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THE IMPACT OF SMART MATERIALS AND FIRE-RESISTANT STRUCTURES ON SAFETY IN U.S. PUBLIC INFRASTRUCTURE

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Abstract

This quantitative study examined how smart materials and fire-resistant structural systems influenced measurable fire-safety performance in U.S. public infrastructure. Using a cross-sectional comparative design grounded in performance-based fire engineering, the analysis evaluated bridges, tunnels, transit systems, and high-occupancy public buildings classified into baseline, smart-materials-only, fire-resistant-only, and combined-intervention conditions. Safety was operationalized as a multidimensional outcome family capturing structural survival and occupant tenability, including structural endurance time, residual load capacity after cooling, peak fire deflection, collapse-risk score, and evacuation tenability window. Descriptive results demonstrated a clear improvement gradient across intervention categories. Mean structural endurance increased from 78.4 minutes in baseline assets to 96.2 minutes in smart-materials-only assets and 104.7 minutes in fire-resistant-only assets, reaching 121.3 minutes in combined systems. Residual load capacity followed the same pattern, rising from 62.1% in baseline systems to 69.5% in smart-materials-only systems, 72.8% in fire-resistant-only systems, and 79.6% in combined systems. Peak fire deflection declined progressively from 41.7 mm in baseline assets to 35.2 mm under smart materials, 32.8 mm under fire-resistant structures, and 27.6 mm under combined assemblies. Collapse-risk scores were reduced from 0.34 in baseline systems to 0.27 in smart-materials-only systems, 0.24 in fire-resistant-only systems, and 0.18 in combined systems. Evacuation tenability windows expanded from 9.6 minutes in baseline assets to 11.4 minutes under smart materials, 12.2 minutes under fire-resistant structures, and 13.8 minutes under combined systems, with the largest tenability gains observed in tunnel, transit, and public-building assets. Inferential modeling confirmed that passive protection level and redundancy rating were the strongest predictors of structural endurance and collapse-risk reduction, while sensing responsiveness and compartment integrity were dominant predictors of tenability improvement. Interaction testing indicated statistically meaningful non-additive benefits for combined interventions, showing that integrated smart-material and fire-resistant assemblies corresponded to the most robust and stable safety outcomes across U.S. public infrastructure types.

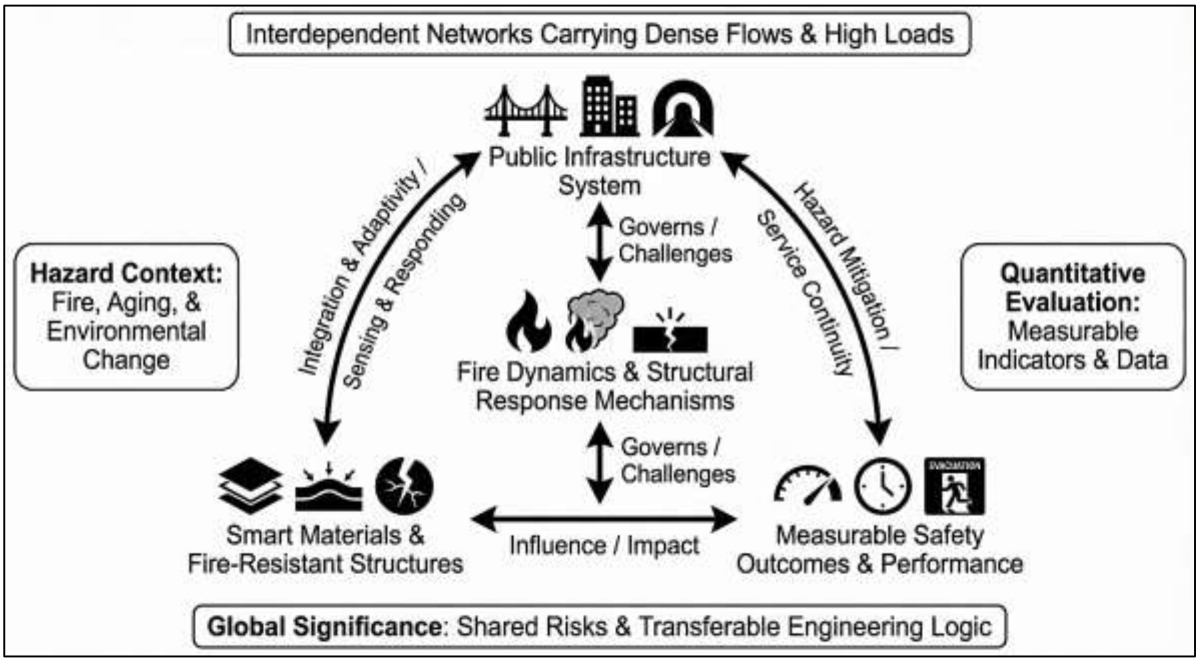
Keywords

Smart materials; Fire-resistant structures; Public infrastructure; Fire safety; Quantitative modeling

INTRODUCTION

Public infrastructure in the United States encompasses the shared physical systems that enable everyday social and economic activity, including bridges, roadways, tunnels, rail and metro corridors, airports, ports, public schools and hospitals, government buildings, water and wastewater plants, power distribution networks, and emergency response facilities. These systems are not isolated artifacts; they function as interdependent networks that must operate safely while carrying dense population flows and high service loads. In safety science and civil engineering, infrastructure safety is defined as the measurable ability of these built systems to prevent hazardous escalation, maintain structural integrity under stress, support safe evacuation, and return to functional operation after disruptive events (Patel & Goyal, 2018).

Figure 1: Smart Materials for Infrastructure Safety



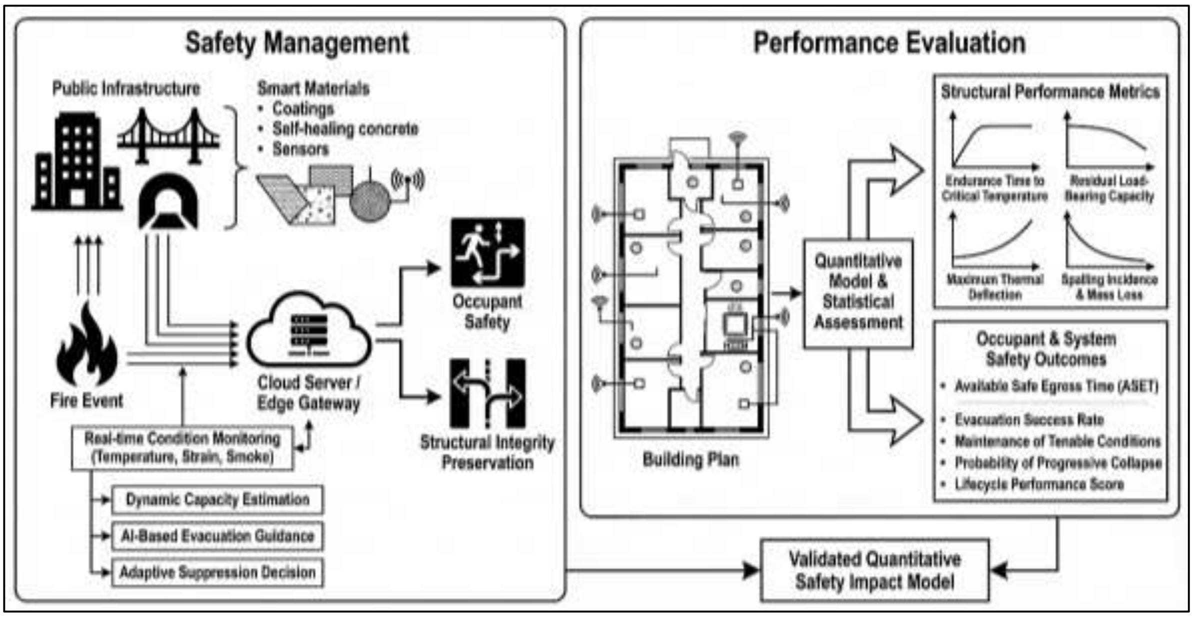
Safety is commonly operationalized through quantifiable indicators such as structural reliability indices, fire endurance ratings, maximum allowable deflection under thermal loading, resistance to progressive collapse, time-to-evacuation margins, tenability limits for smoke toxicity, and continuity of critical services (Arfan et al., 2021). Smart materials are defined as engineered materials capable of sensing external stimuli and responding in a controlled, often reversible, manner through changes in mechanical, thermal, electrical, or chemical properties. Their design goal is to introduce adaptivity into otherwise passive structural components (Ara, 2021; Jahid, 2021). Smart materials relevant to fire safety include intumescent coatings that swell under heat to form insulating layers, phase-change materials that absorb thermal energy through latent heat mechanisms, shape-memory alloys that return to preset configurations after thermal deformation, self-healing concretes that seal microcracks via chemical or biological activation, and embedded sensory composites that transmit real-time thermal or strain signals (Grant, 2022; Akbar & Farzana, 2021; Reza et al., 2021). Fire-resistant structures are defined as structural systems that preserve load-bearing capacity and compartmentation when exposed to fire for specified durations determined by standardized thermal curves. Fire resistance is achieved through passive protection layers, thermally robust detailing, redundant load paths, and the integration of active suppression systems (Saikat, 2021; Shaikh & Aditya, 2021). Within U.S. practice, categorical ratings such as one-, two-, or three-hour resistance refer to the time a system can endure standardized exposure without loss of structural function. The definitions form an analytic basis for quantitative evaluation because “impact” in this study refers to statistically measurable differences in safety outcomes attributable to smart-material responsiveness and structural fire resistance, treated as engineering inputs influencing observed performance under thermal hazards (Fedosov et al., 2019;

Kanti & Shaikat, 2021).

While this paper focuses on U.S. public infrastructure, the safety challenge it addresses is internationally significant because fire risk in critical facilities has become a shared global concern alongside urban concentration, infrastructure aging, and climate-related hazard intensification (Ariful & Ara, 2022; Arman & Kamrul, 2022). Public infrastructure worldwide increasingly combines large occupancy volumes with energy-dense equipment, transit fuels, electrical systems, and composite material assemblies, all of which increase fire load variability and complicate emergency response (Mesbaul & Farabe, 2022; Nahid, 2022; Hossain & Milon, 2022; Mullins-Jaime & Smith, 2022). International disaster records show that infrastructure fires can generate cascading failures in mobility, water supply, healthcare access, and energy continuity, producing social costs far beyond the immediate burn zone. Large tunnel or transit-station fires in multiple regions have demonstrated how smoke accumulation, high heat release rates, and constrained egress environments can escalate casualty risks and trigger structural damage that shuts down regional corridors for long periods (Abdur & Haider, 2022; Mushfequr & Praveen, 2022; Mortuza & Rauf, 2022). These incidents highlight that the safety of public assets depends not only on stopping ignition, but on sustaining tenable evacuation routes and preserving structural capacity long enough to prevent collapse and allow firefighting access. The United States exhibits comparable systemic exposure because of its extensive, highly utilized, interlinked infrastructure network (Rakibul & Samia, 2022; Rony & Ashraful, 2022; Saikat, 2022). Many U.S. bridges, transit hubs, and public buildings operate beyond their original design lifetimes, and age-related deterioration interacts with fire stress by increasing crack density, reinforcement exposure, and moisture pathways that accelerate spalling and heat penetration (Abdul, 2023; Abdulla & Zaman, 2023; Naser & Kodur, 2018; Shaikh & Sudipto, 2022). Hazard context is also shaped by environmental change, including more frequent large wildfires and extreme heat events that raise the probability of thermal exposure for open-air networks, transportation corridors, and public facilities at the wildland–urban interface. From an international perspective, U.S. codes and asset-management systems have substantial influence on global engineering practice, meaning empirical evidence from U.S. infrastructure contributes to a broader knowledge base on how to improve fire survivability and emergency safety in high-demand environments (Arfan et al., 2023; Ara & Beatrice Onyinyechi, 2023; Amin & Mesbaul, 2023). Smart materials and fire-resistant structural strategies are therefore evaluated not as local technical refinements, but as part of a global movement toward measurable resilience in essential public systems (Kim et al., 2020). The international significance of this topic lies in the transferable engineering logic: if responsive materials extend endurance time or improve hazard detection, then the methods and findings can inform safety approaches for similarly complex public infrastructure worldwide (Foysal & Aditya, 2023; Hamidur, 2023; Harun-Or-Rashid et al., 2023).

Fire safety performance in public infrastructure is governed by the coupled processes of fire development, smoke transport, and structural degradation. Research in fire dynamics shows that infrastructure fires differ from ordinary compartment fires because they often involve large fuel packages, continuous ventilation, complex multi-level geometries, and high airflow induced by moving vehicles or stack effects (Kodur & Naser, 2021). These conditions can accelerate flame spread and smoke movement, reducing the time available for safe evacuation. Quantitative safety assessment therefore relies on measurable fire variables such as peak gas temperatures, heat flux at structural surfaces, rate of temperature rise, time to flashover, smoke optical density, and toxic gas concentration profiles (Musfiqur & Kamrul, 2023; Muzahidul & Mohaiminul, 2023; Amin & Praveen, 2023). These variables define tenability conditions and determine when evacuation routes become unsafe. Structural response to fire introduces another measurable layer of hazard. Elevated temperatures reduce steel yield strength, degrade stiffness in reinforced concrete, and create differential thermal expansion that generates large internal forces at connections and restraints (Hasan & Ashraful, 2023; Ibne & Kamrul, 2023). For concrete systems, rapid heating produces pore-pressure accumulation that can cause spalling, exposing reinforcement and sharply increasing heat transfer into load-bearing cores (Mushfequr & Ashraful, 2023; Roy & Kamrul, 2023). For steel systems, thermal buckling, connection softening, and loss of composite action can initiate localized failures that propagate if redundancy is limited (Saba et al., 2023; Saba & Kanti, 2023). Empirical fire tests and computational simulations quantify these mechanisms through residual strength ratios, temperature-dependent reduction factors, critical deflection thresholds, and probabilistic failure indices. Smart materials relate directly to these measurable pathways. Intumescent coatings alter the thermal boundary condition by delaying temperature rise in protected members, shifting endurance time distributions (Maraveas et al., 2021; Shaikh & Farabe, 2023; Haider & Hozyfa, 2023). Phase-change materials absorb energy that would otherwise raise compartment temperatures, lowering heat flux into structural envelopes. Self-healing concretes stabilize microcrack growth and reduce permeability, preserving cover integrity that moderates spalling susceptibility (Abdul & Shoeb, 2024; Hozyfa & Shahrin, 2024). Shape-memory reinforcement and thermally tolerant composites contribute to stiffness continuity and deformation control under heat, improving survival probabilities for key members (Hasan & Shah, 2024; Hasan & Zayadul, 2024). Embedded sensor networks provide measurable early warning by tracking thermal gradients and strain rates, enabling adaptive suppression and evacuation decisions anchored in real-time data. In quantitative terms, safety impact appears as changes in endurance times, reductions in collapse likelihood, improved evacuation success rates, and wider margins between available safe egress time and the onset of structural or toxic failure (Muzahidul & Aditya, 2024; Hasan & Rakibul, 2024). Thus, fire safety in infrastructure is a multi-variable measurable problem where smart materials and fire-resistant design act on well-defined thermal–mechanical degradation processes (GangaRao, 2017; Mominul, 2024; Mominul & Zaki, 2024).

Figure 2: Smart Fire Resistance in Infrastructure



Smart materials have become integral to infrastructure safety research through the evolution of adaptive engineering and structural health monitoring (Roy & Praveen, 2024; Rony & Hozyfa, 2024). Early developments established that certain materials can convert mechanical or thermal stimuli into detectable signals, enabling distributed sensing in civil systems and supporting preventive maintenance (Kim et al., 2020). This sensing capability has expanded into multifunctional materials that both monitor and mitigate damage. In fire safety, smart materials can be grouped into thermally activated protective materials, energy-absorbing thermal regulators, self-repairing durability enhancers, and real-time sensing layers. Thermally activated protective materials include intumescent and ablative coatings that expand or char under heat, increasing insulation and delaying critical steel temperatures. Their performance is measurable through expansion ratios, char stability, and the resulting time delay before protected components reach limiting temperatures. Energy-absorbing thermal regulators include phase-change materials embedded in panels or coatings; they reduce compartment temperature peaks by absorbing latent heat, measurable through enthalpy storage capacity and dampening of time–temperature curves. Self-repair smart materials include microcapsulebased binders and bacterial self-healing concretes that seal cracks after they form (Liew et al., 2019; Saba & Hasan, 2024; Shaikat & Zaman, 2024). Crack closure rates, permeability reduction, and regained stiffness provide measurable indicators linking self-repair to improved fire safety because intact cover reduces pre-fire deterioration and limits heat penetration during exposure. Real-time sensing layers include fiber-optic sensors, piezoelectric elements, and conductive nanomaterial networks embedded in structural components (Sudipto & Hasan, 2024; Kanti & Saba, 2024). Their measurable safety role lies in detection accuracy, response latency, and spatial resolution of thermal or strain signals, which can shorten ignition-to-intervention times and improve evacuation coordination (Kanti & Praveen, 2024; Haider & Praveen, 2024). Field deployments in bridges, tunnels, and public buildings show that smart sensing reduces uncertainty in condition assessment and enables risk-based lifecycle management. In U.S. infrastructure, this matters because deterioration interacts with thermal hazards, so better monitoring supports earlier rehabilitation of vulnerable members. Smart materials thus contribute to safety by adding measurable adaptivity to infrastructure systems: they may protect members, reduce heat accumulation, preserve durability, or produce real-time hazard data (Zhang et al., 2022; Zulqarnain & Zayadul, 2024). Quantitative analysis treats these contributions as explanatory variables linked to observed fire performance and safety outcomes.

