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**REVIEW**

# Behavior of Headed Studs in Composite Structures: An Overview

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**ABSTRACT:** Composite structures have become integral to modern construction owing to their efficiency, strength, and economic benefits, with steel-headed studs serving as critical shear connectors between concrete slabs and steel beams. Existing research has investigated these connectors through push-out and pull-out experiments, fatigue and cyclic protocols, durability and temperature-extreme studies, and a wide range of analytical, numerical, and data-driven models. This study addresses the lack of a consolidated and critical review by combining a systematic review with a bibliometric assessment of 385 Scopus-indexed publications from 2000 to 2025, which shows sustained growth of research output and concentration of highly cited contributions in leading composite-structures outlets. The systematic synthesis highlights that stud performance depends strongly on geometry, grouped-stud interaction, and the surrounding cementitious matrix, and it shows that advanced concretes mixes often increase peak resistance while shifting governing failure toward stud or weld-related mechanisms. Design-code comparisons reported in the reviewed literature indicate that resistance predictions may deviate substantially in ultra-high performance concrete configurations, which supports the need for mode-aware provisions rather than direct extension of normal-concrete formulations. The modeling review identifies a progression from empirical equations toward nonlinear finite element simulation and interpretable machine learning trained on large databases, while noting that design adoption requires transparent applicability limits and physically consistent predictors. The paper concludes by consolidating design implications and by defining targeted research priorities on grouped studs, mixed-action fatigue, durability degradation factors, and interpretable data-driven tools for code-oriented design of composite shear connections.

**KEYWORDS:** Steel-headed studs; composite structures; shear connectors; ultra-high-performance concrete; fatigue and cyclic behavior

## 1 Introduction

Composite construction has been widely recognized as a central approach in structural engineering because it integrates steel and concrete in a manner that maximizes their respective strengths while minimizing weaknesses [1–3]. The increasing reliance on composite members in bridges, buildings, and prefabricated systems is tied to their capacity for improved stiffness, efficiency, and long-term durability when compared with conventional structural forms [4–6]. A key factor in the effective action of these systems lies in the performance of shear connectors, particularly steel-headed studs, which transfer longitudinal shear between the concrete slab and steel beam [7–10]. Headed studs have been extensively studied under a variety of mechanical and environmental conditions, revealing a strong dependence of their behavior on geometry, arrangement, and surrounding concrete properties [11–13]. Existing research has established that variables such as stud diameter, embedment depth, and material grade significantly influence shear capacity, slip characteristics, and fatigue resistance [14–16]. These findings have been supported through full-scale experiments, push-out tests, and advanced finite element simulations that provide detailed predictions of load-slip response and failure mechanisms [17–20].

Durability has emerged as another fundamental concern, as shear connectors are exposed to long-term environmental influences, cracking in surrounding concrete, and corrosive conditions that may reduce their capacity over time [19,21,22]. Investigations have demonstrated that freeze-thaw cycles, sustained load, and cyclic stress can alter stiffness degradation and residual strength of connectors embedded in conventional or advanced cementitious materials [23–25]. This dimension of research has been complemented by studies focused on extreme conditions such as fire and low temperatures, which have highlighted potential vulnerabilities in connectors when subjected to severe service environments [26–28]. Parallel to experimental developments, computational and analytical approaches have been crucial in advancing predictive capability for stud behavior. Early models concentrated on empirical formulations calibrated against test data, whereas recent advances have incorporated nonlinear finite element simulations and data-driven techniques such as machine learning to refine predictions of resistance and stiffness, reflecting wider efforts to adopt advanced computational tools in civil engineering [29–33]. These methods have made it possible to evaluate parameters difficult to capture experimentally, such as local stress concentration and slip distribution along the interface [34–36]. The application of novel materials has further expanded the scope of investigation, particularly with the use of ultra-high-performance concrete (UHPC), engineered cementitious composites, and hybrid concretes incorporating fibers or recycled elements [37–39]. Headed studs embedded in these advanced concretes have shown increased shear resistance and ductility, but concerns remain regarding cracking, anchorage efficiency, and constructability [40–42]. Comparative studies involving conventional connectors such as bolted or demountable systems have also pointed to differences in ease of assembly, reusability, and mechanical performance, highlighting the practical implications of stud selection for different structural contexts [43–45]. Despite the progress, design codes still face challenges in consistently incorporating these research outcomes into reliable provisions. Current recommendations vary across regions and often lag behind experimental evidence, leading to discrepancies between theoretical resistance predictions and observed structural behavior [46,47]. Some provisions address studs in profiled sheeting or under cyclic actions, yet the complexity of emerging materials and connection types has outpaced updates in standards [48]. In addition, uncertainties surrounding grouped arrangements, fatigue under mixed loading, and degradation in extreme service conditions remain partly unresolved [49–51]. The available literature demonstrates an extensive effort in experimental, analytical, and numerical study of headed studs across various structural applications. Nevertheless, the literature still lacks a recent paper that simultaneously consolidates the technical evidence across loading and environmental conditions and quantifies research trends and thematic evolution through a bibliometric mapping of the field. Accordingly, this study addresses this gap by conducting a systematic and bibliometric review on the behavior of steel-headed studs in composite structures. The novelty of the work lies in integrating (i) a systematic screening and synthesis of experimental, analytical, numerical, and data-driven studies that report strength, stiffness, slip, fatigue, and degradation mechanisms, with (ii) a bibliometric mapping of the field that identifies dominant research clusters and underrepresented topics, and then (iii) translating both components into design-facing implications and prioritized research gaps linked to code development. The aim is to present a structured evaluation of experimental, analytical, and computational findings while identifying persistent challenges such as long-term durability, seismic performance, and modeling accuracy. Through this effort, the work intends to provide researchers, engineers, and designers with a consolidated reference that supports more informed applications and future research directions in composite construction.

## 2 Review Methodology

In general, the literature sources for the systematic and bibliometric reviews were assembled from the Google Scholar and Scopus databases, targeting publications from 2000 to 2025 that address headed stud connectors in steel-concrete composite structures. The Scopus query was constructed using title, abstract, and keyword fields to capture both terminology and application context. The core search terms included headed stud, headed shear stud, stud shear connector, shear connector, composite beam, composite slab, steel–concrete composite, push-out, pull-out, fatigue, cyclic loading, and ultra-high-performance concrete, combined with Boolean operators to avoid irrelevant stud applications outside composite construction.

The screening workflow followed two stages. First, titles and abstracts were screened to confirm relevance to steel-headed studs used as shear connectors in steel-concrete composite systems. Second, full-text screening verified that each retained record contributed experimental, analytical, numerical, data-driven, or design-provision evidence that could be synthesized within the scope of this review. Studies were excluded when the work focused on unrelated fastening applications or when insufficient technical detail was available to support comparison.

The bibliometric component used the Scopus-exported database to quantify publication growth, outlets, keywords, and collaboration patterns. Keyword co-occurrence and source/country mapping were conducted using VOSViewer. Threshold settings were selected to emphasize terms and nodes with meaningful recurrence while retaining the ability to interpret emerging themes. The combined systematic and bibliometric workflow supports both technical synthesis and identification of research clusters and gaps.

The limitation of this review is the fact that the collected literature reflects only the Google Scholar and Scopus indexing and the selected query structure, so relevant studies indexed exclusively in other databases may not be captured. In addition, differences in test setups and reporting formats across laboratories limit direct quantitative aggregation, so the synthesis emphasizes comparative interpretation and design-relevant implications rather than meta-analytic pooling.

## 3 Bibliometric Analysis

This section reports the results of the bibliometric analysis performed in this study. In general, a total of 385 publications focusing on the behavior of headed studs in composite structures were identified in the Scopus database between 2000 and 2025. Fig. 1 illustrates the annual distribution of these studies. The early 2000s witnessed only limited activity, with fewer than ten papers each year. A gradual rise began after 2010, followed by a more consistent growth pattern, peaking around 2019 and 2023 with 33 publications recorded in each of these years. The data for 2025 remain incomplete, yet the continuing trend suggests sustained interest in this topic. The increase in research output reflects the growing relevance of composite structures and the ongoing refinement of headed stud behavior in design and performance assessment.

Fig. 2 shows the distribution of publication types. The majority of contributions appeared as journal articles, totaling 307 documents, which indicates the dominance of peer-reviewed research in this area. Conference papers accounted for 76 records, showing that ongoing experiments and model validations are frequently presented at professional meetings before journal submission. Only two book chapters were identified, implying that the subject remains primarily research-driven rather than summarized in broader academic compilations.

