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REVIEW ARTICLE

An in-depth examination of fire-related damages in reinforced concrete structures-A review

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Abstract
Ensuring fire safety measures is a fundamental necessity in the design of buildings to safeguard the well-being of their occupants. Fire-related incidents pose a substantial danger to the integrity of reinforced concrete structures, even though concrete itself is inherently noncombustible. The exposure of concrete to high temperatures can lead to the deterioration of its characteristics related to chemical, physical and mechanical aspects. This review paper provides an in-depth examination of fire-related damages in reinforced concrete structures. With a focus on enhancing understanding and mitigation strategies, the paper explores the complexities surrounding fires in these structures, which serve as homes and functional spaces for numerous people over their planned lifespan. Key objectives include investigating how reinforced concrete structures respond post-fire and exploring assessment techniques for high-rise structures affected by fire damage. Through analysis of various damage phases and identification parameters, the review offers insights into post-fire structural behavior. Additionally, the paper presents future suggestions aimed at improving active and operational conditions, thereby contributing to the advancement of fire safety in reinforced concrete structures.

Keywords Assessment techniques · Damage phases · Structural behavior · Operational conditions · Building design · Well-being · Noncombustible · High temperatures · Deterioration

1 Introduction

Fire disasters are a prevalent and devastating issue worldwide, particularly in underdeveloped nations. Reinforced concrete (R–C) structures displayed impressive resilience, withstanding intense flames without complete collapse. However, most fire disasters are less severe and allow for recovery [1]. Structures encounter various dangers, including earthquakes, hurricanes, fires, and explosions which can lead to structural damage, endangering lives and causing substantial financial losses [2]. Fully developed fires can generate temperatures exceeding 1000°C, deteriorating materials such as steel, wood, and concrete, sometimes resulting in irreversible structural damage. This jeopardizes a building's safety during subsequent hazards [3–9]. Fires in buildings present a substantial risk to human life and safety, especially during both the pre-flashover and post-flashover stages, where poisonous gases like carbon monoxide and hydrogen cyanide are released. Smoke and hot gases can obscure escape routes and reduce oxygen levels, increasing the risk of toxic inhaling gases and experiencing burns. Property damage due to fires amounts to billions of dollars globally [10–12]. Furthermore, fires contribute to environmental pollution, releasing hazardous chemicals into the environment through smoke, firefighting activities, and water contamination. These results in environmental degradation, impacting air, aquatic, and terrestrial ecosystems to ensure the safety of both individuals and the environment, buildings must be designed to withstand various anticipated risks, including fires [13]. Fire damage significantly affects reinforced concrete (R–C) structures, but concrete retains better mechanical properties at high temperatures compared

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to steel and wood. This implies that fire-damaged concrete buildings may still be usable, provided the residual strength of concrete members is assessed accurately [14]. In conclusion, fire is a major hazard that can degrade (R–C) structures, necessitating thorough assessments of fire damage and appropriate treatment techniques to ensure safety and environmental friendliness throughout a building's design life.

2 The purposes of this examination

This article aims to explore the challenges associated with fires in RC buildings. Most structures are designed to endure for many decades, serving as homes and functional spaces for numerous people throughout their planned lifespan. The primary goals of this research are to enhance our comprehension of how (R–C) structures respond after experiencing a major fire and to delve into the techniques employed to assess high-rise structures after being affected by fire damage. Within this analysis it delves into the various phases of damage that (R–C) structures undergo post-fire, including discussions on various identification parameters. It offers future suggestions pertaining to active and operational conditions (Fig. 1).

3 Deterioration of reinforced concrete structures caused by fire

Damage to RC structures following a fire typically does not result in complete destruction [1]. However, conducting a post-fire assessment is crucial because the condition of the concrete in these buildings is not uniform throughout the cross-section. The concrete layer near the surface tends to experience the most significant deterioration [16]. Even with the damage and lingering deformations that may require maintenance (R–C) structures generally maintain stability after fire incident. Numerous scholars have conducted research into the performance of fire damaged concrete structures [14]. When compared to stainless steel and wood structures, reinforced concrete buildings offer impressive natural fire resistance [3]. This is a result of the fact that as fire penetrates the member cross-section, the concrete layer acts as insulation for the reinforcement, allowing to ensuring the building's load-bearing capacity remains relatively high both during and after a fire. It is worth noting that high strength concrete is less fire resistant than ordinary concrete, whilst lightweight concrete exhibits greater fire resistance. However, unlike steel and wood, concrete is seldom entirely obliterated in a fire [17]. Exposure to high temperatures leads to the degradation of concrete's thermal, physical, and chemical properties, affecting its mechanical characteristics [18]. The exceptional thermal characteristics of different types of concrete, including normal concrete, high-strength concrete, lightweight concrete,shotcrete, and mortars, exhibit similarities [19]. Reinforced concrete beams and slabs near the ceiling which experience increased exposure to upward convective currents during a fire, making them more susceptible to damage [20]. RC structures, when properly maintained after a fire incident, often retain significant residual ability owing to its excellent fire-resistant properties of concrete. Consequently, reusing the structure in the future is frequently feasible. However, heat-induced degradation can result in irreversible loss of strength and serviceability.

