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Seismic Performance of Reinforced-Concrete Beam-Column Joints With Conventional Steel and Hybrid Shape-Memory-Alloy/Fiber- Reinforced-Polymer Reinforcement: A Critical Review

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Systematic Review

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Posted Date: November 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10742959/v1

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Additional Declarations: No competing interests reported.

SEISMIC PERFORMANCE OF REINFORCED-CONCRETE BEAM-COLUMN JOINTS WITH CONVENTIONAL STEEL AND HYBRID SHAPE-MEMORY-ALLOY/FIBER-REINFORCED-POLYMER REINFORCEMENT: A CRITICAL REVIEW

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Abstract - Background Reinforced-concrete (RC) beam-column joints are critical regions in moment-resisting frames because they must transfer large cyclic moments, shear forces, and axial forces while maintaining anchorage integrity and structural continuity during earthquakes. Conventional steel-reinforced joints can provide substantial strength and hysteretic energy dissipation when properly detailed, but severe cyclic loading may produce reinforcement yielding, bond deterioration, joint shear damage, corrosion-related durability problems, and permanent residual deformation. Purpose—This review critically evaluates conventional reinforcement, shape-memory-alloy (SMA) reinforcement, fiber-reinforced-polymer (FRP) systems, and emerging SMA+FRP hybrid concepts for improving the seismic performance and resilience of RC beam-column joints. Coverage Particular emphasis is placed on literature published from 2023 to 16 August 2026, supplemented by landmark earlier studies required to establish joint mechanics, SMA constitutive behaviour, FRP strengthening principles, and the origin of hybrid SMA-FRP concepts. Findings—The literature indicates that SMA reinforcement is particularly effective for self-centering and residual-deformation control, whereas FRP systems are attractive for corrosion resistance, joint shear strengthening, confinement, and minimally invasive rehabilitation. However, SMA systems can provide narrower hysteresis than yielding steel, while FRP performance is strongly controlled by bond, anchorage, fiber orientation, substrate condition, and brittle failure. Hybridization offers a rational means of combining restoring capability with strength, confinement, durability, and energy-dissipation mechanisms. Research gap—Direct, recent, full-scale experimental validation of true SMA+FRP RC beam-column joints remains sparse, particularly under bidirectional loading, variable axial force, slab participation, temperature effects, aftershocks, and multi-hazard exposure. Conclusion—SMA+FRP hybrid joints represent a promising resilience-oriented structural concept, but standardized detailing, validated nonlinear models, probabilistic performance assessment, life-cycle evaluation, and code-ready design procedures are required before routine engineering implementation.

Keywords : beam-column joint; shape memory alloy; SMA; fiber-reinforced polymer; FRP; seismic performance; self-centering; residual drift.

1. INTRODUCTION

Reinforced-concrete moment-resisting frames depend strongly on the integrity of their beam-column joints. During earthquake excitation, these compact regions transfer opposing beam moments, column moments, axial forces, and shears through a highly disturbed stress field. Satisfactory global frame behaviour therefore cannot be achieved merely by providing adequate flexural strength in individual beams and columns; joint-panel strength, bond, confinement, anchorage, and deformation capacity must also remain adequate throughout repeated load reversals. Modern provisions such as ACI 318 and IS 13920 consequently prescribe special seismic detailing intended to promote ductile structural response and discourage brittle joint or column failure [1], [2]. The physical basis of joint shear resistance is generally interpreted using interacting diagonal compression-strut and truss mechanisms, together with bond-transfer and reinforcement-anchorage actions [3].

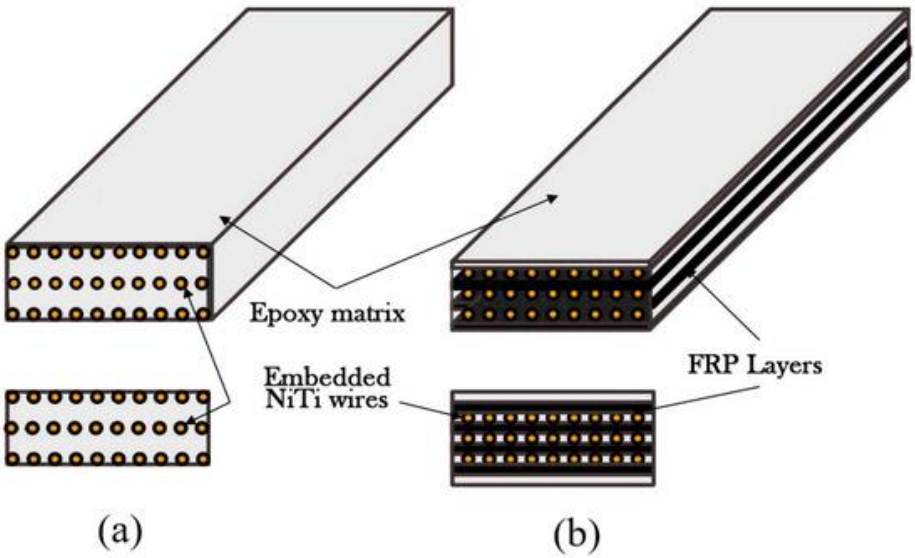


Fig 1. Schematic of SMA-FRP composites: (a) pure composite, (b) hybrid composite

Conventional deformed steel reinforcement remains the benchmark solution because it is economical, widely available, ductile, readily anchored, and supported by a mature design framework. Properly detailed steel-reinforced joints can develop stable cyclic yielding and substantial hysteretic energy dissipation. Nevertheless, severe earthquakes expose several limitations. Plastic deformation of steel is largely irreversible, and consequently a building may retain considerable residual drift even when collapse has been avoided. Repeated inelastic cycling can additionally cause bar buckling, low-cycle fatigue, fracture, deterioration of bond, concrete crushing and spalling, and progressive stiffness degradation. In aggressive environments, reinforcement corrosion further compromises long-term joint durability. These limitations have motivated the application of smart and composite reinforcement. Superelastic shape-memory alloys, particularly nickel-titanium (NiTi) alloys, can undergo comparatively large recoverable deformation through stress-induced reversible phase transformation. Their flag-shaped cyclic response makes them attractive in plastic-hinge regions in which recovery of deformation and control of permanent drift are important [4]. Youssef, Alam, and Nehdi demonstrated the feasibility of SMA reinforcement in RC beam-column connections, establishing an important foundation for self-centering concrete joint research [4].

A particularly relevant landmark was the study by Nehdi, Alam, and Youssef, who developed a corrosion-resistant RC beam-column joint in which SMA and FRP were strategically combined [5]. Their concept placed expensive superelastic SMA reinforcement where recoverability was most beneficial and used FRP elsewhere. This study is important because it provides one of the clearest early demonstrations of a genuine SMA+FRP beam-column joint, rather than an SMA-steel or FRP-steel hybrid. A related study by Billah and Alam later examined hybrid SMA and FRP reinforcement in concrete bridge columns [6]. Kabir et al. subsequently reviewed hybrid reinforcement for concrete beam-column joints and recognized both the potential and unresolved technical issues of combining advanced reinforcement systems [7]. The existence of these early studies establishes feasibility, but it does not mean that the hybrid technology has reached maturity. Research after these initial studies has evolved along two partially separate paths. One group has investigated SMA-reinforced, SMA-retrofitted, self-centering, and actively confined RC joints. Suhail et al. developed active confinement using thermally activated SMA wires for deficient exterior RC joints [8]. Qian et al. investigated prefabricated joints combining SMA bars with engineered cementitious composites (ECC) [9], while Higazey et al. conducted numerical investigations of exterior joints reinforced with SMA [10]. These studies progressively address recoverability, damage localization, confinement, bar anchorage, and practical material placement.

A second, much larger stream concerns FRP strengthening. Recent investigations have moved beyond simple externally bonded sheets toward optimized layouts, FRP anchors, ropes, grooves, combined rehabilitation materials, and minimally invasive systems. Del Vecchio et al. studied minimally invasive FRP strengthening of exterior beam-column joints [11], while del Rey Castillo et al. investigated realistic beam-column joints strengthened using FRP sheets and FRP anchors [12]. Fragility-based assessment has also been introduced for FRP-strengthened joints [13]. Other recent work has examined analytical and numerical prediction of CFRP-strengthened joint shear response [14], three-dimensional exterior joints [15], hybrid CFRP/HPFRCC repair [16], CFRP-steel-plate retrofits [17], detailed nonlinear finite-element representation [18], combined UHP-HFRC and FRP rehabilitation [19], and layouts suited to joints containing plain reinforcement and geometrical obstructions [20]. These developments demonstrate that anchorage, accessibility, load path, and placement are at least as important as nominal FRP quantity. Research from 2025-2026 continues this practical emphasis. Comparative retrofit modelling [21], CFRP rope and sheet systems [22], near-surface-mounted CFRP ropes [23], validated three-dimensional finite-element simulations [24], and BFRP rehabilitation of previously damaged joints [25] extend the material and detailing options. At the same time, Alqarni et

al. examined RC joints combining SMA, conventional steel, and polyvinyl-alcohol fibers, illustrating how self-centering and energy dissipation can be deliberately balanced [26]. A 2026 study by Eswar and Chourasia investigated localized Fe-SMA reinforcement and headed-bar connections [27], highlighting anchorage and economical SMA placement. Contemporary review work also identifies seismic resilience rather than simple strength as the principal motivation for using SMA in RC structures [28].

