# Fire Resistance of Reinforced Concrete Structural Members: A Review of Experimental, Analytical, and Code-Based Approaches

**Pipaliya Dhruv Navinbhai[1], Prof. K. A. Parmar[2]**
[12] Applied Mechanics Department, L.D. College of Engineering, Ahmedabad, Gujarat, India
* Corresponding Author Email: 24amdhr20022@ldce.ac.in | ORCID: https://orcid.org/xxxx-xxxx-xxxx-xxxx

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## Abstract

Fire is one of the most critical accidental actions that reinforced concrete (RC) structures may face in service, yet the three major design codes — IS 456:2000 (India), ACI 216.1-07 (USA), and EN 1992-1-2:2004 (Europe) — approach the problem through fundamentally different methods and account for very different sets of design parameters. This paper reviews published experimental, numerical, and analytical research on the fire resistance of RC beams and frames, covering the temperature-dependent behaviour of concrete and reinforcing steel, the influence of structural and material parameters on fire endurance, a direct comparison of the three code methods, fire scenario effects on RC frame structures, and thermal strain modelling under load. The review finds that corner-bar temperature rise at intermediate fire durations is the key failure trigger in simply supported beams, that steel yield grade changes fire endurance in a way that the Indian prescriptive code cannot detect, and that the analytical method of EN 1992-1-2:2004 gives more physically reliable results than empirical chart methods. The paper also points to specific gaps in Indian fire design practice and outlines directions for future work.

**Keywords** Fire resistance; reinforced concrete; IS 456:2000; ACI 216.1-07; EN 1992-1-2:2004; cover depth; steel temperature; fire scenario; performance-based design.

## I. INTRODUCTION

Fire is among the most severe accidental actions a building may face during its service life. In RC structures, sustained exposure to elevated temperatures causes progressive compressive strength loss in concrete, accelerated yield-strength reduction in steel above 400°C, and large internal thermal strains that can produce cracking, spalling, and geometric distortion. When fire suppression systems fail, structural integrity becomes the last line of defence against collapse [1]. Adequate fire resistance is therefore a genuine structural safety requirement, not a procedural formality.

Fire resistance design of RC members is governed by three broadly different frameworks: the prescriptive tabular approach of IS 456:2000 [2], which specifies only minimum concrete cover and member width; the empirical chart method of ACI 216.1-07 [3], which incorporates load ratio and reinforcement index calibrated against furnace tests; and the analytical reduced-strength method of EN 1992-1-2:2004 [4], which requires explicit temperature calculation and moment equilibrium verification. Systematic divergences between these methods for identical members have motivated substantial research since the 1970s, when rational performance-based fire design was first proposed [5], and the body of work has grown considerably since [6].

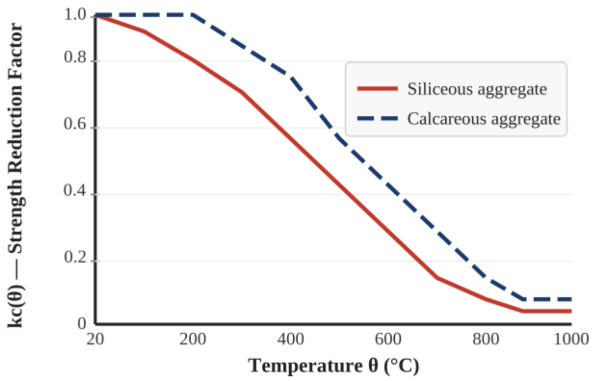
This review has four objectives: (i) to summarise thermally driven degradation of concrete and steel relevant to fire design [4,7]; (ii) to identify structural parameters governing beam fire resistance [6]; (iii) to evaluate comparative merits and limitations of IS 456:2000 [2], ACI 216.1-07 [3], and EN 1992-1-2:2004 [4]; and (iv) to review advances in simplified design equations [6], numerical modelling [12], and thermal strain analysis [8], identifying research gaps relevant to Indian practice.

## II. LITERATURE REVIEW

### 2.1 Concrete at Elevated Temperatures

Khoury [7] documented the thermally driven transformations in concrete: free moisture expulsion near 105°C; gypsum decomposition at 120–163°C; portlandite dehydroxylation with significant strength loss near 450–500°C; the α–β quartz transition at 573°C expanding siliceous aggregate by approximately 5% and propagating radial cracking; and full cement matrix disintegration at 800–1200°C. EN 1992-1-2:2004 [4] represents this through the temperature-dependent compressive strength coefficient kc(θ), tabulated separately for siliceous and calcareous aggregates (Table 3.1 of the code).

