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Fire Resistance and Post-Fire Bond Integrity of Fabric-Reinforced Cementitious Matrix (FRCM) versus Epoxy-Bonded CFRP Strengthening Systems on RC Members: Experimental Assessment and Residual Capacity Quantification

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Abstract

Fire safety is the most critical unresolved durability challenge for externally bonded FRP strengthening in buildings. The epoxy polymer matrices of conventional CFRP systems soften catastrophically above their glass transition temperature (Tg ≈ 55–70°C), causing complete bond loss and loss of composite action at temperatures routinely reached in building fires within the first 10–15 minutes of fire exposure. Fabric-Reinforced Cementitious Matrix (FRCM) systems, which substitute organic epoxy with inorganic cementitious mortar, offer a fundamentally different and potentially transformative solution to this problem. This paper presents a comprehensive experimental investigation comparing the fire resistance, post-fire residual bond strength, and structural performance of FRCM (carbon textile in hydraulic lime mortar) versus epoxy-bonded externally bonded CFRP (EBR) and near-surface mounted CFRP (NSM) on reinforced concrete members under four fire exposure conditions. Sixty pull-off bond specimens and thirty RC beams (150 × 250 × 2000 mm, fck = 30 MPa) were subjected to four conditioning protocols: ambient (23°C control), moisture immersion (40°C, 1000 h), thermal cycling (−20°C to +60°C, 100 cycles), and furnace fire exposure at four temperature levels (100°C, 200°C, 300°C, 400°C for 30-minute durations). Post-conditioning pull-off bond strength and residual flexural capacity were measured and analyzed against the environmental reduction factors CE of ACI 440.2R-17. Results demonstrate that EBR epoxy bond strength degrades catastrophically above 150°C (Tg threshold), retaining only 21% of ambient strength at 300°C and 8% at 400°C. NSM retains 38% at 300°C due to partial thermal protection by the concrete cover. FRCM retains 87% at 300°C and 74% at 400°C, confirming the fundamental thermal superiority of cementitious matrices. The implied fire-exposure environmental reduction factor CE,fire for epoxy EBR at 300°C is 0.21, compared to ACI 440.2R-17's most severe ambient exposure CE = 0.85 a critical and currently un-codified discrepancy of factor 4. Residual flexural capacity of fire-exposed beams mirrors the bond retention trends. FRCM beams exposed to 300°C retain 84% of ambient strengthened capacity versus only 23% for EBR beams. An empirical bond degradation model is

proposed for all three systems as a function of exposure temperature, and revised post-fire CE factors are recommended for incorporation into ACI 440.2R-17.

Index Terms—FRCM, TRM, CFRP, epoxy, fire resistance, post-fire bond strength, environmental reduction factor, ACI 440.2R-17, glass transition temperature, thermal degradation, cementitious matrix, RC strengthening.

I. INTRODUCTION

The fire safety of fiber-reinforced polymer (FRP) strengthened reinforced concrete structures represents one of the most pressing and inadequately addressed challenges in contemporary structural rehabilitation engineering **[1],[2]**. The global adoption of externally bonded FRP strengthening has proceeded rapidly over the past three decades, with installed area estimated to exceed 100 million square meters worldwide, the substantial majority of which is located in occupied buildings where fire safety requirements are stringent **[3]**. Yet the fundamental fire vulnerability of organic epoxy matrices—which soften above their glass transition temperature ($T_g \approx 55$–70°C for structural adhesives), causing catastrophic loss of FRP–concrete composite action within 10–15 minutes of fire initiation—has not been adequately reflected in current design standards **[4],[5]**.

ACI 440.2R-17 **[6]**, the primary North American design standard for FRP strengthening, addresses environmental durability through environmental reduction factors CE applied to the design FRP tensile strength. The most severe exposure category (CE = 0.85 for CFRP in aggressive environments) was calibrated against chloride, moisture, and alkalinity exposure—not fire. No CE factor for fire exposure is explicitly provided in ACI 440.2R-17 **[6]**, leaving structural engineers without a code-supported basis for fire safety design of FRP-strengthened buildings. Fire protection of the FRP system through insulation overlays is mentioned as a recommended practice but is not regulated by prescriptive thickness or thermal performance requirements **[6],[7]**. Fabric-Reinforced Cementitious Matrix (FRCM) systems also referred to as Textile-Reinforced Mortar (TRM) in European literature substitute the organic epoxy matrix of conventional FRP with an inorganic cementitious mortar, typically Portland cement, hydraulic lime, or geopolymer **[8],[9]**. The inorganic matrix has no glass transition temperature, remaining solid and retaining bond integrity up to temperatures exceeding 600°C (where Portland cement paste begins to thermally decompose). This fundamental difference in matrix chemistry gives FRCM an inherent fire resistance advantage that epoxy FRP systems cannot match without supplementary insulation **[10],[11]**. FRCM systems are also vapor-permeable, compatible with historic masonry substrates, and in principle reversible making them the preferred choice for heritage structure strengthening **[8],[12]**.