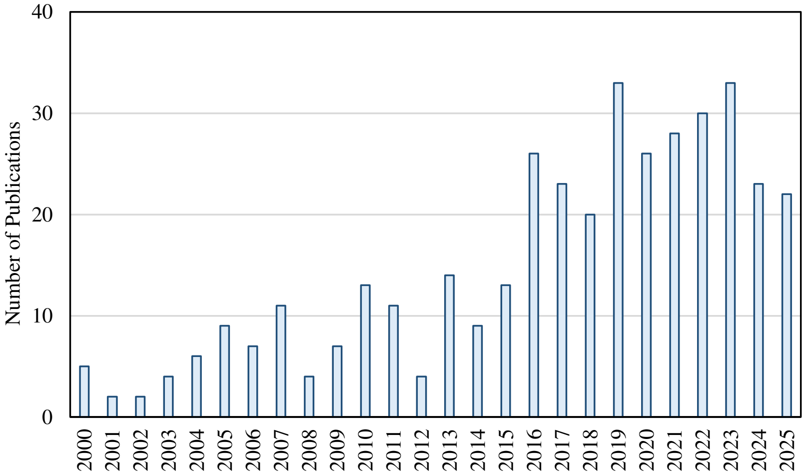

**Figure 1:** Annual number of Scopus-indexed publications on the behavior of headed studs in steel-concrete composite structures (search window 2000–2025; $n = 385$; 2025 reflects partial indexing at the time of database extraction).

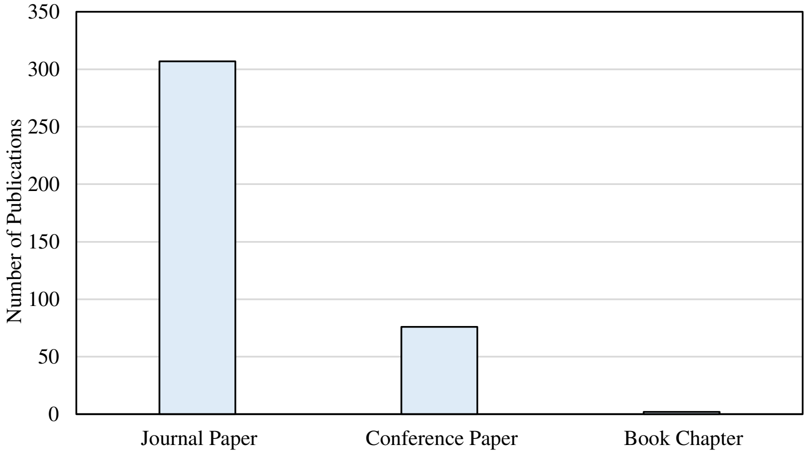

**Figure 2:** Document types within the Scopus dataset on headed stud behavior in steel–concrete composite structures (2000–2025; $n = 385$), showing the relative share of journal articles, conference papers, and book chapters.

Keyword co-occurrence mapping in Fig. 3 provides an overview of the conceptual directions followed by researchers. The most frequent keywords include "studs (fasteners)", "studs (structural members)", "headed stud", and "concrete slabs". Other recurring terms such as "composite beams and girders", "push-out tests", "finite element method", and "shear connector" suggest that the literature has largely concentrated on load transfer mechanisms, structural performance, and computational modeling. The strong clustering of these keywords indicates that mechanical behavior, interface shear resistance, and structural optimization continue to anchor most investigations. This concentration around experimental and analytical modeling reflects a technical rather than theoretical focus in the field. Citation analysis of journals, presented in Fig. 4, reveals that *Engineering Structures* has been the most influential source, with 47 publications and more than 2100 citations. The *Journal of Constructional Steel Research* ranks closely with 34 papers and comparable citation counts. Other active journals include *Steel and Composite Structures*, *Structures*, and *Construction and Building Materials*. Their citation link strengths highlight a stable network of publications dedicated to the interface between steel and concrete performance. The prominence of these journals confirms that research on headed studs remains closely tied to mainstream civil and structural engineering outlets, reinforcing the technical orientation observed in the keyword map.

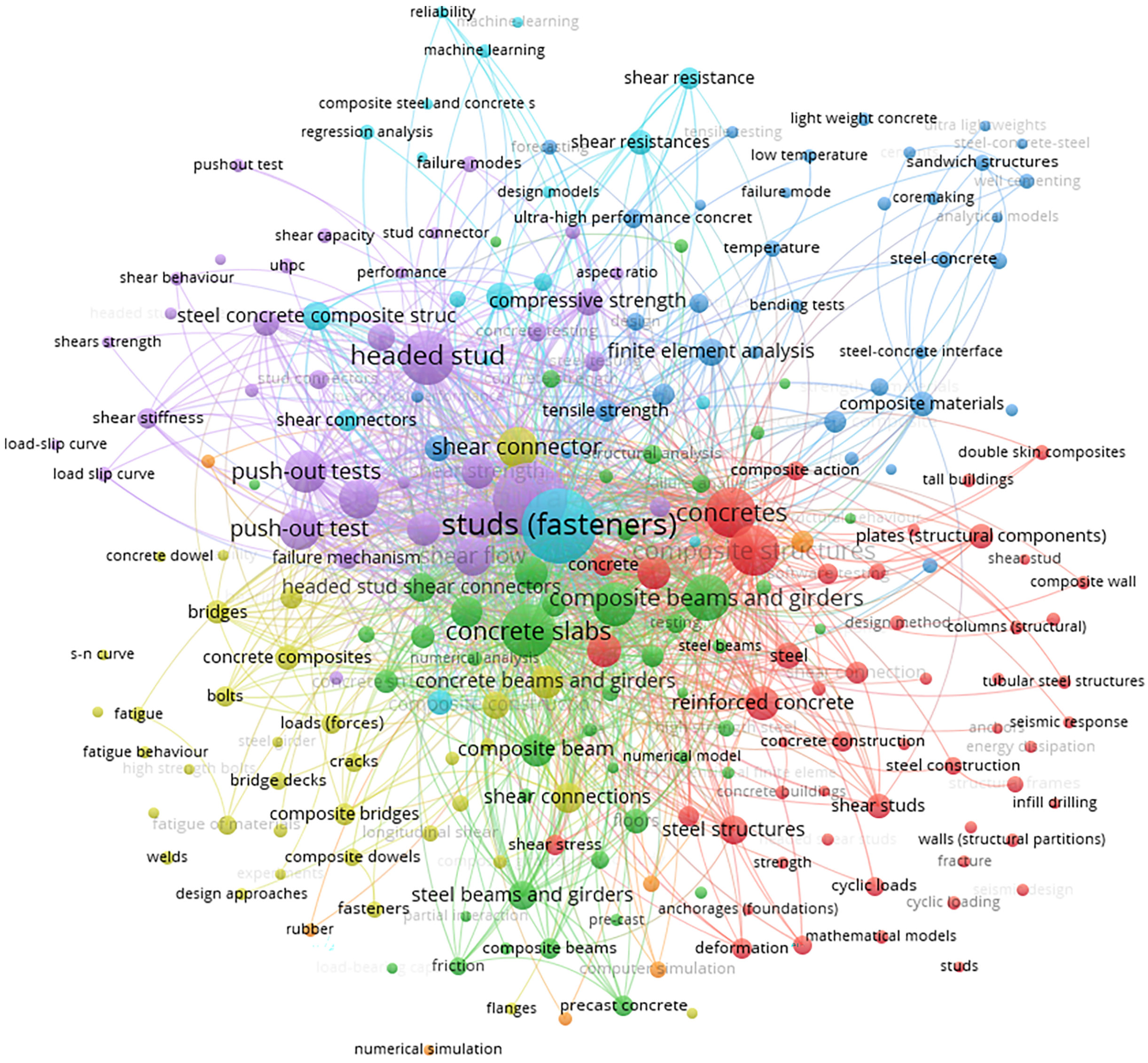

**Figure 3:** Keyword co-occurrence network for the Scopus dataset on headed stud behavior in composite structures (2000–2025; *n* = 385), highlighting dominant clusters related to push-out testing, finite element modeling, and composite beam/slab applications.