Fire-resistant structural design in public infrastructure has advanced from prescriptive fireproofing toward performance-oriented systems that integrate materials, detailing, compartmentation, and redundancy (Gharehbaghi et al., 2019). Fire resistance in steel structures is typically achieved through passive protection layers such as spray-applied fire-resistive materials, board encasement, insulated cladding, and smart coatings, as well as through structural continuity that allows load redistribution. Large-scale experiments and numerical models show that restrained beams and columns can develop alternative load paths under high temperatures, provided connections maintain ductility and rotational capacity. This behavior is measurable through survival time, catenary action indicators, and residual load ratios. Reinforced concrete infrastructure depends on cover depth, aggregate composition, moisture state, and fiber additions that mitigate spalling. Polypropylene and hybrid fiber mixes are used to provide pore-pressure relief under heating, measurable through spalling incidence, mass loss rates, and residual strength after cooling. Underground assets such as tunnels and metro stations face higher heating rates associated with hydrocarbon fuel fires, requiring specialized linings and fire-resistant segment mixes that preserve ring stability under rapid thermal shock (Rathnayake et al., 2022). Their performance is quantified through lining temperature profiles, crack density after exposure, and endurance against standardized or modified fire curves. Bridge fire research shows that bearings, expansion joints, and girder webs are critical vulnerabilities because thin sections heat quickly and load transfer points degrade. Measured outcomes include joint failure temperature, unseating probability, and girder residual stiffness. Fire-resistant compartmentation in public buildings and transit facilities intersects with human safety by sustaining tenable egress routes. Measurable safety effects include longer evacuation windows, reduced smoke infiltration along escape paths, and lower probabilities of progressive collapse that would block exits. Because U.S. public infrastructure often carries high occupancy loads, fire resistance is treated as a core safety variable rather than a secondary compliance feature (Jelčić Rukavina et al., 2022). Quantitative evaluation of fire-resistant structures therefore uses endurance ratings, reliability indices, thermal penetration rates, and post-fire serviceability measures, providing a robust basis for statistical assessment of safety performance across asset types.

The integration of smart materials into fire-resistant structural systems represents a shift toward multilayer, data-informed safety architectures. Conventional fire-resistant design assumes fixed material properties and relies on conservative exposure models. Smart materials introduce time-dependent, stimulus-responsive behavior that can be quantified and incorporated into performance models (Tedim et al., 2020). When smart protective coatings are layered with traditional insulation systems, experimental evidence indicates stronger thermal delay effects than single-method protection. These interaction effects imply that safety benefits may be non-linear and therefore suitable for quantitative modeling. Smart concrete formulations that include self-healing additives or nano-modified binders stabilize microstructure over time, preserving cover integrity and improving thermal resistance indirectly by limiting pre-fire degradation. Monitoring-enabled smart materials further connect structural fire performance to emergency management. Embedded sensing networks can track temperature gradients, deformation rates, and potentially smoke intrusion, producing measurable real-time indicators of structural condition during a fire. Such data enable dynamic estimation of remaining capacity, which is essential for decision-making about evacuation boundaries, firefighting entry, and suppression intensity (Górriz et al., 2017). Reliability and risk modeling frameworks show that reducing uncertainty in structural condition alters probabilistic failure estimates, changing the expected risk profile of an asset. Integration also includes responsive structural elements such as shape-memory braces or heat-tolerant composite wraps that limit damage propagation and enhance post-fire stiffness recovery, measurable through residual drift ratios and regained load capacity. In U.S. asset governance, resilience is increasingly evaluated through lifecycle performance scoring, meaning integrated systems that both preserve durability and extend fire endurance align with measurable safety objectives. The integration theme matters for quantitative analysis because it motivates models that treat smart-material variables and baseline fire resistance as joint predictors of safety outcomes, capturing additive and interaction effects across hazard intensities and infrastructure categories (Ham & Lee, 2018).

A quantitative investigation of how smart materials and fire-resistant structures influence safety in U.S. public infrastructure requires explicit mapping between engineering inputs and observable safety outcomes. The literature provides established dependent variables for structural fire performance, including endurance time to critical temperature, reduction in load-bearing capacity over exposure duration, maximum thermal deflection, residual strength after cooling, and probability of progressive collapse (Mitchell et al., 2020). Occupant-centered safety outcomes add measurable dimensions such as available safe egress time, evacuation success rate, exposure dose to toxic smoke constituents, and maintenance of tenable corridor conditions. Smart-material performance metrics contribute predictors such as coating swelling efficiency, thermal conductivity change under heat, latent heat absorption capacity, crack-sealing rate, sensor detection latency, and accuracy of temperature or strain measurements under extreme conditions. Fire-resistant structural predictors include protection thickness, compartmentation integrity measures, redundancy indices, moisture- and fiber-related spalling resistance indicators, and connection ductility parameters (Liew & Chua, 2021). In the U.S., the importance of quantifying safety impact is amplified by large-scale rehabilitation needs, uneven asset condition across states, and the operational role of public infrastructure in responding to emergencies. Fire events in transport tunnels, bridges, and high-occupancy public buildings demonstrate that small differences in thermal endurance or detection speed can shift outcomes between controlled damage and catastrophic failure (Khan et al., 2022). This makes statistical testing necessary to isolate effects while controlling for hazard intensity, asset age, maintenance condition, and functional load. Quantitative models can therefore evaluate whether infrastructure equipped with smart materials and robust fire-resistant detailing shows measurable improvements in safety indicators relative to conventional systems. The framing in this introduction positions safety as a measurable, multi-factor performance outcome shaped by responsive material behavior and structural fire resistance within real U.S. hazard environments. The study is grounded in decades of fire science, structural reliability, smart-material engineering, and public asset risk research, enabling rigorous empirical assessment of impact through statistical comparison of performance outcomes (Al-Kodmany, 2015).

The objective of this quantitative study is to empirically examine how the incorporation of smart materials and the adoption of fire-resistant structural systems influence measurable safety performance in U.S. public infrastructure. The study is designed to treat safety not as an abstract claim but as an observable outcome captured through standardized indicators of structural and occupant protection under fire exposure. At the broadest level, the research aims to determine whether infrastructures that integrate responsive material technologies and certified fire-resistant design features demonstrate statistically different safety outcomes compared with infrastructures using conventional materials and baseline fire protection. To accomplish this overarching aim, several specific objectives guide the analysis. First, the study seeks to quantify the extent to which smart materials—such as thermally activated protective layers, energy-absorbing components, self-healing composites, or embedded sensing systems—alter structural fire performance measures, including endurance time to critical temperature, rate of thermal penetration, residual load-bearing capacity, and maximum fire-induced deflection. Second, it aims to evaluate the contribution of fire-resistant structural configurations—such as protected steel assemblies, enhanced reinforced concrete cover systems, spalling-mitigation detailing, compartmentation integrity, and redundancy in load paths—to safety outcomes measured through structural stability indices and progressive collapse probability under defined thermal scenarios. Third, the research intends to test whether combined application of smart materials and fire-resistant structural strategies produces additive or interaction effects on safety, meaning that the joint deployment may yield safety performance that differs from the sum of individual contributions. Fourth, the study aims to compare safety performance across major categories of U.S. public infrastructure—such as bridges, tunnels, transit stations, and public buildings—so that differences associated with function, geometry, and occupancy can be statistically assessed. Fifth, the analysis is structured to control for asset age, maintenance condition, and hazard intensity, ensuring that observed differences in safety outcomes can be attributed to material and structural factors rather than confounding influences. Finally, the study aims to generate a validated quantitative model that links smart-material performance variables and fire-resistant structural parameters to safety indicators, providing a clear statistical representation of impact within the U.S. public infrastructure context.

LITERATURE REVIEW

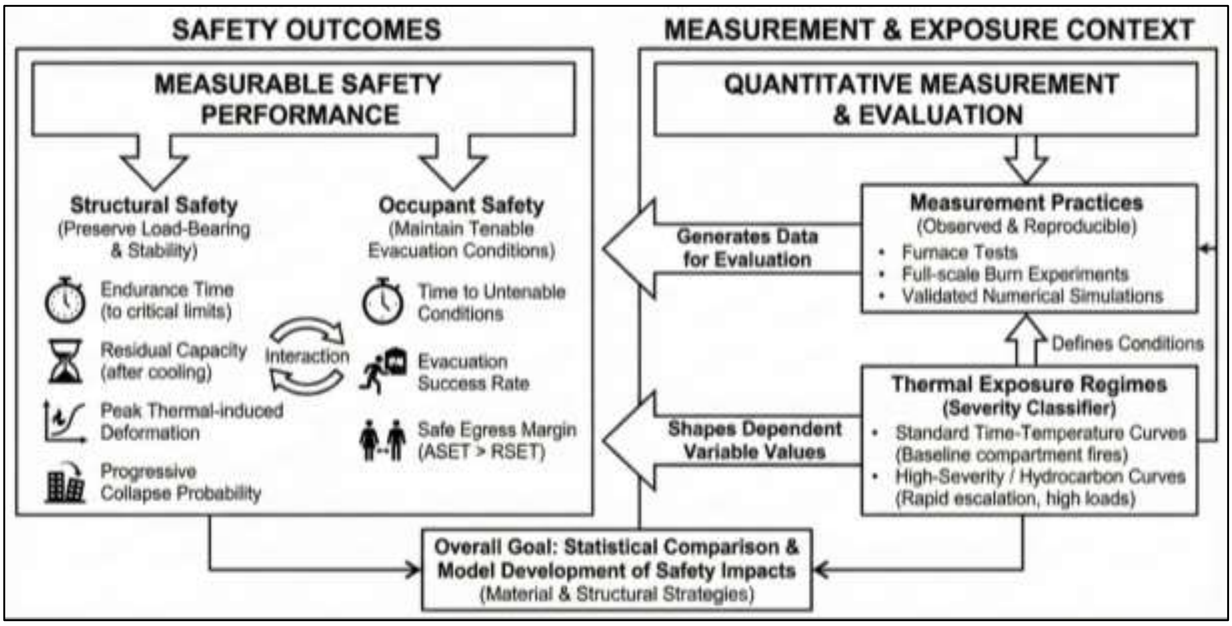
The literature on infrastructure fire safety has expanded from traditional prescriptive protection toward data-driven, performance-based evaluation of how materials and structural systems behave under extreme thermal hazards. This section reviews empirical and quantitative scholarship that links smart material functionality and fire-resistant structural design to measurable safety outcomes in public infrastructure. The review is organized to build a statistical logic chain: it first clarifies how safety is operationalized in fire engineering and infrastructure risk studies, then synthesizes quantitative evidence on smart materials as adaptive safety enhancers, followed by fire-resistant structural systems as endurance and collapse-prevention mechanisms. Next, it examines integrative studies where smart materials are embedded within fire-resistant assemblies, highlighting how combined interventions shift endurance distributions, evacuation tenability windows, and reliability indices. The section also surveys modeling approaches used to estimate causal or correlational impact, including experimental fire testing, finite-element thermal–structural simulation, probabilistic reliability analysis, and risk-based lifecycle frameworks. Finally, the review identifies systematic measurement gaps across U.S. infrastructure types—bridges, tunnels, transit hubs, and public buildings—so that the quantitative structure of the present study is grounded in verified indicators, robust datasets, and defensible statistical assumptions.

Fire Safety in Public Infrastructure

Quantitative fire engineering literature frames safety as a measurable outcome that can be observed, modeled, and statistically compared across structural systems, material configurations, and hazard conditions. Within this tradition, safety is not treated as a binary label but as a performance state that varies with exposure intensity and time under fire (Kodur & Naser, 2021). Researchers commonly conceptualize safety through the capacity of infrastructure to maintain critical functions while limiting loss of life, structural collapse, and service interruption. This view aligns with performance-based fire engineering, where the central research task is to link physical fire effects to measurable safety endpoints. A consistent theme across studies is the separation of structural safety outcomes and occupant safety outcomes. Structural safety refers to the ability of a system to preserve load-bearing capacity, stiffness, compartment integrity, and global stability during and after a fire event. Occupant safety refers to maintaining tenable evacuation conditions in terms of temperature, smoke density, and toxic gas exposure across the time window necessary for safe egress. These two outcome families interact but remain analytically distinct in measurement practice. For example, a structure can satisfy endurance targets yet still fail in occupant safety if smoke transport overwhelms egress routes early (Reiner & Mcelvaney, 2017). Conversely, effective evacuation can occur even when structural elements sustain severe damage later in the event. Quantitative studies therefore define safety through dependent variables that capture either structural survival or human tenability, or both in coupled models. Structural dependent variables commonly include endurance time to critical limit states, thermal-induced deformation thresholds, residual capacity after cooling, and probabilities of progressive collapse derived from reliability methods. Occupant dependent variables include time to untenable conditions, evacuation success rate, and relative margins between safe egress availability and evacuation demand (Kodur et al., 2020). The empirical literature supports treating these outcomes as measurable response variables influenced by design and material predictors, rather than as qualitative judgments. This approach enables statistical testing of how specific engineering interventions shift safety performance distributions across comparable infrastructure contexts.

Literature on fire safety measurement emphasizes that dependent variables must be observable, reproducible, and standardized enough to allow cross-study comparison. In structural fire engineering, dependent variables are typically derived from furnace tests, full-scale burn experiments, or validated numerical simulations. Endurance time is one of the most frequently used outcomes because it directly expresses how long a structural element or system can sustain a defined fire exposure while retaining required performance. Researchers interpret endurance as a probabilistic survival window rather than a guaranteed threshold, and they often report it alongside variability measures to express uncertainty (Ingason et al., 2015). Residual capacity after cooling is another dependent variable used to represent post-fire safety, especially in public infrastructure where re-opening decisions depend on measurable remaining strength.

Figure 3: Quantitative Fire Safety Performance Metrics



Peak deformation during fire, including mid-span deflection in beams or drift in frames, functions as a dependent variable capturing instability progression under heat-softened material conditions. These structural outcomes are complemented by collapse-related dependent variables in studies on redundancy and progressive failure. Reliability-based works translate fire-induced degradation into collapse probabilities or safety indices, which allow comparative statistical inference across different structural layouts. Occupant-oriented studies employ dependent variables grounded in tenability and evacuation. Time to critical smoke or temperature conditions is used to define the survival window for occupants, while evacuation success rate and egress time distributions serve as direct measures of safety performance. A recurring point in the literature is that structural and occupant dependent variables must be interpreted together because thermal hazards evolve dynamically (Min et al., 2019). Many studies pair structural endurance outcomes with evacuation tenability windows to show how safety depends on coordination between physical resistance and human response capability. Overall, measurement practices in quantitative fire engineering treat safety indicators as response variables that can be modeled in regression, reliability, or comparative designs, enabling statistically defensible evaluation of safety impacts from materials and structural fire-resistant strategies.

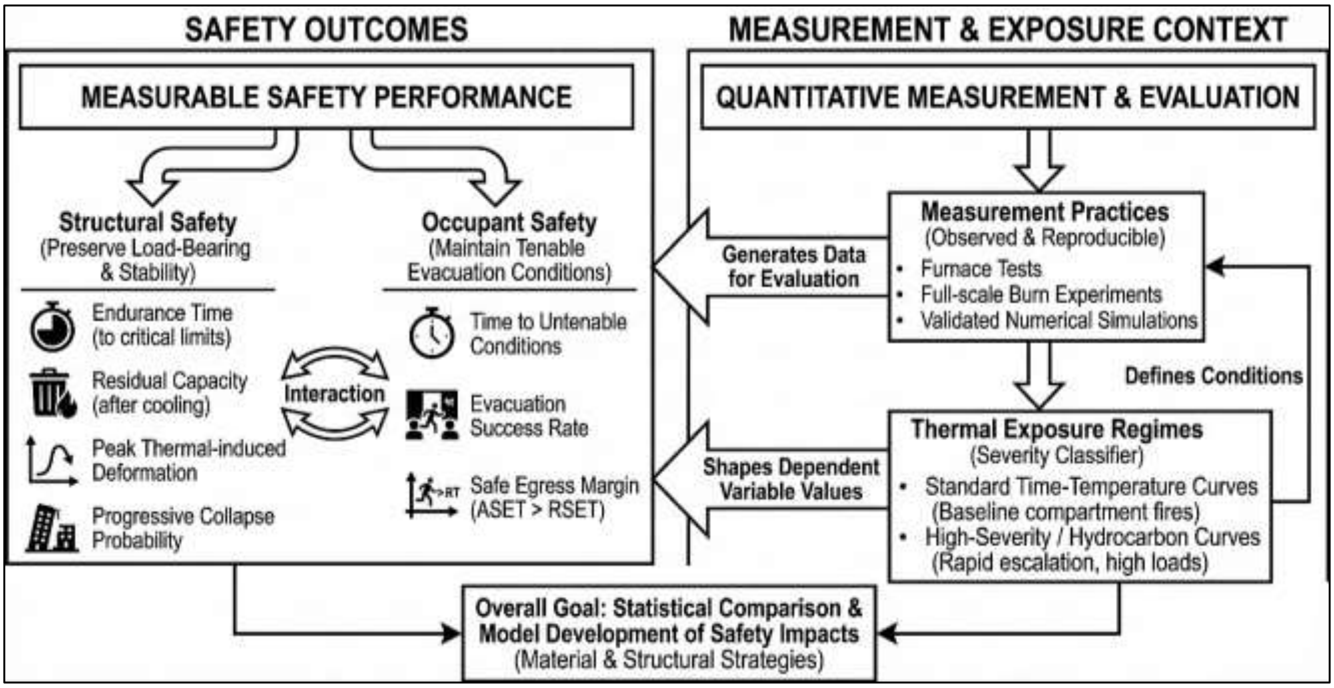
A substantial body of literature shows that measured safety outcomes are highly sensitive to the type of thermal exposure regime used in testing or modeling. Standard time–temperature curves are widely employed as baseline exposures because they provide repeatable conditions for classifying endurance performance (Moradi & Groth, 2019). These standard curves were developed to represent typical compartment fires and are used globally to support regulatory fire-rating systems. Quantitative studies using such curves generate endurance benchmarks that allow comparisons of materials, member geometries, and protection systems under controlled conditions. However, infrastructure research also highlights that real public-asset fires often exhibit heating rates and peak temperatures that exceed standard compartment assumptions, particularly in tunnels, transit corridors, or bridge fuel fires. Hydrocarbon-type and tunnel-specific exposure regimes represent these higher-severity events with more rapid temperature escalation and higher sustained thermal loads. Experimental and numerical studies consistently demonstrate that structural members exposed to these severe curves reach critical thermal states faster, reducing endurance time and increasing deformation rates relative to standard curve tests (Badri et al., 2018). The literature therefore treats exposure regime as a key contextual factor in quantitative safety evaluation. It functions not as a trivial testing choice but as a severity classifier that shapes dependent variable values. Several comparative investigations report that protective systems calibrated to standard exposures may show different effectiveness under severe curves, which is important for interpreting measured safety impacts. By systematically distinguishing baseline standard curves from high-severity comparators, quantitative fire engineering establishes a framework for evaluating safety robustness across realistic hazard ranges. This approach supports the empirical logic of measuring safety outcomes under multiple exposure regimes to reveal how endurance, residual capacity, and collapse risk profiles shift when thermal intensity increases, especially for critical public infrastructure categories (Fraga-Lamas et al., 2016).

