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Fire Performance of Steel-Concrete Composite Wall Panels Under Combined Axial and Lateral Loading

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ABSTRACT

The utilization of steel-concrete composite wall panels has become increasingly prevalent in the construction of modern high-rise and commercially complex structures due to their exceptional load-bearing capacity, rapid construction capabilities, and superior structural efficiency. However, the performance of these structural elements under extreme thermal conditions, particularly when subjected to complex stress states involving both axial and lateral loads, remains a critical area of investigation. This paper presents a comprehensive examination of the fire performance of steel-concrete composite wall panels subjected to combined axial and lateral loading. Through a detailed synthesis of experimental methodologies and advanced numerical simulations, this study explores the thermo-mechanical behavior, thermal gradient propagation, and ultimate failure mechanisms of composite panels exposed to standard fire curves. The research highlights the deleterious effects of lateral loading on the out-of-plane stability of the panels, which significantly accelerates the onset of structural collapse compared to purely axial loading scenarios. Furthermore, the investigation delineates the distinct roles of the steel faceplates and the concrete core in maintaining structural integrity at elevated temperatures. The findings provide critical insights into the degradation of material properties, the evolution of geometric non-linearities, and the interplay between thermal expansion and mechanical loads. The derived conclusions offer vital guidance for structural fire engineers, paving the way for more resilient design guidelines and safety assessments for composite structural systems in fire events.

KEYWORDS

Composite Wall Panels, Structural Fire Engineering, Combined Loading, Thermo-Mechanical Response.

1. Introduction

1.1 Background and Structural Context

The evolution of modern architectural design has consistently pushed the boundaries of structural engineering, leading to the widespread adoption of innovative construction materials and methodologies. Among these advancements, steel-concrete composite structures have emerged as a dominant solution for medium to high-rise buildings, underground facilities, and critical infrastructure projects. Steel-concrete composite wall panels, which typically consist of a plain or reinforced concrete core encased by steel faceplates, capitalize on the synergistic interaction between the two constituent materials. The steel plates serve a dual purpose acting as permanent formwork during the construction phase and providing substantial tensile reinforcement and confinement to the concrete core during the structure service life. Conversely, the concrete core delays the local buckling of the steel plates, enhances the overall stiffness of the panel, and provides critical thermal mass. Despite these inherent advantages, the behavior of composite wall panels under extreme hazards, particularly fire, introduces profound complexities that demand rigorous academic scrutiny [1]. The rapid degradation of mechanical properties at elevated temperatures presents a severe threat to structural stability, making fire safety a paramount concern in the design of composite systems [2]. The application of composite wall panels is often driven by the need for maximized floor space and accelerated construction schedules, which inherently leads to slenderer structural profiles. This slenderness, while architecturally desirable, exacerbates the susceptibility of the panels to instability phenomena when exposed to the high temperatures characteristic of compartment fires [3]. The reduction in the elastic modulus and yield strength of the steel faceplates, coupled with the degradation of the concrete compressive strength and potential spalling, dramatically diminishes the load-carrying capacity of the composite section [4]. Therefore, understanding the fundamental thermo-mechanical mechanisms governing the response of these panels is essential for ensuring life safety and minimizing property loss.

1.2 The Complexity of Combined Loading Scenarios

In practical structural applications, wall panels are rarely subjected to isolated axial loads. The operational environment of a building dictates that structural elements must continuously resist a complex combination of forces. Axial loads arise primarily from gravity, encompassing the dead weight of the structure and live loads from occupancy. Lateral loads, on the other hand, are generated by a variety of sources, including wind pressures, seismic activity, earth pressures in basement structures, and inherent geometric imperfections or eccentricities in load application [5]. The superposition of lateral loads onto axially loaded members induces significant bending moments, which generate a non-uniform stress distribution across the cross-section of the panel. When a fire event occurs, this complex stress state is further complicated by the introduction of severe thermal gradients. As one face of the composite panel is exposed to the fire, the material temperatures rise asymmetrically, causing differential thermal expansion [6]. The fire-exposed steel faceplate attempts to expand rapidly but is restrained by the cooler concrete core and the unexposed steel plate, leading to the generation of significant internal thermal stresses and structural bowing towards the fire source. This thermally induced bowing interacts synergistically with the mechanical moments generated by the lateral loads, significantly amplifying the P-delta effects and precipitating premature structural instability [7]. Previous design codes and simplified assessment methods have often treated fire resistance under axial loading as the primary performance metric, implicitly assuming that lateral load effects are either negligible or adequately covered by inherent safety factors. However, recent forensic engineering analyses of structural failures during severe fires have demonstrated that the presence of lateral forces can drastically alter the failure mode and reduce the fire resistance rating of composite members [8]. Consequently, the scientific community has recognized the urgent need to transition from simplified, single-degree-of-freedom testing protocols to more sophisticated methodologies that accurately replicate the multi-axial stress states experienced by structural elements in real-world fire scenarios [9].

