Review

A Comprehensive Review and Analysis of Shear Strengthening of RC Beams with External Prestressing Bars

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Abstract: Shear failure in reinforced concrete (RC) structures, characterized by their sudden and brittle nature, often results from inadequate shear reinforcement or degradation due to aging or increased loading demands. To increase shear capacity, various retrofitting techniques have been developed, with external prestressing bars recognized as an effective solution. These bars apply an active clamping force to improve shear resistance and delay the formation and propagation of diagonal cracks. This review presents a comprehensive analysis of experimental investigations and numerical models, such as strut-and-tie and damage-plasticity approaches, to evaluate shear strengthening with external prestressing bars. In this review, early exploratory studies, the evolution of experimental programs, and the development of analytical and finite element models for predicting the behavior of strengthened beams are examined. Particular attention is given to validating numerical models against experimental data, focusing on load-sharing mechanisms, ductility, failure modes, and serviceability. Practical design implications are evaluated, research gaps are identified, and recommendations for future studies are proposed to advance the implementation of this technique. Findings from authoritative sources are integrated to provide a definitive reference for researchers and engineers seeking sustainable and efficient shear retrofit solutions.

Keywords: shear strengthening; external prestressing bars; lifecycle assessment; structural durability; bridge technology

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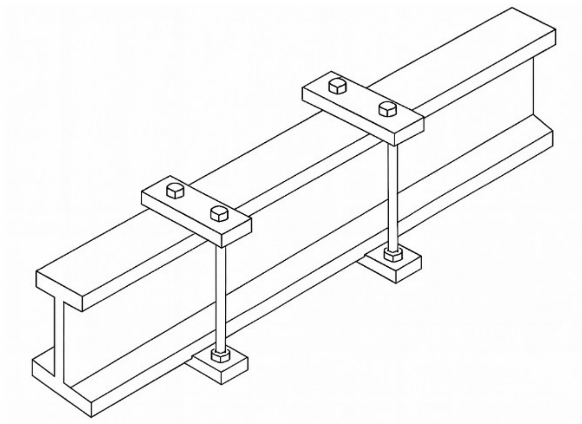
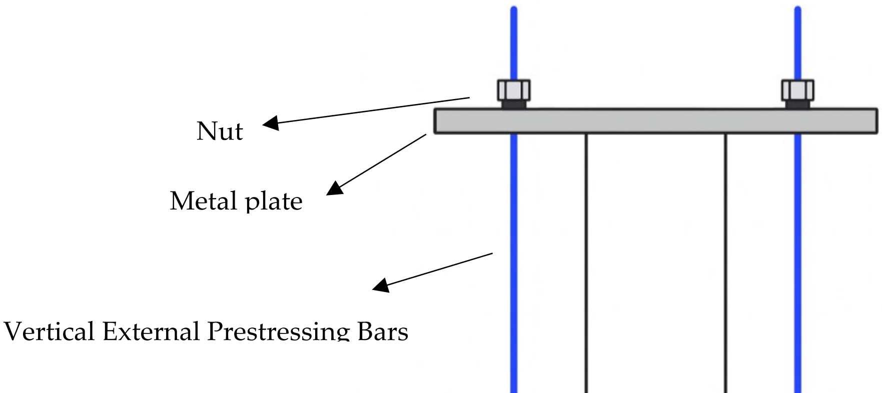
1 Introduction

Reinforced concrete (RC) structures have been widely adopted in civil infrastructure due to their versatility, durability, and cost-effectiveness [1]. However, shear failure, characterized by its sudden and brittle nature, can occur in RC members when internal shear reinforcement is inadequate or when degradation develops due to environmental exposure or increased loading demands [2]. Such failures, often occurring without warning, pose significant risks to structural safety [3]. Consequently, various retrofitting techniques have been developed to increase the shear capacity of RC beams. These techniques include external bonding of fiber-reinforced polymers (FRP), attachment of steel plates, and jacketing methods [4]. While each method offers specific advantages, limitations such as premature debonding of FRP under cyclic or environmental exposure and the invasiveness of bolted steel plates, which may reduce the number of available headrooms, have been reported [5–7].

Among these techniques, shear strengthening through external prestressing bars has emerged as a promising approach [8]. In this method, high-strength steel bars or tendons are externally installed and subjected to controlled post-tensioning to apply an active clamping force across the shear span of a beam [9,10]. This clamping force serves to close potential cracks, increase friction along the concrete web, and increase the overall load-carrying capacity by compensating for insufficient internal shear reinforcement. Initially developed to improve flexural capacity in bridges and beams, the application of external prestressing has been extended to address shear deficiencies [11–13]. Experimental investigations have demonstrated that externally prestressed stirrups or vertical rods can increase the ultimate shear strength of beams by 20–70%, depending on the prestress level and reinforcement configuration [14]. Figure 1.a presents a detailed sketch of an I-beam with external vertical prestressing bars through its flanges, illustrating their positioning external to the beam specimen, acting against a steel plate and secured with a nut. Figure 1.b shows an inverted rectangular beam with external vertical prestressing bars.



