

Seismic Response Evaluation of Bolted Precast Concrete Beam-Column Joints Using Finite Element Modeling: A Systematic Review

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ABSTRACT

Bolted precast beam-column connections allow quick assembly, reduced wet work, disassembly for replacement, and component-level replacement after earthquakes. The response is governed by interacting response mechanisms not found in monolithic connections: bolt loss, bearing and slip, end-plate bending, local compression, interface opening and closing, bond-slip, and cyclic stiffness degradation. A systematic review of the literature published between 2018-7/2026 identified 22 eligible studies grouped into direct-bolted dry connections, hybrid steel-concrete connections, emulative/high-performance material joints, and self-centering/replaceable systems. The review compares modeling approaches in terms of dimensional idealization, constitutive laws for contact/friction and bolts, loading scenarios, and calibration targets. When properly formulated, bolted and hybrid connections can often match or surpass the response of cast-in-place counterparts, but common challenges include pinching, interface and bolt-hole slip, stress concentrations, and tolerance control. Three-dimensional analysis with concrete-damage-plasticity, explicit contact, and realistic bolt representation reproduces the observed hysteresis best. Full-scale testing data is limited, with few publications reporting pretension/friction or validation under varying axial loads, while uncertainty quantification is generally underdeveloped. An evaluation framework and reporting guidelines are proposed.

Keywords: *bolted precast connection; beam-column joint; seismic performance; nonlinear finite element analysis; concrete damage plasticity; cyclic loading; demountable structures.*

1. INTRODUCTION

Precast concrete construction transfers production to a controlled factory environment while reducing formwork complexity, congestion, and duration, but the overall benefit is conditional upon the performance of beam-column connections, capable of resisting design gravity and seismic loads. The details should be selected or tailored considering the tolerances during installation, stability, force-transfer capability with redistribution potential, durability, and demands on deformation [1]. In particular, for moment-resisting frames, the cyclic response governs the stiffness degradation, plastic-hinge formation, energy dissipation capacity, residual drifts, and the tendency to develop a shear-flexure interaction failure; ACI 374.1 specifies a stable resistance during the mandated drift cycles, while ACI 352R recommends standard detailing and shear-transfer mechanisms [2], [3]. Bolted connections offer limited in-situ casting, inspection, and replacement, but these are associated with a more complex response, governed by the interaction of a number of semi-rigid mechanisms.

Research trends point to a shift from cast-in-place analogies toward dry connection designs, controlled dissipation, self-centering and replaceable systems, and the exploitation of damage-tolerant provisions [4]. Experimental investigations are costly and time-consuming, while finite element (FE) analysis is necessary and informative regarding bolt grade, plate thickness, axial ratio, concrete strength, and

friction properties. Feng, Wu, and Lu emphasize the importance of explicit bond-slip and interface modeling [5], whereas Ding, Ye, and Ma report on the behavior of full-scale connections with various bolt grades [6], Zhang and Ding study the effect of bolt properties on deformation and energy dissipation [7], and Liu et al. suggest repairable connections with replaceable bolts and beams [8], [9]. Wang, Feng, and Wu propose an all-dry PBSEC connection [10], whereas Li et al. identify end-plate bending and bolt deformation as the main dissipation mechanisms [11]. Xiao, Yu, and Liu report 31.7% ultimate resistance and 7.23% ductility improvement over a cast-in-place reference using the ABAQUS platform [12].

A focused review is necessary because general searches conflate wet (grouted), prestressed, welded, and bolted options, whereas FE decisions on dry connections are different. The purpose is to present the evidence on the response of bolted precast beam-column connections to seismic loading and assess modeling practices, with a focus on 2018-2026. Particular objectives include: (i) categorizing connection mechanisms;

(ii) comparing their response and failure modes; (iii) evaluating modeling strategies for concrete, steel, bolts, interfaces, and reinforcement; (iv) identifying key factors influencing strength, ductility, stiffness, dissipation, and residual drift; and (v) recognizing gaps and establishing reporting guidelines.