1.3 Research Objectives and Scope

The primary objective of this comprehensive study is to systematically elucidate the fire performance of steel-concrete composite wall panels subjected to the simultaneous application of constant axial compression and varying lateral loads. By isolating the parameters that govern thermo-mechanical interaction, this research aims to bridge the critical knowledge gap surrounding the behavior of composite structures under complex loading states. The investigation seeks to quantify the influence of lateral load magnitude on the critical time to failure, the rate of out-of-plane deflection, and the load-transfer mechanisms between the steel faceplates and the concrete core [10]. Furthermore, this paper aims to analyze the thermal gradient evolution through the thickness of the panel and assess the efficacy of the concrete core in mitigating temperature rises on the unexposed surface. Through a combination of rigorous experimental observations and highly calibrated numerical modeling, the study intends to provide a detailed mapping of the stress and strain distribution across the composite section at various stages of fire exposure. Ultimately, the insights generated from this research are intended to inform the development of more robust, performance-based fire engineering design guidelines, ensuring that structural engineers possess the necessary analytical tools to design composite wall panels that can safely withstand the combined effects of multi-axial loading and extreme thermal exposure [11].

2. Literature Review

2.1 Historical Development of Composite Construction

The integration of steel and concrete into unified structural systems has a rich history that parallels the industrialization of the construction sector. Early applications primarily focused on composite beams and columns, where the distinct advantages of steel in tension and concrete in compression were clearly recognized [12]. As building heights increased and lateral force-resisting systems became more demanding, engineers began to adapt these composite principles to shear walls and load-bearing partitions. The development of double-skin composite walls, featuring steel faceplates interconnected by shear studs or tie bars, represented a significant leap forward. This configuration eliminated the need for conventional reinforcement detailing and traditional formwork, thereby streamlining the construction process. Early experimental campaigns focused heavily on the ambient temperature performance of these panels, validating their high energy absorption capacity, superior ductility, and substantial ultimate load resistance under cyclic loading [13]. However, as the application of these panels expanded into highly regulated environments such as nuclear power plants and high-rise commercial towers, the requirement for comprehensive fire safety assessments became unavoidable [14]. Initial fire tests were largely empirical, focusing on establishing standard fire resistance ratings based on insulation and integrity criteria rather than fully characterizing the fundamental structural mechanics governing high-temperature behavior. These early studies provided valuable baseline data but lacked the sophisticated instrumentation required to capture the intricate interaction between thermal expansion, material degradation, and mechanical loading [15].

2.2 Thermal and Mechanical Behavior under Isolated Loading

Over the past two decades, significant progress has been made in understanding the isolated behavior of composite panels under standard fire conditions. A substantial body of literature has focused on panels subjected exclusively to concentric axial loading. Researchers have extensively documented the phenomenon of load shedding, wherein the initial thermal expansion of the steel faceplates causes them to attract a larger proportion of the applied axial load [16]. As the temperature of the steel continues to rise, its yield strength and elastic modulus diminish rapidly, causing the steel to yield and locally buckle. Upon yielding, the load is progressively transferred back to the cooler, stiffer concrete core. This load transfer mechanism is highly dependent on the efficiency of the shear connection between the steel and concrete, and failure typically occurs when the concrete core, weakened by elevated temperatures and potentially compromised by moisture-induced spalling, can no longer sustain the applied compressive stresses [17]. Concurrently, studies investigating the out-of-plane bending behavior of composite panels without axial loads have highlighted the critical role of thermal bowing. When subjected to one-sided

fire exposure, the differential temperature profile induces a curvature in the panel. The magnitude of this bowing is influenced by the panel slenderness, the specific heat capacity of the concrete, and the degree of rotational restraint at the boundary conditions [18]. While these studies have provided essential insights into the isolated mechanisms of load shedding and thermal bowing, they fundamentally fail to capture the highly non-linear interaction that occurs when these two phenomena happen simultaneously.