(a) Type I Beam



(b) Inverted rectangular beam

(c) application in bridges

Figure 1 Sketch of Reinforced Concrete Beam with External Prestressing Bars

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The mechanisms underlying shear failure in RC beams, including diagonal tension failure, shear compression failure, flexure–shear interaction, and web crushing, have been extensively studied to inform the development of effective strengthening strategies [15–17]. Each failure mode is characterized by distinct crack patterns and stress distributions, necessitating a comprehensive understanding to evaluate the efficacy of strengthening techniques such as external prestressing.

Despite its potential, the adoption of external prestressing for shear strengthening in design practice remains limited [18,19]. Challenges persist in terms of optimizing system design, understanding interactions with existing reinforcements, and accurately modeling behavior through numerical methods [20–22]. To address these challenges, experimental testing has been combined with advanced numerical modeling, validating the hypothesis that external prestressing enhances shear resistance through active confinement and delays brittle failure modes [23–28]. The workflow for analyzing prestressed concrete, encompassing material selection, prestressing techniques, structural analysis, and performance evaluation, is illustrated in Figure 2.

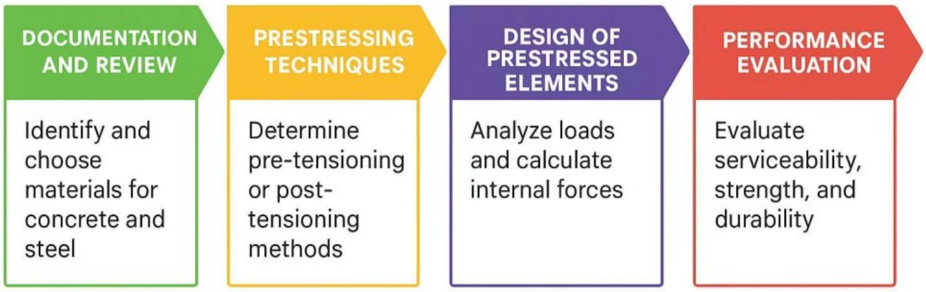


Figure 2 Prestressed Concrete Design Process Workflow

The aim of this review is to provide a comprehensive examination of the current state of research on the shear strengthening of RC beams using external prestressing bars. Emphasis is placed on experimental validations and numerical modeling approaches developed to simulate their performance. Current research gaps are identified, and recommendations for future studies are proposed to advance the practical implementation of this technique.

This paper is organized as follows: First, a historical perspective and state-of-the-art review of shear-strengthening techniques using external prestressing are presented. Next, the experimental methodologies and numerical modeling techniques used to assess the behavior of externally strengthened RC members are examined. Finally, the key findings, their implications for design practice, and avenues for future research are discussed.

2 State of the Art

The evolution of shear-strengthening techniques for RC structures, with a focus on external prestressing bars, is reviewed in this section. Historical developments are first examined, followed by an analysis of key experimental investigations and numerical modeling approaches employed to assess the efficacy of these techniques.

2.1 Historical Development of Shear-strengthening Techniques

Research on strengthening techniques for RC structures has been conducted for several decades [29]. Initially, efforts were directed toward enhancing flexural capacity, with external post-tensioning systems being developed to improve the bending resistance of beams [30–32]. In the 1990s, the inadequacy of shear reinforcement in structures designed under outdated codes or subjected to deterioration was recognized, prompting the development of retrofit techniques specifically targeting shear deficiencies [33–35].

Early investigations into external prestressing for shear strengthening were conducted by Aboutaha and Burns (1994), where prestressed concrete I-girders retrofitted with external prestressing bars were tested [36]. The shear capacity of deficient composite beams was significantly enhanced, and early shear cracking was prevented, thereby enabling the beams to achieve their full flexural capacity [37]. The redistribution of internal forces due to external prestressing enhances shear performance by reducing tensile stresses and delaying crack formation.

Table 1 summarizes the incorporation of external prestressing in shear design varies across international codes. ACI 318-19 [38,39] allows the inclusion of external prestressing as shear reinforcement when effectively anchored, whereas Eurocode 2 [40] relies on strut-and-tie models, requiring rigorous analytical verification. The Chinese Code (GB50010-2010) [41,42] adopts a conservative approach, in which stricter reduction factors are applied to account for long-term effects and anchorage performance. These differences reflect varying emphases on the mechanical principles of external prestressing, as detailed in Table 1.

Table 1 Comparison of the Design Provisions for Shear Strengthening with Post-Tensioned Bars.

