Research on Engineering Structures & Materials
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Research Article

A critical review of structural behavior, torsional performance in reinforced concrete beams having construction joints: Current knowledge and research gaps

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Article Info

Article History:

Received 09 June 2026

Accepted 24 July 2026

Keywords:

Construction joints;
Cold joints;
FRP;
NSM;
Reinforced concrete beams;
Torsional strength

Abstract

This paper investigates related research spanning from 1954 to 2026 focusing on three main areas: the general torsional response of RC beams, the influence of construction joints on mechanical properties of concrete members, and associated analytical and strengthening approaches. The reviewed literature reveals several research gaps: (1) the lack of experimental torsion testing for construction-jointed RC beams; (2) the stress transfer mechanism of the jointed interface under torsional loading is not well understood; (3) the absence of analytical models accounting for jointed discontinuities; (4) the absence of design code provisions addressing torsion in construction-jointed RC members; and (5) the strengthening of construction-jointed RC beams in the presence of torsion has not been experimentally assessed. Previous studies confirm that construction joints can reduce structural performance. Depending on factors such as joint placement, surface preparation, and the time interval between successive pours, construction joints led to 55% reductions in splitting tensile strength, 24% to 83% in the modulus of rupture, and 15% to 59% in the overall load-carrying capacity of structural members. The externally bonded carbon-fiber-reinforced polymer (CFRP) systems have specifically been demonstrated to improve ultimate torsional strength by a range of 40% to 78%. Furthermore, steel-fiber incorporation and near-surface-mounted (NSM) CFRP reinforcement were also identified as effective approaches.

1. Introduction

Construction joints in reinforced concrete (RC) elements are a common consequence of interruptions in the concrete casting process. While extensive research has been conducted on the flexural and shear behavior of RC elements containing such joints, the torsional performance of elements containing these joints has received considerably less attention. However, a critical research gap exists because torsion generates inclined helical tensile stresses along the perimeter of the member. Thus, this may severely influence the structural integrity of the construction joint interface.

Torsion is one of the four main internal forces that act on structural members, along with axial forces, bending moments, and shear forces. Despite the critical role of torsion in maintaining structural integrity, it was largely ignored in the design of reinforced concrete structures until the last few decades of the twentieth century. This has resulted in a number of structural collapses; however, it has also resulted in a substantial increase in the number of research studies related to the behavior of structures under torsion. The consequences of a poorly designed structure are critical since a structure fails severely when it fails in torsion.

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DOI: http://dx.doi.org/10.17515/resm2026-1733st0609rv

One of the factors that make the behavior of structures under torsion complex is the presence of construction joints in structures. Construction joints result from a planned or inadvertent interruption of the casting of concrete. These are a reality in large-scale constructions due to limitations in labor availability, limitations in the availability of formwork, and limitations due to building material shortages. These joints form interfaces where new concrete is placed against old concrete, resulting in a change in the properties of the interface compared to the rest of the monolithic concrete mass. According to the majority of the literature, the weakest plane in a concrete structure is the construction joint, resulting in a decrease in tensile strength, flexural strength, and shear strength of the structure by a small or large amount depending on the characteristics of the construction joint.

The overlap of these two research topics is a critical research gap that needs to be explored. Although a large amount of literature exists on both of these research topics individually, there is a lack of research related to the torsional strength of reinforced concrete structures that have construction joints. To the authors' knowledge, this is the first systematic review to jointly examine the torsional performance of RC beams and the structural influence of construction joints, synthesizing 54 studies (1954–2026) to establish the current knowledge base and to define five specific, previously unarticulated research gaps at this intersection.

2. Methodology

This review followed a structured systematic approach covering identification, screening, retrieval, eligibility assessment, and final inclusion of studies, consistent with PRISMA 2020 reporting principles. The literature search was conducted across Scopus, Web of Science, and Google Scholar using combinations of the following keywords: torsion, torsional strength, reinforced concrete beam, construction joint, cold joint, CFRP, NSM, softened truss model, space truss analogy, and shear-friction. The exact Boolean search string applied across all three databases was: ("reinforced concrete beam" OR "RC beam") AND ("torsion" OR "torsional strength" OR "torsional behavior") AND ("construction joint" OR "cold joint" OR "cast joint"). For Google Scholar, screening was limited to the first 200 results ranked by relevance, given the absence of field-restricted search operators on that platform. The search covered studies published between 1954 and 2026. The initial database search identified 118 records. After duplicate checking, 15 duplicate records were removed, leaving 103 unique records for title and abstract screening. During screening, 22 records were excluded as outside the thematic scope. Accordingly, 81 reports were sought for full-text retrieval. Three reports could not be retrieved in full text, leaving 78 reports assessed for eligibility through the database pathway. In addition, one further record — a study suggested by a peer reviewer during the review process — was identified through other methods and entered directly at the eligibility-assessment stage, bringing the total to 79 reports assessed for eligibility. Of these, 25 reports were excluded for not meeting the quality-assessment threshold or for reporting no usable quantitative torsional or construction-joint-related outcome. Consequently, 54 studies were retained for qualitative synthesis. The study-selection process was reported using the PRISMA 2020 flow diagram framework [54].

Eligibility for inclusion was governed by explicit criteria. Inclusion criteria for the PRISMA-based qualitative synthesis were: (a) peer-reviewed journal articles, conference papers, or theses/dissertations; (b) studies addressing torsional behavior of RC beams, construction-joint effects, torsion analytical/numerical models, or torsional strengthening; (c) studies reporting quantitative experimental, numerical, or analytical results; and (d) studies published in English. Exclusion criteria were: (a) studies with no quantitative torsional or construction-joint-related outcome; (b) duplicate or superseded conference-to-journal publications, with the journal version retained; (c) non-peer-reviewed sources other than theses/dissertations; and (d) studies meeting fewer than two of the four quality-assessment criteria described below.

Design codes and standards, including ACI 318, Eurocode 2, and CSA A23.3, were not counted among the 54 studies included in the PRISMA-based qualitative synthesis. These documents were reviewed separately as supplementary normative sources for comparing existing torsional design provisions and assessing whether current codes explicitly address construction-jointed RC beams under torsional loading.

Quality assessment was conducted using a binary scoring system: each study was scored 1 (met) or 0 (not met) against four criteria — thematic relevance to torsional behavior or construction joints in RC beams, experimental or numerical validity of the reported results, clarity of the methodology and test parameters, and independent corroboration (i.e., whether the reported finding was consistent with, or contradicted by, at least one other independent study) — yielding a composite score of 0 to 4. A minimum composite score of 2/4 was adopted as the inclusion threshold, retaining foundational but older studies (e.g., Waters [43]; Kirillov [29]) that lack modern reporting detail yet remain methodologically sound and widely corroborated, while excluding studies of marginal relevance or unverifiable methodology. To ensure consistency, both authors independently scored a 20% random subsample of the database; percent agreement was 90% (Cohen's κ = 0.80), and discrepancies were resolved by discussion. Individual quality-assessment scores for each of the 54 included studies were recorded by both authors during screening and are available from the corresponding author upon request.

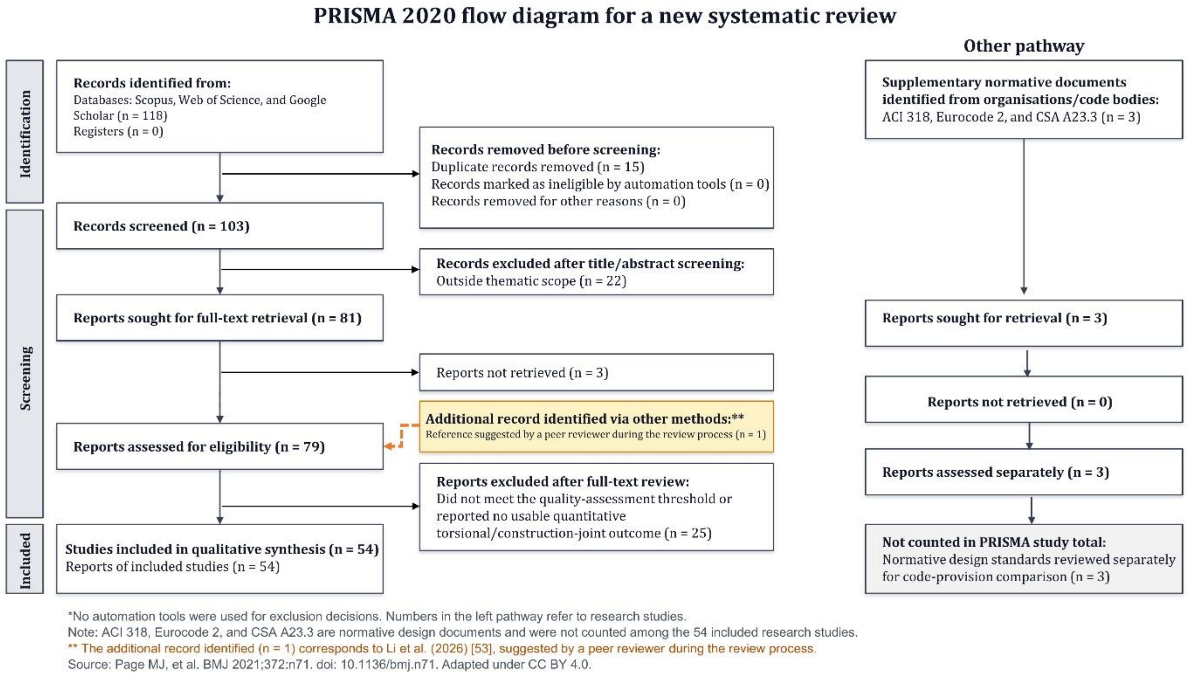

Fig. 1. PRISMA 2020 flow diagram showing the identification, screening, retrieval, eligibility assessment, and final inclusion process of research studies included in the qualitative synthesis. The 54 included studies represent research articles, conference papers, and theses/dissertations only. Design codes and standards, including ACI 318, Eurocode 2, and CSA A23.3, were reviewed separately for code-provision comparison and were not included in the PRISMA study count. Of the 54 included studies, 53 were identified through the database search and one was identified through other methods (a reference suggested by a peer reviewer during the review process). Adapted from Page et al. [54].

Conference papers and theses were not weighted differently from journal articles; all sources were subject to the same quality threshold, and where a conference paper was later published as a journal article, only the journal version was retained. Conflicting results across studies (e.g., Ibrahim et al. [24] versus Abass [1] and Jabir et al. [26], on the directional effect of inclined joints; see Section 4.3) were reconciled by examining differences in loading type, joint orientation relative to the governing crack path, and specimen geometry, rather than treated as contradictory. A research gap was defined as a combination of variables (e.g., torsional loading, construction joint, and strengthening) for which no study meeting the inclusion criteria was identified during the search. Publication bias was partially mitigated by including non-journal sources meeting the quality threshold and by retaining foundational pre-2000 studies; a formal bias assessment (e.g., funnel plot analysis) was not feasible given the heterogeneous, largely non-meta-analytic nature of the underlying data, and this is acknowledged as a limitation of the review. The overall selection process for the 54 research studies included in the qualitative synthesis is illustrated in the PRISMA 2020 flow diagram in Figure 1. Design codes and standards were reviewed separately and were not included in the PRISMA study count.

