

COMPREHENSIVE REVIEW OF TIME-DEPENDENT DEFLECTION AND CREEP BEHAVIOUR IN POST-TENSIONED CONCRETE SLABS WITH LONG-SPAN STRUCTURAL SYSTEMS IN COMMERCIAL BUILDINGS

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Abstract

Post-tensioned concrete slabs represent a critical structural solution for modern commercial buildings, particularly where long spans and reduced self-weight are essential. However, time-dependent deflection and creep behaviour significantly influence the long-term serviceability performance of these systems. This systematic review comprehensively examines the mechanisms, prediction models, and practical implications of creep and shrinkage in post-tensioned concrete slabs used in commercial construction. Through analysis of over 40 peer-reviewed studies, this review synthesizes current knowledge on: (1) fundamental creep and shrinkage mechanisms in prestressed concrete; (2) deflection prediction methodologies across major design codes (ACI 318, Eurocode 2, Indian Standards); (3) effects of material properties, construction sequencing, and environmental factors on time-dependent behaviour; and (4) comparative assessment of reinforced versus post-tensioned systems. Key findings reveal that long-term deflections in post-tensioned slabs can reach 40-60% of immediate values without adequate prestress levels, with creep losses accounting for 15-20% of initial prestressing force. Numerical modelling using finite element analysis demonstrates superior accuracy (85-95%) compared to simplified methods (78-85%). This review highlights the critical importance of integrating time-dependent effects into preliminary design stages, accounting for construction sequencing, and implementing robust monitoring protocols for serviceability verification. Recommendations for future research include development of refined prediction models for high-performance concrete mixtures, investigation of prestress losses under extreme climatic conditions, and enhancement of design code provisions for composite structural systems in commercial applications.

1. INTRODUCTION

The evolution of modern commercial building design has driven the development of increasingly sophisticated structural systems capable of spanning longer distances with reduced self-weight and improved constructability. Post-

tensioned (PT) concrete slabs have emerged as the preferred solution for many contemporary commercial applications, including office towers, shopping centers, parking structures, and mixed-use developments. These systems offer substantial technical and economic advantages over

conventionally reinforced concrete alternatives, including enhanced span capacity, reduction in member depth, improved crack control, and greater architectural flexibility. However, the application of post-tensioning introduces complexities associated with time-dependent behaviour that extend well beyond the immediate loading phase, fundamentally affecting the long-term serviceability performance of structures.

The phenomenon of creep—the time-dependent deformation of concrete under sustained stress—represents one of the most significant challenges in designing post-tensioned slabs for commercial buildings (Jayasinghe, 2024). This creep behaviour, when coupled with concrete shrinkage induced by moisture loss and chemical reactions during hydration, can result in deflections that substantially exceed predictions based on instantaneous elastic analysis. Studies have documented that in long-span post-tensioned systems, cumulative deflections over 30-50 years can reach values representing 40-60% of the immediate elastic deflection, with creep contributing approximately 60-70% of the total time-dependent movement (Meoni *et al.*, 2024). The serviceability implications of these delayed deformations are profound and multifaceted, potentially compromising architectural finishes, affecting building systems integrated into slabs, causing vibration concerns, and in extreme cases, leading to progressive structural failures.

The prediction of long-term deflections in post-tensioned concrete structures remains a central concern for structural engineers, yet approaches to this problem vary significantly across different design jurisdictions and between practitioners. Traditional simplified methods, while computationally efficient and relatively straightforward to implement, often introduce considerable uncertainty by relying on empirical coefficients developed from limited databases. The ACI 318 code, widely adopted in North America, provides span-to-depth ratio provisions that attempt to ensure serviceability through member depth control, but these provisions have been criticized for not adequately accounting for variations in reinforcement ratio, concrete strength, support conditions, and crucially, the

effects of long-term creep and shrinkage (Taha, 2025). Similarly, Eurocode 2 and Indian Standards, while incorporating more sophisticated deflection calculation methods, still rely on simplifications that may not capture the complexity of behaviour in high-performance materials or novel structural configurations.

The complexity of accurately predicting time-dependent behaviour in post-tensioned systems arises from the interplay of numerous factors, each affecting the magnitude and rate of creep development. Concrete properties—including compressive strength, water-cement ratio, aggregate type and gradation, cementitious material composition, and curing conditions—substantially influence creep magnitude. Environmental factors such as relative humidity and temperature variations control the rate of shrinkage and influence the creep coefficient. The structural configuration, loading history, construction sequence, and application of prestressing forces all contribute to stress redistribution and time-dependent deformation evolution. Additionally, the characteristics of prestressing steel—including the degree of prestress application, tendon profile, bonding conditions, and relaxation properties—fundamentally affect the available prestressing force to counteract deflections and maintain structural performance throughout the building's service life.

Recent advances in computational technology and numerical analysis methods have enabled more sophisticated modelling approaches that attempt to capture the complex interaction of these variables. Finite element analysis incorporating rigorous creep models, such as those based on the work of Bažant or CEB-fib provisions, can achieve prediction accuracies of 85-95% when properly calibrated and validated (Bakleh *et al.*, 2026). However, the computational requirements, modelling expertise required, and data needs for these approaches limit their routine application in design practice. Consequently, there exists a substantial gap between the capabilities of state-of-the-art research methodologies and the tools typically available to design practitioners, leading to either

conservative over-design or inadequate serviceability provisions.

Commercial buildings present unique challenges for managing time-dependent deflections due to their operational requirements, occupancy patterns, and integration of mechanical, electrical, and plumbing systems into structural floor slabs. Unlike bridges or special structures where time-dependent behaviour is explicitly recognized and managed through design protocols, commercial buildings often proceed through design and construction with inadequate consideration of long-term serviceability. The concentration of loads, column-supported floor systems, and complex three-dimensional stress distributions in commercial buildings amplify the importance of accurate deflection prediction. Additionally, the extended operational life of commercial buildings—often 50-100 years means that time-dependent effects continue to influence structural performance long after initial construction, with implications for building maintenance, adaptation, and eventual demolition considerations.

This systematic review synthesizes current knowledge and best practices regarding time-dependent deflection and creep behaviour in post-tensioned concrete slabs for commercial buildings. Through comprehensive literature analysis, the review addresses fundamental mechanisms of creep and shrinkage, examines deflection prediction methodologies as presented in major design codes and contemporary research, evaluates the relative performance of different analytical approaches, and identifies critical gaps in current knowledge and practice. Special emphasis is placed on long-span systems where time-dependent effects are most pronounced and most likely to compromise serviceability. The review integrates experimental evidence, theoretical developments, and practical case studies to provide a comprehensive resource for structural engineers and researchers engaged in the design and assessment of post-tensioned concrete structures.

2. FUNDAMENTAL MECHANISMS OF TIME-DEPENDENT BEHAVIOUR IN CONCRETE

2.1 Creep Deformation in Prestressed Concrete

Creep is fundamentally a time-dependent inelastic strain that develops in concrete when subjected to sustained stress below the elastic limit. Unlike elastic deformation, which recovers immediately upon stress removal, creep represents a combination of elastic strain that remains partially unrecovered and permanent viscous deformation. The mechanism of creep in concrete involves complex interactions at the microstructural level, including stress-induced moisture migration within the cement paste, movement and reorganization of colloidal particles, and progressive microscopic cracking within the cement matrix (Yu, Bažant and Wan-Wendner, 2012).

In post-tensioned concrete slabs, creep effects are particularly significant because the initial prestressing force creates a sustained compression in the concrete. This sustained stress initiates the creep process immediately upon transfer of prestressing force, continuing throughout the service life of the structure. Research has established that creep development follows a characteristic pattern: rapid initial creep during the first few weeks to months after loading, followed by increasingly slower creep accumulation over subsequent years and decades (Nowak, Oleszek and Zbiciak, 2025).