Data-driven methods are beginning to influence beam-column-joint research as well. Recent explainable-machine-learning studies have used experimental joint databases to predict shear capacity and identify influential parameters [29], [30]. Although these datasets are dominated by conventional RC joints and cannot yet provide validated SMA+FRP design models, they demonstrate a route toward surrogate modelling, uncertainty quantification, and physics-informed design once sufficiently standardized hybrid-joint datasets become available. The novelty of the present review is therefore not a claim that SMA+FRP joint technology is already extensively established. Instead, the review addresses an important mismatch in the literature: an early hybrid concept exists, but modern research has subsequently developed sophisticated SMA and FRP technologies largely in parallel. The central question is whether those separate developments can now be synthesized into a rational next generation of hybrid joints that achieves four simultaneous objectives: sufficient lateral strength, controlled damage, high recoverability, and improved durability. Accordingly, this review distinguishes true SMA+FRP hybrid reinforcement from broader SMA-steel or FRP-steel hybridization; compares the physical roles of steel, SMA, and FRP rather than treating all advanced reinforcement as interchangeable; emphasizes recent 2023-2026 research; critically examines experimental, numerical, analytical, and detailing limitations; and develops a research roadmap for code-ready hybrid RC beam-column joints. The remainder of the paper presents the review objectives and methodology, explains fundamental joint and material behaviour, classifies existing studies, critically synthesizes experimental and numerical evidence, compares reinforcement systems and controlling parameters, discusses chronological and recent technological developments, identifies research gaps, proposes future research directions, and concludes with implications for structural engineering practice.

2. OBJECTIVES OF THE REVIEW

2.1 Overall Aim

The overall aim is to critically evaluate the seismic behaviour of conventional steel-reinforced RC beam-column joints and advanced joints incorporating SMA and FRP, with particular emphasis on establishing the technical feasibility, limitations, and future research requirements of SMA+FRP hybrid reinforcement.

2.2 Specific Objectives

1. To establish the fundamental mechanisms governing cyclic shear transfer, bond, anchorage, plastic-hinge development, damage, stiffness deterioration, energy dissipation, and residual deformation in RC beam-column joints.

2. To compare conventional steel, SMA, FRP, and SMA+FRP hybrid systems with respect to strength, ductility, self-centering, energy dissipation, durability, failure mechanism, constructability, and design maturity.

3. To critically examine experimental methodologies, specimen configurations, cyclic loading protocols, reinforcement arrangements, strengthening techniques, and measured response parameters used in previous studies.

4. To evaluate numerical and analytical approaches, including finite-element modelling, constitutive representation, bond/interface models, joint-shear models, and emerging data-driven techniques.

5. To synthesize the major developments reported during 2023-2026 and determine whether recent SMA and FRP technologies overcome limitations identified in earlier hybrid-joint studies.

6. To identify specific unresolved problems that currently prevent SMA+FRP hybrid joints from becoming a standardized seismic design solution.

7. To establish technically justified future research directions covering experimental validation, multi-hazard behaviour, optimization, performance-based earthquake engineering, machine learning, life-cycle assessment, and design-code development.

3. THEORETICAL AND FUNDAMENTAL BACKGROUND

3.1 Seismic Behaviour of RC Beam-Column Joints

A beam-column joint is a discontinuity region in which Bernoulli beam theory is not directly applicable because nonlinear strain distribution, diagonal compression, bond stress, anchorage forces, and multi-axial stress occur simultaneously. Under earthquake-induced moment reversal, tensile force in beam longitudinal reinforcement changes direction from one face of the joint to the other, producing large bond demands and joint shear. The average nominal joint shear stress may be expressed as follows.

$$v_j = \frac{V_j}{b_j\, h_c} \tag{1}$$

where:

where: v_j = nominal joint shear stress, MPa; V_j = joint shear force determined from equilibrium, N; b_j = effective joint width, mm; h_c = column depth in the direction of joint shear, mm.

Equation (1) is a stress index rather than a complete failure model. Joint capacity depends additionally on concrete strength, axial compression, transverse reinforcement, anchorage, bond condition, beam reinforcement, geometry, and cyclic degradation. Hwang and Lee developed an analytical framework incorporating strut-and-tie mechanisms for exterior RC joints [3].

$$\theta = (\frac{\Delta}{H}) \times 100 \quad (2)$$

where: θ = drift ratio, %; Δ = imposed lateral displacement or equivalent story displacement, mm; H = reference height associated with the test arrangement, mm.

Because laboratories may define H differently, direct comparison of reported drift values requires verification of each experimental configuration.

3.2 Ductility

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \quad (3)$$

where: μΔ = displacement ductility ratio, dimensionless; Δ_u = ultimate displacement according to the adopted failure criterion, mm; Δ_γ = yield displacement, mm.

The apparent simplicity of Eq. (3) hides a significant comparison problem. Steel joints possess a relatively identifiable yield point, whereas FRP does not exhibit conventional yielding and superelastic SMA transforms gradually. Different studies may therefore use bilinear idealization, secant methods, first-yield definitions, or specified strength degradation to establish yield and ultimate displacement.

3.3 Hysteretic Energy Dissipation

$$E_h = \oint P \, d\Delta \quad (4)$$

where: E_h = hysteretic energy dissipated per cycle, N·mm or kN·mm; P = lateral load, N or kN; Δ = corresponding displacement, mm.

$$\xi_{eq} = \frac{E_h}{4\pi E_s} \quad (5)$$

where: ξ_{eq} = equivalent viscous damping ratio, dimensionless; E_h = area enclosed by the hysteresis loop, units of energy; E_s = reference maximum strain-energy quantity, in the same energy units.

Consistent calculation conventions are essential when comparing different experiments.

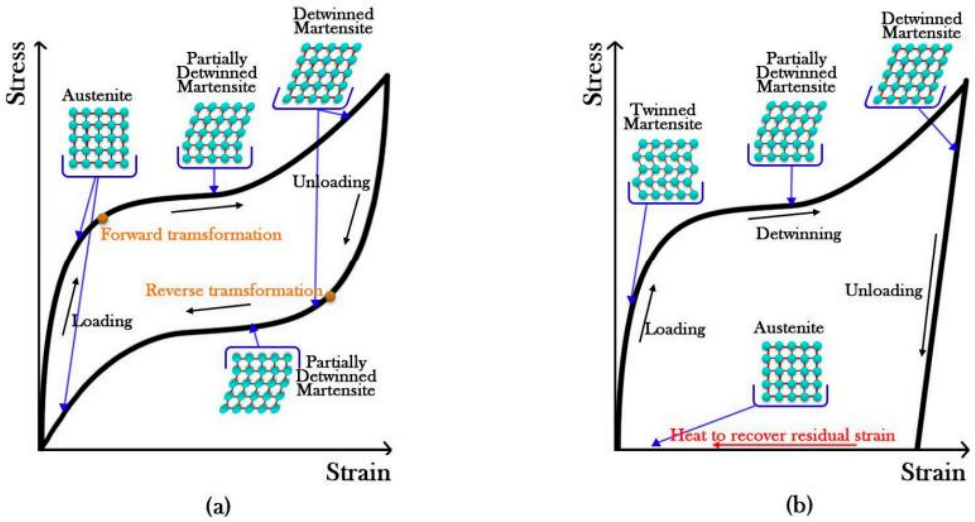


Fig 2. Schematic of the stress–strain curve of SMA (a) super-elastic behavior (T > Af) (b) shape memory effect (T < Mf).

3.4 Stiffness Degradation

$$K_{sec,i} = \frac{|P_i^+| + |P_i^-|}{|\Delta_i^+| + |\Delta_i^-|} \quad (6)$$

where: Ksec,i = secant stiffness in cycle i, kN/mm; P_i^+ and P_i^- = positive and negative peak loads, kN; Δ_i^+ and Δ_i^- = corresponding peak displacements, mm.

Stiffness degradation reflects concrete cracking, bond deterioration, reinforcement inelasticity, interface slip, and accumulation of joint damage.

3.5 Residual Deformation and Self-Centering

$$\theta_r = \frac{\Delta_r}{H} \times 100 \quad (7)$$

where: θ_r = residual drift ratio, %; Δ_r = residual displacement after unloading, mm; H = reference height, mm.

$$R_{SC} = 1 - \left| \frac{\Delta_r}{\Delta_{max}} \right| \quad (8)$$

where: RSC = normalized self-centering index; Δ_r = residual displacement after unloading, mm; Δmax = maximum imposed displacement in the relevant cycle, mm.

RSC = 1 represents idealized complete recentering, whereas decreasing values indicate increasing permanent displacement. Equation (8) is used as a conceptual comparison index in this review and should not be interpreted as a codified acceptance criterion.

3.6 Conventional Reinforcing Steel

Conventional seismic reinforcement obtains energy dissipation primarily from plastic yielding. This behaviour produces wide hysteresis loops but also accumulated permanent strain. Well-confined concrete and appropriate transverse reinforcement delay buckling and sustain cyclic compression. The design philosophy is based on intentional yielding in selected ductile regions while protecting columns and joint cores from brittle failure [1], [2]. Strength is only one component of joint performance; development length, hooks or mechanical heads, joint transverse reinforcement, bar diameter, axial force, and beam-to-column geometry determine whether a desirable beam-flexural mechanism develops.

3.7 Shape-Memory Alloys

SMAs possess thermo-mechanical phase-transformation behaviour. For superelastic NiTi used above the austenite-finish temperature, mechanical loading can induce transformation from austenite to martensite, while unloading triggers reverse transformation and permits substantial strain recovery. Unlike conventional yielding steel, SMA can therefore develop a flag-shaped hysteresis characterized by transformation plateaus and reduced residual strain. Constitutive models developed by Auricchio and co-workers provide an important basis for finite-element simulation of this response [55], [56].

- elastic modulus of austenite and martensite

- forward-transformation start and finish stresses
- reverse-transformation start and finish stresses
- recoverable transformation strain
- transformation temperatures
- hysteresis width
- cyclic degradation
- functional fatigue

NiTi generally provides excellent superelastic characteristics but remains relatively expensive. Fe-based SMAs offer potentially more economical structural applications and have received increasing attention in recent work [27], [28]. The central seismic advantage of SMA is recoverability, not necessarily maximum energy dissipation. A very narrow self-centering hysteresis can reduce residual deformation while dissipating less energy than yielding steel. Hybrid systems should therefore be designed to balance restoring force and dissipation rather than maximizing one response metric in isolation.

