Academic Journal of Applied Sciences
ISSN: 3105-0549 (Print), ISSN: 3105-0557 (Online) | Vol. 1, No. 1, 2026

Concepts Classification and Development of Self-Centering Structures

Tengyu Zhang

School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454000, China

Abstract: Self-centering structures have emerged as a transformative solution for enhancing seismic resilience by minimizing residual deformations after earthquakes. This paper presents a comprehensive state-of-the-art review of self-centering structural systems, focusing on conceptual foundations, classification frameworks, and development trajectories. The historical evolution from ancient rocking structures to modern applications is traced. A systematic classification is proposed based on mechanical principles and structural typologies, including moment frames, braced frames, shear walls, bridge piers, and mass timber systems. Key enabling technologies—post-tensioning, shape memory alloys, and hybrid systems—are critically analyzed. Research gaps and future directions are identified to advance broader implementation of self-centering technologies in resilient infrastructure.

Keywords: Self-centering structures; Seismic resilience; Rocking systems; Post-tensioning; Shape memory alloys; Flag-shaped hysteresis.

1. Introduction

Conventional earthquake-resistant design relies on ductile detailing that allows structural elements to undergo substantial inelastic deformations, dissipating seismic energy while preventing collapse. While this approach ensures life safety, it results in significant damage accumulation and residual deformations that often render structures irreparable or economically unviable for repair following major earthquakes [1]. The economic losses associated with post-earthquake downtime, repair costs, and business interruption have driven the development of resilient structural systems capable of maintaining functionality after seismic events.

Self-centering structures represent a paradigm shift in seismic design, offering the ability to return to their pre-excitation configuration after earthquake loading. These systems typically exhibit a flag-shaped hysteretic response characterized by negligible residual displacements, even after undergoing significant nonlinear deformations [2]. By concentrating damage in replaceable components while maintaining the primary structure elastic, self-centering technologies enable rapid post-earthquake recovery and reduce life-cycle costs.

The concept of self-centering is not new. Ancient Egyptian, Greek, and Chinese civilizations constructed free-standing column systems that inherently exhibited rocking behavior, allowing them to withstand numerous strong earthquakes over millennia [3]. Modern interest in self-centering structures began in the 1960s with Housners foundational work on rocking dynamics and gained momentum through experimental studies on rocking frames and bridges in subsequent decades [4].

This paper aims to provide a comprehensive review of self-centering structural systems, focusing on their conceptual foundations, classification frameworks, and developmental evolution. The review synthesizes findings from experimental, analytical, and numerical studies to present a holistic understanding of the field.

2. Concepts and Historical Development

2.1. Definition and Core Principles

Self-centering structures are defined as structural systems capable of returning to their original position with negligible residual deformation after being subjected to seismic loading. The fundamental mechanical principle underlying self-centering behavior is the provision of a restoring force that overcomes the dissipative forces within the system [2,5].

The self-centering mechanism requires two essential components: (1) a restoring force system that provides the driving force for recentering, and (2) an energy dissipation system that absorbs seismic energy while allowing recentering to occur. When these components are properly balanced, the system exhibits characteristic flag-shaped hysteresis with minimal residual drift [6].

2.2. Historical Evolution

The historical evolution of self-centering structures can be traced through three distinct phases:

Ancient Origins (3000 BC–1800 AD): The earliest self-centering structures were free-standing column systems developed by ancient Egyptian, Minoan, Greek, and Chinese civilizations. These structures relied on gravity as the restoring mechanism, with energy dissipated through friction and impact among stacked stone drums or wooden components. The Parthenon in Athens and numerous ancient temples in China exemplify structures that have survived hundreds of earthquakes over millennia due to inherent rocking behavior [3].

Modern Rediscovery (1960–1990): Modern research on self-centering structures began with Housners seminal 1963 study on rocking dynamics of free-standing blocks, which established fundamental mechanics and demonstrated that tall, slender structures could survive earthquakes while fixed-base structures sustained severe damage [4]. Practical applications emerged in the 1970s and 1980s, notably the South Rangitikei Railway Bridge in New Zealand (1981), a 70-meter-tall rocking structure with torsional-beam dampers that remains operational today [3].

Contemporary Development (1990–Present): Since the 1990s, research on self-centering structures has intensified dramatically. The Northridge (1994) and Kobe (1995) earthquakes highlighted the economic consequences of residual deformations, accelerating development of self-centering technologies. Post-tensioned steel moment frames were introduced in the late 1990s, followed by self-centering braced frames, rocking shear walls, and segmental bridge piers [7]. The past decade has seen rapid expansion into mass timber structures and advanced material applications.

3. Classification of Self-Centering Structures

3.1. Classification by Mechanical Principle

Self-centering structures can be classified into two fundamental categories based on their underlying mechanical principles [2, 6]:

Rocking-Based Systems: These systems achieve self-centering by allowing primary structural elements to rock on their foundations or at critical interfaces. The restoring force is provided by gravity and/or post-tensioning tendons, while energy dissipation is achieved through impact, friction, or supplemental devices. Examples include rocking bridge piers, rocking frames, and segmental columns. These systems are characterized by concentrated rotation at interfaces, minimizing damage to structural members.