Chudzik et al. [8] analysed the total strain of heated concrete under load as a superposition of free thermal strain (FTS), mechanical strain, and load-induced thermal strain (LITS) from transient thermal creep (TTC). TTC occurs only on first heating under compressive load, causing shortening rather than elongation in elements at load ratios above approximately 40–50% once temperature exceeds 300–400°C. Ignoring TTC in structural analysis leads to overestimation of restraint forces and produces unrealistic failure predictions [8].




*Source: EN 1992-1-2:2004, Table 3.1 [4]*

Figure 1. Temperature-dependent compressive strength reduction factor kc(θ) for siliceous and calcareous aggregate concretes, as given in EN 1992-1-2:2004 Table 3.1 [4].

### 2.2 Reinforcing Steel at Elevated Temperatures

The yield strength reduction factor ks(θ) in EN 1992-1-2:2004 Table 3.2a [4] falls steeply above 400°C: for hot-rolled bars, ks drops to approximately 0.47 at 600°C, 0.23 at 700°C, and 0.11 at 800°C. Cold-worked bars degrade faster, with a recovery threshold of only approximately 450°C [9]. Because ks(θ) is applied multiplicatively to the ambient fy, higher-grade steel retains proportionally more residual capacity at any fire temperature — an effect invisible to prescriptive cover tables [2,4].

Kadhum [10] confirmed through fire tests on RC rigid beams that moment capacity reduced by 15–37% at 400–750°C, with water-quenched specimens losing more strength than air-cooled ones due to rapid thermal shock. Corner bars, receiving heat from two exposed faces simultaneously, reach substantially higher temperatures than interior bars at the same nominal cover depth, making them the critical element for fire performance [10].

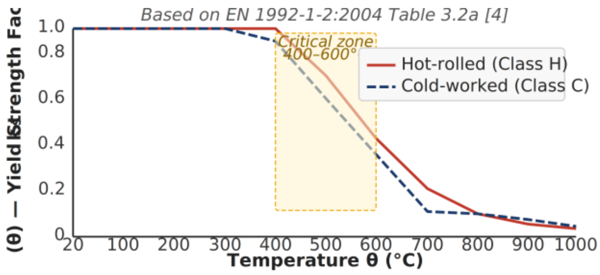



Figure 2. Temperature-dependent yield strength reduction factor ks(θ) for hot-rolled and cold-worked reinforcing steel — EN 1992-1-2:2004 Table 3.2a [4].

### 2.3 Code-Comparison Studies

Džidić [11] compared ACI/TMS 216.1 and EN 1992-1-2 for simply supported RC slabs and found differences of up to 60 minutes for identical geometry. ACI credits longer fire endurance because its empirical base integrates structural reserve and thermal inertia that the section-level EN moment check does not capture [11]. The ACI method cannot resolve ratings finer than 1-hour increments, further limiting its resolution at intermediate fire durations.

Kodur and Dwaikat [6] demonstrated that for a 300×500 mm simply supported beam with 40 mm cover, ACI 216.1 predicts approximately 210 minutes while Eurocode 2 predicts approximately 110 minutes — nearly a factor of two for the same member. The divergence arises because ACI 216.1 provides ratings only at 1, 2, 3, and 4-hour thresholds and does not account for load ratio or span-to-depth ratio.

### 2.4 Fire Scenario and Frame Behaviour

Cvetkovska et al. [12] analysed a three-bay, two-storey RC frame under eight fire scenarios using the SAFIR program. Fire resistance ranged from 173 minutes under multi-bay upper-floor fires to 293 minutes under a middle-span-only fire, confirming that fire compartment position governs structural fire resistance at the frame level in ways that single-member methods cannot predict [12].

## III. METHODOLOGY

This paper employs a systematic literature review methodology. Peer-reviewed journal articles, conference papers, and codes of practice published between 1973 and 2024 were identified through Scopus, Web of Science, and Google Scholar using the keywords: fire resistance, reinforced concrete beams, IS 456, ACI 216.1, EN 1992-1-2, elevated temperature, thermal strain, and fire scenario. Papers were screened for relevance to the fire performance of RC flexural members. Studies were categorised into five themes: (i) material behaviour at elevated temperature [7,8]; (ii) structural parameters governing fire resistance [6]; (iii) code comparison [2,3,4,11]; (iv) fire scenario and frame-level effects [12]; and (v) simplified design equations and numerical modelling [6]. Findings from each category were critically synthesised to identify consensus, contradictions, and research gaps. This review presents no original experimental data or calculation results.