3. Torsional Behavior of Reinforced Concrete Beams

3.1 Fundamental Mechanisms and Failure Modes

The behavior of a reinforced concrete beam under pure torsion may be described in two different phases, separated by the appearance of diagonal cracks. The pre-cracking phase is characterized by the behavior of a homogeneous elastic material, with all cross-sections contributing to the resistance to torsion by means of circulating shear stresses. The cracking torque, Tcr, is the point at which principal tensile stresses exceed the tensile strength of concrete, typically proportional to the square root of f'c. After cracking, the torsional stiffness is reduced substantially, and the structure enters a post-cracking phase in which the primary mechanism of resistance is the space truss consisting of concrete struts and stirrups, and longitudinal bars. The fundamental work of Gesund and Boston [20] established the importance of dowel action in resisting relative rotation between cracked beam segments subjected to combined bending and torsion. The observation that all cracks initially behave as flexural cracks before reorienting to become diagonal cracks is foundational to the interaction between co-existing loading effects.

A detailed experimental study on 15 RC beams under pure torsion was presented by Chalioris [15], in which a new combined analytical model is proposed by using smeared crack analysis for the pre-cracking phase and the softened truss model for the post-cracking phase. The study confirmed that the volumes of both longitudinal and transverse reinforcement are very important in the torsion behavior of RC members, and the torque-twist curve is characterized by very different stiffness in each phase. This model showed good agreement with the results obtained from the experiments and is one of the more rigorous models available.

Building on earlier torsional strength formulations Rahal [40], an authoritative paper by Kamara and Rabbat [28] presented the provisions of the ACI 318-05 code for the design of reinforced concrete members under torsion, including the design philosophy based on the analogy of the thin-walled tube and space truss models. In the post-cracking phase, the cover concrete is not effective in the design, and the transverse reinforcement and longitudinal bars are arranged around the cross-section. The cracking-torque expression in ACI 318 is $Tcr = 0.33\lambda\sqrt{f'c}\cdot(Acp^2/pcp)$ (f'c in MPa; Tcr in N·mm), per ACI CODE-318-25 Table 22.7.5.1 for a no prestressed solid member without axial force, where Acp is the area enclosed by the outside perimeter of the concrete cross-section, pcp is the outside perimeter of the concrete cross-section, and λ is the lightweight-concrete modification factor (1.0 for normal weight concrete); the threshold torsion Tth, below which torsional effects may be neglected, is given separately in Table 22.7.4.1(a) as $Tth = 0.083\lambda\sqrt{f'c}\cdot(Acp^2/pcp)$, and is set at approximately one-quarter of the cracking torque, $Tth \approx Tcr/4$. The minimum reinforcement is specified for ductility. The need for a 135-degree hook on transverse reinforcement is a reflection of the recognized risk of spalling of the concrete cover under torsion, a risk with the potential to impair anchorage. An alternative approach is represented by the Model of Characteristic Failure Cross Sections (MCFC) and is based on the contrary assumption to that of ACI, where the effectiveness of the concrete cover is recognized. In this alternative approach, cover splitting due to the action of longitudinal bars as a result of their dowel action is recognized as the critical phenomenon in torsional failure, thereby requiring a sufficiently thick concrete cover for the purpose of torsional design. This approach has direct implications for the behavior of beams with construction joints.

While the ACI thin-walled-tube/space-truss approach Kamara & Rabbat [28] and the alternative MCFC framework Windisch [50] agree on the governing role of the post-cracking truss mechanism, they disagree fundamentally on whether the concrete cover contributes to torsional resistance — a disagreement with direct consequences for construction-jointed beams, where the joint plane itself may act as a discontinuity analogous to the spalled-cover condition assumed critical in MCFC.

3.2 Effect of Reinforcement Configuration

The influence of reinforcement in post-cracking torsional behavior is well known. A study by Rashidi and Takhtfiroozeh [39] showed conclusively that neither transverse nor longitudinal reinforcement alone is enough to significantly increase the torsional strength; both should be increased simultaneously to achieve meaningful improvement. Their experiments revealed that the combined presence of transverse and longitudinal bars enhanced the torsional strength by 95% and ductility by 50% as compared to unreinforced specimens, whereby transverse reinforcement played the more critical role. This finding is directly relevant to the design of strengthening schemes for beams with construction joints, where the disruption of the stress field may require offsetting reinforcement in both directions.

Abdullah and Abodi [3] studied the effects of stirrup ratio, steel fiber ratio, and longitudinal reinforcement ratio on high strength concrete beams, verifying that U-wrapped FRP strengthening was less effective than full wrapping or full stirrups for post-peak strength, cracking behavior, and torsional stiffness. Their results showed that the ultimate strength of the aramid fiber strips could be improved by 140%, representing a substantial enhancement achieved by external reinforcement. Mostafa et al. [35] concentrated on high-strength concrete box girders reinforced with GFRP bars, ties, and spirals and found that an increment in the web reinforcement ratio had a significant effect on the post-cracking torsional strength and stiffness. Stirrup rupture at bent portions was the primary cause of failure in the GFRP specimens, a failure mode distinct from that observed in steel reinforced beams and relevant to the design of FRP based torsional strengthening systems. Collectively, these reinforcement-configuration studies indicate that torsional resistance depends on the combined, non-substitutable contribution of transverse and longitudinal reinforcement acting around the full section perimeter; a construction joint that interrupts this perimeter along even one face is therefore expected to compromise the mechanism identified across [39], [3], [35] alike, consistent with additional GFRP-reinforced torsion studies ([21]; [34]).

3.3 Effect of Concrete Properties

Hussein et al. [23] investigated the torsional behavior of beams made of ultra-high-performance concrete (UHPC) and showed that UHPC beams had significantly higher ultimate torsional moments than conventional concrete beams. Even beams with small transverse openings exhibited only marginal strength reductions (1.47%), while larger openings resulted in a 17.65% reduction. Geometric discontinuities can be effectively counteracted by material-level enhancements — a principle with direct relevance to the treatment of construction joints.

Al-Khafaji et al. [7] performed systematic experiments on reinforced self-compacting concrete (SCC) beams under pure torsion and the results showed that plain SCC beams of all strength levels were brittle in failure with cracking torque equal to ultimate torque. The inclusion of reinforcement, and particularly the reduction of stirrup spacing, resulted in significantly increased torques and greater ductility. High strength SCC gave significantly higher cracking and ultimate torques as compared to normal strength SCC. The crack patterns in reinforced beams always took the form of a diagonal spiral at about 45 degrees, which is the characteristic form of torsional cracks. Collectively, Sections 3.1–3.3 indicate that torsional resistance depends on the continuity of diagonal compression struts and the anchorage of transverse reinforcement around the full section perimeter; a construction joint interrupts exactly this continuity along at least one face, providing the mechanistic basis for the vulnerability hypothesis explored in Section 4.

In summary, the reviewed literature establishes that torsional resistance in RC beams is governed by the combined, non-substitutable contribution of transverse and longitudinal reinforcement (Section 3.2), that material-level enhancements such as UHPC can offset geometric discontinuities (Section 3.3), and that all existing models assume a monolithic, homogeneous cross-section (Section 3.1). None of the reviewed torsion-specific studies considered a discontinuous casting interface; this observation directly motivates the investigation of construction joints in Section 4 and underlies Research Gaps 1, 2, and 5 (Section 7).

4. Effect of Construction Joints on Structural Behavior of RC Beams

4.1 Historical and Definitional Context

The earliest systematic study of construction joints in the reviewed literature was by Waters [43] whose seminal work on tensile strength across construction joints established that dry surface conditions at the time of fresh concrete placing will result in better bond than wet or saturated surfaces. His finding that abrasive cleaning methods such as sandblasting yield slightly better results than scabbled surfaces provided an empirical basis for joint surface preparation recommendations that persist in current codes and practice.

Table 1 provides a consolidated overview of the key parameters influencing the behavior of construction-jointed RC beams, forming the basis for the quantitative analysis presented in the following section.

Table 1. Summary of studies on the effect of construction joints (CJ) on RC beam performance

Reference	CJ Type	Loading Mode	Key Variables	Main finding (strength reduction / effect)
[43]	Vertical	Tension	Surface condition	Dry surfaces → better bond than wet; sandblasting slightly superior to scabbling
[29]	Mixed	General	Structural type	15–20% reduction in failure load; proposed design coefficient of 0.85
[5]	Transverse	Flexure	Joint location	Optimal joint in compression zone; tension zone reduces cracking load significantly
[4]	Horizontal	Flexure / FE	No. of joints	3 CJs → cracking load ↓20%, ultimate load ↓16%
[1]	Vertical Inclined Key	Flexure	Type · location · surface prep.	Vertical/key joints: 95% capacity retained; inclined: 8–20% reduction; stirrups increase ultimate load 7–15%
[25]	Vertical	Flexure	Concrete mix	Modulus of rupture: 24–83% reduction (fr = 0.28√f'c vs. ACI 0.62√f'c)
[19]	Vertical	Split tension	Compressive strength	~55% reduction in splitting tensile strength; double reinforcement at joint recommended
[26]	Horizontal Inclined	Flexure / shear	Zone · orientation	Compression zone: negligible effect; tension zone: 5–7.5% reduction; inclined: 1.25–2.5% reduction
[2]	Horizontal	Shear	Joint elevation	Capacity reduction: 15.4–26.2%; stiffness ↓ up to 66.5%
[42]	Horizontal (cold)	Flexure	Concrete grade	~55% reduction in MoR; effect worsens with higher concrete grade
[14]	Horizontal	Multi-property	Delay time (0–180 min)	60-min delay: 3.93–4.02% split/flex reduction; 180-min: rebar pull-out ↓17.17%; freeze-thaw loss 38.91% greater
[27]	Horizontal	Shear (deep beam)	Joint height	9–11% reduction in ultimate load; mid-height joint → accelerated crack propagation toward CJ
[30]	Horizontal (cold)	Flexure	Time delay	4.93% (1.5 h delay) to 13.78% (4.5 h delay) reduction in flexural strength
[36]	Horizontal	Flexure (FE)	Stirrup ratio	Stirrup ratio 0.01229→0.049: −10.3% (i.e., an increase in ultimate load); ratio 0.0025: +55.8% (reduction)
[10]	Multi-type	Review (394 studies)	Type · location · reinforcement	Inclined 45° more effective than vertical; L-shaped/key joints: ductility +40% vs. vertical
[11]	Inclined L-shaped	Flexure (splice)	Splice length · CJ geometry	Combined CJ+splice: capacity ↓37–59%; worst case: insufficient splice + inclined/L CJ → brittle bond failure

Note: CJ = construction joint · MoR = modulus of rupture · FE = finite element analysis · ↓ = reduction · f'c = concrete compressive strength (MPa)

Kirillov [29] quantified the structural consequences of construction joints in a foundational study that reported a 15–20% reduction in failure load compared to monolithic beams and proposed a design coefficient of 0.85 in order to account for the reduction in strength. He found low bond strength across the joint as the initiating mechanism for the formation of early cracks, wider joint opening and larger deformations, and suggested that oblique reinforcement in the compression zone at the joint region should be used. Despite being published over fifty years ago, these findings are consistent with results from recent experimental studies, validating the consistency of the fundamental mechanisms involved.