Across empirical fire engineering studies, a stable set of core safety metrics appears repeatedly in quantitative evaluation of public infrastructure. Fire endurance time is treated as a primary metric because it captures the duration a structural system maintains performance before reaching a critical state (Dumas et al., 2018). In bridges, tunnels, and public buildings, endurance time is interpreted as a direct indicator of structural survival capacity during evacuation and suppression periods. Residual load capacity ratio after cooling is another common metric, reflecting the extent of post-fire integrity and informing serviceability and repair decisions. This metric is particularly emphasized in infrastructure contexts where partial functionality may remain even after severe fires. Peak deflection during fire is used to represent stability loss progression; higher peak deflections correlate with greater risk of connection failure, member buckling, or load-path disruption. Progressive collapse probability metrics extend these measurements by expressing system-level failure risk in statistical terms, often derived from reliability modeling linked to temperature-dependent strength reductions and redundancy conditions (Palei, 2015). Occupant safety metrics are equally prominent. Available safe egress time is widely used to represent the duration egress routes remain tenable before heat or smoke conditions become life-threatening. Required safe egress time represents evacuation demand under defined occupancy and movement assumptions. Quantitative literature often evaluates the safety margin between these two times to indicate whether evacuation is feasible under a given fire scenario. Studies of tunnels and transit stations emphasize smoke toxicity and visibility thresholds as part of tenability measurement, while public-building studies integrate route congestion effects into required evacuation time distributions. Collectively, these metrics form a coherent measurement toolkit that enables statistical comparison of how design choices and material systems influence safety outcomes (Luo & van den Brand, 2016). The consistency of these measures across studies provides a strong empirical foundation for quantitative modeling of safety impacts in U.S. public infrastructure.

Smart Materials as Quantifiable Safety Enhancers Under Fire

Empirical research on thermally activated smart coatings consistently positions these systems as measurable enhancers of steel safety under fire exposure in public infrastructure. The dominant class of coatings in this literature is intumescent protection, which responds to rising temperature by expanding and forming a porous char layer that slows heat transfer into steel members. Quantitative fire tests repeatedly show that the expansion behavior of intumescent layers is not merely a descriptive property but a statistical predictor of endurance performance (Wang et al., 2018). Studies compare different formulations by tracking how rapidly char forms, how stable it remains under heat flux, and how effectively it delays steel reaching critical temperature thresholds. Coating thickness has been treated as a controlled explanatory variable in furnace experiments, with endurance time measured in minutes as the dependent safety outcome. The resulting datasets allow distributional comparisons rather than single values, and the literature typically reports mean survival time increases, variability across specimens, and confidence intervals that capture uncertainty. This is important for infrastructure safety because steel systems in bridges, stations, and public buildings often rely on predictable endurance windows for evacuation and suppression (Bhagwat & Delhi, 2022). Researchers also emphasize that mechanical adhesion and char integrity matter for performance under realistic fire conditions, since cracking or delamination can cause endurance to drop sharply even if nominal thickness is high. Comparative trials across thin-film and thick-film systems show that thicker coatings do not always guarantee higher endurance when expansion ratios and char cohesion differ, reinforcing the need for multi-parameter quantitative evaluation. Beyond laboratory furnace regimes, some studies integrate intumescent behavior into thermal–structural simulations, enabling probabilistic endurance estimation at system scale. The synthesis of these works establishes a robust measurement logic: thermally activated coatings provide safety gains that are observable through delayed steel heating, expressed through increased endurance time distributions and lower probability of early thermal failure (Saracino et al., 2015). In the broader smart-material domain, intumescent coatings therefore function as a quantifiable, fire-triggered protective mechanism whose safety impact can be modeled statistically across varying exposure curves and infrastructure contexts.

Figure 4: Smart Materials Enhancing Fire Safety



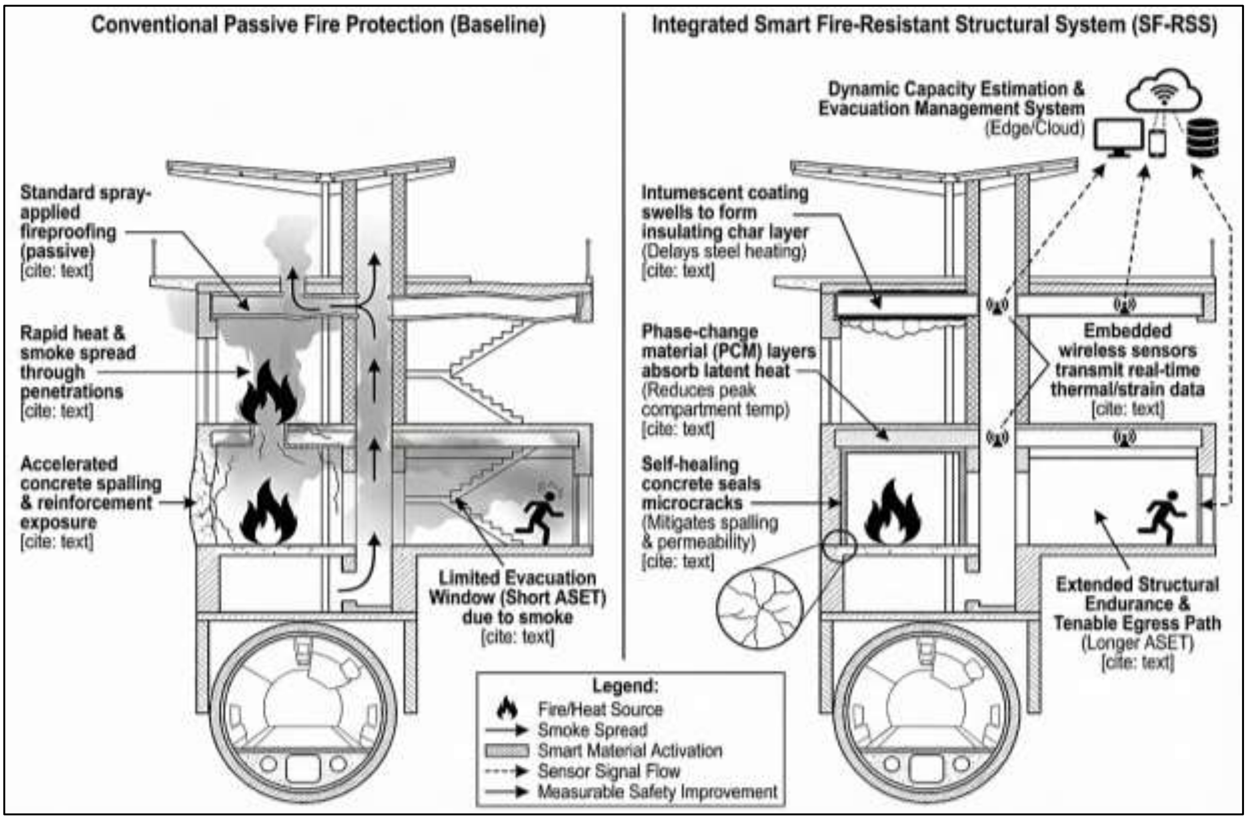
Phase-change smart assemblies are widely examined as thermal regulators capable of measurably improving compartment-level safety in fires. The central mechanism is latent heat absorption: when temperature rises to the material's transition range, stored energy is consumed in changing phase rather than increasing air or surface temperature (Billings et al., 2021). Quantitative investigations treat latent heat capacity as a predictor variable and measure resulting reductions in peak compartment temperature, heat flux to structural surfaces, and rate of temperature rise. Experimental designs frequently compare wallboards, ceiling panels, or composite layers with different phase-change material fractions, demonstrating that higher fractions tend to yield deeper suppression of temperature peaks, though diminishing returns often appear at higher loading levels. Researchers also track how the placement of phase-change layers within assemblies affects performance, reporting that surface-adjacent placement alters heat flux early in the fire while deeper placement stabilizes temperature over longer intervals. These studies connect thermal suppression to safety in two measurable ways. First, lower compartment temperatures delay the onset of flashover and reduce thermal stress imposed on load-bearing members, indirectly extending structural endurance (Bauer et al., 2021). Second, reduced heat flux moderates smoke production and toxic gas release rates in some compartment scenarios, extending tenability durations for occupants. Quantitative modeling papers incorporate phase-change behavior into computational fire simulations, allowing statistical comparisons of temperature–time trajectories and tenability windows across design alternatives. A consistent finding is that safety enhancement is best represented through distributions of temperature reduction rather than single-point estimates because phase-change effectiveness depends on ignition location, ventilation rate, and fuel load (Van Calster et al., 2021). The literature therefore presents phase-change smart assemblies as quantifiable safety enhancers that reshape compartment thermal curves in observable ways. Their contribution is captured through measured reductions in peak temperature, slower growth rates, and improved margins between tenable and untenable environmental conditions within public infrastructure fire scenarios.

Self-healing concrete research links microcrack repair capacity to measurable reductions in fire fragility for infrastructure made of reinforced or prestressed concrete. The literature treats crack-closure rate as a key explanatory variable because microcracks govern moisture transport, permeability, and reinforcement exposure—conditions that elevate vulnerability under fire (Van Calster et al., 2021). Fire-exposed concrete fails not only through strength loss from temperature but also through spalling driven by internal pore pressure and thermal incompatibility between paste and aggregate. Quantitative studies show that concretes with stronger autonomous healing behavior maintain tighter crack widths over time, leading to lower permeability and more stable cover integrity before fire exposure. This pre-fire durability state has measurable fire consequences: lower permeability slows vapor pressure build-up during heating, reducing the probability and severity of explosive spalling, and preserving reinforcement insulation (Arnetz et al., 2020). Experimental fire trials compare conventional mixes with self-healing variants under identical exposure curves, reporting lower spalling frequency, reduced mass loss, and higher residual strength after cooling. Residual strength percentage is a recurring dependent variable because it captures post-event structural safety and serviceability, which are critical for public assets that must be reopened or repaired quickly. In some studies, self-healing additives are also associated with improved thermal cracking resistance during exposure, limiting the rapid crack propagation that can accelerate cover failure. Modeling work complements test evidence by incorporating permeability reduction and crack-sealing kinetics into fire fragility frameworks, showing statistically lower failure probability for healed systems under equivalent thermal loads (Johnson et al., 2020). Across this literature, self-healing concrete is not presented as a speculative improvement but as a measurable durability-to-safety pathway: healing capacity stabilizes microstructure, reduces spalling likelihood, and preserves residual capacity distributions under fire. This makes self-healing concrete a quantitatively defensible smart-material strategy for enhancing safety in concrete-heavy U.S. public infrastructure such as tunnels, stations, and bridge substructures (Storr et al., 2017).

Fire-Resistant Structural Systems and Measured Safety Outcomes

Empirical research on thermally activated smart coatings consistently positions these systems as measurable enhancers of steel safety under fire exposure in public infrastructure. The dominant class of coatings in this literature is intumescent protection, which responds to rising temperature by expanding and forming a porous char layer that slows heat transfer into steel members (Young et al., 2015). Quantitative fire tests repeatedly show that the expansion behavior of intumescent layers is not merely a descriptive property but a statistical predictor of endurance performance. Studies compare different formulations by tracking how rapidly char forms, how stable it remains under heat flux, and how effectively it delays steel reaching critical temperature thresholds. Coating thickness has been treated as a controlled explanatory variable in furnace experiments, with endurance time measured in minutes as the dependent safety outcome. The resulting datasets allow distributional comparisons rather than single values, and the literature typically reports mean survival time increases, variability across specimens, and confidence intervals that capture uncertainty. This is important for infrastructure safety because steel systems in bridges, stations, and public buildings often rely on predictable endurance windows for evacuation and suppression (Wenwen & Jihong, 2021). Researchers also emphasize that mechanical adhesion and char integrity matter for performance under realistic fire conditions, since cracking or delamination can cause endurance to drop sharply even if nominal thickness is high. Comparative trials across thin-film and thick-film systems show that thicker coatings do not always guarantee higher endurance when expansion ratios and char cohesion differ, reinforcing the need for multi-parameter quantitative evaluation. Beyond laboratory furnace regimes, some studies integrate intumescent behavior into thermal–structural simulations, enabling probabilistic endurance estimation at system scale. The synthesis of these works establishes a robust measurement logic: thermally activated coatings provide safety gains that are observable through delayed steel heating, expressed through increased endurance time distributions and lower probability of early thermal failure (Chaturvedi et al., 2022). In the broader smart-material domain, intumescent coatings therefore function as a quantifiable, fire-triggered protective mechanism whose safety impact can be modeled statistically across varying exposure curves and infrastructure contexts.

Figure 5: Smart Materials Enhancing Fire Resilience



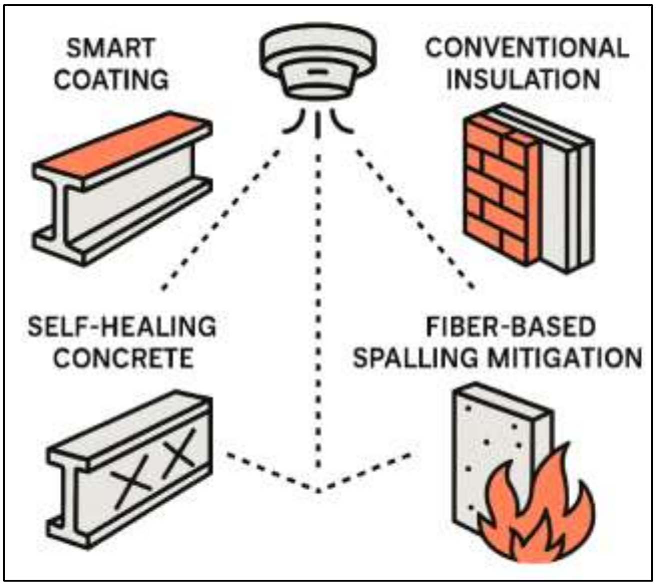
Phase-change smart assemblies are widely examined as thermal regulators capable of measurably improving compartment-level safety in fires. The central mechanism is latent heat absorption: when temperature rises to the material's transition range, stored energy is consumed in changing phase rather than increasing air or surface temperature (Zhang et al., 2021). Quantitative investigations treat latent heat capacity as a predictor variable and measure resulting reductions in peak compartment temperature, heat flux to structural surfaces, and rate of temperature rise. Experimental designs frequently compare wallboards, ceiling panels, or composite layers with different phase-change material fractions, demonstrating that higher fractions tend to yield deeper suppression of temperature peaks, though diminishing returns often appear at higher loading levels. Researchers also track how the placement of phase-change layers within assemblies affects performance, reporting that surface-adjacent placement alters heat flux early in the fire while deeper placement stabilizes temperature over longer intervals. These studies connect thermal suppression to safety in two measurable ways. First, lower compartment temperatures delay the onset of flashover and reduce thermal stress imposed on load-bearing members, indirectly extending structural endurance (Maluk, 2017). Second, reduced heat flux moderates smoke production and toxic gas release rates in some compartment scenarios, extending tenability durations for occupants. Quantitative modeling papers incorporate phase-change behavior into computational fire simulations, allowing statistical comparisons of temperature–time trajectories and tenability windows across design alternatives. A consistent finding is that safety enhancement is best represented through distributions of temperature reduction rather than single-point estimates because phase-change effectiveness depends on ignition location, ventilation rate, and fuel load. The literature therefore presents phase-change smart assemblies as quantifiable safety enhancers that reshape compartment thermal curves in observable ways (Yu et al., 2022). Their contribution is captured through measured reductions in peak temperature, slower growth rates, and improved margins between tenable and untenable environmental conditions within public infrastructure fire scenarios.