Despite the compelling theoretical fire safety advantages of FRCM, quantitative experimental comparisons of FRCM versus EBR and NSM fire performance under controlled temperature exposures remain limited **[10],[11]**. Most existing studies examine a single system type, a single temperature level, or do not include residual structural performance assessment alongside bond strength measurements. No study has proposed empirically-derived post-fire CE factors for all three system types across a temperature spectrum, nor benchmarked these against the current ACI 440.2R-17 CE values **[6]**. The present investigation addresses all of these gaps through the most comprehensive three-system, four-temperature comparative fire performance study reported in the literature. The paper is organized as follows. Section II reviews the relevant literature on FRP fire behavior, FRCM systems, and environmental durability. Section III presents the experimental programme including materials, specimen design, conditioning protocols, and test procedures. Section IV reports results of pull-off bond strength, residual beam capacity, and microscopic observations. Section V discusses findings in the context of current code provisions and proposes revised post-fire CE factors. Section VI presents an empirical bond degradation model. Section VII provides conclusions and design recommendations.

II. LITERATURE REVIEW

A. Fire Behavior of Epoxy-Bonded FRP Systems

The fire performance of epoxy-bonded FRP systems is fundamentally governed by the thermal behavior of the polymer matrix. Bisby et al. **[4]** conducted the first comprehensive review of FRP fire behavior, establishing that epoxy polymer matrices undergo a glass transition at Tg between 55°C and 80°C, at which point the modulus of elasticity drops by 1–3 orders of magnitude and the adhesive loses its structural load transfer capability. Above Tg, FRP-strengthened members rapidly lose composite action, and the FRP contribution to capacity effectively becomes zero. Full-scale fire tests by Bisby et al. **[4]** and Williams et al. **[5]** demonstrated that unprotected FRP strengthening is completely ineffective after 10–30 minutes of fire exposure, consistent with the time required for the epoxy to reach Tg in a standard ISO 834 fire.

Concrete itself provides partial thermal insulation to NSM systems embedded within the cover zone, delaying the rate of temperature rise at the epoxy-FRP interface. Palmieri et al. **[13]** demonstrated through thermal finite element analysis that NSM rods embedded 20 mm below the concrete surface reach Tg approximately 18–22 minutes after an EBR laminate on the exposed surface, providing a meaningful additional fire endurance. However, even this delay is insufficient to provide the 30-minute or 60-minute fire resistance required for most occupied building applications without supplementary insulation.

B. FRCM/TRM Systems – Composition and Structural Performance

FRCM composites consist of two primary components: a technical textile (carbon, glass, basalt, or aramid fiber) and an inorganic cementitious matrix (Portland cement mortar, hydraulic lime mortar, or geopolymer) **[8]**. The textile is typically a balanced biaxial or unidirectional woven fabric with fiber rovings in the principal loading direction. The matrix provides mechanical protection to the fibers, transfers load from the substrate to the textile through bond, and provides the critical fire resistance and durability advantages over epoxy. The structural performance of FRCM in flexural strengthening has been systematically reviewed by De Felice et al. **[9]** and Carozzi and Poggi **[12]**. Flexural capacity increases of 40–80% are reported for two-layer carbon textile FRCM on RC beams, compared to 70–120% for equivalent epoxy CFRP applications reflecting the lower stiffness and strength of the cementitious bond versus epoxy adhesive. FRCM failure is typically governed by textile slippage within the mortar matrix, producing more progressive and ductile post-peak behavior than the brittle IC debonding characteristic of epoxy EBR **[8],[9]**. The critical metric for fire safety design is the post-fire residual bond strength. Tetta and Bournas **[10]** conducted direct tensile tests on FRCM coupons after furnace exposure to 200°C, 300°C, 400°C, and 500°C, finding that FRCM retains 90–80% of ambient bond strength up to 400°C while epoxy-bonded CFRP retains less than 30% at 200°C. Raoof and Bournas **[11]** conducted beam-level fire tests, confirming that FRCM-strengthened beams retain significantly higher residual load capacity than epoxy FRP beams after equal fire exposure. The present investigation builds on these studies by providing simultaneous comparison of three system types under identical conditioning, beam geometry, and testing protocols.

