Journal of Innovations in Engineering Education
JIEE 2026, Vol. 9, Issue 1.

https://doi.org/10.3126/jiee.v9i1.90611

THAPATHALI CAMPUS
Institute of Engineering
Tribhuvan University

Evaluating fire-induced structural degradation of RCC buildings: NDT-based evidence from Nepalese case studies

Bimal Ojha[a], Abhinesh Khatri[b], Gajendra Kumar Jha[c] and Hari Ram Parajuli[d,*]

[a]*Department of Civil Engineering, Thapathali Campus, Institute of Engineering, Tribhuvan University*
[b]*Department of Civil Engineering, Kantipur Engineering College, Tribhuvan University*
[c]*Department of Civil Engineering, Universal Engineering & Science College, Pokhara University*
[d]*Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University*

ARTICLE INFO

Article history:

Received 5 February 2026
Revised in 21 March 2026
Accepted 15 April 2026

Keywords:

Fire-induced damage
Thermo-mechanical degradation
Ultrasonic pulse velocity test
Rebound hammer test

Abstract

Fire incidents pose a serious threat to the structural integrity of reinforced cement concrete (RCC) buildings, particularly when exposure is localized and prolonged. Recently, several RCC buildings in Nepal have been affected by deliberate fire incidents, highlighting the need for systematic post-fire structural assessment. This study evaluates fire-induced structural degradation of RCC buildings through a comprehensive literature review and Non-Destructive Testing (NDT)-based investigation of selected Nepalese case studies. The literature review outlines key thermo-mechanical degradation mechanisms in concrete at elevated temperatures, including strength loss, cracking, spalling, and bond deterioration, and discusses limitations of standard fire exposure models in representing real fire scenarios. Field investigations were conducted using rebound hammer and ultrasonic pulse velocity (UPV) tests to assess residual concrete quality in fire-affected beams, columns, slabs, and beam–column joints. The results reveal significant spatial variability in compressive strength and pulse velocity values, indicating non-uniform thermal damage and internal cracking, with several load-critical elements exhibiting poor to severely degraded concrete quality. The study demonstrates that NDT methods provide an effective preliminary tool for identifying critically damaged zones but are insufficient alone for complete structural safety evaluation. Based on the findings, recommendations are proposed for detailed assessment and destructive testing to support informed decisions regarding repair, strengthening, or demolition of fire-damaged RCC buildings.

1. Introduction

Reinforced concrete (RC) buildings are the most used structural system for residential, commercial and institutional buildings in Nepal because they are strong, cost-effective and suitable for seismic design. While RCC is generally designed to withstand gravity and lateral loads[1], recent events highlight that it may be exposed to multiple hazards during its service life. Among them Fire is one of the most destructive accidental loads that a structure can be subjected during its lifetime. Concrete itself is non-combustible and exhibits relatively slow heat conduction compared to other materials such as steel and timber; these characteristics generally make RCC structures more fire-resistant than steel or timber framed buildings[2][3][4]. However, exposure to elevated temperatures during a fire can cause significant changes in both the concrete matrix and embedded reinforcement, leading to mechanical degradation and reduced structural capacity[5][6]. Concrete exposed to high temperatures undergoes dehydration of cement hydrates, thermal incompatibility between aggregates and cement paste, micro- and macro-cracking, and in severe cases, explosive spalling of the concrete cover [7][8].

Nepal has experienced a noticeable rise in youth-led Gen-Z protest on September 08 and 09, 2025, especially in major urban areas of Nepal which occasionally escalated into violent incidents involving intentional burning of public and private properties. Several RC buildings,

---

[*] Corresponding author:
hariparajuli@ioe.edu.np (H.R. Parajuli)

including commercial complexes, office buildings, and service facilities have reportedly been subjected to deliberately set fires during such protest activities. Although global research on fire-induced damage in RCC structures is well-developed, research within Nepal remains limited. Most structural investigations in Nepal focus on seismic vulnerability[9], retrofit strategies[10], or corrosion assessment rather than systematic evaluation of fire effects on RCC members. Therefore, there is a critical need to systematically evaluate fire-induced structural degradation in RCC buildings using reliable, field-applicable techniques, supported by empirical evidence. This study primarily focuses on effects of fire on reinforced concrete structures in Nepal and damage assessment techniques for fire-damaged structures.

Specifically, the objectives of study includes:

- To synthesize international research on the effects of elevated temperatures and fire exposure on the mechanical and durability properties of concrete and reinforcing steel in RCC structures.
- To assess the residual strength of concrete after fire.
- To propose practical recommendations or assessment method for post-fire evaluation and rehabilitation of RCC buildings.

2. Fire behavior in reinforced concrete structure

Concrete structures exhibit complex behavior when exposed to fire due to coupled thermal, physical, and mechanical phenomena. Although concrete is non-combustible and generally performs better than steel or timber in fire, elevated temperatures can significantly impair its structural performance. The fire behavior of reinforced cement concrete (RCC) structures depends on factors such as temperature magnitude, duration of exposure, heating and cooling rates, material composition, moisture content, and structural detailing[11][12].

