Journal of Science and Technology in Civil Engineering, HUCE, 2026, 20 (1): 10–29

SEISMIC STRENGTHENING OF RC BRIDGE PIERS WITH HIGH-PERFORMANCE CEMENTITIOUS JACKETING: A COMPREHENSIVE REVIEW, RECOMMENDATIONS AND A PRECAST HPC-FRP GRID JACKET PROPOSAL

Doan Cong Chanh[a,b], Phan Hoang Nam[a,*], Hoang Phuong Hoa[a],
Gianluca Quinci[c], Fabrizio Paolacci[c]

[a] *Faculty of Road and Bridge Engineering, The University of Danang – University of Science and Technology,*
54 Nguyen Luong Bang street, Lien Chieu ward, Da Nang, Vietnam
[b] *School of Science and Technology, Tra Vinh University,*
126 Nguyen Thien Thanh street, Hoa Thuan ward, Vinh Long, Vietnam
[c] *Department of Civil, Computer Science and Aeronautical Technologies Engineering,*
Roma Tre University, 00146 Rome, Italy

Article history:
Received 02/10/2025, Revised 02/02/2026, Accepted 09/3/2026

Abstract

This paper reviews high-performance cementitious jacketing for reinforced-concrete (RC) bridge piers under seismic loads. Specifically, the review (i) combines experimental and numerical evidence from monotonic, cyclic, and shaking-table studies; (ii) discusses the key mechanisms such as confinement, crack control, and shear transfer at the interface; and (iii) offers practical advice on jacket height and thickness, splice and plastic-hinge details, and construction in tight spaces. The literature shows that high-performance concrete (HPC) systems, which include ultra-high-performance concrete and ultra-high-performance fiber-reinforced concrete (UHPC/UHPFRC), generally boost lateral strength, drift capacity, and energy dissipation. Thin jackets can also enhance crack control and durability, which helps limit section enlargement, added weight, and foundation demand. They can also support staged construction while traffic remains active. Several key issues persist, including the reliability of jacket-core bonding, field placement and curing, multi-hazard durability (like chlorides, fatigue, and thermal/fire exposure), and the balance between cost and sustainability. To tackle these challenges, the paper highlights hybrid concepts where HPC/UHPC shells use FRP grids to combine compressive and shear strength with tensile crack-bridging and protection from the environment. Expanding on this idea, a precast HPC permanent-formwork jacket with embedded FRP grids and pressure-grouted infill is proposed. This aims to improve the quality of the interface while reducing thickness and shortening closure time compared to cast-in-place jacketing. The paper wraps up with recommendations for further research on interface modeling, long-term durability data, performance-based optimization, life-cycle assessment, and design guidelines for practical use.

Keywords: seismic retrofit/jacketing; RC bridge piers; HPC/UHPC/UHPFRC jacketing; FRP grid reinforcement; precast permanent formwork.

https://doi.org/10.31814/stce.huce2026-20(1)-02

---

1. Introduction

Bridges are essential connections in transport networks. The performance of these structures during earthquakes often depends on how well reinforced-concrete (RC) bridge piers behave [1, 2]. Among the options to improve deficient piers, jacketing is commonly used. It can be done while

---

[*] Corresponding author. *E-mail address:* phnam@dut.udn.vn (Nam, P. H.)

traffic is ongoing, reduces service disruptions, and directly addresses specific issues like inadequate confinement and poor lap splices in critical areas [3, 4].

RC and steel jackets are reliable for strength and stiffness, but they often result in larger sections, increased weight, and higher demands on foundations [5]. Steel jackets also come with corrosion and maintenance issues. Fiber-reinforced polymer (FRP) jackets provide a lightweight, corrosion-resistant solution for confinement and shear reinforcement. However, they face challenges such as debonding, fire performance, and limited ability to handle compressive damage in key areas if not carefully designed [6]. High-performance cementitious jacketing, involving high-performance concrete (HPC), ultra-high-performance concrete (UHPC), or ultra-high-performance fiber-reinforced concrete (UHPFRC), offers a different approach. These materials have dense, high-strength mixtures that can include fibers, allowing for thinner jackets that improve lateral strength, ductility, and energy dissipation while limiting section size and construction footprint [7]. This is particularly useful in tight spaces, over water, and for construction in active traffic.

From a mechanics perspective, high-performance cementitious jackets improve seismic response in several ways: they confine the core concrete, which delays bar buckling and increases usable strain; they control cracking with uniform and well-distributed cracks and maintain stiffness after cracking when fibers are included; they enhance shear resistance in critical regions; and they ensure strong bonding at the jacket-core interface, which stabilizes the structure during loading cycles [8, 9]. Properly designed jackets, with correct thickness, height, and detailing according to expected hinge lengths, can reduce permanent drift, maintain stiffness through repeated cycles, and help prevent brittle failures. Their lighter weight also lessens demands on foundations and bearings.

Despite these benefits, several important issues need addressing. The jacket-core interface is crucial for overall performance. Surface preparation, mechanical interlock, and the details of connectors must be managed to avoid slip and delamination during cycling loads. Factors such as mix stability, fiber distribution, curing, and methods of placement (whether cast-in-place or precast) can significantly impact the effectiveness of the jacketing. Bridges must also be durable against multiple hazards, including chloride exposure, temperature changes, and fatigue. UHPC and UHPFRC have low permeability and resist chloride, but hybrid systems with FRP components require fire and temperature protection [10]. Finally, factors like cost-effectiveness and sustainability, including optimizing jacket thickness and fiber use, as well as considering lifecycle costs and embodied carbon, influence adoption by agencies [11].

Retrofit choices usually follow established seismic design frameworks, such as AASHTO seismic provisions and guidance [12], Eurocode 8 for bridges [13], Japanese retrofit guidance [14]. While HPC and UHPC jacketing is not fully prescribed in these standards, they share important design concepts related to critical areas, ductility, shear safety under cyclic loads, and robust detailing. This consistency aids in using the available information for practical design decisions.

In this context, this paper (i) reviews experimental and numerical data on the performance of RC bridge piers retrofitted with high-performance cementitious jackets; (ii) explains the key mechanisms at play, including core confinement, crack control with sustained stiffness, and shear transfer at the jacket-core interface; and (iii) provides practical guidance on jacket dimensions, detailing for critical regions, and construction in difficult environments. Where applicable, it also presents comparisons with RC, steel, and FRP jacketing using common seismic metrics, such as peak strength and drift at strength loss. Additionally, the paper outlines a precast HPC permanent-formwork jacket featuring embedded FRP grids as a new evolution of hybrid designs, linking material properties to practical applications.

2. High-performance cementitious jacketing

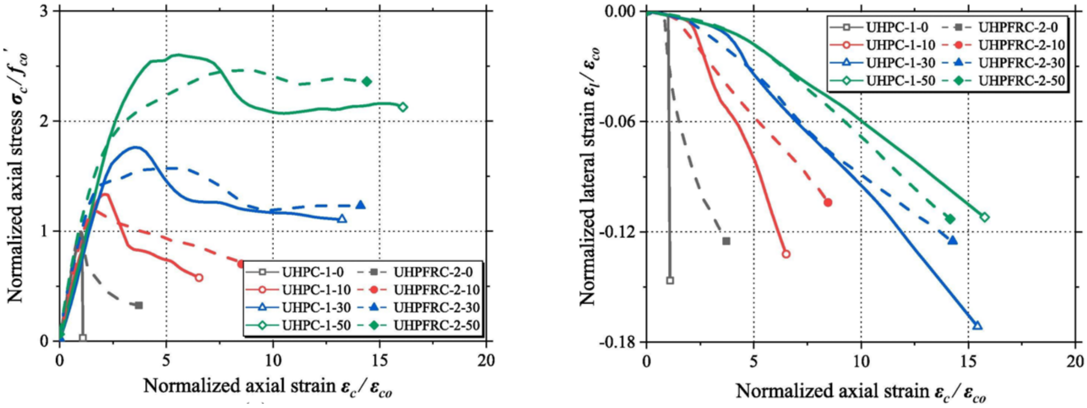
2.1. Properties of HPC/UHPC/UHPFRC

High-performance cementitious materials, i.e., HPC, UHPC, and UHPFRC, have been increasingly applied to strengthen RC piers/columns for seismic demands. HPC denotes dense, low-water-binder-ratio concretes optimized by particle packing and high-quality paste/aggregate interfaces. Typical compressive strengths are $\geq$ 60–100 MPa (often above conventional bridge concretes), with higher elastic modulus, reduced permeability, and superior freeze-thaw and chloride resistance. Mixes may be self-consolidating for vibration-free placement and can incorporate supplementary cementitious materials to balance durability, workability, and early strength for staged construction [15]. For jacketing, HPC's key advantages are: (i) higher compressive strength enabling thinner shells than normal concrete; (ii) improved bond to existing substrates with proper surface preparation; and (iii) constructability under traffic or in confined rights-of-way. These traits motivate its use for seismic retrofits where geometric growth and downtime must be minimized.