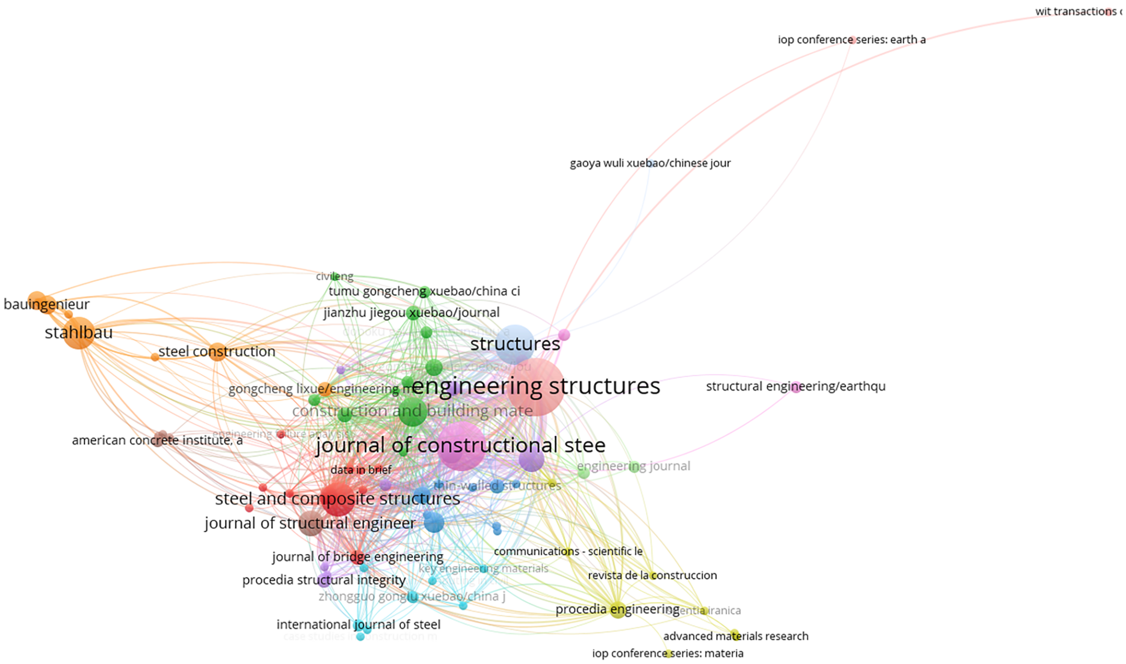

**Figure 4:** Source/journal citation influence within the Scopus dataset on headed stud behavior in composite structures (2000–2025; $n = 385$), reporting the most influential publication venues by output and citation impact.

The distribution of contributing countries in Fig. 5 demonstrates that China leads the field with 120 publications and the highest citation and link strength values. The United Kingdom and the United States follow, showing considerable collaboration links across continents. Germany, Japan, and Australia also appear as strong contributors, while several emerging participants such as Serbia, Singapore, and Brazil signal growing regional interest. The visual clustering of countries in the network diagram points toward active international cooperation, with China and the United States acting as central hubs in shared authorship and citation networks.

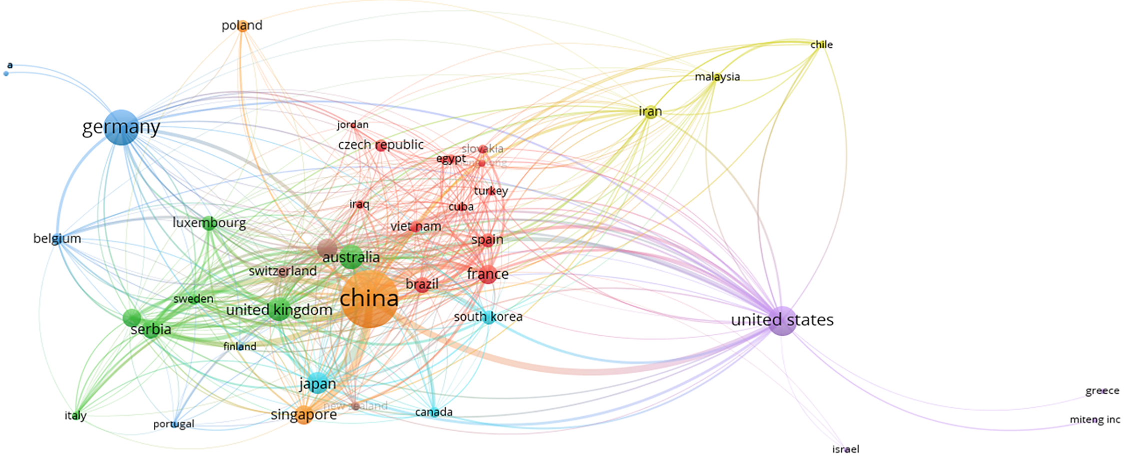

**Figure 5:** Country contribution and collaboration network for Scopus-indexed studies on headed stud behavior in composite structures (2000–2025; $n = 385$), illustrating the main hubs and collaboration link strengths.

A technical interpretation of the bibliometric patterns helps link research activity to engineering themes addressed in the remainder of the manuscript. The dominant keywords and their co-occurrence around push-out tests, shear transfer, finite element method, and composite beams indicate that experimental characterization and mechanics-based modeling form the principal knowledge backbone, which is reviewed in Sections 3 and 4. The repeated appearance of terms associated with fatigue, cyclic behavior, and durability aligns with the growing body of work on bridge and infrastructure demands, which is synthesized in Section 3 and revisited in the Discussion as a code-relevant gap. The increasing presence of UHPC and other advanced cementitious systems in the keyword space is consistent with the recent concentration of highly cited studies on thin high-performance slabs and modified failure modes, which is integrated into Sections 3 and 5. Finally, the emergence of data-driven and machine learning terminology in the literature signals a newer research cluster that complements analytical and numerical approaches, which is reviewed in Section 4 and discussed as a pathway for interpretable design-oriented tools.

Overall, the bibliometric analysis outlines a research field that has developed steadily over the past two decades, characterized by a concentration of studies in a few leading journals and active global collaboration. The results collectively show that investigations into headed studs in composite structures have transitioned from isolated experimental studies to an interconnected body of work grounded in analytical modeling, large-scale testing, and international research partnerships.

## 4 Experimental Evidence on Headed Stud Behavior

Experimental investigations have provided the foundation for understanding the role of headed studs in composite structures, Table 1. Over the decades of research, push-out tests, pull-out tests, fatigue studies, and large-scale structural experiments have been performed to characterize their strength, stiffness, ductility, and long-term durability under diverse conditions [1–3]. These studies have collectively defined the mechanisms through which headed studs transfer shear between steel and concrete, while highlighting how geometry, material properties, environmental exposure, and construction detailing influence their behavior [4–6].

### *4.1 Impact of Cementitious Systems*

The development of UHPC and engineered cementitious composites has motivated a large body of experimental research on headed studs. Static and fatigue push-out studies confirmed the distinctive behavior of studs embedded in thin UHPC layers, where higher strength concretes modify load transfer and reduce slip demand [4,17]. Further studies on steel–UHPC composite sections examined the combined action of studs and UHPC slabs, demonstrating altered mechanical interaction compared with conventional concretes [37,38]. Push-out experiments on studs embedded in steel-engineered cementitious composite (steel–ECC) slabs also highlighted the effect of strain-hardening cementitious composites, showing differences in shear transfer compared with ordinary concretes [13]. Parallel investigations assessed headed studs in steel fiber reinforced systems, extending experimental focus to hybrid concretes with fibers or recycled components [39,41,52]. Such results illustrate the consistent experimental effort devoted to quantifying how novel cementitious materials affect bond, slip, and ultimate shear strength of studs. Studies involving engineered cementitious composites also confirmed that advanced binders provide distinct responses in pull-out testing of studs, further diversifying the knowledge of material–stud interaction [53].

### *4.2 Push-Out Behavior*

Push-out tests have long been employed to examine shear transfer mechanisms of headed studs, producing direct data on shear capacity, load-slip response, and failure modes. One of the most cited comparisons involves the relative performance of bolted connectors and welded headed studs, where push-out testing revealed distinctions in stiffness and failure characteristics that underpin design recommendations [2]. Further comparisons between headed studs and other connector types in prefabricated systems have also reinforced the significance of push-out testing in assessing alternative solutions for composite decks [54]. Large-scale push-out studies have explored the influence of grouped studs, demonstrating how close spacing modifies slip distribution and changes resistance [48,49,55]. Such work has consistently emphasized that the collective behavior of stud groups cannot be simplified to the sum of individual studs, an observation reinforced in later finite element validation studies [48]. Investigations involving thin plates and UHPC further confirmed that stud geometry, plate thickness, and material grade all play defining roles in the shear capacity observed in push-out setups [9,10,56]. Several researchers have extended static testing to large-headed studs embedded in UHPC, highlighting differences in slip stiffness and resistance compared with conventional studs [40]. Other work emphasized how reinforcement detailing within surrounding concrete can alter the overall structural performance of connections, underlining the interdependence of reinforcement design and connector action [16]. Early full-scale beam tests also remain central, demonstrating fundamental patterns in shear transfer of headed studs that continue to influence interpretation of push-out results today [57].