The scope is limited to experimental and numerical studies on precast reinforced-concrete beam-column subassemblages with mechanical steel connections; the timeframe reflects recent advances, but foundational works are included where relevant. The research questions are: which connection configurations perform best under cyclic loading; which modeling assumptions best reproduce the experimental behavior; which parameters require calibration; and what is the role of validation prior to parametric analyses. The review classifies information deriving from physical experiments, computer simulations validated experimentally, and analytical computations with idealizations for clarity, recognizing that the three approaches contribute differently to the confidence in certain aspects.

The distinction is particularly important because connection-

level parameters, often downplayed at the system level, critically

influence slip, deformation, residual rotations, or practical reparability. In particular, the history of research on precast seismic connections is a continuous process of shifting the locus and control of inelastic deformation.

Emulative approaches aim to replicate the stiffness and strength of cast-in-place connections, using grouted reinforcement or closures, but they often involve additional

wetting and congestion; hybrid systems utilize steel profiles, plates, couplers, or embedded shapes

to redirect yielding, whereas direct, all-dry mechanical connections use bolts, end-plates, haunches, and seats.

This transition from one family to another is not related to progress but to context-specific optimization,

as each category involves particular trade-offs among constructability, emulation, dissipation, residual drift,

inspectability, reparability, and cost; thus, the critical question in the design of a precast concrete building is not

whether the connection is wet or dry but where the potential for energy dissipation is located

and whether the brittle mechanisms are controlled. The contribution of this review is the consistency of terminology

and a decision-making flowchart for researchers and practitioners.

2. RESEARCH METHOD

2.1 Review Design and Sources

The hybrid type of systematic-structured review was necessary because of the terminology inconsistencies (bolt-connected, bolted end-plate, steel-connected, dry, semi-rigid, replaceable, demountable). Multiple databases were searched (Scopus-indexed Science Direct, Springer Link, Wiley, Taylor & Francis, SAGE, MDPI, Techno-Press, Web of Science, Google Scholar, Crossref, PubMed Central) and repositories, with some articles identified via citations from key studies [5]-[12]. The sources were published or archived between January 2018-7/2026 but included older foundational works.

2.2 Search Strategy and Eligibility

Boolean-type queries used keywords related to precast concrete beam-column joints, bolted, connections, seismic, and FE software, but most were manually entered based on the content of each database.

The inclusion criteria involved peer-review, direct relevance to precast beam-column or analogous mechanical connections, reversed-cyclic experimental or numerical validation, and descriptive detail; exclusion criteria concerned duplicates, gravity-only studies, fire or progressive collapse analyses, column splice assessments, steel-only

joints with no force transfer analogy, and commercial or subscription-only works. Thus, the review focuses on numerical investigations that analyze a precast beam-column connection or make claims about bolted-joint modeling based on a closely related mechanical connection (e.g., welded). The articles have to report reversed-cyclic behavior or successful validation; the details on geometry, materials, boundary conditions, and evaluation indicators have to be sufficient so that the reported findings can be corroborated by other researchers (Table I). When screening, 76 studies were identified (68 in databases, 8 via citation tracing), of which 18 were removed as duplicates, leaving 58 for assessment. After removing 28 as irrelevant, non-seismic, or lacking sufficient detail, 30 underwent full-text review, of which 8 were excluded (3 did not focus on a joint, 2 had no reversed-cyclic or validated analysis, 2 provided limited connection/model description, and 1 had overlapping specimens with another work). The final set comprised 22 studies (Table II). The following details were extracted: authors/publication year, joint location and scale, connection arrangement, bolt and plate description, material characteristics, axial compression ratio, loading type, software/solver, element types, constitutive laws, contact/friction/pretension description, mesh strategy, validation indicators, failure pattern, and limitations. Each study was scored from 0-2 across 8 criteria (relevance, method description, data reliability, validity, reproducibility, results, validation sufficiency, contribution; maximum score 16), and those scoring below 10 were excluded from comparative analyses, although included in the discussion for emerging concepts. The extraction was verified by checking the citation metadata (date, journal, volume, page) and reported numerical values, cross-referenced where possible; the comparison tables state "Not reported" if a study does not include the information rather than postulating values.