Ammar and Mahmoud [10,11] conducted a comprehensive review synthesizing findings from 394 studies, providing the most complete contemporary summary of construction joint effects on RC beams. It classifies joints as vertical, horizontal, inclined (30°, 45°, 60°) or key-shaped and states that horizontal CJs are not generally recommended in beams and inclined joints at 45° are often found to be more effective in the transfer of loads than vertical joints because there is more overlap and freedom of movement. L-shaped and key joints show an improved performance in certain investigations with an increase in ductility of up to 40% compared to vertical joints. Construction joints are inevitable in large-scale construction due to practical constraints. A summary of previous studies on the effect of construction joints is presented in Table 1.

4.2 Quantified Effects on Mechanical Properties

Gerges et al. [19] reported a decrease in splitting tensile strength of about 55% with a vertical construction joint at midspan, compared to monolithic specimens, and therefore suggested to increase steel reinforcement at the joint region by double. Given that torsion mainly causes tensile stresses to be induced on the surfaces of the beam, this reduction of 55% in tensile capacity at a joint interface represents a critical vulnerability when under torsional loading.

An empirical equation for the modulus of rupture of plain concrete beams with central vertical construction joint was developed by Issa et al. [25], and the value of f_r for the central joint was found to be equal to $0.28\sqrt{f'c}$, compared to the ACI formula of $0.62\sqrt{f'c}$ for monolithic concrete. The reduction variation across seven concrete mix designs tested was 24% to 83%, indicating that the effect is not only quite large, but highly variable depending on the composition of concrete and surface condition.

Vanlalruata and Marthong [42] reported that the modulus of rupture for one day old cold jointed plain concrete beam can be reduced by about 55%, and further found that the detrimental effect increases with concrete grade a counterintuitive result that is explained by the faster strength gain of higher-grade concrete, which exacerbates the strength differential between the fresh and hardened layers at the time of casting. This relationship between concrete grade and severity of joint has important implications for the construction of modern buildings using high-performance concretes.

Bekem Kara [14] studied the influence of different delay times (0, 60, 120, and 180 min) on several mechanical properties and results showed that splitting tensile and flexural strength are more influenced than compressive strength, broadly consistent with Zega et al. [45], who examined joint-direction effects on the mechanical properties of concrete. A 60-min delay caused a 3.93% and 4.02% reduction in splitting tensile strength and flexural strength, and only a 1.06% reduction in compressive strength. The pullout strength between concrete and steel rebar decreased 17.17% at a 180-min delay. Durability testing revealed that the splitting tensile strength loss of cold jointed specimens was 42.07% greater under drying-wetting cycles and 38.91% greater under freeze–thaw cycles than that of monolithic specimens.

Mahdi and Sultan [30] investigated the temporal dimension of cold joint formation and showed that longer time delay between pours reduced the ultimate flexural strength in proportion to the time delay, with the reduction percentage ranging from 4.93% (1.5-h delay) to 13.78% (4.5-h delay) on the joints at the tension face. As summarized in Table 1, construction joints consistently lead to significant reductions in tensile and flexural strength, which directly increases the vulnerability of RC beams under torsional loading. The reported reductions in mechanical properties are summarized graphically in Figure 2.

The wide reported range of strength reduction (from under 5% for compression-zone horizontal joints, [26], to over 80% for certain vertical-joint modulus-of-rupture tests, [25]) is governed primarily by five interacting parameters: (1) joint orientation relative to the principal stress trajectory, with joints perpendicular to tensile stress paths producing the most severe reduction; (2) surface preparation, where sandblasted or roughened surfaces consistently outperform smooth or wet-cured ones [43]; casting-condition effects such as hot-weather retarder use have also been shown to influence joint bond quality [8]; (3) the time interval between successive pours, which governs the differential strength gain and shrinkage incompatibility across the interface ([14]; [30]); (4) reinforcement detailing across the joint, particularly stirrup continuity [36]; and (5) loading type, since flexure-dominated tests [26] generally report smaller reductions than direct tension/splitting tests [19] at the joint plane. This parameter interaction, rather than any single factor, explains the observed scatter and underscores the difficulty of extrapolating existing flexure/shear joint data to a torsional stress state, which imposes tension, compression, and shear simultaneously around the full perimeter.

4.3 Effect of Joint Location and Orientation

The structural consequences of construction joints are strongly dependent on their location and orientation relative to the principal stress field of the member. Jabir et al. [26] confirmed that the optimal location for a horizontal construction joint is within the compression zone, where it has negligible effect on ultimate strength, while a joint at the tension zone produces a 5% to 7.5% strength reduction. Inclined joints had a smaller effect on collapse load (1.25% to 2.5% reduction), and the study noted that construction joints more significantly affect cracking load than ultimate load — an important finding for serviceability assessments.

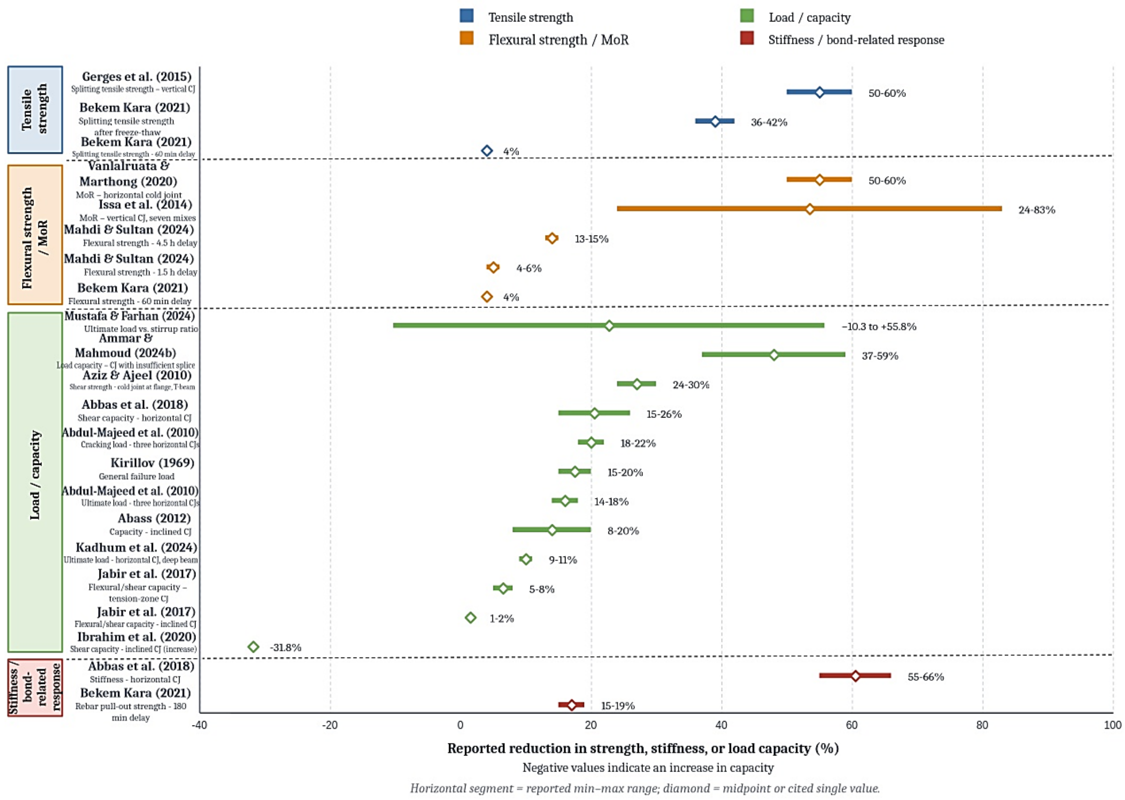

Fig. 2. Reported ranges of strength and stiffness reduction (%) due to construction joints in RC members — grouped by mechanical property. Each bar represents the reported range from reviewed studies; the diamond marker (◆) indicates the most frequently cited or calculated central value. Negative value for Ibrahim et al. [24] indicates an increase in shear capacity for inclined CJ configuration.

CJ = construction joint· MoR = modulus of rupture· FE = finite element.

Abass [1] carried out an extensive experimental study that included joint type, location, and surface preparation. The results showed that vertical and key joints maintained 95% of the reference capacity, whereas inclined joints indicated reductions between 8 and 20%. Notably for torsional strengthening, the benefits associated with the incorporation of stirrups in construction joints were quantified. The ultimate capacity was increased by 7-15%, and deflection was reduced by 20-48%. The study emphasized that surface preparation, including roughening, cleaning, and moistening, is crucial for achieving an acceptable bond.

Table 2. Source data underlying Figure 2. Every value plotted in Figure 2 is drawn from the specific finding reported below and cross-referenced to Table 1 and Section 4 of the main text; values without a numeric finding are qualitative background sources shown in the figure legend but not plotted as bars

Reference	Property / Variable	Reported Value or Range
[43]	Bond condition (qualitative)	Dry surfaces superior to wet-cured; sandblasting slightly superior to scabbling
[29]	Failure load	15–20% reduction; proposed design coefficient of 0.85
[1]	Capacity — joint type/location	Vertical/key joints: 95% capacity retained (~5% reduction); inclined joints: 8–20% reduction; stirrups at joint: +7–15% ultimate load
[25]	Modulus of rupture	24–83% reduction (measured $f_r = 0.28\sqrt{f'c}$ vs. ACI $f_r = 0.62\sqrt{f'c}$)
[19]	Splitting tensile strength	~55% reduction
[26]	Flexural/shear capacity — zone · orientation	Compression zone: negligible; tension zone: 5–7.5% reduction; inclined: 1.25–2.5% reduction
[2]	Shear capacity / stiffness	Capacity: 15.4–26.2% reduction; stiffness: up to 66.5% reduction
[52]	Shear strength (T-beam, cold joint at flange)	~27% reduction
[24]	Shear capacity (inclined CJ, no shear reinforcement)	31.8% increase in capacity (negative reduction)
[42]	Modulus of rupture	~55% reduction; effect worsens with higher concrete grade
[14]	Splitting tensile / flexural strength; rebar pull-out	60-min delay: 3.93–4.02% reduction; 180-min: pull-out ↓17.17%; freeze-thaw loss 38.91% greater
[4]	Cracking / ultimate load (3 CJs)	Cracking load ↓20%; ultimate load ↓16%
[30]	Flexural strength (time delay)	4.93% (1.5 h delay) to 13.78% (4.5 h delay) reduction
[27]	Ultimate load (deep beam, joint height)	9–11% reduction
[36]	Ultimate load vs. stirrup ratio	−10.3% (ratio 0.01229→0.049) to +55.8% (ratio 0.0025) — negative value indicates a capacity increase due to higher stirrup ratio
[10]	Ductility (review synthesis, 394 studies)	Inclined 45° more effective than vertical; L-shaped/key joints: ductility +40% vs. vertical
[11]	Capacity (CJ + splice)	37–59% reduction; worst case (insufficient splice + inclined/L CJ): brittle bond failure

Over et al. [38] combined field and laboratory experiments with numerical analysis to examine cold joints in plain concrete, evaluating compressive strength, flexural strength, modulus of elasticity, toughness, and fracture energy for vertical, horizontal, and angled joint orientations, and used microstructural examination of the joint region to recommend optimum joint locations for compression- and bending-dominated conditions. Although this study addressed plain rather than reinforced concrete and did not consider torsional loading, its finding that joint angle is a first-order variable governing mechanical degradation is consistent with the location- and orientation-dependent capacity reductions reported above for RC beams, reinforcing the case that joint orientation cannot be treated as a secondary parameter in either plain or reinforced members.