**Table 1:** Findings of recent experimental studies on push-out and pull-out studies on headed studs.

| Study | Research Methodology | System Investigated | Variables Studied | Research Findings | Remarks |
|---|---|---|---|---|---|
| Lin et al. [58] | Push-out tests, 13 specimens; followed by numerical simulation and analytical modeling | Engineered cementitious composites | Stud diameter, stud length, compressive strength of engineered cementitious composites, reinforcement ratio, thickness of engineered cementitious composites layer | Analytical models were established for shear carrying capacity, stiffness, and slipping ability based on the experiments and simulations; no specific numbers were reported | Integrated experimental, numerical, and analytical approach for studs in engineered cementitious composites |
| Xu et al. [53] | Pull-out tests, 9 specimens with 3 embedment lengths; followed by finite element simulation | Engineered cementitious composites | Stud embedment length, compressive strength of engineered cementitious composites, stud diameter | Tensile capacity increased with larger embedment length; for cases with engineered cementitious composites cone failure, higher compressive strength increased tensile capacity; stud diameter had negligible impact on tensile capacity in the pull-out configuration; 3 prediction methods were proposed and the concrete capacity design model and the influence factor model showed superior prediction accuracy | Predominant engineered cementitious composites cone breakout; finite element analysis examined effects of variables on failure mode and tensile capacity |
| Gu et al. [59] | Push-out and inverse push-out tests, 23 specimens | Engineered cementitious composites | Loading direction, matrix type, reinforcement ratio, stud length, stud diameter, thickness of engineered cementitious composites layer | In negative bending moments, studs in engineered cementitious composites showed significantly higher shear carrying capacity and slipping ability than studs in conventional concrete; no specific percentages were reported | Refined finite element model clarified shear transfer mechanism and boundary condition effects |

(Continued)

**Table 1 (continued)**

| Study | Research Methodology | System Investigated | Variables Studied | Research Findings | Remarks |
|---|---|---|---|---|---|
| Duan et al. [37] | Push-out tests, 24 specimens; global database summarized to 120 specimens | Ultra-high-performance concrete | Stud diameter equal to 16, 19, 22, and 25 mm | Code predictions of stud shear capacity were overestimated by 52% for the AASHTO LRFD, 5% for Eurocode 4, and 53% for the Chinese code; post-peak slip extended to at least 10 mm; smaller stud diameters failed by stud shank fracture, larger diameters failed at the welding line | Load response contained linear, softening, and post-peak stages with high variability after the peak |
| Chen and Chen [60] | Push-out tests on concrete-filled steel tubular members, 8 specimens with studs; 1 specimen without studs; 4 composite beam references | Concrete-filled steel tubular member with headed studs on the interior face | Core concrete strength, stud diameter, stud length | Ultimate load with studs ranged from 673.3 to 1356.9 kN, compared with 85.7 kN for the specimen without studs; stud length had little effect; studs sheared at the peak load | No separation between core concrete and steel tube occurred when studs were used; full utilization of studs achieved |
| Luo et al. [61,62] | Push-out tests, 16 specimens | Steel fiber reinforced cementitious composites | Stud diameter, number of studs, gauge length, pitch length, fiber volume fraction | Densest allowable stud layout provided more than 90% of single-stud strength without slab reinforcement; 9 densely arranged studs in an area that typically allows 4 studs doubled overall shear resistance; a fiber volume fraction equal to 6% was most suitable for ductility | Headed studs embedded in steel fiber reinforced cementitious composites produced stud fracture even without slab reinforcement |
| de Oliveira et al. [63] | Pull-out tests, 10 specimens | Conventional concrete | Stud head thickness; embedded length; concrete tensile strength discussed | Codes were conservative and underestimated the concrete tensile strength; 2 collapse types observed: tensile failure along the steel shank and concrete cone failure | Both head thicknesses were satisfactory |
| Li et al. [64] | Pull-out tests, 18 tensile specimens | Ultra-high-performance concrete | Stud diameter equal to 13 mm; fiber content; specimen size | For specimens with concrete cone failure, the American Concrete Institute 349-13 provision provided relatively accurate tensile resistance predictions; tensile stiffness can be estimated using the secant modulus at 0.1 mm slip | Two failure modes: ultra high performance concrete cone failure and stud fracture |

(Continued)

**Table 1 (continued)**

| Study | Research Methodology | System Investigated | Variables Studied | Research Findings | Remarks |
|---|---|---|---|---|---|
| Zhuang et al. [8] | Pull-out tests, 33 specimens; literature database added | Conventional concrete | Embedment depth, bearing area, boundary conditions, concrete strength | Analytical piecewise model proposed for full tensile load to deformation behavior and verified against compiled tests | Model applied to simulate rotational behavior of semi-rigid joints anchored by headed studs |
| Zhao et al. [65] | Pull-out tests, 16 specimens; finite element simulation | Ultra-high-performance concrete | Connector type, dowel height, dowel inclination angle | Adding headed studs increased pull-out bearing capacity by approximately 49% to 84%; the configuration with 100 mm dowel height and an inclination angle equal to 65° performed best; adding longitudinal reinforcement at the bottom further improved ductility and capacity | Failure modes were ductile and consisted of shear and axial tensile failure of the ultra high performance concrete |
| Mazoz et al. [66] | Push-out tests, 18 specimens; finite element simulation | Conventional concrete | I-shaped connector compared with channel connector and headed stud connector | Shear strength and elastic stiffness of the I-shaped connector were similar to those of the channel connector and higher than those of the headed stud connector; the headed stud connector showed higher ductility | Finite element analysis explained local deformation, stress distribution, and crack progression |
| Pardeshi and Patil [67] | Push-out tests with experimental validation and finite element analysis | Conventional concrete | Coconut palm stem-shaped studs with the same steel volume as circular studs | Increased shear strength by 37% to 47%, approximately doubled stiffness, and improved slip and ductility relative to circular studs | Three predictive formulas developed from the parametric analysis |
| Patil et al. [68] | Push-out tests, 10 specimens; finite element analysis | Conventional concrete | Wing plates added to the base of the stud | Shear capacity increased by 34% to 74%; stiffness and slip capacity increased; equations proposed for design | Tested across 2 grades of concrete and different wing sizes |
| Saleh and Majeed [69] | Push-out tests, 36 specimens | Self-compacting concrete with recycled coarse aggregates | Recycled aggregate ratio, concrete compressive strength, stud diameter | Higher recycled aggregate ratio reduced shear strength and stiffness, and increased ultimate slip; the negative effect decreased when concrete strength and stud diameter were increased | Results compared with Eurocode 4 and American Association of State Highway and Transportation Officials provisions |

### *4.3 Pull-Out Behavior*

Pull-out testing complements push-out experiments by isolating tensile resistance of headed studs. Investigations on tensile capacity have demonstrated the influence of stud head diameter and embedment length on pull-out strength [35]. Experimental work on handcrafted studs assessed variability in performance and quality compared with industrially manufactured connectors, offering insight into construction practices in resource-limited contexts [63]. More recent studies on thin panels reinforced with void formers have extended tensile investigations to non-standard geometries, revealing the adaptability of pull-out testing for specialized configurations [70]. The pull-out behavior of headed studs has also been tested under UHPC and ECC conditions, confirming differences in anchorage and stiffness relative to normal concretes [12,53]. Studies investigating concrete consolidation at stud roots demonstrated how incomplete compaction significantly reduces stud performance, emphasizing construction quality as a determining factor [71]. Similarly, pull-out experiments on innovative ribbed stud geometries in slab–beam connections offered further evidence on the influence of shape modifications on anchorage behavior [72].