## IV. RESULTS AND DISCUSSION

### 4.1 Parameters Governing RC Beam Fire Resistance

Kodur and Dwaikat [6] quantified parameter influence through parametric studies covering four cross-sections, five support conditions, three load ratios (30%, 50%, 70%), two aggregate types, two concrete types, three span-to-depth ratios, and five fire scenarios. Key findings: fire scenario, load ratio, span-to-depth ratio, axial restraint location, and rotational restraint exert strong influence; cover thickness, beam width, aggregate type, and concrete strength have moderate influence; reinforcement ratio and steel yield strength have minor influence in isolation [6].

The structural modification factor for simply supported beams derived by Kodur and Dwaikat [6] is:

$$\varphi SS = 1.4 - LR - 0.02\psi 0 \quad (\psi 0 \text{ in metres}) \quad \dots (1)$$

where LR = load ratio and ψ0 = section characteristic factor. This confirms load ratio alone can shift fire resistance by 60 minutes over the range 0.3–0.7 — a sensitivity absent from all prescriptive tables [6].

### 4.2 Three-Code Comparative Analysis

IS 456:2000 [2] is fully prescriptive; ACI 216.1-07 [3] is semi-empirical; EN 1992-1-2:2004 [4] is fully analytical. A critical limitation in IS 456:2000 [2] is that Table 16 assigns identical 20 mm cover to both the 60-minute and 90-minute fire ratings for simply supported beams. EN 1992-1-2:2004 [4] shows corner-bar temperatures rise from approximately 700°C at 60 minutes to approximately 875°C at 90 minutes — spanning the steepest part of the ks(θ) curve where hot-rolled bar strength drops from ~0.37fy to ~0.185fy. This prescriptive equivalence is physically unjustified once a temperature calculation is performed [4].

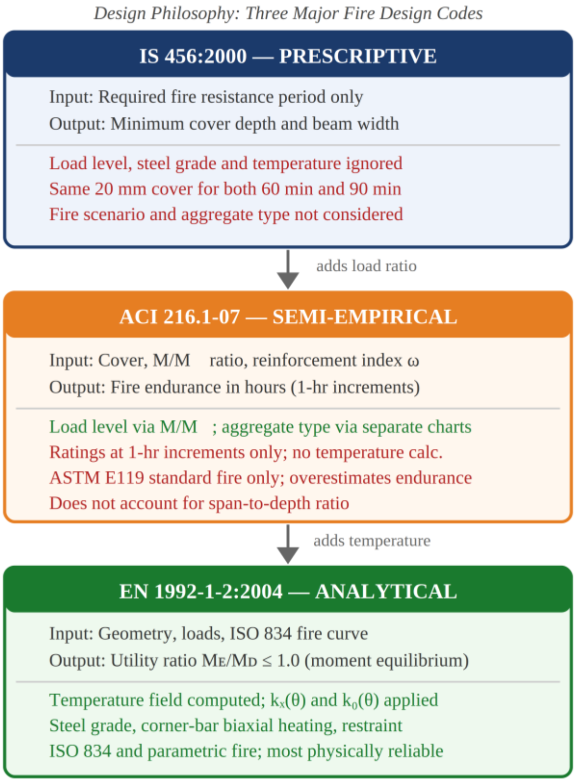



Figure 3. Comparative design philosophy of IS 456:2000 [2], ACI 216.1-07 [3], and EN 1992-1-2:2004 [4].

TABLE I. PARAMETER SENSITIVITY OF THREE FIRE DESIGN CODES [2,3,4,6,11]

| Parameter | IS 456:2000 | ACI 216.1-07 | EN 1992-1-2:2004 |
|---|---|---|---|
| Cover depth | Primary | Primary | Via temperature |
| Load level | Ignored | Explicit (chart) | Moment check |
| Steel grade | Ignored | Via Mn | Explicit ks(θ) |
| Concrete grade | Ignored | Via Mn,ω | Explicit kc(θ) |
| Aggregate type | Ignored | Separate charts | Separate tables |
| Fire scenario | Ignored | ASTM E119 only | ISO 834+parametric |
| Restraint | Ignored | R/UR class | Redistribution |

Sources: IS 456:2000 [2]; ACI 216.1-07 [3]; EN 1992-1-2:2004 [4]; Kodur & Dwaikat [6]; Džidić [11].

### 4.3 Simplified Design Equation

To overcome prescriptive limitations, Kodur and Dwaikat [6] developed a validated design equation:

$$R = \varphi st \cdot \varphi ag \cdot \varphi cs \cdot R_0 \quad \dots (2)$$

where $R_0$ is a cover-and-width base estimate; φst accounts for support conditions, load ratio, span-to-depth ratio, and restraint; φag = 1.2 (carbonate) or 1.0 (siliceous); and φcs accounts for high-strength concrete and spalling. Valid for R = 1–5 hr, span-to-depth ratio 8–18, and f'c = 30–100 MPa [6].