Building on HPC, UHPC employs ultra-low w/b ratios, optimized granular skeletons, and very dense matrices to reach strengths typically $>$ 100 MPa with excellent durability [16]. UHPFRC further adds short fibers so that, in tension, the matrix exhibits multiple micro-cracking and post-cracking stiffness (strain-hardening), which translates to tight crack widths, enhanced ductility, and stable hysteresis under cyclic loads. Consequently, UHPC/UHPFRC jacketing has drawn substantial attention for seismic retrofitting of RC piers/columns, consistently showing gains in bearing capacity, toughness, and durability [7, 8, 17]. Numerous studies confirm that UHPC's high compressive strength, large elastic modulus, and effective crack resistance markedly enhance structural performance under earthquakes [18–20]. Compared with conventional concrete jackets, UHPC jackets can be thinner, limit section enlargement, develop good adhesion to existing concrete, and allow vibration-free placement, which is advantageous in constrained or fast-track works, features that make UHPC particularly appealing in high-seismic regions. Following this trend, HPFRC/UHPFRC systems are valued for superior adhesion, crack control, self-compacting behavior, and lower environmental impact; when wrapped over the plastic-hinge zone, they reduce shear cracking, increase ductility, and stabilize hysteresis over repeated cycles.

Tests on UHPFRC-jacketed columns report compressive strengths up to $\sim$ 180 MPa and direct tensile strengths near ~ 7 MPa, along with substantial increases in maximum load, initial stiffness, and deformation capacity under cyclic loading [21]. Interface preparation is pivotal: introducing longitudinal grooves (and sandblasting) beneath thin ($\approx$ 15 mm) UHPFRC jackets increased compressive strength by $\sim 33\%$ and energy dissipation by $\sim 34\%$, while also improving ductility and dynamic energy absorption, clear evidence that mechanical interlock governs cyclic performance [22].

Recent triaxial tests clarify the constitutive differences between UHPC and UHPFRC (Fig. 1) [23]. For specimens with similar uniaxial strengths, UHPFRC exhibits (i) a longer, more curved ascending branch, (ii) a flatter descending branch, and (iii) a more pronounced residual-stress plateau than UHPC at the same confining pressure, signatures of fiber-driven ductility and residual load-carrying capacity that stabilize hysteresis in plastic-hinge regions. A trade-off is that fibers may slightly reduce the confinement-induced increase in peak axial stress relative to plain UHPC. Companion axial-lateral strain data show two quasi-linear regimes separated by a transition; for a given axial strain, UHPFRC dilates less than UHPC, especially at low-moderate confinement, consistent with the fiber network restraining lateral cracking. Increasing confinement curbs dilation for both materials. Under unconfined loading, UHPC undergoes rapid post-peak dilation and splitting, whereas UHPFRC fails more gradually with inclined post-peak response and progressive fiber pull-out. These observations align with distinct failure modes: (i) UHPC is prone to sudden crushing/splitting near peak, and (ii) UHPFRC exhibits smeared cracking with a more gradual strength loss, and they explain why UHPFRC is often favored when ductility, crack-width control, and stable cyclic behavior are the primary retrofit objectives. A summary of properties and jacketing implications of HPC, UHPC, and UHPFRC is illustrated in Table 1.



(a) Normalized axial stress-strain

(b) Normalized axial strain-lateral strain

Figure 1. Normalized axial stress-strain and normalized axial strain-lateral strain of UHPC and UHPFRC under triaxial confinement (after [23])

Table 1. Properties and jacketing implications of HPC, UHPC, and UHPFRC

Aspect	HPC	UHPC	UHPFRC
Typical compressive strength	≥ 60–100 MPa (above conventional bridge concrete)	> 100 MPa (often 120–180 MPa)	> 100 MPa; similar compressive range to UHPC
Tensile behavior	Quasi-brittle (no designed strain-hardening)	Quasi-brittle; very high strength but limited post-cracking tensile capacity	Strain-hardening tension with multiple micro-cracking; measurable post-cracking stiffness
Elastic modulus	Higher than normal concrete; mix dependent	High, consistent with dense matrix	Like UHPC in compression, added post-cracking tensile stiffness from fibers
Permeability & durability	Reduced permeability; good freeze-thaw and chloride resistance	Very low permeability; excellent chloride/chemical resistance	Very low permeability plus tight crack widths, thus superior durability
Workability/ placement	Can be self-consolidating; vibration-free placement is feasible	Often self-consolidating; vibration-free placement routine	Self-compacting matrices are common; fibers demand mixing/placement quality control
Typical jacketing thickness	Thin to moderate shells; thinner than normal concrete for the same capacity	Thin shells are feasible due to high strength; careful detailing to avoid plastic-hinge relocation with full wraps	Very thin shells are feasible (∼ 15 mm demonstrated) when the interface is engineered (e.g., grooving); ∼ 40 mm is effective for repair/cover restoration

2.2. *Seismic strengthening of bridge piers with HPC jacketing*

Experimental programs on columns and bridge piers generally show that HPC jacketing, often using UHPC/UHPFRC mixes, can strengthen plastic-hinge regions by reducing shear cracking, increasing drift capacity, and stabilizing hysteresis under repeated cycles. Workability and the potential for good bond to existing concrete are practical advantages for staged construction; however, material cost and tighter tolerances remain major barriers to routine use [24–26]. These points recur across focused tests and broader reviews and inform decisions on jacket thickness, height, and, critically, interface detailing.

In a cyclic lateral-loading study, Cho et al. [24] cast the plastic-hinge zones of RC columns with HPFRC and reported a 44.8% increase in peak force together with a ductility jump from 4.2 to 6.5, accompanied by visibly reduced flexural cracking and cover spalling. Beyond strength, the response showed stable, fuller hysteresis loops and delayed degradation, reflecting the crack-control and energy-absorption capacity of HPFRC, which inherits strain-hardening and multiple micro-cracking from engineered cementitious composite (ECC)-type matrices. These attributes translate to improved residual drift and post-event serviceability, key outcomes for bridge owners.

Addressing deterioration, Meda et al. [25] repaired corroded RC columns with a 40 mm HPFRC jacket (steel fibers) and observed +118% restored lateral resistance and a marked gain in deformation capacity. The jacket did more than raise strength: it stabilized geometry, curtailed crack opening and propagation, and provided a durable protective cover, attractive when extending service life without full replacement. The study frames HPFRC jacketing as both a structural and durability intervention executed in a single operation.

A frequent trigger of brittle failures in older bridge columns is the presence of short lap splices in the plastic-hinge zone. Dagenais et al. [26] demonstrated that applying HPFRC at the column base redistributes stress, blunts bond-slip localization, and preserves ductile behavior under cyclic demands. The jacket acts as an effective force-transfer layer, improving confinement and shear transfer while keeping splice-related instabilities in check. Together, [24–26] show that HPC jacketing is not merely a strength booster; it is a comprehensive retrofit that elevates ductility, stabilizes global response, and improves damage tolerance in dynamic environments.

Stepping back, He et al. [3] synthesized post-earthquake repair strategies for RC bridge columns, FRP, RC jacketing, HPC/HPFRC/ECC, and prestressed cables, and offered a comparative perspective: FRP tends to raise ductility by $\approx 45\%$; RC jacketing increases peak load by 30–50% but often with higher initial stiffness; HPFRC/ECC enhance crack control with $> 60\%$ strength gains; and prestressed cables reduce residual deformations, with effectiveness tied to initial damage levels. The implication is goal-driven selection: where ductility and crack control dominate, FRP and HPFRC are natural candidates; where severe damage demands large strength increases, RC or steel jacketing may be prioritized, accepting mass and constructability penalties.

Recent practice trends also explore hybrid jackets that combine material strengths. Faustino & Chastre [27] showed that FRP + fiber anchors + polymer mortar can nearly restore damaged-column capacity, while Bousias & Triantafillou [28] documented that NSM-FRP simultaneously increases flexural capacity and limits bar slip. Although this review centers on HPC jackets, such results underscore the universal importance of tension stiffening and anchorage, and they echo the need, equally critical for HPC, for reliable interface force transfer.

