the conclusion of this period, the intumescent coating proved efficacious in preventing structural and property changes. The adhesive bonding materials between the priming coatings and steel substrates demonstrated stability after 90 minutes of fire testing, as seen in [22]. In [22] the space between the priming coating and the steel substrates, demonstrating the retention of some priming coating on the steel substrate is described. This retention was most likely due to the mechanical interlock system's lock-and-key mechanism on the steel surface, in conjunction with the application of chemical agents that enhanced the adhesive bonding to the steel substrate. Following a period of 90 minutes during which the material was subjected to fire testing, the heat began to damage the CF, resulting in the formation of char on them. The incorporation of carbon fibers served to reinforce the thermochromic coating, thereby facilitating its structural integrity at elevated temperatures. The electron micrographs presented in [22] illustrate the outcomes of the longest fire experiment, which was conducted for a duration of 120 minutes. The structure remained intact, and the steel surface did not shatter. The diagram presents the efficacy of the intumescent coating in protecting the steel at 950 °C for a period of two hours. The stability between the priming coating and intumescent coating is evidenced by the absence of cracks and delamination. The presence of minor fissures within the primer coating structure suggests a potential deterioration of the priming coating, which may be attributed to the heat approaching the coating's melting point. While the lower surface of the steel did not exhibit any cracking, a gap did form along the surface. The microstructure of the steel surface remained unaltered. Following a two-hour fire test, the priming coating exhibited signs of degradation, manifesting as the formation of pores on the surface.

The CFs underwent complete destruction during the two-hour fire test, and exhibited deterioration when the temperature reached their glass transition temperature (T_g). The intumescent coatings served as a fire-retardant layer until the formation of the entire charring layer and the subsequent destruction of the carbon fibers. The utilization of CFs with a melting point that exceeds the temperature at which intumescent disintegration occurs enables the preservation of the carbonization structure. The efficacy of the coating is contingent upon the thickness of the coating applied to the steel surface substrate. To safeguard the fibers from external assaults, diminish residual stress, minimize strength reduction, optimize toughness, and facilitate non-brittle modes of failure, it is essential to select the thermochromic coating layer with meticulous consideration [27]. The high modulus, zero coefficient of thermal expansion, and great strength of CFs render them ideal for structural applications. A multitude of composite materials comprising CFs can be employed at elevated temperatures with minimal degradation, offering exceptional protection against corrosive environments, with the exception of oxygen (O_2) at high temperatures [28].

D. Fire Performance of Steel

This study examines the fire retardant and post-fire performance of common Steel Reinforced Concrete (SRC) structures, including SRC columns, couplings between SRC columns and SRC beams, and SRC composite openings with Reinforced Concrete (RC) and SRC beams. The findings suggest that SRC constructions exhibit ductile behavior during and after a fire, attributable to the "composite beams" formed between the encased steel and other elements, which leads to enhanced fire performance. The following future research needs regarding the fire performance of SRC buildings should be emphasized:

- The load and temperature history should be the focus of post-fire performance studies of SRC structures.
- In terms of material performance during the cooling and post-fire phases, the importance of constituent materials, such as steel at high temperatures, has been emphasized. However, full analysis based post-fire repair and assessment remains limited due to the lack of data on material properties during these periods.
- The fire-retardant characteristics of substructures diverge from those of individual component elements due to the interactions that occur during a fire. Consequently, single-member analyses must be extended to substructures in order to reflect the functioning of a building in a real fire incident.
- In a typical fire scenario, the resistance of steel beams and slabs reinforced with CF fabric is observed to diminish roughly in proportion to the duration of the fire. In the initial phase, the mixture is subjected to thermal softening. In the second phase, the adhesion relaxes until the elastic

modulus of the tensile longitudinal reinforcement begins to decline under fire, although this reduction in resistance is not yet visible. In the third phase, the elastic modulus of the reinforcement continues to deteriorate, and resistance decreases linearly with fire duration.