2.1. Heat transfer and temperature distribution

Heat transfer in concrete during fire exposure occurs primarily through thermal conduction, resulting in non-uniform temperature distributions across structural members. Due to its relatively low thermal conductivity, concrete delays heat penetration, which initially enhances fire resistance when compared to steel structures[13]. However, during prolonged exposure, surface temperatures can rise rapidly, while the core temperature increases more slowly depending on member thickness and concrete cover. Experimental and numerical studies have shown that such temperature gradients induce significant thermal stresses, contributing to cracking and stiffness degradation even before critical strength loss occurs[14][15].

2.2. Standard fire curves (ISO 834 and ASTM E119)

To represent fire exposure in structural fire engineering, standard time–temperature curves are commonly used in laboratory testing and design. Among these, the ISO 834 [16] and ASTM E119 [17] fire curves are the most widely adopted standards. Figure 1 presents the ISO 834 and ASTM E119 standard fire curves, which define the relationship between furnace temperature and time during a fire resistance test. The ISO 834 curve is expressed as:

$$T = T_0 + 345 \log_{10}(8t + 1) \tag{1}$$

where T is the furnace temperature (°C), T_0 is the initial temperature, and t is time in minutes.

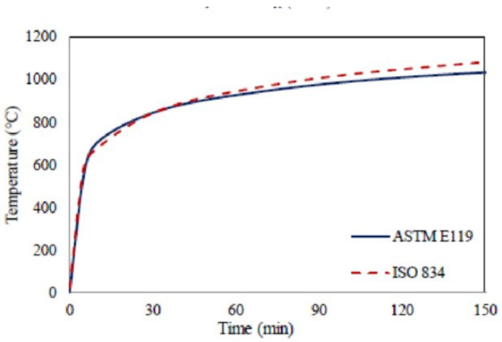

Figure 1: Standard time–temperature fire curves according to ISO 834 and ASTM E119 used in structural fire resistance testing [16][17]

Both ISO 834 and ASTM E119 curves represent fully developed compartment fires, characterized by a rapid rise in temperature reaching approximately 800–900 °C within 60 minutes, and exceeding 1000 °C with longer exposure durations. These curves are intentionally conservative and provide a standardized basis for comparing fire resistance performance of structural elements. However, several researchers have highlighted that real fires often deviate significantly from these standard curves due to variations in fuel load, ventilation conditions, and fire suppression activities[18]. Consequently, while ISO and ASTM fire curves are essential for design and testing, they may not accurately capture localized, fuel-rich, or prolonged fires, such as those observed in urban unrest or storage-related fire incidents.

2.3. Physico-chemical changes in concrete

Fire exposure leads to a sequence of temperature-dependent physico-chemical transformations in concrete as shown in Figure 2. Below 100 °C, evaporation of free water occurs. Between 100 and 300 °C, physically bound water is released, resulting in shrinkage and microcracking[19]. At temperatures exceeding 400 °C, dehydration of calcium silicate hydrate (C–S–H) gel and decomposition of calcium hydroxide significantly weaken the cement paste and increase porosity[20].

Aggregate type also influences fire behavior. Siliceous aggregates undergo phase transformation near 573°C, while carbonate aggregates decompose above 700 °C, contributing to cracking and loss of strength[21]. Differential thermal expansion between cement paste and aggregates causes cracking at the interfacial transition zone (ITZ).

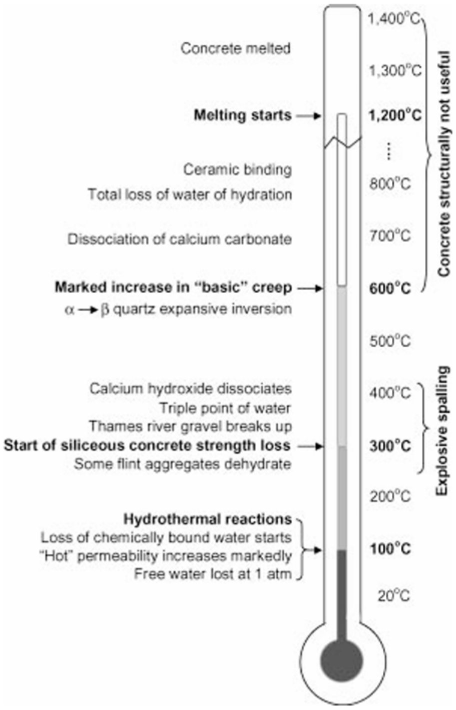

Figure 2: Physicochemical processes in Portland cement concrete during heating [13]

2.4. Spalling of concrete

Spalling is one of the most critical fire-induced damage mechanisms in concrete structures. It involves the violent detachment of surface layers caused by vapor pressure buildup and thermally induced tensile stresses[22][23][24]. High-strength and low-permeability concretes are particularly vulnerable due to restricted moisture migration. Spalling reduces effective cross-sectional area and accelerates heat penetration, potentially exposing reinforcing steel earlier than anticipated, thereby reducing fire resistance[22].