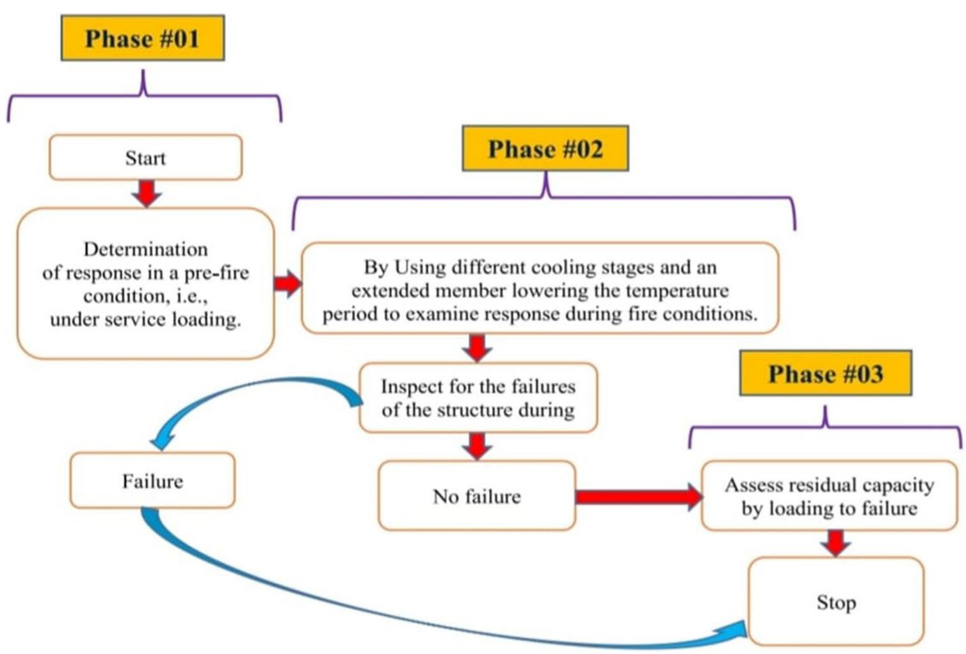

Fig. 1 Assessment of the Remaining Load-Bearing Capacity in Reinforced Concrete [15]

Thus, a comprehensive assessment of the remaining capacity becomes crucial to make informed choices regarding future utilization and the need for the restoration of structures damaged by fire [21] (Figs. 2 and 3).

3.1 Evaluating the structural impact of fire on reinforced concrete: assessing residual strength

To accurately assess the influence impact of a fire on the structural load-bearing capacity and safety of a structure, it is crucial to measure the remaining strength of the concrete. This information can determine the structure's suitability for future use and identify the nature and extent of necessary repairs, or necessitate the demolition of the damaged structure. In cases where structural components have been significantly affected by fire, damages and areas of concrete deterioration are readily visible and identifiable [15]. However, in evaluating less damaged components through the initial visual assessment, observing alterations in the concrete's appearance may not be apparent. For a more comprehensive understanding, laboratory and on-site testing can provide valuable insights into the condition and internal structure of the concrete. Among the various factors to consider after fire damage, concrete compressive strength stands out as one of the most critical. It is crucial to ascertain the thickness of the outer layer of the component where the concrete has been significantly impacted to be classified as damaged [22]. Researchers employ various types of fires, including standard fire, parametric fire, and natural flames to study RC structures. Parametric and natural fires are generally considered more accurate representations of real fires compared to conventional fires [23]. In the assessment of structures following a fire, particular attention is given to determining the thickness of the outer portions where the concrete has been affected to a point where it should be considered as structurally compromised [16] (Fig. 4).

