



A Comprehensive Review of Chemical Anchor Bolt Behaviour in Concrete Structures: Performance, Loading Conditions, and Design Considerations

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Abstract

Chemical anchor bolts have become indispensable in modern construction for post-installation connections in concrete structures, particularly in curtain wall engineering, structural renovation, and seismic retrofitting. This review synthesises findings from five key studies examining the anchoring performance of chemical anchor bolts under various conditions including static loading, cyclic loading, combined tensile and shear loadings, and varied embedment depths and concrete strengths. The reviewed literature collectively demonstrates that, pullout capacity increases with both bolt diameter and concrete compressive strength up to a critical threshold, failure modes transition from anchor pullout to concrete splitting as concrete grade or bolt size increases, cyclic loading degrades bond-anchorage performance, with variable amplitude loading causing greater damage than constant amplitude loading, embedment depth of 15D consistently yields optimal pullout resistance across all concrete strengths and the shear-tension interaction formula prescribed by ACI 318-14 is overly conservative for chemical anchor bolts embedded in high-strength concrete. Key findings suggest that for curtain wall engineering, a C40 concrete substrate with M14 anchor bolts offers the best balance between structural performance and material utilisation. This review identifies research gaps and provides design guidance for practitioners and future investigators.

Keywords: Chemical anchor bolt, Pullout capacity, Cyclic loading, Embedment depth, Failure mode, Shear-tension interaction



I. INTRODUCTION

Chemical anchor bolts post-installed anchors bonded to concrete using epoxy or vinyl-ester adhesives have rapidly displaced traditional cast-in-place embedded anchors across a broad spectrum of construction applications. Their principal advantages are flexibility of positioning after concrete has cured, reliable load transfer, rapid installation, and adaptability to design changes that arise during construction. These attributes have made chemical anchors the preferred connection method in building curtain wall engineering, bridge rehabilitation, high-rise structural retrofitting, and lifeline infrastructure projects.

The force path in a typical curtain wall system passes from cladding panels through the supporting keel framework to the chemical anchor bolt and ultimately into the primary concrete structure. This load path places chemical anchors under complex combinations of tension and shear, sometimes with superimposed cyclic components from wind or seismic action. A thorough understanding of their load-carrying mechanisms, failure modes, and performance limits under each loading scenario is therefore essential to safe and economical design.

Despite the prevalence of chemical anchors in practice, the research landscape has historically been fragmented. Early investigations concentrated on monotonic tension behaviour and the derivation of code-compliant design equations (Cook et al., 1993, 1998). Subsequent work addressed group anchor effects (Xie and Lu, 2009; Quan et al., 2017), shear performance (Eligehausen et al., 2006; Lynch and Burdette, 1991), high-temperature effects (Wan et al., 2010, 2013), and bond quality in high-performance concrete (Barnat et al., 2012). More recently, combined tensile-shear behaviour has received attention (Zhou and Yang, 2024), as have numerical modelling approaches that reduce the need for costly physical tests (Rosyidah et al., 2022).

The present review synthesises findings from five peer-reviewed studies published between 2012 and 2024, each examining a distinct aspect of chemical anchor bolt performance. Together, they span: (a) static pullout performance as a function of concrete grade and bolt diameter in curtain wall applications, (b) cyclic pullout

behaviour under repeated loading at different stress levels, (c) numerical modelling of pullout force as a function of embedment depth and concrete compressive strength; (d) bond strength characterisation of chemical anchors in high-strength concrete, and (e) behaviour under combined tensile and shear loading. The review identifies areas of consensus, highlights discrepancies, and recommends directions for future research.

II. LITERATURE REVIEW

a. Historical Development of Chemical Anchor Research

The behaviour of chemically bonded anchors was systematically investigated from the early 1990s. Cook et al. (1993) proposed a bond stress model for adhesive anchors and demonstrated that failure mode either concrete cone, bond failure at the adhesive-concrete interface, or mixed depends on the ratio of anchorage length to bolt diameter. This foundational work was extended by Cook et al. (1998), who established design equations for single adhesive anchors in uncracked concrete under tensile load. Fuchs et al. (1995) introduced the Concrete Capacity Design (CCD) method, which became the basis for code provisions in ACI 318-14 and European Technical Guideline ETAG 001.

