

Review of the Mechanical Behavior of Precast Concrete Beams with Hybrid Connections

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Abstract

Hybrid connections provide alternative load-transfer mechanisms for precast concrete beams, but their performance depends on the interaction between steel connectors, reinforcement, prestressing, and concrete. This narrative review synthesizes experimental and numerical studies of steel-connected and prestressed hybrid beams, with selected beam-column and segmental-girder studies used as supporting evidence. The discussion is organized around connection configuration, flexural and shear response, cyclic behavior, and modeling limitations. The reviewed evidence indicates that appropriately detailed connections can approach the behavior of monolithic members, while local concrete damage, interface slip, connector geometry, and joint opening may govern performance. Prestressed bolted connections can improve flexural resistance within the tested configurations, although the benefits cannot be generalized across different materials and loading conditions. Steel components can support ductile response, but their presence alone does not prevent brittle concrete-controlled failure. Existing results remain difficult to compare because specimen geometry, loading protocols, and performance measures differ. Further research should combine matched control specimens, interface measurements, and experimentally validated models to clarify the effects of splice location, anchorage, and reinforcement continuity. A connection combining structural steel, lap-spliced reinforcement, and cast-in-place concrete is identified as a research direction requiring validation, rather than an established solution.

Keywords

Precast Concrete Beams; Hybrid Connections; Mechanical Behavior; Flexural Capacity; Structural Steel Connectors

1. Introduction

Prefabricated construction can reduce site operations and improve production consistency, but these benefits depend on reliable assembly and construction quality [1]. For precast concrete structures, connections must transfer forces between components while accommodating fabrication and erection requirements. Existing connection methods differ in the use of mechanical fasteners, embedded steel,

reinforcement continuity, and concrete cast at the interface [2]. Consequently, the mechanical behavior of a precast beam cannot be assessed from its concrete section alone; the connection may control cracking, deformation, and ultimate resistance.

This review examines hybrid connections for precast concrete beams, emphasizing combinations of structural steel, reinforcement, prestressing, and concrete. Beam-column connections are included where they clarify load transfer and confinement, while segmental bridge girders provide related evidence on prestressing and joint behavior. These systems are not treated as mechanically interchangeable. The objective is to identify recurring mechanisms, explain the limits of available comparisons, and define priorities for connections placed within beam segments.

The paper presents a narrative synthesis of selected experimental and numerical studies, rather than a systematic review or quantitative meta-analysis. The discussion does not claim exhaustive coverage, pooled performance improvements, or a universal ranking of connection types. Findings are interpreted in relation to the connection configurations and loading conditions examined in the cited studies.

2. Connection Configurations and Load Transfer

2.1. Steel Connections at Beam Ends and Structural Joints

Beam-column studies illustrate how embedded steel can supplement force transfer across an assembly interface. Rong et al. investigated connections using steel connectors under cyclic loading [3], while Ye et al. examined a hybrid beam-column detail incorporating steel components and high-strength bolts [4]. These studies support examining connector geometry and the interaction between the steel detail and surrounding concrete. However, favorable behavior at a beam-column joint does not establish the performance of the same connector within a beam: restraint, moment distribution, and reinforcement anchorage differ.

Hybrid beam systems incorporating steel and precast concrete have also been studied directly [5]. Yang et al. tested three beams with H-steel members at the ends, examining the effects of in-situ concrete and prestressing within the proposed hybrid system [6]. This experimental scope is more specific than a general comparison between precast and monolithic construction. Liu et al. compared two precast beams with steel end joints and a reinforced concrete control beam; the reported failure and deformation behavior were similar within their loading arrangement [7]. Hu et al. further investigated H-section end connections experimentally [8]. Collectively, these studies identify beam-end steel details as viable candidates for transferring bending actions, but their applicability remains tied to the tested anchorage and connection geometry.

Embedded channel connections offer another arrangement. Guo et al. tested twelve specimens and examined parameters including channel embedment, stirrup spacing, a beam cavity, and connection eccentricity [9]. The study places local connection

behavior alongside member-level resistance. The implication for design is that the embedded length and surrounding reinforcement must be assessed together; increasing steel size without checking concrete force transfer cannot be assumed to provide a proportional increase in capacity.

2.2. Prestressed and Mixed Connections

Prestressing changes the interface force state and can influence joint opening and residual deformation. Li et al. tested three hybrid precast beams with unbonded prestressing under reversed cyclic loading, considering prestress and the properties of nonprestressed reinforcement [10]. Their results indicate that the combination can improve load-carrying and energy dissipation behavior relative to the fully prestressed specimens considered, while retaining self-centering characteristics. The result concerns a particular reinforcement and loading arrangement, rather than all prestressed connections.