2.3 Knowledge Gaps in Combined Loading Scenarios

The critical intersection of structural fire engineering and complex loading states represents a significant gap in the current literature. While a limited number of recent studies have begun to explore the effects of load eccentricity on the fire resistance of composite columns, the specific application of combined axial and distinct lateral loading on composite wall panels remains largely uncharted territory. The fundamental challenge lies in the second-order P-delta effects that dominate the structural response under these conditions [19]. When a panel is subjected to a lateral load, it undergoes an initial out-of-plane deflection. The presence of an axial load acting on this deflected shape generates an additional bending moment, which further increases the deflection [20]. Under ambient conditions, this behavior is well understood and routinely accounted for in structural design. However, during a fire, the rapid reduction in the flexural stiffness of the panel exacerbates these second-order effects exponentially. Furthermore, the thermally induced bowing may either counteract or, more dangerously, compound the mechanically induced deflections, depending on the direction of the lateral load relative to the fire exposure [21]. The current lack of comprehensive experimental data regarding these interactions significantly limits the validation of advanced numerical models and hinders the development of reliable analytical design equations. Most existing design codes rely on simplified interaction curves that were derived from ambient temperature data and heuristically adjusted for high temperatures, a methodology that is increasingly viewed as inadequate for modern, highly optimized composite structures [22].

2.4 Evolution of Numerical Modeling Techniques

To overcome the immense logistical and financial barriers associated with large-scale structural fire testing, the research community has heavily relied on finite element analysis. The progression of numerical modeling capabilities has been instrumental in advancing the field of structural fire engineering. Early models were often restricted to two-dimensional cross-sectional analyses, which could predict temperature distributions and section capacities but failed to capture global buckling phenomena and complex boundary interactions [23]. Modern three-dimensional finite element models utilize sequential thermo-mechanical coupling, wherein a transient heat transfer analysis is first conducted to determine the spatial and temporal distribution of temperatures throughout the element. The resulting thermal field is subsequently applied as a predefined field in a structural analysis, which calculates the corresponding thermal strains, material degradation, and mechanical deformations [24]. The accuracy of these models is heavily dependent on the appropriate selection of material constitutive laws at elevated temperatures. Extensive research has been dedicated to refining the thermal properties such as specific heat, thermal conductivity, and thermal expansion coefficients for various concrete mixes and structural steel grades [25]. Furthermore, accurately modeling the interface behavior between the steel faceplates and the concrete core remains a complex challenge. The interface must be capable of transferring shear stresses to simulate composite action while also allowing for separation and slip as the steel faceplates undergo local buckling. Despite these advancements, the validation of these sophisticated numerical models against reliable experimental data involving combined lateral and axial loading under fire conditions remains a pressing necessity to ensure their predictive reliability [26].

3. Methodology and Analysis

3.1 Experimental Program and Specimen Design

To rigorously investigate the complex phenomena outlined in the preceding sections, a comprehensive experimental program was conceptualized and executed. The foundation of this program involved the design and fabrication of large-scale steel-concrete composite wall panels representative of elements utilized in modern structural applications. The specimens were proportioned to represent a typical floor-

to-floor height, ensuring that realistic slenderness ratios and buckling modes could be accurately captured during testing. Each panel was constructed utilizing a double-skin configuration, comprising two parallel structural steel faceplates encasing a plain concrete core. To ensure robust composite action and prevent premature delamination of the faceplates, a dense array of headed shear studs was welded to the inner surfaces of the steel plates, projecting into the concrete cavity. The geometric parameters, including the overall panel thickness, steel plate thickness, and stud spacing, were meticulously selected based on standard industry practices and scaled appropriately for the testing facility [27].

The material properties were carefully controlled and characterized prior to the main testing phase. The concrete utilized was a normal-weight, high-strength mix designed to provide substantial load-bearing capacity and thermal mass. To mitigate the risk of explosive spalling, which is a common occurrence in high-strength concrete exposed to rapid heating, a specific dosage of monofilament polypropylene fibers was incorporated into the mix design. These fibers melt at relatively low temperatures, creating a network of micro-channels that facilitate the release of internal pore pressure generated by vaporizing moisture. The steel faceplates were fabricated from standard structural carbon steel, extensively tested at ambient temperatures to determine the baseline yield strength, ultimate tensile strength, and elastic modulus. Comprehensive material testing was also conducted at elevated temperatures using steady-state and transient testing methodologies to generate the necessary constitutive data for subsequent numerical modeling [28].

Table 1: Matrix of tested composite wall panel specimens and corresponding failure times.