Research on group anchors quantified the interaction between adjacent bolts. Xie and Lu (2009) showed that group anchor capacity is sensitive to edge distance and anchor spacing, while Quan et al. (2017) investigated shear failure modes of single, double, and four-anchor configurations. Studies on high-temperature performance (Wan et al., 2010, 2013) revealed that bond strength degrades as temperature increases, with the rate of degradation dependent on adhesive composition. Richardson et al. (2019) further showed that fibre reinforcement of the concrete matrix has negligible influence on pullout capacity at ambient temperatures but may confer some benefit under fire conditions.

b. Parameters Governing Pullout Capacity

The tensile bearing capacity of a chemical anchor is jointly determined by: (i) the geometry of the anchor



(diameter d , effective embedment depth h_{ef}), (ii) the mechanical properties of the adhesive, (iii) the compressive strength of the concrete substrate and (iv) the integrity of the drilled hole. Xu et al. (2020a) confirmed experimentally that, for the same concrete grade, pullout force increases monotonically with bolt diameter from M12 to M18 with the notable exception of M16 bolts in lower-grade concrete, where the splitting cone geometry produces anomalous results. Concurrently, at the same bolt diameter, pullout force increases with concrete grade from C30 to C60. Rosyidah et al. (2022) used ANSYS finite element modelling to demonstrate that an embedment depth of 15D consistently maximises pullout force, outperforming 5D and 10D embedments across all concrete strengths from 20 to 60 MPa.

The role of the adhesive is equally important. Barnat et al. (2012) conducted bond strength experiments in high-strength concrete (C55/67 and above) using both commercial epoxy and experimental formulations. Their principal finding was that in high-performance concrete, bond strength is limited by the properties of the adhesive rather than the concrete a critical departure from the behaviour in ordinary concrete, where concrete failure governs. This insight implies that the use of standard adhesives with high-strength concrete is inefficient and potentially unsafe if design equations calibrated for ordinary concrete are applied.

c. Failure Mode Classification

The literature identifies three primary failure modes for chemical anchors under tensile load: (1) anchor pullout, in which the bolt separates from the adhesive while the concrete remains intact, (2) concrete cone failure, in which a cone of concrete is extracted around the anchor and (3) concrete splitting failure, in which radial cracks propagate from the anchor location to the surface of the specimen. Xu et al. (2020a) observed that anchor pullout governs for small-diameter bolts (M12, M14) in low-grade concrete (C30, C40), while concrete splitting dominates for M16 and M18 bolts in any concrete grade and for any bolt diameter in C50 and C60 concrete. This pattern is consistent with the theoretical prediction that splitting failure becomes more likely as the ratio of bolt stiffness to concrete stiffness increases.

Rosyidah et al. (2022) found numerically that all embedment depths initially produce concrete cone failure, progressing to steel bolt fracture at greater depths. This contrasts with the experimental findings of Xu et al. (2020a), reflecting differences in specimen size,

boundary conditions, and bolt material. The Barnat et al. (2012) work on high-strength concrete revealed a distinct glue failure mode fracture at the steel-adhesive interface that is not typically modelled in code-based design.

d. Cyclic and Repeated Loading

Curtain walls and other building envelopes experience cyclic loading from wind pressure, thermal cycling, and seismic ground motion. Xu et al. (2020b) conducted repeated pull-out tests at stress levels of 60%, 75%, and 90% of the static ultimate capacity (F_m) using 30, 50, and 100 loading cycles, together with variable-amplitude loading. Key findings were: at 90% F_m , pull-out failure occurred suddenly within 30 cycles; at 60% and 75% F_m , bearing capacity actually increased slightly after the specified number of cycles, with concrete splitting as the failure mode, variable-amplitude loading caused a 42.1% increase in slip and a 12% reduction in bearing capacity compared to static loading.

These findings have important design implications. The incremental damage model implicit in S-N (stress-number of cycles) fatigue design is not directly applicable; instead, the accumulated slip at the adhesive-concrete interface is the governing damage parameter. The hysteresis curves reported by Xu et al. (2020b) are shuttle-shaped without pinching, indicating good energy dissipation capacity a desirable property in seismic applications. However, energy dissipation per cycle decreases with increasing cycle count, particularly at high stress levels.

e. Combined Tensile and Shear Loading

In practice, chemical anchors are rarely subjected to pure tension or pure shear. Zhou and Yang (2024) investigated the combined loading behaviour of M10 and M12 anchors in C65 concrete through double-shear push-out tests at 0%, 40%, and 80% of the ultimate tension load. Their load-slip curves exhibit four stages: offset friction, anchor slip, overall bearing, and failure. The principal findings were: (i) increasing tension load reduces both yield capacity and ultimate shear capacity (average decreases of 3.07% and 8.44% at $0.4T_u$ and $0.8T_u$ respectively); (ii) horizontal separation between connected members increases with applied tension; (iii) the ACI 318-14 trilinear shear-tension interaction formula is excessively conservative for chemical anchors in high-strength concrete; and (iv) a re-fitted interaction exponent of 3.043 (compared to $5/3$ in ACI 318-14) better represents the experimental data.