Self-healing concrete research links microcrack repair capacity to measurable reductions in fire fragility for infrastructure made of reinforced or prestressed concrete. The literature treats crack-closure rate as a key explanatory variable because microcracks govern moisture transport, permeability, and reinforcement exposure—conditions that elevate vulnerability under fire (Kodur et al., 2020). Fire-exposed concrete fails not only through strength loss from temperature but also through spalling driven by internal pore pressure and thermal incompatibility between paste and aggregate. Quantitative studies show that concretes with stronger autonomous healing behavior maintain tighter crack widths over time, leading to lower permeability and more stable cover integrity before fire exposure. This pre-fire durability state has measurable fire consequences: lower permeability slows vapor pressure build-up during heating, reducing the probability and severity of explosive spalling, and preserving reinforcement insulation (LaMalva et al., 2021). Experimental fire trials compare conventional mixes with self-healing variants under identical exposure curves, reporting lower spalling frequency, reduced mass loss, and higher residual strength after cooling. Residual strength percentage is a recurring dependent variable because it captures post-event structural safety and serviceability, which are critical for public assets that must be reopened or repaired quickly. In some studies, self-healing additives are also associated with improved thermal cracking resistance during exposure, limiting the rapid crack propagation that can accelerate cover failure. Modeling work complements test evidence by incorporating permeability reduction and crack-sealing kinetics into fire fragility frameworks, showing statistically lower failure probability for healed systems under equivalent thermal loads (Suzuki et al., 2016). Across this literature, self-healing concrete is not presented as a speculative improvement but as a measurable durability-to-safety pathway: healing capacity stabilizes microstructure, reduces spalling likelihood, and preserves residual capacity distributions under fire. This makes self-healing concrete a quantitatively defensible smart-material strategy for enhancing safety in concrete-heavy U.S. public infrastructure such as tunnels, stations, and bridge substructures.

Integrated Smart-Material Fire Resistance Assemblies

Quantitative fire-safety literature increasingly treats integrated smart-material and fire-resistance assemblies as multi-layer interventions whose safety value is observable only when material responsiveness and structural protection are evaluated together (Kordosky et al., 2020). In earlier fire engineering studies, passive fire resistance and active detection were often examined separately, producing endurance estimates that assumed fixed material properties and static protection performance. More recent empirical work shifts toward integrated assemblies in which smart coatings, thermal-regulating layers, or self-repair concretes are embedded into certified fire-resistant structural systems. This integration produces measurable changes in structural fire behavior that cannot be explained by either component alone. Experimental programs on protected steel members show that combining intumescent coatings with conventional insulation modifies heat-transfer pathways more strongly than single-layer systems, yielding longer endurance distributions and more stable temperature gradients. Similar patterns appear in reinforced concrete infrastructure where fiber-based spalling mitigation is coupled with self-healing or nano-modified binders, producing measurable reductions in crack-driven permeability and lower spalling frequency under identical exposure regimes (Steau et al., 2020). The quantitative literature interprets these results through a joint-effects lens: safety improvement appears in the combined shift of endurance time, residual capacity, and deformation trajectories. In multivariate designs, integrated assemblies are treated as composite predictors that include both baseline fire resistance parameters and smart-material response variables. Statistical comparisons across single-intervention and combined-intervention groups show that integrated systems more consistently reduce variance in performance, implying not only higher mean safety outcomes but also narrower uncertainty bounds. Several studies also emphasize that the effectiveness of integration depends on compatibility between response mechanisms—such as char-layer formation or latent heat absorption—and the thermal demands of a given structural configuration (J. Li et al., 2022). Overall, the literature positions integrated smart-material/fire-resistant assemblies as empirically demonstrable safety enhancers because they reshape structural survival patterns and post-fire stability in measurable, statistically testable ways.

Figure 6: Integrated Smart Fire Safety Systems



A key focus of joint-impact research is distinguishing simple additive improvement from synergistic interaction effects when smart materials and fire-resistant structures are combined. Additive patterns occur when the measured safety benefit of integration approximates the sum of individual contributions, such as a predictable endurance increase attributable to insulation plus an additional delay attributable to a smart coating (Maluk et al., 2017). Interaction patterns occur when the combined benefit differs from this sum, indicating that one intervention alters the effectiveness of the other. Multivariate fire-performance studies test these patterns by modeling endurance time and residual capacity as dependent outcomes while including both smart-material predictors and fire-resistance predictors in the same statistical framework. Empirical results across diverse systems show interaction behavior in several contexts. For steel assemblies, intumescent layers sometimes increase insulation efficiency by stabilizing boundary temperatures, producing endurance gains larger than predicted from thickness alone. For concrete systems, self-healing mixes coupled with fiber-based detailing reduce pre-fire damage pathways, leading to lower spalling severity and higher residual strength than would be expected from fibers or binder modification in isolation. The literature reports that interaction effects become especially visible under severe exposure regimes, where thermal gradients are steeper and protection failures are more likely without responsive support (Zhou et al., 2020). Quantitative works also note that interaction magnitude varies by asset type and configuration; redundancy, connection detailing, and ventilation conditions influence whether synergy emerges or whether effects remain additive. Importantly, these studies interpret interaction not as a theoretical claim but as an observable statistical outcome derived from comparing modeled and measured endurance distributions. The synthesis across multivariate evidence indicates that joint assemblies frequently generate performance gains that exceed linear expectations, supporting the use of integrated predictors when evaluating safety impact in public infrastructure fire scenarios (Grant, 2022).

Another strong stream of evidence uses survival-curve reasoning to compare how single and hybrid protection systems influence the probability of structural failure over time under fire exposure. In this literature, endurance is treated as a time-to-failure outcome, and the safety contribution of interventions is evaluated by observing shifts in the survival distribution (Chi & Peng, 2020). Hybrid systems—such as conventional insulation combined with smart coatings, or compartmentation-enhanced structures combined with thermal-regulating layers—consistently show delayed failure onset and slower decline in survival probability across standardized exposure trials. The comparative approach is especially common in tunnel lining and transit-station studies, where hybrid protection is tested to maintain structural stability over the evacuation window. By examining time-dependent failure likelihood under identical thermal curves, researchers demonstrate that integrated systems reduce early-failure risk and extend the high-survival portion of the curve, a pattern not mirrored by individual interventions (Appoh & Yunusa-Kaltungo, 2021). In bridge fire studies, hybrid protection on girders and bearings shows measurable reduction in rapid temperature escalation at critical connections, translating into longer times before limit states are reached. Quantitative modeling papers complement these experiments by simulating ensembles of fire scenarios and showing that hybrid systems shift failure distributions rightward, lowering the overall proportion of cases that fail within the critical initial period of a fire. These studies also highlight that risk reduction is not confined to mean endurance increase; hybrid systems often stabilize performance by lowering sensitivity to local damage or protection imperfections. In statistical terms, the dispersion of endurance times narrows and the mass of outcomes clustered near early failure declines (Shams et al., 2021). The survival-curve literature therefore provides a clear measurement framework for joint impact: hybrid assemblies demonstrably reduce failure probability over the duration of fire exposure while extending the time window in which structures remain stable and tenable for emergency operations.

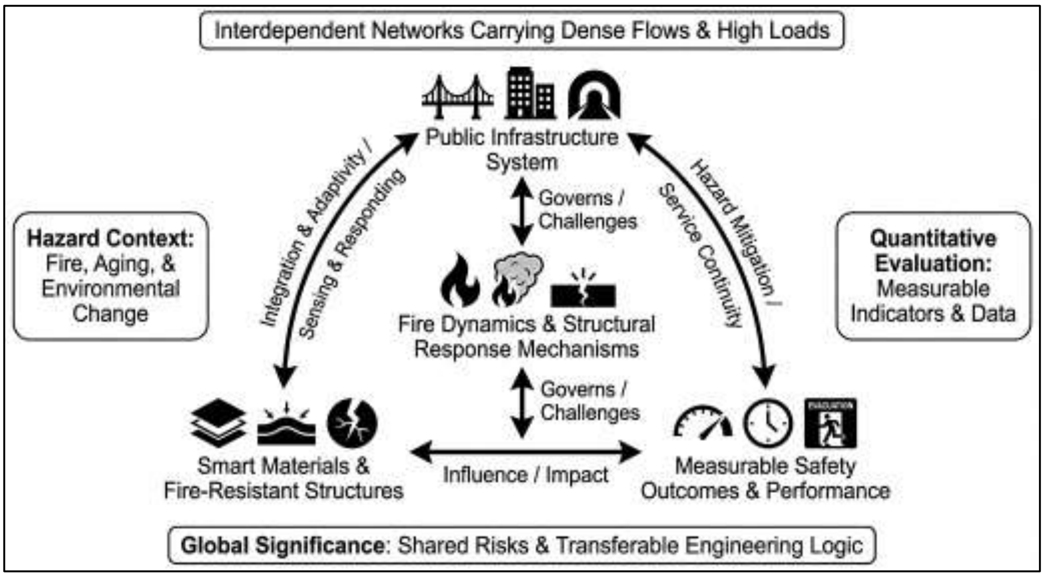
Integrated assemblies often include smart-sensor feedback layers that connect material and structural fire resistance to real-time decision-making, and quantitative studies show measurable safety value through improved timing and reliability of emergency response (A. A. Khan et al., 2022). Structural health monitoring research embeds fiber-optic sensors, thermally robust strain gauges, or conductive composites within fire-resistant systems to track temperature rise, deformation rate, and localized damage progression during fire. In performance-based fire engineering, these sensor outputs are treated as dynamic inputs that update estimates of remaining structural capacity. Quantitative evidence shows that real-time monitoring reduces uncertainty in capacity assessment compared with static pre-fire estimates, improving the accuracy of safety status classification during an event. Field and laboratory studies measure sensor latency, signal survival under high heat, and accuracy relative to reference instrumentation, linking faster and more reliable detection to earlier alarm activation and more targeted suppression decisions (Dimitrova et al., 2015). Infrastructure-focused investigations connect these timing gains to occupant safety outcomes by demonstrating that earlier detection expands the effective evacuation window and reduces exposure to untenable smoke or heat conditions. Some studies also report that dynamic updating of structural condition leads to more conservative or better-timed firefighting entry decisions, reducing responder risk and preventing load-path destabilization caused by premature intervention. Reliability-based modeling integrates sensor feedback into probabilistic frameworks, showing that updated capacity estimates shift failure likelihood downward over the course of fire evolution. Across this literature, smart-sensor integration is treated as an empirically measurable joint-impact mechanism: it does not create safety alone, but it amplifies the effectiveness of fire-resistant assemblies by converting responsive material behavior into actionable safety timing and more reliable survival assessment during critical infrastructure fires (Rajvaidya & Batham, 2021).

Quantitative Modeling Approaches Used in Prior Research

Quantitative fire-safety research in public infrastructure has historically relied on controlled experimental testing to establish measurable relationships between fire exposure and structural or occupant safety outcomes (Bindi et al., 2016). Furnace testing remains the dominant experimental paradigm for rating structural fire endurance, because it offers standardized, repeatable thermal conditions that support cross-study comparability. In typical furnace programs, steel beams, columns, composite members, or reinforced concrete slabs are exposed to predefined fire curves while load is applied to represent service conditions. Datasets from these tests record temperature histories at multiple depths, deformation time series, and the moment when predefined limit states are reached. Tunnel burn tests expand this logic to infrastructure-specific hazards by incorporating high-ventilation flows and hydrocarbon fuel packages that generate more severe temperature and smoke profiles

(Guillen et al., 2020). These trials yield more complex outputs, including spatial temperature gradients along tunnel linings, smoke propagation velocities, and time-to-tenability-loss across evacuation routes. Bridge girder fire experiments form another specialized stream, often using localized pool-fire setups to replicate vehicle or fuel spill scenarios beneath critical members. Such experiments produce measurable outcomes related to girder heating rate, bearing performance, loss of section stiffness, and redistribution of load paths across the bridge system. Across these testing traditions, quantitative designs emphasize replication and sample size adequacy to estimate variability rather than only mean performance. Studies commonly use multiple specimens per configuration, vary protection thickness or material mix systematically, and report endurance distributions that include measures of spread. Measurement intervals are typically short enough to capture rapid thermal transitions, especially early in the fire, and instrumentation setups integrate thermocouples, strain gauges, displacement transducers, and smoke sensors (Mesko et al., 2016). The literature also explicitly accounts for instrumentation error margins, calibration drift, and uncertainty in boundary conditions, recognizing that fire experiments are sensitive to ventilation, moisture content, and loading eccentricities. Experimental testing therefore provides the foundational empirical data that later modeling studies use for calibration, validation, and statistical inference regarding fire safety in U.S. public infrastructure systems (Ten et al., 2017).

Figure 7: Quantitative Fire Safety Research Framework



Finite element simulation has become a primary quantitative approach for expanding experimental evidence to full infrastructure systems that cannot be economically tested at scale. Thermal–structural models represent the coupled processes of heat transfer and mechanical response, allowing researchers to predict temperature fields, deformation trajectories, and failure timing for beams, frames, tunnel rings, or bridge assemblies under realistic fire scenarios (Dobry et al., 2018). A consistent theme in this literature is calibration against laboratory or field fire data so that simulated temperature rise and deflection rates reproduce observed behavior before being used for parametric studies. Model outputs are inherently time-dependent and multidimensional, including surface and internal temperature gradients, displacement histories, stress redistribution paths, and limit-state exceedance times. The quantitative value of simulation lies in enabling large scenario ensembles that vary exposure curve severity, protection thickness, material type, boundary restraints, and load ratios, producing statistical distributions for endurance and collapse probability rather than isolated predictions. Sensitivity analysis is a core methodological step, since simulation outcomes depend on temperature-dependent material properties, thermal conductivity assumptions, and connection behavior under heat. Studies therefore examine how uncertainty in steel strength reduction, concrete spalling behavior, or insulation degradation alters modeled endurance (Zidan et al., 2016). In tunnel and transit research, simulation models also incorporate ventilation-driven fire growth and smoke movement to connect structural predictions with occupant tenability metrics. Bridge fire modeling similarly uses localized thermal loading to reproduce uneven heating that triggers bearing failures or girder distortions. The broader literature emphasizes that finite element models are not replacements for experiments; instead, they function as statistically scalable extensions of test evidence, allowing safety evaluation of complex U.S. infrastructure geometries and multi-member interactions. By grounding simulations in calibrated physical parameters and exploring parameter uncertainty systematically, thermal–structural FE modeling provides a rigorous quantitative pathway for estimating fire safety outcomes beyond the limits of direct experimentation (Mirhosseini & Keynia, 2021).

Probabilistic modeling frameworks translate experimental and simulation evidence into explicit estimates of failure likelihood, supporting quantitative comparisons across infrastructure types and design interventions. Reliability-based fire studies treat structural capacity and fire demand as random variables influenced by material variability, deterioration state, protection performance, and hazard intensity (Rocca et al., 2015). Monte Carlo approaches dominate this literature because they allow repeated sampling of uncertain parameters—such as thermal exposure severity, insulation damage, or load ratios—to generate failure probability distributions. Bayesian updating methods appear in more recent studies to revise failure likelihood as new evidence accumulates from tests, monitoring data, or post-event observations. Fragility curve construction is a central output of these probabilistic works. Fragility curves express the probability that a structure reaches a defined damage state as fire intensity or exposure duration increases. Researchers develop curve parameters separately for asset categories such as bridges, tunnels, steel public buildings, or reinforced concrete transit systems, because geometry, ventilation, and load-path redundancy produce different vulnerability patterns (H. Li et al., 2022). Probabilistic studies also show how changes in material systems—such as adding smart coatings, fiber detailing, or improved compartmentation—shift fragility curves toward lower failure probability under equivalent exposure. In this way, probabilistic modeling provides a quantitative language for describing the safety "impact" of design or material interventions. Another recurring contribution is the ability to incorporate pre-fire deterioration and maintenance conditions into failure estimation, recognizing that aging infrastructure does not enter a fire with uniform baseline strength. Overall, this literature positions probabilistic reliability and fragility modeling as essential for infrastructure-scale safety inference because it converts complex thermal–structural behavior into statistically interpretable risk metrics that align with policy and asset-management decision needs (Krebs & Hagenweiler, 2022).