2.5. Degradation of compressive strength of concrete at elevated temperature

Exposure to elevated temperatures during fire leads to a progressive reduction in the compressive strength of concrete due to moisture loss, microcracking, and chemical decomposition of cementitious phases. Up to approximately 200–300 °C, strength loss is limited and primarily associated with evaporation of free and physically bound water. Beyond 400 °C, dehydration of calcium silicate hydrate (C–S–H) gel and decomposition of calcium hydroxide significantly weaken the cement matrix, resulting in rapid strength deterioration. Experimental studies indicate that concrete retains about 80–90% of its original compressive strength at 300 °C, which reduces to 40–60% at 500 °C and falls below 30% beyond 700 °C, depending on mix composition, aggregate type, and exposure duration[25][26][27]. The degradation of compressive strength with temperature for various types of aggregates is represented in Figure 3. In real fire scenarios, especially localized and prolonged fires, compressive strength degradation is often non-uniform across structural members.

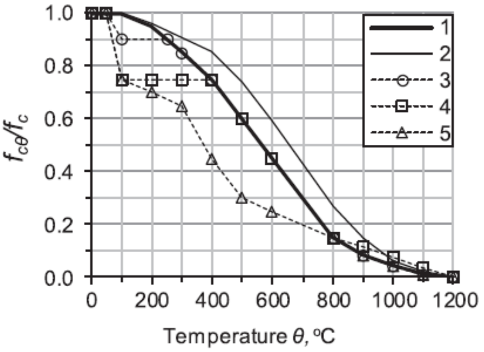

Figure 3: Concrete compressive strength degradation (fch /fc) at high temperature: 1 -ordinary strength concrete with siliceous aggregate, 2 -ordinary strength concrete with calcareous aggregate, 3 -C55/67, C60/75, 4 -C70/85, C80/95, 5 -C90/105; diagram prepared by authors on the basis of Eurocode [25]

2.6. Behavior of reinforcement and composite action

At elevated temperatures, reinforcing steel experiences a substantial reduction in yield strength and modulus of elasticity. According to Eurocode 2 (EN 1992-1-2), reinforcing steel may lose up to 50% of its yield strength at around 600 °C. According to experiment done by Uma

Bharathi and Pradeep Kumar[28], the residual strengths of reinforced steel rebars are lower than their respective design values after 500°C showing 38% to 45% decrease in tensile load carrying capacity at 1000°C.

Simultaneously, cracking and degradation of concrete reduce bond strength between steel and concrete, compromising composite action and load redistribution[29][30]. The combined degradation of concrete and reinforcement governs the overall fire performance and residual load-carrying capacity of RCC members such as beams, slabs, and columns.

2.7. Cooling phase damage

The cooling phase following fire exposure is critical in determining residual structural condition. Rapid cooling, particularly due to water application during firefighting, induces thermal shock, leading to additional cracking and loss of stiffness [31][32]. Research indicates that residual strength measured after cooling may be significantly lower than that observed during heating, highlighting the importance of post-fire evaluation [33][34].

2.8. Residual strength

Although the concrete structure may be damaged during a fire, it can retain a certain amount of residual load bearing capacity[35]. The residual strength of concrete and reinforcing steel after fire exposure is a critical parameter in determining the post-fire safety, serviceability, and rehabilitation strategy of RCC structures. Concrete experiences irreversible degradation of mechanical properties when exposed to elevated temperatures. Numerous experimental studies have shown that residual compressive strength depends primarily on maximum temperature reached, duration of exposure, heating and cooling rates, moisture content, and concrete composition[36][37]. At temperatures below 200 °C, concrete typically retains most of its original compressive strength, with minor losses attributed to moisture evaporation. Between 300 and 400 °C, residual strength begins to decline noticeably due to dehydration of cement hydrates and microcracking. When exposed to temperatures in the range of 400–600 °C, concrete may lose approximately 30–60% of its original compressive strength, depending on aggregate type and exposure duration. Results from the destructive and non-destructive tests done on samples subjected to fire show that losses of strength vary from a minimum of 37.73% to a maximum of 86.67% [38].

2.9. Effect of coating protection (plaster)

Under fire, the plastering layer can act as a barrier to decelerate the change of temperate of the internal concrete structure. The plaster layer absorbs heat and undergoes moisture evaporation and cracking, which helps dissipate thermal energy and reduces the rate of temperature rise in the underlying concrete. Studies have shown that plastered (or fire-retardant coating) concrete members exhibit lower peak internal temperatures and reduced compressive strength degradation compared to uncoated members, particularly during short- to medium-duration fires[39][40][41]. However, the effectiveness of plaster protection depends on its thickness, bonding quality, moisture content, and integrity under thermal loading, as cracking or debonding of the plaster layer can significantly diminish its protective role.

3. Methodology of fire damage assessment and evaluation of RC structure

Fire damage assessment and evaluation of reinforced concrete (RC) structures is done for determining the extent of fire-induced deterioration, residual structural capacity, and suitability for continued use or rehabilitation. A fire damage assessment flowchart for RC structures as shown in Figure 4 typically begins with visual inspection (mapping cracks, spalling, deformation) to gauge fire severity, followed by non-destructive testing (NDT) like rebound hammer and UPV for deeper damage, then potentially destructive testing (cores, lab analysis) for residual strength, and finally analysis & repair planning, deciding if the structure is repairable or needs demolition. The process moves from general observation to detailed material property evaluation, determining the extent of concrete degradation (color changes, spalling depth) and steel integrity to assess load-bearing capacity.