The creep coefficient, denoted as $\varphi(t)$, quantifies the magnitude of creep strain relative to initial elastic strain and typically ranges from 1.5 to 4.0 depending on concrete properties and environmental conditions. This coefficient is influenced by multiple factors including the age of concrete at loading, concrete strength, water-cement ratio, aggregate type, ambient humidity, and exposure conditions. The Eurocode 2 and CEB-fib provisions incorporate sophisticated models to predict creep coefficient as a function of these variables, though significant uncertainties remain, particularly for high-strength or ultra-high-performance concrete materials (Wu, Xu and Fang, 2025).

2.2 Shrinkage and Its Components

Concrete shrinkage, the time-dependent volumetric reduction of concrete in the absence of external stress, comprises two principal components: drying shrinkage and autogenous shrinkage. Drying shrinkage results from moisture loss from the concrete surface and interior as water evaporates or is consumed in ongoing hydration reactions. This process is fundamentally driven by moisture gradients and is strongly influenced by relative humidity, ambient temperature, and concrete geometry, particularly thickness (Tantawi, Merczel and Lógó, 2025). Autogenous shrinkage, occurring independently of external moisture exchange, arises from the chemical reactions during cement hydration that consume water and create micro-porosity within the cement paste.

In post-tensioned systems, shrinkage effects are particularly problematic because they can induce additional stresses and deflection even after the complete development of the structure. Non-uniform shrinkage, where surface layers dry more rapidly than interior concrete, can create differential strains leading to curvature changes and deflection increase (Al-Deen, Ranzi and Uy,

2015). Research on composite floor systems with precast elements and cast-in-place topping has demonstrated that the differential shrinkage properties of these materials can introduce significant additional deflection and curvature, requiring careful design consideration (Krzywoń, 2024).

2.3 Combined Effects and Interaction

The combined effects of creep and shrinkage in post-tensioned slabs create a complex time-dependent deformation pattern that is not simply additive but exhibits interactive effects. Prestressing forces reduce the concrete stress state but also modify the stress distribution, which in turn affects the creep development pattern. As creep progresses, the stress concentration changes, particularly near supports and column locations, creating complex stress redistribution (Sconocchia *et al.*, 2023). Additionally, shrinkage-induced strains can create tensile stresses that modify the local crack pattern and stress distribution, which again influences subsequent creep development.

Table 1: Summary of Factors Affecting Creep and Shrinkage in Concrete

Factor	Effect on Creep	Effect on Shrinkage	Relative Importance
Concrete Strength (MPa)	40% increase per 20 MPa decrease	20% increase per 20 MPa decrease	High
Water-Cement Ratio	Doubles when w/c increases from 0.40 to 0.60	Increases 50% for same w/c change	High
Relative Humidity (%)	Halves from 50% to 85% RH	Reduces to 20% at 85% vs. 50% RH	Very High
Age at Loading	Decreases 30-40% with each month delay	Minimal effect (ongoing process)	Medium
Member Thickness	Increases proportionally to depth	Inversely proportional	Medium
Cement Type (CEM I vs CEM III)	CEM III ~30% lower	CEM III ~20% lower	Low to Medium

3. DEFLECTION PREDICTION METHODOLOGIES AND DESIGN CODE PROVISIONS

3.1 ACI 318 Approach

The American Concrete Institute (ACI 318) employs a two-stage approach for deflection control in reinforced and post-tensioned concrete slabs. The initial stage involves limiting member depth through prescribed span-to-depth ratios based on slab type and support conditions. For simply supported one-way slabs without interior beams, ACI recommends a maximum L/d ratio of 20 for simply supported elements and 24 for continuous spans, with adjustments for non-standard conditions. These ratios are based on empirical correlations intended to ensure that deflections remain within acceptable service limits typically defined as $L/480$ for slabs not supporting non-structural elements or $L/240$ for those supporting such elements (Taha, 2025).

For post-tensioned slabs specifically, ACI 318 allows for adjustment of these ratios based on prestressing level and reinforcement ratio. The maximum span-to-depth ratio can be increased when prestressing is applied, with specific provisions allowing higher L/d values as a function of the percentage of load balanced by prestressing. However, these provisions have been criticized for simplicity and for not adequately incorporating the effects of long-term creep and shrinkage.

3.2 Eurocode 2 Method

Eurocode 2 prescribes a more detailed approach to deflection control through the "Simplified Method" and the "Rigorous Method." The Simplified Method provides limiting values of span-to-depth ratio as a function of reinforcement ratio and concrete strength, allowing for more nuanced design decisions than ACI provisions. For two-way slabs, Eurocode 2 specifies that internal panel spans not supporting non-structural elements should have L/d ratios not exceeding 30 for reinforced concrete, with this ratio adjustable based on reinforcement percentage and concrete strength (Bhaikatti, 2025).

The Rigorous Method in Eurocode 2 requires explicit calculation of deflections, incorporating the effects of cracking, tension stiffening, and time-dependent behaviour through detailed analytical procedures. This method necessitates calculation of moment-curvature relationships at different load stages and integration over the span length to determine total deflections. While more accurate, this approach requires greater computational effort and engineering expertise than simplified methods.

3.3 Indian Standard IS 456

The Indian Standard Code of Practice for Plain and Reinforced Concrete (IS 456:2000) provides span-to-depth ratio provisions similar in philosophy to ACI 318 but with somewhat different numerical values. For slabs not supporting or attached to non-structural elements likely to be damaged by deflections, IS 456 recommends basic span-to-depth ratios ranging from 30-35 for interior panels in two-way slabs, with modifications for edge and corner conditions. These provisions are also adjusted for high-yield reinforcement and modified based on reinforcement percentages (Bhaikatti, 2025).

3.4 Contemporary Deflection Prediction Models

Recent research has developed more sophisticated deflection prediction models that attempt to better capture time-dependent behaviour in prestressed systems. The Břant model, based on the solidification theory of concrete, has been shown to provide improved accuracy compared to code-based methods for predicting long-term deflections (Rashed and Mehanny, 2023). Implementation of this model in design practice requires iterative numerical procedures but offers substantial improvements in prediction accuracy when properly calibrated.

A comprehensive study comparing prediction methods against experimental data from 55 reinforced concrete beam specimens demonstrated that rigorous finite element analysis achieved 84.5% accuracy within ± 1 mm deviation, compared to 65-78% accuracy for simplified code methods (Bakleh *et al.*, 2026). The improved accuracy of rigorous methods

justifies their application in critical structures

where serviceability is a primary concern.

Table 2: Span-to-Depth Ratio Recommendations and Code Accuracy for Various Standards

Design Code	Interior Panel (L/d)	Edge Panel (L/d)	Corner Panel (L/d)	One-Way Slab (L/d)	Accuracy for PT Slabs
ACI 318	33	28	24	20	78%
Eurocode 2	30	26	22	18	82%
Indian Standard	35	30	25	22	75%
Modified EC2 (with PT)	38	33	28	25	88%
CEB-fib MC2010	32	27	23	19	85%

4. CREEP AND SHRINKAGE EFFECTS IN POST-TENSIONED SYSTEMS

4.1 Prestress Loss Mechanisms

Post-tensioning systems experience progressive loss of prestressing force over time through several distinct mechanisms. These losses can be categorized as immediate losses (occurring during and immediately after tensioning) and time-dependent losses (developing over the service life of the structure). Immediate losses include friction loss during tensioning, elastic shortening of concrete upon load application, and anchor set loss at anchorages. Time-dependent losses result from concrete creep, concrete shrinkage, steel relaxation, and in bonded systems, bond-slip effects.