Device-Based Systems: These systems incorporate self-centering devices as main structural or supplemental members. The self-centering mechanism relies on superelastic materials (e.g., shape memory alloys), disc springs, or pre-compressed springs that provide restoring forces. Energy dissipation is typically integrated through friction, metal yielding, or viscous elements. These systems offer greater flexibility in tuning mechanical properties but may require more sophisticated fabrication.

3.2. Classification by Structural Typology

Based on structural typology, self-centering systems can be categorized into five primary types [1, 7]:

Self-Centering Moment Frames: Post-tensioned steel and precast concrete moment frames represent the most extensively studied self-centering systems. Unbonded post-tensioning tendons pass through beams and columns, providing restoring forces. Energy dissipation is typically achieved through friction devices or yielding angles at beam-column connections. Research has demonstrated that these systems can achieve drift capacities exceeding 4% with negligible residual deformations [8].

Self-Centering Braced Frames: Eccentrically braced frames with self-centering capabilities combine replaceable energy dissipation links with post-tensioning or shape memory alloy elements. These systems concentrate damage in replaceable components, facilitating post-earthquake repair. Concentrically braced frames incorporating buckling-restrained braces with self-centering mechanisms have also been developed [9].

Self-Centering Shear Walls: Rocking shear walls with vertical post-tensioning tendons provide self-centering capability while replaceable energy dissipation devices at the wall base concentrate damage. Both reinforced concrete and steel plate shear walls have been developed, demonstrating enhanced repairability compared to conventional shear walls [5].

Self-Centering Bridge Piers: Segmental bridge columns with unbonded post-tensioning represent the most mature application of self-centering technology. These systems have been implemented in several bridges worldwide. Three primary configurations exist: pure rocking systems relying on gravity, controlled rocking systems with post-tensioning, and dissipative rocking systems with supplemental dampers [3].

Self-Centering Mass Timber Structures: Mass timber structures have gained popularity in mid-rise building applications. Since 2005, self-centering techniques have been applied to timber structures using post-tensioning tendons and shape memory alloy connections. Post-tensioned timber frames and rocking timber walls demonstrate significant potential for achieving seismic resilience in sustainable construction [10].

3.3. Classification by Enabling Technology

The enabling technologies for self-centering can be classified into three primary approaches [1, 6]:

Post-Tensioning (PT): Unbonded post-tensioning tendons provide restoring forces through elastic elongation. This approach is practical, efficient, and widely used in precast concrete frames, segmental bridges, and rocking walls. The PT tendons remain elastic during loading, providing the driving force for recentering. Key considerations include debonding strategies to reduce stress concentrations and corrosion protection for durability.

Shape Memory Alloys (SMA): Superelastic SMAs, particularly nickel-titanium alloys, undergo stress-induced martensitic transformation, exhibiting flag-shaped hysteresis with inherent self-centering. SMAs are used as reinforcing bars, cables, bolts, or dampers. Their unique properties combine self-centering with significant energy dissipation, though cost remains a limiting factor for widespread adoption.

Hybrid Systems: Contemporary research emphasizes hybrid systems that combine multiple technologies to achieve optimal performance. Examples include PT combined with friction dampers, PT combined with metallic yielding elements, and SMA combined with PT. These systems leverage the strengths of individual technologies to achieve balanced performance.

4. Enabling Technologies and Mechanical Behavior

4.1. Post-Tensioning Technology

Post-tensioning is the most mature and widely adopted self-centering technology. High-strength steel tendons are placed unbonded within structural elements and anchored at boundaries. When lateral loading causes joint opening, tendons elongate elastically, storing restoring energy. Upon unloading, tendon forces close the joint, returning the structure to its original configuration [5].

Critical design considerations for PT systems include:

- Debonding strategies: Partial debonding along tendon lengths reduces stress concentrations and improves damage tolerance
- Anchorage performance: Anchorage systems must accommodate cyclic loading without relaxation or failure
- Corrosion protection: Essential for durability, particularly in bridge and marine applications

4.2. Shape Memory Alloy Technology

NiTi shape memory alloys exhibit superelastic behavior with characteristic flag-shaped hysteresis. Unlike conventional materials, SMAs can undergo large recoverable strains (up to 6–8%) through stress-induced phase transformation. Upon unloading, the reverse transformation occurs, providing restoring forces [6].

Applications of SMAs in self-centering structures include:

- SMA reinforcing bars for concrete structures
- SMA cables for braces and tension members
- SMA bolts and connectors for beam-column joints
- SMA-based dampers combined with other energy dissipation mechanisms

4.3. Flag-Shaped Hysteretic Behavior

The defining characteristic of self-centering systems is the flag-shaped hysteretic response. Unlike conventional systems that exhibit pinched or degraded hysteresis with significant residual deformations, self-centering systems return to near-zero displacement upon unloading [2].