3.8 Fiber-Reinforced Polymers

$$\sigma f = Ef\varepsilon f (9)$$

where: σf = FRP tensile stress, MPa; Ef = longitudinal FRP modulus, MPa; εf = longitudinal strain, dimensionless.

Unlike steel, ordinary FRP reinforcement does not develop a metallic yield plateau. Failure is typically brittle and may occur by fiber rupture, anchorage failure, laminate separation, or debonding from the concrete substrate. For externally bonded systems, effective design strain is normally lower than coupon rupture strain and is constrained by substrate and bond behaviour [58]. CFRP generally offers high stiffness and strength; GFRP is more economical and corrosion resistant but has a lower elastic modulus; BFRP has received increasing attention as another corrosion-resistant strengthening option.

3.9 Concept of SMA+FRP Hybrid Reinforcement

A rational hybrid system should assign each material to the structural function it performs most effectively. SMA is suitable for local re-centering, deformation recovery, prestressing or active confinement, and control of permanent drift. FRP is suitable for corrosion-resistant longitudinal reinforcement, joint shear strengthening, passive confinement, or external rehabilitation. Conventional steel or a dissipative cementitious material may be retained where stable hysteretic energy dissipation and familiar anchorage are desirable.

1. Internal hybrid reinforcement: SMA in beam plastic-hinge or joint-critical zones, with FRP reinforcement in lower-demand regions.

2. Hybrid retrofit: external SMA prestressing or active confinement combined with externally bonded or anchored FRP.

3. Multi-material joint: SMA combined with FRP and a ductile cementitious matrix such as ECC or HPFRCC to control both residual deformation and damage localization.

The 2010 hybrid joint of Nehdi et al. [5] is a key precedent for the first architecture. More recent active SMA and advanced FRP anchorage studies provide technologies that could enable the second and third architectures but have rarely been combined within the same modern experimental beam-column-joint program.

4. CLASSIFICATION OF EXISTING RESEARCH

4.1 Classification by Reinforcement System

A. Conventional Steel RC Joints: Reference systems for strength, stiffness, ductility, damage, energy dissipation, and code compliance.

B. SMA-Reinforced Joints: SMA replaces steel entirely or locally in longitudinal plastic-hinge reinforcement.

C. SMA-Retrofitted Joints: External SMA bars or wires provide confinement, re-centering, prestressing, or active restoration.

D. FRP-Reinforced Joints: GFRP/CFRP/BFRP bars replace some or all conventional internal longitudinal or transverse reinforcement.

E. FRP-Strengthened Joints: Externally bonded sheets, strips, ropes, plates, anchors, or near-surface-mounted systems strengthen existing joints.

F. Hybrid SMA+FRP Joints: SMA and FRP operate concurrently as structural reinforcement or strengthening components.

G. Broader Hybrid Systems: SMA-steel, FRP-steel, FRP-HPFRCC, SMA-ECC, and SMA-fiber-concrete combinations provide mechanistic evidence relevant to development of a true SMA+FRP system.

4.2 Classification by Research Methodology

- quasi-static reversed-cyclic experimental testing
- monotonic proof-of-concept testing
- nonlinear finite-element analysis
- fiber-element/frame analysis
- analytical strut-and-tie or empirical joint-shear modelling
- fragility/performance-based earthquake assessment
- machine-learning-based prediction

4.3 Classification by Joint Geometry

- exterior joints
- interior joints
- corner joints
- two-dimensional subassemblies
- three-dimensional joints with transverse beams
- beam-column-slab assemblies
- prefabricated connections

Exterior planar joints are disproportionately represented because they offer a manageable laboratory configuration. This creates uncertainty when results are transferred to realistic three-dimensional building joints.

4.4 Classification by Performance Objective

- strength enhancement
- ductility
- joint shear protection
- residual-drift reduction
- self-centering
- confinement
- corrosion resistance
- repair of damaged joints
- prevention of bond failure
- constructability/minimally invasive retrofit
- collapse safety/fragility
- resilience and reparability

Figure 2. Taxonomy of RC Beam-Column-Joint Research Involving Steel, SMA, and FRP. An original hierarchical diagram should separate new construction from rehabilitation and then subdivide systems by material, reinforcement location, structural function, and evaluation methodology. This avoids treating all “hybrid” joints as one category.

5. DETAILED CRITICAL LITERATURE REVIEW

5.1 Conventional Reinforcement as the Reference Condition

The conventional ductile RC joint provides the performance benchmark. Its ideal seismic mechanism involves flexural yielding in the beam while the column and joint remain sufficiently strong. Such behaviour distributes inelastic demand into intentionally detailed plastic hinges rather than permitting brittle diagonal joint shear failure.

Poorly detailed older joints often lack adequate joint stirrups, use insufficient anchorage, contain smooth or deficient bars, or were designed primarily for gravity loading. Under cyclic lateral loading, such joints may exhibit diagonal cracking, reinforcement slip, severe pinching, rapid strength loss, and premature joint shear failure.

Accordingly, an advanced reinforcement system should not be evaluated only against a weak non-seismic control specimen. A more demanding and scientifically useful benchmark is a code-compliant steel joint designed to achieve ductile beam hinging. An advanced material can appear highly effective when compared with a deliberately deficient control while still failing to equal the cyclic robustness of well-detailed conventional reinforcement.

5.2 Early SMA and Hybrid SMA+FRP Research

Youssef et al. [4] demonstrated that superelastic SMA reinforcement could be introduced into RC beam-column connections to reduce permanent deformation. The research established the basic engineering proposition that conventional steel need not be the only reinforcement capable of sustaining cyclic joint demand.

Nehdi et al. [5] then developed a corrosion-free beam-column-joint concept using SMA and FRP in combination. This work remains unusually important because the advanced materials were assigned complementary functions rather than applied independently. SMA was concentrated where large reversible deformation was expected, while FRP contributed corrosion-resistant reinforcement away from the critical inelastic region. The study demonstrated technical feasibility but also exposed challenges involving anchorage, cost, bond compatibility, and the balance between self-centering and hysteretic dissipation.

Billah and Alam [6] extended hybrid SMA-FRP thinking to concrete columns. Although bridge-column response is not identical to joint-panel behaviour, the research demonstrated that hybridization can distribute deformation demands between expensive smart material and corrosion-resistant composite reinforcement. Kabir et al. [7] later reviewed hybrid RC beam-column joints and identified material compatibility, anchorage, cost, and modelling as important challenges; many of those issues remain unresolved at code level.

5.3 Development of SMA Beam-Column Joints

Oudah and El-Hacha investigated SMA anchorage and joint behaviour in a series of studies. Their 2017 Engineering Structures paper examined concrete beam-column connections reinforced using SMA smart material [31], followed by an innovative self-centering connection in ACI Structural Journal [32]. These investigations established that the behaviour of an SMA-reinforced joint can be governed by anchorage as much as by the intrinsic superelasticity of the alloy.

Azariani et al. investigated exterior joints reinforced with SMA bars [33], while Halahla et al. employed concrete-damage-plasticity modelling to study the influence of SMA on exterior RC beam-column-joint ductility [34]. Nahar et al. conducted a numerical seismic-performance evaluation involving different superelastic SMA reinforcement arrangements [35]. Collectively, these studies showed that localization of SMA within the plastic-hinge region can provide a more economical route than replacing conventional reinforcement throughout an entire structural member.

Yurdakul et al. studied deficient beam-column joints retrofitted using post-tensioned superelastic SMA bars [36]. The external or post-tensioned approach is conceptually important for existing construction because it separates the re-centering device from the original reinforcement and can reduce invasive demolition.

Suhail et al. later investigated SMA and FRP as active and passive confinement systems for low-strength concrete columns [37]. Although the specimens were columns rather than beam-column joints, the study is highly relevant to a future hybrid retrofit: SMA can produce recoverable active confining pressure through activation, while FRP provides passive confinement after lateral dilation. Elbahy et al. numerically studied RC beam-column joints retrofitted with external superelastic SMA bars [38], reinforcing the potential for external SMA systems while also illustrating the need to validate local connection mechanisms.

5.4 SMA-ECC and Damage-Controlled Joint Concepts

Qian et al. investigated self-centering joints reinforced using superelastic SMA bars and ECC [39]. The concept combines a restoring reinforcement with a high-ductility cementitious matrix capable of distributed cracking. A subsequent 2023 study investigated prefabricated concrete joints using SMA bars and ECC [9]. These systems recognize that replacing steel alone does not necessarily prevent concrete damage; a truly resilient joint must control both reinforcement residual strain and matrix cracking or spalling.

Chen et al. also reported a precast beam-column-joint concept incorporating SMA fibers and ECC [40]. These studies establish a broader principle applicable to SMA+FRP joints: the best hybrid configuration may require three levels of material design—re-centering reinforcement, corrosion-resistant or shear reinforcement, and a damage-tolerant cementitious matrix.

5.5 Active SMA Confinement of Existing Joints

Suhail et al. [8] investigated active confinement of nonseismically detailed exterior RC beam-column joints using SMA wires. The approach exploits thermal activation to introduce confinement around an existing joint. This differs fundamentally from ordinary passive FRP wrapping because the SMA can apply an active confining action before significant concrete dilation occurs.

This technique is especially relevant to future SMA+FRP hybrid retrofits. Active SMA could provide restoring force and preconfinement, while FRP could stabilize concrete dilation and provide additional shear resistance at higher deformation. The materials could therefore be arranged sequentially in the resistance mechanism rather than merely superimposed.

5.6 Recent SMA Numerical Research

Higazey et al. [10] investigated exterior beam-column joints reinforced with SMA using nonlinear numerical analysis. The study contributes to evidence that finite-element models can represent joint-level SMA response, but reliability depends on concrete damage calibration, reinforcement bond, SMA constitutive parameters, and cyclic validation.