Specimen ID	Axial Load Ratio	Lateral Load (kN)	Fire Exposure Type	Time to Failure (min)
CWP-A30-L00	0.30	0.0	Standard ISO 834	142
CWP-A30-L15	0.30	15.0	Standard ISO 834	108
CWP-A30-L30	0.30	30.0	Standard ISO 834	76
CWP-A50-L15	0.50	15.0	Standard ISO 834	64
CWP-A50-L30	0.50	30.0	Standard ISO 834	41

3.2 Testing Apparatus and Combined Loading Protocol

The execution of fire tests involving combined, multi-axial loading required the utilization of a highly specialized and custom-engineered structural fire testing furnace. The furnace was specifically designed to accommodate vertical structural elements while allowing for the simultaneous application of mechanical loads from multiple directions. The internal chamber of the furnace was lined with high-density ceramic fiber insulation to ensure maximum thermal efficiency and minimize heat loss. An array of gas-fired burners, controlled by an advanced automated system, was utilized to precisely replicate the time-temperature relationship defined by standard fire curves. The control system continuously monitored the atmospheric temperature within the furnace using a network of shielded plate thermometers and dynamically adjusted the fuel flow to maintain strict adherence to the target heating profile [29]. The loading protocol was designed to sequence the mechanical and thermal actions in a manner that accurately simulated a realistic fire scenario. Initially, the designated axial load was applied concentrically to the top boundary of the wall panel using a high-capacity hydraulic ram. This axial load was maintained at a constant, pre-determined level throughout the duration of the test, simulating the gravity loads that a column or wall must perpetually support. Following the stabilization of the axial load, the lateral load was introduced. The lateral load was applied at the mid-height of the panel via a specialized mechanical actuator positioned outside the furnace chamber. A high-temperature resistant

loading arm penetrated the furnace wall, transferring the lateral force directly to the specimen. This lateral load was also held constant. Once the complex mechanical stress state was fully established and stabilized, the burners were ignited, initiating the thermal exposure phase. The tests were continued until structural failure occurred, which was defined by a combination of criteria including the inability to maintain the applied axial load, excessive axial shortening, or runaway out-of-plane deflection [30].

3.3 Instrumentation and Data Acquisition Systems

The precise measurement of structural and thermal responses during the hostile environment of a fire test requires a robust and redundant instrumentation strategy. To capture the evolution of the thermal gradient through the thickness of the composite panel, an extensive array of high-temperature Type-K thermocouples was embedded within the specimen during the fabrication process. These thermocouples were strategically positioned at multiple elevations and depths, including the exposed steel surface, the interface between the exposed steel and the concrete, the geometric center of the concrete core, the interface between the concrete and the unexposed steel, and the exterior surface of the unexposed steel plate. This dense grid of temperature sensors provided the high-resolution thermal mapping required to understand the heat transfer mechanisms and to validate the transient heat transfer numerical models.

To monitor the mechanical deformations, a network of highly sensitive Linear Variable Differential Transformers was deployed. These sensors were utilized to measure the global axial displacement of the loading platen, providing a continuous record of the axial expansion and subsequent shortening of the panel. Furthermore, several sensors were arrayed horizontally along the unexposed face of the panel to accurately trace the profile of the out-of-plane deflection over time. This allowed for the precise quantification of the interacting effects of thermal bowing and lateral load-induced bending. Additionally, high-temperature strain gauges were affixed to critical regions of the unexposed steel faceplate to monitor the evolution of mechanical and thermal strains, providing valuable insights into the onset of yielding and load redistribution phenomena [31].

3.4 Numerical Modeling Framework

Complementing the experimental program, a sophisticated three-dimensional finite element model was developed utilizing a commercially available advanced simulation platform. The modeling framework employed a sequentially coupled thermo-mechanical analysis procedure. The initial phase involved a highly detailed transient heat transfer analysis. The furnace environment was modeled using a combination of convective heat transfer coefficients and surface radiation emissivity values calibrated against the experimental plate thermometer data. The thermal properties of the concrete and steel, including specific heat, thermal conductivity, and density, were defined as highly non-linear functions of temperature, strictly adhering to established international structural fire design codes. The latent heat of vaporization associated with the moisture content in the concrete was explicitly accounted for by defining a peak in the specific heat formulation within the expected evaporation temperature range.