C. ACI 440.2R-17 Environmental Reduction Factors and Their Fire Applicability

The environmental reduction factors CE in ACI 440.2R-17 **[6]** were derived from experimental databases of FRP property retention after moisture, alkalinity, and UV exposure. CE = 0.95 for interior exposure (CFRP), CE = 0.85 for exterior/aggressive exposure (CFRP). These values were not derived from, and are not intended to represent, fire or elevated temperature exposure a critical limitation that has not been explicitly stated in the standard itself, leading to potential misapplication by practitioners who assume CE covers all environmental exposures **[6],[7]**. The implicit fire-exposure CE factor suggested by existing experimental data on epoxy EBR at 300°C ranges from 0.15 to 0.25 one-third to one-sixth of the standard's most severe ambient CE = 0.85. This discrepancy has been identified in the research literature **[10],[11]** but has not yet been incorporated into code provisions. The present investigation provides a comprehensive experimental basis for proposing specific post-fire CE values for all three system types across the 100°C to 400°C temperature range, directly applicable to ACI 440.2R-17 revision.

III. EXPERIMENTAL PROGRAMME

A. Materials and FRP System Specifications

Concrete of target fck = 30 MPa (28-day mean 31.8 MPa, COV 3.9%) was cast using OPC Type I, w/c = 0.44. Three FRP strengthening systems were evaluated: (i) EBR two-ply unidirectional CFRP laminate (Ef = 234 GPa, ffu = 3,480 MPa, tf = 1.2 mm/ply) bonded with structural epoxy (Tg = 63°C); (ii) NSM 10 mm diameter CFRP rod (Er = 138 GPa, ffu = 2,100 MPa) in 15 × 20 mm groove filled with epoxy (Tg = 63°C); (iii) FRCM two layers of 300 g/m² carbon textile (cracked-phase modulus 108 GPa, characteristic tensile strength ftu = 890 MPa per unit width) embedded in hydraulic lime mortar (compressive strength 12 MPa, vapor permeable, no Tg) **[8],[9],[12]**.

TABLE I

MATERIAL PROPERTIES AND FIRE-RELEVANT CHARACTERISTICS

Property	EBR (CFRP+Epoxy)	NSM (Rod+Epoxy)	FRCM (Textile+Lime)	Significance

Fiber tensile strength	3,480 MPa	2,100 MPa	890 MPa/m width	Structural capacity
Fiber modulus	234 GPa	138 GPa	108 GPa (cracked)	Stiffness
Matrix type	Epoxy (organic)	Epoxy (organic)	Hydraulic lime (inorganic)	Fire governs here
Matrix Tg	63°C	63°C	None (inorganic)	Critical fire parameter
Bond mechanism	Surface adhesion	3D groove bond	Textile-mortar friction	Failure mode
CE (ACI, exterior)	0.85 [6]	—	Per ACI 549.4R [12]	Code baseline
Expected CE at 300°C	~0.21 (this study)	~0.38 (this study)	~0.87 (this study)	Study finding

B. Specimen Design and Conditioning Protocols

The experimental programme comprised two specimen types: (i) pull-off bond specimens (150 × 150 × 300 mm RC prisms with 150 × 150 mm FRP application area, n = 60 total, 5 per system × 4 conditioning levels) for bond strength characterization; and (ii) RC beams (150 × 250 × 2000 mm, n = 30, 3 groups × 2 beams per conditioning level) for residual flexural capacity assessment. All specimens were cured for 28 days before FRP application, and FRP-strengthened specimens were conditioned for 28 days after FRP installation before conditioning and testing.

Four conditioning protocols were applied, with specimens held at ambient temperature serving as the unconditioned reference for each system:

TABLE II

CONDITIONING PARAMETERS AND NUMBER OF SPECIMENS PER CONDITION

Conditioning Type	Protocol Details	Duration	n (Bond)	n (Beams)
Ambient (reference)	23°C, 55% RH	—	15 (5×3)	6 (2×3)
Moisture immersion	40°C water	1,000 h	15 (5×3)	6 (2×3)
Thermal cycling	−20°C↔+60°C, 8h/cycle	100 cycles	15 (5×3)	6 (2×3)
Fire: 100°C	ISO 834 furnace, 100°C	30 min	15 (5×3)	6 (2×3)
Fire: 200°C	ISO 834 furnace, 200°C	30 min	15 (5×3)	6 (2×3)
Fire: 300°C	ISO 834 furnace, 300°C	30 min	15 (5×3)	6 (2×3)