Aspect	ACI 318-19 (USA)	Eurocode 2 (EN 1992-1-1)	Chinese Code (GB50010-2010)
Treatment of External Prestressing	Treated as external prestressing bars contributing to shear reinforcement if effectively anchored	Considered within advanced design methods, such as strut-and-tie models; not explicitly detailed	Treated similarly to internal transverse reinforcement with additional conditions
Effective Stress Considered in Design	Only effective prestressing force after losses is used	Long-term losses verified; conservative approach	Effective prestress considered with stricter reduction factors
Shear Contribution Calculation	Included in V_s term for shear resistance	Relies on strut-and-tie models or detailed supplementary calculations	Included via empirical coefficients
Crack Control	Crack widths limited under service loads	Strong focus on crack width and spacing limitations	Crack control mandatory, especially near anchorage zones
Ductility and Failure Mode	Ductile behavior ensured; brittle failure avoided	Redistribution capacity checks required; plastic rotation limits	Brittle failure avoided with detailed checks
Anchorage Detailing Requirements	Detailed requirements for anchors and transfer zones	Full verification of anchorage via strut-and-tie model	High emphasis on anchorage efficiency and strength checks

Aspect	ACI 318-19 (USA)	Eurocode 2 (EN 1992-1-1)	Chinese Code (GB50010-2010)
Shear Design Approach	Sectional method with interaction diagrams	Variable angle truss model (VATM) preferred	Hybrid between sectional and empirical methods
Use in Retrofitting	Widely accepted, particularly in seismic retrofitting	Allowed with engineering judgment; less common in codes	Permitted with supplementary checks; used in bridge retrofitting

In Table 1, V_S = Shear resistance provided by the **transverse reinforcement** (such as stirrups or external transverse post-tensioned bars).

2.2 *Shear Enhancement Using External Prestressing Bars: Experimental Verification*

Numerous experimental studies have been conducted to validate and refine the application of external prestressing bars for shear enhancement. In a study by Sirimontree et al. (2011), eight RC beams with shear span-to-depth ratios of 1.5 and 2.0 were tested [43]. High-strength threaded steel rods were vertically installed on both sides of the beam’s shear span, anchored using steel plates, and prestressed with a hydraulic jack. An increased prestressing force was reported to proportionally enhance shear capacity and improve ductility, with strengthened beams exhibiting higher ultimate loads and transitioning from sudden diagonal shear cracking to a more ductile flexural-shear failure.

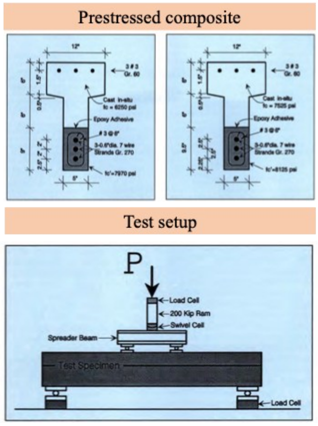
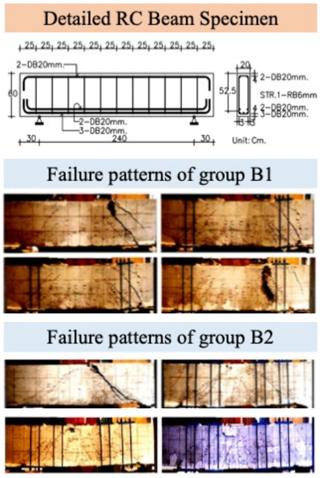
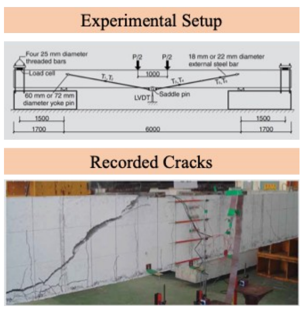
The shear strengthening of continuous T-beams was investigated by Lee et al. (2014), where external prestressing bars were applied to the interior span of a three-span system [44]. In their study, only the interior span of a three-span continuous beam was retrofitted with draped external bars. The experimental results indicated that compared with the unstrengthened control, the strengthened span showed an approximately 35% increase in load-carrying capacity. Additionally, serviceability parameters such as uncracked stiffness and deflection recovery were markedly improved. Interestingly, the experimental data were in good agreement with existing design equations (e.g., ACI 318-11 and AASHTO LRFD), suggesting that external prestressing could be effectively integrated into standard design practices if proper detailing and anchorage are ensured [45].