From a methods vantage, Gkournelos et al. [29] classified seismic upgrades for existing RC buildings into local and global interventions: RC jacketing may raise stiffness to 70% and strength by $> 50\%$, but is intrusive and geometry-altering; FRP/TRM can deliver similar efficiency with 30–45%

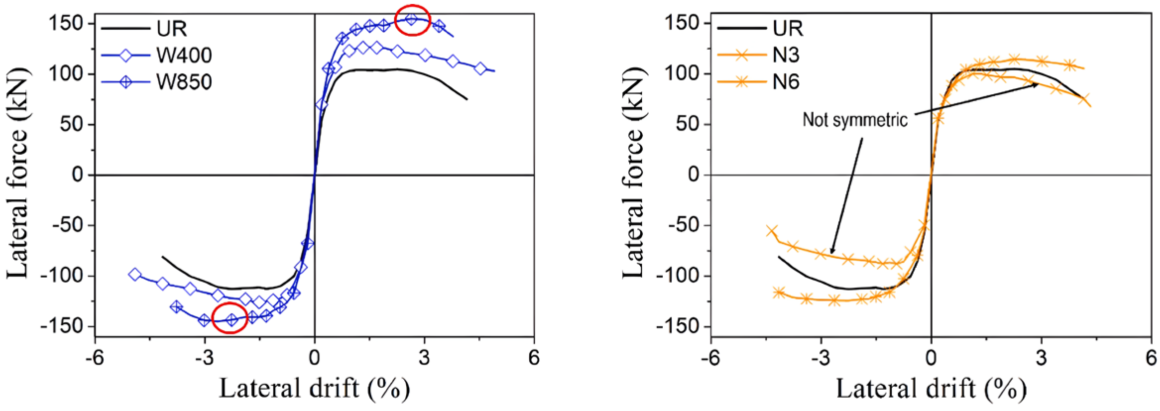
ductility gains and faster, less invasive construction, provided thermal protection and suitable site methods are available. This context helps position HPC jacketing; it aims to combine high structural efficiency with limited section growth, while delivering durability superior to conventional RC or steel solutions.

Within the mechanics of HPC jacketing, the jacket-core interface is decisive. Dadvar et al. [22] tested thin ($\approx$ 15 mm) UHPFRC jackets on small circular columns (D = 120 mm, L = 500 mm) and highlighted the effect of surface preparation: longitudinal grooves, compared with sandblasting, delivered +33% compressive strength and +34% energy dissipation; ductility rose 29%, and dynamic energy absorption jumped 380% relative to non-retrofitted controls. Two insights follow: (i) thin shells are feasible and mechanically effective when the interface is engineered for shear transfer; and (ii) mechanical interlock complements adhesion in sustaining cyclic demands, a prerequisite for stable hysteresis and delayed degradation.

For RC jacketing benchmarks, Navarrete et al. [30] reported 1.2–3.5× increases in shear strength of bridge piers, with improved ductility and reduced risk of sudden failure under earthquakes; however, performance depends strongly on the longitudinal steel ratio in the jacket, and the method increases mass and foundation demand with a propensity for long-term cracking. By contrast, UHPFRC offers higher inherent strength, tighter crack control, and better durability, while enabling thinner sections, a recurring advantage where clearance and foundation demand constrain design.

Scaling up, Hong et al. [21] examined UHPFRC-jacketed RC columns and reported +75.3% in maximum load, +26.4–32.2% in initial stiffness, and +233% in deformation capacity [16]. Reported material properties included compressive strength up to ~ 180 MPa and tensile strength ~ 7 MPa, explaining the observed crack control and post-cracking stiffness. Adding textile reinforcement (TR-UHPFRC) further limited brittle shear, increased ductility, and shifted failure mechanisms toward flexural-shear, desirable for bridge piers requiring stable, repeatable plastic-hinge behavior.

For rectangular piers, Tong et al. [31] conducted quasi-static tests and showed that an 850 mm UHPFRC jacket increased ultimate capacity by 32%, while a 400 mm jacket improved ductility by 46% and cumulative energy dissipation by 58% relative to non-retrofitted piers. They also noted a ~ 23% longer period of stiffness retention and reduced cracking due to passive stress control. Against RC and FRP jackets, UHPFRC produced $\approx$ 72% higher flexural strength, albeit with the caveat that quality control (mix, placement, curing) must be tighter to realize laboratory-level performance.



(a) Pier UR, W400 and W850

(b) Pier UR, N3 and N6

Figure 2. Skeleton curves of the tested piers (after [32])

Moving from component tests to system reliability, Tong et al. [32] combined tests with seismic vulnerability assessment for UHPC-coated piers, evaluating full-height wraps (W-UHPC) and strip/segmental wraps (N-UHPC). Full wraps (W400, W850) maximize strength, as shown in Fig. 2(a), but can relocate the plastic hinge, which demands careful detailing to avoid unintended curvature concentration. Multi-strip N-UHPC jackets (N3, N6) primarily enhance ductility and reduce residual drift by mitigating cracking/spalling; their strength increase is modest, and performance is sensitive to construction quality and the continuity of contact at seams (note the asymmetry of N3). Across scenarios, UHPC-coated piers exhibited significantly lower failure probabilities than non-retrofitted piers. Compared with traditional RC coatings, UHPC offered higher strength, less cracking, and better rebar protection, with the recurring practical note that strict quality control is essential in the field. Comparative key advantages and disadvantges across RC, FRP, TRM, prestressed, HPC/UHPC/UHPFRC, and hybrid systems is summarized in Table 2, while quantitative summary of experimental studies on high-performance cementitious jacketing for RC bridge piers/columns is presented in Table 3.

Table 2. Comparative effectiveness of seismic strengthening methods for RC bridge piers

Retrofit material/system	Key advantages	Key limitations/caveats
HPC/ UHPC/ UHPFRC jacketing	High strength/ductility and energy dissipation; thin sections limit geometric enlargement and added mass; vibration-free workability; strong adhesion; improved durability	Requires engineered interface (grooving/mechanical interlock); tighter quality control (mix, placement, curing); higher material cost than conventional concrete
RC jacketing	Mature method; large strength and stiffness gains; well-known detailing practices	Intrusive, adds mass and foundation demand; increases initial stiffness; prone to long-term cracking; clearance constraints
TRM (textile-reinforced mortar)	Good crack control; better high-temperature tolerance than polymers; rapid application	Requires substrate prep and compatible mortars; anchorage detailing is still critical
Hybrid FRP systems	Enhanced anchorage/tension stiffening; improved utilization of FRP; targeted strengthening	Still sensitive to temperature/fire; anchorage detailing, and quality control are decisive

Most studies reviewed here are conducted on reduced-scale columns, and transfer to full-scale bridge piers should be made with care. The response of jacketed piers depends not only on material strength but also on the interaction between flexure, shear, confinement, and interface slip under cyclic reversals. These mechanisms can be scale-sensitive, particularly when local phenomena control the global response (e.g., bond-slip localization, interface cracking/delamination, and construction tolerances). A practical way to improve transferability is to interpret results through non-dimensional parameters rather than absolute dimensions. Key ratios that should be reported and used for comparison include: (i) jacket thickness relative to column diameter or column width); (ii) jacket height relative to the plastic-hinge length; (iii) axial load ratio; (iv) shear-span ratio; (v) longitudinal and transverse reinforcement ratios and spacing; and (vi) interface detailing descriptors, including roughness level and connector index. Reporting these ratios makes it clearer which mechanisms are likely to persist at full scale and which may change with geometry, detailing, and construction variability.

3. HPC/UHPC with FRP grid jacketing: an integrated fix for prior drawbacks

Each established retrofit option has a clear cost–benefit profile. RC and steel jackets can be effective but are intrusive, add mass, and may increase foundation demand. FRP wraps are lightweight and

Table 3. Quantitative summary of key experimental studies on high-performance cementitious jacketing for RC bridge piers/columns

