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Post-Fire Structural Condition Assessment and Remediation Strategy for a Seven-Storied Reinforced Concrete Industrial Building: A Case Study from the Ready-Made Garment Sector in Bangladesh

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ABSTRACT

Post-fire assessment of existing reinforced concrete (RC) structures is frequently carried out using a single assessment technique, most commonly visual inspection, in isolation, an approach that risks two opposite failure modes: unnecessary demolition of members whose fire exposure did not compromise structural capacity, and continued occupation of members whose internal damage is not visible at the surface. Existing codes and guidance establish individual test methods but offer limited practical guidance on how visual, non-destructive and destructive evidence should be combined into a single, consistent, evidence-based decision on member-level remediation. This study addresses that gap by developing and demonstrating an integrated, tiered assessment framework that combines visual crack survey, phenolphthalein carbonation testing, ultrasonic pulse velocity (UPV) testing and cylindrical concrete core extraction with compressive-strength testing, cross-checked against a structural capacity verification, to classify fire-affected members and select a matched remediation strategy. The framework's central methodological contribution is a clear decision rule: a member is classified as core-damaged, and assigned to concrete removal, epoxy-injection and jacketing, only where the combined carbonation and UPV/crack evidence shows damage penetrating beyond the reinforcement clear cover; members with distress confined to the cover concrete are instead assigned a lower-cost plaster or wire-mesh reinstatement. The framework is demonstrated on a seven-storied RC industrial building in Bangladesh following a third-floor fire, where it distinguished core-damaged from surface-damaged columns, beams and a flat-plate slab, and was cross-validated by an independent punching-shear capacity check of the fire-affected slab-column connections. Beyond the specific case, the framework is presented as a generalizable, replicable protocol for practising structural engineers undertaking post-fire condition assessment and rehabilitation planning of existing RC buildings, particularly in ready-made garment and other industrial facilities where rapid, defensible return-to-service decisions are operationally critical.

INTRODUCTION

Fire is among the most severe accidental loads that a reinforced concrete (RCC) structure can experience, and it is a recurring hazard for ready-made garment (RMG) and light-industrial facilities in Bangladesh, where dense storage of combustible raw materials, finished goods and packaging significantly increases fire load and duration. Unlike gravity or wind loading, a fire event subjects structural concrete and reinforcing steel to a combination of high, non-uniform temperature, rapid heating and, subsequently, thermal shock from fire-fighting water, all of which can degrade material properties without producing damage that is always visible at the surface. Elevated temperature causes progressive loss of concrete compressive and tensile strength, dehydration of cement hydration products, aggregate-paste incompatibility (particularly for siliceous aggregates above 300 to 400 degrees Celsius), spalling of cover concrete, and an accelerated carbonation front that reduces the alkaline protection afforded to embedded reinforcement. Reinforcing steel similarly loses yield strength and stiffness above approximately 400 to 500 degrees Celsius, though it largely recovers strength on cooling unless significant deformation or bond loss has occurred. Because the extent of internal damage from a fire event is rarely proportional to the visible surface distress, a rigorous, code-informed structural condition assessment is essential before any decision is made to demolish, repair or continue occupying a fire-affected building. Regulatory frameworks applicable to the RMG sector in Bangladesh, together with international practice guidance such as ACI 562 (Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures), require that such an assessment combine visual condition survey with non-destructive testing (NDT) and, where necessary, destructive testing (DT) of representative concrete samples, so that repair decisions are based on measured residual material properties rather than visual judgement alone. This paper presents a case study of the post-fire structural condition assessment and remediation strategy developed for a seven-storied RCC industrial building following a fire incident that affected the entire third floor. The specific objectives of the study are: (i) to document a practical multi-method testing protocol (visual crack survey, carbonation testing, ultrasonic pulse velocity testing and concrete core extraction with

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compressive-strength testing) suitable for post-fire assessment of RCC columns, beams and flat-plate slabs in an industrial setting; (ii) to classify the fire-affected structural members into damage categories based on the measured depth of fire-induced deterioration relative to the reinforcement clear cover; and (iii) to present the resulting targeted remediation methodology, structural verification (punching-shear capacity check) and phased work programme, so that the approach can serve as a reference for similar post-fire assessments of industrial RCC buildings in Bangladesh and comparable regions.