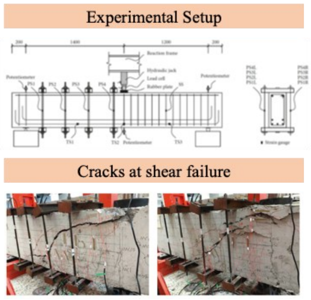
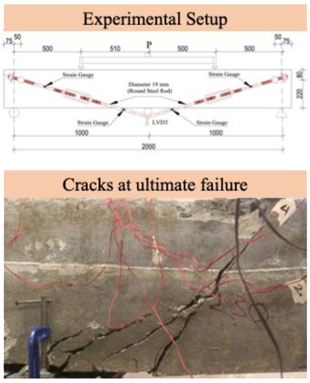
In China, Xue et al. (2019) examined RC beams without internal stirrups strengthened with external vertical prestressing rebars (EVPRs) [46]. In these studies, beams retrofitted with EVPRs were subjected to monotonic loading until failure. The experimental observations were striking: beams strengthened with EVPRs achieved higher ultimate shear capacities, exceeding code predictions for members with minimal shear reinforcement, and exhibited improved crack control and deflection characteristics. Enhanced performance was added to the active clamping force provided by the EVPRs, which significantly reduced the width of the diagonal cracks and increased the overall ductility of the beam.

In another innovative approach, Rai and Phuvoravan (2020) investigated deep RC beams strengthened by a V-shaped assembly of external prestressing rods [47]. Their tests compared a control deep beam with retrofitted samples and revealed that the V-rod configuration markedly improved shear performance and delayed the onset of brittle shear failure. The retrofitted beams exhibited a higher ultimate load and a more gradual post-cracking response, indicating a shift from a brittle failure mechanism to a more ductile failure mechanism. This finding is particularly significant for deep beams where achieving ductility is a major design challenge.

Key findings from these experimental campaigns, such as beam geometries, prestressing configurations, and shear capacity improvements, are summarized in Table 2.

Table 2 Summary of Selected Experimental Investigations.

Reference	Beam Type/Geometry	External Prestressing Configuration	Key Findings	Shear Capacity Increase	Schematic diagram
[36]	T-shaped prestressed composite beams (precast 229 × 406 mm T-section topped by cast-in-place flange); clear spans of 4.26 m (B1/R3) and 4.87 m (R1/R2/R4)	Vertical external prestressed stirrups using 16 mm Ø high-strength bars, drilled through the flange into the web, anchored with steel plates, and post-tensioned by hydraulic jack to 75% fpu (≈1380 MPa)	Prestressed stirrups shifted failure from sudden diagonal-tension to ductile flexural-shear, delayed both flexural and shear cracking, and enabled the development of the full flexural capacity even with very short strand embedment lengths	Considerable increase over control beams (exact percentage not specified)	
[43]	RC beams divided into two groups with shear span-to-depth ratios of 1.5 and 2.0 (eight specimens total)	Transverse external prestressing by vertical post-tensioned high-strength steel strands (12.7 mm Ø) installed over the shear spans via bearing plates and turnbuckles	Ultimate shear capacity increased in direct proportion to the applied prestress; failure mode shifted from brittle diagonal tension to more ductile shear–compression or flexural failure, with notable gains in ductility and stiffness	45.7–75.6% increase over control beams	
[44]	Continuous three-span RC beams (400 × 600 mm section; total length = 9 400 mm; interior span = 6 000 mm, exterior spans = 1 500 mm; shear span-to-depth a/d = 4.6)	V-shaped draped external steel bars: two 18 mm or 22 mm Ø mild-steel bars, unbonded, prestressed to ≈35% fpu, deviator at midspan, anchor plates through width; d_{p0} = 644 mm; d_1=d_2 = 150 mm	Strengthened beams exhibited a 12–13% increase in first-peak load and a 36–41% increase in second-peak load (catenary action), for an overall capacity boost of ≈35%; failure was ductile shear, and both ACI 318-11 (detailed) and	≈35% (first peak) and 36–41% (second peak)	

			AASHTO LRFD predictions matched the measured strengths and failure locations closely		
[46]	Rectangular RC beams without web reinforcement; 250 × 500 × 3000 mm; clear span = 2600 mm; a/d ≈ 3.33	External vertical prestressing rebars (Φ14 mm bars spaced 240–340 mm, prestressed to 18–26 kN)	Failure shifted from brittle diagonal-tension to ductile shear–compression; greatly improved ductility and full crack development before failure	85.3–96.4% increase over control beams	
[47]	RC deep beams tested under two-point loading (shear span = 1 m; a/h < 2); 200 mm × 300 mm cross-section; minimum web stirrups (9 mm @ 135 mm)	V-shaped external post-tension rods (2 × 19 mm Ø unbonded rods, prestressed to 24 MPa via turn-buckles and steel anchor plates)	V-rod retrofit delayed the onset of diagonal shear cracks, reduced crack inclination (to 36°–43°), and shifted failure from brittle to ductile, with higher stiffness and full crack development before collapse	21% at first shear failure; 20% at ultimate load	

From the data presented in Table 2, it is evident that external prestressing techniques consistently yield significant increases in shear capacity. Notably, the studies conducted by Sirimontree et al. and Xue et al. confirm that vertical or draped prestressing bars improve ductility by delaying the onset of diagonal cracking. These results suggest that the efficacy of external prestressing in increasing both strength and ductility is not limited to a single type of beam configuration but can be applied across various shapes (I-girders, rectangular sections, and T-beams). This broad applicability reinforces external prestressing as a versatile retrofit strategy for shear-critical RC structures.