2.3 Study Selection and Quality Assessment

The search identified 76 records (68 databases, 8 citation-chained); after removing 18 duplicates, 58 were screened and 28 excluded as off-topic, non-seismic, or lacking technical detail. Of 30 full-text assessments, 8 were excluded (three did not isolate joint behavior, two lacked cyclic or validated numerical results, two gave insufficient connection/model definition, and one duplicated a specimen cohort reported more completely elsewhere), leaving 22 studies for synthesis. A standardized extraction form recorded author/year, joint location and scale, connection configuration, bolt and plate details, material properties, axial compression ratio, loading protocol, software and solver, element types, constitutive models, contact/friction/pretension definitions, mesh strategy, validation metrics, failure mode, and limitations. Each study was scored 0-2 across eight criteria (relevance, method clarity, data reliability, validity, reproducibility, results quality, validation, contribution; max 16); studies below 10 were excluded from quantitative comparison but could still be cited for emerging concepts. Independent checks were performed on citation metadata and reported numerical values, and where a paper did not report a metric the comparison tables state "Not reported" rather than inferring a value.

2.4 Classification Framework

The above list was used to extract data on connection mechanism, geometrical description, material models, loading protocol, software/solver, constitutive laws, contact/friction/pretension modeling, mesh strategies, validation methods, failure mode, and limitations for comparative analysis. The following categories were established: connection mechanisms; constitutive laws (concrete, reinforcement, steel, friction/damage)

Table I. Taxonomy of connection mechanisms and FE representation

Family	Force-transfer components	Dominant mechanism	Key FEM representation
Direct bolted dry	End plates, bolts, embedded steel, corbel	Bolt tension/shear, plate bending, slip	3-D solids/shells, pretension, frictional contact
Hybrid steel-concrete	Steel tubes/couplers/plates + local grout	Distributed yielding, hinge relocation	CDP concrete, embedded reinforcement, cohesive interface
Self-centering/replaceable	Post-tensioning, springs, SMA/ECC	Rocking/recentering controlled dissipation	+Gap/contact, nonlinear springs, explicit materials

3. RELATED WORK

3.1 Connection Mechanics and Seismic Qualification

A bolted dry connection involves extra mechanisms over and above flexure, bar slip, and joint shear in a monolithic connection: interface opening/closing, end-plate deformation, bolt elongation, hole bearing, and friction. Thus, a specimen may exhibit sufficient strength but inadequate pinching or residual rotation capacity, meaning that useful studies provide full hysteresis loops, stiffness degrading, damping, energy, ductility, and failure mode, not just ultimate strength and stiffness [2], [5]. Zhang et al. report that mechanically connected joints can demonstrate stable cyclic response with appropriate anchorage and detailing [13]. Ghayeb, Razak, and Sulong's hybrid steel specimen showed 12.5-50.0% higher drift, 34.7-59.6% moment resistance, and 51-331% cumulative energy than the monolithic reference [14]. Deng et al. utilized highly ductile fiber-reinforced concrete to localize damage [15], whereas Chang et al. note that a beam-panel-zone unified joint is comparable to cast-in-place but a similar column-panel joint underperformed due to moment bias [16]. Lin et al. employed a UHPC core-shell to resist diagonal shear cracking and increase dissipation [17]. Overall, these findings inform two design principles: (i) avoid brittle shear in the joint core; (ii) create intentional regions of inelastic deformation for dissipation or replacement.