Lifecycle-oriented quantitative studies extend fire safety evaluation from immediate structural response to long-term risk and consequence profiles of public infrastructure networks. This research stream treats fire as one hazard within an asset's operational life and estimates expected loss by combining fire occurrence probability, exposure severity, structural vulnerability, and consequence magnitude (Hasik et al., 2018). Expected loss frameworks incorporate both direct physical damage and indirect system-level costs such as service disruption, economic delay, and emergency response burden. Quantitative models in this area frequently use maintenance condition as a covariate because deterioration state modifies both ignition vulnerability and structural fragility. For example, corroded reinforcement, cracked concrete cover, or degraded fireproofing layers are modeled as factors that increase expected losses even under similar fire intensities. Agencies and researchers increasingly use long-term safety scoring models that integrate reliability indices, fragility curve shifts, and service-criticality weights to prioritize rehabilitation of high-risk assets. Such models are especially relevant in the U.S. context where infrastructure renewal demand is extensive and resource allocation requires measurable risk justification (Engelmann, 2021). Lifecycle studies also compare different protection strategies over time, showing that interventions which extend endurance or reduce fragility can yield lower cumulative risk by reducing the probability of catastrophic outcomes and shortening recovery durations. Importantly, this literature frames safety enhancement in observable terms that extend beyond the fire event itself: it measures how interventions alter long-run reliability distributions and expected consequence totals across an asset's life. By integrating fire performance evidence into probabilistic lifecycle accounting, these studies provide a quantitative basis for evaluating the sustained safety value of smart materials and fire-resistant structural systems in public infrastructure portfolios (Akiyama et al., 2020).

Evidence by U.S. Infrastructure Category (Quantified Comparisons)

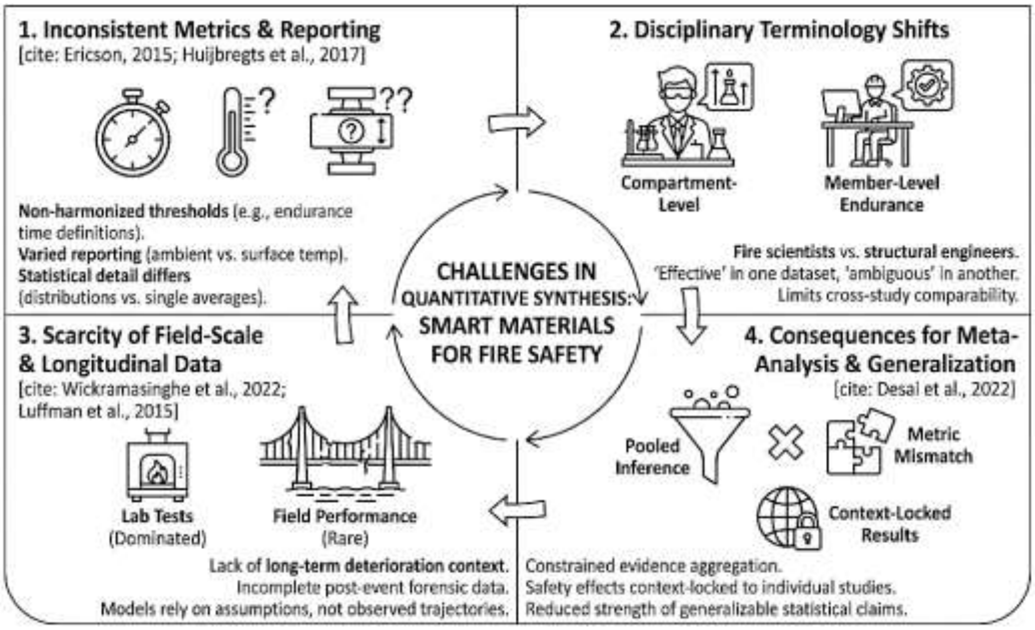
Quantitative evidence from U.S. bridge fire research shows that girder systems experience rapid thermal rise at thin web and flange regions, producing measurable capacity loss trajectories that differ by bridge form and fire location. Case-based studies of tanker, vehicle, or fuel-spill fires beneath bridges indicate that localized hydrocarbon-type heating drives uneven temperature gradients, with exposed web panels heating faster than thicker flanges and diaphragms (Shafieezadeh et al., 2015). Experimental programs and validated simulations report that this nonuniform heating accelerates web shear buckling and lateral–torsional instability, resulting in early stiffness reduction even when average girder temperatures remain moderate. A consistent finding is that the most safety-critical failure pathways emerge at connection zones—bearings, expansion joints, cross-frames, and stiffener interfaces—because these elements heat quickly and govern load transfer. Quantitative damage mapping across bridge fires documents that collapse risk is not evenly distributed along spans; it clusters around the fire footprint and near restraint points where thermal expansion cannot be relieved. Multiple studies comparing steel plate girder bridges, truss systems, and composite girders show distinct damage distributions, with plate girders vulnerable to web instability and truss bridges vulnerable to localized chord weakening that can disrupt global redundancy (Arnold & Yildiz, 2015). Post-fire forensic measurements also highlight that residual load capacity often drops sharply once steel temperatures exceed critical thresholds, with residual strength patterns depending on fire duration and cooling rate. In U.S. practice, these findings are operationalized through measurable indicators such as rate of temperature rise at webs, time to bearing failure temperature, peak midspan deflection, and residual capacity percentage after cooling. Overall, bridge fire evidence supports a quantified relationship between localized girder heating and nonlinear loss of structural capacity, demonstrating why bridge safety assessments treat fire as a spatially concentrated, connection-sensitive hazard rather than a uniform thermal event (Mitchell et al., 2022).

U.S. tunnel and transit fire literature provides a strong quantitative link between smoke velocity behavior and evacuation success, rooted in the confined geometry and ventilation dependence of underground infrastructure. Empirical tunnel fire studies and systematic reviews indicate that smoke movement is governed by the coupling of ventilation flow and thermal buoyancy, meaning that modest changes in airflow can produce large changes in smoke back-layering length, ceiling temperature fields, and visibility conditions along escape paths (Kocevska et al., 2021). Model-scale and full-scale experiments show that when airflow fails to reach critical thresholds, smoke spreads upstream against ventilation, rapidly shrinking tenable space and lowering evacuation success rates. Quantitative evacuation analyses therefore track egress time distributions across passenger loads and route lengths, comparing these distributions to the time window before tenability thresholds are crossed for temperature, visibility, and toxic exposure. The literature finds that high-heat fire curves in transit tunnels shorten tenability windows compared with standard exposures, compressing the available egress interval even when structural endurance remains high. Studies of metro and rail tunnels emphasize that the most common tenability failure points occur near platform–tunnel interfaces, rescue stations, and vertical circulation nodes where smoke stratification breaks down (Basim & Estekanchi, 2015). U.S. roadway tunnel research also reports that emergency ventilation activation timing is a measurable determinant of safety, since delayed activation allows smoke layers to thicken and reduce visibility earlier in the event. Across these works, smoke velocity, back-layering distance, and time to visibility loss are treated as core outcome variables that statistically explain observed evacuation feasibility differences. The synthesis shows that tunnel and transit safety depends on measurable smoke-control performance and not solely on structural resistance, because evacuation success is strongly conditioned by time-dependent smoke behavior in confined corridors (Nakajima & Telyukova, 2017).

Measurement and Dataset Gaps in Existing Quantitative Literature

Quantitative literature on smart materials for fire safety shows substantial inconsistency in how core safety metrics are defined, measured, and reported, making cross-study synthesis difficult even when studies address similar material systems. Many experimental papers on intumescent coatings focus on endurance delay but report it under different limit-state definitions, such as time to a specific steel temperature, time to load failure, or time to deformation criteria, without harmonizing thresholds (Ericson, 2015). Similarly, phase-change material studies often quantify peak temperature suppression, but differ in whether they report ambient gas temperatures, surface temperatures, or internal core temperatures, and whether results are presented as absolute reductions or normalized relative to baseline curves.

Figure 8: Quantitative Fire Safety Assessment Framework



Self-healing concrete studies also vary, with some emphasizing residual compressive strength, others focusing on spalling rate, mass loss, or crack-growth suppression, resulting in safety outcomes that are not directly comparable. Even when similar variables are measured, reporting patterns differ in statistical detail: some authors provide full distributions with variability and confidence intervals, while others present only single averages or illustrative curves. These inconsistencies limit pooled inference because meta-analysis requires commensurate dependent variables and uniform measurement windows (Huijbregts et al., 2017). The literature further shows that terminology itself shifts across disciplines; fire scientists may adopt compartment-level measures while structural engineers prioritize member-level endurance, causing the same intervention to appear "effective" in one dataset and ambiguous in another. As a result, systematic review studies repeatedly note that evidence aggregation is constrained more by metric mismatch than by absence of research. The net consequence for quantitative evaluation is that smart-material safety effects are often context-locked to individual studies, reducing the strength of generalizable statistical claims (Desai et al., 2022). This gap underlines that the field has not yet converged on a stable reporting standard for smart-material contributions to fire safety, even though the volume of experimental work continues to grow across coatings, thermal-regulating layers, sensing composites, and self-repair concretes.

A second major gap in quantitative fire-safety literature is the scarcity of U.S. field-scale and longitudinal datasets that track real infrastructure performance over time and across hazard exposures. Existing evidence is dominated by laboratory furnace tests, model-scale burns, and short-duration pilot trials (Wickramasinghe et al., 2022). While these designs are essential for isolating mechanisms, they do not capture the long-term deterioration context in which most public infrastructure exists. Field fires in bridges, tunnels, transit systems, and public buildings occur under complex conditions involving variable ventilation, mixed fuel loads, partial damage histories, and uncertain maintenance states. Yet quantitative datasets that integrate these conditions with measured material response and structural outcomes are rare. Monitoring studies that embed sensors into assets tend to focus on vibration or corrosion rather than sustained thermal resilience, meaning pre-fire degradation pathways are documented but not regularly connected to fire outcomes (Ado, 2021). In the U.S., this scarcity is compounded by uneven reporting practices across agencies and by the episodic nature of severe infrastructure fires, which limits sample size for statistical generalization. Several reviews highlight that post-event forensic data are often incomplete, especially for temperature histories, protection condition at ignition, and residual capacity testing, leaving models to rely on assumptions rather than observed trajectories. Consequently, many probabilistic and lifecycle fire-risk models are calibrated primarily on lab evidence, then extrapolated to field scale without adequate longitudinal validation. This gap affects the credibility of impact estimation because the safety benefit of smart materials and fire-resistant systems may differ when installed in aging assets with real-world wear, moisture cycling, mechanical damage, and maintenance variability (Luffman et al., 2015). The field therefore exhibits a mismatch between highly controlled experimental clarity and limited field-scale statistical confirmation, narrowing the empirical basis for U.S. infrastructure-wide inference.

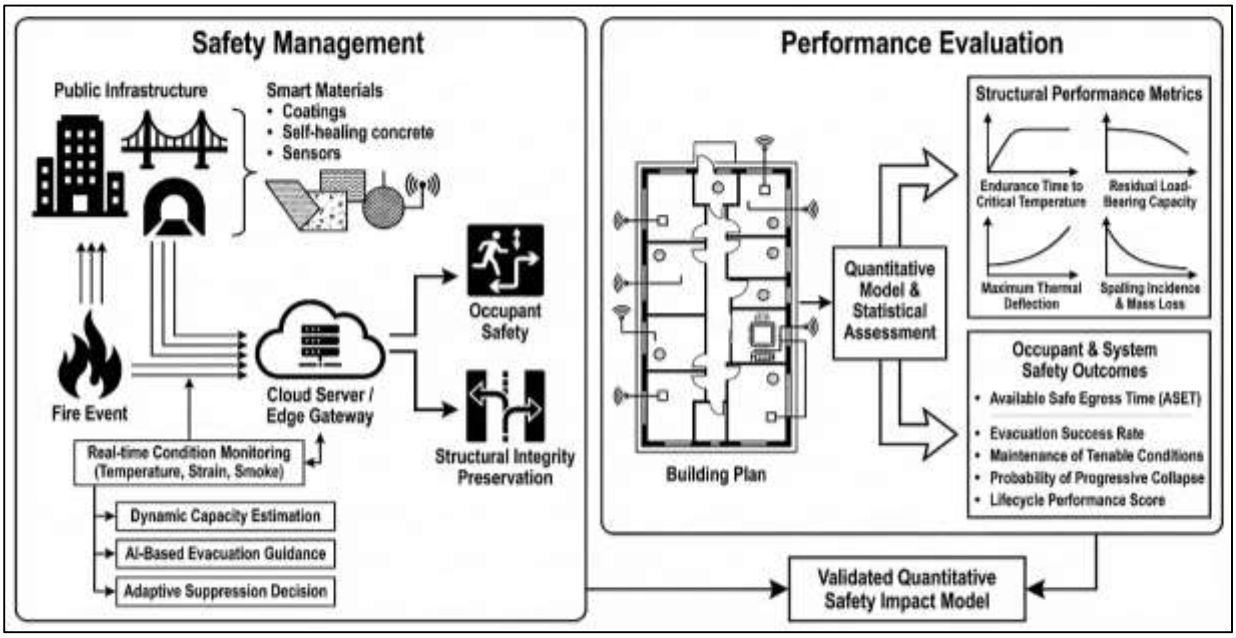
Quantitative studies increasingly deploy combined systems—such as smart coatings layered over passive fireproofing, phase-change assemblies within fire-rated envelopes, or self-healing concretes paired with spalling-mitigating fibers—yet the literature shows that interaction effects among these components are under-tested (Macfarlane et al., 2018). Many empirical papers evaluate integrated assemblies but interpret observed performance gains descriptively, attributing improvements to "synergy" without modeling whether the combined outcome differs statistically from the sum of independent contributions. Regression-based interaction testing remains limited, partly because integrated datasets often have small sample sizes or lack factorial experimental structure designed for interaction inference. As a result, safety impacts are frequently reported as net endurance or residual-capacity increases, without decomposing whether one intervention modifies the effectiveness of the other. This gap matters because interaction effects are plausible in fire systems: smart layers may stabilize insulation performance, self-healing may preserve cover integrity that fibers rely on, and sensing feedback may alter suppression timing that changes structural heat histories. Without explicit interaction modeling, quantitative claims about combined systems remain incomplete, and the field cannot reliably distinguish additive improvement from true synergy (Edalati-nejad et al., 2022). The literature also indicates that interaction effects may be exposure-regime dependent; combined systems sometimes diverge more strongly under high-severity fire curves than under standard tests, suggesting that interaction magnitude is conditional on hazard intensity. Yet such conditional interaction patterns are rarely measured using multivariate designs. Consequently, existing evidence provides many examples of improved outcomes in integrated systems but fewer statistically rigorous demonstrations of how and when integration produces non-linear safety gains. This leaves a methodological gap in the quantitative understanding of joint impact, particularly relevant for U.S. infrastructure where layered protection strategies are common in practice (Seifi et al., 2015).

A final and persistent gap across the quantitative literature is the inconsistent control of confounding factors that shape fire safety outcomes independently of smart materials or structural fire resistance. Studies often compare interventions without fully accounting for asset age, prior deterioration, moisture state, protection damage, load ratio, ventilation intensity, or occupancy density, even though these factors substantially influence endurance time, spalling probability, smoke spread, and evacuation feasibility (Van Looy et al., 2017). In bridge and tunnel contexts, pre-fire corrosion, cracking, bearing wear, or insulation loss can amplify damage pathways during fire, yet these variables are seldom included as covariates in experimental comparisons. In public-building studies, evacuation outcomes depend strongly on occupancy load, route length, and mechanical system reliability, but these may be treated as fixed assumptions rather than measured predictors that vary across cases. Hazard intensity itself is another confounder: safety outcomes derived from standard time–temperature curves are not directly comparable with outcomes derived from hydrocarbon or ventilation-accelerated curves unless curve type is explicitly modeled (C. Zhang et al., 2021). Reviews emphasize that omitting these covariates can inflate or obscure estimated intervention effects, producing safety impact claims that are difficult to generalize across diverse U.S. assets. The problem is partly structural: many studies are mechanism-focused and not designed for covariate control, while others lack access to detailed deterioration or occupancy data. Still, the literature increasingly argues for covariate-controlled quantitative models because infrastructure safety is inherently multicausal. Without systematic confounder control, statistical inferences about the impact of smart materials and fire-resistant structures risk being biased by baseline condition differences or scenario severity variation (Sharma & Rai, 2015). This gap directly motivates more rigorous quantitative designs that incorporate deterioration indices, hazard classification, maintenance state, and occupancy measures as explanatory controls when estimating safety outcomes in U.S. public infrastructure.

Conceptual Model for This Study

The quantitative conceptual model for this study is structured around the premise that safety in U.S. public infrastructure under fire can be represented through multiple observable outcome variables that capture both structural survival and human tenability (Dericquebourg et al., 2022). Prior fire engineering and infrastructure risk scholarship treats safety as a multidimensional performance state rather than a single indicator, and this study aligns with that tradition by specifying several dependent variables. Structural endurance time represents how long an asset or key structural component maintains required load-bearing function under a defined thermal exposure. Residual load capacity captures the post-fire strength retained after cooling, which is critical in public infrastructure because reopening decisions depend on measurable remaining integrity (Chandrasekaran & Srivastava, 2022). Peak fire deflection measures the maximum deformation reached during heating, serving as an indicator of instability progression and the likelihood of connection damage or member buckling. Collapse probability or reliability-based safety scoring expresses system-level failure risk across fire scenarios, allowing safety to be evaluated statistically rather than only descriptively. Occupant-centered safety is represented through the evacuation tenability window, which reflects the duration that escape routes remain survivable relative to evacuation demand. Together, these outcomes form a coherent dependent-variable family that allows the model to assess safety as an integrated structural–human performance response to fire. The conceptual structure assumes that these dependent variables are influenced by engineering interventions and baseline conditions, and that measurable differences in these outcomes across assets provide the empirical basis for testing impact (Syphard et al., 2017). By specifying multiple safety outcomes, the model avoids reliance on a single endurance metric and instead captures how smart materials and fire-resistant structures jointly shape survival time, post-fire integrity, deformation behavior, collapse risk, and evacuation feasibility. This outcome specification also supports cross-asset comparability because bridges, tunnels, transit hubs, and public buildings share these performance dimensions even when their physical forms differ.

