

SEISMIC PERFORMANCE ENHANCEMENT OF STEEL STRUCTURES USING SHAPE MEMORY ALLOYS FOR IMPROVED POST-EARTHQUAKE RECOVERY

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Abstract

The increasing demand for resilient infrastructure in earthquake-prone regions has driven the development of structural systems capable of both resisting seismic forces and recovering rapidly after seismic events. Conventional steel structures, although ductile and efficient in energy dissipation, often experience permanent deformation and residual drift due to plastic hinge formation, leading to significant repair costs and downtime. This study investigates the integration of Shape Memory Alloys (SMAs) into steel structures as an innovative approach to enhance seismic performance and post-earthquake recovery.

SMAs, particularly Nickel–Titanium (NiTi) and iron-based (FeSMA) alloys, exhibit unique properties such as superelasticity and the shape memory effect, enabling large recoverable strains and stable energy dissipation under cyclic loading. A finite element-based analytical framework is employed to evaluate the behavior of SMA-integrated steel systems subjected to simulated seismic loading. The structural response is analyzed in terms of load–displacement behavior, hysteretic performance, and residual drift.

Results indicate that SMA-integrated systems significantly reduce residual deformation, enhance self-centering capability, and maintain stable cyclic performance compared to conventional steel structures. The study highlights the potential of SMA technology in transforming traditional steel systems into smart, resilient structures. Practical challenges such as material cost, design complexity, and the need for standardized guidelines are also discussed, providing direction for future research and implementation.

Keywords

Keywords: Shape Memory Alloys (SMA); Seismic Performance; Steel Structures; Self-Centering Systems; Residual Drift; Energy Dissipation; Finite Element Analysis; Smart Structures

1. Introduction

The increasing occurrence of earthquakes and rapid urbanization in seismic-prone regions have created a critical demand for structural systems that ensure not only life safety but also rapid post-earthquake recovery. Conventional seismic design methodologies primarily focus on preventing collapse by allowing controlled inelastic deformation. Although this approach is effective in safeguarding human life, it often results in **permanent structural damage, residual drift, and high repair costs**, rendering structures unserviceable after major seismic events [1,2].

Steel structures are widely adopted in earthquake-resistant construction due to their inherent ductility, strength, and energy dissipation capacity. In moment-resisting frames, seismic forces are typically dissipated through **plastic hinge formation** in beams and columns. However, this mechanism leads to **irreversible deformation and stiffness degradation**, which significantly affects the structural integrity and increases downtime after earthquakes [3,4]. Consequently, modern structural engineering is transitioning toward **resilience-based design**, where structures are expected to maintain functionality and recover quickly after seismic disturbances [5].

1.1 Behavior of Conventional Steel vs SMA Systems

A fundamental limitation of conventional steel systems is their inability to recover deformation after yielding. In contrast, Shape Memory Alloys (SMAs) exhibit unique thermomechanical properties that enable **self-centering and deformation recovery**. As illustrated in **Fig. 1**,

SMA demonstrate a superelastic stress–strain response characterized by flag-shaped hysteresis loops, which allow large strains to be recovered upon unloading [6,7].

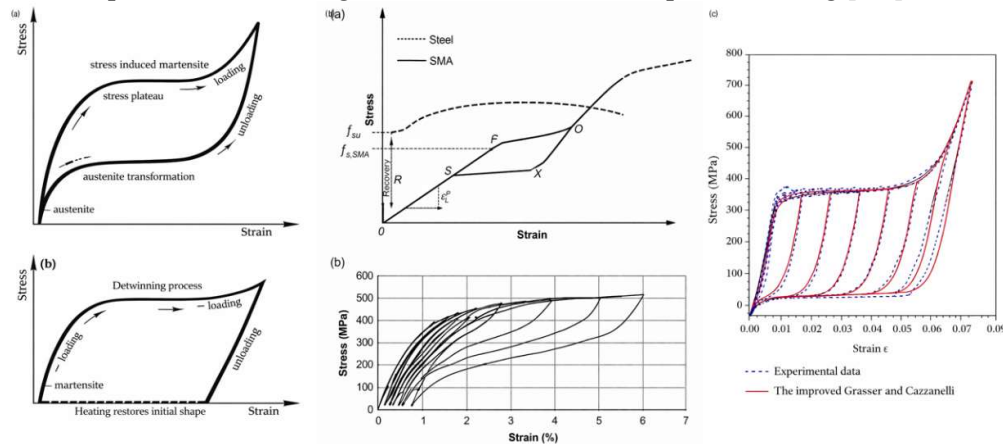


Fig. 1. Comparative stress–strain and hysteresis behavior of conventional steel and Shape Memory Alloys showing superelastic response and self-centering capability. Unlike steel, which accumulates permanent strain after yielding, SMA materials undergo reversible phase transformation between austenite and martensite phases. This behavior enables SMA-based systems to minimize residual deformation and maintain structural integrity under cyclic loading.