Zhang et al. investigated eight precast ultra-high-performance concrete (UHPC) beams with prestressed bolted, prestressed, and bolted joints [11]. The hybrid joints achieved flexural capacities 46.8%-60.3% above the conventional prestressed joints in that test series. The reported failure involved local compression-zone crushing and bolt shearing, demonstrating that enhanced resistance did not eliminate local connection failure. This improvement should not be transferred directly to ordinary concrete beams, different bolt arrangements, or other loading protocols.

Related bridge research examined steel-prestressed concrete hybrid girders with dedicated interfaces between steel and concrete segments. Kim et al. compared candidate connection arrangements [12] and subsequently investigated a full-scale spliced girder [13]. These studies are useful for understanding interface force transfer and scale effects. Nevertheless, bridge-girder dimensions, prestressing systems, and loading conditions limit direct extrapolation to building beams.

3. Mechanical Performance and Governing Parameters

3.1. Flexural Resistance and Deformation

The reviewed flexural studies suggest that connection adequacy should be evaluated through both local response and overall beam behavior. Similar ultimate resistance does not necessarily imply similar cracking, interface slip, or serviceability. Liu et al. reported limited slip and elastic steel end joints in their tests [7], whereas the UHPC hybrid-joint tests demonstrated an important role for joint opening and the subsequent engagement of the bolted connection [11]. These observations concern different mechanisms and should not be merged into a single performance claim.

Splice position affects the force demand imposed on a connection. Cheng et al. tested precast beams with structural steel connections and developed corresponding finite element models [14]. Within their specimen configuration, capacity decreased as the distance between the connection and support increased. This is evidence of a

parameter-dependent trend, not a universal inverse-proportional law. The choice of splice position should therefore be evaluated against the relevant moment and shear distribution, rather than adopted from a geometric rule alone.

Connector proportions are also important. Hu et al. examined the effects of connector length, web and flange thickness, and steel strength using tests and numerical analysis [15]. Chen investigated beams with steel sleeve connections and reported sensitivity to sleeve thickness and embedment [16]. Together, these studies justify treating steel dimensions and anchorage as interacting variables. They do not establish a common optimum, because changes in geometry can alter both stiffness and the location of damage.

Section-based capacity models provide useful benchmarks where their assumptions are satisfied. Xue et al. evaluated flexural-capacity calculations against precast steel-reinforced concrete beam tests [17], and Yang et al. investigated partially precast steel-reinforced concrete beams in flexure [18]. Such calculations require particular care near an assembly interface: section equilibrium alone does not establish that the assumed reinforcement or steel forces can be developed through the connection.

3.2. Shear Transfer and Concrete-Controlled Failure

Shear behavior deserves separate assessment because a connection that transfers bending effectively may still exhibit local brittle failure. Colajanni et al. investigated the shear response of hybrid steel-trussed concrete beams and identified failure associated with the compressed concrete strut [19]. Yielding of steel members contributed to ductility, but the concrete response remained central to the governing mechanism. The study is related evidence from a composite beam system, rather than direct validation of every hybrid splice detail.

Tests on partially precast steel-reinforced concrete beams provide complementary evidence on shear response [20]. Channel-connected beams likewise demonstrate the need to consider embedment and transverse reinforcement in the connection region [9]. The common engineering concern is the ability of concrete and reinforcement to transfer concentrated forces introduced by steel components. Accordingly, the review supports checking local concrete damage and connection slip alongside the nominal shear resistance of the beam section.

Results for keyed cast-in-place connections provide a useful comparison. Sun et al. reported similar cracking and ultimate loads for their precast beams and monolithic control specimen [21]. This finding shows that a connection without the same embedded-steel arrangement can also perform satisfactorily within a specific test program. Connection selection should therefore compare the required performance and construction constraints, rather than assume that adding steel is inherently superior.

3.3. Cyclic Behavior and Fatigue

Cyclic loading introduces requirements that cannot be inferred from monotonic flexural capacity. Ersoy and Tankut found that adequately detailed welded plate connections could achieve satisfactory reversed-cyclic behavior and emphasized the role of side plates and joint width [22]. Their results underline the importance of the complete connection detail, rather than the presence of a welded plate alone. Beam-column investigations provide further evidence on cyclic response [3, 4], although their restraint conditions differ from those of beam splices.