The conservatism of ACI 318-14 appears to stem from its calibration against steel anchors in low-strength concrete, where concrete cone failure governs. When the adhesive layer is the critical interface as in high-strength concrete the interaction is less severe. This finding aligns with the Barnat et al. (2012) observation that adhesive properties, rather than concrete strength, are limiting in high-performance substrates.

III. RESEARCH METHODOLOGY OF REVIEWED STUDIES

a. Experimental Approaches

The experimental studies reviewed employed the central drawing (pull-out) test method using a microcomputer-controlled electro-hydraulic servo universal testing machine. Specimens consisted of 150 mm × 150 mm × 150 mm concrete cube blocks with a single anchor bolt installed by drilling, cleaning, injecting adhesive, and inserting the bolt. The loading rate was maintained at 2 mm/min in accordance with Chinese standard GB/T 50081-2002 for static tests. Dial indicators and displacement transducers measured slip at the loading end throughout each test.

Xu et al. (2020a) produced 48 specimens across 16 groups combining four concrete grades (C30, C40, C50, C60) and four bolt diameters (M12, M14, M16, M18), using epoxy-based adhesive with a compressive strength of 60 N/mm² and tensile strength of 18 N/mm². Xu et al. (2020b) fabricated 33 specimens (11 sets of 3) of M12 bolts in C40 concrete to investigate repeated loading. The repeated loading protocol comprised three equal-amplitude stress levels (60%, 75%, 90% F_m) with up to 100 cycles each, plus one variable-amplitude series increasing by 5 kN per level.

Zhou and Yang (2024) employed a double-shear push-out configuration with H200 × 200 × 8 × 12 steel beams and concrete slabs (480 × 380 × 200 mm) of C65 grade. Constant tension loads of 0.4T_u and 0.8T_u were maintained by transverse jacks while shear load was applied monotonically at 5 kN/min. Strain gauges on embedded reinforcing bars and displacement gauges at anchor height monitored specimen response.

b. Numerical Modelling

Rosyidah et al. (2022) modelled chemical anchors in ANSYS Workbench using tetrahedral mesh elements (15 mm size) for all components (concrete, anchor, epoxy).

Material nonlinearity was captured through isotropic elasticity with strength parameters derived from ACI 363R and SNI 2847-2019. Three embedment depths (5D, 10D, 15D) and five concrete strengths (20–60 MPa) were analysed for a 16 mm diameter anchor rod (ASTM F568M Grade 5.5) using Polyamide epoxy grout. Boundary conditions imposed fixed support on the concrete top surface. Maximum pullout force was determined at the onset of concrete cone failure using the reaction probe in ANSYS.

Statistical significance of embedment depth effects was evaluated using Kruskal-Wallis and U-Mann Whitney non-parametric tests, because the small sample sizes and non-normal distributions precluded parametric methods. Chi-square values exceeded the critical value of 5.991 (d_f = 2) for all concrete strengths, confirming that embedment depth significantly affects pullout force. Pairwise U-Mann Whitney tests between 5D–15D and 10D–15D pairs returned significance values of 0.021, confirming 15D as the statistically optimal embedment depth.

IV. RESULTS AND DISCUSSION

a. Effect of Concrete Strength on Pullout Capacity

All five reviewed studies confirm a positive relationship between concrete compressive strength and chemical anchor pullout force. In the static tests of Xu et al. (2020a), the average pullout capacities for M12 bolts were 27 kN, 32 kN, 47 kN, and 54 kN for C30, C40, C50, and C60 substrates respectively a 100% increase from C30 to C60. This trend was consistent across M14 and M18 bolt diameters. The numerical study by Rosyidah et al. (2022) predicted maximum pullout forces of 27.0, 53.5, 68.7, 69.0, and 84.4 kN for 20, 30, 40, 50, and 60 MPa concrete at 15D embedment a 212% increase from 20 to 60 MPa.