Following the successful generation of the nodal temperature histories, the mechanical analysis phase was executed. The structural elements were discretized using fully integrated, solid continuum elements for the concrete core and conventional shell elements for the steel faceplates. The highly complex interaction between the steel and concrete was modeled using a surface-to-surface contact algorithm. The tangential behavior of the interface was governed by a penalty friction formulation, while the normal behavior utilized a hard contact mathematical model allowing for separation. To accurately capture the degradation of structural capacity, the mechanical properties of the materials, encompassing the yield strength, proportional limit, and elastic modulus for steel, as well as the compressive strength and tensile cracking behavior for concrete, were prescribed as temperature-dependent variables. The model rigorously accounted for geometric non-linearities to ensure that the critical P-delta effects, which govern the failure of slender panels under combined loading, were accurately simulated.

4. Results and Discussion

4.1 Evolution of Thermal Gradients

The data extracted from the embedded thermocouple arrays revealed a highly complex and non-linear

propagation of heat through the composite wall panels. Upon initiation of the fire exposure, the temperature of the fire-exposed steel faceplate escalated rapidly, closely mirroring the atmospheric temperature of the furnace due to the high thermal conductivity of steel and the minimal thermal resistance at the boundary. However, the transmission of heat into the concrete core was significantly delayed. The substantial thermal mass and low thermal conductivity of the concrete resulted in the formation of extreme temperature gradients across the thickness of the panel. During the initial stages of the test, a distinct plateau in the temperature rise was observed at the inner regions of the concrete core, typically occurring around the boiling point of water. This plateau clearly signified the endothermic process of moisture vaporization, which absorbed a considerable amount of thermal energy and temporarily halted the temperature increase. Once the local moisture was fully driven off, the temperature rise resumed at a steady rate. The unexposed steel faceplate exhibited a highly delayed and muted temperature response, remaining at relatively safe operational temperatures for a significant portion of the test duration. This thermal behavior underscores the excellent insulation characteristics provided by the concrete core, which is vital for preventing fire spread to adjacent compartments and maintaining the integrity of the unexposed structural elements.

4.2 Structural Deformation and Kinematic Response

The structural response of the composite panels was characterized by a complex interplay of thermal expansion, material softening, and mechanical stress. In the initial phase of thermal exposure, all specimens exhibited a distinct period of axial elongation. This phenomenon was driven by the rapid thermal expansion of the heavily heated exposed steel faceplate, which initially outpaced the degradation of its mechanical stiffness. However, as the temperatures continued to climb, the elastic modulus and yield strength of the exposed steel deteriorated severely. Consequently, the steel could no longer sustain the imposed compressive stresses and began to yield, initiating the transfer of the applied axial load to the cooler, more rigid concrete core and the unexposed steel plate. This load transfer marked the cessation of axial elongation and the commencement of axial shortening. Simultaneously, the specimens experienced significant out-of-plane deflections. The asymmetric heating induced a severe thermal gradient, causing the exposed face to expand significantly more than the unexposed face, leading to thermal bowing towards the heat source. The presence of the lateral load profoundly influenced this behavior. In specimens subjected to combined loading, the mechanically induced bending moments synergized with the thermally induced bowing. As the overall stiffness of the cross-section degraded due to the escalating temperatures, the lateral displacements increased exponentially. This rapid increase in lateral deflection dramatically magnified the secondary P-delta moments generated by the constant axial load, creating a destructive feedback loop that rapidly accelerated the structural degradation. The data clearly indicated that increasing the magnitude of the lateral load drastically reduced the time required to reach critical deflection limits.