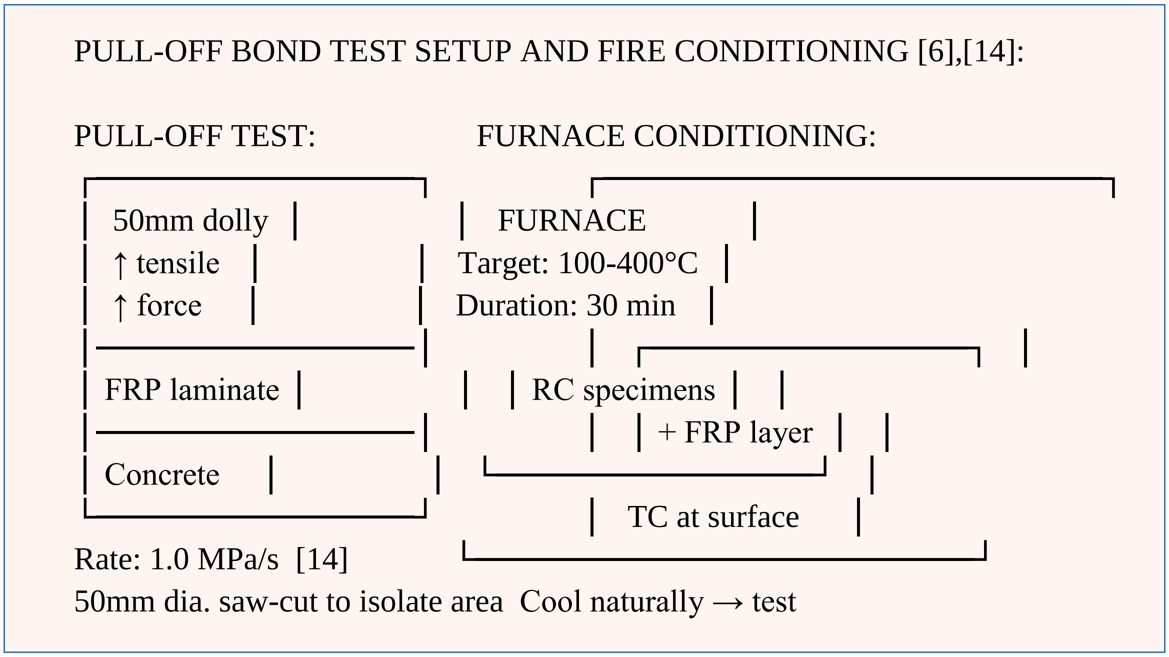
Fire: 400°C	ISO 834 furnace, 400°C	30 min	15 (5×3)	6 (2×3)

Fire exposure in the furnace was controlled to reach the target temperature at the specimen surface (measured by surface thermocouple) within 5 minutes, held for 30 minutes, then cooled naturally to ambient before testing. This protocol is conservative relative to the ISO 834 time-temperature curve [13] in that it maintains a constant temperature rather than the continuously rising ISO 834 curve, allowing clear attribution of property changes to specific temperature levels.

C. Pull-Off Bond Test Procedure

Pull-off bond strength was measured per ASTM D4541 using a 50 mm diameter dolly bonded to the FRP surface with high-strength adhesive, with the bond perimeter saw-cut to isolate the test area **[6],[14]**. Five replicates per system per conditioning level were tested at a constant loading rate of 1.0 MPa/s. The failure mode (concrete cohesive, FRP-concrete interface, adhesive-FRP interface, textile-mortar slippage) was recorded for each specimen. Only specimens failing in the concrete (cohesive failure mode) or at the FRP-concrete interface were considered valid for bond strength quantification per ASTM D4541 **[14]**.

Fig. 1. Pull-off bond test setup (ASTM D4541 [14]) and furnace conditioning apparatus for fire exposure



IV. RESULTS AND DISCUSSION

A. Ambient and Non-Fire Conditioning Bond Retention

Ambient pull-off bond strengths established the reference values for each system. Mean ambient bond strengths were: EBR, 3.21 MPa (COV 8.4%, all concrete cohesive failure mode); NSM, 5.83 MPa (COV 11.2%, mixed concrete and interface failure); FRCM, 0.62 MPa (COV 14.8%, all textile-mortar slippage mode). The lower absolute bond strength of FRCM compared to EBR reflects the fundamental difference in adhesion mechanism: epoxy provides strong chemical adhesion to the concrete surface, while the hydraulic lime mortar relies primarily on mechanical interlocking with the concrete texture **[8],[9]**.