Types of Fire Damage:

1. Structural Damage: Involves the impact on a building's integrity due to fire.
2. Surface Damage: Refers to visible damage to interior and exterior surfaces from fire.
3. Material Damage: Deals with the deterioration of items and materials due to fire.
4. Smoke and Soot Damage: Encompasses the residues left by smoke and soot, affecting air quality and surfaces.
5. Water and Chemical Damage: Damage resulting from firefighting efforts or chemical reactions during a fire.

It is possible to restore the structure back to its original form, economically by carrying out appropriate repair methods only for the elements that has been affected even though the fire damage is severe[42].

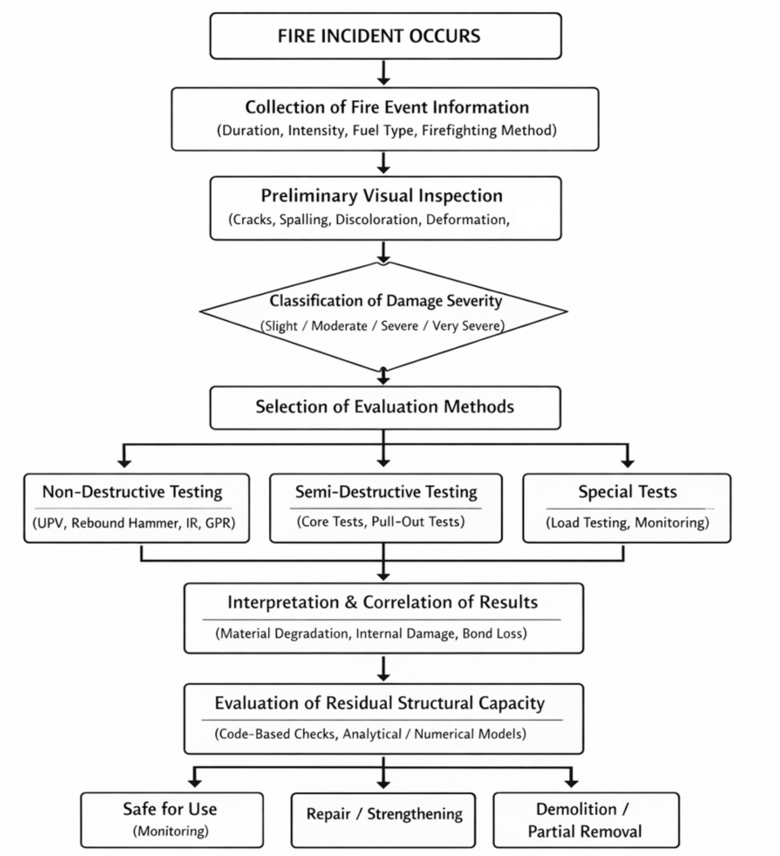

Figure 4: Flowchart for fire damage assessment and evaluation of RC buildings

3.1. Preliminary and qualitative evaluation methods

These methods provide an initial understanding of fire damage and are mainly observational in nature.

- Visual inspection (cracking, spalling, discoloration, deformation)
- Documentation of fire characteristics (duration, fuel type, intensity, fire-fighting method)
- Damage severity classification (slight, moderate, severe, Very Severe)
- Historical records and eyewitness accounts

Preliminary assessment of fire damaged concrete can also be done with visual observation of color change as shown in Figure 5. On heating above 300°C, the colour of siliceous aggregate concrete is said to change from normal to pink or red (300-600°C),whitish grey (600-900°C), and buff (900-1000°C)[43].

Although RC structures often remain standing after fire due to the non-combustible nature of concrete, exposure to elevated temperatures can cause significant deterioration of concrete and reinforcement that may not be evident through visual observation alone.

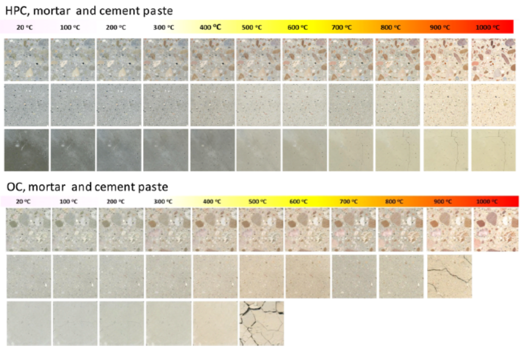

Figure 5: Color change of high-performance and ordinary concrete heated to temperatures ranging from 100°C to 1000°C [43]

3.2. Material testing and analysis

3.2.1. Non-destructive test

These methods assess internal damage and material degradation without harming the structure.

- Ultrasonic Pulse Velocity (UPV) – internal cracking and concrete quality

- Rebound Hammer Test – surface hardness and relative compressive strength
- Infrared Thermography – delamination and subsurface defects
- Impact Echo – internal voids and layer separation
- Ground Penetrating Radar (GPR) – reinforcement layout and cover depth

3.2.2. Semi-destructive test

These methods involve minor damage to the structure but provide higher reliability.

- Core sampling and compressive strength testing
- Pull-out tests
- Chemical and Petrographic Analysis
- Carbonation and chloride tests (post-fire durability)

3.2.3. Analytical and numerical evaluation methods

These methods assess structural capacity using engineering models.