1.2 Structural Response Under Seismic Loading

The difference in material behavior directly influences the overall structural response. Conventional steel structures exhibit **pinched hysteresis loops and significant residual displacement**, whereas SMA-integrated systems show **stable cyclic behavior and reduced residual drift**, as depicted in Fig. 2 [8,9].

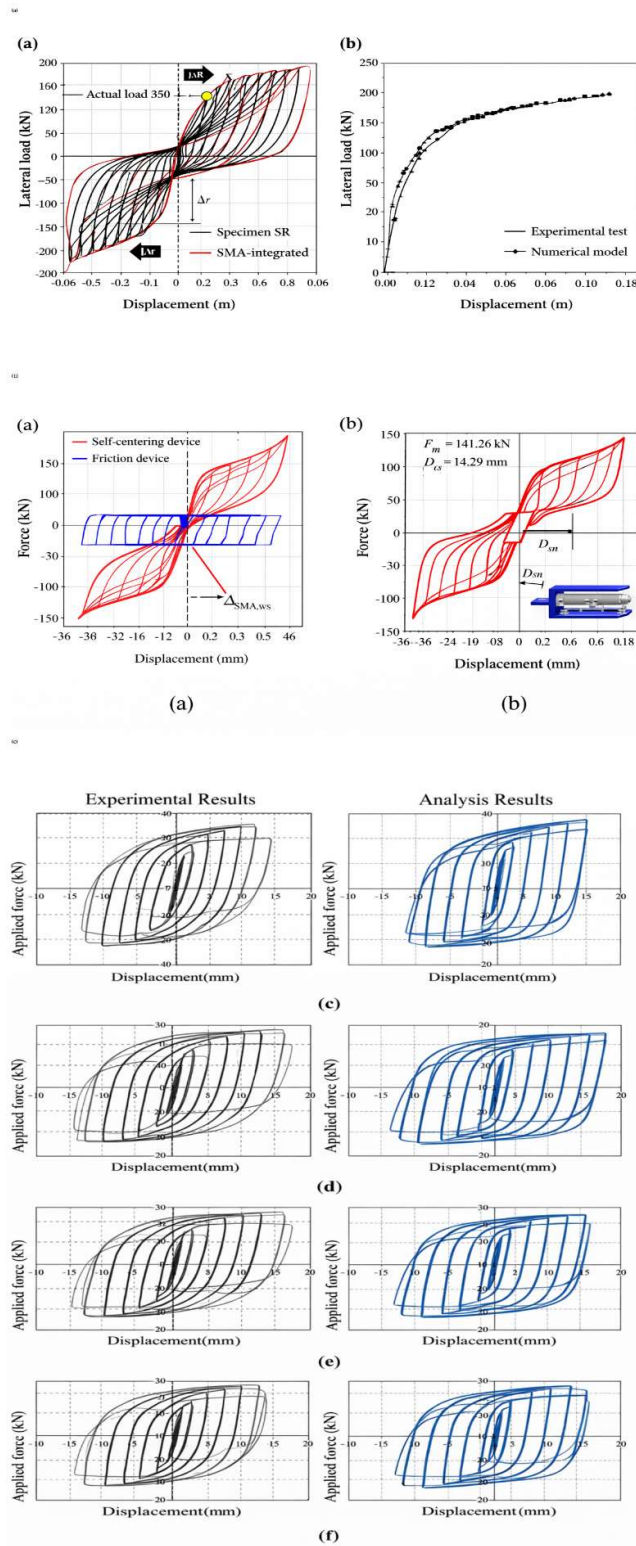


Fig. 2. Load–displacement response comparison between conventional steel structures and SMA-integrated systems under cyclic loading. The self-centering capability of SMAs significantly improves post-earthquake usability by allowing structures to return close to their original configuration after unloading. This behavior

reduces the need for extensive repairs and enhances structural resilience.