- The fire-resistant capabilities of steel beams and slabs reinforced with CF fabric can be enhanced by applying fire-resistant coatings to the CFRP sheets at the required thickness. It has been demonstrated that the greater the thickness of the necessary fire-retardant coating, the larger the improvement in resistance over time. Similarly, the deeper the fire-retardant layer, the greater the increase in resistance and the higher the fire resistance achieved.

E. Intumescent Coating Preparation

In this study, a priming coating was applied to the steel surface via spraying, after which a 20 cm² × 20 cm² CF mat was positioned on top. The steel base, priming coating, and CF mat exhibited thicknesses of 1.5 mm, 1 mm, and 0.20 mm to 0.22 mm, respectively. The primary coating was allowed to fully dry at room temperature for a period of six to seven hours. The efficacy of the priming coating in filling the irregular interface on the steel surface is contingent upon the interfacial tension between the coating and the substrate. The presence of surface imperfections and debris on the steel surface increases the surface tension, which in turn results in poor priming coating adhesion. To address this issue, flaws on the steel surface must be removed by thoroughly cleaning the surface, thereby allowing intimate contact to form as the bond spreads uniformly across the surface [22]. The appropriate amounts of epoxy intumescent coating and curing agent were mixed with mass ratios of resin to hardener at 2.45:1 and 4:1 for intumescent and priming coatings, respectively. To enhance the viscosity of the mixture for application to the steel substrate, a modest quantity of solvent was incorporated. The solvent evaporated without affecting the coating properties. The coatings for the steel beams were prepared by mixing the hardener and epoxy at 600 rpm in a mixer to create a homogeneous material, which was then applied to the steel surface (20 cm² × 20 cm²). The objective of this research was to investigate the depth of a 10 mm intumescent coating on steel surfaces. The dry coating layer thickness was determined using a digital vernier caliper, as presented in [22].

F. Fire Retandant Steel Coating

Given its applicability to a multitude of scientific and technical domains, adhesion phenomena have recently emerged as a significant area of investigation. Adhesion is defined as the phenomenon that occurs when a solid comes into contact with coatings, paints, composites, or nanocomposites. The characteristics of the interface between a coating and substrate have a substantial impact on the functionality of these materials in real-world applications [32-35]. The phenomenon of adhesion is of particular importance in the context of steel constructions, particularly in the case of steel components that have been treated with intumescent coatings [36, 37]. Steel is a material with a wide range of applications, including the development of megastructures and bridges, the construction of offshore platforms, and the production of marine furniture. Given its extensive use in construction, there is a need for the use of fire-resistant materials in order to minimize the costs and risks associated with fires, as well as the risks to life and assets [37, 38]. It is possible to avert structural collapse during a fire by ensuring that the load-bearing steel structure does not reach 550 °C [39, 40]. At temperatures exceeding 650 °C, rapid recrystallization of ferrite occurs due to the recrystallization temperature of pure iron, which is approximately 500 °C [41]. It is of great importance to ensure the safety of the public in the event of a fire, which has resulted in the implementation of rigorous building standards in various countries, including United Kingdom, Europe, and the United States [42-44]. Intumescent coatings are designed to maintain structural integrity for up to three hours in temperatures reaching 1100 °C under severe fire conditions [45, 46]. These coatings are widely recognized for their ability to reduce combustibility and prevent the penetration of heat and flame, thereby preserving the mechanical properties of the coated structure [47].