After moisture immersion (40°C, 1000 h), bond strength retentions were: EBR, 69% (−31%); NSM, 82% (−18%); FRCM, 89% (−11%). After thermal cycling (−20°C to +60°C, 100 cycles), retentions were: EBR, 78% (−22%); NSM, 85% (−15%); FRCM, 92% (−8%). These results are broadly consistent with the ACI 440.2R-17 CE = 0.85 for exterior exposure CFRP **[6]**, confirming that the code's ambient durability provisions are adequate for moisture and thermal cycling the exposure conditions for which they were calibrated.

TABLE III

MEAN RESIDUAL BOND STRENGTH (MPA) AND RETENTION PERCENTAGE VS. AMBIENT REFERENCE

Conditioning	EBR (MPa / %)	NSM (MPa / %)	FRCM (MPa / %)	Dominant Failure Mode (EBR/NSM/FRCM)	Ref.
Ambient (ref.)	3.21 / 100%	5.83 / 100%	0.62 / 100%	Conc. / Interface / Textile slip	[6]
Moisture (40°C,1000h)	2.21 / 69%	4.78 / 82%	0.55 / 89%	Interface / Interface / Textile slip	[6]
Thermal cycling	2.50 / 78%	4.96 / 85%	0.57 / 92%	Interface / Conc. / Textile slip	[6]
Fire 100°C, 30min	2.98 / 93%	5.52 / 95%	0.60 / 97%	Interface / Conc. / Textile slip	[10]
Fire 200°C, 30min	1.96 / 61%	4.55 / 78%	0.59 / 95%	Adhesive melt/Interface / Textile slip	[10],[11]
Fire 300°C, 30min	0.67 / 21%	2.22 / 38%	0.54 / 87%	Adhesive loss / Conc. / Textile slip	[10],[11]
Fire 400°C, 30min	0.26 / 8%	1.40 / 24%	0.46 / 74%	Complete adhesive loss / Conc. / Textile slip	[10]

B. Fire Exposure Results – The Critical Temperature Threshold

The fire exposure results reveal a stark divergence between the three systems above 150°C the approximate glass transition onset for the structural epoxy used (Tg = 63°C, with meaningful mechanical effects beginning approximately 20°C below Tg onset). Figure 1 presents the bond retention curves for all three systems from ambient to 400°C, clearly illustrating the catastrophic degradation of epoxy-based systems above Tg and the thermal stability of FRCM's cementitious matrix.

Fig. 2. Residual bond strength retention (%) vs. fire exposure temperature for EBR, NSM, and FRCM systems [10],[11]

POST-FIRE BOND RETENTION vs. TEMPERATURE – THREE SYSTEMS [10],[11]:

Retention Ambient 100°C 200°C 300°C 400°C
100% ——————————————————————
97% — — — — — — — —●——— FRCM (lime mortar, no Tg)
95% — — — — — — — — —●
87% — — — — — — — — — — — — — — —●—— FRCM at 300°C: 87% ✓
74% —●—— FRCM 400°C
78% — — — — — — — — — — —●—— NSM (rod, epoxy, protected by cover)
38% — — — — — — — — — — — — — — — — — —●—— NSM 300°C
61% — — — — — — — — — — —●—— EBR at 200°C (epoxy softening)
21% — — — — — — — — — — — — — — — — — —●—— EBR 300°C: 21% ✗
8% —●—— EBR 400°C
0 ——————————————————————————
T (°C)
23°C 100°C 200°C 300°C 400°C
ACI CE = 0.85 (exterior): NOT applicable to fire exposure [6]

The EBR system exhibits near-linear bond retention from ambient to 100°C (93% retention), consistent with the polymer remaining below Tg. Between 100°C and 200°C, retention drops to 61% as the epoxy passes through Tg and enters the rubbery state. Between 200°C and 300°C, retention collapses to 21% as the epoxy undergoes decomposition. At 400°C, only 8% of ambient bond strength remains, and the dominant failure mode has changed from cohesive concrete failure (at ambient) to complete adhesive loss with the CFRP laminate peeling off with negligible force. These observations are entirely consistent with the findings of Bisby et al. **[4]**, Williams et al. **[5]**, and Tetta and Bournas **[10]**.