2.3 *Shear Enhancement Using External Prestressing Bars: Numerical Simulation*

The successful replication of experimental behavior through numerical models is critical for designing and implementing external prestressing techniques in practice [48]. Various numerical methods have been employed to simulate the behavior of externally strengthened RC beams, ranging from simplified analytical models to sophisticated three-dimensional finite element (FE) models [49–55].

2.3.1 Analytical and Simplified Models

One common analytical approach involves the use of strut-and-tie models (STMs) to represent the load transfer mechanisms in RC beams [56]. This approach models the external prestressing force as an active axial force in a vertical tie that crosses the shear span. Sirimontree et al. (2011) demonstrated that such an STM could conservatively predict the ultimate shear capacity of beams retrofitted with external rods. Although simplified, these models capture the key mechanism by which the external prestress enhances shear resistance by providing a clamping force that improves aggregate interlock and reduces the likelihood of crack propagation [57].

Similarly, Lee et al. (2014) modified existing shear design equations (from ACI and AASHTO) to incorporate the additional contribution of external prestressing. Their analytical formulation added an extra term to account for the prestress-induced clamping effect on the concrete web. The modified equations were found to accurately predict the experimental results, suggesting that external prestressing could be integrated into conventional design frameworks with proper calibration [58]. More comprehensive discussions of the governing equations and modeling strategies for external prestressing bars can be found in the literature [59–62].

2.3.2 Finite Element Modeling

FE modeling has become a standard tool for simulating the nonlinear behavior of externally prestressed RC beams [63–65]. Researchers such as Zhou et al. (2021) have developed detailed three-dimensional FE models using commercial software (e.g., ABAQUS) to simulate the structural response under flexural and shear loads [66]. In these models, concrete is typically represented using a damage–plasticity formulation, whereas the reinforcement is modeled as embedded bar elements with elastic–plastic behavior. The external prestressing bars are often modeled as discrete truss or bar elements with an initial tensile strain corresponding to the applied prestress [67].

One critical challenge in FE modeling is accurately representing the bond–slip behavior at the interface between the external prestressing bars and the surrounding concrete [68,69]. In many models, this interaction is simplified by assuming suitable anchorage [70]; however, experimental studies have shown that slight slip at the anchorage can significantly affect the load transfer and overall behavior. To address this issue, some researchers have introduced contact algorithms or spring elements to simulate bond behavior more realistically [71].

A parametric FE study by Zhou et al. (2021) investigated the influence of key parameters such as the shear span-to-depth ratio, prestress level, and anchorage stiffness on the structural response of externally strengthened beams. Their results indicated that a deeper arrangement of external prestressing bars (i.e., closer spacing) and higher prestress levels resulted in a more pronounced delay in diagonal cracking, reduced crack widths, and increased ultimate shear capacity. Moreover, the FE models were able to replicate both the load–deflection behavior and the observed failure modes (transitioning from brittle shear to ductile flexural failure), with errors typically within 5–10% of the experimental values.

Other researchers have employed nonlinear FE models to conduct sensitivity analyses and predict environmental factors' effects (such as temperature and corrosion) on the long-term performance of externally prestressed systems [72–77]. These studies are crucial for developing robust design guidelines that account for immediate structural performance, durability, and service life.

2.3.3 Hybrid and Multi-scale Modeling Approaches

Given the complexity of shear behavior in externally prestressed RC members, several studies have combined different modeling approaches to capture both global structural behavior and local bond phenomena [78–82]. Hybrid models often couple a global FE model with localized analytical models of the bond–slip relationship between the external reinforcement and the concrete [83–86]. This multi-scale approach allows researchers to simulate the overall structural response while incorporating detailed information on interfacial mechanics, which is critical for accurately predicting failure modes [87–89].

For example, a study by Fayed et al. (2024) developed an analytical–numerical hybrid model that integrated a modified STM with local bond models. Their results demonstrated that the hybrid model could predict the ultimate shear capacity of retrofitted beams more accurately than conventional models that did not account for bond degradation or slip. These advances have contributed to a better understanding of how external prestressing interacts with internal reinforcement and concrete to provide enhanced shear capacity.