For prestressed systems, the combination of self-centering and energy dissipation requires careful interpretation. The hybrid beams investigated by Li et al. retained small residual deformation while improving energy dissipation relative to the comparison specimens [10]. These measures should be reported separately: high energy dissipation and low residual displacement describe different aspects of response. Their balance depends on the tested prestressing and nonprestressed reinforcement arrangement.

Studies of precast steel-reinforced concrete beams examined the effects of shear span and section configuration on hysteretic behavior [23]. Research on hybrid steel-concrete beams also considered overall response and deformation characteristics [24, 25]. Such results strengthen the case for monitoring the location of damage and deformation, rather than relying only on peak load. Fatigue constitutes a further loading regime; the fatigue-strength analysis by Xian and Tong [26] should be distinguished from low-cycle seismic testing. Evidence obtained under one regime is insufficient to establish performance under the other.

4. Evidence Limitations and Research Priorities

4.1. Comparability and Numerical Validation

The literature covers ordinary reinforced concrete, steel-reinforced concrete, UHPC, and prestressed systems with different support conditions and connection locations. Differences in material strength, reinforcement, specimen scale, and loading protocol prevent direct interpretation of reported capacity gains as a ranking of technologies. A meaningful comparison requires a matched reference specimen and a clear statement of which variables were changed. Quantitative results should remain attached to the test conditions from which they were obtained.

Finite element models can help interpret local mechanisms and extend tested parameter ranges, as illustrated by the beam studies discussed above [7, 14, 15]. Their predictive value, however, depends on validation against the response of interest. Agreement in ultimate load alone does not demonstrate that a model reproduces interface slip, cracking, stiffness degradation, or failure location. Future studies should compare these responses where measurements are available and report the sensitivity to assumptions about contact, bond, and material behavior. These are recommendations arising from the synthesis, not a claim that every reviewed study omitted such checks.

4.2. Priorities for Hybrid Connections within Beam Segments

A useful research direction is a beam-segment connection combining structural steel connectors, lap-spliced longitudinal reinforcement, and concrete cast at the interface. The concept seeks to combine mechanical assembly with reinforcement continuity and a cast-in-place interface; however, the present review does not provide experimental validation of that specific combination. Its proposed benefits, including faster assembly or reduced temporary support, remain hypotheses requiring assessment during construction as well as under service loading.

An experimental program should isolate splice location and lap length while maintaining comparable beam dimensions, reinforcement, and material properties. Companion monolithic specimens would provide a reference for cracking, stiffness, resistance, and failure mode. Interface opening and slip, connector strains, and reinforcement strains should be measured to distinguish connection failure from beam-section failure. Connector thickness, embedment, and transverse reinforcement can then be varied within a validated numerical framework, rather than changed simultaneously without a basis for attributing their effects.

Repeated loading, construction tolerances, and long-term behavior also deserve attention. The evidence reviewed here does not establish a general durability or fatigue advantage for hybrid connections. A design recommendation should state the material and geometric range supported by the tests, the expected failure mechanism, and the conditions under which the numerical model has been validated. This would make results more useful than a broad assertion that a proposed detail is safe or superior.

5. Conclusions

Hybrid connections offer several ways to transfer forces between precast concrete segments. The reviewed evidence indicates that appropriately detailed steel-connected and prestressed systems can provide satisfactory member behavior, but performance remains conditional on anchorage, interface behavior, reinforcement, and loading. Comparability with monolithic construction has been demonstrated for particular specimens and should not be generalized to all connection types.

Flexural resistance, shear resistance, cyclic deformation, and fatigue should be evaluated as distinct performance requirements. Local concrete damage, joint opening, and slip can govern response even when steel components increase resistance or contribute to ductility. Reported improvements therefore require interpretation in the context of the tested materials and failure mechanisms.

Research on hybrid connections within beam segments should prioritize controlled comparisons and measurements of interface behavior. Combining structural steel, continuous force transfer through reinforcement, and cast-in-place concrete is a plausible direction, but its mechanical and construction-stage benefits require

dedicated validation. The review supports this research agenda without presenting planned tests or numerical investigations as completed results.

Conflicts of Interest

Declaration of Generative AI and AI-assisted technologies in the writing process

During manuscript preparation, OpenAI Codex was used to assist with language editing, condensation, organization, reference formatting, and drafting the abstract. The author is responsible for reviewing and verifying the final manuscript before submission.

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