1.3 Role of Shape Memory Alloys in Smart Structures

Shape Memory Alloys, particularly Nickel–Titanium (NiTi) and iron-based SMAs (FeSMA), have emerged as promising materials for seismic applications due to their ability to combine **energy dissipation and deformation recovery**. When integrated into structural components such as beam–column connections, bracing systems, and dampers, SMAs act as **re-centering elements**, improving overall system performance [10,11].

These materials provide:

- Self-centering capability
- Stable hysteretic response
- Reduced residual drift
- Improved fatigue resistance

Such characteristics make SMAs highly suitable for developing **smart structural systems** capable of adapting to seismic loading conditions.

1.4 Research Gap and Motivation

Despite the promising potential of SMA-based systems, several challenges remain:

- Lack of **comprehensive structural-level studies** integrating SMA behavior
- Limited **finite element modeling frameworks** for realistic simulation
- High cost of NiTi alloys
- Absence of standardized design guidelines

Existing studies primarily focus on material behavior or component-level analysis, with limited emphasis on **full structural performance evaluation under cyclic loading** [12,13].

1.5 Objective of the Study

In response to the identified gaps, this study aims to investigate the effectiveness of Shape Memory Alloys in enhancing the seismic performance of steel structures. A finite element-based approach is adopted to evaluate structural behavior under cyclic loading conditions.

The study focuses on:

- Load–displacement response
- Hysteretic behavior
- Energy dissipation
- Residual drift reduction

The findings aim to contribute to the development of **resilient and smart structural systems** capable of both resisting and recovering from seismic events.

2. Literature Review

2.1 Evolution of Seismic Design Concepts

Seismic design philosophies have evolved from conventional force-based approaches to performance-based and resilience-oriented frameworks. Traditional design methods allow controlled inelastic deformation to dissipate seismic energy and prevent collapse. However, this approach often results in **permanent structural damage, residual drift, and increased post-earthquake repair costs**, limiting structural functionality after seismic events [1,2].

To overcome these limitations, recent research has focused on developing **resilient structural systems** that can maintain functionality and recover rapidly after earthquakes. This shift has led to increased interest in smart materials and innovative structural solutions [5].

2.2 Fundamentals of Shape Memory Alloys

Shape Memory Alloys (SMAs) are a class of smart materials that exhibit unique thermomechanical behavior due to reversible phase transformation between austenite and martensite phases. The fundamental properties of SMAs include:

- **Shape Memory Effect (SME)**
- **Superelasticity (SE)**

These properties enable SMAs to undergo large strains and recover their original shape upon unloading or heating [4,6].

NiTi alloys are widely used due to their superior superelastic behavior and high recoverable strain capacity. Advanced constitutive models have been developed to represent SMA behavior under cyclic loading, incorporating nonlinear stress–strain relationships and transformation strain evolution [7].

2.3 Applications of SMAs in Structural Engineering

The application of SMAs in civil engineering has gained significant attention due to their ability to enhance seismic performance.

2.3.1 SMA-Based Bracing Systems

SMA braces have been extensively studied for seismic applications. These systems exhibit **flag-shaped hysteresis behavior**, which enables self-centering and reduces residual deformation compared to conventional steel braces [8,9]. Experimental and numerical studies confirm that SMA braces maintain stable performance under repeated cyclic loading.

2.3.2 SMA Dampers

SMA-based dampers utilize the superelastic properties of SMAs to dissipate seismic energy effectively. Compared to traditional steel dampers, SMA dampers offer:

- Improved fatigue resistance
- Reduced permanent deformation
- Stable energy dissipation

Studies indicate that SMA dampers significantly improve structural response under cyclic and dynamic loading conditions [10].

2.3.3 Beam–Column Connections

Beam–column connections are critical components in steel structures and are often subjected to severe damage during earthquakes. Research on SMA-integrated connections has demonstrated improved **moment–rotation behavior and reduced residual drift** [11].

Experimental studies show that SMA-based connections can reduce residual deformation by up to **90%**, significantly enhancing post-earthquake structural performance [12].

2.4 Development of Fe-Based SMAs

Although NiTi SMAs provide excellent superelastic properties, their high cost limits large-scale applications. To address this issue, **iron-based SMAs (Fe-Mn-Si alloys)** have been developed as cost-effective alternatives [13].

Fe-based SMAs offer:

- Lower material cost
- Compatibility with steel structures
- Adequate recovery stress through thermal activation

These materials have been successfully used in prestressing and retrofitting applications, making them suitable for large-scale infrastructure [14].

2.5 Numerical Modeling of SMA Systems

The complex nonlinear behavior of SMAs requires advanced numerical modeling techniques. The Finite Element Method (FEM) has been widely used to simulate SMA behavior under cyclic loading [15,16].