- Temperature-based material reduction models
- Section capacity analysis using residual properties
- Finite Element Modeling (FEM) of fire-damaged members
- Code-based assessment (Eurocode 2, ACI, IS guidelines)

3.2.4. Decision-support and risk-based evaluation

These methods integrate technical findings into final decisions.

- Repair vs Demolition criteria
- Safety and risk assessment
- Lifecycle and cost–benefit analysis

4. Case study: Damage assessment of RC fire-affected building in Kathmandu

Recently, Nepal has experienced a noticeable rise in youth-led protest movements, especially in major urban areas such as Kathmandu Valley which occasionally escalated into violent incidents involving intentional burning of public and private properties. Several RC buildings, including commercial complexes, office buildings, and service facilities have reportedly been subjected to deliberately set fires during such protest activities. These incidents represent a new and under-studied category of structural hazard within the Nepalese built environment. Unlike accidental building fires, protest-related fires are typically localized, intense, and prolonged, fueled by high-calorific combustible materials such as petroleum products, plastics, furniture, tires, and stored goods. Such fires are rarely controlled and often occur in critical structural zones, including ground floors, entry lobbies, parking levels, stairwells, and façade regions. These conditions can generate localized temperatures exceeding those assumed in standard fire resistance design, resulting in severe thermal gradients and asymmetric heating of RC members.

In this study case studies from three buildings in Kathmandu valley damaged by fire has been taken.

- Building A: 3 storeyed RCC Institutional building located in Babarmahal
- Building B: 4 storeyed RCC Institutional Building located in Koteshwor
- Building C: 3 storeyed RCC Residential Building located in Koteshwor

4.1. Visual observation

The visual observation of damage in the crucial location of Building A, Building B, and Building C, selected as case study in this research are represented in Figure 6, Figure 7, and Figure 8, respectively. All three of these Reinforced Concrete buildings located in Kathmandu valley were subjected to fire after the Gen Z movement on September 8 and 9, 2025.

Figure 6: Showing damages in various locations of Building A (a) Fire-damaged structural beam showing extensive soot deposition, blistered paint, and heat-induced surface cracking (b) Damage in electrical point and crack propagated in slab along the line of wiring (c) Porous, bubbled surface texture—classic signs of thermal decomposition of cement paste due to high fire temperatures (d) Fire-induced spalling of concrete

Figure 7: Showing damages in various locations of Building B (a) Discoloration of outer face of building due to fire (b) Fire-induced spalling of concrete with exposed reinforcement in the beam soffit (circled in red) (c) Porous, bubbled surface texture-classic signs of thermal decomposition of cement paste due to high fire temperatures (d) Fire-damaged structural beam showing extensive soot deposition, blistered paint, and heat-induced surface cracking (e) Damage in electrical point

Figure 8: Showing damages in various locations of Building C (a) Exterior view of an RCC building showing fire damage (b)Fire-affected RCC slab soffit with extensive soot accumulation and exposed suspended service lines, indicating prolonged fire duration and elevated ceiling temperatures (c) Close-up view of an RCC beam exhibiting surface discoloration, fine flexural cracking, and localized material degradation due to elevated temperature exposure (d) Damage to slab–beam junction with partial loss of plaster cover, exposed reinforcement, and hanging electrical conduits following intense fire action (e) Interior wall and column surface showing cracking, plaster debonding, and thermal discoloration (f) Beam–column joint with plaster spalling, cracking, and exposed reinforcement, highlighting degradation of load-critical regions under fire exposure

From visual observation of three different buildings assessed after fire, the typical damage pattern observed were:

- Surface discoloration and heavy soot deposition on concrete and plaster surfaces
- Cracking of plaster and concrete due to thermal stresses and differential expansion
- Spalling of concrete cover, particularly in slab soffits, beams, and beam–column joints
- Partial or full exposure of reinforcing steel in load-critical elements
- Loss of plaster adhesion and debonding of protective coatings
- Localized severe damage near fire sources, with comparatively minor damage in adjacent regions
- Non-uniform damage distribution indicating steep thermal gradients and asymmetric heating
- Cracking was observed along the alignment of embedded electrical conduits within beam and slab, indicating a localized response of the concrete to thermal and material incompatibility effects during fire exposure.

4.2. Non-destructive test Results and discussion

In order to assess the residual quality of concrete in the fire-affected structure without causing significant damage, non-destructive tests (NDT) were carried out on RCC beams and columns that exhibited visible deterioration such as cracking, discoloration, and spalling. The tests were performed using the Rebound Hammer (RH) and Ultrasonic Pulse Velocity (UPV) methods in accordance with IS 13311 (Part 1 & 2)[44][45].

The compressive strength results (Table 1) show considerable variation across and within the investigated RCC buildings, indicating non-uniform fire-induced damage. Building A exhibits consistently low strength values (12–13.5 MPa) with high variability, suggesting severe degradation due to prolonged fire exposure. Building B shows moderate to low strengths, with the ground-floor beam recording the lowest value (11.5 MPa), likely due to direct exposure to fire. Building C demonstrates the widest strength range (10–33 MPa), with significant differences observed even within the same member, highlighting localized thermal effects and post-fire deterioration. The area subjected to the gas cylinder blast shows severely reduced compressive strength, directly linked to the explosive force. This is compounded by heavy water seepage, which has likely washed away cementitious matrix and initiated corrosion in the embedded steel reinforcement.