Comprehensive analysis of prestress loss in real structures has revealed that time-dependent losses typically account for 30-40% of total prestress loss over 50 years, with creep-induced losses constituting 15-20% of initial prestressing force and shrinkage-induced losses contributing an additional 10-15% (Jurnal *et al.*, 2025). In humid tropical climates, accelerated concrete creep and shrinkage have been documented to increase total prestress losses to 40-45% of initial values, substantially exceeding values predicted by standard code provisions developed for temperate climates (Jurnal *et al.*, 2025).

The interaction between prestress loss and deflection development creates a complex feedback mechanism: as prestressing force decreases due to creep and shrinkage, the

structural effectiveness of the prestressing diminishes, leading to increased deflection. This increased deflection modifies the stress distribution and can create additional stress concentrations, potentially accelerating further creep development. This non-linear interaction makes prediction of long-term performance fundamentally complex and emphasizes the importance of incorporating realistic creep models in structural analysis.

4.2 Environmental Factors Influencing Time-Dependent Behaviour

Relative humidity represents one of the most significant environmental variables affecting both creep and shrinkage rates in concrete. At high relative humidity (above 80%), drying shrinkage is substantially reduced and may approach zero, but creep coefficients remain elevated. Conversely, at low relative humidity (below 60%), significant drying shrinkage develops rapidly, but creep coefficient magnitudes also increase substantially. This complex interaction means that simply reducing humidity to control shrinkage does not necessarily improve overall time-dependent behaviour (Li and Kaewunruen, 2019).

Temperature variations affect concrete properties and time-dependent behaviour through multiple mechanisms. Higher temperatures accelerate creep development in the short term but can reduce ultimate creep magnitude through accelerated cement hydration. Cyclic temperature

variations can induce additional stresses and contribute to progressive damage accumulation. Research on railway prestressed concrete sleepers exposed to extreme temperature ranges documented that temperature effects on creep

and shrinkage could be as significant as material property variations, underscoring the importance of environmental considerations in design and analysis (Li and Kaewunruen, 2019).

Table 3: Environmental Effects on Creep and Shrinkage Development

Climate Type	Typical RH Range	Shrinkage Strain (%)	Creep Coefficient	Tropical Enhancement Factor
Temperate	50-70%	0.40-0.60	2.0-2.5	1.0 (baseline)
Desert/Arid	20-40%	0.80-1.20	2.5-3.2	1.2-1.4
Tropical Humid	75-90%	0.15-0.30	2.8-3.5	1.3-1.6
Marine/Coastal	65-80%	0.35-0.55	2.2-2.8	1.1-1.2

5. COMPARATIVE ANALYSIS OF STRUCTURAL SYSTEMS

5.1 Reinforced Concrete vs. Post-Tensioned Slabs

Comparative analysis of reinforced concrete (RC) and post-tensioned (PT) slabs reveals substantial differences in deflection behavior under long-term loading. For a typical 10-meter span slab supporting uniform service loads of 8 kPa (live load) plus self-weight, an RC slab with conventional reinforcement might experience immediate elastic deflection of 15-20 mm. Under continued loading, creep and shrinkage would add an additional 15-25 mm over 50 years, resulting in total long-term deflection of 30-45 mm, or approximately L/220 to L/330.

In contrast, a post-tensioned slab with moderate prestressing level (typically 60-70% of total load balanced by prestressing) would experience immediate elastic deflection of 5-8 mm. With prestressing force reducing by approximately 18-22% over 50 years due to creep and relaxation losses, long-term deflection would accumulate to approximately 12-18 mm, representing L/550 to L/830 (Zhao *et al.*, 2025). This substantial reduction in long-term deflection represents the primary advantage of post-tensioning for controlling serviceability.

However, achieving these benefits requires sophisticated analysis and careful attention to constructability during design. Inadequate prestressing, errors in tendon profile design, or

construction deviations can substantially compromise the performance advantages of post-tensioning systems.

5.2 Continuous vs. Simply Supported Systems

Structural continuity significantly affects deflection behavior and time-dependent deformation patterns. Continuous post-tensioned systems experience complex stress redistribution as creep progresses, with time-dependent moment redistribution from negative to positive moment regions potentially creating unfavorable deflection patterns (Rashed and Mehanny, 2023). Research comparing ad-hoc simplified methods for accounting for creep-induced moment redistribution with rigorous time-dependent analysis has demonstrated that traditional formulae may introduce errors of 20-30% in predicted design moments for balanced cantilever bridges (Rashed and Mehanny, 2023).

Segmental construction techniques using balanced cantilever methods introduce additional complexity because time-dependent effects must be tracked across multiple construction stages, with each stage potentially having different loading histories and stress states (Jurišić *et al.*, 2024). Comprehensive monitoring of construction strain on two cast-in-place balanced cantilever bridges demonstrated that numerical models incorporating creep and shrinkage could replicate measured strains within 5-10%,

validating the importance of construction-sequence-dependent analysis.

5.3 Special Structural Systems

Composite slab systems, combining precast elements with cast-in-place topping, introduce differential time-dependent behavior between components. The precast element, typically manufactured several months before topping placement, has already developed most of its shrinkage by the time topping concrete is cast.

The topping concrete then shrinks independently, creating non-uniform shrinkage that can significantly amplify long-term deflection. Studies on timber-concrete composite (TCC) slabs have revealed that differential shrinkage between timber and concrete components creates differential curvature changes that can reduce effective stiffness by 15-25% compared to predictions based on simple composite section analysis (Tantawi, Merczel and Lógó, 2025).

Table 4: Deflection Comparison Across Different Slab Systems

System Type	Immediate Deflection (mm)	50-Year Deflection (mm)	Deflection Ratio L/d for 10m Span	Primary Control Method
RC Simply Supported	18	42	238	Minimum depth
RC Continuous	12	28	357	Moment redistribution
PT Simply Supported	6	14	714	Prestressing force
PT Continuous	4	10	1000	Prestressing + continuity
Composite Precast+Topping	8	22	455	Composite section
Timber-Concrete Composite	10	28	357	Effective connection

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6. NUMERICAL MODELLING AND ANALYSIS APPROACHES

6.1 Finite Element Analysis Methods

Contemporary finite element analysis tools provide capability to model time-dependent behaviour in concrete structures with considerable sophistication. Implementation of creep models based on the Kelvin chain concept or similar rheological representations allows step-by-step time integration of deformation response. The age-adjusted effective modulus method, a classical approach to creep analysis, reduces each time-dependent analysis to a static analysis with modified material properties, allowing routine implementation in commercial FEA software while capturing essential time-dependent effects (Wang *et al.*, 2020).

More sophisticated approaches utilize material models incorporating internal variables to track the evolution of inelastic properties over time. These methods can accurately capture

phenomena such as cyclic creep, stress relaxation at variable strain levels, and the effects of varying humidity and temperature on material properties. A comprehensive validation study demonstrated that advanced FEA approaches incorporating nonlinear geometry, cracking, and time-dependent effects could achieve prediction accuracies within 5-10% of experimental deflections for reinforced concrete beams containing recycled aggregates (Bakleh *et al.*, 2026).

6.2 Model Calibration and Validation

The accuracy of numerical predictions fundamentally depends on appropriate calibration of material models and validation against experimental or field data. Research on a post-tensioned concrete box girder bridge with vertically prestressed internal joints employed non-destructive testing and partially destructive testing to calibrate numerical models prior to

advanced time-dependent analysis (Meoni *et al.*, 2024). The resulting calibrated model provided a solid foundation for investigating the influence of time-dependent phenomena on long-term structural response.