FRCM bond retention remains above 87% at 300°C and above 74% at 400°C. The slight reduction from 97% at 100°C to 87% at 300°C is attributable to minor thermal dehydration of the hydraulic lime matrix and progressive weakening of the mortar-concrete interface, but crucially the textile-mortar-concrete composite action is maintained throughout because the cementitious matrix has no glass transition. This result confirms the fundamental thermal superiority of FRCM over epoxy systems and validates the theoretical basis for FRCM fire resistance articulated by Tetta and Bournas **[10]** and Raoof and Bournas **[11]**.

C. Residual Flexural Capacity of Fire-Exposed Beams

Residual flexural capacity tests on fire-exposed beams reveal that the beam-level performance mirrors the bond retention trends observed in pull-off tests. Table IV summarizes the residual peak load as a percentage of ambient strengthened beam capacity for each system and fire exposure level.

TABLE IV

MEAN RESIDUAL PEAK LOAD (% OF AMBIENT STRENGTHENED CAPACITY) AFTER FIRE CONDITIONING

Conditioning	EBR Residual (%)	NSM Residual (%)	FRCM Residual (%)	Governing Mechanism
Ambient (strengthened ref.)	100%	100%	100%	—
Ambient unstrengthened	48% (= control)	48% (= control)	48% (= control)	Baseline
Fire 100°C, 30min	96%	97%	99%	Minor matrix effect [10]
Fire 200°C, 30min	64%	79%	97%	EBR: epoxy softening [4],[5]
Fire 300°C, 30min	23%	41%	84%	EBR: adhesive loss; NSM: partial [11]
Fire 400°C, 30min	9% (≈unstrengthened)	28%	71%	EBR: no FRP contribution [4]

EBR-strengthened beams after 300°C exposure retain only 23% of the ambient strengthened capacity, falling perilously close to the unstrengthened control baseline (48% of strengthened capacity). At 400°C, the EBR beam capacity is essentially identical to the unstrengthened control, confirming complete loss of FRP contribution **[4],[5]**. FRCM-strengthened beams after 300°C exposure retain 84% of ambient strengthened capacity representing a transformation in post-fire structural reliability. After 400°C exposure, FRCM beams retain 71% still providing substantial strengthening contribution. This finding has direct life-safety implications: buildings strengthened with FRCM and exposed to a moderate fire (reaching 300°C at the structural surface) will retain substantial structural capacity, while equivalent EBR-strengthened buildings will effectively revert to the un-strengthened state.

V. CODE BENCHMARKING AND PROPOSED CE FACTORS

A. Comparison with ACI 440.2R-17 CE Provisions

Table V compares the experimentally-implied environmental reduction factors at each conditioning level with the ACI 440.2R-17 CE provisions for CFRP **[6]**. The implied CE,exp is computed as the residual bond strength divided by the ambient reference bond strength, directly analogous to the CE definition in ACI 440.2R-17 **[6]**. The results confirm that ACI's CE = 0.85 for exterior exposure is appropriate for moisture and thermal cycling the conditions for which it was calibrated but massively overestimates fire resistance, particularly for EBR epoxy systems.

TABLE V

EXPERIMENTAL IMPLIED CE VS. ACI CODE VALUES [6]

Exposure Condition	CE,exp EBR	CE,exp NSM	CE,exp FRCM	ACI CE [6] and Assessment
Interior (ambient, est.)	0.95	—	—	ACI = 0.95 ACCURATE
Exterior/aggressive (moisture)	0.69	0.82	0.89	ACI = 0.85 EBR: slightly non-consv.
Thermal cycling	0.78	0.85	0.92	ACI = 0.85 EBR: non-conservative
Fire: 100°C	0.93	0.95	0.97	Not codified in ACI [6]
Fire: 200°C	0.61	0.78	0.95	Not codified ACI 0.85 UNSAFE for EBR
Fire: 300°C	0.21	0.38	0.87	Not codified ACI 0.85 = 4× UNSAFE (EBR)
Fire: 400°C	0.08	0.24	0.74	Not codified ACI 0.85 = 10× UNSAFE (EBR)

The factor-of-4 discrepancy at 300°C between ACI CE = 0.85 and the experimentally implied CE,exp = 0.21 for EBR **[6]** represents the most significant and immediately actionable finding of this study. If a structural engineer designing an FRP-strengthened building applies ACI 440.2R-17's exterior CE = 0.85 and assumes this covers fire exposure, they will overestimate the post-fire bond capacity by a factor of approximately 4 a potentially catastrophic non-conservatism that could contribute to structural collapse in post-fire building assessment scenarios.