High standard deviation values across all buildings indicate internal cracking and loss of material homogeneity. Overall, the results confirm that fire damage in RCC

Table 1: Rebound hammer test results

Building	S.N.	Beam	Compressive Strength (MPa)	Standard Deviation	Remarks
Building A	1.	FF beam (staircase)	13.5	4.2	
	2.	Column at Northeast FF	13	3.8	
	3.	Column at South west FF	12	5.9	
Building B	1.	First floor beam (9” × 14”)	23.5	6.8	
	2.	First floor beam (9” × 14”)	17.5	5.6	
	3.	Ground floor beam (9” × 14”) hall	11.5	3.5	
Building C	1.	Col A2 FF (9” × 9”) Face	16.5	8.8	Location 1
			17	6.9	Location 2
	2.	Col B2 FF (9” × 9”) Face	19	3.9	
	3.	Col B1 FF (9” × 9”) Face	26	3.2	
	4.	Col C4 FF (9” × 9”) Face	28.5	3	
	5.	Col D5 FF (9” × 9”) Face	15.5	4.9	
	6.	Col B5 SF (9” × 9”) Face	10	4.6	Location 1
			33	6.6	Location 2
	7.	Col C4 SF (9” × 9”) Face	21	3.3	
	8.	Col C5 GF (9” × 9”) Face	16.5	8.5	Location 1
			12	2	Location 2
	9.	Beam C4-D4	17	7	
	10.	Slab GF	24.5	8.1	
	11.	Slab SF AB-45	14.5	9.2	Seepage area
			31.5	3.7	Cantilever Portion

GF – Ground Floor, FF – First Floor, SF – Second Floor

structures is highly localized and that NDT-based assessment is essential for identifying critically weakened structural zones.

Ultrasonic Pulse Velocity (UPV) test is done to evaluate the internal quality, homogeneity, and presence of cracks or voids within the beams. Direct transmission method was adopted wherever possible, with transducers placed on opposite faces of the beam. In locations where direct access was limited, semi-direct transmission was applied.

The ultrasonic pulse velocity (UPV) results (Table 2) indicate varying degrees of internal damage and concrete quality across the investigated RCC buildings. In Building A, pulse velocities range from 1852 to 2356 m/s, suggesting poor to questionable concrete quality, likely caused by fire-induced cracking and material degradation in first-floor columns and beams. Building B shows comparatively higher pulse velocities (2250–2785 m/s), indicating moderate concrete quality, although the lower value recorded in the ground-floor beam reflects localized fire damage near the fire source. Building C exhibits the widest variation, with very low pulse velocity in Column A2 (1341 m/s), indicating severely damaged and cracked concrete, while other columns show moderate quality. Several readings fell into the “poor to

Table 2: Ultrasonic pulse velocity test results

Building	S.N.	Beam	Pulse Velocity (m/s)	Remarks
Building A	1.	FF beam (staircase)	2356 m/s	
	2.	Column at Northeast FF	1852 m/s	
	3.	Column at South west FF	1987 m/s	
Building B	1.	First floor beam (9” × 14”)	2785 m/s	
	2.	First floor beam (9” × 14”)	2570 m/s	
	3.	Ground floor beam (9” × 14”) hall	2250 m/s	
Building C	1.	Col A2 FF	1341 m/s	
	2.	Col B4 FF	2041 m/s	
	3.	Col B5 SF	1787 m/s	
	4.	Col C5	2700 m/s	

doubtful quality" category, as per IS 13311 classifications.

Overall, the results confirm that fire exposure has caused non-uniform internal deterioration, and UPV testing is effective in identifying critically damaged zones that may not be evident from surface inspection alone.

5. Conclusion and recommendations

This study investigated fire-induced structural degradation of reinforced cement concrete (RCC) buildings through a comprehensive literature review and Non-Destructive Testing (NDT)-based assessment of selected Nepalese case studies. The findings confirm the following conclusions:

- Fire exposure causes significant deterioration of concrete quality and structural performance, even when no immediate collapse is observed.
- The elevated temperatures lead to progressive degradation of concrete compressive strength, stiffness, and bond characteristics due to physico-chemical transformations, cracking, and spalling.
- Field investigations using rebound hammer and ultrasonic pulse velocity (UPV) tests reveal substantial spatial variability in residual concrete properties within and across buildings.
- Several structural elements exhibited compressive strength and pulse velocity values indicative of poor to severely damaged concrete, particularly in ground-floor beams, columns, and beam–column joints exposed to direct fire action.

Based on the findings and limitations of this research, the following recommendations are proposed for further detailed assessment and decision-making:

- Detailed destructive testing should be carried out in critically fire-affected structural members to validate NDT results and quantify residual compressive strength through core sampling and laboratory testing.
- Petrographic and chemical analyses of extracted concrete cores should be conducted to identify microcracking, cement paste decomposition, and fire-induced mineralogical changes.
- Bond strength evaluation between concrete and reinforcement should be considered in severely damaged regions to assess the integrity of composite action.
- A detailed numerical modeling or full-scale load testing can be done for precise evaluation of residual structural capacity.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgment

The Authors would like to thank the Material Testing Laboratory of the Institute of Engineering, Thapathali Campus, for providing Non-destructive testing equipment (Schmidt Hammer and Ultrasonic Pulse Velocity).