Specimen	Jacketing thickness t_j, length L_j, and interface	Test protocol	Normalized gains vs. control
Square RC composite columns, HPFRC mortar in plastic hinge [24]	$t_j = 50$ mm; $L_j = 1.5$–$2.0d$; interface: NR	Reversed cyclic lateral loading (axial load 196.2 kN)	Peak force +35% to +45%; ductility 6.3–6.5 vs 4.2
Square corroded RC columns, steel-fiber HPFRC jacket [25]	$t_j = 40$ mm; L_j: full height; interface: 80 mm deep pocket + sandblasting	Cyclic loading (axial load 400 kN) on three specimens	Strength (vs C): peak lateral load +95% and +118%; energy dissipation: +50% vs UC and +30% vs C
Rectangular bridge piers, UHPFRC retrofit at lap-splice/hinge [26]	t_j: $1d_b$ behind splice bars; L_j: splice length $24d_b$ + 100 mm; interface: NR	Unidirectional reversed cyclic lateral tests (axial load 1500 kN)	Drift capacity 5.9–8.3% vs 1.9%; ductility 4.6–8.1 vs 1.51; cumulative energy >750–2126 kN·m vs 212 kN·m
Circular columns, thin UHPFRC jacket [22]	$t_j \approx 15$ mm; L_j: full height; interface: grooving + sandblasting	Axial/compression-based tests	Strength +33%; energy +34%; ductility +29%; dynamic energy absorption +380%
Square RC columns, UHPFRC and TR-UHPFRC jackets [21]	$t_j = 30$ mm; L_j: full height; interface: sandblasting	Reversed cyclic loading; axial load ratio 0.3–0.45	Max load +75.3–92.7%; stiffness +26.4–32.2%; deformation capacity +233%
Rectangular bridge piers, UHPFRC jacket at plastic-hinge heights [31]	$t_j = 50$ mm; $L_j = 850$ or 400 mm; interface: surface roughening + watering	Quasi-static reversed cyclic tests	850 mm: ultimate capacity +32%; 400 mm: ductility +46% and cumulative energy +58%
Rectangular RC bridge piers (UR, W400, W850, N3, N6), UHPC jacket [32]	$t_j = 50$ mm; W-UHPC heights $L_j = 400$ mm ($\approx 1L_p$) and 850 mm ($\approx 2L_p$); N-UHPC strips: 100 mm height, 50 mm gap	Quasi-static reversed cyclic tests (axial load: $P = 0.08 f'_c A_g$)	W400: peak strength +16.2%; W850: peak strength +37.8%; N6: peak strength +7.9%; N3: peak strength −15.0%

Note: Values normalized w.r.t. unretrofitted control specimens; NR = not reported.

corrosion-resistant, yet their performance depends on anchorage and bond, and can be sensitive to elevated temperature without protection. Cementitious HPC/UHPC jackets can be thin and durable, but in the hinge zone, they still depend on reliable interface shear transfer and adequate tensile resistance after cracking. A hybrid jacket that embeds an FRP grid within an outer HPC/UHPC layer directly targets these gaps: the concrete matrix supplies compressive strength, shear capacity, and environmental protection, while the FRP grid supplies high tensile resistance, crack-bridging, and corrosion immunity. The result is a thin, damage-tolerant, and durable shell well-suited to seismic plastic hinges and aggressive exposures. Particularly, HPC/UHPC are proportioned for compressive strengths ≥ 100 MPa and superior durability/crack resistance; FRP grids, typically carbon FRP (CFRP), glass FRP

(GFRP), or basalt FRP (BFRP), provide very high tensile strengths (up to ∼ 3000 MPa), low weight, and corrosion resistance in chemical or marine environments [33–35].

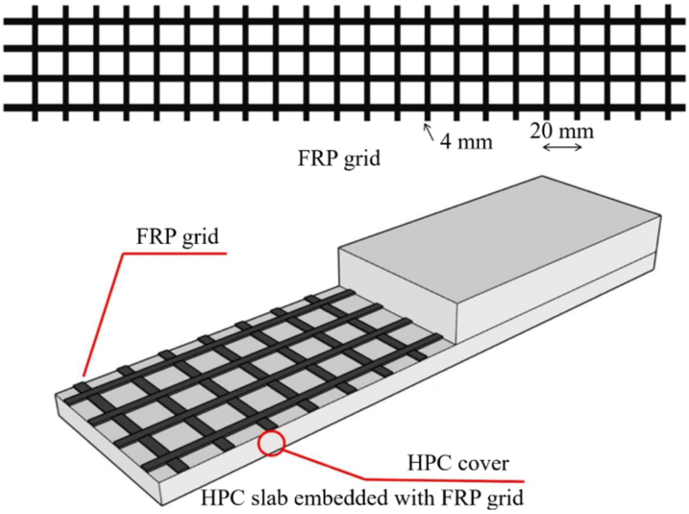
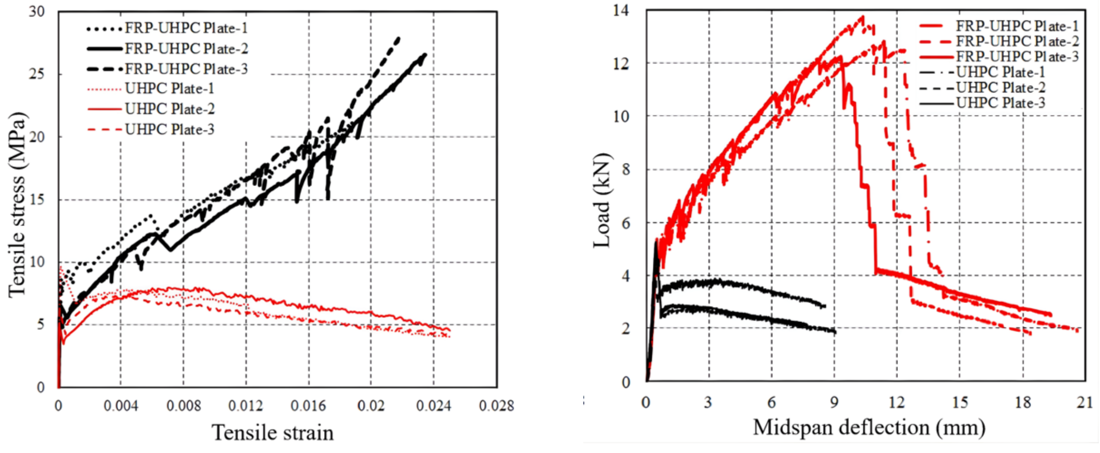


Figure 3. An example of an HPC slab embedded with FRP grid (after [36])

An example of an HPC slab embedded with FRP grid is shown in Fig. 3 [36]. The hybrid results in complementary mechanics: the HPC/UHPC layer carries compression and shear while shielding the polymeric reinforcement; the FRP grid bridges cracks, provides tension stiffening, and ensures redundant force paths across potential interface micro-slip. This synergy has also shown benefits under extreme actions: rapid G-HPC/FRP mesh repairs with G-UHPC overwrap reduced contact-blast damage by ∼ 60–70%, preventing back-face fracture and enhancing energy dissipation [35].



(a) Tensile behavior

(b) Flexural behavior

Figure 4. Tensile and flexural behavior of FRP-UHPC plates (after [37])

In the hybrid, the mineral matrix limits crack widths and distributes strains; the grid arrests crack opening and delays localization, thereby stabilizing cyclic hysteresis and raising cumulative energy dissipation. This two-way protection is reciprocal: the concrete shell protects the FRP from mechanical, thermal, and chemical attack, while the FRP stabilizes tensile zones and restrains crack growth, an interaction repeatedly identified as the source of the hybrid's comprehensive gains in strength, ductility, and durability [38, 39].

As demonstrated from [37], under direct tension (dumbbell specimens; loading rate 0.5 mm/min), UHPC plates have a linear-then-softening stress–strain response (Fig. 4(a)). By contrast, FRP-UHPC plates showed tensile stiffening after first cracking, with tensile strength (based on actual thickness) exceeding 25 MPa, evidencing effective crack-bridging by the grid. In three-point bending results (three FRP-UHPC vs three plain UHPC plates), FRP-UHPC specimens displayed a linear segment followed by pronounced deflection hardening (ultimate midspan deflection ≈ 10 mm in Fig. 4(b)). Measured grid strains exceeded 6000 $\mu\varepsilon$, confirming that the FRP reinforcement carried substantial longitudinal tension. Overall, the tensile and flexural results indicate that embedding an FRP grid in UHPC enhances tensile capacity, post-cracking stiffness, and deformation capacity, enabling thin plates with stable, energy-dissipating behavior.

Moreover, tests on hollow HPC blocks reinforced with CFRP ±45° grids reported up to 89% higher load capacity versus unreinforced controls. Both 1600 tex and 3700 tex grids performed well, although excessive overall thickness prompted delamination from strain incompatibility, underscoring the need to optimize jacket thickness and grid layout [40]. UHPC-clad hollow columns reinforced with carbon grids/composite meshes achieved ~ 50–80% gains in capacity and exhibited improved fire performance when FRP was included judiciously [39]. These results are consistent with the hybrid intent: thin outer shells that do more with less material, provided strain compatibility and interface detailing are engineered.