3.2 Evaluation of structural damage and failure analysis of fire exposure

Heat exposure significantly impacts the mechanical and thermal properties of both concrete and steel. This can result in a loss of strength and durability, leading to structural component impairments. The transfer of heat from the fire-affected area to other parts of the structure occurs through thermal propagation. In both concrete and reinforcing

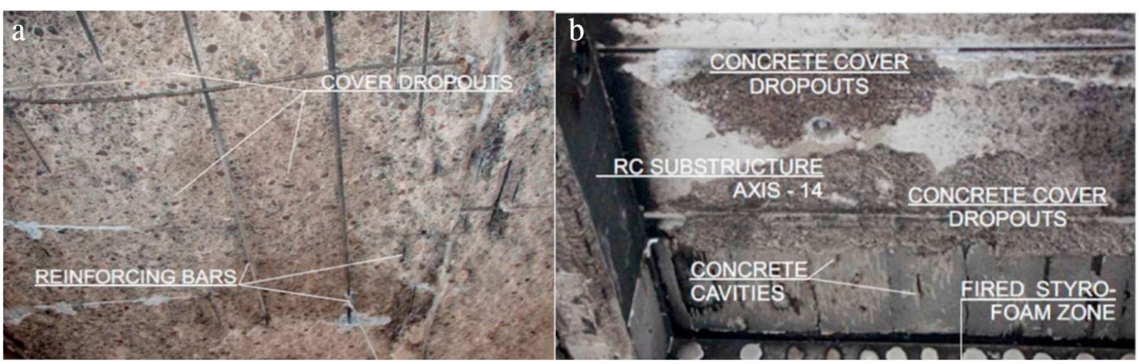

Fig. 2 Instances of floor slab damage (**a**) detachment of the cover in areas with reinforcing bars (**b**) localized cover defects [15]

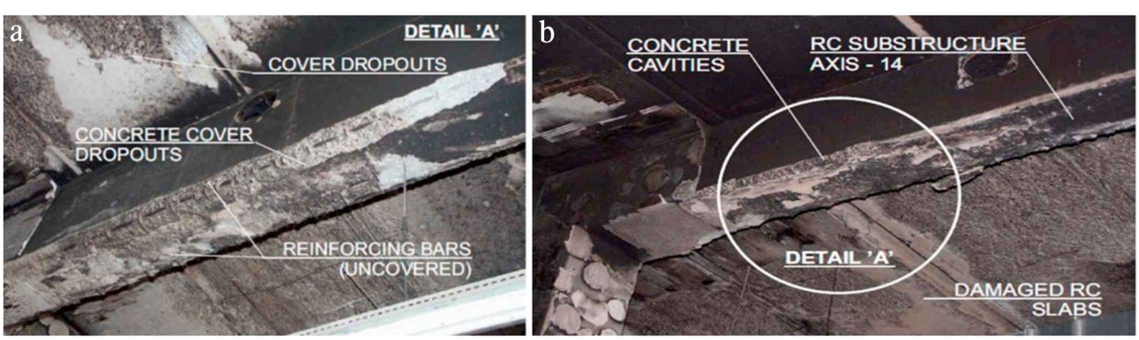

Fig. 3 Reinforcement covers loss at the edges (**a**) within the span area (**b**) within the support region

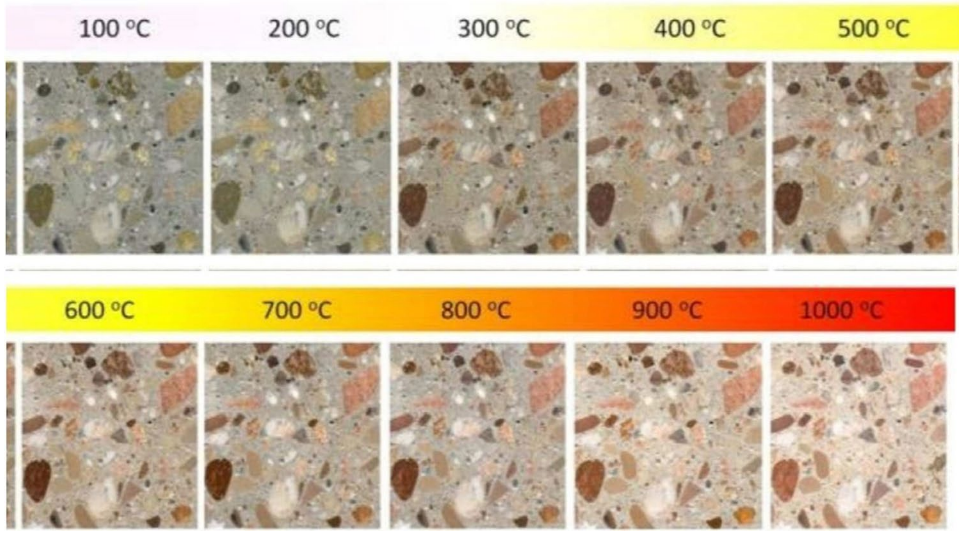

Fig. 4 Change in Color of Heated Concrete: Surface with Visible Aggregates and Exterior of the Concrete Sample [24]