Eswar and Chourasia [27] advanced this direction in 2026 by studying SMA-reinforced joints with headed-bar connections and localized Fe-SMA placement. From a constructability viewpoint, the study is important because economical SMA use requires dependable transitions between SMA and conventional reinforcement; headed bars, couplers, development length, local bearing, and stress concentration become primary design variables.

Mahamood et al. [28] synthesized the state of SMA-based seismic resilience and highlighted the transition of the field from material feasibility toward resilience-oriented structural applications. This reflects the broader shift from simple life-safety criteria toward residual drift, repairability, downtime, and post-earthquake functionality.

5.7 FRP Strengthening: From Sheets to Anchored Systems

FRP strengthening of beam-column joints has a much larger experimental database than true SMA+FRP hybrid reinforcement. Earlier work by Mahmoud et al. [41], Bousselham [42], Le-Trung et al. [43], and Wang et al. [44] established that externally bonded CFRP can improve deficient joint response. These studies also identified practical issues including premature debonding, inadequate development, joint geometry, beam or column obstruction, and difficulty transferring tensile force around joint corners.

This explains why recent work increasingly focuses on anchorage rather than merely increasing the number of FRP layers. Del Vecchio et al. [11] investigated minimally invasive strengthening of exterior joints, while del Rey Castillo et al. [12] studied realistic beam-column joints with shear failure using FRP sheets and dedicated FRP anchors. Yurdakul et al. [13] developed fragility functions for FRP-strengthened joints, shifting the evaluation from deterministic specimen strength toward probabilistic performance.

Saad et al. [14] investigated shear strength of existing non-seismic joints strengthened using CFRP through numerical and analytical methods. Farhang et al. [15] studied shear strengthening of three-dimensional exterior joints with CFRP sheets using experimental and numerical methods. These studies reinforce the need to represent the real joint geometry, transverse members, substrate cracking, and interface behaviour.

5.8 Hybrid FRP Rehabilitation Systems

Barmi et al. [16] combined CFRP with a high-performance fiber-reinforced cementitious composite for restoration of damaged RC joints. The concept recognizes that damaged concrete may need reconstruction using a ductile matrix before external strengthening can be effective.

Fan et al. [17] investigated CFRP-steel-plate strengthening of eccentric beam-column joints, demonstrating that hybrid strengthening can outperform a single strengthening mechanism when the steel plate and composite reinforcement are configured to share force transfer. Mostofinejad et al. [19] investigated hybrid rehabilitation using UHP-HFRC and FRP wrapping. The mechanism is analogous to future SMA+FRP concepts: separate materials are selected for complementary rather than identical roles.

Abu-Farsakh et al. [18] used nonlinear finite-element models to investigate CFRP plate configurations. Such studies are useful for screening a large design space, but simulated FRP retrofit is highly sensitive to interface representation. Perfect tie constraints can suppress the debonding failure that may control actual tests.

5.9 FRP Ropes, NSM Systems, and Practical Detailing

Recent studies increasingly use CFRP ropes because they can be placed around complicated joint geometries and anchored into grooves or drilled regions. Golias et al. [45], Golias and Karayannis [22], Kalogeropoulos et al. [23], and Golias et al. [24] collectively demonstrate growing interest in rope-based and near-surface-mounted systems for deficient joints.

The significance for SMA+FRP hybridization is substantial. A future hybrid retrofit does not necessarily require full CFRP sheet wrapping. SMA wires could provide active confinement around the joint core, while CFRP ropes or anchors provide localized passive shear transfer and anchorage around obstructed joint faces.

5.10 BFRP and Sustainable Composite Strengthening

Magagnini and Bettucci [25] investigated the influence of BFRP strengthening layout on previously damaged RC joints. The study confirms that layout is a first-order design parameter. The amount of composite material alone is insufficient to predict performance because fibers must intersect critical cracks and develop adequate anchorage.

BFRP also broadens the sustainability discussion. Advanced seismic strengthening should not be evaluated solely using structural performance. Material energy, resin system, transport, repairability, replacement frequency, and end-of-life management should ultimately be incorporated into life-cycle assessment.

5.11 Emerging Multi-Material Smart Joints

Alqarni et al. [26] investigated exterior joint configurations involving conventional reinforcement, SMA, PVA fibers, and a hybrid SMA/steel arrangement under reversed cyclic loading. Their findings illustrate a central design trade-off: SMA contributes to deformation recovery and reduced deterioration, while conventional steel or fiber-reinforced concrete can improve energy-dissipation behaviour. The study therefore supports a performance-based hybrid philosophy rather than a universal recommendation for all-SMA reinforcement.

This study does not contain FRP and should not be misreported as SMA+FRP evidence. Its relevance is mechanistic: a restoring material can be paired with a dissipative or damage-controlling material to offset the limitations of a pure self-centering response.

5.12 Hybrid GFRP/Steel and GFRP Joint Research as Supporting Evidence

Selim et al. examined beam-column joints using hybrid GFRP and steel reinforcement in fly-ash-based concrete [46]. Safdar et al. conducted finite-element analysis of GFRP-RC exterior joints with diagonal reinforcement [47], and El-Naqeeb et al. reviewed GFRP-RC beam-column connections [48]. These studies provide useful information about bond, low modulus, brittle FRP rupture, joint deformation, and reinforcement configuration.

Miralami et al. investigated column-foundation connections using GFRP/SMA reinforcement and CFRP wrapping [49]. Although the connection type differs from a beam-column joint, it is one of the closer structural examples of integrating SMA, GFRP, and CFRP within a reinforced-concrete connection.

6. LITERATURE REVIEW SUMMARY TABLE

Ref.	Author & Year	Research Method	Model / Material	Parameters Studied	Major Contribution / Findings	Principal Limitation
[4]	Youssef et al., 2008	Experimental	RC connection with SMA	SMA reinforcement; cyclic response	Established feasibility of SMA for recoverable RC connection behaviour.	Early-scale technology; limited design guidance.
[5]	Nehdi et al., 2010	Experimental	Hybrid SMA+FRP RC joint	Hybrid reinforcement; cyclic response	Landmark corrosion-free SMA+FRP joint concept.	Limited subsequent full-scale replication.
[6]	Billah & Alam, 2012	Numerical / parametric	Hybrid SMA-FRP concrete column	Material distribution; seismic response	Demonstrated broader structural viability of hybrid reinforcement.	Column rather than beam-column joint.
[31]	Oudah & El-Hacha, 2017	Experimental / analytical	SMA RC connection	SMA anchorage; joint response	Showed importance of SMA anchorage.	Specialized connection details.
[32]	Oudah & El-Hacha, 2018	Experimental	Self-centering SMA RC connection	Plastic hinge; anchorage	Developed self-centering joint and identified anchorage failure issue.	SMA anchorage remained critical.
[33]	Azariani et al., 2018	Experimental	Exterior SMA RC joint	SMA bar arrangement	Evaluated SMA bars under cyclic joint loading.	Limited joint configurations.

[36]	Yurdakul et al., 2018	Experimental	Deficient joint + external SMA bars	Post-tensioning; retrofit	Demonstrated SMA-based retrofit concept.	External hardware / constructability.
[34]	Halahla et al., 2019	FE analysis	SMA exterior joint	SMA reinforcement; ductility	Applied damage-plasticity modelling to SMA joint.	Requires experimental calibration.
[35]	Nahar et al., 2019	Numerical	SMA RC beam-column joint	SMA location / configuration	Compared superelastic reinforcement configurations.	Predominantly computational.
[44]	Wang et al., 2019	Experimental	CFRP-strengthened exterior joint	Bonded CFRP	Demonstrated seismic retrofit using bonded CFRP.	Debonding and anchorage concerns.
[49]	Miralami et al., 2019	Experimental	GFRP/SMA bars + CFRP wrap	Hybrid reinforcement / confinement	Demonstrated multi-material connection concept.	Column-foundation rather than BCJ.
[37]	Suhail et al., 2020	Experimental	SMA + FRP confinement	Active/passive confinement	Showed complementary SMA and FRP confinement mechanisms.	Conducted on columns.
[38]	Elbahy et al., 2021	Numerical	External SMA retrofit	SMA bars; retrofit geometry	Demonstrated external SMA retrofit potential.	Connection / bond idealizations.
[39]	Qian et al., 2022	Experimental	SMA + ECC joint	Self-centering; ECC	Combined recoverable reinforcement and damage-tolerant matrix.	Specialized material system.
[40]	Chen et al., 2022	Experimental / numerical	Precast SMA-fiber / ECC joint	Prefabrication; SMA/ECC	Extended smart-material concept to precast joint.	Limited long-term data.
[8]	Suhail et al., 2023	Experimental	SMA wire active confinement	Activation / confinement	Improved deficient exterior-joint response through active confinement.	Activation and installation requirements.

[9]	Qian et al., 2023	Experimental	Prefabricated SMA-ECC joint	Re-centering; energy dissipation	Balanced self-centering with ECC-based damage control.	Limited generalization to ordinary cast-in-place joints.
[10]	Higazey et al., 2023	Numerical	Exterior SMA joint	SMA reinforcement parameters	Expanded FE evaluation of SMA joint performance.	Model-dependent results.
[13]	Yurdakul et al., 2023	Probabilistic	FRP-strengthened RC joints	Damage states; fragility	Introduced fragility-based assessment of strengthened joints.	Dependent on underlying experimental database.
[14]	Saad et al., 2023	Numerical / analytical	CFRP-strengthened joint	Shear strength; CFRP	Developed numerical / analytical understanding of joint shear retrofit.	Interface assumptions influence prediction.
[15]	Farhang et al., 2023	Experimental + FE	3D CFRP exterior joint	CFRP arrangement	Addressed realistic three-dimensional joint behaviour.	Limited specimen population.
[11]	Del Vecchio et al., 2024	Experimental	FRP exterior-joint retrofit	Minimally invasive layout	Advanced practical strengthening around geometrical constraints.	Application-specific details.
[12]	del Rey Castillo et al., 2024	Experimental	FRP sheets + anchors	Shear failure; anchorage	Demonstrated importance of positive FRP anchorage.	Workmanship sensitivity.
[16]	Barmi et al., 2024	Experimental / numerical	CFRP + HPFRCC	Repair strategy	Combined matrix repair and composite strengthening.	Multi-stage rehabilitation complexity.
[17]	Fan et al., 2024	Experimental	CFRP + steel plate	Eccentric joint; hybrid retrofit	Demonstrated complementary strengthening mechanisms.	Steel component remains corrosion-sensitive.
[18]	Abu-Farsakh et al., 2024	FE analysis	CFRP plate layouts	Plate configuration	Compared nonlinear retrofit configurations.	Interface laws require validation.
[19]	Mostofinejad et al., 2024	Experimental / analytical	UHP-HFRC + FRP	3D rehabilitation	Integrated concrete repair and FRP wrapping.	Material and construction complexity.