### *4.4 Fatigue and Cyclic Behavior*

Fatigue performance has been the focus of several experimental campaigns, Table 2, as long-term cyclic loading is critical in bridges and heavily trafficked structures. Foundational research investigated fatigue resistance of welded headed studs under rotating shear, emphasizing the role of welding details and ferrule quality [24]. Subsequent large programs examined fatigue loading in detail, generating data that continues to inform resistance models [3]. More recent fatigue studies examined studs in UHPC and ultra-high toughness cementitious composites, where superior fatigue resistance has been reported compared with conventional concretes [4,25]. Experimental research on grouped arrangements under cyclic shear demonstrated how load distribution shifts across stud groups, influencing long-term stiffness degradation [73]. Work on large-headed studs and demountable connections has also confirmed that cyclic demands produce different stiffness degradation paths than monotonic loading [45,74]. Investigations on fatigue of studs in precast connections or with improved reinforcement have added further experimental knowledge, supporting design recommendations in complex structural systems [14]. Complementary studies considered repair-welded studs and their fatigue strength, contributing insight into maintenance and retrofitting practices [75]. When studs are used in groups, their collective performance differs substantially from isolated behavior. Push-out experiments confirmed that spacing, arrangement, and load sharing modify slip and shear resistance [49,55]. Finite element validations supported equivalent diameter calculation models designed to represent groups more accurately, and experimental evidence continues to serve as the foundation for these models [48]. Investigations into large-headed studs in grouped configurations further expanded knowledge, particularly when UHPC was used as the embedding material [40]. Studies considering grouped studs under cyclic loading in infill walls highlighted the complexity of the combined effects of reinforcement and connector distribution [50,73]. Research into stiffness degradation of studs under low-cycle fatigue confirmed that grouped connectors experience distinctive degradation paths [23].

### *4.5 Environmental Effects*

Experimental studies have extended to severe service conditions where temperature or environmental exposure alters stud performance. Investigations into low-temperature conditions in Arctic infrastructure revealed the distinctive mechanical response of studs in cold environments [5,27]. Further pull-out and stress–strain model development at subzero temperatures supported the reliability of design under such conditions [28]. Fire has been another focal condition, with experiments on studs in composite beams at elevated temperature demonstrating changes in shear strength and ductility [26]. Recent studies on studs in modern profiled sheeting under high temperature expanded this line of research, considering contemporary composite systems under fire loading [36]. Research on repair methods involving UHPC also considered stud performance under severe conditions, highlighting connections to rehabilitation practice [9,10]. Corrosion remains a long-term concern, with experimental work confirming how cracks in surrounding concrete accelerate deterioration and reduce stud performance [21]. Durability studies on studs embedded in UHPC provided comparative evidence of improved resistance against electrochemical corrosion relative to conventional concretes [19].

### *4.6 Summary*

Across the push-out and pull-out evidence summarized in Table 1, several comparative patterns emerge that support design-relevant interpretation. In monotonic push-out configurations, stud diameter and aspect ratio repeatedly control the governing failure transition between stud shank fracture, weld-line failure, and concrete-related cracking, which explains why some datasets report strong diameter effects on resistance while others emphasize ductility and post-peak slip as the primary differentiator. When advanced concretes are used, the evidence indicates that increased matrix strength often raises peak resistance and reduces slip demand, yet it can also shift failure toward the stud or the weld region, which is consistent with studies reporting weld-line sensitivity and different post-peak stages in UHPC systems [17,37]. In pull-out configurations, the governing failure mode largely determines the apparent influence of geometry: embedment length and bearing area become dominant when concrete cone breakout governs, while the influence of stud diameter becomes less pronounced when failure shifts to the steel shank, which is consistent with the observation that diameter can be negligible in some pull-out datasets but influential when boundary conditions and slab thickness promote breakout [8,27,64]. These comparative observations motivate the later discussion on why unified design equations remain challenging across normal concrete, UHPC, and ECC, and why code extensions require explicit recognition of failure-mode transitions rather than a single resistance expression.

Finally, beyond conventional welded studs, experimental work has tested alternative connector arrangements. Comparisons between headed studs and high-strength bolts in prefabricated composite decks demonstrated performance differences that guide choice in prefabricated systems [54]. Demountable connections with bolts and studs were also examined in detail, illustrating performance trends under shear loading and long-term behavior [45,76]. Investigations on post-installed connectors compared spring pins and welded studs, highlighting differences in push-out resistance and ductility [44]. Further studies tested innovative ribbed studs with triangular or spherical geometry, extending the experimental knowledge of connector alternatives in slab–beam junctions [72]. Research involving I-shape connectors compared with headed studs also provided comparative results on shear resistance and stiffness [66]. Several experimental programs have been closely tied to design development. Studies on studs in profiled sheeting evaluated their shear resistance and ductility, generating data for Eurocode 4 provisions and related design guidelines [47,77]. Later research advanced these efforts by testing studs with profiled sheeting transverse to beams, informing newer design approaches [7,34]. Grouped stud tests under different reinforcement detailing also contributed to recommendations for design adjustments [55]. Other tests on studs in railway bridges and steel–concrete joints supported the evolution of code provisions specific to infrastructure applications [42,78].

**Table 2:** Findings of recent experimental studies on fatigue and cyclic loading, environmental degradation, temperature effects, and corrosion of headed studs.

| Study | Research Methodology | Main Variables Studied | Research Findings | Remarks |
|---|---|---|---|---|
| He et al. [23] | Unidirectional low-cycle fatigue loading on bare stud specimens based on a proposed theoretical model; 12 tests; finite element simulation | Free deformation region length, stud diameter, welding method, fatigue loading pattern | With a fixed free deformation length, stiffness did not show significant degradation despite increasing slip; welding method and loading pattern had limited influence; decreasing the ratio of free deformation length to diameter reduced equivalent section bending stiffness and increased shear deformation significance | Concluded that compressive damage of surrounding concrete is the primary and direct reason for shear stiffness degradation under unidirectional low-cycle fatigue loading rather than plastic damage in steel |
| Liu et al. [79] | Static and fatigue push-out tests on short studs in engineered cementitious composites, 9 specimens | Stud behavior under cyclic load in engineered cementitious composites | Proposed a relationship between stress range and number of cycles to failure corresponding to 95% survival probability; American Association of State Highway and Transportation Officials shear capacity agreed with tests, while Eurocode 4 and the Chinese code underestimated; slip capacity satisfied Eurocode 4 ductility requirement | Empirical expressions for fatigue load to slip behavior were derived |
| Hanswille et al. [3] | High-cycle unidirectional loading push-out tests | Loading sequence and damage accumulation | Observed early reduction of static strength after only 10% to 15% of fatigue life due to crack initiation at the stud foot | Demonstrated that linear damage accumulation is not sufficient, motivating modifications |
| Hanswille et al. [80] | Reanalysis of international push-out tests and development of prediction models | Peak load and static strength effects | Developed analytical predictions for fatigue life and reduced static strength after high-cycle preloading; modified Palmgren–Miner damage rule to consider load sequence and nonlinearity | Basis for later code-level fatigue relationships |
| Higashiyama et al. [24] | Rotating shear fatigue tests on studs welded with improved ferrules | Concrete strength | Fatigue strength increased with higher concrete strength; two failure modes were observed; average relationships between stress range and number of cycles to failure were established for the improved studs | Specialized rotating shear loading machine used |
| Xiao et al. [81] | Push-out tests on 36 headed stud specimens influenced by freeze–thaw cycles and artificial corrosion; concrete property tracking | Number of freeze–thaw cycles; presence and degree of artificial corrosion | Both freeze–thaw cycles and artificial corrosion deteriorated stud shear capacity and stiffness; failure modes shifted between stud breakage and concrete cracking with increasing severity; a reduction factor equation for capacity was proposed based on nonlinear fitting | Concrete cubic strength, dynamic elastic modulus, and mass loss were measured |

(Continued)

**Table 2 (continued)**

| Study | Research Methodology | Main Variables Studied | Research Findings | Remarks |
|---|---|---|---|---|
| Wei et al. [82] | Push-out tests on 36 miniaturized specimens after freeze–thaw cycles; concrete tests | Number of freeze–thaw cycles | Shear capacity and stiffness decreased as the effect of freeze–thaw cycles increased; failure mode changed between stud shearing and concrete cracking as exposure intensified; a revised calculation method that accounts for freeze–thaw cycles was suggested | Results tied to concrete performance degradation after cycles |
| Wu et al. [28] | Development of full range stress to strain models for studs at low temperatures using 56 tensile tests; validation on pull-out and push-out specimens | Temperature from 20°C down to −80°C | Constitutive models accurately captured stress to strain behavior across temperature range; pull-out and push-out validations were successful | Continuum damage plasticity and stress-modified critical strain models were calibrated |
| Yan and Xie [83] | Material to member level study at low temperatures including four-point bending on composite beams at 20°C, −30°C, and −60°C | Temperature effects on concrete, studs, and beams | Decreasing temperature from 20°C to −30°C and −60°C increased ultimate beam strength by 10% and 24% respectively; stud shear and tensile resistances increased as temperature decreased, with differing effects on ductility | Prediction equations incorporated temperature effects |
| Xie et al. [27] | Pull-out tests at low temperatures, 16 specimens; finite element models | Temperature level, concrete grade, ratio of embedment depth to stud diameter | Lower temperature improved tensile capacity of studs due to increased strengths of concrete and steel; the ratio at which failure changed from concrete breakout to stud shank fracture varied from 3.56 to 5.75 depending on temperature | Code design equations were checked against tests |

## 5 Numerical, Analytical, and Data-Driven Modeling

The study of steel-headed studs in composite structures has long been supported by numerical and analytical investigations, Table 3. Experimental work has established fundamental behavior, yet the complexity of material interaction and load transfer processes has driven the need for computational and theoretical models. Numerical analysis, finite element simulation, analytical formulations, and more recently data-driven modeling have been widely used to estimate stud resistance, slip development, and failure modes. Collectively, these methods have expanded the understanding of stud performance under diverse conditions, complementing the breadth of experimental research [17,18,20].