2.4 *Summary of the State of the Art*

In summary, Figure 3 illustrates the progression of investigative approaches, from early experimental studies to advanced hybrid modeling methods, highlighting the increasing sophistication in understanding and applying external prestressing for shear strengthening. :

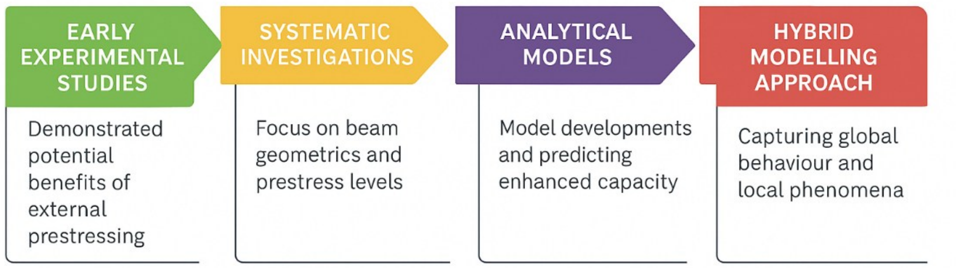


Figure 3 Evolution of Research on Shear Strengthening of RC Beams Using External Prestressing Bars

Despite these advancements, several research gaps remain. The optimal design of anchorage systems, the long-term behavior of external prestressing under cyclic and environmental loading, and the integration of these techniques into standard design codes are areas that require further study. The following sections describe the experimental and numerical methods used in recent studies and discuss the implications of their findings for future research and design practices.

3 Experimental Methodology

This section outlines the methodology employed in experimental investigations of RC beams strengthened with external prestressing bars. Detailed descriptions of the specimen preparation, instrumentation, test setup, and procedures used to apply external prestress are provided. A detailed flowchart outlining the procedure for testing prestressed concrete, such as specimen preparation, loading conditions, instrumentation setup, and data acquisition, is shown in Figure 4.

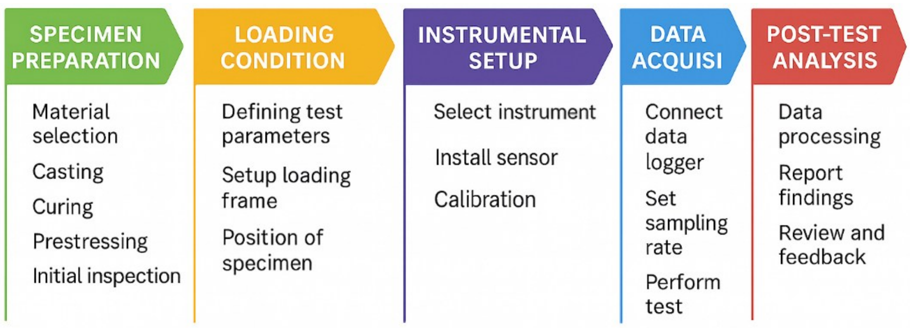


Figure 4 Procedure for Testing Prestressed Concrete

3.1 Specimen Design and Preparation

Several RC beam specimens were designed to simulate common shear-critical regions, as observed in practical structures [90–98]. These beams typically have rectangular or T-shaped cross-sections and were constructed with minimal internal shear reinforcement to ensure that shear failure is the governing limit state. The primary reinforcement (longitudinal steel bars) was designed to ensure sufficient flexural capacity, whereas internal stirrups were either omitted or provided in minimal amounts. This design approach was chosen to highlight the effect of the externally applied prestressing bars on the overall shear capacity.

The dimensions of the test beams were chosen based on typical values used in full-scale laboratory studies. For example, several investigations have used beams with spans ranging from 3.0 to 6.0 m and cross-sectional depths between 600 and 750 mm [99–110]. The beams were cast using a normal-strength concrete mix with an average compressive strength of 25–35 MPa. The concrete mix design, aggregate size, and curing conditions were carefully controlled to ensure consistency across all the specimens.

The external prestressing bars were installed in two primary configurations:

- External Vertical Prestressing Rebars (EVPRs): These bars were installed vertically on the sides of the beam web by drilling pre-determined holes or slots in the concrete and inserting high-strength steel bars. The bars were then anchored at the top and bottom of the beam using steel plates, torque-controlled expansion anchors, or mechanical anchorages.
- Draped External Prestressing Bars: In some specimens, the external bars were configured in a draped or V-shaped arrangement. This configuration allowed the prestressing force to be applied vertically and with an inclined component, potentially enhancing both flexural and shear behavior.
- In all cases, the bars were pre-tensioned using hydraulic jacks to a specified force level, typically set as a percentage of the yield strength of the prestressing steel (often between 25% and 50%). The prestressing force was monitored using strain gauges attached to the bars. Special care was taken to ensure that the installation process did not damage the concrete or compromise the integrity of the reinforcement.

3.2 Instrumentation and Data Acquisition

Each test beam was equipped with a variety of sensors to record the entire spectrum of structural activity, including the following:

- Load Cells: Positioned at the supports and beneath the hydraulic jack to accurately record the applied loads.
- Linear Variable Differential Transformers (LVDTs): Installed at mid-span and other critical locations to measure deflections and crack openings.
- Strain Gauges: Affixed to both the internal reinforcement and the external prestressing bars to monitor the strain levels during loading.
- Crack Meters and Digital Image Correlation (DIC): In some tests, additional instruments were used to document crack propagation and measure localized deformations on the beam surface.