[24]	Golias et al., 2024	Experimental + 3D FE	FRP ropes	Rope strengthening	Validated 3D simulation against real-scale testing.	Specific strengthening geometry.
[20]	Karabini et al., 2025	Experimental	Minimally invasive FRP	Plain bars; FRP layout	Addresses vulnerable older joints and realistic constraints.	Limited seismic typologies.
[21]	Sayed Ahmed et al., 2025	Numerical	CFRP and other retrofits	Alternative strengthening	Comparative assessment of retrofit strategies.	Mainly model-based.
[22]	Golias & Karayannis, 2025	Experimental	CFRP rope / sheet	Shear response	Clarified influence of rope and sheet strengthening.	Strongly detailing-dependent.
[23]	Kalogeropoulos et al., 2025	Experimental	NSM CFRP ropes	Joint shear rehabilitation	Developed near-surface-mounted rope solution.	Groove / anchorage workmanship.
[25]	Magagnini & Bettucci, 2026	Experimental	BFRP-strengthened damaged joint	BFRP layout	Shows layout strongly influences recovered performance.	Limited layouts / specimens.
[26]	Alqarni et al., 2026	Experimental + ABAQUS	SMA, steel, PVA, hybrid	Strength; energy; stiffness; cracks	Demonstrates trade-off between recentering and dissipation.	Not a true SMA+FRP system.
[27]	Eswar & Chourasia, 2026	Numerical	Localized Fe-SMA + headed bars	SMA length; connection detail	Advances economical SMA placement and anchorage modelling.	Requires broader experimental validation.
[29]	Kamal & Abd El Ghany, 2026	Machine learning	Exterior RC joint database	Multiple joint parameters	Explainable ML for shear-capacity prediction.	Advanced-material hybrid data remain sparse.
[30]	Shah et al., 2026	Machine learning	Experimental joint database	Geometry / material / reinforcement	Demonstrates data-driven prediction potential.	Generalization beyond database uncertain.

7. CHRONOLOGICAL DEVELOPMENT OF RESEARCH

7.1 Before 2010: Mechanics, Seismic Detailing, and Material Feasibility

The first stage focused on understanding joint shear, bond, anchorage, and ductile detailing. Analytical models such as the strut-and-tie formulation of Hwang and Lee [3] helped rationalize force transfer in exterior joints. During the 2000s, SMA began moving from smart-material research into civil structural applications. Alam et al. examined superelastic SMA reinforcement in concrete structures [50], while Youssef et al. [4] demonstrated SMA use in RC connections.

7.2 2010-2015: Emergence of Hybrid Advanced Reinforcement

Nehdi et al. [5] produced the landmark hybrid SMA+FRP RC beam-column joint in 2010. The objective was not simply higher strength; the concept addressed corrosion resistance, recoverability, and energy dissipation simultaneously. Billah and Alam [6] extended hybrid concepts to columns, while FRP retrofit research expanded and highlighted bond and anchorage limitations [41]-[43].

7.3 2016-2020: Self-Centering, Anchorage, and Advanced Numerical Modelling

The period from 2016 to 2020 moved toward structural detailing. Kabir et al. [7] critically reviewed hybrid joints. Oudah and El-Hacha [31], [32] investigated SMA joint anchorage and self-centering. Azariani et al. [33], Halahla et al. [34], and Nahar et al. [35] expanded experimental and numerical knowledge. Suhail et al. [37] demonstrated combined active SMA and passive FRP confinement, providing an important conceptual bridge between the two technologies.

7.4 2021-2022: Damage Control and External Smart-Material Retrofit

Elbahy et al. [38] explored external SMA retrofit, while Qian et al. [39] and Chen et al. [40] combined SMA with ECC or high-deformation-capacity matrices. The research objective was increasingly framed in terms of damage reduction and recentering rather than simply nominal strength. State-of-the-art SMA reviews consolidated knowledge of material behaviour and structural applications [51]-[53].

7.5 2023-2026: Resilience, Practical Anchorage, Hybrid Rehabilitation, and Data-Driven Methods

The most recent period is characterized by active SMA confinement of deficient joints [8]; prefabricated SMA-ECC joints [9]; numerical SMA joint optimization [10]; FRP fragility assessment [13]; realistic FRP anchors [12]; minimally invasive strengthening [11], [20]; hybrid FRP-cementitious rehabilitation [16], [19]; ropes and NSM strengthening [22]-[24]; BFRP layout optimization [25]; localized Fe-SMA and headed connections [27]; multi-material SMA/steel/fiber joints [26]; and explainable machine learning [29], [30]. The technological trend therefore moves from material substitution toward multi-mechanism resilience design. Figure 3. Development Timeline of Advanced RC Beam-Column-Joint Technology, 2008-2026. The timeline should identify the transition from early SMA feasibility, to 2010 SMA+FRP hybridization, to anchorage/self-centering development, and finally to active confinement, minimally invasive FRP, Fe-SMA detailing, and data-driven models.

8. COMPARATIVE ANALYSIS

8.1 Material-Level Comparison

Criterion	Conventional Steel	SMA	FRP	SMA+FRP Hybrid
Primary cyclic mechanism	Plastic yielding	Reversible phase transformation	Elastic fiber action up to rupture	Transformation + elastic composite action
Energy dissipation	Generally high with stable yielding	Moderate; hysteresis-width dependent	Low intrinsically; system benefit through damage control	Potentially tunable
Self-centering	Low after extensive yielding	High potential	Elastic recovery alone is insufficient after concrete damage	High potential
Residual drift	Can be significant	Generally reduced	Depends on concrete and other reinforcement	Potentially low
Corrosion resistance	Limited without protection	High for many SMA systems	Excellent	High
Failure concerns	Buckling, fatigue, fracture, corrosion	Anchorage, functional fatigue, fracture,	Debonding, rupture, anchorage, brittle failure	Multiple interfaces and compatibility

		temperature sensitivity		
Design-code maturity	High	Low	Moderate for established FRP applications	Very low
Material cost	Low	High, especially NiTi	Moderate to high	High initial cost
Construction familiarity	Very high	Low	Increasing	Low
Best present role	Standard ductile construction	Re-centering/local smart zones	Strengthening/confinement/corrosion resistance	Resilience-oriented advanced joints

The qualitative terms in Table 2 should not be converted into design factors. Material response is controlled by grade, geometry, reinforcement ratio, loading history, and connection details.

8.2 Experimental Versus Numerical Approaches

Approach	**Major Advantages**	**Major Limitations**	**Cost**	**Complexity**	**Best Use**
Full-scale cyclic testing	Direct failure mechanism; realistic cracking/bond	Expensive; limited specimen number	Very high	High	Final validation
Reduced-scale cyclic testing	More economical parameter studies	Scale effects; anchorage distortion	High	Moderate-high	Comparative screening
Detailed nonlinear FE	Rich stress/damage information	Constitutive and bond uncertainty	Moderate	Very high	Parametric investigation
Fiber/frame modelling	Efficient system analysis	Joint local behaviour simplified	Low-moderate	Moderate	Frame-level response
Analytical strut-and-tie	Transparent mechanics	Limited cyclic degradation representation	Low	Moderate	Preliminary design
Fragility analysis	Links component response to risk	Requires reliable probabilistic data	Moderate	High	PBEE

Machine learning	Captures nonlinear data patterns rapidly	Extrapolation and interpretability risks	Moderate	High	Surrogate prediction / data mining

8.3 Conventional Versus Hybrid Design Philosophy

A conventional joint generally concentrates energy dissipation in yielding steel. An SMA-dominant joint instead attempts to minimize residual deformation. A pure FRP system emphasizes corrosion resistance and elastic strength but lacks steel-like yielding. A hybrid system should therefore be designed around a target hysteresis, not an arbitrary material percentage. A desirable hybrid joint may retain sufficient dissipative capacity while using SMA to provide restoring force and FRP to protect the joint core or provide corrosion-resistant reinforcement. The ideal proportions cannot presently be specified universally because direct experimental parameter studies remain insufficient.

9. IMPORTANT PARAMETERS AFFECTING SEISMIC PERFORMANCE

9.1 Joint Shear Demand

The ratio of joint shear demand to joint capacity governs diagonal cracking and potential brittle failure. Increasing beam flexural capacity without increasing joint resistance can unintentionally shift failure into the joint core. Advanced strengthening must therefore be designed at the system level.

9.2 Column Axial Load

Column axial compression can initially improve concrete strut action and joint confinement, but excessive axial load may reduce deformation capacity and accelerate compression damage. Most laboratory tests use a constant axial load, whereas earthquake-induced overturning can produce variable axial force.

9.3 Beam-to-Column Flexural Strength Ratio

A strong-column-weak-beam hierarchy is essential to avoid undesirable story mechanisms. If SMA or FRP substantially increases beam capacity, the column/joint hierarchy must be rechecked rather than assuming that strengthening is automatically beneficial.