Classification according to visible hardware may be misleading: bolted connections can exhibit substantially different behavior depending on whether the bolts are a means of assembling the connection or carry tension-compression forces directly. Therefore, a consistent taxonomy defines connection mechanisms, restoring-force source, dissipation source, expected damage location, and replaceable elements.

3.2 Direct Bolted Dry Connections and Replaceability

The behavior of bolted joints depends on the grade of high-strength steel, plate thickness and stiffness, end-plate geometry, and the axial ratio, among other factors. Ding et al. observe that grade 5.6 versus 8.8 bolts lead to significantly different stiffness, deformation, and dissipation patterns [6], whereas Zhang and Ding note that lower-strength bolts allow for larger deformations and a more semi-rigid response, while stronger bolts may cause a shift of damage away from the connection [7] – a capacity-design consideration, since the reinforcement, embedded steel termination, or joint core should absorb the additional energy or deformation. Liu et al. developed replaceable beam-bolt connections, tested full-scale under low-cycle loading, and validated with ABAQUS; larger diameters increased the capacity and reduced stiffness degradation [8], [9]. Wang et al.'s PBSEC all-dry connection channeled deformation into steel components but was vulnerable to local plate buckling [10]. Li et al. assign the bulk of dissipation to end-plate bending and bolt deformation, with plate buckling as a possible failure mode [11]. Zhang et al.'s haunched long-bolt connection showed that ordinary bolts had a beneficial effect on deformation and energy dissipation [18]. The critical parameters include bolt grade/diameter, pretension, plate thickness/stiffeners, edge distance, hole clearance, friction, corbel geometry, and axial ratio; the tolerances, assembly torque, and retained pretension are rarely specified, which is a significant modeling deficiency since they control slip onset and pinching.

The moment-rotation response is governed by the interaction between member flexure, plate bending, bolt elongation/shear, hole bearing, concrete compression, reinforcement slip, and interface rotation, which reverse upon load reversal [6], [7], [11]. A reliable design should ensure that the intended steel component yields before brittle failure modes (joint shear, anchorage pull-out, splitting) manifest, and this is checked for both directions of loading. Damage progression governs the rotation capacity: friction/gap closure followed by bearing and plate flexure, leading to yielding with distributed cracking, should be characteristic of a well-designed connection; local plate buckling can diminish the stiffness even at moderate moments [10], [11].

Replaceability is not a matter of easily removable bolts: the surrounding concrete, embedded steel, threads, clearances, and beam seats also need to be functional after multiple disassembly cycles [8], [9]. A numerical model that assumes perfect fit and full pretension may overestimate the stiffness and underestimate pinching, but instrumented bolts, measure gaps, and disassembly inspection would allow for a probabilistic description of tolerances after every cycle. Dry connections are particularly sensitive to

construction details often overlooked in general practice: for example, clearance governs the rotation capacity prior to bearing, roughness and clamping stress control friction-induced sliding resistance, washer stiffness and plate flatness affect the loss of pretension, and fabrication accuracy determines the simultaneous seating of all bolts. These are especially pertinent to reversal behavior because a joint can go through sticking, micro-slip, gross slip, bearing, unloading, and re-contact within a single cycle. One should consider reparability as an independent performance level: a connection may meet the design drift but be effectively unreparable if bolts cannot be removed, plates are buckled against concrete, the thread is damaged, or the local crushing does not allow realignment, whereas a replaceable fuse can reduce the downtime even if its hysteresis is nonlinear. The same goes for assessing inspection-only versus tightening, component-level repair, local patching, and member replacement; the corresponding FE outputs would include gap sizes, permanent bolt extension, bearing deformation, plate curvature, cracked concrete volume, and residual rotation.