The hybrid helps address brittleness, bond, and maintenance. FRP adds a non-corroding tensile network that reduces maintenance burden; the mineral matrix confines and anchors the grid, mitigating classic FRP-only weaknesses (peel-off, debond, UV/chemical exposure). Conversely, the grid mitigates the potential tension-side brittleness of plain HPC/UHPC jackets by providing post-cracking capacity and crack-width control. To realize these advantages, construction must ensure HPC-FRP compatibility, delamination control, and grid geometry tailored to the member and demand type (flexure- vs shear-dominated) [40, 41]. In addition, HPC/UHPC, especially UHPFRC, exhibits excellent chloride-blocking and crack-resisting behavior, decisive in marine/deicing environments [42, 43]. When combined with FRP, the hybrid further reduces steel exposure and slows deterioration processes. Optimization studies indicate that HPC + CFRP can achieve target flexural upgrades with up to ~ 38% less FRP than conventional layouts, while UHPFRC maintains stable behavior under cyclic, impact, and seismic demands, benefits amplified by the grid's energy-absorption and crack-control roles [44, 45].

In terms of thermal response and fire. BFRP meshes in thin HPC plates have been shown to help control spalling and cracking during heating; however, polymer matrices degrade at ~ 200–300 °C, so hybridization (e.g., selective steel, anchorage detailing, or thermal protection) is needed where long-duration fire resistance is required [46]. Recognizing and designing for this limit is central to bridging applications with fire scenarios.

Field ability depends on placement logistics and surface preparation. For slabs, placing CFRP on the top surface can resolve access constraints and avoid brittle shear plug failures during installation [44, 47]. The adhesion efficiency of the grid to HPC/UHPC and the existing substrate hinges on proper substrate preparation, roughening/grooving, and cleaning protocols, significantly improving stress transfer and environmental performance, particularly for pre-placed FRP on self-compacting HPC [47]. Sustainability and life-cycle value. Using fly-ash-modified HPC preserves high mechanical performance while recycling industrial by-products; pairing such matrices with non-corroding FRP (long service life, rapid install) yields a green retrofit that can reduce CO_2, extend life, and support circular construction goals for bridge networks [48].

As summarized in Table 4, the hybrid HPC/UHPC + FRP grid system mitigates the key drawbacks of RC jacketing, FRP-only wraps, and HPC/UHPC-only jackets; Table 5 translates these insights into actionable recommendations for RC bridge piers (hinge-based geometry, interface detailing, and quality control).

Table 4. Hybrid HPC/UHPC + FRP grid: what it solves and prior approaches

Comparison target	Benefits of hybrid HPC/UHPC + FRP grid	References
Versus RC jacketing	Similar or better strength/ductility with thinner sections, lower added mass, and superior durability; alleviates clearance/foundation constraints; limits long-term cracking	[39, 40]
Versus FRP-only wraps	Embedding the grid within HPC/UHPC improves anchorage/bond, protects FRP from environment/impact, and adds compressive & shear capacity not available to polymer laminates alone	[33–35, 38, 39]
Versus HPC/UHPC-only jackets	The grid supplies tension capacity and crack-bridging, reducing reliance on jacket-core bond in tension zones; it enhances energy dissipation and post-cracking stiffness under seismic cycling	[33, 40, 45]

Table 5. Implementation notes for RC bridge piers (plastic-hinge zones)

Design aspect	Recommendation	Notes	References
Jacket height	Envelop the entire plastic hinge with a margin	Verify that partial/strip layouts do not relocate the hinge	[33, 39–41, 44, 47]
Grid orientation & density	Use ±45° for shear-flexure interaction; choose 1600–3700 tex to match demand	Ensure anchorage/overlaps at corners and discontinuities; confirm strain compatibility	[33, 39–41, 44, 47]
Total thickness	Limit thickness to avoid strain incompatibility/delamination	Balance shell stiffness with substrate strains; tailor to member demand	[33, 39–41, 44, 47]
Quality control & surface prep	Enforce quality control on mix stability, placement, curing, and surface preparation	Require roughening/grooving; pre-production pull-off/interface shear tests where appropriate	[33, 39–41, 44, 47]

4. Precast HPC permanent formwork jacketing with embedded FRP grids: method, rationale, and practice

Section 3 showed that combining a high-performance cementitious matrix (HPC/UHPC) with an internal FRP grid resolves key drawbacks of single-material jackets: the mineral matrix supplies compressive/shear capacity and environmental protection, while the FRP grid provides tensile capacity and crack-bridging for stable hysteresis. Building directly on that hybrid logic, a precast HPC permanent-formwork jacket is proposed in this paper in which thin precast HPC skins, factory-embedded with an FRP grid, are assembled around the pier, and the annular gap is pressure-grouted with non-shrink mortar or UHPC, as shown in Fig. 5. The precast skins stay in place and contribute structurally: the dense HPC faces provide confinement, shear capacity, and environmental protection, while the internal FRP grid supplies tension stiffening and crack-bridging, stabilizing hysteresis, and reducing residual drift. Critical to seismic reliability, interface quality is engineered up-front: the panel's inner surface is grooved/roughened in the plant, dowels or studs are coordinated with panel recesses, and the grouted annulus delivers uniform contact, mitigating slip/delamination risks that often limit thin jackets. Modular panel heights (full-wrap or strip/segmental) make it straightforward to envelop the plastic hinge with a margin while avoiding hinge relocation.

Compared with cast-in-place jackets, as shown in Table 6, the permanent-formwork approach shifts variability from the field to the factory. Plant quality assessment controls mix, panel geometry, grid placement, and surface texture; field work becomes lift-set-grout, enabling short closures, minimal formwork, and safer operations over water or traffic. For a given target, permanent-formwork jackets can be thinner (≈ 15–30 mm; ≈ 40 mm when cover restoration is combined), cut added mass/foundation demand, and still achieve high confinement and energy dissipation, provided grooves/connectors and strain-compatible grid detailing (e.g., ±45° orientation, proper laps/anchors) are specified. Design checks remain hinge-focused (height, thickness, interface shear transfer), with practical controls on grout continuity (injection/vent ports, optional non-destructive testing - NDT) and curing; where elevated-temperature scenarios govern, apply passive fire protection or selective hybridization for FRP components.

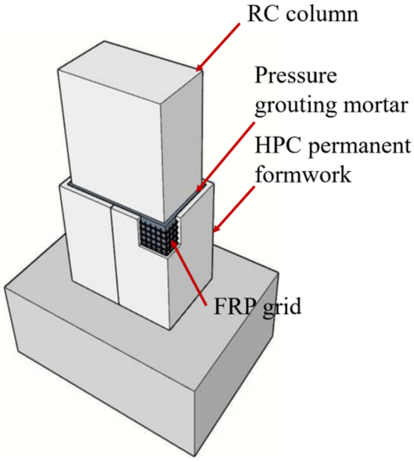


Figure 5. A schematic of precast HPC permanent formwork jacketing with embedded FRP grids

Beyond structural performance, method selection is often governed by delivery constraints (traffic management, access, available crews) and by life-cycle considerations. For jacketing retrofits, total cost and schedule can be dominated by labor, access, and traffic control rather than by unit material price, especially when work windows are short.

Cast-in-place RC/steel jackets typically require extensive formwork and reinforcement installation; FRP wraps reduce formwork and added mass but depend on careful surface preparation and may require fire protection; UHPC/UHPFRC solutions can limit section growth but demand controlled mixing/curing and specialized quality control. The proposed precast permanent-formwork approach shifts part of fabrication and quality control to the plant, potentially reducing onsite labor and closure duration while introducing drivers related to lifting, fit-up tolerances, and grouting. These cost/time and life-cycle drivers are summarized in Table 7.

The jacket–core interface often governs the effectiveness of cementitious jacketing under cyclic loading. To reduce variability between laboratory conditions and field delivery, interface requirements should be stated in measurable terms and verified through simple, repeatable tests. A practical approach is to specify surface roughness using the ICRI concrete surface profile [49] scale and to confirm bond quality using standardized pull-off testing (ASTM C1583 [50]).

For projects with limited prior experience in HPC/UHPC jacketing, pre-production mock-ups are recommended to validate the chosen surface preparation method, grout/repair material, and installation sequence. At minimum, the mock-up should reproduce the expected substrate condition and include the planned surface treatment and curing regime. Pull-off tests on the mock-up and early field panels can be used as acceptance checks and as a trigger for corrective actions (e.g., additional roughening, revised curing, or modified grout).