Abbas et al. [2] evaluated the effect of elevating the longitudinal construction joint position along the beam height. The findings indicated that elevating the construction joint position from 70 mm to 210 mm above the beam bottom resulted in a reduction in ultimate capacity from 15.4% to 26.2%, together with reductions in stiffness up to 66.5%. All specimens failed by diagonal shear, with cracks initiating near supports and propagating at approximately 45 degrees toward the construction joint a failure geometry directly relevant to torsional crack patterns. For deep beams, Kadhum et al. [27] found that horizontal construction joints at different heights produced reductions in ultimate load of 9% to 11%, with the optimal location being above mid-height (1% reduction). The acceleration of crack propagation toward the construction joint, particularly when the joint was at mid-height, is a critical observation for understanding the torsional vulnerability of jointed members, as the spiral crack path characteristic of torsion would inevitably encounter the joint interface.

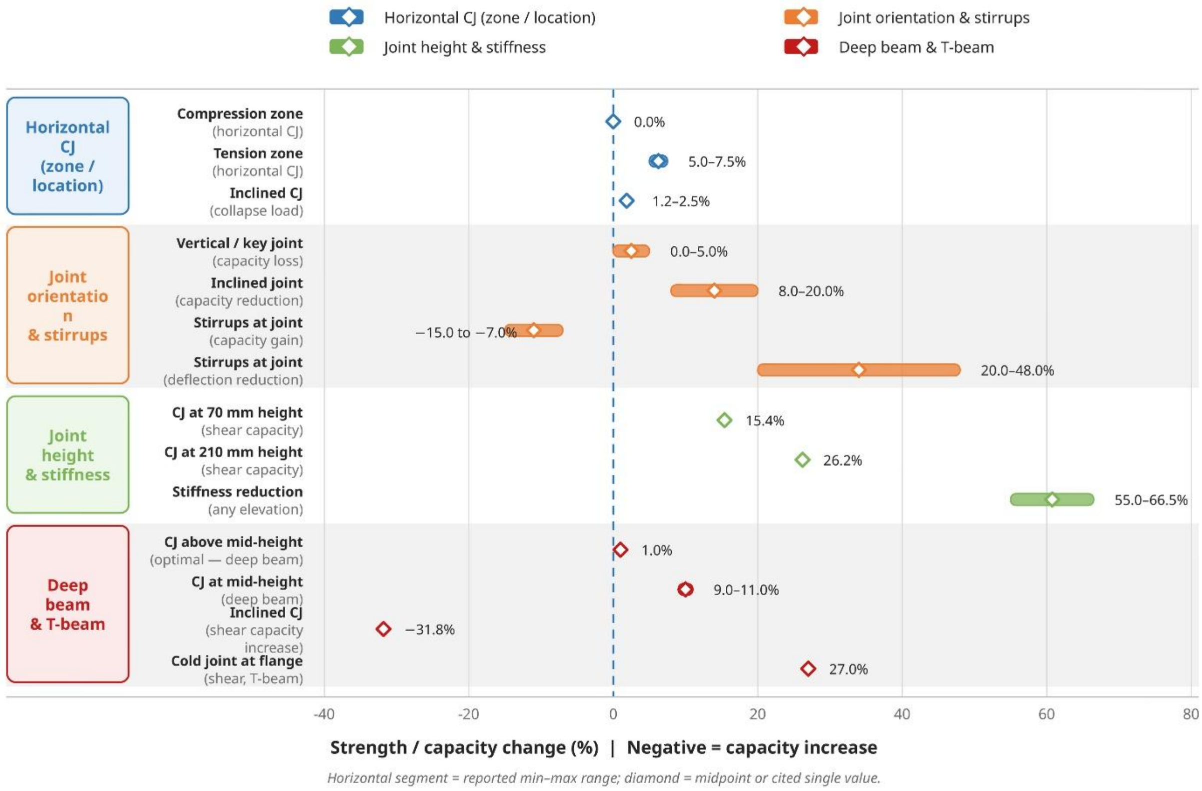

Fig. 3. Effect of construction joint (CJ) location and orientation on RC beam strength and capacity. Bars represent the reported range (min–max); diamond marker (◆) indicates the cited or calculated midpoint value. Negative values denote a capacity increase. Deflection reduction for stirrups at joint (Abass [1]) is plotted as a positive reduction value.

CJ = construction joint · RC = reinforced concrete · FE = finite element.

Ibrahim et al. [24] examined the influence of construction joints on shear capacity of RC beams without shear reinforcement and found that inclined construction joints produced a counterintuitive increase in shear capacity of about 31.8 percent in configurations that caused slender beams to act like deep beams. This observation contradicts the uniform characterization of the construction joints as weaknesses and implies that the orientation of joints with respect to the shear crack path is a critical variable. The post-crack behavior and failure mode were significantly affected by the orientation of an inclined construction joint, consistent with the general joint-failure classification framework proposed by Naderpour and Mirrashid [37].

This apparent contradiction is attributable to loading type (shear vs. flexure/tension) and joint-to-crack-path orientation rather than to any inconsistency in construction-joint behavior itself: Abass [1] and Jabir et al. [26] both loaded inclined joints in flexure or combined flexure-shear, where an inclined joint plane runs roughly parallel to the principal tensile stress trajectories and therefore offers a ready-made crack path, whereas Ibrahim et al. [24] loaded an inclined joint in pure shear on a slender beam, where the same inclination instead crosses the shear-crack path at a steep angle and forces a shorter, steeper strut that behaves like a deep-beam mechanism. The direction of the effect therefore depends on the geometric relationship between the joint plane and the governing crack path for the loading type considered, not on any difference in the intrinsic weakness of the joint interface. Aziz and Ajeel [52] established that the shear strength reduced by about 27 percent in RC T-beam specimens with cold joint at the flange, which confirmed that the disruption in composite sections is a major structural issue. This has major implications for torsional behavior because torsional resistance in T-sections is critically dependent on the contribution of the flange to the peripheral shear flow. The quantitative effects of joint location and orientation on RC beam capacity across all reviewed studies are summarized in Figure 3.

Table 3. Source data underlying Figure 3. Every value plotted in Figure 3 is drawn from the specific finding reported below, cross-referenced to Table 1 and Section 4.3 of the main text.

Reference	Property / Variable	Reported Value or Range
[26]	Zone / orientation	Compression zone: negligible; tension zone: 5–7.5% reduction; inclined: 1.25–2.5% reduction
[1]	Joint type / location	Vertical/key joints: ~5% reduction; inclined joints: 8–20% reduction; stirrups at joint: +7–15% ultimate load
[2]	Joint elevation	Capacity: 15.4–26.2% reduction; stiffness: up to 66.5% reduction
[27]	Joint height (deep beam)	9–11% reduction in ultimate load; mid-height joint accelerates crack propagation toward the CJ
[24]	Inclined CJ, no shear reinforcement	31.8% increase in shear capacity (negative reduction)
[52]	Flange cold joint (T-beam)	~27% reduction in shear strength

4.4 Effect on Stiffness and Ductility

Across all investigations, construction joints consistently reduce the stiffness and ductility of RC beams, in addition to their documented effects on peak strength. The stiffness reduction is attributed to the reduced modulus of elasticity at the joint interface and the earlier onset of cracking in the joint region. AbdulMajeed et al. [4] found through finite element analysis that the presence of horizontal construction joints decreased both cracking load and ultimate load proportionally to the number of joints, with three horizontal joints reducing cracking load to 80% and ultimate load to 84% of reference values. Shear transfer across joints occurs through chemical adhesion, friction, and dowel action of reinforcement mechanisms that are progressively mobilized as relative displacement at the joint increases.

Mustafa and Farhan [36] used ANSYS finite element analysis to demonstrate that the presence of a horizontal construction joint in the tension zone made beams less stiff, while increasing stirrup ratio from 0.01229 to 0.049 led to a 10.3% increase in ultimate load, and decreasing it to 0.0025 resulted in a 55.8% reduction. The strong sensitivity of jointed beam behavior to stirrup ratio reinforces the fundamental role of transverse reinforcement in bridging the joint interface.

Ammar and Mahmoud [10,11] found that beams with CJs and reinforcement splices experienced combined deterioration that reduced load capacity by 37% to 59% depending on splice length and joint geometry, with the worst performance observed for insufficient splice lengths combined with either inclined or L-shaped joints. The presence of a joint with a splice caused failure before the steel reached yield, indicating a transition from ductile flexural to brittle bond splitting failure-a mode that would be even more pronounced under torsional loading, where the stress state is more complex and the joint interface is subjected to combined shear, tension, and compression across its full perimeter. The quantitative effects of construction joints on stiffness and load capacity are summarized comparatively in Figure 4.