LITERATURE REVIEW

The behaviour of concrete and reinforcing steel at elevated temperature has been studied extensively, and Khoury (2000) provides a comprehensive review of the physical, chemical and mechanical changes that occur in concrete during and after a fire, including progressive loss of compressive strength above approximately 300 degrees Celsius, dehydration of calcium silicate hydrate, decomposition of calcium hydroxide near 450 to 550 degrees Celsius, and thermally induced microcracking that can persist long after cooling. Neville (2011) similarly notes that residual compressive strength of ordinary Portland cement concrete typically falls below 75 percent of its original value once temperatures exceed 300 degrees Celsius, with more severe reductions where spalling has removed cover concrete and exposed aggregate or reinforcement directly to flame. Bazant and Kaplan (1996) present a detailed mathematical treatment of the thermal, hygral and mechanical response of concrete at high temperature, while Chan *et al.* (1999) demonstrated experimentally that the residual strength loss and spalling propensity of concrete are also strongly influenced by moisture content and mix design at the time of the fire. At the microstructural level, Lin *et al.* (1996) used scanning electron microscopy to show that fire-induced microcracking and paste-aggregate debonding propagate inward from the exposed face in a manner broadly consistent with the depth-of-damage classification approach adopted in the present study, while Elghazouli *et al.* (2009) established that reinforcing steel retains most of its room-temperature yield strength on cooling below approximately 400 degrees Celsius but can suffer permanent strength and ductility loss above this threshold, underscoring the importance of assessing exposure severity rather than assuming full recovery of embedded reinforcement. Because the temperature history of a real fire cannot be measured directly after the event, post-fire assessment relies on indirect indicators of the depth to which damage has penetrated. Carbonation depth testing, using a phenolphthalein indicator solution sprayed on a freshly broken or cored concrete surface (following the RILEM CPC-18 procedure), is widely used because fire accelerates carbonation by driving off moisture and creating microcracks that allow carbon dioxide ingress; a carbonation front that has advanced beyond the reinforcement clear cover is a strong indicator that the alkaline protection of the steel, and potentially the surrounding concrete strength, has been compromised (RILEM TC 56-MHM, 1988). Ultrasonic pulse velocity (UPV) testing, conducted in accordance with BS EN 12504-4 (British Standards Institution, 2004), measures the transit time of a stress wave between transducers placed on either side of a crack or defect; because the wave must diffract around a discontinuity, the additional transit time relative to sound concrete can be used to estimate the depth of surface-breaking cracks, providing a non-destructive complement to visual crack measurement. Concrete core testing remains the most direct method of establishing in-situ compressive strength: ACI 214.4R-10 (ACI Committee 214, 2010) sets out the procedure for obtaining and testing cores and for applying statistical and geometric correction factors, while ACI 562-19 (ACI Committee 562, 2019) provides the overarching framework for using such in-situ test data to classify existing concrete members and select an appropriate assessment and repair strategy. Fire-resistance design guidance, such as ACI 216.1-14 (American Concrete Institute, 2014), establishes the expected performance of normal-weight concrete members under standard fire exposure and is a useful benchmark against which the observed depth of damage in a real fire event can be compared. However, published case studies that combine all four assessment methods, visual survey, carbonation, UPV and core testing, on an operating RMG factory building in Bangladesh remain limited, which is the gap this case study addresses by presenting a complete, replicable field assessment and classification procedure together with the resulting repair design and construction sequencing. Beyond the carbonation, UPV and coring methods adopted in this study, several complementary field techniques have been reported in the literature. Annerel and Taerwe (2011) proposed a colorimetric method that quantifies the characteristic discolouration of heated concrete to estimate peak temperature exposure, offering a rapid, low-cost screening tool that could complement carbonation testing in future assessments. Aseem *et al.* (2019) documented a comparable multi-method case study of a fire-damaged reinforced concrete building using rebound hammer, ultrasonic pulse velocity and micrographical forensic analysis, and, consistent with the present findings, concluded that no single test method was sufficient on its own and that combined destructive and non-destructive evidence was necessary to reliably delineate damaged from sound concrete. Complementary destructive and non-destructive test standards, including ASTM C42/C42M for core sampling, ASTM C597 for pulse-velocity measurement, ASTM C805/C805M for the rebound hammer, and BS 1881-120 for core compressive strength testing, together with sector guidance such as Concrete Society Technical Report 68 (2008) on the assessment, design and repair of fire-damaged concrete structures and the Institution of Structural Engineers' (2008) guide to advanced fire safety engineering, provide the wider procedural basis within which the site-specific testing programme described in Section 3 was designed. Recent work published in the American Journal of Civil Engineering and Constructions (AJCEC) reinforces several of the durability and inspection themes relevant to this case study. Ridoy *et al.* (2026) evaluated the mechanical strength and durability of concrete incorporating recycled aggregate and fly ash, finding that in-situ strength and durability of concrete are highly sensitive to mix composition and curing history, which supports the present study's use of direct in-situ core testing, rather than as-designed strength alone, as the basis for post-fire capacity checks. Mohibullah and Sheam (2026) similarly reviewed the long-term mechanical and durability performance of fiber-reinforced concrete, noting that crack width and shrinkage-related distress are strongly influenced by the internal condition of the concrete matrix, consistent with the present study's finding that surface crack width alone under-represented true internal crack depth. From an inspection-technology perspective, Afolabi *et al.* (2026) reviewed the use of augmented reality (AR) for civil infrastructure inspection and reported that AR-assisted defect measurement can improve inspection accuracy to millimeter-scale tolerances and reduce inspection time by up to 30 percent relative to conventional manual survey; while the present assessment relied on conventional tape-based crack survey combined with UPV and coring, the AR-based defect-registration approaches reviewed by Afolabi *et al.* (2026) represent a promising complementary tool for future post-fire assessments of similarly large, multi-storey industrial floor plates.