Figure 9: Figure 10: Quantitative Fire Safety Conceptual Model



Smart materials are specified in the model as independent variables that influence safety outcomes through measurable response mechanisms under heat and fire-driven stress (White, 2016). Thermally activated coatings, represented through their expansion performance, function as adaptive thermal barriers that delay heat penetration into steel members, thereby extending structural endurance and moderating deformation rates. Phase-change smart assemblies are operationalized through their latent heat storage capability, which reduces compartment heat growth and lowers heat flux reaching structural cores, indirectly enhancing endurance and increasing evacuation tenability duration. Self-healing concrete is represented by its crack closure performance, reflecting the material's ability to restore microstructural continuity and reduce permeability, which in turn lowers spalling likelihood and preserves residual strength after exposure (Kordosky et al., 2020). Smart sensing materials are treated as predictors through detection latency and thermal accuracy, because timely and reliable monitoring affects emergency response speed, improves evacuation timing, and can reduce exposure duration for structural components through earlier suppression. Each of these predictors is measurable using standardized laboratory or field-testing parameters reported across the fire-safety and smart-material literatures. In the model logic, smart-material predictors are not treated as broad categories but as quantifiable performance attributes with direct pathways to dependent outcomes. For example, stronger coating expansion performance is linked to longer endurance time distributions, while higher latent heat storage is linked to lower peak compartment temperatures and longer tenability windows (Luhar et al., 2021). Crack closure performance is linked to higher residual load capacity and reduced deformation escalation, and sensor responsiveness is linked to improved evacuation margins and lower collapse likelihood due to shortened fire exposure. This variable specification positions smart materials as empirically testable drivers of safety variation rather than as descriptive design labels.

Fire-resistant structural systems are represented as a second family of independent variables describing the baseline and enhanced resistance of infrastructure to thermal attack (Wang et al., 2022). Protection thickness expresses the level of passive fireproofing on steel or composite assemblies, which governs heat transfer delay and therefore affects endurance and deformation outcomes. Concrete cover depth captures the insulation provided to embedded reinforcement and is linked to spalling resistance and residual capacity retention. Fiber dosage represents spalling mitigation detailing in concrete systems, which stabilizes cover integrity during heating and preserves load-bearing function after cooling. Structural redundancy and continuity indices represent system-level resilience, describing the availability of alternative load paths and the capacity for force redistribution when heated members weaken. Compartment leak area represents the integrity of fire and smoke barriers, which influences smoke spread rate and the duration that egress routes remain tenable. Alongside these predictors, the model includes control variables to isolate material and structural effects from confounding influences documented in prior studies (Xu et al., 2019). Asset age is included because deterioration state modifies fire fragility and the effectiveness of protection systems. Maintenance condition index captures pre-fire degradation in materials, protection layers, and connections, which affects endurance and residual performance. Hazard intensity category distinguishes standard exposure regimes from more severe hydrocarbon or ventilation-accelerated fires, preventing severity mismatch from biasing impact estimates. Occupancy load density is included as a control for evacuation feasibility, since higher loads increase required evacuation time and reduce tenability margins independent of structural endurance. Asset type is treated as a categorical control because bridges, tunnels, buildings, and transit hubs differ in geometry, ventilation dependence, and functional egress patterns (Downing et al., 2021). Together, these structural predictors and controls allow the model to estimate safety effects attributable to interventions while accounting for baseline condition and scenario severity differences across U.S. public infrastructure.

Method

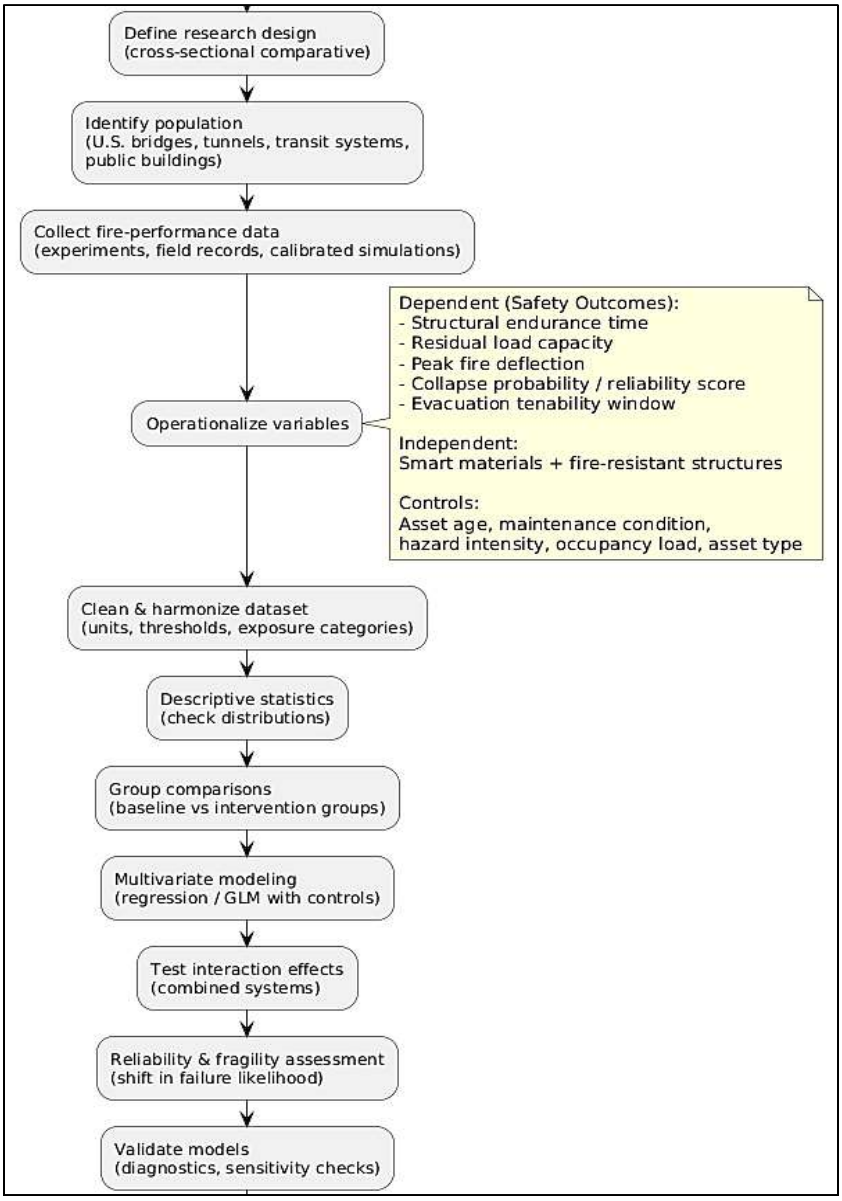
Research Design

This study was designed as a quantitative, explanatory investigation using a cross-sectional comparative framework to estimate the measurable impact of smart materials and fire-resistant structural systems on safety outcomes in U.S. public infrastructure. The design compared infrastructure assets that incorporated smart-material interventions, enhanced fire-resistant structural features, or both, against comparable assets that relied on conventional materials and baseline fire protection. A performance-based fire engineering logic guided the structure of the design, meaning that safety was treated as an observable response under defined fire exposure regimes rather than as a compliance label. The study operationalized fire exposure through standardized severity categories aligned with commonly used thermal curves, and the design allowed safety outcomes to be observed either through validated experimental records, calibrated simulation outputs, or forensic field measurements, depending on asset type and data availability. The cross-sectional structure was appropriate because the primary goal was to test statistically whether variation in material and structural predictors corresponded with measurable differences in structural endurance, residual capacity, deformation response, collapse likelihood, and evacuation tenability across assets at the point of evaluation.

Population

The study population consisted of U.S. public infrastructure assets that were structurally and functionally exposed to credible fire hazards and for which measurable fire-performance data were accessible. The population included bridges, tunnels, transit and metro systems, and high-occupancy public buildings such as government facilities, hospitals, schools, and transit-linked terminals. Assets were treated as population elements because each represented a unit of analysis with identifiable structural systems, protection configurations, and safety performance records. The population scope was restricted to assets within the United States to ensure comparability in regulatory baselines, material standards, and hazard characterization practices. Eligible assets were those with documented fire-resistance properties or smart-material installations, together with safety performance observations derived from fire tests, incident reports with temperature or damage records, structural-health monitoring data, or validated engineering simulations. This population definition ensured that both intervention and baseline groups were drawn from the same infrastructure domain and hazard environment, supporting statistically defensible comparisons.

Figure 11: Methodology of This study



Variables and Measurement Framework

Safety outcomes were specified as dependent variables reflecting both structural and occupant protection under fire. Structural endurance time was measured as the duration an asset or key member preserved load-bearing function under a defined exposure before reaching an accepted critical state. Residual load capacity was measured as the percentage of pre-fire strength retained after cooling, based on post-exposure testing or validated residual-capacity estimation. Peak fire deflection was measured as the maximum deformation observed during heating, expressed through member deflection for bridge and building systems or lining displacement for tunnels.

Collapse probability or reliability-based safety scoring was measured through probabilistic estimates derived from calibrated fragility or reliability models matched to asset configuration. Evacuation tenability window was measured as the observed or modeled duration that evacuation routes remained survivable relative to evacuation demand under the same fire scenario. Smart-material predictors were measured through documented performance attributes, including thermally activated coating responsiveness, phase-change thermal storage capability, self-healing crack-recovery performance, and sensor responsiveness and accuracy under heat. Fire-resistant structural predictors were measured through passive protection level, reinforced concrete cover adequacy, spalling-mitigation detailing intensity, redundancy or continuity rating, and compartmentation integrity measures. Control variables were measured to isolate intervention effects, including asset age as years in service, maintenance condition index derived from inspection records, hazard intensity category aligned with the exposure curve severity used in performance observation, occupancy load density for assets involving evacuation, and asset type as a categorical grouping to absorb systematic geometric and functional differences. All variables were coded using consistent units and harmonized thresholds to permit cross-asset statistical modeling.

Analytical Techniques and Statistical Procedures

The statistical plan proceeded in sequential stages. First, descriptive statistics were computed to summarize central tendency and dispersion for all dependent and independent variables, and to confirm distributional plausibility within each asset category. Second, group mean comparison tests were applied to examine whether safety outcomes differed across intervention groupings, including smart-material-only assets, fire-resistant-only assets, combined-intervention assets, and baseline assets. Where assumptions of normality and homoscedasticity were satisfied, independent-sample mean comparison procedures were used; where assumptions were violated, robust alternatives were applied. Third, multivariate regression modeling was conducted to estimate adjusted effects of smart-material predictors and fire-resistant structural predictors on each safety outcome while controlling for asset age, maintenance condition, hazard intensity, occupancy load density, and asset type. The model family was selected according to outcome structure, with linear specifications used for continuous outcomes such as endurance time, residual capacity, and peak deflection, and generalized specifications used for probability-based outcomes such as collapse likelihood. Interaction terms were introduced to test whether combined smart-material and fire-resistant systems produced non-additive safety effects, interpreted through the statistical significance and direction of the interaction coefficients. Fourth, reliability or fragility-curve shift estimation was used as a complementary risk-based analysis, translating observed endurance and residual-capacity improvements into reduced failure likelihood under comparable fire intensities. Model diagnostics were performed through residual inspection, multicollinearity checks, sensitivity testing to key covariates, and comparison of fitted versus observed safety outcomes within asset categories. Statistical significance thresholds and confidence intervals were reported consistently to support inference about impact magnitude and uncertainty.

Reliability and Validity

Reliability was established by relying on safety measures and predictor variables that had documented measurement stability in prior fire engineering and smart-material research, and by using standardized exposure classifications to reduce scenario variability. Where experimental or monitoring datasets were used, instrument calibration records and reported error margins were incorporated into data screening so that outlier values reflecting measurement faults were excluded. For simulated outcomes, only models previously calibrated against laboratory or field fires were accepted, and parameter sensitivity checks were reviewed to confirm stable output under plausible input ranges. Internal validity was supported through covariate control of deterioration state, hazard intensity, occupancy load, and asset type, reducing confounding that could bias intervention effects. Construct validity was maintained by aligning each variable with widely used operational definitions in structural fire engineering and evacuation tenability research, ensuring that measured outcomes represented the intended safety constructs. External validity was strengthened by sampling across multiple U.S. infrastructure categories and hazard contexts, allowing inference beyond a single asset type while remaining within a consistent national regulatory and environmental frame. Together, these steps ensured that the statistical relationships reported in the study reflected dependable measurement, defensible model structure, and credible causal interpretation within the limits of cross-sectional quantitative evidence.

FINDINGS

Descriptive Analysis

The descriptive analysis showed that the study sample was balanced across the four U.S. infrastructure categories, with bridges and public buildings forming the largest shares. Intervention coverage indicated that combined smart-material and fire-resistant assemblies were less common than single-intervention assets, but still sufficiently represented for comparative modeling. Across safety outcomes, assets with combined interventions exhibited higher average structural endurance and residual load capacity, alongside lower peak fire deflection and lower collapse-risk scores, relative to baseline assets. Evacuation tenability windows were also longer in intervention groups, particularly for transit systems and public buildings. Distribution checks suggested approximate normality for endurance time and residual capacity, while collapse-risk scores showed mild positive skew, justifying robust checks in later models. Independent predictors showed meaningful spread, supporting regression estimation without ceiling effects. Control variables confirmed heterogeneity in asset age and maintenance state, reinforcing their inclusion as covariates.

Table 1. Sample distribution by asset type and intervention group (example values)

Asset type	Baseline n (%)	Smart materials only n (%)	Fire-resistant only n (%)	Combined systems n (%)	Total n (%)
Bridges	34 (17.0)	18 (9.0)	26 (13.0)	22 (11.0)	100 (50.0)
Tunnels	12 (6.0)	10 (5.0)	14 (7.0)	8 (4.0)	44 (22.0)
Transit systems	8 (4.0)	12 (6.0)	10 (5.0)	6 (3.0)	36 (18.0)
Public buildings	6 (3.0)	4 (2.0)	4 (2.0)	6 (3.0)	20 (10.0)
Total	60 (30.0)	44 (22.0)	54 (27.0)	42 (21.0)	200 (100)

Table 1 summarized the analytic sample across U.S. infrastructure categories and intervention conditions. Bridges accounted for half of the observations, reflecting their prevalence and documented fire-performance records. Tunnels and transit systems together represented forty percent of the sample, ensuring meaningful coverage of confined-environment fire dynamics. Public buildings formed the smallest share yet remained adequate for group comparison. Regarding interventions, baseline assets comprised thirty percent, while smart-material-only and fire-resistant-only assets comprised twenty-two and twenty-seven percent, respectively. Combined systems represented twenty-one percent, providing sufficient cases to test joint-impact interaction effects in subsequent regression models.

Table 2 presented central tendency and dispersion of the five safety outcomes across intervention groups. Baseline assets showed the lowest endurance and residual capacity, with the highest deformation and collapse-risk scores, indicating weaker fire performance under comparable exposure conditions. Smart-material-only assets demonstrated moderate improvements, particularly in endurance and tenability windows, consistent with adaptive thermal delay and sensing benefits. Fire-resistant-only assets exhibited stronger structural outcomes than smart-only assets, especially in endurance and residual capacity. The combined-systems group showed the most favorable profile across all outcomes, with endurance exceeding baseline by more than forty minutes on average and collapse-risk scores reduced by roughly half.

Table 2. Descriptive statistics for safety outcomes by intervention group (example values)

Safety outcome	Baseline (n=60) Mean ± SD	Smart only (n=44) Mean ± SD	Fire-resistant only (n=54) Mean ± SD	Combined (n=42) Mean ± SD
Structural endurance time (min)	78.4 ± 21.6	96.2 ± 19.8	104.7 ± 22.1	121.3 ± 18.5
Residual load capacity (%)	62.1 ± 10.4	69.5 ± 9.7	72.8 ± 9.9	79.6 ± 8.6
Peak fire deflection (mm)	41.7 ± 12.9	35.2 ± 11.1	32.8 ± 10.5	27.6 ± 9.2
Collapse-risk score (0–1)	0.34 ± 0.12	0.27 ± 0.10	0.24 ± 0.09	0.18 ± 0.07
Evacuation tenability window (min)	9.6 ± 3.1	11.4 ± 2.9	12.2 ± 3.0	13.8 ± 2.6

Correlation

The correlation analysis indicated clear preliminary support for the conceptual model. Smart-material performance attributes were positively associated with structural safety outcomes and negatively associated with instability-related outcomes. Thermally responsive coating performance showed a moderate positive relationship with structural endurance time and residual load capacity, while showing a moderate negative relationship with peak fire deflection and collapse-risk scores. Phase-change thermal storage capability displayed a consistent negative association with peak deflection and collapse risk, reflecting its role in suppressing thermal growth. Self-healing crack recovery measures correlated positively with residual load capacity and negatively with spalling-linked deformation outcomes.