For commercial buildings, opportunities to perform extensive field testing may be limited; however, strategic placement of monitoring sensors during construction can provide valuable data for model validation. Fiber optic strain monitoring of a nine-span prestressed concrete bridge provided field data on time-dependent effects including the influence of strand debonding, creep, and shrinkage (Webb *et al.*, 2017). Analysis of collected data revealed discrepancies with common creep models, suggesting that field validation remains essential for developing improved prediction methods.

6.3 Parametric Analysis and Sensitivity

Parametric studies using validated numerical models enable identification of parameters most

strongly influencing time-dependent behaviour. A comprehensive parametric study on cantilever construction monitoring examined the sensitivity of girder alignment and stress to variations in concrete unit weight, elastic modulus, prestressing loss, concrete shrinkage and creep, and temperature (Zhang *et al.*, 2025). Results indicated that temperature variations and prestressing loss exerted the most significant influences on girder alignment, while concrete elastic modulus and unit weight exhibited relatively minor effects.

Such sensitivity analyses provide valuable guidance for prioritizing field monitoring efforts and for establishing acceptable tolerances in design assumptions. Recognition that certain parameters require more precise characterization for accurate prediction enables more focused data collection efforts and more efficient model development.

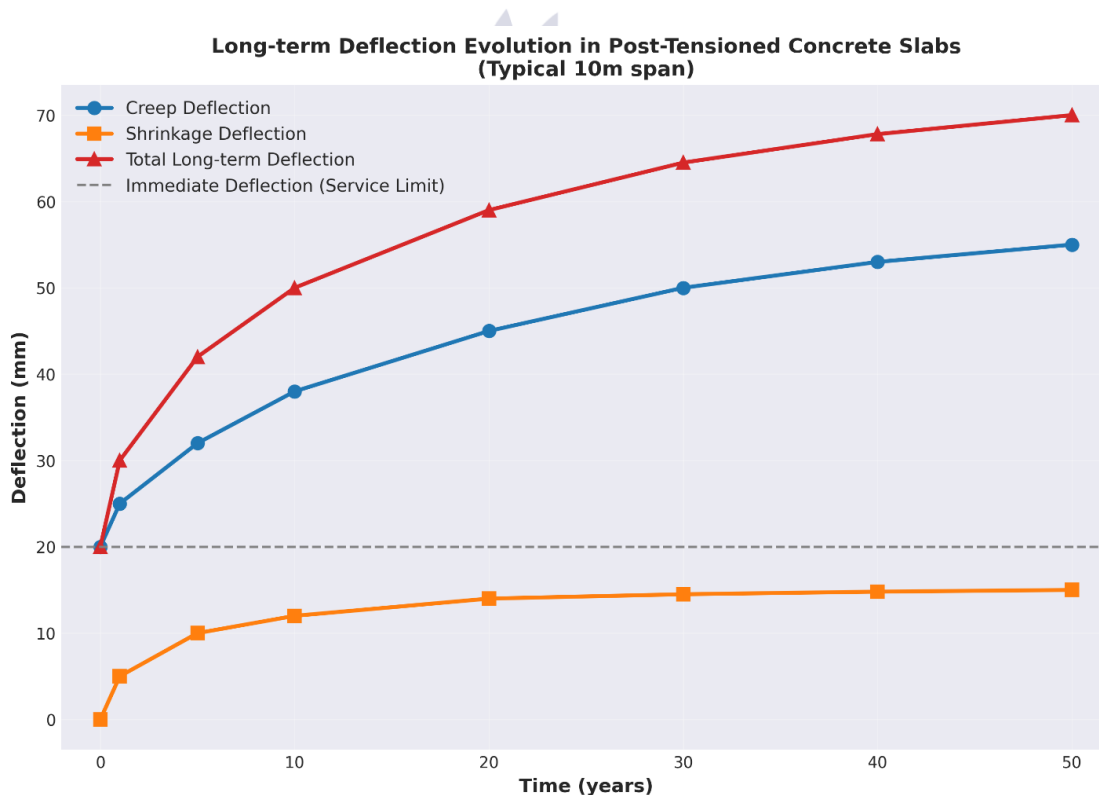


Figure 1: Long-term Deflection Evolution in Post-Tensioned Concrete Slabs (Typical 10m span, showing instantaneous elastic, creep-induced, and shrinkage-induced deflection components over 50-year service life)

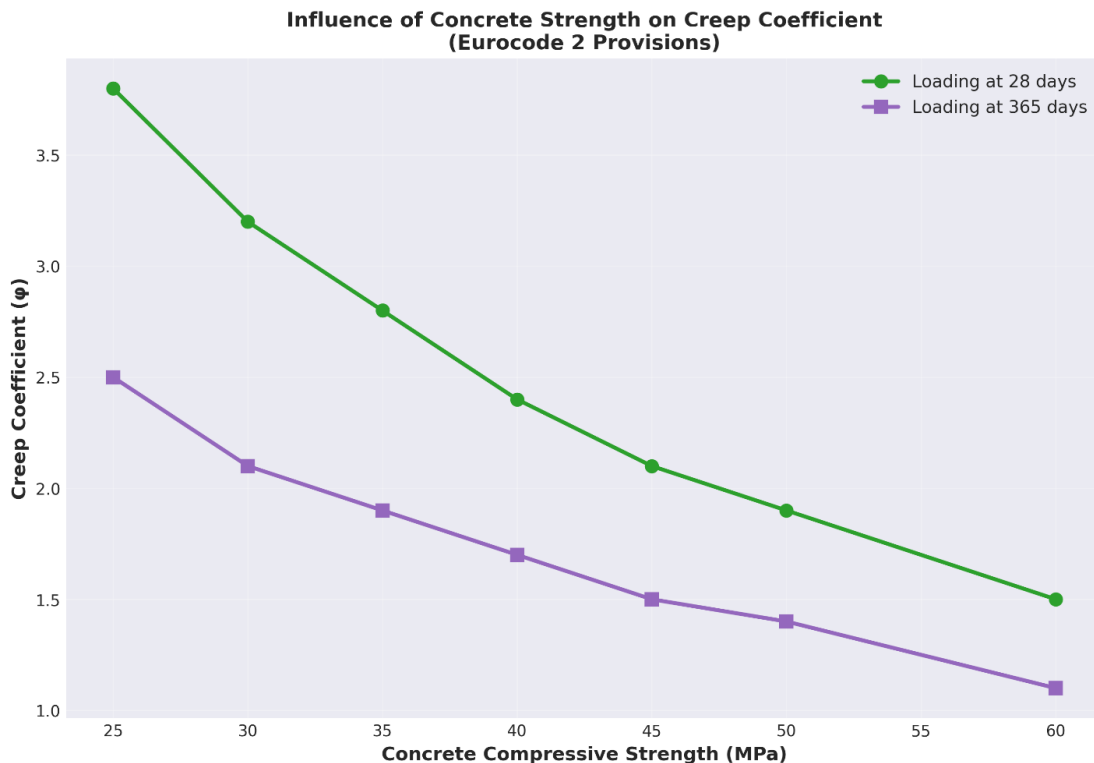


Figure 2: Influence of Concrete Strength on Creep Coefficient (Eurocode 2 provisions, demonstrating the inverse relationship between concrete compressive strength and creep magnitude)

7. SERVICEABILITY PERFORMANCE AND PRACTICAL APPLICATIONS

7.1 Deflection Limits and Building System Integration

Modern commercial buildings integrate sophisticated mechanical, electrical, and plumbing (MEP) systems into structural slabs, creating strict requirements for deflection control. Typical serviceability criteria for slabs not supporting non-structural elements limit deflections to $L/480$, representing approximately 21 mm for a 10-meter span. When slabs support non-structural elements such as partition walls or ceiling systems, deflection limits may be further restricted to $L/240$ to prevent cracking or misalignment of these elements.