References

[1] Ojha B, et al. Comparative analysis of structural response of multi-storey reinforced concrete framed building with different infill wall materials[J/OL]. American Journal of Civil Engineering, 2025, 13(4): 245-256. DOI: 10.11648/j.ajce.20251304.16.

[2] Pasztetnik M. A literature review of concrete ability to sustain strength after fire exposure based on the heat accumulation factor[J]. 2021.

[3] Du Y. Research progress on fire resistance of steel-concrete composite structures[J]. 2022, 28: 154-160.

[4] Zhang Y, Li L, Zhang L, et al. Quantitative study of thermal response of timber–concrete composite structures under traveling fire using energy equivalence method[J/OL]. The Structural Design of Tall and Special Buildings, 2024, 33(18). DOI: 10.1002/tal.2190.

[5] Elizalde R R. Journal of civil engineering research & technology[J]. 4(3): 1-10.

[6] Kildashti K, Katwal U, Tao Z, et al. Numerical simulation of steel-concrete composite beams and slabs at elevated temperatures[J/OL]. Engineering Structures, 2024, 315: 118297. DOI: 10.1016/j.engstruct.2024.118297.

[7] Parthasarathy S. Evaluation of fire-damaged concrete structures with a case study[EB/OL]. 2014. https://www.researchgate.net/publication/275531847.

[8] Georgali B, Tsakiridis P E. Microstructure of fire-damaged concrete. a case study[J/OL]. Cement and Concrete Composites, 2005, 27(2): 255-259. DOI: 10.1016/j.cemconcomp.2004.02.022.

[9] Poudel S, Ram H. Seismic vulnerability assessment of school building[J]. 2021, 8914: 139-146.

[10] Chaulagain H, Silva V, Rodrigues H, et al. Earthquake loss estimation for the Kathmandu valley[J].

[11] Beams C. Fire induced spalling in high strength concrete[J/OL]. 2010: 251-274. DOI: 10.1007/s10694-009-0088-6.

[12] Kodur V K R. Spalling in high strength concrete exposed to fire – concerns, causes, critical parameters and cures[R]. Institute for Research in Construction, National Research Council of Canada, 2004.

[13] Khoury G A. Effect of fire on concrete and concrete structures[J]. 2000.

[14] Shen L, Ren Q, Zhang L, et al. Experimental and numerical study of effective thermal conductivity of cracked concrete[J/OL]. Construction and Building Materials, 2017, 153: 55-68. DOI: 10.1016/j.conbuildmat.2017.07.038.

[15] Feng W, Hussin T A R, Yang X. A temperature-indexed concrete damage plasticity framework for thermomechanical analysis of concrete structures[J/OL]. Journal of Engineering and Applied Science, 2025, 72(1): 177. DOI: 10.1186/s44147-025-00753-2.

[16] International Organization for Standardization. ISO 834-1975 international standard – fire-resistance tests – elements of building construction[S]. International Organization for Standardization, 1975.

[17] ASTM International. ASTM E119 – standard test methods for fire test of building construction and materials[S]. ASTM International, 2020.

[18] Kodur V K R, Phan L. Critical factors governing the fire performance of high strength concrete systems[J/OL]. Fire Safety Journal, 2007, 42(6–7): 482-488. DOI: 10.1016/j.firesaf.2006.10.006.

[19] Lie T T, Harmathy T Z. Fire endurance of concrete-protected steel columns[J/OL]. Journal of the American Concrete Institute, 1974, 71(1): 29-32. DOI: 10.14359/11166.

[20] Mindeguia J C, Pimienta P, Carré H, et al. Experimental analysis of concrete spalling due to fire exposure[J/OL]. European Journal of Environmental and Civil Engineering, 2013, 17(6): 453-466. DOI: 10.1080/19648189.2013.786245.

[21] Krauss P, Paret T. Review of *Properties of Concrete*, 5th ed., by A. M. Neville[J/OL]. Journal of Performance of Constructed Facilities, 2014, 28(3): 630. DOI: 10.1061/(ASCE/CF.1943-5509.0000595.

[22] Hertz K D. Limits of spalling of fire-exposed concrete[J/OL]. Fire Safety Journal, 2003, 38(2): 103-116. DOI: 10.1016/S0379-7112(02/00051-6.

[23] Amran M, Huang S S, Onaizi A M, et al. Fire spalling behavior of high-strength concrete: A critical review[J/OL]. Construction and Building Materials, 2022, 341: 127902. DOI: 10.1016/j.conbuildmat.2022.127902.

[24] van der Merwe J E. Spalling of concrete in fire – an overview and local relevance[J/OL]. Journal of the South African Institution of Civil Engineering, 2023, 65(2): 2-9. DOI: 10.17159/2309-8775/2023/v65n2a1.