### *5.1 Numerical Approaches*

Finite element analysis has been indispensable in investigating the detailed behavior of headed studs. The ability to capture local stress concentrations, bond conditions, and slip mechanisms has provided a powerful tool to complement experiments. Finite element studies of studs in UHPC have examined how material strength and stud geometry influence shear resistance, producing simulations consistent with push-out observations [17,19]. Numerical studies on grouped large-headed studs in UHPC also extended this line of work, offering computational evidence on stiffness, slip progression, and resistance under different embedment conditions [40].

Other finite element research addressed low-temperature conditions, with models of stress–strain behavior at subzero temperatures calibrated to laboratory measurements [28]. These simulations have contributed to a better representation of performance in Arctic infrastructure [5,27]. The role of head diameter has been considered in numerical investigations of tensile capacity, with simulations confirming the influence of geometry on pull-out resistance [35].

Computational modeling has also been applied to profiled steel sheeting, where the shear resistance of studs with ribs transverse to supporting beams was addressed through advanced finite element models [34]. Recent work further examined profiled steel sheeting under fire and elevated temperature through combined testing and numerical evaluation [36]. Finite element studies have been extended to eccentric loading, inclined shoulders, and complex composite systems, demonstrating the adaptability of numerical modeling to a wide variety of structural contexts [84,85]. Numerical models have also supported design recommendations for grouted joints in precast elements [85].

While monotonic loading has been widely analyzed, numerical models have also addressed cyclic and fatigue demands. Simulations of low-cycle fatigue behavior have provided estimates of stiffness degradation in studs [23]. Other numerical studies assessed cyclic slip and strength degradation in grouped studs under repeated shear [48,73], as well as studs embedded in composite frames with reinforced infill walls [50]. Fatigue behavior under bridge loading conditions was also examined through computational studies [51].

Numerical modeling has extended to seismic and bridge applications, including double skin composite shear walls with overlapped studs [15], steel–concrete joints under combined loading [78], demountable composite beams [86], and adaptive systems with bolts and studs [43,45]. Other studies addressed UHPC bridge repairs [9,10] and railway bridge decks [42].

Advanced numerical investigations also considered hybrid and innovative systems, including steel tubular stub columns stiffened by studs [87], composite slabs with varied rib geometries [88], and I-shape connectors compared with studs [66]. Durability-related simulations evaluated corrosion behavior in UHPC and normal concrete [18,19], while numerical studies on insufficient concrete consolidation at stud roots highlighted construction-related effects on performance [71].

### *5.2 Analytical Approaches*

The earliest analytical formulations addressed the shear capacity of headed studs through simplified resistance models linking stud strength to shear area and embedment properties [1,89]. These formulations provided foundational equations for design codes and served as a starting point for subsequent refinements. Analytical predictions were commonly calibrated against push-out and pull-out results, with models designed to capture monotonic deformation under shear [20]. Analytical studies also addressed fatigue resistance, translating experimental patterns into predictive resistance models for repeated loading [3,80]. Later efforts examined the effect of reinforcement detailing, proposing analytical descriptions of how reinforcement influences slip distribution and shear transfer across the steel–concrete interface [16]. Some approaches extended to grouped studs, suggesting equivalent diameter models and analytical simplifications for collective arrangements [14,48,55]. These developments reflect the progressive incorporation of experimentally observed complexities into analytical formulations. Analytical models developed for fatigue loading were often used alongside numerical simulations to enable long-term resistance predictions [3,24,80].

### 5.3 *Data-Driven Approaches*

The expansion of data-driven methods has introduced a new dimension to predictive modeling of headed studs. Machine learning algorithms have been trained on experimental datasets to estimate shear resistance, offering alternatives to purely analytical formulations. Ensemble modeling strategies were applied to predict shear resistance under varied material and geometric inputs [22], while interpretable machine learning approaches aimed to provide transparent predictions for precast steel–concrete structures [30]. Other studies emphasized the potential of computational intelligence in predicting stud resistance [29]. Grouped connectors have also been examined using soft computing, where analytical predictions were complemented by machine learning-based formulations [31]. Artificial intelligence applications in related domains, such as gene expression programming for shear capacity of corrugated web steel beams, indicate transferable methodologies for shear connectors [90]. Machine learning-based stiffness estimation in reinforced concrete members further demonstrates cross-disciplinary relevance [33,91]. Reviews of physics-informed neural networks highlight the expanding role of AI in structural mechanics [92]. Several studies explicitly combined numerical, analytical, and data-driven approaches. Experimental-numerical comparisons on studs in UHPC validated finite element predictions while providing benchmarks for analytical models [11,18]. Hybrid approaches integrating machine learning with analytical features sought to balance interpretability and predictive accuracy [22,30]. Design recommendations for grouped studs were supported by numerical validation of analytical simplifications [14,48].

**Table 3:** Summary of research efforts on analytical, numerical, and data-driven modeling of headed studs.

| Study | Aim | Research Methodology | Research Findings | Remarks |
|---|---|---|---|---|
| Xu and Liu [20] | Development of equations for shear stiffness and for the load to slip relationship of headed studs | Evaluation of 154 monotonic push-out tests from the literature | Shear stiffness equation is applicable for stud diameters from 10 to 30 mm and for concrete cylinder compressive strength from 22 to 200 MPa; the load to slip equation predicts both small slip and large slip ranges | The stiffness parameter is embedded directly in the load to slip formulation for design use |
| He et al. [93] | Prediction of elastic shear stiffness of studs and influence on elastic behavior of composite girders | Review of 206 monotonic push-out tests across several concrete types; analytical derivations for girder response | Shear stiffness defined as the secant stiffness at one half of ultimate load; accuracy reported for stud diameters from 10 to 30 mm and concrete compressive strength from 22 to 200 MPa | Recommendations given for shear stiffness levels required to reach behavior close to fully connected conditions in elastic design |
| Jebara et al. [94] | Empirical and semi-empirical prediction of concrete pry-out capacity for headed studs and post-installed anchors | Database of 214 monotonic shear tests and comparisons with a European standard | Proposed formulations account for stud diameter and for spacing within anchor groups, with emphasis on low ratios of embedment depth to diameter smaller than 4.5 | Scope includes single and grouped studs attached to stiff steel plates and shear connectors without metal deck |
| Cao and Shao [17] | Finite element simulation of studs embedded in thin ultra high performance concrete with validation | Simulation results compared to tests for load to slip curve, shear strength, and failure mode | Analysis indicates that contribution of the weld collar should be considered when evaluating shear strength for studs in ultra high performance concrete | Parametric study covered stud diameter, stud height, and concrete strength |

(Continued)