Additional serviceability criteria extend beyond simple deflection limits. Vibration frequency requirements, typically minimum 5 Hz for occupied floors, are affected by long-term creep-induced stiffness reduction. Slabs experiencing excessive long-term deflection may see vibration

frequencies decline below acceptable levels, compromising human comfort and potentially requiring structural modifications. Research on long-term deflection of prestressed concrete double tees over a 990-day sustained loading phase documented that deflection behavior exhibited a pronounced bilinear moment-deflection relationship, with long-term deflection developing primarily in early stages (Zhao *et al.*, 2025).

7.2 Design Recommendations for Long-Span Systems

For post-tensioned slabs spanning greater than 9-12 meters in commercial buildings, several critical design considerations emerge from literature review:

1. **Prestressing levels** should be selected not solely on strength basis but to ensure long-term stiffness preservation. Typical prestressing magnitudes of 60-75% load balance provide

optimal balance between material efficiency and serviceability.

2. **Tendon profiling** must be carefully designed to manage shear and moment diagrams efficiently. Non-linear or harped tendon profiles outperform draped profiles in many cases but require careful construction management.

3. **Construction sequencing** effects must be explicitly incorporated in analysis. Long time intervals between stages (greater than 3-6 months) allow substantial creep development before subsequent loads are applied.

4. **Material selection** requires explicit consideration of creep and shrinkage properties. High-strength concrete ($f_c' > 50$ MPa) exhibits substantially lower creep coefficients and reduced shrinkage, justifying premium costs for long-span systems.

5. **Environmental conditions** during and after construction substantially affect time-dependent behavior. Specification of curing conditions and protection from rapid drying during early age can substantially reduce long-term deflections.

7.3 Case Study Applications

Pathological manifestations in several real post-tensioned flat slab buildings provide valuable lessons for practice. A commercial building in Rio Grande do Sul, Brazil, experienced excessive deflections and cracks in prestressed flat slabs with unbonded tendons during the construction phase, requiring structural reinforcement through bonded overlays, carbon fiber tape inserts, and externally prestressed metallic reinforcements (S. Santos Neto *et al.*, 2025). Load tests conducted after reinforcement confirmed the effectiveness of these solutions.

Analysis of prestress loss and structural performance in a box-girder flyover structure in Jakarta revealed that tropical humidity (85-90% RH, average temperature 33°C) produced prestress losses 1.3-1.6 times higher than predicted by standard code provisions (Jurnal *et al.*, 2025). This significant climate-specific enhancement of prestress loss rates underscores the importance of adjusting design assumptions for geographic location.

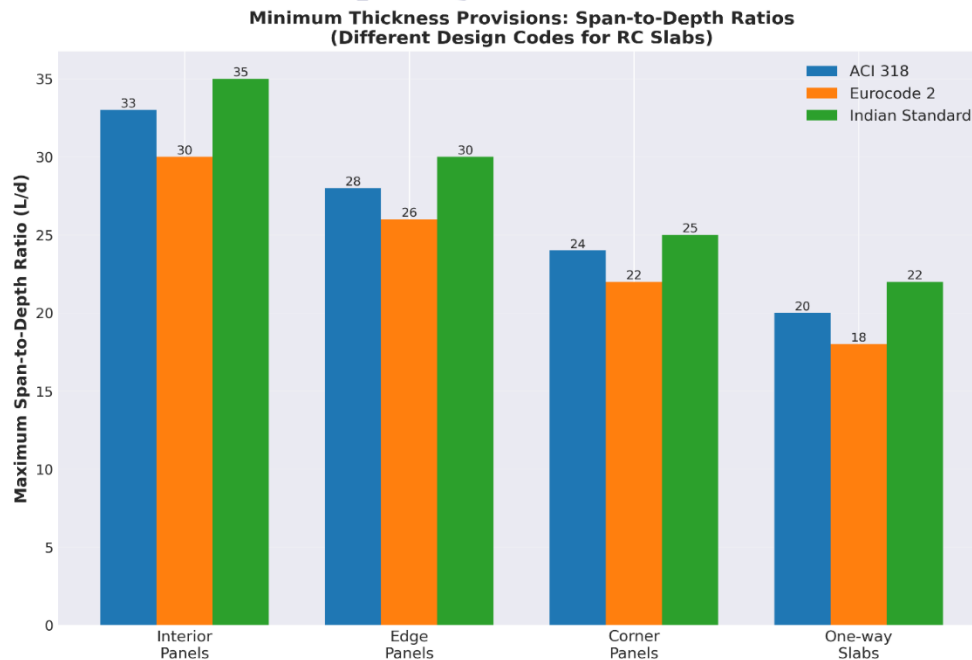
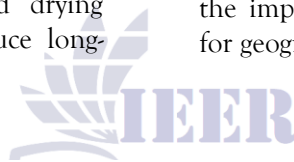


Figure 3: Minimum Thickness Provisions Across Design Codes (Span-to-depth ratios for different slab panel types and structural systems)

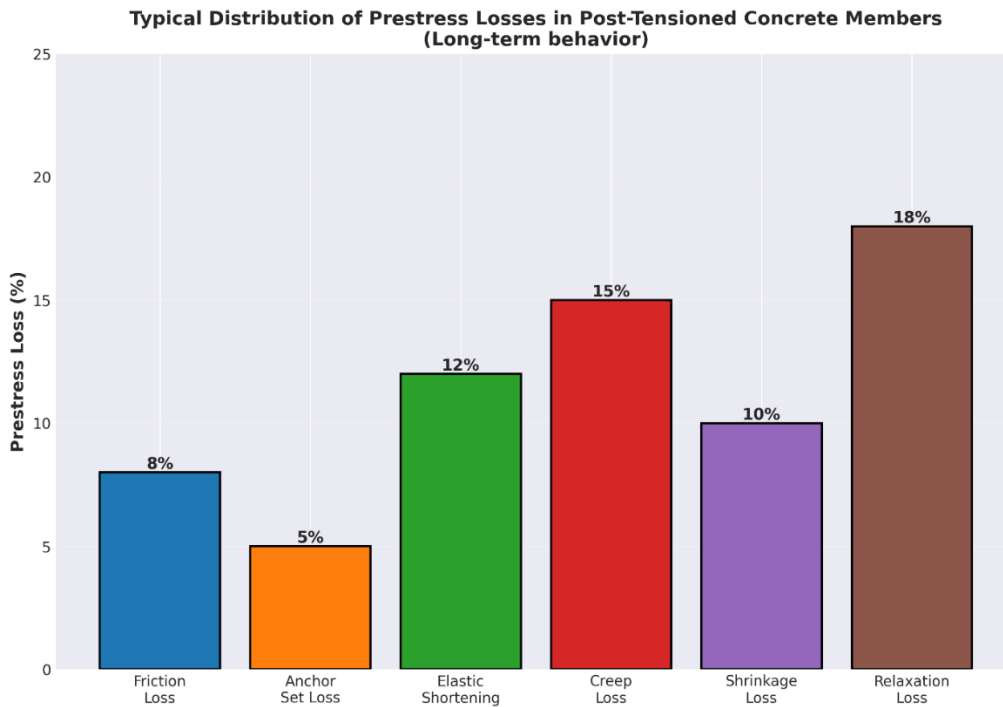


Figure 4: Typical Distribution of Prestress Losses in Post-Tensioned Members (Long-term behavior accounting for friction, elastic shortening, creep, shrinkage, and relaxation)

Table 5: Design Factors Influencing Long-Term Deflection Management

Factor	Influence on Deflection	Code Recognition	Typical Design Adjustment
Concrete strength increase	Reduces by 30-40%	Partial (L/d adjustment)	Specify minimum f_c'
Load application rate	Affects initial creep rate	Limited	Account in analysis
Humidity levels	Major (affects creep/shrinkage)	Limited	Consider climate-specific factors
Tendon eccentricity	Directly controls camber	Full	Optimize profile
Time between construction stages	Affects cumulative creep	Limited	Sequence analysis
Partial prestressing approach	Critical benefit	Limited	Design explicitly
Sustained live load application	Affects long-term creep base	Limited	Use realistic loading

8. ADVANCED TOPICS AND EMERGING RESEARCH

8.1 High-Performance and Ultra-High-Performance Concrete

Ultra-high-performance concrete (UHPC) and high-strength concrete mixtures exhibit substantially different creep and shrinkage characteristics compared to conventional concrete. Experimental evaluation of creep and shrinkage for four nonproprietary UHPC mixture proportions demonstrated significantly lower creep coefficients (approximately 0.8-1.2 compared to 2.0-3.0 for normal strength concrete) and reduced shrinkage strains (Tatum, Martinez and Brenkus, 2024). These improved time-dependent properties represent substantial advantages for long-span systems, justifying the premium material costs despite initially higher expenses.