Table 6. Precast HPC permanent-formwork jacket with embedded FRP grid and cast-in-place HPC/UHPC jacket

Domain	Precast HPC permanent -formwork + embedded FRP grid	Cast-in-place HPC/UHPC jacket	References
Seismic effectiveness	Factory grooves + pressure-grouted annulus, thus strong interface shear transfer; grid adds tension stiffening & crack-bridging, thus stable hysteresis with thin shells (≈ 15–30 mm)	Good potential, but field variability in prep/mixing/curing can reduce realized confinement; tension capacity often needs added ties or external FRP	[33–36, 38–40]
Plastic-hinge control	Modular panel heights (full or strip) envelope hinge with a margin; easier to avoid hinge relocation by predefined height	Height/tolerances controlled on site, thus higher risk of unintended hinge relocation	[31, 32]
Geometry & mass	Thinner envelope, lower added mass, reduced foundation/bearing demand for the same targets	Typically, thicker to meet field tolerances and bond quality	[29–32]
Interface quality	Plant-formed grooves/texture + flat panels + shims, thus uniform annulus; injected/vented grout limits voids; bond easier to verify	In-situ roughening quality varies; continuous contact is harder near congestion/obstructions	[47]
Constructability & schedule	Lift-set-grout; minimal formwork; short closures; safer over water/traffic	Full formwork, longer on-site time; weather-sensitive consolidation/curing	[31, 32]
Quality control focus	Quality control mostly in plant (mix, geometry, grid, texture); field QC on bond tests, thickness, grout continuity (optional NDT), curing	Quality assessment must control mixing-placement-vibration-curing in variable conditions; wider performance spread	[21, 22, 25, 26]
Durability – marine/chlorides	Dense HPC shell + pressure grouted annulus; very low permeability; thin shells help limit crack widths; FRP grids are corrosion resistant	Comparable low permeability is achievable, but field variability and wider cracking can increase transport	[39, 40, 42]
Durability – fatigue	UHPFRC/UHPC generally exhibits high fatigue endurance; check cyclic bond/connector fatigue and grout interface slip under repeated loading	Similar material fatigue resistance is expected, but construction variability can localize cracking and raise stress ranges	[35, 42]
Durability – thermal/fire	Cementitious matrix is non-combustible; however, dense UHPC can be susceptible to explosive spalling. FRP resin softening near T_g ($\sim$ 65–120°C) can reduce tensile contribution, thus cover or fire protection required	Same mechanisms apply; cast-in-place thickness may ease cover/fire protection detailing	[6, 43, 44]

Where demand is high, such as in plastic-hinge regions, where large shear transfer and repeated slip reversals are expected, bond alone may be insufficient. In these cases, mechanical connectors (e.g., dowels or studs) should be considered to supplement adhesion and frictional interlock. If the design relies on interface shear transfer for strength or hysteretic stability, additional interface shear testing (or conservative interface design assumptions with connector redundancy) should be adopted.

Table 7. Relative cost/schedule and life-cycle drivers

Jacketing option	Cost	Duration	Dominant cost drivers	Dominant schedule drivers	Life-cycle implications
RC jacket	M	H	Rebar + formwork + concrete volume; traffic control	Rebar/formwork installation; curing; staged pours	Conventional durability; larger section/mass may increase demand
Steel jacket	M–H	M	Fabrication; lifting; corrosion protection	Fit-up and welding/bolting; grout; coating	Coating/inspection needs; corrosion risk in aggressive environments
FRP wrap	M	L–M	FRP/resin; surface prep; anchors; fire protection if required	Surface prep; resin cure; weather limits	Good corrosion resistance; temperature/fire sensitivity requires mitigation
Cast-in-place HPC	M–H	M–H	Specialty mix; formwork; quality control	Placement logistics; curing; quality control	Improved crack control; lower permeability reduces corrosion risk
Cast-in-place UHPC/UHPFRC	H	M	UHPC material; controlled mixing/curing; quality control	Batching/mixing capacity; curing regime; supply chain	Very low permeability; reduced maintenance potential
Hybrid cementitious + FRP grid	H	M	FRP grid + cementitious; detailing/anchorage	Grid placement; grout/shotcrete; curing; quality control	Combined protection and crack-bridging; fire/temperature protection for FRP
Precast HPC shell + grouted infill (proposed)	M–H	L–M	Precast fabrication/transport; lifting; grout; tolerances	Access for lifting; fit-up; grouting/curing	Factory-controlled quality; thin envelope; low permeability

Note: L = low, M = medium, H = high. Ratings are qualitative and project-specific.

5. Future directions and recommendations

The studies reviewed here indicate that high-performance cementitious jackets, and newer hybrid variants, can significantly improve the cyclic and dynamic response of RC bridge piers. The main obstacles to consistent field performance are also clear: translating observed mechanisms into design checks, achieving dependable interface shear transfer under reversed loading, and ensuring that construction and quality control deliver the assumed material properties on site. In practice, retrofit selection is often governed as much by durability, access, traffic control, and life-cycle trade-offs as by peak strength.

The recommendations below focus on steps that can be adopted in design documents and specifications to improve reliability and applicability:

(1) Close the mechanics-to-design gap for thin HPC/UHPC jackets: Practice needs calibrated interface models to reliably size thin shells. Priorities: (i) constitutive laws that capture mechanical interlock from longitudinal grooving/roughening in shear and slip; (ii) cyclic degradation rules for reversed loading; and (iii) detailing guidance for dowels/connectors when demand exceeds bond capacity. Reported gains from grooved interfaces, ∼+33% strength and +34% energy dissipation for ∼ 15 mm jackets, demonstrate the payoff of codifying these details [22].

(2) Leverage hybrid jackets (HPC/UHPC + FRP grid): Embedding CFRP/GFRP/BFRP grids within thin mineral shells merges compressive/shear capacity and environmental shielding (HPC/UHPC) with tensile capacity, crack-bridging, and corrosion immunity (FRP), addressing anchorage/temperature limits of FRP-only wraps and tension-side brittleness of plain cementitious jackets [33–35, 38, 39]. Hybrid evidence under impact/blast (G-HPC/FRP + G-UHPC) shows ∼ 60–70% damage reduction, motivating standardized rules for grid orientation, anchorage/cover, and strain compatibility for seismic use [40].

(3) Optimize jacket geometry to the plastic hinge, without relocating it: Design must explicitly size height (cover hinge with margin) and thickness (stiffness and strain-compatibility). Tests on rectangular piers indicate taller jackets maximize strength, whereas shorter jackets can better enhance ductility and cumulative energy, provided detailing prevents hinge relocation [31, 32]. Very thin (∼ 15 mm) shells are feasible with engineered interfaces; ∼ 40 mm layers remain effective for corrosion/cover restoration [22, 25].

(4) Address durability and multi-hazard demands in design, not by exception: Specifications should address chlorides, fatigue, underwater works, and thermal/fire from the outset. UHPC/UHPFRC shells and underwater/BFRP solutions show durable performance [35], while G-HPC/UHPC overwraps enhance impact/blast resistance [40]. Set acceptance criteria for crack width, chloride ingress, and residual drift. Recognize FRP matrix softening at ∼ 200–300 °C and provide fire protection or hybridization where needed.

(5) Institutionalize quality control and constructability for field reliability: Realized performance depends on surface preparation, mix stability, fiber/grid dispersion, placement, and curing. Require mock-ups, pre-production pull-off/interface-shear verification, and documented curing/thermal plans. Select cast-in-place and precast based on site constraints; literature consistently links outcomes to preparation quality and method [31, 32].

(6) Use goal-driven method selection with transparent trade-offs: For ductility and crack control, favor HPC/UHPC (± FRP grids). For large strength restoration of severely damaged members, RC/steel jackets remain viable, with explicit checks on mass, stiffness, and constructability. Synthesis studies report typical gains: FRP ≈ +45% ductility; RC +30–50% strength; HPFRC/ECC > 60% strength with superior crack control, supporting performance-based selection frameworks [3, 29].

(7) Prioritize benchmark datasets and parametric models for codification: Agencies need: (i) curated databases of cyclic/shaking-table tests on HPC/UHPC and hybrid FRP-grid jackets with common metrics (peak strength, drift at degradation, equivalent viscous damping, cumulative energy, residual drift); (ii) validated FE/interface models for jacket-core interaction and hinge mechanics; and (iii) simplified design equations calibrated to those datasets. Existing evidence on UHPFRC/UHPC jackets and vulnerability reductions provides a strong foundation [21, 31, 32].

(8) Standardize hybrid details and strain-compatibility checks for FRP grids: Set default grid orientations (e.g., ±45° for shear-flexure), linear densities (e.g., 1600–3700 tex), anchor/overlap rules at corners and seams, and strain-compatibility limits to prevent delamination in thicker jackets. Large gains for CFRP-grid-reinforced shells reinforce the need for detailing rules and corresponding inspec-

tion methods [40, 42–44, 47].

(9) Integrate life-cycle and sustainability metrics: Procurement should weigh life-cycle performance (maintenance, corrosion immunity, durability) alongside first cost. Encourage lower-embodied-carbon binders (e.g., fly-ash-modified HPC) where performance permits, and credit extended service life for UHPFRC bridge applications. Embed hybrid HPC/FRP choices within asset-management plans, especially in marine/deicing regions [39, 45, 47].