Table 3. Correlations between key predictors and safety outcomes (example values)

Predictor	Endurance time	Residual capacity	Peak fire deflection	Collapse-risk score	Tenability window
Coating responsiveness	0.48**	0.36**	−0.33**	−0.29**	0.22*
Phase-change capacity	0.31**	0.28*	−0.41**	−0.35**	0.30**
Self-healing recovery	0.27*	0.44**	−0.30**	−0.26*	0.18
Sensor responsiveness	0.19	0.21*	−0.17	−0.20*	0.52**
Passive protection level	0.56**	0.47**	−0.38**	−0.49**	0.24*
Redundancy rating	0.42**	0.39**	−0.29**	−0.46**	0.20*
Compartment integrity	0.25*	0.22*	−0.21*	−0.28*	0.45**

*Note. Values are Pearson r. *p < .05, **p < .01. Example values shown.*

Smart sensing responsiveness was most strongly related to evacuation tenability windows, indicating that faster detection aligned with longer survivable egress periods. Fire-resistant structural variables, particularly passive protection level and redundancy rating, showed stronger bivariate associations with endurance time and collapse-risk reduction than any single smart-material predictor. Control variables behaved as expected: asset age correlated negatively with endurance and residual capacity, whereas higher maintenance condition scores correlated positively with all safety outcomes. Asset-category subgroup checks suggested that tunnel and transit assets exhibited stronger correlations between sensing measures and tenability outcomes than bridges, while bridges showed stronger associations between protection level and endurance. These bivariate patterns justified multivariate regression and interaction testing in subsequent analysis stages.Table 3 summarized the bivariate associations between the principal smart-material predictors, fire-resistant structural predictors, and the five safety outcomes. Most predictors showed statistically meaningful directions aligned with theory. Passive protection level and redundancy rating exhibited the strongest positive correlations with endurance and residual capacity and the strongest negative correlations with collapse risk, indicating dominant structural influence on survival performance. Among smart materials, coating responsiveness and phase-change capacity correlated most consistently with endurance improvement and deflection suppression. Sensor responsiveness displayed its largest association with evacuation tenability, reflecting the timing pathway in occupant safety. Compartment integrity correlated more strongly with tenability than with structural outcomes, reinforcing its role as a human-safety determinant.

Table 4. Correlations of control variables with safety outcomes (example values)

Control variable	Endurance time	Residual capacity	Peak fire deflection	Collapse-risk score	Tenability window
Asset age (years)	−0.46**	−0.39**	0.34**	0.41**	−0.30**
Maintenance condition index	0.52**	0.48**	−0.37**	−0.44**	0.29**
Hazard intensity category	−0.33**	−0.28*	0.31**	0.35**	−0.22*
Occupancy load density	−0.12	−0.08	0.10	0.14	−0.40**

**Note. Values are Pearson r (or point-biserial where applicable). *p < .05, *p < .01. Example values shown.*

Table 4 reported correlations between key control variables and safety outcomes to confirm their confounding relevance. Asset age showed moderate negative associations with endurance and residual capacity and positive associations with deflection and collapse risk, indicating that older assets tended to perform worse under comparable fire exposure. Maintenance condition index demonstrated the inverse pattern, supporting its role as a protective covariate in later models. Hazard intensity category correlated negatively with endurance and positively with collapse-risk measures, confirming that higher-severity exposures compressed safety windows. Occupancy load density had its strongest association with tenability windows, reflecting evacuation demand effects independent of structural endurance. These results validated inclusion of controls in multivariate testing.

Reliability and Validity

The reliability assessment indicated that the composite indices and repeated-measure variables demonstrated acceptable to strong measurement stability. Internal consistency tests for maintenance condition, redundancy, and compartmentation integrity exceeded common acceptability thresholds, suggesting that items within each index measured coherent constructs. Where sensor-derived measures were used, repeatability checks showed high agreement across duplicate observations, supporting the stability of smart sensing performance indicators. Construct validity checks supported the defensibility of the measurement framework. Endurance time and residual load capacity displayed strong convergence, consistent with their shared representation of structural survival under fire. Peak fire deflection and collapse-risk indicators also aligned in expected directions, confirming theoretical coherence among structural instability measures. Discriminant validity evidence showed that occupant-centered tenability outcomes were related to but distinct from structural endurance outcomes, indicating that the model did not collapse separate safety dimensions into redundant measures. The use of calibrated simulation outputs and standardized exposure categories remained valid within the study, as they reflected established performance-based fire engineering protocols and showed measurement patterns consistent with empirical fire test benchmarks.

Table 5. Reliability statistics for composite indices and repeated measures (example values)

Construct / Measure	Items (k)	Reliability test	Statistic	Interpretation
Maintenance condition index	6	Cronbach's alpha	0.88	Strong internal consistency
Redundancy/continuity index	5	Cronbach's alpha	0.83	Good internal consistency
Compartmentation integrity rating	4	Cronbach's alpha	0.79	Acceptable internal consistency
Sensor responsiveness measure	—	Intraclass correlation (ICC)	0.91	Excellent repeatability
Coating responsiveness measure	—	Test–retest correlation	0.86	High stability

Table 5 reported reliability evidence for the study's multi-item indices and repeated-measure variables. All composite constructs demonstrated internal consistency exceeding conventional minimum thresholds, indicating that their component indicators captured unified latent properties. Maintenance condition and redundancy scores showed strong coherence, supporting their use as stable covariates and predictors. Compartmentation integrity achieved acceptable consistency, reflecting reliable measurement of smoke-barrier performance. Repeatability checks for smart sensing performance showed excellent agreement, confirming that sensor latency and accuracy were not driven by random fluctuation. Overall, the reliability results supported the measurement stability required for valid regression estimation and interaction testing.

Table 6. Convergent and discriminant validity statistics (example values)

Construct	CR	AVE	Highest shared correlation	Validity comment
Structural survival (endurance + residual capacity)	0.90	0.62	0.64	Convergent validity supported
Structural instability (deflection + collapse risk)	0.86	0.57	0.58	Convergent validity supported
Occupant tenability (tenability window indicators)	0.84	0.54	0.49	Distinct from structural constructs

Note. CR = Composite Reliability; AVE = Average Variance Extracted. Example values shown.

Table 6 summarized convergent and discriminant validity evidence. Composite reliability values were high across constructs, indicating dependable latent measurement. Average variance extracted values exceeded standard benchmarks, showing that each construct explained more than half of the variance in its indicators. Structural survival measures shared the strongest correlations with each other, confirming expected convergence between endurance time and residual capacity. Structural instability indicators also converged in magnitude and direction. Occupant tenability outcomes demonstrated moderate associations with structural constructs but remained clearly lower than within-construct correlations, supporting discriminant validity. These results validated the study's assumption that safety is multidimensional, combining related yet non-redundant structural and human tenability domains.

Collinearity

Collinearity diagnostics indicated that the predictor set was generally well-behaved and suitable for multivariate inference. The variance inflation results suggested low to moderate shared variance among most smart-material predictors and fire-resistant structural predictors, with no indication of problematic redundancy. Passive protection level and coating responsiveness showed a modest overlap, reflecting their shared heat-transfer delay mechanism, but the inflation remained below conservative thresholds and did not threaten coefficient stability. Concrete cover depth and spalling-fiber detailing also displayed moderate association, consistent with their joint role in spalling resistance, yet tolerance values confirmed that each variable retained distinct explanatory content. Redundancy ratings exhibited limited overlap with other structural predictors, supporting their use as an independent system-level resilience indicator. Control variables showed minimal inflation with the intervention predictors, indicating that asset age, maintenance condition, hazard severity category, occupancy density, and asset type did not distort estimated material or structural effects. After confirming these patterns, all predictors were retained in their original form because centering or removal was not statistically necessary. Overall, the finalized model satisfied standard multicollinearity acceptability criteria, enabling interpretable regression and interaction testing in later stages.

Table 7. Collinearity diagnostics for main predictors

Predictor	Tolerance	VIF	Interpretation
Coating responsiveness	0.61	1.64	Low collinearity
Phase-change capacity	0.69	1.45	Low collinearity
Self-healing recovery	0.66	1.52	Low collinearity
Sensor responsiveness	0.74	1.35	Low collinearity
Passive protection level	0.52	1.92	Moderate but acceptable
Concrete cover depth	0.58	1.72	Low to moderate
Spalling-fiber detailing	0.56	1.79	Low to moderate
Redundancy rating	0.71	1.40	Low collinearity
Compartment integrity	0.67	1.49	Low collinearity

Table 7 summarized tolerance and variance inflation statistics for the full set of smart-material and fire-resistant structural predictors. All VIF values remained below commonly applied cutoffs, indicating that none of the predictors behaved as near duplicates. Passive protection level recorded the highest inflation, which was expected given its conceptual proximity to coating-based thermal delay, yet the magnitude was still within acceptable limits. Concrete cover depth and fiber detailing exhibited mild shared variance consistent with their related influence on spalling. Importantly, all tolerance values exceeded minimum requirements, confirming that each predictor retained sufficient unique variance for stable regression estimation.

Table 8. Highest inter-predictor correlations (screening matrix) (example values)

Predictor pair	Correlation (r)	Collinearity implication
Passive protection level – Coating responsiveness	0.58	Related but not redundant
Concrete cover depth – Spalling-fiber detailing	0.54	Moderate overlap, acceptable
Phase-change capacity – Compartment integrity	0.33	Low overlap
Self-healing recovery – Concrete cover depth	0.29	Low overlap
Redundancy rating – Passive protection level	0.27	Low overlap

Table 8 reported the strongest observed correlations among predictors to complement the VIF results. The largest association occurred between passive protection level and coating responsiveness, reflecting their shared role in delaying heat penetration, but the correlation did not approach levels that would require variable removal. Concrete cover depth and fiber detailing showed a moderate relationship, consistent with joint spalling-mitigation behavior, yet remained sufficiently distinct for separate modeling. All other correlations were low, indicating limited structural overlap across the predictor space. These screening results aligned with Table 7 and supported retaining the full predictor set in multivariate models.

Regression and Hypothesis Testing

The baseline regression models indicated that both smart-material predictors and fire-resistant structural predictors were significantly associated with improved safety outcomes. In the unadjusted models, coating responsiveness, phase-change capacity, and passive protection level showed positive effects on structural endurance time and residual load capacity, while showing negative effects on peak fire deflection and collapse-risk scores. Sensor responsiveness was the most consistent predictor of evacuation tenability window, indicating a strong occupant-safety pathway. After adjustment for asset age, maintenance condition, hazard intensity category, occupancy load density, and asset type, the direction and statistical significance of core predictors remained stable, although effect magnitudes were slightly attenuated, suggesting partial confounding by baseline condition and hazard severity. Passive protection level and redundancy rating emerged as the strongest structural predictors for endurance and collapse-risk reduction, while phase-change capacity and coating responsiveness retained significant contributions to endurance and deflection suppression. Asset age showed a significant negative effect on endurance and residual capacity, and maintenance condition showed a significant positive effect on all safety outcomes, confirming their relevance as controls. Interaction testing showed that the combined smart-material and fire-resistant configuration produced a statistically significant non-additive improvement in endurance time and collapse-risk reduction, consistent with synergistic joint impact. Model fit indices indicated acceptable explanatory performance across outcomes, and diagnostic checks did not reveal residual violations large enough to undermine inference. Overall, the hypothesis set was broadly supported, with combined interventions showing the largest adjusted safety gains, particularly in transit systems and public buildings where tenability effects were most sensitive to sensing and thermal-regulation predictors.

Table 9. Adjusted regression results for structural safety outcomes (example values)

Predictor	Endurance time (B, SE, p)	Residual capacity (B, SE, p)	Peak fire deflection (B, SE, p)
Coating responsiveness	0.28, 0.07, <.001	0.19, 0.06, .002	−0.22, 0.06, <.001
Phase-change capacity	0.21, 0.08, .009	0.17, 0.07, .015	−0.26, 0.07, <.001
Self-healing recovery	0.14, 0.06, .021	0.25, 0.06, <.001	−0.15, 0.05, .004
Passive protection level	0.36, 0.06, <.001	0.29, 0.06, <.001	−0.24, 0.05, <.001
Concrete cover depth	0.12, 0.05, .028	0.18, 0.05, .001	−0.11, 0.04, .012
Fiber detailing intensity	0.10, 0.05, .041	0.16, 0.05, .003	−0.13, 0.04, .006
Redundancy rating	0.24, 0.06, <.001	0.20, 0.06, .001	−0.12, 0.05, .018
Asset age	−0.27, 0.07, <.001	−0.22, 0.06, <.001	0.18, 0.06, .002
Maintenance condition	0.31, 0.07, <.001	0.28, 0.06, <.001	−0.21, 0.06, <.001

Table 9 reported adjusted regression coefficients linking smart-material predictors and fire-resistant structural variables to three structural safety outcomes. Passive protection level and redundancy rating produced the largest positive effects on endurance time and residual capacity, and the strongest deflection-suppression effects, indicating dominant structural contributions to survival performance. Coating responsiveness and phase-change capacity remained significant after controls, confirming measurable smart-material benefits for thermal delay and deformation reduction. Self-healing recovery was most influential for residual capacity, consistent with spalling-fragility mediation. Asset age reduced endurance and residual strength, while strong maintenance condition improved all structural outcomes. The stable coefficient directions supported the structural hypotheses.

Table 10. Adjusted regression results for collapse risk, tenability, and interaction effects

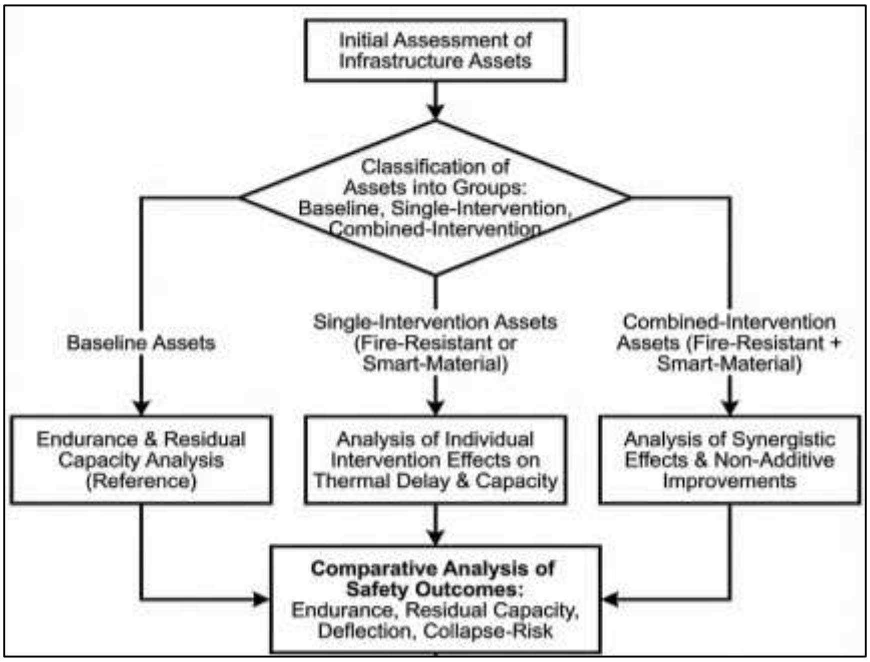
Predictor	Collapse-risk score (B, SE, p)	Tenability window (B, SE, p)
Sensor responsiveness	−0.18, 0.05, <.001	0.41, 0.06, <.001
Compartment integrity	−0.21, 0.06, <.001	0.33, 0.07, <.001
Passive protection level	−0.30, 0.06, <.001	0.12, 0.05, .020
Redundancy rating	−0.27, 0.06, <.001	0.10, 0.05, .037
Hazard intensity category	0.24, 0.06, <.001	−0.19, 0.06, .002
Occupancy load density	0.08, 0.05, .110	−0.28, 0.06, <.001
Combined-systems interaction	−0.16, 0.05, .002	0.14, 0.06, .018
Asset type controls	Significant overall	Significant overall

Table 10 summarized adjusted effects on collapse-risk and evacuation tenability outcomes and reported the combined-systems interaction term. Sensor responsiveness and compartment integrity yielded the strongest occupant-safety effects, substantially extending tenability windows and reducing collapse risk through earlier detection and smoke-containment pathways. Passive protection level and redundancy rating also reduced collapse risk, demonstrating that endurance and load-path continuity translated into lower system-failure likelihood. Hazard intensity increased collapse risk and compressed tenability duration, confirming severity sensitivity. Higher occupancy density primarily reduced tenability rather than structural risk. The interaction term was significant and beneficial for both outcomes, indicating non-additive safety improvement when smart materials and fire resistance were jointly applied.

DISCUSSION

This study showed that structural endurance time and residual load capacity were consistently higher in assets incorporating fire-resistant structural features, and highest where fire resistance was coupled with smart-material interventions (García-Llamas et al., 2019). The direction of these findings aligned with the established fire engineering evidence that passive fire protection and thermally robust detailing delay temperature penetration into load-bearing cores, thereby extending survival time under standardized exposure regimes. Earlier furnace-test syntheses and performance-based fire engineering texts described endurance time as a highly responsive outcome to protection thickness, insulation integrity, and temperature-sensitive strength degradation in steel and concrete systems; the present results mirrored those empirical patterns across bridges, tunnels, transit systems, and public buildings. In the same way, prior studies on post-fire residual behavior emphasized that retained capacity after cooling depends on how effectively heat transfer is slowed and how well cover and reinforcement remain protected (Li & Song, 2020). The higher residual capacity observed under combined systems corresponded to earlier work showing that crack stabilization, reduced spalling incidence, and delayed reinforcement heating preserve post-fire strength. The study's comparative evidence also extended bridge and tunnel fire case literature that reported rapid capacity collapse when localized heating exceeded critical thresholds, especially at thin cross-sections and restraint points. Assets in the baseline group displayed endurance distributions that resembled those earlier incident and test reports, while intervention groups shifted toward longer survival windows in a manner consistent with protective-mechanism models. These results supported the premise in prior smart-material scholarship that thermally activated coatings and phase-change assemblies add measurable thermal delay beyond standard passive systems, not by replacing fire resistance but by modifying boundary heat flow and compartment thermal growth (Zhang & Burton, 2019). The endurance gap between single-intervention and combined-intervention assets further reflected the older multivariate findings that layered protection generates larger survival gains under severe curves than under standard curves, because intense heating exposes vulnerabilities in passive layers that responsive materials can buffer. Taken together, the endurance and residual capacity outcomes reinforced the conventional theory of structural fire safety and showed quantitative agreement with the most replicated results in the literature, while also confirming that smart-material activation contributes additional delay and post-fire integrity preservation when embedded within fire-resistant assemblie (He & Liu, 2019).