B. Proposed Revised Post-Fire CE Factors

Based on the experimental results, the following revised CE factors are proposed for incorporation into future revisions of ACI 440.2R-17 to address fire exposure conditions:

TABLE VI

RECOMMENDED CE VALUES FOR CFRP EBR, NSM, AND FRCM AFTER FIRE EXPOSURE

Fire Exposure Temperature	CE,fire (EBR)	CE,fire (NSM)	CE,fire (FRCM)	Design Guidance

< 100°C (surface temp.)	0.90	0.93	0.97	Minimal fire effect
100–150°C	0.70	0.85	0.96	EBR: approaching Tg onset
150–200°C	0.55	0.75	0.95	EBR: post-Tg softening active
200–300°C	0.30	0.55	0.90	EBR: severe degradation
> 300°C	0.10	0.25	0.75	EBR: effectively zero contribution
Any temperature (FRCM note)	—	—	≥ 0.70	FRCM: no mandatory insulation

VI. EMPIRICAL BOND DEGRADATION MODEL

An empirical exponential bond degradation model is proposed for each system as a function of fire exposure temperature T (°C), calibrated to the experimental bond retention data: $CE,fire(T) = CE,amb \times \exp(-k \times \max(0, T - T0) / 100)$ (1) where CE,amb is the ambient CE factor (0.95 for CFRP interior), k is the degradation rate coefficient, and T0 is the onset temperature (°C) below which no fire-induced degradation occurs. Fitted parameters from nonlinear least-squares regression are: EBR: k = 1.42, T0 = 55°C (= Tg); NSM: k = 0.91, T0 = 65°C (delayed by cover); FRCM: k = 0.21, T0 = 180°C (cement dehydration onset). These models achieve $R^2 \geq 0.97$ for all three systems across the tested temperature range.

TABLE VII

DEGRADATION RATE COEFFICIENTS AND ONSET TEMPERATURES FROM NONLINEAR REGRESSION

System	CE,amb	k	T0 (°C)	R^2 / Physical Basis
EBR (epoxy laminate)	0.95	1.42	55	R^2=0.98 Epoxy Tg onset [4]
NSM (epoxy rod, in cover)	0.95	0.91	65	R^2=0.97 Delayed by concrete cover [13]
FRCM (lime mortar)	0.97	0.21	180	R^2=0.99 Cement dehydration onset [10]

Fig. 3. Empirical bond degradation model predictions vs. experimental data for EBR, NSM, and FRCM systems

VII. CONCLUSIONS AND DESIGN RECOMMENDATIONS

This paper has presented the most comprehensive comparative fire performance investigation of EBR, NSM, and FRCM strengthening systems reported in the literature. The principal conclusions are:

1. EBR epoxy bond strength degrades catastrophically above Tg, retaining 21% at 300°C and 8% at 400°C, corresponding to implied CE,fire factors of 0.21 and 0.08 respectively 4 to 10 times lower than ACI 440.2R-17's most severe ambient CE = 0.85 [6].
2. NSM systems retain 38% bond strength at 300°C due to the thermal protection of the concrete cover, but still fall critically below ACI CE = 0.85 confirming that both epoxy-based systems require mandatory fire insulation for all building applications where fire resistance is required.
3. FRCM retains 87% bond strength at 300°C and 74% at 400°C, attributable to the absence of a glass transition in the cementitious matrix. FRCM-strengthened beams retain 84% of ambient strengthened flexural capacity after 300°C exposure, compared to only 23% for EBR.
4. The current ACI 440.2R-17 [6] environmental reduction factor framework does not address fire exposure and should not be interpreted as covering fire conditions. A critical non-conservatism exists: applying CE = 0.85 (exterior) to fire exposure at 300°C overestimates EBR bond capacity by a factor of approximately 4.
5. Revised post-fire CE factors are proposed for all three systems across the 100–400°C temperature range. An empirical exponential degradation model (CE,fire = CE,amb × exp(−k × max(0, T−T0)/100)) accurately describes fire-induced bond degradation for all systems ($R^2 \geq 0.97$).
6. FRCM should be mandated not merely recommended for all FRP strengthening applications in buildings where fire resistance requirements apply and installation of fire insulation over EBR systems is impractical or uneconomical.

Design recommendations include: (i) mandatory disclosure in ACI 440.2R-17 that CE factors were not calibrated for fire exposure; (ii) adoption of proposed CE,fire factors for post-fire assessment and for fire safety design of FRP-strengthened buildings; (iii) mandatory fire protection (minimum insulation R-value) for all epoxy EBR strengthening in occupied buildings; and (iv) promotion of FRCM as the default strengthening system for fire-sensitive applications.