Key considerations in numerical modeling include:

- Accurate constitutive modeling
- Mesh convergence analysis
- Validation with experimental results

Despite advancements, modeling SMA behavior remains challenging due to:

- Nonlinear phase transformation
- Temperature dependency
- Cyclic degradation effects

2.6 Comparative Performance of SMA and Conventional Systems

Several studies have compared the performance of SMA-integrated systems with conventional steel structures. The results consistently show that SMA systems provide:

- Significant reduction in residual drift
- Enhanced self-centering capability
- Stable hysteretic behavior
- Improved energy dissipation

However, limitations such as high material cost and lack of design guidelines restrict their widespread adoption [17,18].

2.7 Research Gap

Based on the reviewed literature, the following gaps are identified:

- Limited studies on **full structural systems** incorporating SMAs
- Lack of **comprehensive FEM-based analysis frameworks**
- Insufficient focus on **combined performance of SMA and steel systems**
- Absence of **standardized design codes**

2.8 Contribution of the Present Study

To address these gaps, this study focuses on:

- Developing a **finite element-based framework** for SMA-integrated steel structures
- Evaluating **seismic performance under cyclic loading**
- Analyzing **load–displacement behavior and residual drift reduction**
- Bridging the gap between **material behavior and structural response**

3. Methodology

3.1 Research Framework

This study adopts an integrated **analytical–numerical approach** to evaluate the seismic performance of SMA-integrated steel structures. The methodology combines **material modeling, finite element analysis (FEA), and structural response evaluation under cyclic loading**. The objective is to quantify improvements in self-centering capability, energy dissipation, and residual drift reduction compared to conventional steel systems.

Finite element modeling is widely used for simulating nonlinear structural behavior, particularly for systems incorporating advanced materials such as Shape Memory Alloys [15,16].

3.2 Material Modeling

3.2.1 Structural Steel Model

Structural steel is modeled using a **bilinear isotropic hardening model**, which captures both elastic and plastic behavior.

3.2.2 Shape Memory Alloy (SMA) Model

SMAs are modeled using a **nonlinear superelastic constitutive model**, incorporating phase transformation between austenite and martensite phases.

The model captures:

- Nonlinear hysteresis behavior
- Transformation plateau stress
- Full strain recovery upon unloading

These characteristics are essential for simulating the self-centering behavior of SMA-based systems [6,7].

3.3 Finite Element Modeling (ANSYS Framework)

The numerical analysis is performed using **ANSYS**, which is widely used for nonlinear structural simulations involving complex material behavior.

3.3.1 Model Geometry and Configuration

The study considers:

- Steel frame models without SMA (reference model)

- Steel frame models with SMA integration
- SMA elements are incorporated into:
- Beam–column connections
 - Bracing systems

3.4 Finite Element Model Representation

^(a) **A: Static Structural**
 Minimum Combined Stress
 Type: Minimum Combined Stress
 Unit: MPa
 Time: 1