materials, the mechanical properties experience changes, including reductions in compression and tension strength, as well as fluctuations in strain [25]. Fires, particularly those following earthquakes, pose a significant threat to human civilization, with far-reaching consequences. The decline in concrete strength at elevated temperatures is associated with chemical-physical processes, and mechanical damage within the concrete microstructure plays a pivotal role in determining the load-bearing capacity of a building under fire conditions. This aspect has attracted considerable attention [26]. When assessing the load-bearing capacity of structures, concrete exposed to temperatures of 500–600 °C is generally considered to be compromised from a practical standpoint. Even after cooling, concrete's strength typically remains lower than that at room temperature [27]. Concrete's thermal inertia, especially in large-scale members exposed to fire for an extended duration, allows for prolonged temperature adjustments even after the heat source has been extinguished [16]. Collected experimental data illustrates a connection between concrete temperature and the degradation of relative compressive strength. The reduction in concrete strength at elevated temperatures is affected by multiple factors, such as aggregate type, concrete porosity, member size, duration of heating, and loading conditions [28]. Damage due to fire includes the loss of concrete cover along the longitudinal edges in support areas and local regions at the base of major beams, a consequence of the thermal expansion of reinforcing bars. Subsequent testing with a steel hammer revealed more extensive damage, with primary reinforcing bars exposed due to the removal of concrete cover. The absence of concrete cover, typically 35–45 mm thick, resulted in reduced compacted concrete near the supports. However, concrete in the primary beam areas and stirrups remained undamaged and demonstrated the desired strength class according to tests [15]. The research revealed several cases of concrete cover loss on the lower surfaces of precast panels, varying from 3 to 4 cm, due to thermal spalling. In certain instances, steel reinforcement was fully exposed, and some bars became detached from the inner concrete layer [15]. Consequently, the core of the member is exposed to higher temperatures for an extended period, leading to a reduction in concrete member strength. This process can continue for many hours after the fire has been extinguished. Another significant factor is the cooling rate, which results in a non-uniform temperature distribution within the member's cross-section, generating tension known as "self-equilibrating" tension. This tension increases as the cross-section temperature gradient becomes steeper, indicating faster cooling [29]. When compared to elements that cool naturally in the open air, the reduction in compressive strength can be as much as twice as significant [16]. It is commonly recognized that the favorable effect on concrete strength at high temperatures from compressive stress is equivalent to 20–40% of the strength at room temperature [27]. Continuous watering during a fire can led to rapid cooling, particularly with low-temperature components in the range of 300–350 °C, which are stiffer and more susceptible to stress-induced damage from fast cooling [29]. Changes in concrete color at various temperature ranges experiments have revealed that higher concrete strength leads to increased temperature rises because of greater density and thermal conductivity, facilitating faster heat transfer. These factors also influence the development of a moisture clog zone, resulting in temperature distribution variations across wall thickness, dependent on the heated region and concrete strength [30]. Additionally, the strength of steel reinforcement decreases as temperature rises. Concrete spalling plays a crucial role in reducing fire resistance when exposed to high temperatures [31]. The accumulation of pores during heating contributes to this breakdown, and high-strength concrete is considered more susceptible to pressure build-up due to its increased brittleness compared to ordinary concrete, resulting in reduced fire resistance. Codes of practice dictate that temperature increases can lead to weakening of strength in both steel and concrete, contingent on aggregate type and steel grade [31]. Numerous concrete testing techniques in buildings are currently in use, with previous studies providing comprehensive insights into concrete spalling [32, 33] (Fig. 5).