MATERIALS AND METHODS

Description of the structure and the fire incident

The subject building is a seven-storied RCC industrial (ready-made garment manufacturing) building in Bangladesh, employing a flat-plate slab-column structural system. A fire incident that occurred on the building affected the entire third floor, resulting in visible spalling of plaster, cracking of columns and beams, and localized concrete deterioration. A structural investigation was commissioned and carried out by an independent structural engineering consultancy, with the assessment team visiting the site on multiple occasions between August and October 2022 to conduct a visual inspection, plan the location of destructive and non-destructive tests, and subsequently interpret the results.

Visual condition survey

A grid-referenced visual survey of all third-floor columns, beams and the flat-plate slab was performed to document plaster spalling, exposed reinforcement, and surface cracking. Each observed crack was assigned a unique identifier (e.g., Cr-01 to Cr-18 for columns) with its grid location, existing cross-sectional dimension, and physically measured crack width and depth recorded using a steel tape and feeler technique. Eighteen (18) columns exhibited crack and spalling distress warranting further testing, while an additional ten (10) columns exhibited plaster spalling only, without visible cracking of the concrete core.

Carbonation depth testing

Carbonation testing was carried out on freshly exposed concrete surfaces (chipped or cored) using a phenolphthalein indicator solution, following standard RILEM CPC-18 practice. A colour change to pink/magenta indicates concrete with a pH above approximately 9, while the uncoloured zone indicates carbonated concrete with reduced alkalinity. The depth of the uncoloured (carbonated) zone was measured perpendicular to the exposed face at each column, beam and slab test location. Carbonation testing was conducted independently at multiple locations by the investigating consultancy and by a second independent testing firm, to cross-verify results, and additionally verified through an accredited materials testing laboratory following standard concrete testing procedures used in Bangladesh.

Ultrasonic pulse velocity (UPV) testing

UPV testing was performed at selected third-floor columns following BS EN 12504-4 practice, using paired transducers positioned across observed cracks at multiple heights on each column face (stations A, B and C). The transit time of the ultrasonic pulse across the crack (tc) was compared against the transit time along the surface of equivalent, defect-free concrete (tc0) at the same station spacing, and the approximate crack depth was back-calculated from the additional path length implied by diffraction of the pulse around the crack tip. Four columns (UPV-1 to UPV-4, grid locations E-6, E-4, D-4 and C-6) were tested at three stations each, giving twelve individual crack-depth estimates.