Data from these sensors were recorded at regular intervals throughout the loading process. Testing was conducted under monotonic load application using a four-point bending configuration. This setup generated a constant-moment region in the mid-span while exposing the shear spans near the supports to high shear forces. The load was gradually increased until failure, and the load–deflection response, strain distributions, and crack patterns were recorded.

3.3 Test Setup and Loading Procedure

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The test equipment was created to replicate actual boundary circumstances for simply supported or continuous beams. To enable rotation and lateral movement, the supports were set up with a hinged support at one end and a roller at the other. The beams were placed on a rigid testing frame capable of applying loads up to 1000 kN. Hydraulic jacks were used to apply the load in a controlled, displacement-driven manner.

The loading procedure was divided into several stages:

- Initial Loading: The beam was gradually loaded in the uncracked, elastic range. The reaction at this point was linear and served as a stiffness baseline.
- Cracking Stage: As the load increased, flexural cracks appeared in the tension zone, reducing stiffness. The external prestressing bars, already in tension, began to provide an active clamping force that limited the crack width.
- Post-Cracking Behavior: Following the start of cracking, the load–deflection response of the beam was continuously observed. An assessment was conducted to determine how external prestressing helped redistribute forces and postpone the development of crucial diagonal shear cracks.
- Ultimate Failure: Finally, the beam reached its ultimate load. At this point, a transition in the failure mode (from brittle shear to ductile flexural failure) was observed in the strengthened samples. The ultimate load and corresponding deflections were recorded, along with any signs of bond slip or debonding at the external prestressing interface.

The test results provided detailed insight into the improvement in shear capacity and overall ductility imparted by the external prestressing system.

4 Discussion

The collective evidence drawn from more than three decades of testing and simulation underscores the robustness of external prestressing as a shear-retrofit strategy for RC beams. By actively clamping the web, the technique not only restores (or exceeds) the original shear capacity of deficient members but also improves ductility and serviceability in ways that other passive systems rarely achieve.

4.1 Experimental Observations

This subsection presents an examination of the key experimental outcomes, focusing on the improvements in shear capacity, failure mode transitions, and serviceability enhancements observed in beams strengthened with external prestressing bars.

4.1.1 Improvement in Shear Capacity

The results from Table 2 indicate that studies such as Sirimontree et al. (2011) reported shear capacity increases of 45.7% to 75.6% in beams with shear span-to-depth ratios of 1.5 and 2.0, respectively, that were retrofitted with vertical post-tensioned steel rods. Similarly, Xue et al. (2019) reported increases of 85.3% to 96.4% in beams without internal stirrups using external vertical prestressing rebars (EVPRs). These improvements stem from the active clamping force, which improves aggregate interlocking and limits crack propagation, as described in Section 3.1. Lee et al. (2014) further demonstrated a 35% increase in the load-carrying capacity for continuous T-beams with draped bars, highlighting the technique's applicability across diverse beam configurations.

4.1.2 Changes in Failure Mode

Unstrengthened RC beams typically exhibit brittle diagonal shear cracking, as noted in Section 1. However, experiments have shown that prestressing delays such cracking and often shifts the failure mode to ductile flexural–shear or flexural. For instance, Aboutaha and Burns (1994) reported that prestressed stirrups in composite beams prevented sudden diagonal-tension failure, promoting ductility. Rai and Phuvoravan (2020) reported that V-shaped external rods in deep beams reduced crack inclination and facilitated a gradual post-cracking response, as summarized in Table 2. This shift enhances the deformation capacity and provides warning before collapse.

4.1.3 Serviceability and Deflection behavior

Strengthened beams exhibit enhanced stiffness and reduced deflections under service loads. Lee et al. (2014) reported improved uncracked stiffness and deflection recovery in continuous T-beams, along with a 35% capacity increase. Xue et al. (2019) reported better crack control with EVPRs, resulting in narrower crack widths, as supported by the instrumentation data in Section 3.1.2. These improvements ensure better long-term functionality and reduced maintenance needs.

4.2 Numerical Model Performance

This section is focused on the accuracy of finite element models, where validation metrics and modeling assumptions play pivotal roles in replicating experimental findings.

4.2.1 Accuracy of Finite Element Models

As detailed in Section 2.3.2, Zhou et al. (2021) demonstrated that ABAQUS-based models, using a concrete damage plasticity approach, predicted ultimate loads within 5–10% of experimental values. These models accurately captured crack progression and failure mode shifts, aligning with observations from Section 3.1.3. The incorporation of bond–slip interactions, although simplified, improved the agreement with the strain gauge readings, confirming the models' reliability for design applications.