3.3 Petrographic analysis for evaluating fire-induced structural damage

Petrographic studies are essential for recognizing distinct minerals, rock textures, grain sizes, and the relative or quantitative proportions of different components in geological materials. Additionally, they provide insights into the physicochemical characteristics of stones and their stage of degradation, alongside precise typology [35]. Petrographic examinations are extensively employed to assess the extent of fire damage in reinforced concrete (RC) components, enabling a direct examination of microcracking and mineralogical alterations. Moreover, fire-damaged masonry structures constructed with stone, brick, and mortar can also undergo petrographic analysis, which aids in the precise identification of damaged geological materials. This approach leads to cost savings and enhances safety assurance during construction repairs [36]. In a separate study conducted by researchers conducted core strength tests and employed optical microscopy to investigate fire-damaged concrete. Samples were collected from concrete slabs exposed to heat, and laser microscopy was used to examine aggregate morphology, cement paste, cracks, and micro-voids. By evaluating the physical state of the concrete sample and conducting microscopic inspections, petrographers could reasonably estimate the minimum exposure temperature and its relative impact on the depth of concrete damage [37]. Petrographic examination was instrumental in confirming the presence of early-stage alkali-silica reaction (ASR) damage and identifying distinct micro-cracking patterns in specimens containing reactive fine aggregate (RFA) and reactive coarse aggregate (RCA). This observation could potentially explain discrepancies in linear resonance data. Notably, the results of nonlinear resonance tests on both RCA and RFA specimens effectively detected the onset of ASR damage and exhibited a significant correlation with ASR expansion across various mix designs. This underscores the high sensitivity and utility of the nonlinear resonance test in quantifying ASR damage in concrete specimens without requiring a baseline measurement [38]. In a different research effort a comprehensive analysis was conducted on the physical and chemical properties of historical concrete buildings in the Dominican Republic, encompassing their usage and construction between 1917 and 1955. These structures, designed and built by American and Dominican engineers, represent an entire generation of construction history. The study included a detailed examination of the concrete utilized during that period. Various analytical techniques were employed, including X-ray Diffraction (XRD), Scanning Electron Microscope with Energy-Dispersive X-ray Spectroscopy (SEM–EDS), X-ray Fluorescence (XRF), Mercury Intrusion Porosimetry (MIP), petrographic inspection, and Visual Testing (VT). The findings revealed that concrete composition evolved over time. Most of the samples exhibited typical peaks of crystalline phases, including quartz, albite, and calcite, albeit in varying proportions [39]. Petrographic analysis, conducted using the Carl Zeiss Jenapol petrographic microscope, involves examining a thin rock sheet,

Fig. 5 Deterioration of precast deck panels due to concrete spalling when subjected to elevated temperature [34]

typically around 30 µm thick (at such thin thicknesses, rocks become transparent). This technique enables direct scrutiny of a rock's mineralogy, texture, and composition based on its optical characteristics. However, it may have limitations in detecting extremely small minerals and is often complemented by microscopic inspection and X-ray diffraction. The examinations adhere to the ASTM C-856 standard and provide insights into factors such as compaction degree, paste matrix homogeneity, and cement dispersion. Chemical analysis results are integrated into the description of each sample, facilitating comparative analysis. For instance, Sample T1 comprises uniform-sized grains in various shades (cream, dark grey, light grey) within a light grey matrix. This sample features numerous altered quartz and feldspar crystals, some displaying mirmechitic textures indicative of breakdown from acidic igneous rocks. The aggregates appear semi-triangular and spherical, ranging in size from four to five millimeters down to less than 100 µm. Notably, there are no indications of alkali-silica reaction halos or deformation fractures, as illustrated in Fig. 6 [40]. Finally, the exploration of new deep learning methods for concrete petrographic analysis was undertaken by [41]. The study demonstrated the effectiveness of convolutional neural networks (CNN) in segmenting concrete images without relying on phenolphthalein to color the cement paste. In summary, CNNs have the potential to serve as a valuable tool for concrete petrographic analysis, contributing to improved machine-based visual comprehension [41] (Tables 1 and 2).

3.4 Deficiencies in firefighting systems for reinforced concrete (rc) structures

Despite the advancements in fire safety technology and prevention methods, fire incidents remain a leading cause of fatalities and property damage in commercial structures worldwide. Extensive research suggests that substandard materials and faulty electrical equipment are predominant

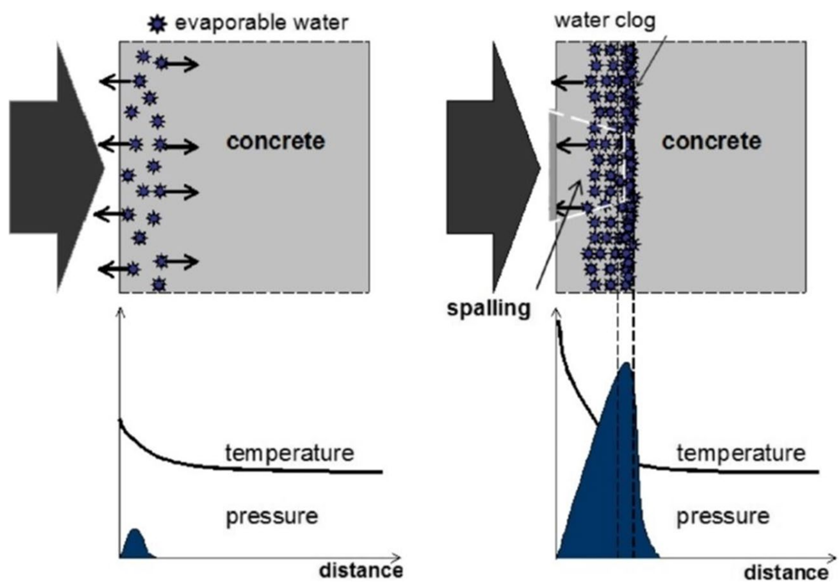

Fig. 6 Formation of water accumulation and internal pore pressure in heated concrete components [34]