Concrete core extraction and compressive strength testing

Cylindrical concrete cores were extracted from third-floor columns and from the fourth-floor slab (and, separately, the third-floor roof slab) using a diamond core-cutting rig, in general accordance with ACI 214.4R-10. Four core specimens were tested from third-floor columns (grid locations C8, C4) and four from the fourth-floor slab, with core diameter, height, cross-sectional area, crushing load and mode of failure recorded for each specimen. Testing was performed by an accredited materials testing laboratory following standard concrete testing procedures used in Bangladesh, under sealed-condition sample handling. The measured core crushing strengths were converted to an equivalent in-situ specified concrete strength (fceq) using the statistical procedure of ACI 562/ACI 214, incorporating the sample mean, standard deviation, coefficient of variation and an appropriate modification factor (Kc) for the number of specimens, followed by application of the relevant ACI 214 length-to-diameter correction factor.

Punching-shear capacity verification

Because the structural system is a flat-plate slab, a punching-shear capacity check was carried out at a representative typical interior column and separately at a column supporting an additional masonry wall load in the toilet zone, using the two-way (punching) shear provisions consistent with ACI 318 practice: Vc = 4 x 0.85 x sqrt(f'c) x b0 x d, where f'c is the concrete compressive strength (psi), b0 is the perimeter of the assumed critical shear section located at d/2 from the column face, and d is the effective slab depth. The design ultimate load per unit area was computed from the factored combination of slab self-weight, superimposed floor finish and live load (1.2D + 1.6L), and, for the toilet-zone column, an additional factored masonry wall reaction.

RESULTS AND DISCUSSION

Concrete core compressive strength

Table 1 summarizes the individual core-crushing strengths and the corresponding equivalent in-situ specified concrete strength (fceq) computed per ACI 562/ACI 214 for both the third-floor column cores and the fourth-floor/roof slab cores.

All four column-mode failures were classified as "combined" except one "shear" failure occurring at a construction joint, indicating that the extracted specimens were broadly representative of sound bulk concrete rather than fire-degraded material at the core interior, since the cores were taken from locations away from directly exposed, spalled faces. The resulting equivalent strengths (2192 psi for columns; 3634 psi for slab) both remain below the nominal 4000 psi design strength commonly assumed for such structures, which is consistent with expected in-situ strength variability and core-testing corrections rather than being attributable solely to fire damage, and were subsequently used as the basis for the punching-shear capacity verification discussed in Section 4.5.

Carbonation depth results

Carbonation depth measurements were obtained at ten core locations spanning columns, a beam and slabs (Table 2), each averaged from five measurement positions per core.

The maximum individual (single-position) carbonation depth recorded across all column locations was 48.1 mm, while the maximum average slab carbonation depth was 23.6 mm, both of which are reported in the classification results below. Carbonation depths of this magnitude are broadly consistent with accelerated post-fire carbonation

Table 1: Summary of concrete core compressive strength test results and ACI 562 equivalent strength.

Member	n	Individual core strengths (psi)	Mean (psi)	SD (psi)	fceq (psi, ACI 562)
3rd floor columns	4	2996, 2823, 2218, 3165	2800.5	413	2192
4th floor / roof slab	4	5067, 4171, 3961, 5070	4567.25	586	3634

reported in the literature (RILEM TC 56-MHM, 1988; Khoury, 2000), where thermally induced microcracking increases the effective diffusivity of the cover concrete to atmospheric carbon dioxide relative to unheated concrete of similar age and

Crack survey and UPV-estimated crack depth

Physical crack measurement combined with UPV testing was carried out at eighteen columns (Cr-01 to Cr-18) and two beam spans (FB-01, FB-02). Crack depths measured directly ranged from approximately 8 mm to 200 mm, while UPV-based estimates at four columns where both methods were applied (grids E-6, E-4, D-4 and C-6) ranged from 155.2 mm to 213.7 mm and were found to closely corroborate the physically measured values, in three of four cases exceeding the tape-measured depth by only 1 to 15 percent, confirming that the visible crack length on the concrete surface generally under-represented the true depth of fire-induced internal cracking. Where UPV results were available, the larger of the two values was conservatively adopted for damage classification. The most severely affected locations were columns at grids D-4 (UPV-measured depth 213.7 mm, carbonation depth 48.1 mm) and E-6 (measured depth 202 mm), both of which exhibited cracking that clearly penetrated beyond the nominal 1.5-inch reinforcement clear cover. Both beam spans FB-01 and FB-02, located along grid line B between grids 3 and 9, exhibited full-depth mid-span cracking with a carbonation depth of 25.2 mm and were consequently excluded from the retained structural model pending repair.