As summarized in Table 8, the key design takeaways, hinge coverage, interface preparation, thickness selection, matrix reinforcement, and quality control, are consolidated into a practitioner checklist.

Table 8. Actionable recommendations for practice (bridge piers)

#	Objective/scenario	Recommended action	Key details & checks
1	Choose the retrofit path by performance objective	Prefer HPC/UHPC (± FRP grid) when drift capacity & crack control dominate; use RC/steel for large strength restoration after severe damage	Quantify trade-offs in added mass/foundation demand; document target drift/residual drift acceptance
2	Set the jacket geometry to the plastic hinge	Envelope hinge with margin; verify partial/strip layouts do not relocate the hinge	Height from expected hinge length; check curvature distribution; document post-retrofit hinge location
3	Engineer the jacket-core interface	Require grooving/mechanical interlock; add connectors where needed; pre-production pull-off/interface-shear tests	Avoid smooth substrates; specify roughness class; acceptance criteria for τ–δ response
4	Thin and thick shells	Use ~ 15 mm shells where interfaces are engineered; use ~ 40 mm where cover restoration/corrosion repair is targeted	Check strain-compatibility to avoid delamination; verify uniform thickness
5	Hybrid option for aggressive or access-limited sites	Consider HPC/UHPC + FRP grid jackets	Grid provides tension capacity & crack-width control; verify strain-compatibility, anchorage/overlaps; protect FRP within mineral shell
6	Quality control and construction logistics	Plan mock-ups, specify self-compacting placement, and control curing/temperature	Select cast-in-place and precast shells per site; verify fiber/grid dispersion
7	Durability & multi-hazard provisions	Include chloride ingress, fatigue, and fire/thermal in baseline design	Fire: FRP temperature limits, thus fire protection/hybridization; set criteria for crack width and residual drift
8	Support codification	Report standardized cyclic metrics and details for each project/test	Peak strength, drift at degradation, equivalent damping, cumulative energy, residual drift; share to common databases

6. Conclusions

The reviewed literature supports the following conclusions:

(1) Results from monotonic, cyclic, and shaking-table studies show that high-performance cementitious jackets, particularly UHPC and UHPFRC, can increase lateral strength, drift capacity, and cumulative energy dissipation. Because these materials allow thin shells, retrofits can limit section enlargement and added mass, helping to control foundation demand and maintain constructability under traffic.

(2) The main mechanisms are core confinement, improved crack control (and post-cracking stiffness when fibers are used), and dependable interface shear transfer. When jacket height covers the plastic-hinge region and thickness matches demand, response typically shifts away from brittle modes toward a more stable flexure–shear behavior with smaller residual drifts.

(3) Jacket–core interaction often governs the global response. Mechanical interlock (through grooving/roughening and, when required, connectors), supported by pull-off or interface-shear verification, is needed to limit slip and delamination and to realize the expected strength and ductility gains.
(4) Jacket height should extend over the plastic-hinge region with an appropriate margin. Thickness can range from very thin shells (~ 15 mm) when the interface is engineered, to thicker layers (~ 40 mm) when cover restoration and corrosion repair are key objectives. Detailing for lap splices and shear demand remains critical; partial or strip jackets should be checked to avoid hinge relocation.

(5) Hybrid jackets that embed CFRP/GFRP/BFRP grids in a thin cementitious shell combine compressive and shear capacity with environmental protection, while the grid provides tensile resistance and crack bridging. This configuration can improve anchorage compared with FRP-only wraps and provides tensile robustness that plain cementitious shells may lack, which is useful in aggressive or access-constrained sites.

(6) Precast HPC shells with factory-embedded FRP grids and a pressure-grouted infill (mortar/UHPC) provide a practical route to implement the hybrid concept. Potential advantages include improved interface quality, more uniform thickness control, thinner envelopes, and reduced closure time relative to cast-in-place jackets. Modular panel heights can simplify hinge coverage, though detailing must still prevent unintended hinge relocation.

(7) Field performance depends on substrate preparation, interface verification, mix stability, fiber/grid placement, annulus continuity (for permanent-formwork systems), and curing/thermal control. Mock-ups, clear acceptance criteria, and targeted inspection (including NDT where appropriate) should be part of standard practice.

(8) Durability and multi-hazard demands, chloride exposure, traffic fatigue, thermal/fire actions, and underwater construction, should be treated explicitly. Where FRP temperature limits govern, passive fire protection or selective hybridization is needed; in marine or deicing regions, the low permeability and tight crack control of UHPC/UHPFRC are key advantages.

(9) For improving ductility and controlling crack widths in plastic-hinge regions, UHPC/UHPFRC jackets are generally well suited, with optional FRP grids or the proposed precast permanent-formwork concept. For major strength restoration of severely damaged members, RC or steel jackets remain viable, but added mass, stiffness changes, constructability, and durability trade-offs should be checked explicitly.

(10) Priority needs include: (i) curated datasets of cyclic and shaking-table tests (including hybrid and precast permanent-formwork variants) reported with common metrics such as peak strength, drift at degradation, equivalent viscous damping, cumulative energy, and residual drift; (ii) interface models that capture grooved and connector-assisted transfer under reversed loading; (iii) parametric

guidance for shell thickness, grid density/orientation, annulus width, and connector layouts; and (iv) simplified design provisions calibrated to these datasets and considered alongside life-cycle assessment.

Overall, high-performance cementitious jacketing, used alone or in hybrid FRP-grid form, and potentially as precast permanent-formwork shells, offers a thin and durable retrofit option for RC bridge piers. With hinge-focused detailing, an engineered interface, and disciplined quality control, these systems can meet the mechanical and construction demands required for broader, code-consistent use.

References

[1] Kopiika, N., Di Bari, R., Argyroudis, S., Ninic, J., Mitoulis, S.-A. (2025). Sustainability and resilience-driven prioritisation for restoring critical infrastructure after major disasters and conflict. *Transportation Research Part D: Transport and Environment*, page 104592.

[2] Gidaris, I., Padgett, J. E., Barbosa, A. R., Chen, S., Cox, D., Webb, B., Cerato, A. (2017). Multiple-hazard fragility and restoration models of highway bridges for regional risk and resilience assessment in the United States: State-of-the-art review. *Journal of Structural Engineering*, 143(3):04016188.

[3] He, R., Yang, Y., Sneed, L. H. (2015). Seismic repair of reinforced concrete bridge columns: Review of research findings. *Journal of Bridge Engineering*, 20(12):04015015.

[4] Buckle, I. G., Friedland, I., Mander, J., Martin, G., Nutt, R., Power, M. (2006). *Seismic retrofitting manual for highway structures. Part 1, Bridges*. Federal Highway Administration (FHWA), MCEER-06-SP10.

[5] Rodrigues, H., Pradhan, P., Furtado, A., Rocha, P., Vila-Pouca, N. (2018). Structural repair and strengthening of RC elements with concrete jacketing. In *Strengthening and Retrofitting of Existing Structures*, Springer, 181–198.

[6] Sezen, H., Miller, E. (2007). Retrofit of circular reinforced concrete columns using FRP, steel and concrete jackets. In *New Horizons and Better Practices*, 1–3.

[7] Farzad, M., Shafieifar, M., Azizinamini, A. (2019). Retrofitting of bridge columns using UHPC. *Journal of Bridge Engineering*, 24(12):04019121.

[8] Yuan, W., Wang, X., Guo, A., Li, C., Dong, Z., Wu, X. (2022). Cyclic performance of RC bridge piers retrofitted with UHPC jackets: Experimental investigation. *Engineering Structures*, 259:114139.

[9] Al-Abbas, B. H., Alsabbagh, A., Hasan, D. M., Semendary, A. A., Aaleti, S. (2024). Comparative studies on interfacial bond performance of ultrahigh performance concrete (UHPC) for sustainable repair of bridges and pavements. *Results in Engineering*, 24:103525.

[10] Firmo, J. P., Correia, J. R., Bisby, L. A. (2015). Fire behaviour of FRP-strengthened reinforced concrete structural elements: A state-of-the-art review. *Composites Part B: Engineering*, 80:198–216.

[11] Bertola, N., Schiltz, P., Denarié, E., Brühwiler, E. (2021). A review of the use of UHPFRC in bridge rehabilitation and new construction in Switzerland. *Frontiers in Built Environment*, 7:769686.

[12] AASHTO (2011). *AASHTO guide specifications for LRFD seismic bridge design*. American Association of State Highway and Transportation Officials, Washington, D.C.