Table 1 Fire safety examination checklist [42]

Examination	Primary investigation	Simple examination	Primary investigation Comprehensive analysis Mechanical testing	Material inquiry	Computational analysis
Approaches	Visual assessment	Simple technique	a. Specimen of the concrete core	a. UV spectrum method	a. UV spectrum method
	a. Discoloration of the concrete	Schmidt hammer test	b. Sample of steel bar	b. Microwave capacity	b. Microwave capacity
	b. Dimensions of the crack	Test of concrete carbonation	c. Vibration test	c. Thermo-luminescence measurement	c. Thermo-luminescence measurement
	c. Spalling		d. Loading test	d. Ultrasonic test	d. Ultrasonic test
				e. X-ray diffraction analysis	e. X-ray diffraction technique

Table 2 Variations in concrete structure color across temperature ranges [24]

Temperature Range (°C)	Around 300 degrees Celsius	300–600(°C) degrees Celsius	600–950 (°C)degrees Celsius	Above 950(°C) degrees Celsius
Color	Typical	Pink to red	Whitish grey	Polish
Aspect	Typical	Surface cracking, crazing, aggregate spalling	The exposure of reinforced steel as a result of spalling and its persistent presence	Severe spalling
State	Typical	Structurally sound, yet strength might be compromised	Fragile	Intense

factors contributing to these disasters in commercial buildings [43]. Even within confined spaces, there can be significant temperature variations during a fire, as indicated by an analysis of compartment fire data [44]. Electrical faults are identified as the primary cause of fires by 42% of respondents, with 20.5% attributing fires to electrical faults and resident negligence. Ensuring that high-level building personnel are well-versed in fire safety and defense systems could enhance overall safety. Key fire safety components, such as the fire detection system, are often non-operational due to irregular testing and maintenance. While fire extinguishers are available and functional, residents lack awareness of their proper use. Each floor has clear evacuation instructions leading to stairwells in case of a fire, and fire shovels are accessible on each level for firefighters to access water from the main supply. Unfortunately, high maintenance costs have led to the disconnection of these systems. The architect specified fire safety measures during construction, but these plans were not consistently implemented or maintained, rendering them ineffective [45].

3.5 Fire damage remediation measures for reinforced concrete structures

Combustion, commonly referred to as fire, constitutes a chemical process where a substance reacts with oxygen from the air, releasing energy in the form of heat when activated by high temperature itself. Fire, in any structure, relies on a consistent supply of heat, fuel, and oxygen. Therefore, attention must be directed towards these three elements a constant source of oxygen from the environment, a heat source, and combustible materials. Incidents of fire in constructed environments are typically unexpected and unplanned events, often caused by human errors or the use of faulty electrical equipment [46]. Recent developments in structural engineering have led to a new design philosophy known as structural fire engineering. Fire safety design incorporates both active and passive fire prevention technologies. Active systems, like fire detectors, smoke control systems, and sprinklers, activate automatically when a fire starts. Passive systems, on the other hand, include building code limitations, barriers, fire-resistant windows, and construction materials designed to delay or minimize temperature increases in structural elements [31]. A crucial element in comprehensive fire protection planning for tall structures is a thorough understanding of fire behavior. Without taking the necessary measures, a fire safety strategy cannot be adequately optimized and made robust. Insights from experiments like the Cardington tests and advancements in finite element modeling have shown that structural systems need to be comprehensively assessed to understand their performance under fire conditions [47]. Fire disaster preparedness involves actions to protect property, limit damage and disruption during and after a disaster, and improve life safety in case of a fire disaster. Common actions associated with fire disaster preparedness include establishing planning procedures for readiness, formulating disaster response plans, stockpiling resources for effective response, and building capabilities and competencies for disaster-related tasks. The training and preparedness of fire disaster managers play a vital role in their effectiveness during and after a fire disaster. Preparedness efforts also ensure that necessary resources and equipment are available and that people are trained to use them effectively [48]. Conducting timely fire safety assessments are crucial to preventing high-rise building fires [49]. Eleven parametric modules for fire safety analysis and risk assessment in buildings have been identified, and their use can enhance national fire safety engineering practices in construction processes [50]. Designers and property owners must improve their fire safety procedures as highlighted by these findings. Strict adherence to fire safety measures outlined in building regulations is imperative in high-rise structure design [45]. Various techniques can be employed for structural repairs, including cast-in-place solutions, shotcrete, trowel-applied mortars, and injecting epoxy resins under pressure into prominent cracks to bond structures in situ. Regardless of the chosen repair technique, the goal is to restore the reinforced concrete asset to its original design intent.To address deficiencies in firefighting systems in reinforced concrete structures, remedial measures related to fire safety are necessary. The building's design should facilitate easy access for firefighting equipment in the event of a fire. The construction should be designed in a way that inhibits the spread of fire between floors, with clear signage for escape routes on each floor. Walls should be constructed using poor heat-conducting materials like bricks to impede fire penetration.