9.4 Joint Transverse Reinforcement

Joint hoops contribute confinement, truss action, restraint of diagonal cracking, and bar stability. Advanced external strengthening cannot always compensate for fundamentally inadequate internal anchorage.

9.5 Concrete Compressive and Tensile Behaviour

Concrete strength affects diagonal-strut capacity, but cyclic joint response also depends on tensile cracking, fracture energy, confinement, and damage accumulation. Using only compressive strength to characterize concrete can therefore be inadequate in numerical comparisons.

9.6 SMA Type

NiTi offers strong superelastic capability but higher cost. Fe-SMA may provide economic advantages but can require different activation and constitutive considerations. Transformation temperatures must remain compatible with the expected service environment.

9.7 SMA Length and Location

Using SMA only where inelastic rotation is expected can reduce cost [27]. However, reducing SMA length creates transitions requiring mechanical couplers, lap zones, or headed anchorage. Stress concentration can shift the failure mode away from the intended plastic hinge.

9.8 SMA Reinforcement Ratio

Too little SMA may provide inadequate restoring force, whereas excessive SMA may increase joint demand and reduce economic feasibility. Because superelastic stress-strain behaviour differs from yielding steel, direct substitution based only on equal bar area is mechanically questionable.

9.9 SMA Prestrain and Activation

For active SMA retrofit systems, initial strain and activation temperature determine the confining or restoring action [8], [37]. Installation tolerances and thermal management therefore become structural-design variables.

9.10 FRP Type and Modulus

CFRP, GFRP, and BFRP should not be assumed to be equivalent. Elastic modulus affects crack control and deformation, while ultimate strain and environmental durability influence failure.

9.11 FRP Fiber Orientation

FRP is highly anisotropic. Fibers must be aligned with principal tensile demands or arranged in multiple directions. Incorrect orientation may add material without developing useful joint-shear resistance.

9.12 Number of FRP Layers

Increasing thickness can increase theoretical tensile capacity but may produce diminishing structural benefit if debonding, concrete-cover separation, or inadequate anchorage governs.

9.13 FRP Anchorage

Recent studies repeatedly demonstrate the importance of anchorage [11], [12], [20], [22]-[24]. Anchors, ropes, grooves, and mechanical termination can permit greater utilization of fiber capacity than unanchored surface sheets.

9.14 Existing Damage

Retrofit effectiveness depends strongly on substrate condition. Strengthening an intact joint differs from rehabilitating a previously cracked or shear-damaged joint [16], [19], [25]. Crack injection, concrete replacement, surface preparation, or a repair matrix may be required before composite strengthening.

9.15 Loading Protocol

Peak drift, number of repeated cycles, loading rate, sequence, and axial load influence cumulative damage. Hybrid systems containing SMA are especially sensitive to cyclic history because phase transformation and functional fatigue can evolve with repeated cycling.

9.16 Temperature

SMA stress-strain behaviour is thermo-mechanically coupled, while FRP resin properties are also temperature dependent. This creates a uniquely important interaction for SMA+FRP systems that has received limited joint-level investigation.

9.17 Scale and Three-Dimensional Effects

Slabs, transverse beams, confinement, reinforcement congestion, and bidirectional loading can alter behaviour substantially. Results from a planar one-third-scale exterior joint cannot automatically be transferred to a full-scale three-dimensional building joint.

10. EXPERIMENTAL RESEARCH

10.1 Typical Specimen Configuration

Most joint experiments use beam-column subassemblies extracted approximately between points of contraflexure. Columns are commonly subjected to constant axial compression, while a servo-hydraulic actuator imposes reversed cyclic displacement through the beam or column. Exterior joints are especially common because they are easier to construct and load. Interior joints require two beams and often additional actuators or restraints; three-dimensional joints require transverse members and are substantially more expensive.

10.2 Instrumentation

- actuator load and displacement
- column axial force
- beam and column longitudinal-bar strains
- joint transverse-reinforcement strains
- SMA strain and, ideally, temperature
- FRP strain
- anchor/coupler strain or slip
- diagonal joint deformation
- beam rotation
- joint-panel shear deformation
- crack width
- residual displacement
- concrete surface strain using digital image correlation where possible
- post-test documentation of rupture, debonding, pullout, and internal damage

Merely reporting the global load-displacement envelope is insufficient to establish how a hybrid system works.

10.3 Loading Protocol

Quasi-static reversed-cyclic displacement control remains the standard experimental approach. It permits systematic measurement of stiffness degradation, pinching, energy dissipation, residual drift, and failure mode. However, slowly applied cyclic loading does not reproduce strain-rate effects, high-cycle vibration, temperature changes in SMA, or complex earthquake sequences. Hybrid-joint development should therefore eventually progress from quasi-static qualification to dynamic or hybrid simulation.

10.4 Failure Modes

- beam flexural yielding
- beam-bar fracture
- joint diagonal shear cracking
- joint concrete crushing
- column hinging
- anchorage pullout
- bond slip
- SMA rupture or anchorage failure
- FRP rupture
- adhesive debonding
- concrete-cover separation
- FRP-anchor pullout
- failure at SMA-steel/FRP transition zones

A successful hybrid joint should ideally transfer the critical failure away from the brittle joint core toward a repairable and predictable deformation mechanism.

10.5 Key Experimental Evidence

Suhail et al. [8] provide important evidence for active SMA confinement of deficient joints. Del Vecchio et al. [11] and del Rey Castillo et al. [12] provide contemporary evidence for practical FRP rehabilitation. Qian et al. [9] demonstrate modern SMA/ECC self-centering behaviour, while Alqarni et al. [26] illustrate the balance between self-centering and dissipation in multi-material smart joints. The unresolved need is a matched experimental program that compares a code-compliant steel control, SMA-only, FRP-only, and true SMA+FRP hybrid joints under identical geometry, reinforcement hierarchy, axial load, concrete batch, and cyclic loading protocol.

11. NUMERICAL AND COMPUTATIONAL RESEARCH

11.1 Finite-Element Approaches

ABAQUS is frequently used because it supports three-dimensional continuum modelling, nonlinear contacts, concrete-damage-plasticity formulations, and user-defined or specialized SMA behaviour. Other general FE platforms may provide equivalent capabilities. Concrete is usually represented by solid elements, while reinforcement can be modelled by embedded truss or beam elements or explicit solid bars. FRP sheets may be represented using shell, membrane, or continuum elements, and adhesive layers can be modelled explicitly or through cohesive interfaces.

11.2 Concrete Constitutive Modelling

The concrete-damage-plasticity family of models is widely applied to RC joint simulations. Lubliner et al. established an influential plastic-damage formulation for concrete [54]. Successful cyclic simulation requires calibration of compressive stress-strain behaviour, tensile cracking, fracture energy, dilation angle, stiffness recovery, compression and tension damage, confinement, and mesh regularization. A model calibrated only to monotonic tests may reproduce peak strength while failing to represent cyclic pinching and stiffness deterioration.

11.3 Reinforcement-Concrete Bond

Many FE studies use embedded-region or perfect-bond constraints. This assumption is computationally convenient but potentially problematic because cyclic bond deterioration is a major cause of pinched hysteresis and bar slip. For SMA reinforcement, perfect bond can exaggerate self-centering by forcing recovered bar strain to recover surrounding joint deformation without anchorage slip. Explicit bond-slip or connector formulations are therefore desirable.

11.4 SMA Constitutive Models

SMA modelling must represent reversible transformation rather than conventional plastic yielding. Foundational constitutive approaches by Auricchio and Taylor [55] and Auricchio and Lubliner [56] provide frameworks for numerical simulation. Parameters should be obtained from cyclic coupon tests of the actual SMA batch whenever possible; generic NiTi properties can introduce large uncertainty because transformation stress, plateau width, recoverable strain, and temperature dependence vary among alloys and thermomechanical treatments.

11.5 FRP-Concrete Interface

For externally bonded FRP, the interface is frequently the governing numerical uncertainty. Three strategies are common: perfect tie, cohesive traction-separation laws, and contact/interface elements with damage evolution. Perfect tie is suitable only when debonding is demonstrably prevented by mechanical anchorage or when the objective does not include interface failure; otherwise it may produce unconservative strength and ductility.

11.6 Mesh Strategy

Mesh refinement should be concentrated in the joint core, beam plastic-hinge region, SMA couplers or headed-bar zones, FRP anchor locations, adhesive interfaces, and regions of high concrete damage. A mesh-sensitivity study should demonstrate that peak strength, energy, crack localization, and joint strain are not artifacts of element size.

11.7 Validation Requirements

A credible SMA+FRP FE model should be validated simultaneously against initial stiffness, positive and negative peak load, unloading stiffness, hysteresis pinching, residual displacement, cumulative energy, joint shear deformation, reinforcement strain, crack and failure location, and FRP/SMA anchorage behaviour. Agreement only with the backbone curve is insufficient.

11.8 Emerging Machine Learning

Kamal and Abd El Ghany [29] and Shah et al. [30] investigated interpretable machine learning for RC joint shear. These studies are significant for future hybrid design, but direct application to SMA+FRP joints is restricted by data availability. A machine-learning model cannot reliably learn SMA transformation, FRP debonding, or hybrid anchorage if these behaviours are absent from the training database. Physics-informed hybrid modelling, in which mechanistic constraints are combined with data-driven corrections, is therefore a preferable future strategy.

12. ANALYTICAL RESEARCH

12.1 Joint-Shear Models

Analytical joint-shear models commonly resolve the joint into diagonal compression-strut and truss mechanisms [3]. Such models are physically meaningful for ordinary RC but require modification for hybrid reinforcement because FRP transverse reinforcement does not yield like steel, external FRP may act outside the original joint core, SMA longitudinal reinforcement develops transformation plateaus rather than conventional yield, external SMA prestressing changes the initial stress state, and hybrid anchorage introduces concentrated forces.