[25] Wróblewska J, Kowalski R. Assessing concrete strength in fire-damaged structures[J/OL]. Construction and Building Materials, 2020, 254. DOI: 10.1016/j.conbuildmat.2020.119122.

[26] Shen J, Xu Q. Effect of elevated temperatures on compressive strength of concrete[J/OL]. Construction and Building Materials, 2019, 229: 116846. DOI: 10.1016/j.conbuildmat.2019.116846.

[27] Liu C, Chen J. High temperature degradation mechanism of concrete with plastering layer[J/OL]. Materials, 2022, 15(2): 398. DOI: 10.3390/ma15020398.

[28] Uma Bharathi M, Pradeep Kumar C. Study on fire performance characteristics of steel reinforcement in RCC structures[J/OL]. IOP Conference Series: Earth and Environmental Science, 2022, 1086(1): 012005. DOI: 10.1088/1755-1315/1086/1/012005.

[29] Baloch W L, Siad H, Lachemi M, et al. Effect of fire exposure on the bonding behavior of hybrid engineered composite systems[J/OL]. Journal of Building Engineering, 2023, 71: 106442. DOI: 10.1016/j.jobe.2023.106442.

[30] Karka B R, Bruno B, Ngarmaïm N, et al. The effects of degradation phenomena of the steel-concrete interface in reinforced concrete structures[J/OL]. Journal of Materials Science and Chemical Engineering, 2023, 11(3): 1-21. DOI: 10.4236/msce.2023.113001.

[31] Peng G F, Bian S H, Guo Z Q, et al. Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures[J/OL]. Construction and Building Materials, 2008, 22(5): 948-955. DOI: 10.1016/j.conbuildmat.2006.12.002.

[32] Songkhla W N, Chaikaew C, Chatveera B, et al. Comparative assessment of rapid and natural cooling effects on post-fire flexural strength of fly ash blended concrete[J/OL]. Results in Engineering, 2025, 28: 107594. DOI: 10.1016/j.rineng.2025.107594.

[33] Sam V S, Alin Joe J A, Anand N, et al. Residual behaviour of cold formed stainless steel following a fire[J/OL]. Results in Engineering, 2025, 28: 107840. DOI: 10.1016/j.rineng.2025.107840.

[34] Phan L T, Carino N J. Fire performance of high strength concrete: Research needs[C/OL]// Advanced Technology in Structural Engineering. Reston, VA: American Society of Civil Engineers, 2000: 1-8. DOI: 10.1061/40492(2000/181.

[35] Annerel E, Taerwe L. Assessment techniques for the evaluation of concrete structures after fire[J/OL]. Journal of Structural Fire Engineering, 2013, 4(2): 123-130. DOI: 10.1260/2040-2317.4.2.123.

[36] Babalola O E, Awoyera P O, Le D H, et al. A review of residual strength properties of normal and high strength concrete exposed to elevated temperatures: Impact of materials modification on behaviour of concrete composite[J/OL]. Construction and Building Materials, 2021, 296: 123448. DOI: 10.1016/j.conbuildmat.2021.123448.

[37] Xiaoyong L, Fanjie B. Residual strength for concrete after exposure to high temperatures[C/OL]// 2011: 382-390. DOI: 10.1007/978-3-642-23998-4_53.

[38] Onundi L O, Ben Oumarou M, Alkali A M. Effects of fire on the strength of reinforced concrete structural members[J/OL]. American Journal of Civil Engineering and Architecture, 2019, 7(1): 1-12. DOI: 10.12691/ajcea-7-1-1.

[39] Hodhod O A, Rashad A M, Abdel-Razek M M, et al. Coating protection of loaded RC columns to resist elevated temperature[J/OL]. Fire Safety Journal, 2009, 44(2): 241-249. DOI: 10.1016/j.firesaf.2008.06.010.

[40] Kovalov A, Otrosh Y, Ostroverkh O, et al. Fire resistance evaluation of reinforced concrete floors with fire-retardant coating by calculation and experimental method[J/OL]. E3S Web of Conferences, 2018, 60: 00003. DOI: 10.1051/e3sconf/20186000003.

[41] Allam S M, Elbakry H M F, Rabeai A G. Behavior of one-way reinforced concrete slabs subjected to fire[J/OL]. Alexandria Engineering Journal, 2013, 52(4): 749-761. DOI: 10.1016/j.aej.2013.09.004.

[42] Cho H C, Lee D H, Ju H, et al. Fire damage assessment of reinforced concrete structures using fuzzy theory[J/OL]. Applied Sciences, 2017, 7(5). DOI: 10.3390/app7050518.

[43] Hager I. Colour change in heated concrete[J/OL]. Fire Technology, 2014, 50(4): 945-958. DOI: 10.1007/s10694-012-0320-7.

[44] Bureau of Indian Standards. IS 13311 (part 1): Method of non-destructive testing of concrete – part 1: Ultrasonic pulse velocity[S]. Bureau of Indian Standards, 1992.

[45] Bureau of Indian Standards. IS 13311 (part 2): Non-destructive testing of concrete – methods of test part 2: Rebound hammer[S/OL]. Bureau of Indian Standards, 1992. https://law.resource.org/pub/in/bis/S03/is.13311.2.1992.pdf.