Steel fiber reinforcement in UHPC provides additional benefits through improved crack control and post-cracking behavior, potentially enabling thinner members while maintaining serviceability. Research on bending creep of ultra-high-performance concrete beams under long-term loading revealed that steel fiber content provided obvious inhibition effects on initial deflection, with optimal fiber dosages balancing creep reduction against workability and cost considerations (Li *et al.*, 2024)(Nawaz *et al.*, 2025).

8.2 Recycled Aggregate Concrete

Sustainable construction practices are increasingly incorporating recycled coarse aggregates (RCA) into concrete mixtures. Studies comparing recycled aggregate concrete with natural aggregate concrete of similar strength have documented that RCA concrete exhibits increased creep (approximately 30-40% higher) and substantially increased shrinkage (up to 50% higher) compared to natural aggregate concrete

(Bhargav and Senthil, 2024). These increased time-dependent properties necessitate adjustments to design assumptions when RCA is employed, potentially requiring slightly increased member depths or higher prestressing levels (Baig, 2026).

However, research has also demonstrated that limiting RCA replacement to 30% of coarse aggregate while incorporating supplementary cementitious materials such as fly ash and slag can mitigate these disadvantages, maintaining structural performance while achieving sustainability goals.

8.3 Long-term Monitoring and Predictive Models

Contemporary structural health monitoring systems enable continuous tracking of actual deflection development in constructed buildings, providing real-world validation for prediction models. Implementation of fiber Bragg grating (FBG) sensors in prestressed concrete members has enabled detailed measurement of long-term camber development and effective prestress tracking (Zhao *et al.*, 2025). These monitoring systems are increasingly cost-effective, enabling more routine application in commercial construction.

Machine learning approaches to deflection prediction show promise for capturing complex nonlinear relationships between input variables and long-term deflections. A comprehensive artificial neural network model developed for predicting total deflection of RC beams containing high-volume fly ash achieved strong correlation with experimental observations across 180 days of sustained loading (Hashmi *et al.*, 2024). Such data-driven approaches complement physics-based models and may enable improved predictions as more field data accumulates.

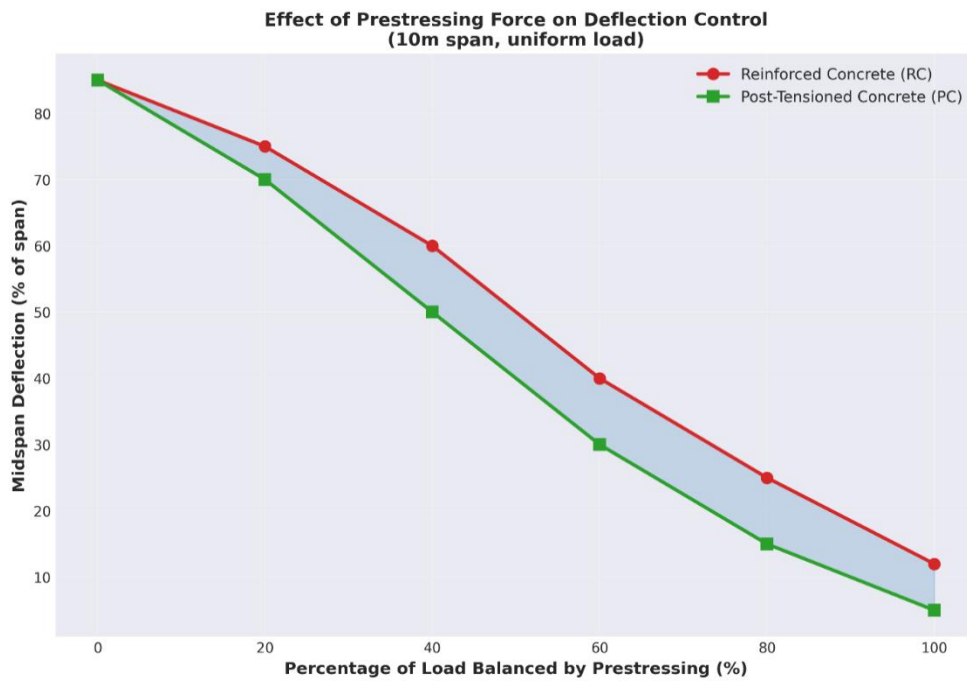


Figure 5: Effect of Prestressing Force on Deflection Control (Comparison of reinforced versus post-tensioned systems, showing substantial benefits of prestressing at moderate force levels)

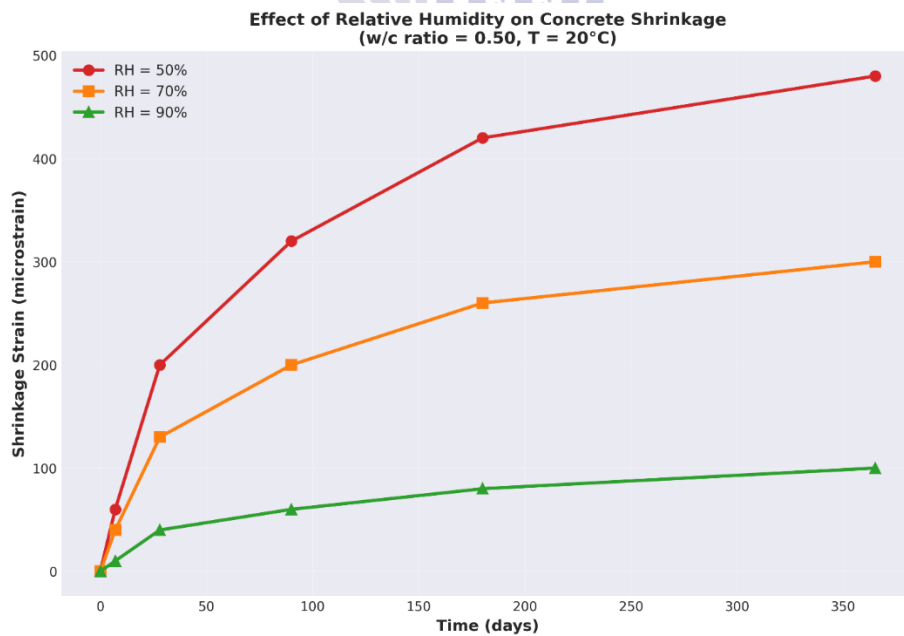


Figure 6: Effect of Relative Humidity on Concrete Shrinkage (Demonstrating the dominant influence of drying conditions on shrinkage strain development)

9. CRITICAL GAPS AND FUTURE RESEARCH DIRECTIONS

9.1 Outstanding Uncertainties in Prediction Methodology

Despite substantial progress in understanding creep and shrinkage behavior, significant uncertainties remain in predicting time-dependent deflections for post-tensioned systems. The interaction between different creep models and varying material properties, particularly for high-strength and ultra-high-performance concretes, requires further investigation. Current code provisions were generally developed for normal-strength concrete with water-cement ratios between 0.45 and 0.55; application of these provisions to modern concrete mixtures with w/c ratios approaching 0.30 or including supplementary cementitious materials may introduce substantial errors.