The relationship is not perfectly linear, however. Rosyidah et al. (2022) found that the increment from 40 to 50 MPa was much smaller than adjacent increments, suggesting a plateau associated with the transition from concrete-governed to adhesive-governed failure. This is entirely consistent with the findings of Barnat et al. (2012), who demonstrated that for concrete above C50/60, the adhesive bond strength not the concrete tensile strength controls capacity. Practitioners should note that specifying high-strength concrete without selecting a correspondingly high-performance adhesive yields diminishing returns.



b. Effect of Bolt Diameter on Pullout Capacity

The influence of bolt diameter is more nuanced than that of concrete strength. In C30 and C40 concrete, Xu et al. (2020a) observed that pullout capacity increased with diameter up to M16 (where concrete splitting governed), then decreased slightly for M18 due to the enlarged drilled hole diameter inducing micro-cracking in the substrate. In C50 and C60 concrete, all bolt sizes produced splitting failure, and capacity increased monotonically with bolt diameter across the M12–M18 range.

The implication for design practice is that there exists an optimal bolt size that maximises the contribution of the adhesive without triggering premature splitting of the substrate. Xu et al. (2020a) concluded that the C40 substrate with M14 anchor bolt is the preferred combination for curtain wall engineering, fully mobilising both adhesive and concrete mechanical properties while avoiding splitting-induced brittleness.

c. Failure Mode Transitions and Design Implications

The observed failure mode is a critical design outcome because it governs the post-peak load-displacement behaviour and thus the ductility of the connection. Anchor pullout failure (observed in C30 and C40 concrete with M12 and M14 bolts) is characterised by a smoothly descending post-peak response with displacements of 4–6 mm at peak load. Concrete splitting failure (observed in higher grades or larger diameters) is sudden and brittle, with a cliff-type load drop to near zero at displacements of only 0.4–0.7 mm. The post-failure residual capacity recovers to approximately 20% of peak (due to mechanical interlock of the split surfaces) before declining as the bolt is extracted.

From a seismic design perspective, the pull-out failure mode is preferable because the progressive, ductile response allows energy absorption and redistribution. The brittle splitting mode, while associated with higher peak load, offers negligible ductility and would be particularly hazardous in ground-shaking scenarios where dynamic amplification can instantaneously exceed the static capacity.

d. Cyclic Loading Behaviour and Energy Dissipation

The repeated loading tests of Xu et al. (2020b) reveal a complex dependence of bond-anchorage performance on both stress level and loading history. At 60% and 75% Fm, 100 cycles of repeated loading caused only modest degradation bearing capacity actually increased marginally, attributed to densification and micro-

interlocking at the adhesive-concrete interface under repeated compressive clamping. Concrete splitting remained the final failure mode in these groups, occurring after the prescribed number of cycles.

At 90% Fm, the anchor bolt was pulled out suddenly within 5 to 26 cycles, with no prior visual warning. This threshold behaviour defines a practical upper bound for service-level cyclic loads: stress levels at or above 90% Fm should not be sustained under repeated loading. The finding aligns with the concept of a fatigue endurance limit, though the number of cycles to failure at intermediate stress levels (75%–90%) requires further investigation.

Energy dissipation per cycle, calculated as the area of the load-displacement hysteresis loop, was stable at approximately 6.19 kN/mm and 7.32 kN/mm for 60% and 75% Fm groups respectively after an initial transient. At 90% Fm, energy dissipation was stable for cycles 1–15 but declined sharply between cycles 15 and 26, presaging imminent failure. This pattern suggests that energy dissipation monitoring could serve as a non-destructive indicator of incipient bond degradation in instrumented field installations.

Variable-amplitude loading, simulating storm or seismic sequences with progressively increasing load intensity, caused significantly greater damage than constant-amplitude loading at comparable average stress levels: peak slip increased by 42.1% and bearing capacity decreased by 12%. This finding has practical importance for curtain wall design in wind-prone or seismically active regions, where the assumption of constant-amplitude loading in traditional fatigue assessment may be unconservative.

e. Embedment Depth Optimisation

The numerical study by Rosyidah et al. (2022) provides systematic, parametrically controlled evidence on the effect of embedment depth across a wide range of concrete strengths. At 15D embedment, pullout forces were 27.2 kN, 53.5 kN, 53.8 kN, 69.0 kN, and 84.4 kN for 20, 30, 40, 50, and 60 MPa concrete respectively consistently exceeding 5D and 10D embedments by substantial margins. At 5D embedment, pullout forces were only 13.8, 13.9, 16.8, 16.9, and 24.3 kN for the same concrete strengths 30%–50% of the 15D values. The near-constant pullout force at 5D across 20–40 MPa concrete indicates that at shallow embedments, the concrete cone geometry is fully formed and additional concrete strength provides negligible benefit.