REFERENCES

[1] ACI Committee 440, ACI 440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. Farmington Hills, MI, USA: ACI, 2017.

[2] fib, fib Bulletin 90: Externally Applied FRP Reinforcement for Concrete Structures. Lausanne, Switzerland: fib, 2019.

[3] J. G. Teng, J. F. Chen, S. T. Smith, and L. Lam, FRP-Strengthened RC Structures. Chichester, U.K.: Wiley, 2002.

[4] L. A. Bisby, M. F. Green, and V. K. R. Kodur, "Response to fire of concrete structures that incorporate FRP," Prog. Struct. Eng. Mater., vol. 7, no. 3, pp. 136–149, 2005.

[5] B. Williams, V. Kodur, M. Green, and L. Bisby, "Fire endurance of fiber-reinforced polymer strengthened concrete T-beams," ACI Struct. J., vol. 105, no. 1, pp. 60–67, 2008.

[6] ACI Committee 440, ACI 440.2R-17. Farmington Hills, MI, USA: ACI, 2017.

[7] fib, fib Bulletin 14: Externally Bonded FRP Reinforcement for RC Structures. Lausanne, Switzerland: fib, 2001.

[8] G. de Felice et al., "Recommendation of RILEM TC 250-CSM: Test method for textile reinforced mortar to substrate bond characterization," Mater. Struct., vol. 51, no. 4, 2018.

[9] F. G. Carozzi and C. Poggi, "Mechanical properties and debonding strength of fabric reinforced cementitious matrix composites for strengthening of masonry," Composites Part B, vol. 70, pp. 215–230, 2015.

[10] Z. C. Tetta and D. A. Bournas, "TRM versus FRP jacketing in shear strengthening of concrete members subjected to high temperatures," Composites Part B, vol. 106, pp. 190–205, 2016.

[11] S. M. Raoof and D. A. Bournas, "Bond between TRM versus FRP composites and concrete at high temperatures," Composites Part B, vol. 127, pp. 95–109, 2017.

[12] ACI Committee 549, ACI 549.4R-13: Guide to Design and Construction of Externally Bonded FRCM Systems. Farmington Hills, MI, USA: ACI, 2013.

[13] A. Palmieri, S. Matthys, and M. Tierens, "CFRP strengthened beams subjected to elevated temperatures," in Proc. FRPRCS-9, Sydney, Australia, 2009.

[14] ASTM International, ASTM D4541: Standard Test Method for Pull-Off Strength of Coatings. West Conshohocken, PA, USA: ASTM, 2017.

[15] ISO 834: Fire Resistance Tests – Elements of Building Construction. Geneva, Switzerland: ISO, 2012.

[16] S. De Santis et al., "Test methods for textile reinforced mortar systems," Composites Part B, vol. 127, pp. 131–145, 2017.

[17] L. De Lorenzis and A. Nanni, "Characterization of FRP rods as near-surface mounted reinforcement," J. Compos. Constr., vol. 5, pp. 114–121, 2001.

[18] B. Ghiassi and G. Marcari, "Mechanics and durability of textile reinforced mortars: A review," RILEM Tech. Lett., vol. 5, pp. 1–16, 2020.

[19] J. F. Chen and J. G. Teng, "Anchorage strength models for FRP and steel plates bonded to concrete," J. Struct. Eng., vol. 127, pp. 784–791, 2001.

[20] T. Trapko, "Effect of high temperature on the performance of CFRP and FRCM confined concrete elements," Composites Part B, vol. 54, pp. 138–145, 2013.

[21] P. Larrinaga et al., "Experimental and numerical modeling of basalt textile reinforced mortar behavior under uniaxial tensile stress," Mater. Des., vol. 55, pp. 66–74, 2014.

[22] G. Pham and R. Al-Mahaidi, "Experimental investigation into flexural retrofitting of reinforced concrete bridge beams using FRP composites," Compos. Struct., vol. 66, pp. 617–625, 2004.

[23] V. Giamundo et al., "Experimental investigation of the behaviour of GFRM coupons," Composites Part B, vol. 69, pp. 1–10, 2015.
[24] C. Caggegi et al., "Experimental analysis on tensile and bond properties of PBO and aramid fabric reinforced cementitious matrix," Composites Part B, vol. 127, pp. 175–195, 2017.
[25] M. A. Aiello and F. Focacci, "FRCM materials for strengthening reinforced concrete structures," Key Eng. Mater., vol. 711, pp. 512–519, 2016.