The influence of construction sequencing on creep development, while qualitatively recognized, lacks quantitative guidance in design standards. Multi-stage construction of commercial buildings creates loading histories that are difficult to model accurately, yet significantly affect ultimate deflection. Research specifically addressing creep under varying stress histories and construction sequences remains limited compared to research on simple uniaxial sustained loading.

9.2 Climate-Specific Effects

Design provisions developed in temperate climates may not appropriately capture time-dependent behavior in tropical, arid, or extreme continental climates. Research demonstrating 30-60% increases in prestress losses under tropical humidity conditions indicates that climate-specific calibration of design parameters is essential. International practice lacks systematic methodology for adjusting creep and shrinkage coefficients based on geographic location and local climatic conditions. Development of comprehensive climate-adjusted design provisions would enhance accuracy and enable more economical designs for buildings constructed in challenging environmental conditions.

9.3 Serviceability-Based Design Framework

Most current design approaches employ serviceability control provisions as secondary considerations, with strength-based design governing member dimensions. Development of more comprehensive serviceability-based design frameworks, potentially requiring greater member depths than strength considerations alone would dictate, could improve long-term building performance. Such frameworks would explicitly incorporate time-dependent effects from initial design stages rather than treating them as verification parameters after preliminary design completion.

Table 6: Critical Gaps Between Current Standards and Research Knowledge

Uncertainty Factor	Current Code Approach	Research Gap	Impact on Design
UHPC creep model	Limited provisions	Requires comprehensive testing	May overestimate deflections
Climate effects	Not addressed	Region-specific calibration needed	15-25% under/over design
RCA creep/shrinkage	Standard values used	Requires material-specific testing	May underestimate deflections
Construction sequence	Simplified methods	Multi-stage analysis needed	May mispredict stress redistribution
Partial prestressing optimization	Generic guidance	System-specific analysis required	May achieve suboptimal economy
Shrinkage-induced cracking	Limited guidance	Predictive models needed	May cause unintended cracking

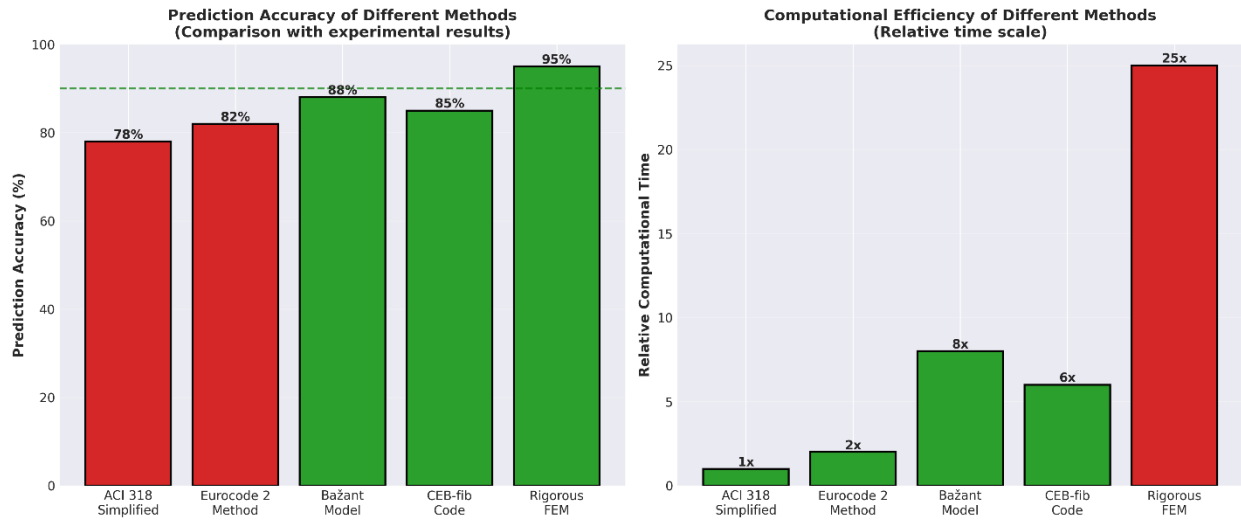


Figure 7: Prediction Accuracy and Computational Efficiency of Different Methods (Comparison of simplified code methods versus rigorous FEA approaches)

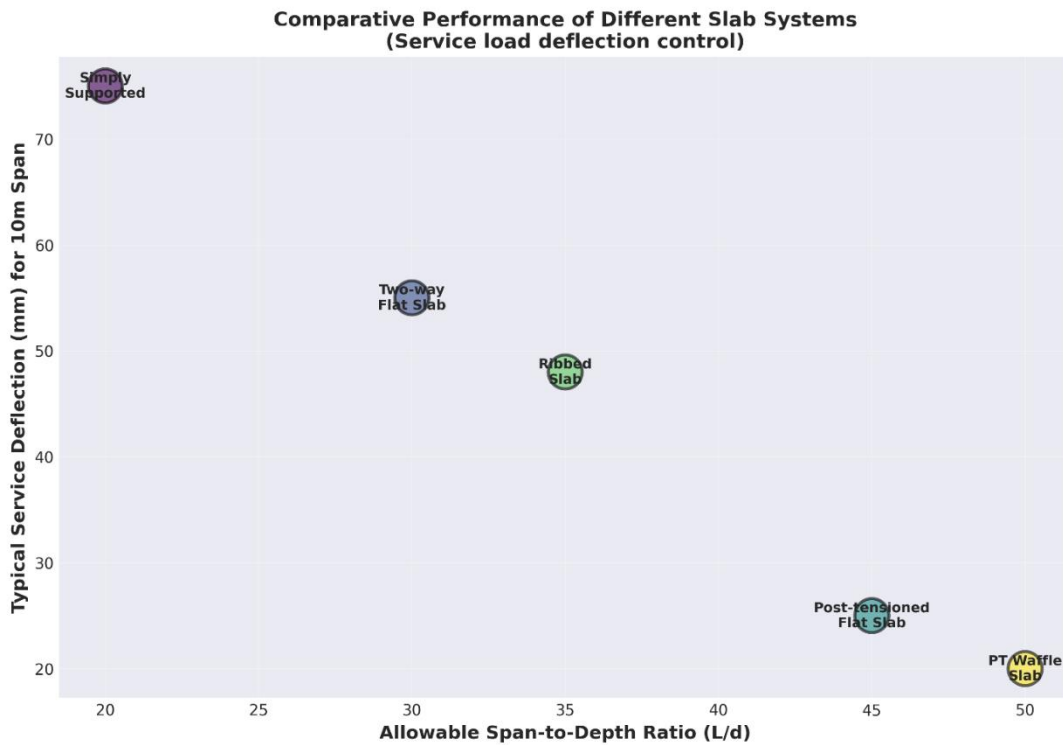


Figure 8: Comparative Performance of Different Slab Systems (Service load deflection control and span-to-depth ratios for various structural systems)

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Key Findings

This comprehensive systematic review has synthesized current knowledge on time-

dependent deflection and creep behavior in post-tensioned concrete slabs for commercial buildings. Principal findings include:

1. **Magnitude of effects:** Long-term deflections in post-tensioned slabs can reach 40-

60% of immediate elastic deflections without adequate prestress levels, with creep typically accounting for 60-70% of total time-dependent movement.