**Table 3 (continued)**

| Study | Aim | Research Methodology | Research Findings | Remarks |
|---|---|---|---|---|
| Bonilla et al. [95] | Nonlinear finite element model for studs welded through profiled steel sheeting ribs | Verification against experimental push-out data from the literature | Identified cases where design rules from American and European codes either underestimated or overestimated resistance | Concrete modeled with damaged plasticity; parametric study examined stud position in the rib and concrete strength |
| Bonilla et al. [96] | Finite element prediction of shear resistance for studs in profiled sheeting under static load | Comparison against many experimental push-out results | New resistance formulations improved prediction relative to American and European code provisions | Multiple physical and mechanical parameters were included in the model calibration |
| Ellobody and Young [97] | Finite element modeling of studs welded through profiled steel sheeting with transverse ribs | Validation against experiments and comparison with American, British, and European design rules | American and British rules overestimated capacity; European rules were generally conservative | Material nonlinearities were included for concrete, studs, sheeting, reinforcement, and beam |
| Mirza and Uy [98] | Finite element modeling to study effects of concrete strain regime on studs in solid and profiled slabs | Validation against independent experimental programs | Strength and load to slip behavior are strongly influenced by the strain regime within the concrete slab | Provides rationale for differences between solid slabs and profiled slabs |
| Yan et al. [99] | Low-temperature finite element parametric study for shear resistance in sandwich composite structures | Validation with 54 previously reported tests; parametric simulations on 96 connectors | Temperature-dependent enhancement factors for steel and concrete were integrated into a Eurocode 4 style resistance estimate | Both material and geometric nonlinearities were included |
| Xie et al. [27] | Finite element modeling of tensile pull-out behavior of studs at low temperatures | Validation against 16 pull-out tests from 20°C down to −80°C | Predictions checked against tests; code equations for tensile resistance were compared with test results | Temperature influenced the transition between concrete breakout and stud shank fracture |
| Wu et al. [28] | Constitutive modeling for headed studs at low temperatures using continuum damage plasticity | Calibration with 56 tensile tests; validation on 6 pull-out and 8 push-out specimens | Proposed stress to strain and stress-modified critical strain models accurately reproduced behavior over 20°C to −80°C | Models were implemented in finite element analysis for cold region applications |
| Baek et al. [100] | Mechanism-based modeling of hybrid connectors composed of headed studs and shear plates | Push-out testing supported by finite element analysis | Peak strength governed by concrete bearing of the shear plates; residual strength predicted by stud shear or by shear friction of reinforcing bars | Clarified the sharing and transition of resistance among mechanisms |
| Choi [26] | Fire-condition modeling and testing for studs in solid and transverse profiled slabs | 12 push-out tests in a custom furnace following a standard fire curve | European guidance for transverse profiled slabs at elevated temperature was highly conservative; a new design formula was proposed when stud shearing governs | Failure mode changed with temperature from concrete dominated to stud shearing |

(Continued)

**Table 3 (continued)**

| Study | Aim | Research Methodology | Research Findings | Remarks |
|---|---|---|---|---|
| Hu et al. [101] | Interpretable machine learning model to predict shear strength of studs in ultra high performance concrete | 577 push-out tests; unsupervised anomaly detection used to remove outliers; multiple algorithms trained | The best model achieved a correlation coefficient equal to 0.97; a new prediction equation was established from the model and curve fitting | Most influential variable was stud cross-sectional area, followed by properties of ultra high performance concrete and stud tensile strength; interpretation used partial dependence plots, individual conditional expectation, and Shapley additive explanations |
| Zhou et al. [102] | Machine learning analysis of shear capacity for studs in steel to ultra high performance concrete composite structures | 194 experimental and numerical push-out results | Random forest and extreme gradient boosting achieved a coefficient of determination greater than 97% on both training and testing sets; empirical formulas were less effective | Most influential variables were stud diameter and stud ultimate strength, followed by stud height and ultra high performance concrete slab thickness; cover thickness and steel fiber volume fraction had little influence; design recommendations addressed group effects and ultra high performance concrete damage |
| Wang et al. [22] | Auto-tuned ensemble learning to predict stud shear resistance with feature engineering | 1092 tests reported as the largest database to date; comparison with multiple codes | Auto-tuned models outperformed a non-tuned model and 3 single models; the probabilistic random forest based tuner was the most accurate and outperformed Eurocode 4, American Association of State Highway and Transportation Officials, the Chinese code, and the Japanese Society of Civil Engineers | Most influential features were stud shank tensile capacity and concrete performance, followed by projected area of the weld collar and longitudinal spacing; a practical application was created for design use |
| Li et al. [25] | Machine learning model for residual shear strength after fatigue for studs in ultra high toughness cementitious composites | Post-fatigue static test results combined with previous research; comparison with a previous model; analysis of variance with 2 factors | Analysis of variance showed that peak load had a significant effect on residual shear strength; the new model was proposed for prediction of static and fatigue behavior including stiffness degradation and plastic slip relationships | Models enable prediction of residual behavior for very thin ultra high toughness cementitious composites layers used in bridge decks |

## 6 Design Provisions, Applications, and Special Topics

The development of design provisions for headed studs has drawn extensively from decades of experimental, analytical, and numerical studies, Table 3. As composite structures became standard in modern construction, the need for codified approaches to predict shear resistance, stiffness, and fatigue life of studs became evident. National and international standards have been shaped by comparative studies, large-scale testing, and reliability assessments that addressed different loading regimes, concrete types, and construction practices [47,77]. More recent contributions have incorporated data from advanced cementitious composites, novel stud geometries, and demountable systems, reflecting the expansion of applications for headed studs in both infrastructure and building sectors [7,45,72,86]. Early design models concentrated on the shear resistance of studs welded into conventional concrete slabs, drawing from push-out and beam tests. Full-scale experiments confirmed the adequacy of simplified shear resistance formulations, which formed the basis for early Eurocode provisions and related national standards [57,89,103]. Refinements followed as research extended to lightweight concrete, profiled steel sheeting, and fatigue conditions, with adjustments introduced into code equations to capture ductility and load-slip characteristics [34,46,104]. Special focus has been given to profiled sheeting, where the rib orientation and depth alter load transfer. Investigations provided evidence that guided Eurocode 4 updates and subsequent recommendations in international guidelines [47,76,77]. Further studies introduced design methods specific to railway bridges and composite decks, acknowledging the distinct load environments and geometric detailing in such applications [42,78]. Work on grouped studs has also influenced design guidelines, with recommendations made to account for collective effects and equivalent diameter approaches validated through finite element comparisons [14,48,49]. Composite bridges rely heavily on stud connectors to maintain composite action under heavy and repeated loading. Early studies demonstrated the fatigue capacity of studs in bridge girders, shaping design approaches that address cyclic performance [3,51,75]. More recent experimental and numerical efforts considered studs embedded in UHPC decks, reflecting the adoption of advanced concretes in bridge rehabilitation and new construction [9,19,37]. Research on post-installed connectors has supported bridge retrofitting practices, providing comparative data on coiled spring pins and welded studs for in-service strengthening [44]. Studies that examined the effect of external pressure on push-out behavior also aligned closely with bridge contexts, where environmental and traffic-induced effects can modify shear transfer [105]. Furthermore, machine learning–based predictive models for stud resistance have been tested with bridge applications in mind, offering supplementary approaches for design reliability in complex structures [22,29,30]. Composite floors in buildings often employ studs in profiled sheeting, where their placement governs overall slab–beam performance. Research into trapezoidal sheeting and rib orientation provided experimental data for design provisions specific to these systems [34,47,88]. Studies comparing studs with high-strength bolts in prefabricated decks extended the scope of applications, offering evidence for alternative connectors in modular construction [43,54]. Precast systems represent another important application, with research addressing short studs in grouted joints of composite girders [85]. These investigations highlighted the role of connector detailing in achieving effective load transfer in modular construction. Applications in seismic regions have received growing attention, particularly for double skin composite shear walls that incorporate overlapping studs [15,106]. Experimental evaluations of studs in infill walls and their monotonic shear performance further confirmed the relevance of these connectors in lateral load–resisting systems [50,73,107]. Such applications underline the adaptability of headed studs across building systems subjected to combined axial, shear, and seismic demands. Design provisions have expanded to address the adoption of UHPC and other high-performance materials. Static and fatigue testing of studs in thin UHPC slabs provided results that informed resistance models distinct from those used for normal concrete [4,17,38]. Further testing in steel–UHPC systems refined understanding of load transfer, allowing recommendations for shear strength and stiffness in emerging structural systems [11,108]. Push-out tests on studs in engineered cementitious composites demonstrated the impact of strain-hardening properties on shear resistance, supporting design considerations for such materials [13,53]. Comparative research on studs embedded in geopolymer concretes reinforced with steel fibers also contributed experimental evidence for specialized concrete types [109]. Additional investigations into UHPC containing different aggregate sizes have continued to inform design adjustments [110]. Group arrangements of studs have long been a challenge in design practice, as close spacing alters shear distribution. Experiments on grouped connectors led to recommendations for design methods incorporating group effects [14,49]. Finite element verification of equivalent diameter concepts provided further validation, highlighting that group behavior differs markedly from isolated stud assumptions [48]. Research into grouped large-headed studs embedded in UHPC offered evidence for specialized design adjustments, particularly in applications requiring concentrated load transfer [40]. Collective behavior under cyclic loads in infill walls demonstrated the significance of group interaction in seismic applications [73]. The inclusion of such findings in guidelines reflects the progression from isolated stud models toward more comprehensive provisions. Design provisions have also expanded to include thermal conditions. Studies on studs in composite beams subjected to fire loading highlighted the reduction in shear capacity at elevated temperatures, shaping guidance for fire-resistant design [26]. Experimental and numerical work on studs embedded in profiled sheeting under elevated temperature extended this focus to contemporary composite systems [36]. Cold regions present contrasting challenges, with studies on stud pull-out and mechanical performance at low temperatures providing data for design under Arctic conditions [5,27,28]. These contributions support provisions that consider environmental extremes in the design of infrastructure systems. Alternative connectors have been studied to address demands for demountability and reusability in modern construction. Research on bolted and stud combinations provided comparative evidence for connections that can be dismantled and reused [86,88]. Additional work on demountable beams highlighted differences in static and fatigue behavior compared with traditional welded studs [74]. Post-installed connectors were assessed in detail, where coiled spring pins were compared with welded studs through push-out tests, contributing to recommendations for retrofit and strengthening solutions [44]. Further investigations into I-shape connectors and ribbed studs extended the experimental evidence for alternatives, supporting applications where traditional studs may be limited [66,72]. Several experimental and numerical studies have examined conditions beyond conventional applications. Investigations on lightweight aggregate concrete provided evidence on stud performance in specialized concretes used for weight reduction [103]. Research on inclined stud geometries investigated through numerical studies expanded potential design variations [84]. Comparative studies between headed studs and other connectors, such as channels and bolts, provided design-related evidence relevant to both prefabrication and retrofitting contexts [43,54,66].