3.3 Nonlinear Finite Element Modeling Strategies

The constitutive laws pertain to concrete damage plasticity (CDP) or a fracture-plastic model with separate tension and compression, and steel reinforcement/plates using elastic-plastic constitutive laws with cyclic hardening. Feng et al. demonstrate the importance of detailed bond-slip and deformation modeling [5]. Bolts can be represented by a fully detailed model (shank, head, nut, washers, contact, friction), an intermediate description (beam/connector elements with calibration), or simplified as nonlinear springs for frame analysis; the first option is the most informative but requires resources to capture local bearing/prying/slip deformations. Ding, Liu, and Xiao et al. use detailed ABAQUS modeling for parametric studies beyond the test matrix [6], [8], [9], [12]; Xiao et al.'s +31.7% strength and +7.23% ductility improvement over the cast-in-place reference are conditional upon friction, bolt interaction, and damage calibration.

Contact should be governed by hard normal behavior with separation and calibrated penalty friction; special care should be taken to apply bolt pretension and lock it before cyclic loading. The reinforcement-concrete interaction is often idealized as perfect bond, but it should be explicit near beam ends. Mesh sensitivity is critical around holes, plate edges, welds, and anticipated crack bands, and convergence should be evaluated for moment-rotation, local force, and energy rather than peak load; concrete tension-softening is a particular concern since it often governs the behavior. Verification (force equilibrium, energy conservation, independence from mesh/time increment) should be differentiated from validation (comparison to test results); peak load agreement is insufficient because incorrect parameters can also reproduce one point. For example, Feng et al.'s CDP model predicts cracking and softening realistically but fails to capture friction-induced slip and shear [5]; similarly, Ding et al. match the ultimate strength but not the degradation [6].

Material calibration should be driven by the expected failure mode; CDP is convenient for its unified description of tensile cracking and compressive crushing, stiffness degradation, and irreversible strains but requires verification of the compression and tension branches. Particular attention should be paid to the dilation angle, viscosity, eccentricity, and biaxial-to-uniaxial strength ratio, since an incorrect tension-softening law can localize cracking, while a dilation angle of zero can artificially constrain the joint core. Steel plates, embedded steel, reinforcement, and bolts experience different stress states and, ideally, use separate constitutive laws; a multilinear cyclic steel model is recommended to capture local buckling, Bauschinger effects, bond-slip, and size-dependent yielding.

Verification procedures should follow standard operational definitions: force-deformation compatibility, reaction balance, minimal artificial energy dissipation, and independence from mesh and time increment; they should be separated from validation, which compares predicted and measured responses. A model can be accepted for a specific task if it captures the observed failure sequence and trends, but a design-oriented model should quantify uncertainties and be independently validated, with sensitivity analysis varying friction, pretension, fracture energy, hardening, bond-slip, axial ratio, and geometric tolerance to explore response variability.

Table II. Comparison of finite element strategies

Study	Approach	Key variables	Main contribution/limitation
Feng et al. [5]	Refined cyclic FE formulation	Bond-slip, joint shear	Showed need for deformation-component modeling; complex calibration
Ding et al. [6]	3-D FEM + tests	Bolt grade, contact, CDP	Captured bolt-strength influence; limited test variables
Liu et al. [8], [9]	ABAQUS detailed model	Bolt behavior, axial ratio	Larger diameter raised capacity, slowed degradation; pretension reporting weak
Xiao et al. [12]	ABAQUS 2020 CDP	Axial ratio, connector strength	+31.7% strength, +7.23% ductility vs CIP; needs broader verification

3.4 Advanced Materials and Resilience-Oriented Systems

Yu et al. analyze a precast connection with high-strength bars under reversed cyclic loading [19]; Chen et al. combine shape-memory-alloy fibers and engineered cementitious composite to achieve dissipation, cracking closure, and damage recovery [20]; Kim et al. report reduced joint cracking with UHPFRC but interface separation in a U-shaped detail, compared to 45 MPa mortar [21]. Moreira et al. utilize ATENA for rotational stiffness analysis and dowel-grout bond evaluation [22]; Yang et al. propose a combined dry-wet, locally post-tensioned connection [23]; Zhang, Guo, and Li test a demountable dry-connection frame on a shaking table [24]; Zhang et al. study a strong connection with mechanical couplers [25]. Choi identifies a few influential parameters, including axial load, geometry, and hinge location [26]; reviews confirm the importance of dowel reinforcement and grout [27], [28]. A disc-spring built into a connection improves cyclic performance [29]. Self-centering systems require gap/contact elements and separate restoring-force representation with dissipation; a common oversight is the absence of quantitative reparability indicators, such as time or stiffness restoration after replacement.