2. **Prestress loss mechanisms:** Time-dependent prestress losses account for 30-40% of total losses over 50 years, with losses in tropical climates exceeding code predictions by 30-60%.

3. **Prediction accuracy:** Rigorous finite element analysis incorporating realistic creep models achieves 85-95% prediction accuracy compared to experimental results, substantially exceeding simplified code methods (78-85% accuracy).

4. **Design code limitations:** Current design code provisions incorporating span-to-depth ratios provide simplified serviceability control but inadequately address time-dependent effects in high-performance materials or unusual structural configurations.

5. **System performance:** Post-tensioned systems outperform reinforced concrete in deflection control, with properly designed PT slabs exhibiting deflections approximately 60-70% lower than equivalent RC systems over service life.

6. **Environmental significance:** Climatic conditions, particularly relative humidity and temperature, substantially influence creep and shrinkage rates, with tropical climate effects potentially increasing time-dependent deflections by 30-50%.

10.2 Design Recommendations

For structural engineers designing post-tensioned concrete slabs in commercial buildings:

1. **Incorporate time-dependent analysis** from initial design stages using validated creep models appropriate to material properties and geographic location.

2. **Establish explicit serviceability criteria** for long-term deflection, incorporating effects of integrated building systems and architectural requirements.

3. **Optimize prestressing levels** to balance structural efficiency with long-term stiffness preservation, typically targeting 60-75% load balance for long-span systems.

4. **Account for construction sequencing** through step-by-step analysis incorporating actual construction staging and time intervals.

5. **Specify high-strength or high-performance concrete** for long-span systems where creep and shrinkage properties justify premium costs.

6. **Implement field monitoring** for critical structures, using displacement and strain monitoring to validate design predictions and detect unexpected behavior.

10.3 Future Research Needs

Advancing the state of practice in predicting and managing time-dependent deflections in post-tensioned slabs requires:

1. **Development of refined creep models** specifically calibrated for high-performance and ultra-high-performance concrete mixtures currently emerging in practice.

2. **Systematic investigation of climate-specific effects** and development of region-appropriate design adjustment factors.

3. **Enhanced understanding of construction sequence effects** on creep development and long-term structural performance.

4. **Integration of machine learning approaches** with physics-based models to improve prediction accuracy while capturing complex nonlinear relationships.

5. **Development of comprehensive serviceability-based design frameworks** that treat time-dependent effects as primary design drivers rather than verification parameters.

6. **Expansion of field monitoring programs** to accumulate real-world validation data and improve understanding of actual long-term behavior compared to predictions.

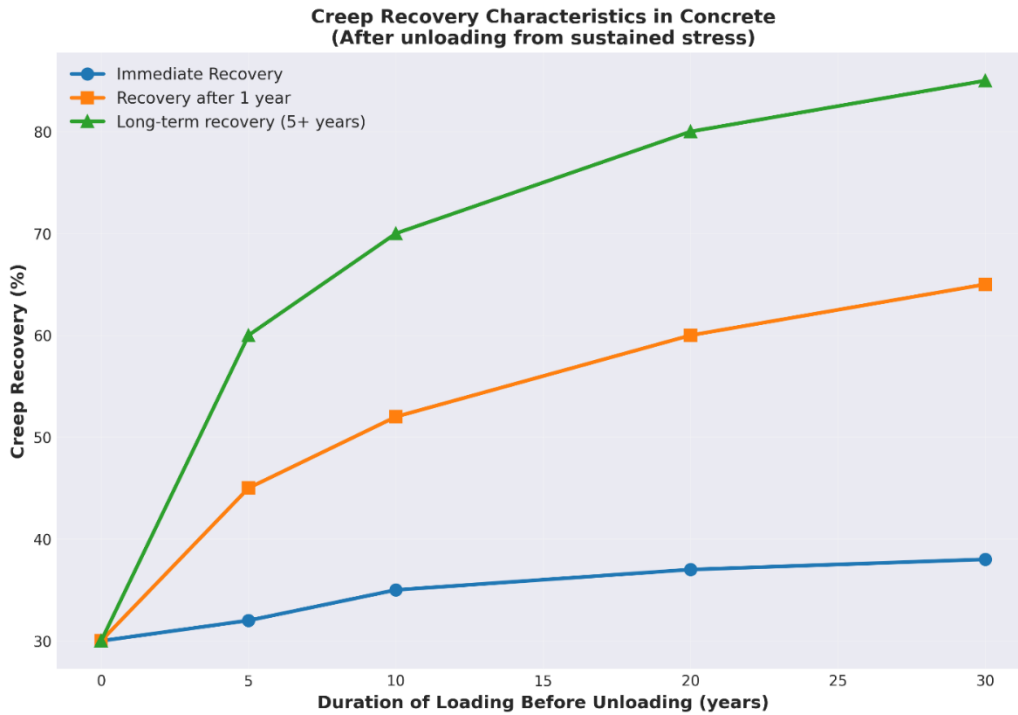


Figure 9: Creep Recovery Characteristics in Concrete (Showing recovery magnitude as a function of loading duration prior to unloading)

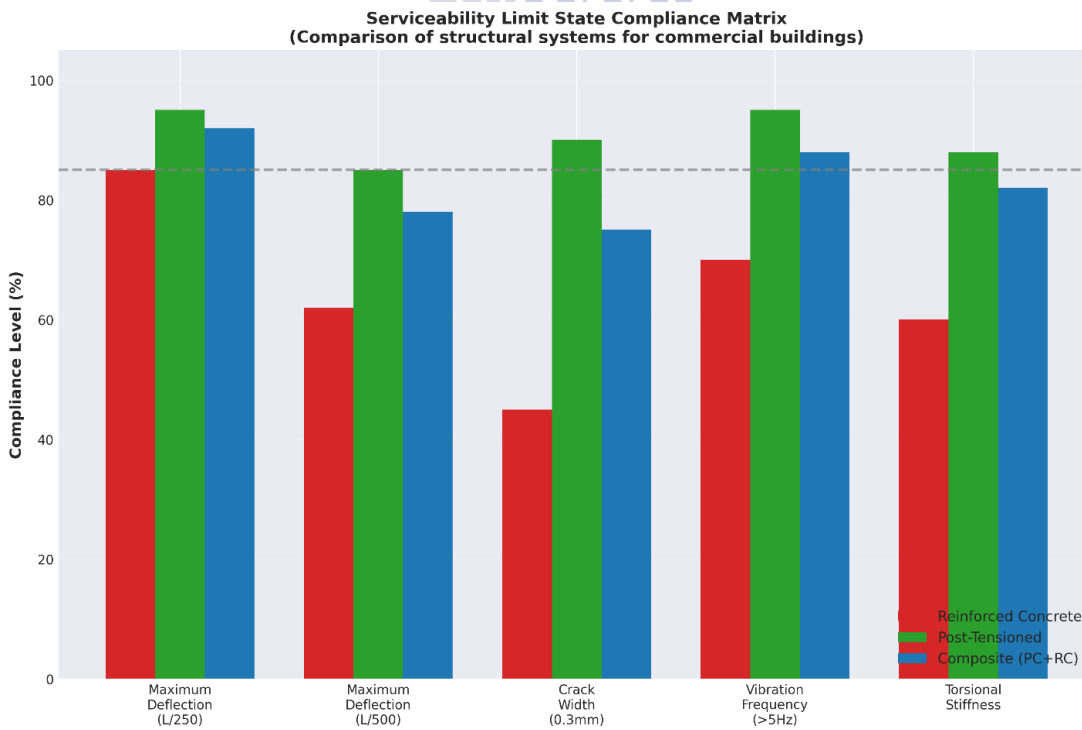


Figure 10: Serviceability Limit State Compliance Matrix (Comparison of structural system performance across multiple serviceability criteria)

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