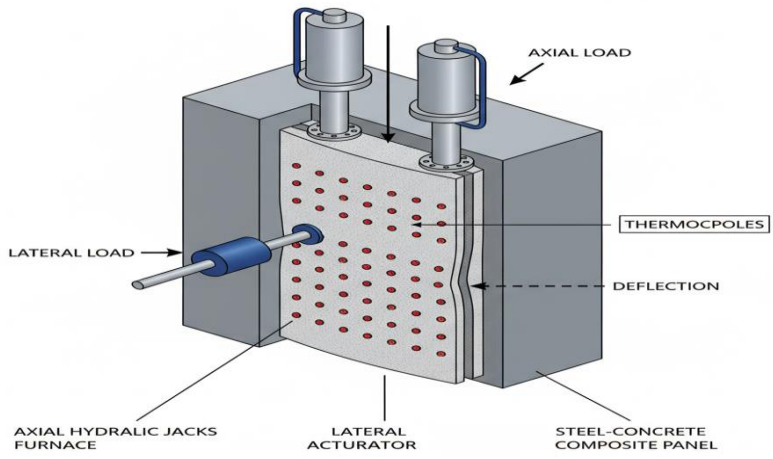


Figure 1: Failure Mechanism and Deflection

4.3 Mechanisms of Structural Failure

The ultimate failure of the composite wall panels was intrinsically linked to the severity of the applied combined loading and the degree of material degradation. For panels subjected to purely axial loading, failure was typically characterized by a global buckling mode, heavily influenced by the localized yielding and outward buckling of the fire-exposed steel faceplate. The concrete core, bearing the majority of the transferred load, eventually reached its temperature-reduced compressive capacity, resulting in crushing and a rapid loss of axial stability. Conversely, the failure mechanisms for panels subjected to combined axial and lateral loading were distinctly different and significantly more abrupt. The superposition of compressive stresses from the axial load and the compressive bending stresses generated by both the lateral load and thermal bowing created a highly localized zone of extreme stress on the fire-exposed face. The rapid degradation of the exposed steel plate in this high-stress region led to premature, localized plastic hinging. Once this localized instability initiated, the effective cross-section available to resist the complex loading was drastically reduced. The concrete core, already weakened by the thermal exposure and subject to severe strain gradients, could not compensate for the sudden loss of confinement and structural contribution from the steel faceplate. This cascading sequence of local failures rapidly transitioned into a catastrophic global collapse, characterized by runaway lateral deflection and an immediate inability to support the vertical load.

4.4 Parametric Sensitivities and Numerical Validation

The comprehensive parametric study conducted using the validated numerical framework provided critical insights into the structural sensitivities of the composite system. The models demonstrated a high degree of correlation with the experimental data, accurately capturing both the thermal distribution and the non-linear mechanical displacement trajectories. The parametric analysis revealed that the axial load ratio acts as a massive amplifier for lateral load vulnerability during a fire. At low axial load ratios, the panels exhibited a degree of resilience to lateral forces, absorbing the bending moments through the unexposed steel plate. However, as the axial load ratio increased, the threshold for lateral load tolerance plummeted. Under high axial loads, even minimal lateral forces were sufficient to initiate the destructive P-delta feedback loop early in the fire exposure, leading to severely truncated fire resistance times.

Furthermore, the slenderness of the panel was identified as a critical vulnerability factor. Highly slender panels, which are increasingly common in modern architectural designs seeking optimized floor space, demonstrated extreme sensitivity to the combined loading state. The reduced bending stiffness inherent in slender sections resulted in significantly larger initial lateral displacements under the applied lateral load. When exposed to fire, these larger initial deflections translated into massively amplified second-order moments, causing the slender panels to reach structural instability significantly faster than their thicker, more robust counterparts. This highlights a fundamental conflict between architectural optimization and high-temperature structural resilience, underscoring the necessity for stringent design checks when deploying slender composite walls in multi-hazard environments.

5. Conclusion

This comprehensive academic investigation has systematically explored the highly complex fire performance of steel-concrete composite wall panels subjected to the severe conditions of combined axial and lateral loading. By integrating large-scale, custom-designed experimental testing with advanced, sequentially coupled thermo-mechanical finite element modeling, the research has successfully illuminated the intricate mechanisms governing the structural response and ultimate failure of these critical architectural elements. The findings definitively demonstrate that the application of lateral loads fundamentally alters the behavior of composite panels during a fire event, shifting the failure paradigm from pure axial capacity loss to complex, instability-driven collapse. The primary conclusions derived from this study highlight the critical danger of P-delta effects in elevated temperature environments. The synergy between mechanically induced bending from lateral forces and thermally induced bowing from asymmetric fire exposure creates a rapidly escalating stress state that traditional, isolated axial fire tests completely fail to capture. The research established that increases in

lateral load magnitude drastically curtail the fire resistance time of the panels, initiating premature yielding of the fire-exposed steel faceplate and localized crushing of the concrete core. Furthermore, the parametric analysis conclusively showed that high axial load ratios and increased structural slenderness act as severe vulnerability multipliers, exponentially increasing the susceptibility of the panel to rapid out-of-plane buckling when lateral forces are present. The validated numerical modeling framework presented in this study provides a robust and highly accurate analytical tool for structural engineers, enabling the precise simulation of these complex multi-axial loading scenarios without the need for prohibitively expensive physical testing. Ultimately, this research underscores the urgent necessity for current structural fire engineering design codes to evolve. It is imperative that future design methodologies explicitly incorporate the interactive effects of combined loading to ensure the genuine resilience and life-safety of modern composite structures when exposed to the catastrophic reality of a severe fire event.

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