The building should also incorporate large openings that can serve as ventilation outlets during a fire, and windows should provide natural light to staircases [49–54].

Spalling leads to a reduction in an element's load-bearing capacity and loss of section. High-temperature concrete spalling occurs in various forms, ranging from total obliteration to the explosive dislodging of concrete pieces of varying thickness, ranging from millimeters to centimeters. In all cases, spalling exposes the reinforcement steel, which is susceptible to high temperatures. The phenomenon of concrete spalling is particularly intriguing in fire conditions and has been extensively described in the literature through experimental studies [55–57]. When concrete is heated, water is carried into cooler areas, leading to the creation of a completely saturated layer known as a moisture clog. This zone is marked due to low permeability and acts as a barrier impervious to gases(refer to Fig. 6). Simultaneously, the temperature increase causes the water to turn into steam, unable to escape due to the presence of the moisture clog. Consequently, this situation leads to the buildup of internal pressure [58]. Pore pressure serves solely as a catalyst for the spalling phenomenon. After the pore pressure initiates the crack, the subsequent growth of the crack and the explosive spalling that occurs as a result are determined by stresses related to temperature variations [59].

3.6 Fire-induced spalling in reinforced concrete structures

Spalling, the detachment of concrete layers due to high temperatures, poses a significant challenge to the structural integrity and fire resistance of various constructions like buildings, parking structures, and tunnels. This study delves into a simplified method, considering temperatures exceeding 400°C, to assess the thermo-mechanical response of reinforced concrete (RC) slabs under severe fire conditions. Utilizing numerical analysis via SAFIR software, the research systematically evaluates spalling risks by removing concrete layers based on predefined criteria. The comparison of numerical predictions with real-world experiments validates the efficacy of this method in accurately anticipating concrete spalling behavior during hydrocarbon fire exposure.

Moreover, the research underscores the vital importance of factoring in spalling when calculating fire resistance in concrete structures. Despite the complexity arising from multiple influencing factors, the layering technique emerges as a valuable tool for forecasting RC slab behavior under fire scenarios, eliminating the need for expensive experimental tests. The study achieves satisfactory alignment between numerical simulations and experimental measurements, particularly in terms of temperature distribution and mid-span deflections in simply supported RC slabs exposed to sustained gravity and fire loading. Furthermore, the study investigates the ramifications of thermal spalling on the fire resistance of RC structures post-seismic events, employing nonlinear dynamic analyses to evaluate structural damage. It highlights the significant role of reinforcement configurations, including one-layer and two-layer distributions, in mitigating collapse risks under post-earthquake fire conditions. Additionally, the review addresses challenges posed by ultra-high performance concrete (UHPC) in fire-induced spalling, stressing the necessity for robust modeling methods and mitigation strategies to ensure structural safety. The paper also addresses the vulnerability of reinforced high-strength concrete (RHSC) walls to spalling under standard fire conditions. Through experimental trials, it identifies key factors influencing spalling behavior such as concrete strength, axial load levels, thickness, and reinforcement configurations. The findings underscore the significance of reducing wall thickness and optimizing reinforcement arrangements to bolster fire resistance in RHSC walls. In summary, this study offers valuable insights into the complexities of fire-induced spalling in concrete structures, providing guidance for enhancing design standards and mitigating fire hazards across various construction applications [60–69]

3.7 The cooling behavior of reinforced concrete elements

Recent literature predominantly focuses on the heating phase of concrete columns concerning potential delayed failure, coupled with a linear descending cooling phase. This area of research has only recently gained attention, particularly revolving around a parametric temperature–time curve, which includes a linear cooling regime as an initial approximation suitable for design purposes. A simple linear relationship between the burn-out resistances of a column subjected to a parametric fire and the ISO fire rating time, particularly applicable to heavily loaded columns. However, it is acknowledged that the linear cooling curve associated with the parametric fire does not adhere to Newton's fundamental law of cooling in transient situations, rendering it non-natural. This underscores the importance of investigating alternative cooling regimes with slopes or shapes that may better reflect reality. Moreover, the significance of load levels warrants careful examination, as not all columns in real buildings is heavily loaded, leading to variations in dimensions.