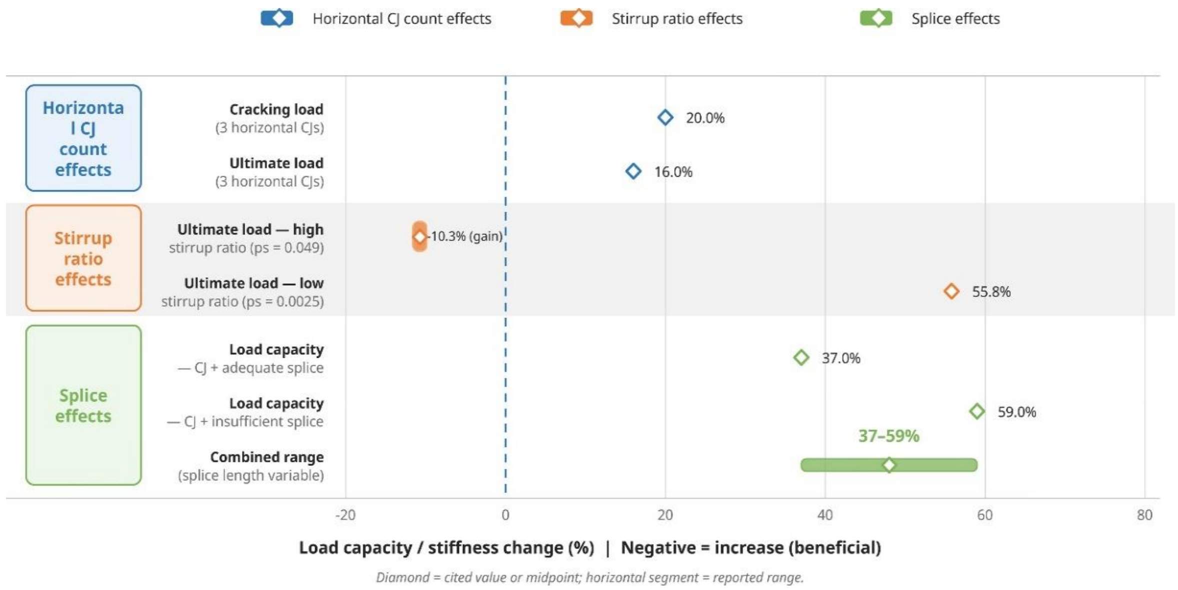

Fig.4. Effect of construction joints on stiffness and load capacity of RC beams (Section 4.4). Bars represent single cited values or ranges (min–max); diamond marker (◆) indicates the cited or midpoint value. Negative value indicates a capacity increase due to higher stirrup ratio Mustafa & Farhan [36].

Table 4. Source data underlying Figure 4. Every value plotted in Figure 4 is drawn from the specific finding reported below, cross-referenced to Table 1 and Section 4.4 of the main text.

Reference	Property / Variable	Reported Value or Range
[4]	Cracking / ultimate load (3 CJs)	Cracking load ↓20%; ultimate load ↓16%
[36]	Ultimate load vs. stirrup ratio	−10.3% (ratio 0.01229→0.049) to +55.8% (ratio 0.0025) — negative value indicates a capacity increase due to higher stirrup ratio
[11]	Capacity (CJ + splice)	37–59% reduction; worst case (insufficient splice + inclined/L CJ): brittle bond failure

Note: CJ = construction joint · ρs = stirrup ratio · FE = finite element · RC = reinforced concrete.

5. Analytical and Numerical Models for Torsion

It should be noted that not all analytical and numerical models reviewed in this section explicitly incorporate construction joints. These models are included as they represent the theoretical and computational framework upon which future construction joint-specific models should be developed a gap identified in Section 7.

5.1 Space Truss Models

Modern torsion design is based on the space truss analogy (STA) first introduced by Rausch [51]. In this model, the cracked RC beam is modeled as a thin-walled tube whereby torsional resistance is provided by the circulatory shear flow around the perimeter. The tube wall is modeled as a space truss that consists of inclined concrete diagonal struts, closed transverse stirrups and longitudinal bars. The variable angle space truss model (VATM) is an extension of this idea, in which the diagonal crack angle (θ) is a free variable calculated using equilibrium and compatibility, instead of fixing the angle to 45 degrees as in previous models.

Hassan and Deifalla [22] evaluated the CSA S806-12 [47] torsion design provisions for concrete beams with FRP reinforcement against the ACI 318 approach, finding that CSA S806-12 provided acceptable predictions of ultimate torque while ACI is more conservative and ignores concrete contribution to torsional strength. The torsional failure mode was found to differ between beams with bent GFRP stirrups and those with adhesively bonded GFRP stirrups, indicating that the detailing of transverse reinforcement significantly influences both the failure mechanism and the accuracy of code predictions. Razaqpur et al. [49] applied the Modified Compression Field Theory (MCFT) framework from CSA A23.3 and AASHTO LRFD to FRP reinforced and prestressed concrete members under torsion, establishing that cracking torque is essentially independent of reinforcement type and can therefore be calculated identically for FRPRC and steel RC members. The nominal torsional strength is resisted by concrete diagonal struts and the tensile forces in transverse and longitudinal reinforcement, with failure assumed when struts crush or reinforcement yields (or ruptures in the case of FRP).

5.2 Softened Truss Models

The softened truss model (STM), developed by Hsu and colleagues, extends the basic space truss concept by incorporating the softening effect of the concrete the reduction in compressive strength of cracked concrete due to transverse tensile strains. The model is a more physically realistic representation of post-cracking behavior, and can be used to predict the full torque-twist curve, with the full post-peak descending branch. Majed et al. [31] used the STM to analyze the FRP wrapped RC beams whereby the torsional behavior prediction was correct prior to and after the cracking, and the torque twist relationship was in good agreement with experimental results.

The Generalized Softened Variable Angle Truss Model (GSVATM) is a model that includes the tensile stress-strain relationship of concrete in the formulation, which allows the prediction of the cracking torque, the transition between pre-cracking and post-cracking stages, and the ultimate torque in a single model. The GSVATM has demonstrated a significantly higher degree of consistency with experimental results in comparison with simpler code-based models in the prediction of both cracking and ultimate torques over a variety of reinforcement schemes and concrete strengths.

5.3 Finite Element Models

The application of nonlinear finite element analysis to torsional behavior has expanded considerably in recent years, and this is attributed to the commercial software packages like ABAQUS and ANSYS with sophisticated constitutive models for concrete. Elkheshen et al. [18] confirmed a nonlinear FE model of concrete beam reinforced with longitudinal FRP bars and FRP stirrups and the final agreement was found within the range of 6.5% of the ultimate torque of the experiment. A parametric study indicated that increasing concrete compressive strength from 25 MPa to 50 MPa increased ultimate torque by 28.9% and increasing the longitudinal reinforcement ratio by 284% increased twist capacity by 140% with negligible effect on ultimate torque. Mustafa and Farhan [36] applied ANSYS and Solid 65 element and concrete damage plasticity model to study SCC beams with horizontal construction joints and treated the joint as an interface between two different concrete layers. The results showed clear crack patterns propagating at ultimate load, with high compressive stresses concentrated at midspan under the applied load — a spatial distribution that would be fundamentally altered under torsional loading, where the stress state involves shear around the entire perimeter.

A more advanced modelling approach was recently presented by Li et al. [53], who developed a three-dimensional meso-scale numerical model to investigate the pure torsional performance of CFRP-strengthened RC beams under both static and dynamic loading. Unlike macro-scale models such as that of Mustafa and Farhan [36], this meso-scale representation explicitly captured the heterogeneity of concrete, including the mortar matrix, interfacial transition zone, and randomly distributed aggregates, together with bond-slip behavior at the rebar-concrete and CFRP-concrete interfaces. Through 48 simulation cases spanning four strain rates, four CFRP fiber ratios, and three beam sizes, the study demonstrated that increasing the strain rate from 10^{-5}/s to 1/s raised the peak torsional moment of an unstrengthened beam by 74%, while a 0.69% CFRP fiber ratio produced a further 48% enhancement. Critically, the study also identified a pronounced size effect on torsional strength, with nominal torsional capacity decreasing by up to 20% as beam height increased from 300 mm to 900 mm under quasi-static loading, and proposed an extended torsional size-effect law that quantitatively incorporates both strain rate and fiber ratio. Although this model, like those discussed above, did not incorporate construction joint discontinuities, it represents the most refined meso-scale torsional framework to date and introduces two variables, loading rate and specimen size, that remain entirely unexamined in the context of construction-jointed RC beams under torsion.

5.4 Torsion at Jointed Interfaces

The most closely related analytical study to the current review paper was done by Ren et al. [41], who analyzed the torsional behavior of prestressed concrete towers with horizontal joints both experimentally and numerically. Their study identified that the ultimate state under torsion is governed by the coupled effects of joint failure and tower segment torsion, and that increasing the horizontal reinforcement ratio significantly improves torsional performance and ductility more so than vertical reinforcement. The crucial result that in high reinforcement ratios torsional capacity is controlled by the ultimate torque of the joint interface and not the cross-section capacity of the tower segment is directly applicable to the design of the construction joint zone in RC beams, where the joint itself may become the controlling factor.

The torsional performance of flat face epoxy bonded concrete joints was physically modeled by Chernin et al. [16], who found two failure modes: a cohesive mode (cracking in the concrete body, dominant, higher torsional strength, more ductile) and a mixed one (partial debonding of the epoxy joint, stiffer, more brittle, lower strength). The concrete epoxy interface weakness has been found to play a controlling role in the transition between these modes and the finding that increasing joint thickness can offset torsional strength loss by partial debonding provides a framework for understanding the behavior of construction joint interfaces under torsional loading and how they might be effectively strengthened. Table 5 summarizes the capabilities and limitations of existing analytical and numerical models for torsional behavior of RC beams, with particular emphasis on their applicability to construction-jointed members. As summarized in Table 5, existing analytical and numerical models are generally formulated for monolithic RC members and do not explicitly incorporate construction-joint discontinuities under torsional loading. This limitation confirms the need for joint-specific torsional models capable of accounting for interface slip, aggregate interlock, bond degradation, and stiffness reduction at the joint plane.

To directly compare current code-based torsional design approaches, Table 6 summarizes the underlying structural model, treatment of the concrete tensile contribution after cracking, and cracking-torque basis adopted by ACI CODE-318-25, Eurocode 2, and CSA A23.3. Critically, none of the three codes provides any explicit reduction factor or design provision addressing the presence of a construction joint, directly reinforcing Research Gap 3 identified in Section 7. As Table 6 illustrates, although the three codes differ in their treatment of the concrete tensile contribution after cracking, they converge in providing no explicit design guidance for construction-jointed RC members under torsional loading.