12.2 FRP Contribution

$$Tf = AfEf\varepsilon fe \tag{10}$$

where: Tf = effective FRP tensile force, N; Af = effective FRP area crossing the critical crack, mm²; Ef = FRP elastic modulus, MPa; εfe = effective FRP strain limited by bond, anchorage, and material rupture, dimensionless.

The important term is effective strain, not coupon ultimate strain. Design guidance such as ACI 440 emphasizes limitations related to debonding and effective strain [58].

12.3 SMA Restoring Mechanism

$$MSMA = \Sigma Fizi \tag{11}$$

where: MSMA = restoring moment provided by SMA reinforcement, N·mm; Fi = constitutive force in SMA bar i, N; zi = lever arm of the bar about the section reference axis, mm.

The value of SMA bar force must be obtained from a validated superelastic constitutive model rather than a steel-yield approximation because loading and unloading stresses differ at the same strain.

12.4 Absence of a Unified Hybrid Design Equation

No widely adopted analytical equation presently integrates concrete joint shear, steel yielding, SMA transformation and recentering, FRP shear or confinement contribution, cyclic bond deterioration, SMA anchorage, FRP debonding, residual drift, and cumulative deterioration. Development and calibration of such a framework is one of the most important needs for future code implementation.

13. RECENT TECHNOLOGICAL DEVELOPMENTS AND RESEARCH TRENDS

13.1 Localized Fe-SMA

The 2026 study by Eswar and Chourasia [27] reflects increasing attention to Fe-SMA and localized smart reinforcement. This is important economically because complete replacement of steel with NiTi can be prohibitively expensive.

13.2 Active Confinement

Thermally activated SMA wires provide a fundamentally different rehabilitation mechanism from passive jackets [8]. Their ability to introduce active confining stress before severe joint dilation could be combined with FRP to develop staged confinement.

13.3 Minimally Invasive FRP

Recent strengthening research increasingly addresses construction constraints rather than idealized full wrapping [11], [20]. This trend is essential for practical seismic rehabilitation.

13.4 FRP Anchors and Ropes

Anchors, ropes, grooves, and near-surface-mounted solutions improve force transfer and accessibility [12], [22]-[24]. These technologies could provide the passive composite component of an SMA+FRP retrofit.

13.5 Damage-Tolerant Cementitious Matrices

ECC, HPFRCC, and UHP-HFRC are increasingly combined with advanced reinforcement [9], [16], [19], [39], [40]. The rationale is that a self-centering bar alone cannot make crushed concrete self-repairing.

13.6 Basalt-FRP

BFRP is emerging as an alternative composite for strengthening damaged joints [25]. Its relevance extends to sustainability and diversification of composite-material supply.

13.7 Explainable Artificial Intelligence

Explainable ML models for joint shear [29], [30] are methodologically important because structural engineering adoption requires both prediction and interpretation. Direct application to hybrid SMA+FRP joints must await larger experimentally validated databases.

13.8 Digital Twins and Real-Time Monitoring

Digital twins, IoT, and real-time structural monitoring are promising future technologies but cannot yet be described as mature SMA+FRP beam-column-joint practices based on the verified corpus. Future hybrid joints could incorporate strain and temperature sensing to monitor SMA transformation and FRP interface behaviour, but this remains primarily a research opportunity.

14. BIBLIOMETRIC AND TREND INTERPRETATION

A quantitative bibliometric analysis has deliberately not been fabricated. Publication counts by year, country, institution, journal, co-authorship network, and keyword occurrence require an auditable Scopus or Web of Science export. A future bibliometric extension should export complete records and analyze them using VOSviewer or the Bibliometrix/Biblioshiny ecosystem. Nevertheless, qualitative thematic evolution is clear from the reviewed corpus: early research focused on material feasibility and strength; the next phase emphasized self-centering and anchorage; FRP research shifted from simple sheets toward anchored and minimally invasive configurations; current SMA research increasingly considers localized material use, Fe-SMA, active confinement, and resilience; current hybrid-material research combines complementary mechanisms; probabilistic fragility and explainable machine learning are emerging assessment tools; and direct SMA+FRP beam-column-joint experimentation has not expanded at the same rate as the separate SMA and FRP literature.

Recommended Graph 1. Annual Publication Trend. The graph should only be produced after exporting Scopus/WoS records. The horizontal axis should represent year and the vertical axis verified publication count, with separate series for SMA joints, FRP joints, and SMA+FRP hybrid joints.

Recommended Graph 2. Research-Theme Evolution. A Sankey or alluvial diagram could map papers from material category to methodology and performance objective. This graph can be generated from manually coded bibliographic records without inventing structural response values.

15. CRITICAL DISCUSSION

15.1 Areas of Agreement

Across the literature, there is broad agreement that ordinary non-seismic joints with poor transverse reinforcement or anchorage are vulnerable to brittle joint shear damage. Strengthening techniques are most successful when they alter the failure hierarchy toward ductile beam behaviour. There is also strong agreement that SMA is valuable primarily because of recoverability and residual-deformation reduction, while FRP is attractive because of high tensile strength, low mass, and corrosion resistance. Both material systems are connection-sensitive: SMA performance can be lost if anchorage fails before transformation develops [31], [32], whereas FRP tensile capacity cannot be exploited if debonding or anchor failure occurs first [11], [12].

15.2 Energy Dissipation Versus Self-Centering

The principal conceptual tension is the relationship between energy dissipation and recentering. Conventional steel dissipates energy by permanent plastic deformation, whereas SMA seeks to reverse a large portion of deformation. Consequently, an SMA-only joint may exhibit narrower hysteresis than a steel-dominated joint. This is not necessarily a deficiency because seismic resilience depends on both peak response and permanent deformation. However, a system with insufficient damping may experience greater transient displacement. Hybridization should therefore optimize restoring force and dissipation rather than maximize one parameter.

15.3 FRP Strength Does Not Guarantee Joint Ductility

FRP is frequently described as high strength, but high coupon tensile strength is not equivalent to high joint ductility. FRP has essentially elastic-brittle tensile behaviour, and externally bonded systems are frequently controlled by the substrate or interface. The most convincing recent FRP studies therefore emphasize anchorage, layout, and crack interception rather than simple material strength [11], [12], [20], [22]-[25].

15.4 Experimental Heterogeneity

Direct comparison of published improvement percentages can be misleading because studies use different scales, joint geometries, concrete strengths, reinforcement ratios, axial load ratios, loading protocols, drift increments, failure criteria, FRP systems, SMA grades, strengthening objectives, and control specimens. For this reason, the review does not create a synthetic graph mixing percentage improvements from incompatible experiments.

15.5 Validation Deficiencies in Numerical Work

Numerical studies often reproduce global lateral-load envelopes reasonably well while underrepresenting local bond slip, cyclic pinching, interface debonding, and reinforcement anchorage. For hybrid SMA+FRP joints this issue becomes more severe because a single model must represent concrete cracking, SMA transformation, FRP anisotropy, adhesive damage, and multiple bond interfaces.

15.6 Scale Effects

Many smart-joint studies use reduced-scale specimens to control cost. Scaling bar diameter, concrete aggregate, bond length, couplers, mechanical heads, and FRP anchors does not necessarily preserve all relevant mechanics. Full-scale testing is therefore essential before recommending construction details.

15.7 Lack of System-Level Validation

Most research remains at component level. A joint that performs well in isolation may behave differently in a multi-story frame because of P-Δ effects, higher-mode response, varying axial force, redistribution, slab participation, and cumulative earthquake sequence.

15.8 Economic Limitations

NiTi remains substantially more specialized than conventional reinforcing steel. The economic rationale for hybrid systems is therefore likely to depend on localized SMA deployment rather than full replacement. Fe-SMA provides another promising path, but joint-specific cyclic evidence remains limited. FRP also involves costs beyond material quantity, including surface preparation, resin, anchorage, skilled installation, inspection, fire protection, and access.

15.9 Sustainability Concerns

Claims that an advanced system is sustainable cannot be based solely on corrosion resistance. A complete assessment must include embodied energy, resin production, SMA manufacturing, replacement frequency, earthquake repair, service life, downtime, and end-of-life treatment. Reduction of post-earthquake demolition caused by lower residual drift may provide a major life-cycle benefit of SMA, but this requires quantitative life-cycle assessment rather than assumption.

16. RESEARCH GAPS

Gap 1 – Scarcity of Modern Direct SMA+FRP Beam-Column-Joint Experiments

Early studies demonstrated the feasibility of hybrid SMA+FRP reinforcement [5], but recent research has largely developed SMA and FRP separately. There is insufficient modern experimental evidence comparing conventional steel, SMA-only, FRP-only, and true SMA+FRP joints under an identical test matrix. Future studies should use common geometry, material batches, loading protocols, and performance metrics.

Gap 2 – Lack of Full-Scale Three-Dimensional Joint Validation

Recent work includes realistic FRP joints, but advanced SMA research remains dominated by planar subassemblies. Slabs and transverse beams can modify confinement, reinforcement stress, and accessible retrofit surfaces. Full-scale 3D corner, exterior, and interior joints are required.

Gap 3 – Limited Bidirectional Loading Research

Most tests impose uniaxial reversed cyclic displacement. Real earthquakes can produce biaxial joint shear and changing principal stress direction. Hybrid reinforcement layouts should therefore be tested under two horizontal loading components.

Gap 4 – Constant Rather Than Variable Column Axial Force

Many experiments maintain a constant axial load. In actual frames, overturning causes varying column axial force that interacts with joint shear and flexural response. Future testing should synchronize variable axial force with lateral loading.

Gap 5 – No Established Optimum SMA-to-FRP Distribution

Research demonstrates benefits of localized SMA and optimized FRP layouts individually, but there is no experimentally calibrated method for selecting optimum SMA length, FRP reinforcement ratio, fiber orientation, and transition location in a hybrid joint.