To delve deeper into these aspects, a study was conducted involving heating a selected column on four, three, or two sides to examine the effects of cooling regimes and load levels. A combination of thermal loads from the parametric fire, the more natural cooling BFD curve, and a heavily forced, very slow cooling regime was implemented. The material model incorporated a proposed strength loss of 10% (EN 1994–1-2, 2005), verified against a 20% loss observed in various experiments from literature. Additionally, explicit formulation of creep was employed to account for time-dependent strength loss.

The relevance of this research lies in assessing the residual capacity of concrete structures in post-fire scenarios, which is crucial for determining their load-bearing capacity or post-fire fire rating. Both aspects are essential for evaluating the structural reliability for further use after exposure to fire. It was demonstrated that differences in cooling regimes, load levels, and the number of exposed sides can lead to failure and significantly influence the post-fire bearing capacity.

Experimental results for "NSC" regular concrete columns subjected to periodic fire with axial load were provided. The aim was to investigate the behavior of reinforced concrete columns under experimental conditions when exposed to fire flame with axial loading. Compared to control samples, the columns experienced a reduction of approximately 82.38%, 77.78%, and 72.80% in their bearing capacity after exposure to periodic burning at 400 °C for one cycle, two cycles, and four cycles, respectively. Moreover, as the number of fire cycles increased, the residual bearing capacity dropped dramatically [70–82].

3.8 Future studies and suggestions

Enhancing fire safety in reinforced concrete (R–C) structures involves advancing monitoring systems, exploring fire-resistant materials, refining simulation techniques, developing comprehensive protection strategies, addressing multi-hazard resilience, improving building codes, and fostering interdisciplinary collaboration. Tailored monitoring systems for R–C structures facilitate real-time data acquisition during and after fires, aiding accurate post-fire assessments. Research into fire-resistant materials is pivotal for R–C structures to withstand high temperatures while preserving integrity. Enhanced simulation techniques guide proactive safety measures and post-fire evaluations. Developing holistic fire protection strategies, encompassing both passive and active measures, is imperative. Multi-hazard resilience, including seismic and extreme weather events, must be integrated into these strategies. Continuous refinement of building codes ensures adaptability to evolving challenges. Interdisciplinary collaboration drives innovation and comprehensive solutions. Prioritizing these endeavors enhances resilience and sustainability in built environments. Implementing appropriate repair techniques for rehabilitating fire-damaged concrete structures further strengthens safety measures.

4 Conclusions

This study primarily focused on conducting a comprehensive assessment of the damage incurred, post-fire structural responses, and the identification of deficiencies within firefighting systems specifically concerning reinforced concrete (RC) structures following severe fire incidents.

The core information essential for evaluating the structural integrity of fire-damaged buildings was precisely examined. This encompassed a wide array of critical factors, including the classification of building elements and materials, pinpointing the origins of fire ignition, assessing exposure conditions, gathering necessary data, comprehending the expected fire temperatures, and considering the duration of the fire event. Furthermore, the study underscored the significant challenges posed by limited fire prevention equipment and various contributing factors, all of which can potentially culminate in a heightened risk of fire ignition. These findings strongly advocate for a fundamental enhancement of fire safety measures. Design considerations emerged as a key facet of the study's insights. It highlighted the pivotal role of both designers and property owners in the realm of fire safety procedures. A particular emphasis was placed on high-rise structures, where strict adherence to building regulations governing fire safety is not just advisable but crucial. Moreover, the research incorporated a thorough review of past studies conducted over the last decade, complemented by relevant case studies. This comprehensive approach revealed the prevalence of surveys and case studies centered on fire damage in RC structures. Among the prominent findings, it was noted that electrical issues, faulty fire detection systems, insufficient firefighting equipment, and impediments in emergency exit routes were recurrent causes of fire damage in RC structures. In light of these findings, the study advocated for further, detailed research endeavors aimed at controlling fire ignition and addressing the gamut of fire-related concerns specifically in high-rise buildings. Despite the ongoing efforts of building owners to preempt fires, the study observed that fire prevention remains a persistent challenge, often rooted in human decision-making processes, especially in the selection of building materials. Consequently, the study proposed a series of operational solutions as recommendations to fortify fire safety in RC high-rise buildings. Collectively, these recommendations serve as a comprehensive strategy to enhance fire safety and mitigate the impact of fires in RC high-rise structures.

Author's contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by G.B. and N.R. The draft of the manuscript was written by G.B. and all authors commented on previous versions of the manuscript. S.R.C. verified the results section and verified entire manuscript. All authors read and approved the final manuscript.

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Declarations

Consent to participate Not applicable.

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