Table 5. Analytical and numerical models for torsional behavior of RC beams — capabilities and limitations relevant to construction-jointed members

Model/ framework	Basis	Key reference(s)	Predicts full torque–twist?	FRP strengthening included?	CJ discontinuity modelled?	Limitation regarding CJ
Space Truss Analogy (STA) incl. Variable Angle (VATM)	Thin-walled tube + truss equilibrium; crack angle θ as free variable	[28]; ACI 318	Partial (post-crack only)	No	No	Ignores concrete tensile contribution post-cracking; no provision for interface discontinuity; conservative
Softened Truss Model (STM)	Extends STA with concrete softening (reduction in f'c due to transverse tensile strains)	[31]; [48]	Yes — full T–θ curve	Yes (FRP wrapping)	No	Homogeneous section assumed throughout; joint interface not treated as discrete discontinuity

Model/ framework	Basis	Key reference(s)	Predicts full torque–twist?	FRP strengthening included?	CJ discontinuity modelled?	Limitation regarding CJ
Generalized SVATM (GSVATM)	STM + tensile stress–strain of concrete; predicts Tcr, transition, and Tu in one model	[48]	Yes — pre- and post-crack	Partial	No	Most accurate of truss-family models but still monolithic section assumption; CJ reduces fr and tensile constitutive law would need modification
Modified Compression Field Theory (MCFT)	CSA A23.3 / AASHTO framework; equilibrium + compatibility + constitutive laws	[49]; [22]	Yes	Yes (FRP reinforcement)	No	Cracking torque independent of reinforcement type — valid for monolithic; not calibrated for jointed interface; no code provision for CJ in torsion (Gap 3)
Machine learning / ANN model	Regression on experimental database of EBFRP RC beams	[17]	Strength only	Yes (EBFRP)	No	No jointed specimens in training database; debonding failure poorly captured; cannot extrapolate to CJ scenario
Nonlinear FE (ABAQUS/ANSYS) Concrete damage plasticity	3-D continuum; Solid65/C3D8R elements; CDP constitutive model	[18]; [36]	Yes — full response	Yes	Partial — flexure only	Mustafa & Farhan modelled CJ as interface between layers under flexure (±6.5% accuracy); torsional stress state (helical shear on all 4 faces) not yet modelled with CJ; Gap 5
Torsion at jointed interface (prestressed tower study)	Coupled joint failure + tower segment torsion; experimental + numerical	[41]	Yes — for tower joints	No	Yes — horizontal joints	Specific to prestressed wind-tower geometry; horizontal joint only; not applicable to conventionally reinforced RC beams with 45°/60°/L-CJ (Gap 2)

STA = space truss analogy · VATM = variable angle truss model · STM = softened truss model · GSVATM = generalized softened variable angle truss model ·MCFT = modified compression field theory · CDP = concrete damage plasticity · Tcr = cracking torque · Tu = ultimate torque · CJ = construction joint

Table 6. Comparison of torsional design provisions in ACI CODE-318-25, Eurocode 2, and CSA A23.3, highlighting the absence of any construction-joint-related reduction factor in all three codes (Research Gap 3)

Code	Underlying Model	Concrete Tensile Contribution After Cracking	Cracking-Torque Basis	Construction-Joint Provision
ACI CODE-318-25	Thin-walled tube / space truss	Neglected (cover concrete ignored post-cracking)	Tcr = $0.33\lambda\sqrt{f'c}\cdot(Acp^2/pcp)$, MPa units	None specified
Eurocode 2	Thin-walled closed section / truss analogy	Neglected after cracking; design based on shear flow	Based on concrete tensile strength, f_ctd	None specified

CSA A23.3	Modified Compression Field Theory (MCFT)	Included via tension-stiffening in constitutive model	0.38λφc√f′c (Ac²/pc), per Clause 11.2.9.1; post-cracking behavior governed separately by MCFT-based β–θ	None specified

Note: The code provisions summarized in this table are based on ACI CODE-318-25 [55], Eurocode 2(EN 1992-1-1:2004) [56], and CSA A23.3:19 [57]. In ACI CODE-318-25, the cracking torque, T_cr, is given directly by T_cr = 0.33λ√f′c·(A_cp²/p_cp) per Table 22.7.5.1, for a no prestressed solid member without axial force, where A_cp is the area enclosed by the outside perimeter of the concrete cross-section, p_cp is that outside perimeter, and λ is the lightweight-concrete factor. The threshold torque, T_th, below which torsional effects may be neglected, is given separately in Table 22.7.4.1(a) as T_th = 0.083λ√f′c·(A_cp²/p_cp), and is set at approximately one-quarter of the cracking torque, T_th ≈ T_cr/4. The exact clause and equation numbers should be confirmed by the authors against their copy of ACI CODE-318-25, as numbering has shifted between recent editions. The Eurocode 2 cracking-torque basis is established explicitly in Clause 6.3.2(5) and Expression (6.31) of EN 1992-1-1:2004, wherein the torsional cracking moment, T_Rd,c, is obtained by setting the wall shear stress τ_t,i equal to the design tensile strength of concrete, f_ctd. In CSA A23.3:19, the cracking torque, T_cr, is defined independently of the β–θ (MCFT-based) design framework: Clause 11.2.9.1, Expression (11.2), establishes T_cr from a closed-form expression in 0.38λφ_c√f′_c (A_c²/p_c), structurally analogous in form to the ACI threshold-torque approach, while the subsequent design of torsional reinforcement beyond cracking is governed by the β–θ relationships of Clause 11.3.6.

6. Torsional Strengthening Techniques

Similar to the analytical models discussed in Section 5, the strengthening studies reviewed herein were not conducted exclusively on beams with construction joints. They are included because they establish the technical basis for strengthening strategies that are yet to be evaluated in the specific context of construction joints under torsional loading representing one of the key research gaps identified in this review.

6.1 Externally Bonded FRP Systems

Among the most investigated methods for torsional strengthening of RC beams is the use of externally bonded fiber reinforced polymer (EBFRP) composites. The basic mechanism is similar to the introduction of closed stirrups in a conventional reinforced section, i.e., the introduction of supplementary closed loop transverse reinforcement around the beam perimeter. Askandar and Mahmood [12] carried out a comparative study on CFRP sheets and NSM steel bars for torsional strengthening of combined torsion and bending. They found that CFRP wrapping gives better improvement in ultimate torsional moment than NSM steel and full CFRP wrapping was found to give the maximum effect compared to strips configurations. Failure in partially wrapped beams occurred in unwrapped spaces emphasizing the importance of coverage continuity.

Mohammad and AlSulayfani [33] tested five solid rectangular beams under pure torsion strengthened with CFRP in four configurations — U-strips, full strips, U-wrap, and full wrap — finding that full wrapping achieved the highest increase in ultimate torque (73%) compared to U-strips (20%), full strips (47%), and U-wrap (27%), confirming that strengthening effectiveness is governed primarily by the continuity of the wrap around the section rather than the total quantity of CFRP material used.

Meshram and Ahire [32] reported ultimate torque increases of up to 20.5% and improvements in torsional stiffness for FRP wrapped beams compared to controls for RC beams. These results collectively establish the efficacy of EBFRP as a torsional strengthening method, though the specific behavior at construction joint interfaces has not been systematically investigated. Despite the proven effectiveness of EBFRP, a key limitation of such systems is the premature debonding failure mode which does not allow the FRP to reach its ultimate strain, and thus limits the efficiency of the strengthening. Yuan et al. [44] provided a complete analytical treatment to the bond slip behavior of the FRP to concrete interface. They found that the shear in the concrete layer adjacent to the interface governs the mode of failure, the ultimate load is strongly dependent on concrete strength, and there exists an effective bond length beyond which the increase of the bonded area does not increase the strength. The concept of effective bond length is important for the design of torsional strengthening schemes in which the bonded FRP needs to develop sufficient force in the available anchorage length to mobilize the desired contribution to torsional resistance. Deifalla [17] reviewed the accuracy of existing torsion strength models for EBFRP strengthened beams, concluding that current models lack the accuracy required for reliable design, particularly for debonding failure modes. The consistent finding that FRP ultimate strain is not reached with available bond models underscores the need for improved design frameworks that account for the specific mechanics of bond in torsional applications.

6.2 Near Surface Mounted FRP

The NSM FRP technique, in which FRP laminates or ropes are embedded into the concrete cover after cutting grooves, has advantages over EBFRP in anchorage and protection from environmental damage and vandalism. Al-Bayati et al. [6] conducted an extensive experimental comparison of NSM CFRP laminates with CFRP ropes using epoxy and cement-based adhesives for torsional strengthening. The results demonstrated that epoxy offers better strength enhancement than cement-based adhesive (23.3% vs. 16.9% for CFRP ropes), and CFRP ropes consistently outperformed CFRP laminates irrespective of adhesive type because of the continuous nature of the rope at corners which led to lower internal reinforcement strains. Failure modes varied between adhesive types, with epoxy strengthened beams failing by concrete cover delamination and mortar bonded beams failing by stirrup yielding followed by concrete spalling.

6.3 Steel Fiber Reinforced Concrete

A different material-level approach to torsional strengthening of concrete is the use of steel fibers in the concrete mix design. This approach acts through the volume of the member rather than just on the surface. Abdullah and Abodi [3] indicated that increasing the steel fiber ratio changes the concrete behavior from brittle to ductile under torsional loading. Reports of previous studies have shown increases in the ultimate torsional strength of self-compacting concrete beams ranging from 60% to 160% for steel fiber volume fractions of 0.4% to 0.8%, with increases proportional to the increase in fiber content.

AlSalim et al. [9] investigated fiber reinforced concrete beams under combined flexure and torsion at a T/M ratio of 1, finding that the influence of fibers on torsional stiffness and ductility was more pronounced than on flexural properties, attributable to the enhancement of tensile strength by fibers. Hooked steel fibers showed greater improvement than straight fibers, and synthetic fibers at 55 mm length achieved the highest first crack and ultimate moment values. Notably, the approximately 20% decrease in brittleness compared to normal concrete, which is highly relevant for jointed beams where brittle failure at the joint interface is a primary concern.

6.4 Shear Key Connections

Shear keys are mechanical interlocking devices used to strengthen joints of precast and segmental concrete members. Raiyani et al. [58] reported that the inward and outward shear keys enhanced the peak torque resistance relative to monolithic specimens by 24% and 16%, respectively, with the inward keys performing better. The larger initial stiffness of keyed connections compared to flat-face joints confirms the positive contribution of mechanical interlocking to the torsional resistance. Zou et al. [46] demonstrated that steel shear keyed joints in precast segmental beams exhibited 72.96% higher shear capacity than conventional concrete key joints under dry conditions. Unlike concrete key joints, which are characterized by brittle post-cracking failure, steel key joints maintained a measurable residual capacity after initial cracking. This behavior is attributed to the contact pressure mechanism between steel and concrete, which provides a stable load transfer path that persists beyond the cracking stage. Baghdadi et al. [13] explored novel dry concrete joint geometries fabricated using robotic CNC techniques. Among the configurations tested, connection C9 — an optimized pinned geometry incorporating wooden and steel elements — achieved 64% of monolithic beam flexural capacity while exhibiting notable resistance to both torsional and shear loading. These findings highlight that joint geometry is a critical design parameter governing not only flexural but also torsional performance, reinforcing the need for careful detailing of construction joints in members subjected to combined loading. A summary of the performance of various torsional strengthening techniques is presented in Table 7.