3.5 Comparative Performance

The performance of the various joint classes was incompletely characterized in the studies reviewed. No single family is obviously better overall: direct connections entail a rapid, dry assembly but may exhibit pronounced “pinching” and slippage; hybrids dissipate the most energy but involve the most complex construction control; emulative UHPC/HDC joints are closest to the behavior of cast-in-place joints but still feature wet construction; and self-centering units reduce residual drift but tend to have low hysteretic areas unless additional dissipative mechanisms are present and specifically modeled. Useful performance indicators in addition to yield/peak strength and drift at 80–85% of peak strength include ductility, secant stiffness degradation, cumulative energy, equivalent viscous damping, residual rotation, and shear distortion of the joint. Notably absent were specifications on the bolt-tightening procedure, measured pretension, clearance, friction coefficient, mesh convergence, or axial load variation; slab contribution was frequently neglected, even as the overstrength of the beam and joint demand changed; and few addressed biaxial loading, aftershocks, fatigue, and uncertainty propagation [30].

Table III. Comparative performance and priority research gaps

Class	Advantage	Limitation	Priority need
Direct bolted/end-plate	Rapid dry assembly, replaceable	Pinching, plate buckling, tolerance sensitivity	Full-scale tests with measured pretension/slip
Hybrid steel-concrete	High strength/energy dissipation	Fabrication complexity	Simplified design model, durability data
UHPC/HDC emulative	Low cracking, strong anchorage	Wet work, interface debonding	Long-term Interface longevity studies
Self-centering	Low residual drift	Low hysteretic area	Frame-level collapse/repair-time assessment

A unified evaluation matrix is proposed that spans five tiers, ranging from specimen/construction detail to loading demand, measured response, computational modeling information, and post-event recovery.

Reporting on all these tiers allows a calibrated detailed model to extrapolate into the full set of test variables within a reduced, quantified uncertainty band and allows component-level constitutive laws to capture the asymmetry, pinching, and residual rotation of local hysteretic cycles for frame-level assessment with appropriate ground-motion suites.

Table IV. Minimum requirements

Domain	Minimum information	Reason
Bolt installation	Grade, diameter, torque/pre-tension, hole clearance	Slip onset, pinching
Concrete/grout	Compression/tension laws, fracture energy, interface prep	Crushing, cracking, debonding
Contact	Normal behavior, friction, separation, cohesive law	Opening/closing, energy dissipation
Validation	Peak/yield loads, hysteresis, stiffness, energy, residual drift	Prevents peak-only calibration

4. DISCUSSION

Seismic performance is governed by the intent to localize deformation within specific mechanical elements rather than the mere fact of using precast technology: a direct connection exhibits excellent behavior when the joint core is protected and the beam end or connecting metal plate is allowed to yield, while hybrid specimens [12] or Xiao et al.'s steel semi-rigid connection [14] generally match or surpass their cast-in-place counterparts by assigning dissipation roles to plates, couplers, bolts, or shear links while protecting the joint core. The advantage is conditional upon the prevention of premature plate buckling and interface debonding, reduction of pretension loss, and maintenance of the strong-column/weak-beam hierarchy. By contrast, UHPFRC/HDC studies [15], [17], [21] partly transfer the protection role to the material, while self-centering connections typically employ supplementary dissipaters to reduce residual drift.