[13] EN 1998-2:2005 (2005). *Eurocode 8: Design of structures for earthquake resistance – Part 2: Bridges*. European Committee for Standardization, Brussels.

[14] Japan Society of Civil Engineers (2018). *Guidelines for structural intervention of existing concrete structures using cement-based materials*. Japan Society of Civil Engineers, Tokyo, Japan.

[15] ACI Committee 363, ACI 363R-10 (2010). *Report on High-Strength Concrete*. American Concrete Institute, Farmington Hills, MI.

[16] Russell, H. G., Graybeal, B. A. (2013). *Ultra-high performance concrete: A state-of-the-art report for the bridge community*. Federal Highway Administration (FHWA), FHWA-HRT-13-060.

[17] Chen, C., Cai, H., Cheng, L. (2021). Shear strengthening of corroded RC beams using UHPC-FRP composites. *Journal of Bridge Engineering*, 26(1):04020111.

[18] Guan, D., Chen, Z., Liu, J., Lin, Z., Guo, Z. (2021). Seismic performance of precast concrete columns with prefabricated UHPC jackets in plastic hinge zone. *Engineering Structures*, 245:112776.

[19] Tong, T., Wang, J., Lei, H., Liu, Z. (2021). UHPC jacket retrofitting of reinforced concrete bridge piers with low flexural reinforcement ratios: Experimental investigation and three-dimensional finite element modeling. *Structure and Infrastructure Engineering*, 17(10):1315–1337.

[20] Ye, M., Guo, Z., Chen, C., Chen, Y. (2021). Shaking table test study on seismic performance of UHPC rectangular hollow bridge pier. *Composite Structures*, 275:114435.

[21] Hong, S.-G., Lee, J.-H., Choi, Y., Gu, I.-Y. (2021). Seismic strengthening of concrete columns by ultrahigh-performance fiber-reinforced concrete jacketing. *Journal of Structural Engineering*, 147(10): 04021157.

[22] Dadvar, S. A., Mostofinejad, D., Bahmani, H. (2020). Strengthening of RC columns by ultra-high performance fiber reinforced concrete (UHPFRC) jacketing. *Construction and Building Materials*, 235: 117485.

[23] Zhang, S., Wang, J., Lin, G., Yu, T., Fernando, D. (2023). Stress-strain models for ultra-high performance concrete (UHPC) and ultra-high performance fiber-reinforced concrete (UHPFRC) under triaxial compression. *Construction and Building Materials*, 370:130658.

[24] Cho, C.-G., Kim, Y.-Y., Feo, L., Hui, D. (2012). Cyclic responses of reinforced concrete composite columns strengthened in the plastic hinge region by HPFRC mortar. *Composite Structures*, 94(7):2246–2253.

[25] Meda, A., Mostosi, S., Rinaldi, Z., Riva, P. (2016). Corroded RC columns repair and strengthening with high performance fiber reinforced concrete jacket. *Materials and Structures*, 49:1967–1978.

[26] Dagenais, M.-A., Massicotte, B., Boucher-Proulx, G. (2018). Seismic retrofitting of rectangular bridge piers with deficient lap splices using ultrahigh-performance fiber-reinforced concrete. *Journal of Bridge Engineering*, 23(2):04017129.

[27] Faustino, P., Chastre, C. (2016). Damage Effect on Concrete Columns Confined with Carbon Composites. *ACI Structural Journal*, 113(5).

[28] Bousias, S. N., Triantafillou, T. C., Fardis, M. N., Spathis, L., O'Regan, B. A. (2004). Fiber-reinforced polymer retrofitting of rectangular reinforced concrete columns with or without corrosion. *ACI Structural Journal*, 101(4):512–520.

[29] Gkournelos, P., Triantafillou, T., Bournas, D. (2021). Seismic upgrading of existing reinforced concrete buildings: A state-of-the-art review. *Engineering Structures*, 240:112273.

[30] Navarrete, B. A. O., Guerrero, J. M. J., Juana, M. d. l. C. T., Soberón, G., Díaz, M. J. (2016). Influence of RC jacketing on the seismic vulnerability of RC bridges. *Engineering Structures*, 123:236–246.

[31] Tong, T., Yuan, S., Zhuo, W., He, Z., Liu, Z. (2019). Seismic retrofitting of rectangular bridge piers using ultra-high performance fiber reinforced concrete jackets. *Composite Structures*, 228:111367.

[32] Tong, T., Lei, H., Yuan, S., Liu, Z. (2020). Experimental investigation and seismic vulnerability assessment of low flexural strength rectangular bridge piers retrofitted with ultrahigh-performance concrete jackets. *Engineering Structures*, 206:110132.

[33] Hollaway, L. (2010). A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. *Construction and Building Materials*, 24 (12):2419–2445.

[34] Mia, M., Reza, M., Islam, K., Billah, A., Shahriar, A. (2020). A state-of-the-art review of the application of ultra-high-performance fiber-reinforced concrete in bridge engineering. In *IABSE-JSCE Joint Conference on Advances in Bridge Engineering-IV*.

[35] Xu, S., Zeng, H., Yuan, P., Liu, J., Yang, T., Shao, R., Su, Y., Wu, C. (2024). Experimental and numerical study of G-HPC slabs rapidly repaired by G-HPC canvas and G-UHPC under contact detonations. *Engineering Structures*, 306:117877.

[36] Zeng, J.-J., Yan, Z.-T., Jiang, Y.-Y., Li, P.-L. (2024). 3D printing of FRP grid and bar reinforcement for reinforced concrete plates: Development and effectiveness. *Composite Structures*, 335:117946.

[37] Zeng, J.-J., Feng, P., Dai, J.-G., Zhuge, Y. (2022). Development and behavior of novel FRP-UHPC tubular members. *Engineering Structures*, 266:114540.

[38] Ma, C. H., Deng, P., Matsumoto, T. (2021). Fatigue analysis of a UHPFRC-OSD composite structure considering crack bridging and interfacial bond stiffness degradations. *Engineering Structures*, 249:113330.

[39] Řepka, J. (2023). Lightened Elements Made of High-Performance Concrete with Fiber Composite Reinforcement. PhD thesis, Czech Technical University.

[40] Vlach, T., Řepka, J., Hájek, J., Pošta, J., Fürst, R., Hájek, P. (2024). Shear Capacity of Hollow High-Performance Concrete Beams with Cross-Wound Carbon Fiber-Reinforced Polymer Reinforcement. *Polymers*, 17(1):75.

[41] Hamoda, A. A., Eltaly, B. A., Ghalla, M., Liang, Q. Q. (2023). Behavior of reinforced concrete ring beams strengthened with sustainable materials. *Engineering Structures*, 290:116374.

[42] Lliso-Ferrando, J. R., Gandía-Romero, J. M., Soto, J., Valcuende, M. (2023). OC, HPC, UHPC and UHPFRC Corrosion Performance in the Marine Environment. *Buildings*, 13(10):2439.

[43] Orouji, M., Najaf, E. (2023). Effect of GFRP rebars and polypropylene fibers on flexural strength in high-performance concrete beams with glass powder and microsilica. *Case Studies in Construction Materials*, 18:e01769.

[44] Nguyen, H. Q., Yang, K., Kim, J. J. (2022). An Efficient Method for Optimizing HPC-FRP Retrofit Systems of Flexural Strengthened One-Way Continuous Slabs Based on ACI 440.2R. *Materials*, 15(23): 8430.

[45] Saeed, F. H., Hejazi, F. (2025). A Comprehensive Review of Retrofitted Reinforced Concrete Members Utilizing Ultra-High-Performance Fiber-Reinforced Concrete. *Materials*, 18(5):945.

[46] Hulin, T., Lauridsen, D. H., Hodicky, K., Schmidt, J. W., Stang, H. (2016). Influence of basalt FRP mesh reinforcement on high-performance concrete thin plates at high temperatures. *Journal of Composites for Construction*, 20(1):04015034.

[47] Ostrowski, K. A., Furtak, K. (2021). The influence of concrete surface preparation on the effectiveness of reinforcement using carbon fibre-reinforced polymer in high-performance, self-compacting, fibre-reinforced concrete. *Composite Structures*, 276:114522.

[48] Al Mashhadani, D., Wong, L. S., Kong, S. Y., Al-Zand, A. W., Midhin, M. A. (2023). An evaluative review of recycled waste material utilization in high-performance concrete. *Civil Engineering Journal*, 9 (11):2927–2957.

[49] Winkler, P. (2013). *Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair*. International Concrete Repair Institute (ICRI).

[50] ASTM C1583 (2004). *Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials by direct tension (pull-off method)*. ASTM International, West Conshohocken, PA.