Table 7. Comparison of torsional strengthening techniques for RC beams — performance, limitations, and applicability to construction-jointed members

Technique	Reference	Specimen type	Ultimate torque gain (%)	Cracking torque gain (%)	Failure mode	Key limitation	Applicable to jointed beams?
EB-CFRP Externally bonded	[33]	Solid rectangular	20% – 73%	~4.0–5.0 kN.m	Diagonal cracking & CFRP debonding (U-strips/U-wrap); crushing & CFRP rupture (full strips/full wrap)	U-strip/U-wrap configurations failed prematurely via debonding at unanchored free edges (B2, B4); full wrapping was most effective (73% gain) but often impractical where all beam faces are inaccessible	Uncertain — anchorage-dependent (U-configs); full wrap may be geometrically blocked by a joint if it intersects the wrap path
	[12]	Rect. RC, combined T+M	44–134%	Moderate	Unwrapped zone failure		
	[32]	FRP-wrapped RC	Up to 20.5%	Improved	Cover delamination		
NSM-CFRP Near surface mounted	[6]	Rect. RC, CFRP rope + laminates	15–23%	Up to 17%	Cover delamination (epoxy) / stirrup yielding (CBA)	Groove cutting risk at joint face; stress concentration at NSM groove ends	Uncertain — NSM groove at joint may concentrate stress (Gap 4)
	[6]	RC with CFRP rope, CBA adhesive	10–23%	10–17%	Cover spalling		
Steel fiber RC Volume-distributed	[3]	HSC beams, Vf 0.4–0.8%	60–160%	Up to 72.8%	Ductile (fiber pull-out)	Pre-cast only — must be in original mix; cannot be applied post-construction; U-GFRP wrapping may disrupt shear flow	Most compatible — acts volumetrically through joint zone; reduces brittleness ~20% [9]
	[9]	FRC beams, T/M=1	Significant (ductility focus)	Significant (hooked > straight)	Fiber pull-out, ductile		
Shear keys Mechanical interlock	[13]	CNC dry joint, geometry C9	64% of monolithic cap.	Enhanced initial stiffness	Geometric interlocking	Precast only — not applicable to in-situ CJ; brittle post-crack (concrete keys)	Precast/segmental contexts only; steel keys maintain residual capacity post-cracking [46]
	[46]	Steel shear key, precast segmental	Shear cap. +73%	—	Contact pressure mechanism		

EB = externally bonded · NSM = near surface mounted · CFRP = carbon fiber-reinforced polymer · CBA = cement-based adhesive · HSC = high-strength concrete · FRC = fiber-reinforced concrete · Vf = fiber volume fraction · T = torsion · M = bending moment · CJ = construction joint

7. Research Gaps and Future Directions

Despite the substantial body of literature reviewed, five critical research gaps are identified that warrant focused future investigation:

Gap 1: Direct Torsional Testing of RC Beams with Construction Joints

Future experimental programs should directly investigate the torsional strength and failure behavior of RC beams incorporating construction joints as the primary variable. Such studies should systematically examine the influence of joint orientation, surface preparation, and reinforcement detailing on torsional capacity and crack propagation.

Gap 2: Stress Transfer Mechanics at the Joint Interface Under Torsion

The mechanisms governing stress transfer across a construction joint subjected to combined torsional shear, tension, and compression in a helical pattern remain undescribed. Future analytical and experimental work should characterize the interface constitutive behavior under this multiaxial stress state and develop appropriate bond-slip models for jointed RC beams under torsion. Specifically, a construction joint interrupts the continuity of the diagonal concrete struts assumed in the space-truss analogy along the joint plane; extending the Modified Compression Field Theory (MCFT) to this condition would require a modified compatibility formulation admitting a discontinuous strain field, together with an interface constitutive law analogous to shear-friction provisions, calibrated for the combined shear-tension-compression state produced by torsion rather than for shear alone. Aggregate interlock across the joint surface is expected to govern the residual shear-transfer capacity once the interface debonds, in a manner analogous to crack-plane aggregate interlock in monolithic concrete, though this has not yet been quantified for different construction-joint roughness levels. The inclination of a torsional crack, which typically follows a characteristic helical path at approximately 45° to the member axis, would also be expected to locally reorient where it intersects an inclined construction joint, since the joint plane presents a discontinuous, lower-resistance path relative to the surrounding monolithic concrete; quantifying this crack-path deviation as a function of joint angle relative to the principal tensile stress trajectory remains an open experimental question.

Gap 3: Code Provisions for Torsional Design of RC Beams Having Construction Joints

Current design codes, including ACI 318, Eurocode 2, and CSA, provide no provisions for the torsional design of RC beams containing construction joints. Future research should generate the experimental database necessary to calibrate reduction factors and propose code-compatible design procedures that explicitly account for joint presence and condition. A joint-specific torsional failure criterion would need to combine an interface bond-slip law with the classical diagonal-tension criterion governing monolithic sections; until the requisite experimental database exists (Gap 1), any torsional reduction factor analogous to Kirillov's [29] 0.85 flexural coefficient can only be proposed provisionally and would require calibration against dedicated jointed-torsion test data. Whether existing shear-friction provisions can be extended to torsional loading, and how torsional stiffness degradation varies with joint roughness, remain open questions that this calibration effort would need to resolve. A practical starting point for such calibration would be to normalize the joint's mechanical influence through dimensionless parameters, such as the joint-to-section-depth ratio, the joint orientation angle relative to the member's principal stress trajectory, and a surface-roughness index, so that torsional capacity reduction can be expressed as a function of these ratios rather than of joint type alone.

Gap 4: Strengthening Strategies for Torsional Deficient Jointed Beams

The effectiveness of externally bonded FRP, NSM FRP, and steel fiber reinforcement for restoring torsional capacity in beams with construction joints has not been examined. Future studies should evaluate the interaction between the strengthening system and the joint interface, with particular attention to debonding initiation at the joint plane for EBFRP systems and stress concentrations at NSM grooves.

Gap 5: Analytical and Numerical Modeling of Jointed Beams Under Torsion

No analytical or finite element model currently accounts for the mechanical influence of a construction joint on torsional response. Future work should develop predictive models capable of incorporating joint type, location, surface condition, and reinforcement detailing as input parameters for torsional capacity estimation. Furthermore, recent meso-scale modelling of CFRP-strengthened RC beams under pure torsion has demonstrated that both loading rate and specimen size significantly affect torsional capacity and stiffness degradation Li et al. [53], yet no study to date has examined either variable in the presence of a construction joint, indicating that the influence of dynamic loading and member scale on jointed torsional members remains an entirely open area for future investigation.

8. Conclusions

Based on a systematic review of literature spanning 1954 to 2026, the following conclusions are drawn:

- The torsional behavior of RC beams is governed by two distinct phases: pre-cracking, dominated by the uncracked concrete section, and post-cracking, where resistance is provided by the interaction of closed stirrups, longitudinal reinforcement, and diagonal concrete struts acting as a space truss. Effective torsional resistance requires both transverse and longitudinal reinforcement acting simultaneously; neither provides an optimal torsional response when used independently.
- ACI CODE-318-25 and Eurocode 2 adopt thin-walled-tube and truss-based analogies that disregard the concrete tensile contribution after cracking, whereas CSA A23.3 employs a Modified Compression Field Theory (MCFT) framework that explicitly incorporates tension-stiffening. More advanced analytical models such as the softened truss model and its generalized variants explicitly account for concrete tensile constitutive behavior and demonstrate improved accuracy across a wide range of experimental results.
- Construction joints consistently reduce the mechanical properties of RC members. The degree of reduction depends on joint orientation, location, surface preparation, concrete grade, and time elapsed between successive pours. Joints located in tension zones or regions of high shear produce the most severe reductions. Joints placed in compression zones or areas of low shear exhibit the least structural impact.
- Externally bonded FRP wrapping, NSM FRP reinforcement, and steel fiber incorporation are all effective strategies for restoring or enhancing the torsional capacity of RC beams. The effectiveness of each technique varies with configuration, fiber volume fraction, and anchorage conditions.
- No experimental or analytical study has specifically investigated the torsional behavior of RC beams containing construction joints. This combination represents a clear and unaddressed research gap of direct engineering relevance, given that torsional stress imposes helical diagonal tension across all four faces of a beam, creating a stress state particularly likely to activate joint interface weakness. From a practical design standpoint, engineers dealing with large-scale RC structures where construction joints are unavoidable should treat the joint zone as a critical detail requiring explicit torsional assessment. Until dedicated code provisions are established, a conservative approach would include full closed-stirrup confinement at joint regions, roughened and moistened joint surfaces, and the avoidance of joint placement in zones of high torsional demand. Where torsional loading is anticipated, externally bonded CFRP wrapping remains the most evidence-supported intervention currently available.
- The application of torsional strengthening techniques to RC beams with construction joints remains entirely unexplored, constituting a further frontier for future experimental and numerical investigation.

Acknowledgement

The authors would like to extend their sincere thanks and appreciation to all those who contributed to the completion of this work.

References

[1] Abass ZW. Effect of construction joints on performance of reinforced concrete structural elements. Journal of Engineering and Development. 2012;16(4):1-20.
[2] Abbas AN, Al-Naely HK, Abdulzahra HH, Al-Khafaji ZS. Structural behavior of reinforced concrete beams having construction joint at different elevation. Journal of Engineering and Sustainable Development. 2018;22(5):1-15.