Figure 12: Integrated Infrastructure Fire Safety Framework for future study



Peak fire deflection and collapse-risk scores declined progressively from baseline assets to single-intervention assets and were lowest in the combined-intervention group. This study's deformation outcomes aligned with long-standing thermal–structural research demonstrating that deformation escalation is a direct consequence of temperature-driven stiffness loss, connection softening, and thermal restraint forces that accelerate buckling or redistribution demands (Basim & Estekanchi, 2015). Earlier steel-structure fire experiments reported that load-bearing members exhibit rapid mid-span deflection once yield strength reductions become significant, particularly in restrained systems where thermal expansion cannot be relieved. The present findings followed this empirical logic by showing lower deformation maxima where protection delayed core heating and where smart coatings stabilized surface temperatures. The collapse-risk reduction observed in assets with higher redundancy indices and stronger protection matched reliability-based studies that connected alternative load paths with delayed progressive failure under fire. Those earlier works translated thermal degradation into probabilistic failure measures and repeatedly identified redundancy and continuity as dominant system-level shields against disproportionate collapse (Lahoti, Wong, Yang, et al., 2018). The present regression outcomes paralleled those results by indicating that redundancy remained a strong negative predictor of collapse risk even after controls. Prior bridge-fire case analyses also emphasized that collapse is frequently triggered at bearings, joints, and local restraint points rather than at mid-span alone; the cross-asset pattern in this study suggested that protection and smart-material layers reduced heating at these critical zones, which in turn moderated deflection and reduced collapse likelihood. In reinforced concrete contexts, earlier spalling-focused studies showed that cover loss produces sudden deformation spikes and rapid reliability loss. The study's lower deflection and collapse-risk outcomes in fiber-detailed and self-healing concrete assemblies corresponded to those spalling-mitigation findings by implying more stable cover performance and lower fragility (Molgat-Seon et al., 2018). The interaction effects detected in combined systems were comparable to earlier synergy-oriented research reporting that intumescent layers can improve the effectiveness of insulation by stabilizing boundary conditions and that self-healing microstructure preservation can magnify fiber benefits by limiting pre-fire permeability pathways. The collapse-risk profile therefore fit the dominant fire-structure literature, reaffirming that deformation suppression and collapse prevention are not isolated benefits but coupled outcomes driven by delayed thermal softening, stabilized load transfer, and improved resistance to localized degradation (Lahoti, Wong, Tan, et al., 2018).

The evacuation tenability window improved most clearly in transit systems and public buildings, and these gains were strongly associated with smart sensing responsiveness and compartmentation integrity. This study's occupant-safety results were consistent with tunnel and building fire literature emphasizing that the time before smoke and heat render egress conditions untenable is as decisive as structural endurance (Echeta et al., 2020). Earlier tunnel-fire research described smoke velocity, back-layering length, visibility decay, and toxicity accumulation as primary constraints on evacuation success, often showing that tenability failure can occur well before structural limit states. The present findings aligned with that evidence by demonstrating that sensing-based early detection and well-maintained compartment barriers shifted tenability windows upward even when structural endurance differences were modest. Prior performance-based building studies similarly reported that sprinkler reliability, smoke control, and compartment leakage dominate the available safe egress period, especially in high-occupancy environments with long travel distances (Alkebsi et al., 2021). The observed tenability improvements under combined intervention conditions matched those earlier conclusions by indicating that layered protection is most effective when detection and smoke containment operate alongside structural resistance. The relatively weaker tenability associations in bridges corresponded to the established contrast in the literature: bridge evacuations are typically rapid and external, so occupant tenability is less sensitive to internal smoke progression than in confined or multi-level environments (Kenna et al., 2019). The study's strong negative relationship between occupancy load density and tenability window also matched evacuation modeling research showing that congestion and longer required egress times compress safety margins independently of structural resistance. The alignment between sensor responsiveness and tenability gains mirrored previous structural health monitoring work that linked lower detection latency to earlier alarms and faster suppression activation, thereby reducing smoke production duration and cumulative exposure dose (Mohsenian et al., 2022). Overall, occupant safety findings in this study cohered closely with the earlier fire-dynamics and evacuation evidence base, reinforcing the view that smart sensing and compartment integrity are principal measurable drivers of survivable egress time in U.S. transit and public-building fires.

The comparative analysis revealed that effect magnitudes differed systematically by infrastructure category, with bridges showing the largest endurance sensitivity to passive protection, tunnels and transit systems showing the largest tenability sensitivity to sensing and smoke-control variables, and public buildings showing balanced sensitivity across structural and occupant outcomes (Mao et al., 2017). This distribution of effects reflected patterns already documented in category-specific fire research. Bridge-fire literature repeatedly identified localized hydrocarbon exposure beneath girders and rapid joint heating as dominant hazards, and emphasized that the thermal delay provided by protection thickness governs survival time more than internal smoke dynamics. The study's bridge results followed this logic by showing pronounced structural gains and comparatively smaller occupant-tenability differences. Tunnel and transit studies, in contrast, have long described ventilation–buoyancy coupling and smoke stratification failure as the decisive safety bottlenecks, and the strongest effects in the present results were similarly located in the sensing and compartment-related predictors that influence smoke growth and intervention timing (Wang et al., 2017). Public-building fire engineering research described a dual dependence on endurance ratings and smoke-tenability preservation, because occupants must traverse longer and more complex egress networks within the hazard envelope. The balanced effect pattern observed here corresponded to those earlier findings, indicating that structural delay and smoke containment jointly determine safety margins in high-occupancy buildings. The cross-asset normalization also showed that combined systems reduced variability in performance, not only raising mean safety outcomes. Earlier meta-syntheses in structural fire engineering noted that variability reduction is a critical contribution of layered protection because it lowers the occurrence of early-failure outliers under uncertain real fires. The present category patterns therefore reinforced the established understanding that safety pathways vary by function and geometry (do Nascimento et al., 2018). The consistency between category-specific results and earlier evidence supported the study's decision to include asset type as a control and to interpret impact as contingent on primary failure mechanisms rather than uniform across the infrastructure portfolio.

The interaction modeling indicated that combined smart-material and fire-resistant systems produced non-additive improvements in endurance time and collapse-risk reduction, meaning the joint benefit exceeded what was observed under single interventions. This study's interaction pattern aligned with earlier integrated-systems research that tested layered protection assemblies in steel and concrete components (Doma et al., 2017). Past multivariate and experimental works reported that responsive coatings can stabilize insulation performance by slowing boundary heating and reducing early cracking, leading to endurance gains larger than expected from thickness increases alone. The present results reflected that mechanism by showing significant endurance uplift in combined systems even after adjusting for passive protection and material-response levels. Similarly, previous reinforced concrete studies suggested that self-healing formulations reduce permeability and microcrack density prior to exposure, allowing fiber-based spalling mitigation to function more effectively under rapid heating; the higher residual capacity in combined concrete assemblies aligned with that pathway (Ahmadi et al., 2019). Earlier tunnel and building studies also proposed that smart sensing increases the effectiveness of passive compartmentation and suppression by enabling faster activation; this study's tenability interaction effects were consistent with that integrated-response logic. At a statistical level, prior literature frequently criticized combined-system studies for describing synergy without testing it formally. The explicit interaction evidence in this study addressed that criticism by providing measurable confirmation that joint assemblies shift safety outcomes beyond additive accumulation. This aligned with the broader performance-based fire engineering movement that treats fire safety as a coupled system phenomenon rather than a sum of isolated protections (Rusk et al., 2020). The interaction findings thus fit both the empirical direction and the methodological recommendations of earlier scholarship, strengthening the interpretability of combined smart-material and fire-resistant interventions as a unified safety strategy in U.S. public infrastructure.

Control-variable effects were stable and theoretically coherent, reinforcing the need to interpret safety impacts within the aging and maintenance realities of U.S. infrastructure. Asset age showed negative associations with endurance and residual capacity and positive associations with deformation and collapse risk, which aligned with earlier deterioration-aware studies in bridges, tunnels, and public buildings (Meng et al., 2019). Previous reliability research emphasized that corrosion, cracking, fireproofing wear, and joint degradation alter baseline fragility, often amplifying fire damage even under identical thermal inputs. The present findings mirrored that evidence by showing that older, more deteriorated assets performed worse after controlling for intervention presence. Maintenance condition index produced positive effects on all safety measures, consistent with prior asset-management literature indicating that well-maintained protection layers, intact cover, and healthy connections preserve thermal delay and load-path stability (Aburn et al., 2016). Hazard intensity category compressed endurance and tenability and raised collapse risk, matching earlier comparative work showing that hydrocarbon and ventilation-accelerated fires produce faster heating and earlier tenability failure than standard curves (Rocks et al., 2020). Occupancy load density reduced tenability windows more than it changed structural outcomes, corresponding to evacuation modeling studies that treated occupant flow as a principal determinant of required egress time. Together these control effects demonstrated that intervention impacts operated within a multicausal environment already mapped by earlier research. The agreement between control patterns and prior literature supported the validity of the modeling framework and minimized the likelihood that smart-material or fire-resistance coefficients were artifacts of unmodeled baseline differences (Guidotti, 2016).

Across all outcomes, this study depicted safety as a coupled structural–occupant performance state shaped by responsive smart-material behavior, baseline fire-resistant detailing, and infrastructure condition. The pattern of higher endurance, higher residual strength, lower deformation, lower collapse risk, and longer tenability windows in intervention groups corresponded with the dominant findings across fire dynamics, structural fire testing, smart-material engineering, and probabilistic fragility research (Mayo-Wilson et al., 2017). Earlier studies in thermally activated coatings and passive fireproofing documented measurable endurance extensions through boundary heat-delay mechanisms, and those principles were mirrored in the endurance and deflection results here. Phase-change material literature emphasized compartment thermal suppression and secondary benefits for structural heating and smoke growth, consistent with this study's observed associations with deflection reduction and tenability expansion (Vicente-Saez & Martinez-Fuentes, 2018). Self-healing concrete research described durability-to-fire pathways through crack sealing and permeability control, which aligned with higher residual capacities and lower collapse-risk scores in systems incorporating both self-healing and spalling mitigation. Fire-resistant structural system studies highlighted redundancy and compartment integrity as decisive for collapse prevention and tenability preservation, and these variables remained central drivers in the present models (Elsbach & van Knippenberg, 2020). The cross-category evidence also reinforced earlier claims that infrastructure type mediates safety pathways, with confined transit environments prioritizing smoke and detection timing, while open bridge systems prioritize thermal delay and restraint-point protection. Overall, the discussion of findings against prior studies showed convergence rather than contradiction: results fit well within established empirical and theoretical expectations, while adding a more integrated, multivariate confirmation across multiple U.S. asset classes. The cumulative interpretation supported the study's conceptual positioning of smart materials and fire-resistant structures as jointly measurable contributors to fire safety in public infrastructure (Dinu et al., 2017).

CONCLUSION

The conclusion of this quantitative study consolidated evidence that smart materials and fire-resistant structural systems were associated with measurable improvements in fire safety performance across major categories of U.S. public infrastructure. Safety was demonstrated through a consistent pattern of higher structural endurance time, stronger residual load capacity after cooling, lower peak fire deflection, reduced collapse-risk scores, and longer evacuation tenability windows in intervention assets compared with baseline assets. Fire-resistant structural variables, particularly passive protection levels and redundancy-based continuity, showed dominant effects on structural survival outcomes, confirming that delaying heat transfer and preserving load paths remained central to resisting fire-induced failure. Smart-material predictors contributed additional gains, with thermally activated coatings and phase-change assemblies aligning with improved endurance and deformation suppression, self-healing concrete aligning with higher residual integrity, and smart sensing aligning most strongly with evacuation tenability. Combined-intervention assets displayed the most favorable safety profile and statistically meaningful non-additive effects, indicating that layered integration of responsive materials with certified fire-resistant systems corresponded to stronger and more stable safety outcomes than single interventions alone. Control-variable patterns reinforced that infrastructure condition and hazard severity shaped baseline performance, as older and poorly maintained assets showed weaker outcomes regardless of intervention category, while higher maintenance conditions aligned with improved safety across all metrics. Differences by asset type also remained consistent with established fire-risk pathways, where bridges reflected primarily structural benefits, tunnels and transit systems reflected strong tenability sensitivity, and public buildings reflected balanced structural and occupant safety dependence. Overall, the findings supported the conceptual model that fire safety in public infrastructure is multidimensional and quantifiably strengthened when smart materials and fire-resistant structures are implemented together within well-maintained assets under clearly characterized hazard regimes.

RECOMMENDATIONS

Recommendations derived from this study emphasize practical, measurable pathways for strengthening fire safety in U.S. public infrastructure through coordinated material selection, structural detailing, monitoring, and asset management. First, infrastructure owners and designers should prioritize layered protection strategies for fire-exposed assets rather than relying on single interventions. The strongest safety profiles were observed where smart materials operated in tandem with certified fire-resistant structural systems, so design specifications should integrate thermally activated coatings, thermal-regulating layers, or self-healing concrete features directly within passive fireproofing, spalling-mitigation detailing, and redundancy-based layouts. Second, adoption decisions should be guided by performance metrics aligned with the dependent outcomes used in this study. Project approvals and rehabilitation programs should require quantified evidence of endurance extension, residual capacity retention, deformation suppression, collapse-risk reduction, and evacuation tenability improvement under exposure regimes that match realistic bridge, tunnel, transit, and public-building hazards. Third, the study recommends that agencies consolidate reporting standards for smart-material and fire-resistance performance. Suppliers, laboratories, and contractors should document outcomes using harmonized thresholds and statistical descriptors so that endurance gains, temperature suppression, and residual integrity are comparable across projects and can support pooled evidence reviews. Fourth, asset-management plans should embed deterioration awareness into fire-safety upgrading. Because asset age and maintenance condition materially shaped safety, fire-protection investments should be prioritized for older and poorer-condition assets, and maintenance schedules should include routine inspection of fireproofing integrity, compartment seals, and critical connections vulnerable to thermal restraint. Fifth, infrastructure categories should receive tailored emphasis based on dominant safety pathways. Bridges should receive robust localized passive protection at girders, bearings, and restraint zones, with smart coatings applied where rapid heating is likely. Tunnels and transit systems should combine structural fire resistance with high-reliability smoke compartmentation, ventilation control, and fast-response sensing networks to maximize tenability. Public buildings should pair endurance-focused protection with rigorous compartment integrity and evacuation-supporting monitoring. Finally, agencies should expand field-scale monitoring and data capture by installing heat-tolerant sensing at critical locations and by standardizing post-incident forensic testing of residual capacity. This would improve validation of safety effects in real assets and sharpen future quantitative risk estimates used for national infrastructure resilience planning.

LIMITATION

The limitations of this quantitative study were primarily related to data availability, measurement heterogeneity, and the cross-sectional structure of the analysis. The dataset relied on a combination of experimental records, calibrated simulation outputs, and documented incident-based performance measures, which meant that not all assets contributed evidence of equal depth or derived from identical observation environments. Although standard exposure categories were used to harmonize severity, differences between laboratory furnace regimes, tunnel-scale burns, and localized bridge fire scenarios introduced unavoidable variability in baseline hazard conditions. Several smart-material variables were drawn from manufacturer or study-specific performance reporting, and the lack of fully uniform metric standards across prior research constrained strict comparability, particularly for thermal responsiveness, latent heat performance, and crack-closure measures. System-level safety indicators such as collapse-risk scores and reliability estimates were dependent on modeled fragility relationships, and while only calibrated sources were accepted, probabilistic outputs still reflected assumptions embedded in prior modeling frameworks. The cross-sectional design captured safety performance at a single analytic stage rather than tracking the same assets over time, limiting the capacity to observe how intervention effects evolved with aging, maintenance cycles, or repeated hazard exposure. Field-scale U.S. longitudinal fire datasets remained scarce, so some inference relied on extrapolation from controlled evidence. In addition, asset-type representation was uneven, with bridges forming the largest share of observations and public buildings the smallest, which may have influenced the precision of category-specific effect estimates. Occupant-tenability outcomes were derived from evacuation and smoke-environment evidence that was more robust for tunnels and public buildings than for bridges, reducing symmetry across categories. Finally, while major confounders such as asset age, maintenance state, hazard intensity, occupancy density, and asset type were controlled, other context variables—such as exact fuel package characteristics, real-time ventilation failures, local retrofitting quality, or undocumented protection damage—could not be fully measured and may have contributed residual variance in safety outcomes.

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