4.2.2 Parametric Studies and Sensitivity Analysis

FE analyses, as described in Section 2.3.2, reveal that higher prestress levels and closer bar spacing delay diagonal cracking and enhance shear capacity, which is consistent with the findings in Table 2. Anchorage stiffness is critical, with rigid systems ensuring effective prestress transfer, whereas flexible anchorages risk partial loss, as noted in Section 3.1. These results emphasize the importance of optimized design configurations to maximize strengthening benefits.

4.3 Comparison of Experimental and Numerical Results

Both approaches confirm enhanced shear capacity, ductility, and serviceability, with FE models predicting ultimate loads within 5–10% of the experimental values, as seen in Sections 2.2 and 2.3. However, numerical models occasionally underestimate crack widening and secondary crack development due to simplified bond–slip assumptions, particularly in regions of high stress concentrations. Despite these minor discrepancies, the strong alignment in load–deflection behavior and failure mode transitions supports the combined use of experimental and numerical methods for robust analysis.

5 Challenges and Limitations

Several challenges must be addressed to facilitate the practical adoption of external prestressing for shear strengthening. Despite these encouraging findings, the implementation of external prestressing for shear strengthening faces several challenges. The effectiveness of the external prestressing system relies on a robust bond between the external bars or tendons and the concrete. Any degradation of the bond over time, due to corrosion, debonding, or improper installation, can compromise the system's performance, necessitating advanced monitoring techniques and non-destructive evaluation methods to ensure long-term

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performance. Additionally, while FE models are powerful tools for design and analysis, they require significant expertise and computational resources, and simplified analytical models may fail to capture the full complexity of the behavior. The cost and feasibility of retrofitting existing structures with external prestressing systems can be prohibitive in some cases, as field implementation requires careful planning, specialized equipment, and often temporary closure of the structure, which may not be acceptable in all scenarios. Furthermore, current design codes do not fully incorporate external prestressing for shear strengthening, and significant research is needed to develop reliable, standardized design guidelines that the industry can adopt.

6 Implications for Design and Future Research

The shift to ductile failure modes (Section 4.1.2) improves safety, whereas reduced deflections and crack widths (Section 4.1.3) increase longevity. The results align with the predictions of ACI 318-11 and AASHTO LRFD (Section 2.2), suggesting the potential for code updates to incorporate external prestressing provisions. A robust anchorage design is critical for effective prestress transfer (Section 4.2.2). Future research should investigate long-term durability under cyclic and environmental loading, leveraging the experimental setups in Section 3.1, and explore hybrid strengthening systems that combine external prestressing with techniques such as FRP bonding to address multiple deficiencies.

7 Conclusions

It is evident from the thorough analysis of experimental research and numerical modeling initiatives that using external prestressing bars to reinforce RC beams against shear has significant advantages. Compared with unstrengthened members, experimental research has consistently shown that external prestressing can increase the ultimate shear capacity of RC beams by 20–70%. This improvement is largely attributed to the active clamping provided by the external bars, which delays the onset of diagonal cracking and enhances aggregate interlocking. Moreover, the application of external prestressing tends to transition the failure mode from brittle diagonal shear failure to more ductile flexural or flexural–shear failure, thereby increasing structural safety by providing greater deformation capacity and earlier warning before collapse.

In terms of serviceability, externally prestressed beams exhibit lower deflections and reduced crack widths under service loads owing to improved stiffness in the uncracked stage and enhanced recovery upon unloading. Advanced finite element models that incorporate concrete damage plasticity and detailed bond–slip representations have been validated against experimental data, demonstrating the ability to accurately predict load–deflection behavior, strain distributions, and ultimate failure loads within a margin of 5–10%. Parametric studies further revealed that critical factors, such as the prestress level, bar spacing, anchorage stiffness, and shear span-to-depth ratio, significantly influence the performance of external prestressing, with optimal configurations generally involving higher prestress levels and denser bar arrangements, particularly in beams with lower a/d ratios.

The strong correlation between the experimental findings and numerical predictions suggests considerable potential for integrating external prestressing provisions into existing design codes, such as ACI 318-11 and AASHTO LRFD, through the development of standardized design guidelines. However, challenges remain regarding the long-term performance of external prestressing systems, especially concerning bond degradation and anchorage design. Any deterioration in the bond can reduce the prestressing force and compromise the overall system effectiveness, necessitating further research into robust anchorage details and non-destructive evaluation methods. Additionally, comprehensive field studies and pilot projects must address practical considerations, such as installation complexity, cost implications, and the need for temporary structural closures.

Future research should prioritize the long-term durability of externally prestressed systems under cyclic and environmental loading, explore hybrid strengthening solutions that combine external prestressing with other techniques, and develop simplified yet accurate analytical models for routine design applications. Overall, when properly designed and implemented, external prestressing increases the ultimate load capacity and improves ductility and serviceability, thereby extending the service life of existing structures. Integrating experimental testing with advanced numerical modeling provides a strong basis for further development and eventual code adoption.

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