Damage classification and remediation methodology

Following ACI 562 practice, each surveyed member was classified into a damage category based on whether the measured crack and/or carbonation depth penetrated beyond the reinforcement clear cover (core-damaged) or remained confined to the plaster/cover concrete (surface-

Table 2: Measured depth of carbonation at representative core locations (mm).

Core ID	Grid / Floor	Member type	Average carbonation depth (mm)
Core-1	B-9, 3rd floor	Column	14.9
Core-2	C-6, 3rd floor	Column	8.7
Core-3	C-9, 3rd floor	Column	26.5
Core-4	B-7/9, 4th floor	Beam	14.8
Core-5	C-D-6/9, 4th floor	Slab	19.0
Core-6	C-D-9 cantilever, 4th floor	Slab	21.8
Core-7	F-1, 3rd floor	Column	30.4
Core-8	F-6, 3rd floor	Column	20.7
Core-9	F-9, 3rd floor	Column	18.4
Core-10	E-9, 3rd floor	Column	16.1

damaged only), using engineering judgement informed by the combined NDT/DT results. The resulting classification for the third floor is summarized in Table 3. The column and beam jacketing methodology comprised: (1) removal of plaster and loose or fire-damaged concrete from the existing member down to sound concrete; (2) chipping up to the identified crack; (3) surface cleaning; (4) application of anti-corrosive coating to any exposed, corroded reinforcement; (5) provision of two 4-inch by 4-inch openings through the slab at the beam-column joint to allow new concrete to be poured; (6) epoxy injection grouting to repair residual cracks; (7) installation of new supplemental reinforcement (rebar core) and shear connectors doweled into the existing member with epoxy; (8) application of an epoxy bonding coat to the prepared existing concrete surface; (9) installation of shuttering; (10) placement of non-shrink, normal-weight micro-concrete (approximately 6000 psi design strength) around the existing core; and (11) a minimum 7-day fresh-water curing period. For the flat-plate slab, existing plaster and clear cover were removed, 10 mm diameter shear connectors were epoxy-doweled at 48-inch centres, an 18-gauge wire mesh (38 mm centre-to-centre) was fixed with nails at 24-inch centres, and the surface was reinstated with a 1/2-inch coarse-sand (1:3) plaster coat followed by a 1/4-inch fine-sand (1:4) finish coat. At the toilet-zone slab, where an additional masonry wall load is carried, a ferrocement overlay (1.5-inch mortar with wire mesh, cement:sand = 1:3) bonded with an epoxy coating and mechanically anchored through drilled slab holes was proposed in place of the standard wire-mesh plaster detail, to provide additional reserve capacity.

Punching-shear capacity verification

Using an 8-inch slab thickness, 15-inch by 24-inch column, an effective depth of 6.5 inches, and a factored load of 197.64 psf (1.2 x (88.7 psf self-weight + 20 psf finish)

Figure 1: Physical measurement of fire-induced crack depth (approximately 8 mm) at a column face using a feeler/ruler technique.

Figure 2: Tape measurement of a fire-induced column crack (approximately 105 mm) prior to correlation with the corresponding UPV-estimated crack depth

+ 1.6 x 42 psf live load), the punching-shear demand at a typical interior column was calculated as 81.15 kips, against an available concrete punching-shear capacity of 4 x 0.85 x sqrt(4000) x 104 x 6.5 = 145.4 kips, a capacity-to-demand ratio of 1.79. At the toilet-zone column (grid C-9), which additionally carries a factored masonry wall reaction of approximately 44.46 kips, the punching demand increased to 110.74 kips, still comfortably within the same 145.4 kip capacity (ratio 1.31). Both checks confirm that the flat-plate slab-column punching-shear capacity is adequate at the equivalent in-situ concrete strength established from core testing, and that no structural strengthening of the slab-column connection was required as a consequence of the fire, consistent with the classification of the slab as unimpaired by fire in Section 4.4.