Nevertheless, the interactions occurring at the interface between the steel surface and the thermochromic coating remain poorly understood and are in need of further analysis [48–52]. The adhesive strength of a building's coating is of crucial importance in the analysis of performance, as it also determines the coating properties. The bonding strength is contingent upon the substrate wetting capacity, chemical composition, surface tension, and the roughness of steel. The effective adhesion of the coating to the steel surface substrate is contingent upon the establishment of intimate contact between the two surfaces, and the two materials must exhibit compatibility [53]. The interaction between the steel surface and the coating material, along with the intrinsic properties of the coating, represent critical factors influencing the durability of the coating. In an intumescent system, the reactions between the components and additives are of particular significance, particularly at the interface between the steel substrate and the intumescent coating. Furthermore, the adhesion strength is contingent upon the coating thickness. The optimal adhesion strength is achieved when the substrate exhibits the requisite smoothness and coating thickness [39, 54]. Priming coatings are frequently employed to enhance adhesion and seal voids beneath the steel surface. Additionally, organic coatings may comprise inhibitive compounds, such as zinc phosphate, to forestall corrosion of underlying components [55-58]. During high-temperature exposure, the majority of reactions occurring in intumescent coatings do so in a condensed phase. The combustion of intumescent coatings is a complex process, with a multitude of reactions occurring as the burning progresses. Nevertheless, there is a paucity of research examining the adhesive bonding between intumescent coatings and steel surfaces, particularly with regard to post-burn adhesion and the durability of priming coatings in harsh environments. Consequently, one of the most common causes of deterioration in structural steel is the dissociation of steel and thermochromic coatings, which is often due to inadequate adhesive strength. This highlights the necessity for further investigation into the critical area of adhesion in the contact zone.

G. Steel Substrate Preparation

The chemical composition of the steel substrate specimens includes toluene, xylene, and methyl ethyl ketone. The chemical substances were removed from the surface of the steel samples using an oil-based lacquer cleaning agent. Following the cleaning process, the surface was then sandblasted using an Airman 370 cfm air compressor. Garnet sands with grain sizes of 30–60 mesh and 20–40 mesh was applied to each steel surface for approximately ten minutes using a 1.8 mm nozzle. In accordance with NACE SSPC-SP10 standards, the steel surface substrate exhibited a micrometer-to-micrometer profile range. A Mohr profilometer was employed to assess surface roughness, with three measurements taken at 12.5-millimeter intervals. The device calculated the average surface quality by measuring all peaks and valleys relative to the mean line and then averaging them across the entire cutoff length. The arithmetic mean of the absolute values of the deviations from the mean line is designated as Rz, representing the mean depth of smoothness. The Ra value indicates the overall surface smoothness.

III. CONCLUSIONS

The use of current thick fire-retardant coatings for structural steel may also be applied to structures comprising Carbon Fiber Reinforced Polymers (CFRPs) and strengthened reinforced steel. To provide an example, a CFRP-strengthened reinforced steel beam with a 50 mm thick fire-retardant coating on three sides exhibits a fire resistance rating of over 2.5 hours. The fire-retardant coating used for CFRP-strengthened structures is thinner due to its application via plastering in successive layers. This method facilitates the removal of individual layers in the event of a fire. It is advised that steel wire mesh be placed outside the fire-retardant coating, as this can assist in preventing the insulating layer from breaking and collapsing under fire conditions. The test results indicate that the thick fire-retardant coating effectively insulates CFRP-strengthened reinforced steel beams. This methodology may also be applied to steel structures reinforced with steel plates, CFRP-reinforced steel slabs, and coatings. However, it should be noted that varying coating thicknesses are required depending on the specific fire prevention needs of the structure in question. Further research is recommended to enhance construction measures for fireproof coatings, optimize thickness, and investigate the impact of different materials on fire resistance. The shear force was observed to be inversely proportional to the thickness of the thermochromic coating on a steel surface. A coating thickness of 1 mm yielded a maximum lap shear strength of 1.95 MPa. Despite the observed increase in toughness, the mechanical properties indicated no new phase development or re-crystallization, suggesting that the strength of the steel substrate remained intact. The convex surface of the steel enhanced the surface area, thereby enabling the surface coating to assume a crucial role in the enhancement of adhesive bonding. In general, further experimental investigations are required to assess the performance of CFRP with/without GFRP in fire accidents when used to reinforce steel structural members.

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