TABLE II(A). BEAM PROPERTIES USED IN VALIDATION [6]

| Beam ID | Source in [6] | Section (mm) | Cover (mm) | Support | f'c (MPa) |
|---|---|---|---|---|---|
| Ex. SS | Appendix B, Table B.1 | 400×600 | 50 | SS | 40 |
| Ex. AR | Appendix B, Table B.1 | 400×600 | 50 | AR | 40 |
| Beam B1 | Table 1; tested by [15] | 254×406 | 40 | SS | 52 |
| Beam B3 | Table 1; [6] | 200×600 | 40 | SS | 91 |

Beam B1: carbonate aggregate, fy=450 MPa, LR=0.54, tested by [15]. Beam B3: siliceous, LR=0.263.

TABLE II(B). FIRE RESISTANCE PREDICTIONS vs CODE METHODS [6]

| Beam ID | Fire Test (min) | ACI 216.1 (min) | EC2 (min) | Proposed Eqn [6] (min) |
|---|---|---|---|---|
| Ex. SS | — | 240 | 156 | 153 |
| Ex. AR | — | >240 | N/A* | 204 |
| Beam B1 | 180 | 240 | — | ~165 |
| Beam B3 | 160 | 240 | — | ~152 |

* EN 1992-1-2 [4] does not provide clear guidance for axially restrained beams [6]. IS 456:2000 [2] was NOT included in the [6] validation study.

### 4.4 Fire Scenario Effects on RC Frames

Cvetkovska et al. [12] showed that the fire compartment location within a frame governs structural fire resistance. Middle-span-only fires produced resistance of 293 minutes due to beneficial compressive forces from cold outer bays acting as restraint-induced prestress, while multi-bay upper-floor fires resulted in only 173 minutes on the same structure. These system-level effects are invisible to all three prescriptive code methods.

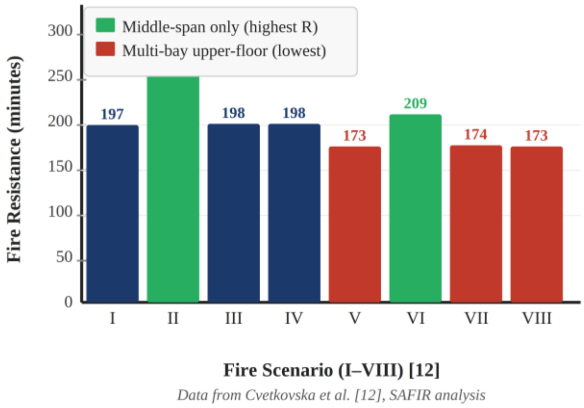



Figure 4. Fire resistance (min to failure) for eight fire scenarios on a 3-bay 2-storey RC frame [12]. Middle-span-only fire (Scenario II) achieves the highest resistance (293 min).

## V. CONCLUSION

This review synthesised research on fire resistance of RC structural members across material behaviour [7,8], structural parameter sensitivity [6,11], three-code comparison [2,3,4], fire scenario effects [12], and simplified design equations [6].

Corner-bar temperature rise at intermediate fire durations — where the ks(θ) curve is steepest between 400°C and 600°C — is the controlling failure mechanism in simply supported RC beams. IS 456:2000 [2] assigns the same 20 mm cover to both 60-minute and 90-minute fire ratings, an equivalence that EN 1992-1-2:2004 [4] temperature calculations show to be physically unjustified.

Steel yield grade has a decisive influence on fire resistance that prescriptive methods cannot capture. Because ks(θ) is multiplicative on fy, upgrading from Fe 415 to Fe 500 at constant geometry can convert a failing section into a passing one at 90 minutes — a distinction IS 456:2000 [2] cannot make.

ACI 216.1-07 [3] consistently overestimates fire resistance relative to EN 1992-1-2:2004, with divergences up to 100 minutes documented [6,11]. The simplified equation of Kodur and Dwaikat [6] provides substantially better predictions by accounting for load ratio, span-to-depth ratio, aggregate type, and support conditions.

Key research gaps include: (i) systematic validation of IS 456:2000 [2] cover requirements against analytical temperature-based methods for Indian material grades and member types; (ii) evaluation of IS-designed members under realistic parametric fires; and (iii) development of performance-based fire design guidance compatible with Indian design practice.

## ACKNOWLEDGMENT

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