Table 3: Summary of fire-damage classification and remediation approach by structural member

Member type	Grid locations (representative)	Count	Governing finding	Remediation approach
Column - core damaged	G/4, F/1, F/4, F/6, F/9, E/4, E/6, E/9, D/4, D/6, D/9, C/6, C/9, B/3, B/5, B/6, B/7, B/9	18	Max. carbonation 48.1 mm; max. UPV crack depth 213.7 mm, exceeding clear cover	Remove damaged concrete, epoxy-inject crack, new rebar core, jacket with non-shrink micro-concrete, epoxy bonding coat
Column - plaster only	H/1, H/4, G/1, G/6, G/7A, G/9, E/1, D/1, C/2	10	Plaster spalling only; core concrete unimpaired by fire	Remove and reinstate plaster; concrete assessed only if further damage found on removal
Beam - core damaged	B/(3-9), spans FB-01 & FB-02	2 spans (4 nos.)	Max. carbonation 25.2 mm; mid-span full-depth cracking observed	Remove damaged concrete/ plaster, epoxy-inject, jacket beam soffit and sides with new concrete
Flat-plate slab	H~A (typical) and toilet zone (C-9)	Full 3rd floor	Max. carbonation 23.6 mm; core concrete unimpaired by fire	Reinstate clear cover with 18-gauge wire mesh plaster; ferrocement overlay with shear connectors at toilet zone

Remediation sequencing and work programme

Temporary propping was installed throughout the third floor prior to commencement of remediation to support construction and any residual dead and live loads during member repair. Given the number and spatial distribution of affected members, the column and beam jacketing work was sequenced into five successive seven-day phases to allow curing of each phase before adjacent or supporting members were disturbed. An overall remediation programme spanning approximately seven months was developed, comprising: (i) mobilization; (ii) column remediation (jacketing) work; (iii) column plastering; (iv) slab plastering with wire mesh; (v) column retrofitting; and (vi) proposed supplementary steel bracing, with production activity on the affected floor withheld until completion of the remediation works.

Figure 3: Spalling of soffit plaster on the third-floor flat-plate slab, typical of the surface-only distress observed across the slab away from the toilet zone.

CONCLUSION

A combined visual, non-destructive (carbonation and UPV) and destructive (core compressive strength) testing programme was used to assess a seven-storied RCC industrial building following a third-floor fire incident. The approach allowed a clear, quantitative distinction between structural members requiring core-concrete replacement and jacketing (18 of 28 surveyed columns and two beam spans, where fire-induced cracking and carbonation penetrated beyond the reinforcement clear cover, with UPV-estimated crack depths of up to 213.7 mm and carbonation depths of up to 48.1 mm) and members requiring only cosmetic plaster reinstatement (10 columns and the entire flat-plate slab, where carbonation and cracking remained within the clear cover, with a maximum slab carbonation depth of 23.6 mm). A punching-shear capacity check confirmed that the flat-plate slab-column system retained adequate capacity at both a typical interior column (ratio 1.79) and a wall-loaded toilet-zone column (ratio 1.31), demonstrating that the slab required no structural strengthening despite exposure to the fire. The resulting remediation strategy, comprising epoxy-injection crack repair, reinforced micro-concrete jacketing of damaged columns and beams, and wire-mesh or ferrocement plaster reinstatement of the slab, together with a phased, propped seven-month construction programme, illustrates that a tiered, test-based classification approach can substantially reduce the extent of demolition and repair required after a fire event in an RCC industrial building, while providing an evidence-based basis for restoring the facility to production use. This case study is offered as a practical reference framework for structural engineers undertaking similar post-fire assessments of RMG and light-industrial RCC buildings in Bangladesh and comparable settings; future work could usefully extend the framework with a full nonlinear structural re-analysis of the repaired frame and long-term monitoring of repaired member performance.

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