The statistical analysis confirmed that 15D is the optimal embedment depth, with U-Mann Whitney significance values of 0.021 for comparisons of 5D vs. 15D and 10D vs. 15D across all five concrete strengths. These findings reinforce the prescriptive guidance in SNI 2847-2019, which recommends embedment depths in the range 5D–15D, and argue for adopting the upper end of this range whenever structural headroom permits.

f. Combined Tensile and Shear Loading

Zhou and Yang (2024) provide the most detailed treatment of combined loading behaviour to date for chemical anchors. Their double-shear push-out tests at three tension levels (0, 0.4Tu, 0.8Tu) and two bolt diameters (M10, M12) produced the following trends in a C65 substrate: ultimate shear capacity decreased by 3.07% and 8.44% at 0.4Tu and 0.8Tu respectively; yield capacity decreased more markedly; and horizontal separation between connected members increased from 2.84 mm (shear only) to 4.02 mm (0.8Tu + shear) for M10 bolts.

The load-slip relationship was successfully fitted using an exponential form (Eq. 2) with fitting parameters calibrated for each loading condition and bolt diameter. The fitted shear-tension interaction exponent of 3.043 substantially exceeds the 5/3 exponent prescribed by ACI 318-14, indicating that chemical anchors in high-strength concrete can sustain proportionally more combined loading than the code assumes. The proposed trilinear design expression, which permits full shear capacity and requires a reduced interaction check only when both tension and shear ratios exceed threshold values, offers a more rational and economical design framework.

g. Bond Strength in High-Strength Concrete

Barnat et al. (2012) investigated four adhesive formulations in concrete exceeding C55/67. Their central finding that bond strength is independent of concrete strength in this high-performance regime has significant implications. Current ETAG 001 certification covers anchoring in concrete up to C50/60, and bond strength values for commonly used epoxy adhesives range from 15 to 20 MPa. Using standard adhesives in stronger concrete wastes the concrete's capacity and may not achieve the bond strength assumed in design.

The experimental glue EXP2012/3 achieved a mean shear strength of 35.3 MPa at the steel-adhesive interface, substantially exceeding commercial products. This demonstrates that formulation of higher-

performance adhesives specifically for high-strength concrete is technically feasible and could unlock significant capacity improvements. The key failure mode adhesive fracture at the steel-glue interface rather than at the glue-concrete interface points to the steel surface treatment (thread form, roughness, and coating) as the most promising target for further improvement.

V. CONCLUSIONS

This review has synthesised five experimental and numerical studies on the behaviour of chemical anchor bolts in concrete structures. The following principal conclusions are drawn:

Concrete strength and bolt diameter both positively influence pullout capacity, but their interaction determines the governing failure mode. In lower-grade concrete (C30–C40), anchor pullout failure governs for smaller bolts (M12, M14), yielding ductile load-displacement behaviour. In higher-grade concrete (C50–C60) or with larger bolts (M16, M18), concrete splitting governs, producing brittle, sudden failure with minimal displacement capacity. The combination of C40 concrete and M14 anchor bolt is identified as optimal for curtain wall engineering, providing full utilisation of both adhesive and substrate mechanical properties. Under service loads below 9 kN, no damage occurs; the design failure load is 44 kN anchor pullout a ductile failure mode with desirable safety characteristics. Cyclic loading at stress levels up to 75% of ultimate capacity does not significantly degrade chemical anchor performance; bearing capacity may even increase slightly due to interface densification. At 90% of ultimate capacity, sudden pull-out failure can occur within 30 cycles. Variable-amplitude loading causes more damage than constant-amplitude loading at comparable average stress, with slip increasing by 42.1% and bearing capacity decreasing by 12%. Embedment depth of 15D is statistically optimal across all concrete strength classes from 20 to 60 MPa. Reducing embedment to 5D reduces pullout capacity to 30–50% of the 15D value. Practitioners should specify the maximum practical embedment depth within allowable constraints. In high-strength concrete (C50/60 and above), the adhesive properties rather than the concrete tensile strength govern chemical anchor capacity. Standard commercial adhesives with bond strengths of 15–20 MPa are inadequate for fully utilising high-strength concrete substrates. Development of adhesives with bond strengths exceeding 30 MPa is technically feasible and warranted. The ACI 318-14 shear-tension



interaction formula is overly conservative for chemical anchors in high-strength concrete. A revised interaction exponent of 3.043 (compared to 5/3 in ACI 318-14) better fits experimental data. Under combined loading, chemical anchor bolts retain approximately 80% of their shear capacity even when subjected to 80% of their ultimate tension load.

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