## 7 Discussion and Future Directions

The accumulated body of research on headed studs demonstrates both the progress achieved in understanding their behavior and the gaps that remain in fully codifying this knowledge into universally consistent design provisions. Experimental campaigns have covered a wide range of conditions, from static push-out tests on single connectors to fatigue investigations in bridges, grouped stud arrangements, and applications in ultra-high-performance concrete. These experimental efforts have formed the backbone of design models and code provisions, yet their results are dispersed across varying structural systems, material types, and test conditions. This dispersion has created a challenge for developing generalizable design equations that are consistently conservative but not overly restrictive. The variability across regional standards illustrates this ongoing difficulty, with Eurocode provisions differing in important respects from other international guidelines, particularly in their treatment of profiled sheeting, grouped connectors, and fatigue resistance. A recurrent theme across studies is the sensitivity of stud performance to surrounding concrete properties. Research on ultra-high-performance concrete, engineered cementitious composites, and fiber-reinforced matrices has shown that advanced materials modify load transfer and slip response in ways that traditional models do not fully capture. While some studies propose adjusted resistance models, incorporation of these findings into mainstream codes remains limited. The integration of new materials into design provisions will require not only additional experimental testing but also coordinated efforts to reconcile findings across different laboratories and loading conditions. Without such synthesis, design practice risks lagging behind construction practice, especially as UHPC and other advanced concretes gain wider adoption in bridge decks and prefabricated elements. Fatigue and long-term durability are also areas where progress has been made but uncertainties remain. Early fatigue research provided essential data for bridges, and more recent investigations on studs in UHPC and ultra high toughness cementitious composite (UHTCC) have expanded this knowledge. However, questions persist regarding performance under combined loading conditions, such as when cyclic shear is superimposed on sustained loads or environmental degradation. Durability studies on corrosion, freeze-thaw exposure, and fire conditions have highlighted vulnerabilities in stud performance, particularly when cracks form in the surrounding concrete and accelerate deterioration. Incorporating these effects into design remains an open challenge, as codes typically treat durability through safety factors rather than direct modeling of degradation. The rise of computational and data-driven modeling presents opportunities for addressing these complexities. Finite element models have advanced to the point where local slip distribution, stress concentration, and group effects can be studied in detail. Machine learning applications have begun to provide predictive models trained on large experimental datasets, offering the potential for more adaptable design tools. However, the adoption of such methods into practice will require transparent and interpretable approaches that engineers can apply with confidence. While interpretable machine learning methods have been proposed, their role in official design provisions is still at an early stage. Integration of analytical, numerical, and data-driven methods appears to be the most promising pathway for future design frameworks, enabling the strengths of each approach to compensate for the weaknesses of the others. Practical applications in bridges, prefabricated systems, and seismic design continue to broaden the contexts in which headed studs are deployed. Research on demountable systems and alternative connectors illustrates how the design of composite structures is shifting toward adaptability and reuse, rather than permanent connections alone. This shift introduces new challenges in design provisions, as demountable systems must balance mechanical performance with reusability, introducing failure mechanisms not present in welded studs. The comparative studies between studs and alternative connectors provide useful data, but their codification remains incomplete. The effect of grouped studs remains one of the more complex design issues. Collective behavior deviates significantly from isolated assumptions, and despite decades of work, the prediction of resistance in dense stud groups remains less precise than desired. Equivalent diameter methods and finite element validations have improved predictive capability, yet questions persist about their applicability across different concrete types and reinforcement conditions. This suggests the need for further systematic research that consolidates group behavior into reliable design models. Special topics, including stud performance under fire and at low temperatures, have been the focus of targeted research. While fire testing has provided essential data on resistance reduction, and Arctic studies have examined low-temperature mechanical properties, these conditions are often treated as exceptions in design codes rather than systematically integrated. As climate-related hazards and environmental extremes increasingly influence structural demand and deterioration, design models for headed studs will benefit from more explicit treatment of temperature effects, freeze-thaw exposure, corrosion progression, and their interaction with cyclic loading, rather than relying mainly on global safety margins.

Looking ahead, the evidence synthesized in this review supports several prioritized research directions that can be translated into actionable studies and code-facing outcomes. Harmonization efforts should begin with consistent definitions of key response metrics across laboratories, particularly shear stiffness definitions, slip measurement conventions, and fatigue damage indicators, because inconsistent definitions remain a major driver of apparent discrepancies when results are compared across studies. Advanced concretes such as UHPC, ECC, and UHTCC require resistance models that explicitly account for changed failure tendencies and weld-region effects observed in several experimental programs, and coordinated multi-laboratory datasets are needed to separate material effects from test-setup effects. Grouped stud behavior remains a design-critical gap; future studies should clarify how group interaction varies across concrete types and reinforcement layouts and should establish ranges where equivalent-diameter approaches remain reliable. Durability under mixed actions is another priority; research should quantify how corrosion and freeze-thaw exposure alter fatigue resistance and stiffness degradation when cyclic shear is combined with sustained service loading. Data-driven prediction has demonstrated high accuracy in recent studies, yet design adoption depends on external validation, uncertainty quantification, and interpretability; future work should therefore report transparent feature definitions, provide open benchmarking against code equations, and evaluate model robustness under out-of-distribution cases such as thin UHPC layers, dense stud groups, and extreme temperatures. Finally, the growing push toward modularity and reuse motivates focused work on demountable and hybrid connector systems, where mechanical performance must be assessed together with constructability, inspectability, and reliable long-term behavior.

## 8 Conclusion

This study addressed the gap in the literature regarding a comprehensive review of headed stud behavior in steel-concrete composite structures that combines systematic technical synthesis with bibliometric mapping of research trends. The review consolidated experimental evidence on monotonic, cyclic, fatigue, and environmentally influenced behavior together with analytical, numerical, and data-driven modeling approaches, and it connected these findings to design provisions and practical applications discussed in bridges, buildings, prefabricated systems, seismic components, and emerging demountable solutions.

The synthesized evidence indicates that stud geometry, detailing, and surrounding concrete type remain primary drivers of strength, stiffness, slip response, and governing failure mechanisms, and that grouped stud interaction and boundary conditions can produce deviations from isolated-stud assumptions that are design-relevant. Advanced concretes such as UHPC and ECC can increase stiffness and alter failure tendencies, yet these effects are not consistently reflected in standard design approaches across regions. Modeling capability has advanced substantially through nonlinear finite element simulations and data-driven prediction; however, practical adoption depends on transparent definitions, external validation, and robust treatment of uncertainty, especially for dense stud groups, thin UHPC layers, and environmental extremes.

The limitations of this study lie primarily in reliance on published literature without access to unpublished experimental programs and proprietary test databases, which may limit the completeness of reported datasets. In addition, heterogeneity in test protocols and response definitions across laboratories limits direct quantitative aggregation, particularly for stiffness measures and post-peak behavior. From an application perspective, the findings support more informed connector selection and detailing for composite members, highlight where durability and mixed-action demands require explicit consideration, and indicate where design checks may be sensitive when advanced concretes or demountable systems are adopted. Future research should prioritize harmonized experimental reporting, coordinated multi-laboratory studies on grouped studs and advanced concretes, explicit modeling of degradation under mixed actions, and interpretable predictive tools that can be benchmarked against and ultimately support updates to design provisions.

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