[3] Abdullah MD, Abodi JT. Effect of stirrup, longitudinal reinforcement and steel fibers ratios on the torsional behavior of high strength concrete beams. Periodicals of Engineering and Natural Sciences. 2022;10(4):5-17. https://doi.org/10.21533/pen.v10.i4.677
[4] Abdul-Majeed Q, Ghaleb LA, Ghaddar MG. Effect of the number of horizontal construction joints on the behavior of RC beams. Engineering and Technology Journal. 2010;28(19):5803-5821. https://doi.org/10.30684/etj.28.19.1
[5] Abdul-Majeed Q. Evaluation of transverse construction joints of reinforced concrete beams. Engineering and Technology Journal. 2010;28(14):4750-4773. https://doi.org/10.30684/etj.28.14.6
[6] Al-Bayati G, Al-Mahaidi R, Hashemi MJ, Kalfat R. Torsional strengthening of RC beams using NSM CFRP rope and innovative adhesives. Composite Structures. 2018;187:190-202. https://doi.org/10.1016/j.compstruct.2017.12.016
[7] Al-Khafaji J, Al-Shaarbaf I, Abbas RF. Reinforced self-compacting concrete beams under torsion. Journal of Engineering and Sustainable Development. 2016;20(2):82-99.
[8] Al-Mamoori FHN, Al-Mamoori AHN. Reduce the influence of horizontal and vertical cold joints on the behavior of high strength concrete beam casting in hot weather by using sugar molasses. Journal of Engineering and Sustainable Development. 2018;22(6):1-18.
[9] Al-Salim NH, Jaber MH, Hassan RF, Mohammed NS, Hussein HH. Experimental investigation of compound effect of flexural and torsion on fiber reinforced concrete beams. Buildings. 2023;13(4):935. https://doi.org/10.3390/buildings13051347
[10] Ammar SI, Mahmoud AS. State of art of construction joints of reinforced concrete beams. Proceedings of the 2nd International Conference on Engineering Science (CESC), University of Mustansiriyah, 81-96, 2024.
[11] Ammar SI, Mahmoud AS. Performance of steel spliced reinforced concrete beams having construction joints. Annales de Chimie - Science des Matériaux. 2024;48(4):519-527. https://doi.org/10.18280/acsm.480409
[12] Askandar N, Mahmood A. Comparative investigation on torsional behaviour of RC beam strengthened with CFRP fabric wrapping and near-surface mounted (NSM) steel bar. Advances in Civil Engineering. 2019;2019:9061703. https://doi.org/10.1155/2019/9061703
[13] Baghdadi A, Ledderose L, Ameri S, Kloft H. Experimental and numerical assessments of new concrete dry connections concerning potentials of robotic CNC manufacturing technique. Engineering Structures. 2023;280:115605. https://doi.org/10.1016/j.engstruct.2023.115605
[14] Bekem Kara İ. Experimental investigation of the effect of cold joint on strength and durability of concrete. Arabian Journal for Science and Engineering. 2021;46:10587-10601. https://doi.org/10.1007/s13369-021-05400-5
[15] Chalioris CE. Behaviour model and experimental study for the torsion of reinforced concrete members. WIT Transactions on the Built Environment. 2006;85:583-592. https://doi.org/10.2495/HPSM06045
[16] Chernin L, Newlands M, Khosravi N. Flat-face epoxy-bonded concrete joints loaded in torsion: Physical modelling. Construction and Building Materials. 2024;411:134558. https://doi.org/10.1016/j.conbuildmat.2023.134558
[17] Deifalla A. A machine learning model for torsion strength of externally bonded FRP-reinforced concrete beams. Polymers. 2022;14(6):1256. https://doi.org/10.3390/polym14091824
[18] Elkheshen M, Eltahawy R, Shedid M, Abdelrahman A. Numerical verification for concrete beams reinforced with CFRP subjected to pure torsion. Alexandria Engineering Journal. 2022;61(12):9799-9815. https://doi.org/10.1016/j.engstruct.2022.114739
[19] Gerges NN, Issa CA, Fawaz S. Effect of construction joints on the splitting tensile strength of concrete. Case Studies in Construction Materials. 2015;3:83-91. https://doi.org/10.1016/j.cscm.2015.07.001
[20] Gesund H, Boston LA. Ultimate strength in combined bending and torsion of concrete beams containing both longitudinal and transverse reinforcement. ACI Journal Proceedings. 1964;61(11):1363-1382. https://doi.org/10.14359/7834
[21] Hadhood A, Gouda MG, Agamy MH, Mohamed HM, Sherif AG. Torsion in concrete beams reinforced with GFRP spirals. ACI Structural Journal. 2020;117(4):107-120. https://doi.org/10.1016/j.engstruct.2020.110174
[22] Hassan MM, Deifalla A. Evaluating the new CAN/CSA-S806-12 torsion provisions for concrete beams with FRP reinforcements. Materials and Structures. 2016;49(7):2715-2729. https://doi.org/10.1617/s11527-015-0680-9
[23] Hussein A, Hai TN, Tien DV, Hassan W. Torsional performance of UHPC beams with transverse openings. Buildings. 2024;14(8):2447.
[24] Ibrahim MS, Solomon Y, Demere A, Shiferaw A, Sultan A, Moges A, Dawit K. Effect of construction joint on the shear behavior of reinforced concrete beams. Proceedings of the fib Symposium 2020: Concrete Structures for Resilient Society, Held Online, China, 2020. https://doi.org/10.1016/j.engstruct.2020.110790

[25] Issa CA, Gerges NN, Fawaz S. The effect of concrete vertical construction joints on the modulus of rupture. Case Studies in Construction Materials. 2014;1:25-32. https://doi.org/10.1016/j.cscm.2013.12.001
[26] Jabir HA, Salman TS, Mhalhal JM. Effect of construction joints on the behavior of reinforced concrete beams. Journal of Engineering. 2017;23(5):47-60. https://doi.org/10.31026/j.eng.2017.05.04
[27] Kadhum SB, Al-Zuhairi AH, Al-Zaidee SR. Experimental investigation of the effect of horizontal construction joints on the behavior of deep beams. Open Engineering. 2024;14(1):20220554. https://doi.org/10.1515/eng-2022-0554
[28] Kamara ME, Rabbat BG. Torsion design of structural concrete: Based on ACI 318-05. Portland Cement Association, Skokie, USA, 2007.
[29] Kirillov AP. Effect of construction joints on the performance of reinforced concrete structures. Beton i Zhelezobeton. 1969;15(3):1-10. https://doi.org/10.1007/BF02377208
[30] Mahdi MA, Sultan AA. Effect of time elapsed between concrete pours on the flexural strength of singly reinforced concrete beams with horizontal cold joints. Journal of Engineering. 2024;30(4):1-18.
[31] Majed MM, Tavakkolizadeh M, Allawi AA. Analytical study on torsional behavior of FRP-strengthened RC beams using softened truss model. Advances in Structural Engineering. 2021;24(8):1642-1654. https://doi.org/10.1177/1369433220981693
[32] Meshram K, Ahire NA. Rotational behaviour of reinforced concrete beam wrapped with different fibers. International Journal of Scientific & Technology Research. 2020;9(3):6833-6838.
[33] Mohammad KI, Al-Sulayfani BJ. Torsional strengthening of RC beams with CFRP wrap. Tikrit Journal of Engineering Sciences. 2013;20(3):1-9. https://doi.org/10.25130/tjes.20.3.01
[34] Mohamed HM, Benmokrane B. Strength and behavior of glass fiber-reinforced polymer RC box girders under torsion. ACI Structural Journal. 2023;120(3):97-110.
[35] Mostafa IT, Mousa S, Mohamed HM, Benmokrane B. Behavior of high-strength concrete box girders reinforced with GFRP bars, ties, and spirals under torsion. Journal of Composites for Construction. 2023;27(4):04023030. https://doi.org/10.1016/j.engstruct.2023.116726
[36] Mustafa MA, Farhan OS. Finite element analysis of reinforced self-consolidation concrete beams having a horizontal construction joint. Al-Nahrain Journal for Engineering Sciences. 2024;27(2):141-148. https://doi.org/10.29194/NJES.27020141
[37] Naderpour H, Mirrashid M. Classification of failure modes in ductile and non-ductile concrete joints. Engineering Failure Analysis. 2019;103:361-375. https://doi.org/10.1016/j.engfailanal.2019.04.047
[38] Over D, Ozbakan N, Şamdan F, Orhan T, Canbaz M. An experimental and numerical study on the effects of cold joint location and angle in concrete. Construction and Building Materials. 2023;392:131832.
[39] Rashidi M, Takhtfiroozeh H. The role of transverse and longitudinal reinforcement on the torsional strength of RC beams. International Journal of Civil Engineering. 2016;14(5):299-308.
[40] Rahal KN. Torsional strength of reinforced concrete beams. Canadian Journal of Civil Engineering. 2000;27(3):445-453. https://doi.org/10.1139/l99-083
[41] Ren W, Deng R, Zhou XH, Wang YH, Liu YS. Torsional behavior of prestressed concrete towers for wind turbines considering the effect of horizontal joint. Thin-Walled Structures. 2025;216:113610. https://doi.org/10.1016/j.tws.2025.113610
[42] Vanlalruata J, Marthong C. Effect of cold joint on the flexural strength of RC beams. Materials Today: Proceedings. 2020;28(2):862-867. https://doi.org/10.1080/24705314.2020.1823556
[43] Waters T. A study of the tensile strength of concrete across construction joints. Magazine of Concrete Research. 1954;6(18):151-153. https://doi.org/10.1680/macr.1954.6.18.151
[44] Yuan H, Teng JG, Seracino R, Wu ZS, Yao J. Full-range behavior of FRP-to-concrete bonded joints. Engineering Structures. 2004;26(5):553-565. https://doi.org/10.1016/j.engstruct.2003.11.006
[45] Zega CJ, Villagrán-Zaccardi YA, Carrasco MF, Di Maio ÁA. Effects of cold joint and its direction on the mechanical properties of concrete. Construction and Building Materials. 2021;290:123249.
[46] Zou Y, Xiang T, Xu D. Shear behavior and construction method of steel shear keyed joints in precast segmental beams. Scientific Reports. 2023;13:11166. https://doi.org/10.1038/s41598-023-37442-0
[47] Canadian Standards Association. Design and construction of building components with fibre-reinforced polymers, CAN/CSA-S806-12, 1st edition, Toronto, Canada, CSA Group, 2012.
[48] Bernardo LFA, Andrade JMA, Lopes SMR. Generalized softened variable angle truss model for RC beams under torsion. Materials and Structures. 2015;48(7):2169-2193. https://doi.org/10.1617/s11527-014-0301-z
[49] Razaqpur AG, Bencardino F, Rizzuti L, Spadea G. FRP reinforced/prestressed concrete members: A torsion design model. Composites Part B: Engineering. 2015;79:144-155. https://doi.org/10.1016/j.compositesb.2015.04.034
[50] Windisch A. Pure torsion-Application of model of characteristic failure cross sections. ACI Structural Journal. 2022;119(1):55-66. https://doi.org/10.14359/51733010
[51] Rausch E. Berechnung des Eisenbetons gegen Verdrehung [Design of Reinforced Concrete in Torsion], Ph.D. Thesis, Technische Hochschule, Berlin, Germany, 1929.

[52] Aziz AH, Ajeel AE. Effect of existing flange openings and cold joints on strength of RC T-beams. Journal of Engineering. 2010;16(1):4535-4546. https://doi.org/10.31026/j.eng.2010.01.11

[53] Li D, Wang M, Zhang J, Jin L, Du X. Research on the pure torsional performance and size effect of CFRP-strengthened RC beams considering the influence of strain rate. Journal of Building Engineering. 2026;120:115401. https://doi.org/10.1016/j.jobe.2026.115401

[54] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ. 2021;372:n71. https://doi.org/10.1136/bmj.n71

[55] American Concrete Institute. Building code requirements for structural concrete (ACI CODE-318-25) and commentary (ACI CODE-318R-25). American Concrete Institute, Farmington Hills, USA, 2025.

[56] European Committee for Standardization. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, EN 1992-1-1:2004, Brussels, Belgium, 2004.

[57] CSA Group. Design of concrete structures, CSA Standard No. A23.3:19, Toronto, Canada, 2019.

[58] Raiyani SD, Patel PV, Joshi DD. Effectiveness of shear key on torsional resistance of precast beam: An experimental and numerical investigations. Structures. 2024;70:107668. https://doi.org/10.1016/j.istruc.2024.107668