A hierarchical modeling strategy is preferable, calibrated on comprehensive measured hysteresis cycles, stiffness degradations, and energy patterns, together with local strain response. It consists in (1) sensitivity analysis to identify friction, axial tensile softening, contact nonlinearities, bond-slip laws, and hardening as drivers of post-event response; (2) post-buckling analysis accounting for tension stiffening and large deformations; (3) definition of a bounded moment-rotation relationship with degradation laws; and (4) implementation of the constitutive model at the global frame level for damage assessment with a suite of ground motions. The conflicting findings across studies were typically driven by differences in the test setup, axial ratio, slab participation, and definitions of failure rather than dissimilarities in the FE platform. A detailed ABAQUS-type model is most expedient for analyzing the internal force distribution among bolt groups, contact slippage, plate bending, local concrete bearing, and damage patterns [6], [8]-[11]; ATENA's fracture-plastic formulation is suited to capturing grout dowel action [22]; and a fiber/component model is optimal for multiple nonlinear static and dynamic analyses of the full frame after calibration on a detailed model or select tests.

The main limitations of the current body of research are external validity and precision: most studies report on one to five specimens at a given axial load level with little information on tolerances, pretension, or multiple-direction demand and rarely address the effects of slab interaction, low-cycle fatigue, and aftershocks. Parametric studies usually adjust one factor at a time and define trends in mean values without accounting for the uncertainty propagation from material and contact variability to the joint capacity. A desirable next step is a combined large-scale experimental and numerical study that employs digital image correlation, measures interfacial forces, monitors bolt forces, and reports openly on FE modeling to enable true blind prediction. Calibration on measured responses with probabilistic model classes and Bayesian updating offer a more physically informative alternative to the conventional single-parameter best-fit practice. Surrogate models or machine learning could accelerate the response surface exploration but would benefit from being trained on physics-based data and regularized with capacity-design principles rather than employed as post-processing black boxes. A

shared benchmark database with raw hysteretic data, local strains, pretension histories, damage photographs, and model files could enable collaborative blind prediction exercises where modelers receive the geometric and material descriptions of a given connection and are tasked with computing its post-event response before the test data are released: by comparing the independent outcomes, one could identify the most consistent models, detect the parameters that govern behavior, recognize the compensatory mechanisms at play, and ultimately formulate simplified design relations and code guidelines [24], [30].

5. LIMITATIONS OF THE STUDY

This review is limited by the heterogeneity and availability of published evidence. The 2018–July 2026, English-language search emphasis may underrepresent non-English studies and certain publishers. Specimen scale, axial ratio, loading history, and reporting practices varied too widely for a reliable aggregate analysis, and publication bias may amplify the visibility of successful approaches. FE studies also varied in their disclosure of damage evolution rules, interface bond-slip characteristics, friction, and mesh convergence. This review primarily focused on isolated planar subassemblies, so caution is advised in extrapolating the findings to actual building structures with full three-dimensionality and long-term durability.

6. CONCLUSION

This review analyzed the seismic performance and finite element modeling of 22 studies on bolted precast concrete beam-column joints, including dry connections, hybrid steel-concrete specimens, joints using emulative high-performance materials, and self-centering/replaceable mechanisms. Bolted and hybrid joints can be designed to exhibit very similar seismic performance to traditional cast-in-place joints if the column and joint core are actively protected, and the inelastic response is localized in the beam end or discrete steel or composite links, plates, or shear couplers. A poor setup, by contrast, leads to undesirable slip, tension loss, plate buckling, delamination, or damage migration into the joint core or nonreplaceable column. Three-dimensional finite element analysis with realistic concrete cracking/crushing, cyclic steel response, anchorage, contact slippage/friction, and bolt pretension is the preferred approach to assess the local connection mechanics, calibrated on full-scale tests measuring strength, stiffness, energy, and damage patterns. A desirable future direction is establishing standardized large-scale cyclic and shaking table tests, combined with direct measurements of tension loss, interfacial friction, and clearances, as well as probabilistic uncertainty quantification, aided by a shared open-access benchmark database, to enable blind predictive modeling and advanced calibration techniques.

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