The flag-shaped response is characterized by:

- Initial stiffness: Provided by self-centering elements (PT tendons or SMAs)
- Activation: Energy dissipation mechanisms activate at a specified displacement
- Stiffness change: Loading reversal causes deactivation of dissipative elements
- Recentering: Complete or near-complete recentering at zero load

Key performance metrics include residual displacement ratio (typically maintained below 0.5%), energy dissipation capacity, and recentering ratio—the ratio of restoring force to dissipated force determining self-centering effectiveness [7].

5. Research Gaps and Future Directions

5.1. Identified Research Gaps

Despite significant advances, several critical gaps remain in the development and implementation of self-centering structures [1, 3, 10]:

Table 1. Summary of key research gaps in self-centering structures

Gap Area	Description
Durability and Long-Term Performance	Limited data on PT tendon relaxation, SMA fatigue behavior, and corrosion resistance under combined environmental and service loading
Design Methodology	Lack of standardized performance-based design procedures and clear acceptance criteria for residual drift control
System-Level Integration	Insufficient research on multi-story, multi-bay applications and interactions between self-centering components
Connection Detailing	Need for constructible, inspectable, and replaceable connection details suitable for practical construction
Economic Justification	Inadequate life-cycle cost analysis to demonstrate long-term economic benefits over conventional systems

5.2. Future Research Directions

Based on the synthesized literature, future research should prioritize the following areas:

Long-Term Experimental Programs: Extended duration testing investigating durability under combined cyclic loading and environmental exposure. This includes relaxation behavior of PT tendons over decades, fatigue performance of SMA elements under repeated seismic demands, and corrosion protection strategies for various applications.

Large-Scale System Validation: Full-scale testing of multi-story, multi-bay self-centering systems to validate system-level performance and interaction effects. Shake table tests of complete structural systems are needed to verify analytical models and design methodologies.

Optimization Methodologies: Development of practical design optimization approaches that balance self-centering and energy dissipation requirements while considering constructability and cost constraints. Multi-objective optimization frameworks considering both seismic performance and economic factors are needed.

Hybrid System Development: Exploration of synergistic combinations of PT, SMA, and spring-based technologies to achieve enhanced performance. Research should focus on optimal integration strategies that leverage the strengths of individual technologies.

Design Code Development: Collaborative efforts to develop code-ready design provisions, performance acceptance criteria, and construction specifications. This includes establishing standardized testing protocols and qualification procedures for self-centering components.

Technology Transfer and Demonstration: Demonstration projects showcasing self-centering technologies in real-world applications to build industry confidence and document constructability, performance, and economic outcomes.

6. Conclusion

Self-centering structures represent a transformative approach to seismic design, enabling resilient infrastructure with minimal post-earthquake residual deformations. From ancient free-standing column systems to modern post-tensioned frames and shape memory alloy-based devices, the evolution of self-centering principles spans millennia. Contemporary research has established comprehensive classification frameworks encompassing rocking-based and device-based systems across diverse structural typologies.

The characteristic flag-shaped hysteretic response provides the defining mechanical behavior, combining energy dissipation with recentering capability. Post-tensioning, shape memory alloys, and hybrid systems constitute the primary enabling technologies, each with distinct advantages and limitations. While significant progress has been made in developing self-centering moment frames, braced frames, shear walls, bridge piers, and timber structures, critical gaps remain in durability validation, design methodology standardization, and code implementation.

As urbanization continues in seismically active regions and societal demands for resilient infrastructure increase, self-centering technologies offer a promising pathway toward earthquake-resilient communities with reduced economic losses and improved post-event recovery capacity. Addressing identified research gaps through coordinated efforts will accelerate broader adoption of these transformative structural systems.

References

[1] Xu L H, Xie X S, Zhang G. Review of research on self-centering structural components for seismic resilience

improvement. Journal of Southeast University (Natural Science Edition), 2023, 53(6): 1177-1188.

[2] Self-centering eccentrically braced steel frames: A comprehensive review on post-tensioning, SMA, and energy-dissipating technologies. Structures, 2025, 79: 109425.

[3] Zhong C, Christopoulos C. Self-centering seismic-resistant structures: Historical overview and state-of-the-art. Earthquake Spectra, 2022, 38(2): 1321-1356.

[4] Housner G W. The behavior of inverted pendulum structures during earthquakes. Bulletin of the Seismological Society of America, 1963, 53(2): 403-417.

[5] Review of self-centering bridge piers. Journal of Beijing University of Civil Engineering and Architecture, 2025, 41(5): 73-87.

[6] Zhang Q, Xiong E, Guo R. State-of-the-art of research progress of self-centering structure system. IOP Conference Series: Earth and Environmental Science, 2021, 825: 012037.

[7] Mortazavi P, et al. Replaceable cast steel yielding links for eccentrically braced frames: Design and experimental validation. Structures, 2025.

[8] Chen F, Li M, Li Z. Self-centering mass timber structures: A review on recent research progress. Engineering Structures, 2024, 303: 117474.

[9] Wang H, et al. Seismic performance of self-centering steel frames with replaceable energy dissipation components. Journal of Constructional Steel Research, 2024, 215: 108523.

[10] Zhang G, Xu L H, Xie X S. Development and application of self-centering seismic-resistant structures: A critical review. Soil Dynamics and Earthquake Engineering, 2025, 178: 108491.