Gap 6 – Hybrid Anchorage and Transition-Zone Mechanics

SMA requires specialized anchorage, while FRP requires reliable development without brittle splitting or debonding. The interaction among SMA heads or couplers, FRP bars or sheets, concrete bearing, and cyclic bond remains insufficiently studied.

Gap 7 – Thermo-Mechanical Compatibility

SMA transformation behaviour is temperature sensitive, while FRP resin stiffness and bond also change with temperature. The combined effects of seasonal temperature, thermal activation, solar heating, fire exposure, and repeated activation have not been adequately established for hybrid joints.

Gap 8 – Functional and Low-Cycle Fatigue

SMA may lose transformation stability after repeated severe cycles, and FRP interfaces can accumulate fatigue damage. Earthquake-aftershock sequences therefore require dedicated cyclic protocols extending beyond single-event laboratory testing.

Gap 9 – Post-Earthquake Residual Capacity

A joint may recenter geometrically while retaining hidden concrete, bond, anchor, or FRP-interface damage. Residual strength and reparability after a design-level earthquake need to be quantified before self-centering can be equated with full structural recovery.

Gap 10 – Multi-Hazard Behaviour

Fire after earthquake, marine exposure, freeze-thaw action, humidity, elevated temperature, and long-term chemical exposure can influence SMA, FRP, adhesive, and concrete differently. Hybrid-joint durability should be investigated using sequential multi-hazard protocols.

Gap 11 – Frame-Level and Collapse-Level Validation

Component cyclic testing dominates the literature. Hybrid joints need to be incorporated into multi-story nonlinear models validated against component data to assess drift concentration, P-Δ instability, collapse margin, and residual frame deformation.

Gap 12 – Absence of Hybrid Fragility and Loss Functions

Fragility functions are becoming available for FRP-strengthened joints [13], but equivalent functions do not yet exist for well-characterized SMA+FRP joints. Probabilistic demand, damage, repair cost, downtime, and demolition probability should be evaluated.

Gap 13 – Lack of Code-Calibrated Analytical Procedures

ACI provides mature guidance for conventional RC and separate FRP applications, but no unified design procedure exists for SMA+FRP RC beam-column joints. Strength reduction factors, material limits, development requirements, and performance criteria need reliability-based calibration.

Gap 14 – Insufficient Life-Cycle Cost and Carbon Assessment

High SMA material cost may be offset by reduced repair and residual drift, but this hypothesis remains inadequately quantified. Future studies should combine initial construction cost, maintenance, earthquake loss, downtime, material carbon, and replacement probability.

Gap 15 – Absence of Open Standardized Hybrid-Joint Databases

Modern ML methods are being applied to ordinary RC joint shear [29], [30], but hybrid smart-joint datasets are too sparse and inconsistent. A standardized open database should store specimen geometry, raw hysteresis curves, material coupon data, temperature, anchor details, crack histories, residual deformation, and failure mode.

17. FUTURE RESEARCH DIRECTIONS

A coordinated future research program should proceed from material characterization to component validation and finally to system-level performance. Coupon testing should first establish cyclic NiTi or Fe-SMA behaviour across temperature and strain-rate ranges together with CFRP, GFRP, or BFRP tensile properties and bond parameters. Anchorage subassemblies should be tested before full joints. SMA headed bars, threaded or mechanical couplers, FRP anchors, transition zones, and combined local bearing require separate characterization. Matched joint experiments should then compare conventional steel control, SMA-enhanced joint, FRP-enhanced joint, and true SMA+FRP hybrid joint. Experiments should progress from planar exterior joints to full-scale 3D exterior, corner, and interior beam-column-slab assemblies. Validated FE models should be used for multi-parameter optimization rather than replacing experiments. Frame-level nonlinear response-history analysis should establish the relationship between component self-centering and building residual drift. Finally, probabilistic fragility, repair, loss, and life-cycle assessments should determine whether the increased initial material cost produces meaningful resilience benefits.

18. PRACTICAL AND ENGINEERING IMPLICATIONS

For structural designers, the literature indicates that SMA should be viewed as a targeted resilience material rather than a direct one-for-one substitute for conventional steel. Its strongest role is in regions where deformation recovery is valuable.

For retrofit engineers, the combination of active SMA confinement with anchored FRP sheets or ropes is particularly promising because the materials could be installed externally and assigned complementary structural functions.

For contractors, implementation will require procedures for mechanical SMA anchorage, activation temperature, FRP surface preparation, resin curing, anchor placement, inspection, and quality assurance.

For asset owners, potential benefits extend beyond life safety to reduced residual drift, lower demolition probability, improved corrosion resistance, and faster post-earthquake recovery. These benefits require explicit loss and life-cycle analysis before they can justify higher initial cost.

For manufacturers, standardized SMA bar sizes, headed connections, couplers, FRP anchorage systems, and traceable cyclic material certification would considerably improve practical adoption.

For code committees and policymakers, the principal requirement is not immediate prescriptive adoption but development of qualification protocols. Hybrid systems should first demonstrate stable cyclic response, predictable failure, durability, and reliability through standardized testing.

Current conventional and FRP design resources—including ACI 318 [1], ACI 440.11 [57], ACI 440.2 [58], ASTM D7957/D7957M [59], fib Bulletin 103 [60], and seismic component-testing guidance such as ACI 374.1 [61]—provide useful foundations, but none constitutes a complete design standard for SMA+FRP hybrid beam-column joints.

19. LIMITATIONS OF THE REVIEW

The primary focus was English-language literature, and relevant work in other languages may not have been captured.

Although a systematic search framework was used, a complete Scopus or Web of Science RIS/CSV export was not available. Consequently, formal PRISMA counts and quantitative bibliometric statistics are intentionally omitted.

Open-access full texts and verifiable publisher records were prioritized. Some technically relevant subscription papers could be evaluated only using bibliographic information and available abstracts.

Direct SMA+FRP hybrid beam-column-joint research remains limited. The review therefore uses closely related evidence from SMA-only joints, FRP-strengthened joints, SMA-ECC joints, SMA-steel joints, hybrid FRP rehabilitation, and SMA+FRP concrete components to identify mechanisms and future opportunities. These sources are not treated as direct hybrid-joint experiments.

Experimental results are heterogeneous with respect to geometry, scale, axial load, reinforcement ratio, concrete properties, cyclic loading protocols, and failure definitions. A pooled numerical meta-analysis would be misleading without prior normalization and detailed study-level data extraction.

The review cut-off is 16 August 2026. Papers scheduled for later 2026 publication should not be treated as part of the review corpus unless formally published online before that date.

20. CONCLUSIONS

1. RC beam-column-joint performance depends on joint shear transfer, bond, anchorage, confinement, reinforcement cyclic behaviour, and the intended beam-column failure hierarchy; advanced materials cannot compensate for fundamentally incorrect capacity design.

2. Conventional steel remains the most mature and economical reinforcement for ductile seismic construction because it combines reliable yielding, energy dissipation, established anchorage, construction familiarity, and comprehensive design standards.

3. The principal seismic advantage of superelastic SMA is its ability to develop restoring force and reduce permanent deformation through reversible phase transformation. Its benefit should therefore be assessed using residual drift and reparability as well as conventional peak strength.

4. SMA does not automatically provide greater energy dissipation than yielding steel. Narrow flag-shaped hysteresis can improve self-centering while reducing loop area, creating an important trade-off between transient response and permanent deformation.

5. FRP systems provide high tensile capacity, low mass, corrosion resistance, and significant opportunities for joint shear strengthening and confinement, but their structural effectiveness is strongly governed by anchorage, bond, fiber orientation, substrate condition, and prevention of brittle rupture or debonding.

6. Recent FRP research from 2023-2026 has progressed from simple externally bonded sheets toward FRP anchors, ropes, near-surface-mounted systems, minimally invasive layouts, BFRP systems, and hybrid repair matrices, increasing practical applicability.

7. Recent SMA research emphasizes active confinement, SMA-ECC combinations, localized smart reinforcement, Fe-SMA, improved anchorage, and resilience-oriented response rather than simple material substitution.

8. A genuine SMA+FRP RC beam-column-joint concept was demonstrated in earlier landmark research, but the recent literature does not contain a comparably mature body of direct 2023-2026 hybrid-joint experiments. This is the central research opportunity identified by the review.

9. Hybridization is technically rational because SMA and FRP perform different functions: SMA can provide re-centering and active restoring or confining action, while FRP can provide corrosion-resistant reinforcement, passive confinement, joint shear strengthening, and crack-control support.

10. The most promising future configuration is unlikely to involve complete replacement of conventional reinforcement with expensive SMA. Localized SMA in critical inelastic regions combined with strategically anchored FRP represents a more economical research direction.

11. Anchorage is one of the most important unresolved problems. Premature SMA connection failure, FRP debonding, and failure of hybrid transition zones can prevent the advanced materials from reaching their intended constitutive capacities.

12. Present numerical models require stronger validation of cyclic bond, SMA transformation, FRP interface damage, concrete cracking, and anchorage behaviour. Matching only the global load-displacement envelope is not sufficient for a predictive hybrid-joint model.

13. Full-scale three-dimensional testing under bidirectional loading, variable column axial force, slab participation, temperature variation, aftershock sequences, and multi-hazard exposure remains necessary before routine practical application.

14. Emerging explainable-machine-learning methods are promising for joint shear and parameter sensitivity, but reliable application to SMA+FRP systems requires standardized open experimental databases containing hybrid-material and interface data.

15. SMA+FRP hybrid beam-column joints should therefore be regarded as a promising but pre-standardization seismic-resilience technology. Progress toward engineering adoption requires coordinated experimental validation, mechanics-based modelling, fragility and loss assessment, life-cycle optimization, standardized qualification testing, and ultimately code-calibrated design rules.

Declaration:

- Ethics, Consent to Participate, and Consent to Publish declaration: Not applicable
- Funding: No funding was received for this research

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