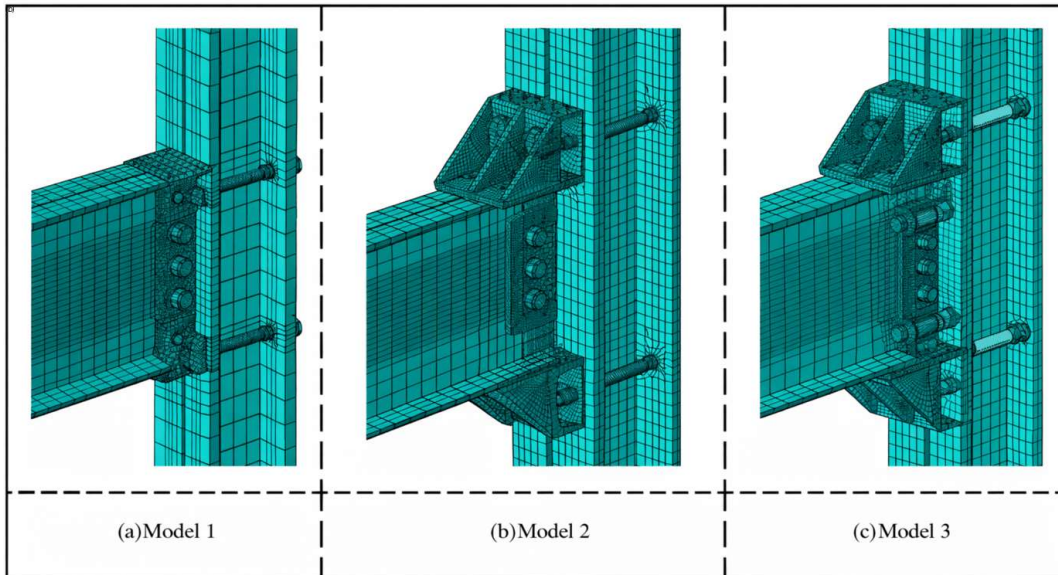
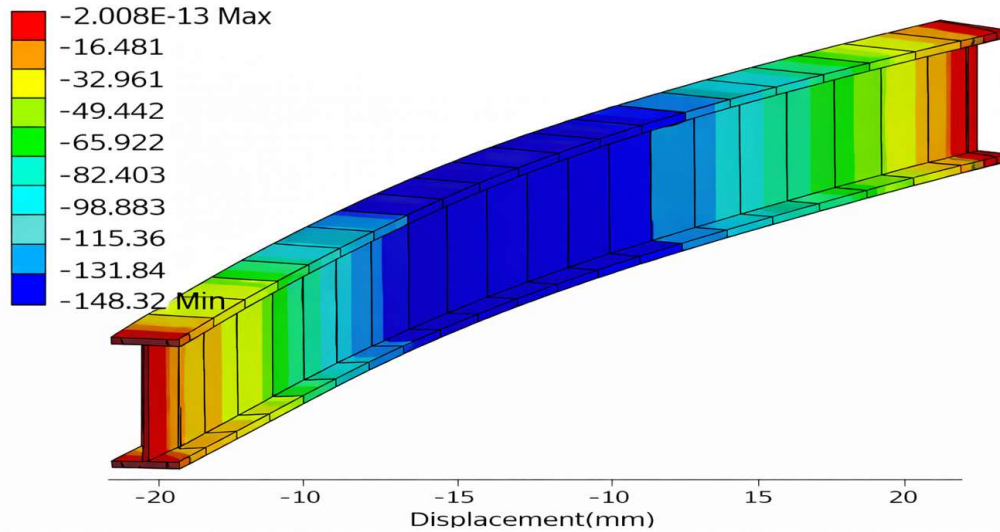


Fig. 3. Finite element model of steel frame with SMA integration showing mesh configuration and structural components.

The model includes:

- BEAM188 elements for beams and columns
- SOLID185 elements for detailed component modeling
- CONTACT elements for connection interaction

These elements effectively capture geometric and material nonlinearities [15].

3.5 Boundary Conditions

The following boundary conditions are applied:

- Fixed support at the base
- Lateral displacement applied at the top nodes
- Appropriate constraints to simulate realistic structural behavior

3.6 Loading Protocol

To simulate seismic effects, **cyclic displacement-controlled loading** is applied. The loading protocol includes:

- Incremental loading–unloading cycles
- Increasing displacement amplitudes
- Load reversal in each cycle

This approach captures:

- Hysteretic behavior
- Energy dissipation
- Residual deformation

Such loading protocols are widely used in seismic performance evaluation [9,10].

3.7 Mesh Convergence Study

A mesh convergence study is conducted to ensure numerical accuracy. Models with different mesh densities are analyzed, and convergence is evaluated based on:

- Load–displacement response
- Stress distribution

A refined mesh is selected when further refinement produces negligible changes in results [16].

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3.8 Performance Evaluation Parameters

The structural response is evaluated using the following parameters:

- **Load–displacement behavior**
- **Hysteresis loops**
- **Energy dissipation capacity**
- **Residual drift ratio**
- **Stress–strain distribution**

These parameters are essential for assessing seismic performance and structural resilience [11,17].

3.9 Validation of Numerical Model

The developed finite element model is validated by comparing simulation results with established experimental and analytical findings reported in the literature. Key validation parameters include:

- Hysteretic response
- Load–displacement curves
- Residual deformation trends

This ensures the reliability and accuracy of the modeling approach [12,18].

4. Results and Discussion

4.1 General Structural Response

The numerical analysis compares the behavior of conventional steel structures and SMA-integrated systems under cyclic loading. The results indicate a clear improvement in structural

performance when SMAs are incorporated. Conventional steel systems exhibit stiffness degradation and permanent deformation, whereas SMA-based systems demonstrate stable response and self-centering capability.

4.2 Load–Displacement Behavior

The load–displacement response highlights the effectiveness of SMA integration in improving cyclic performance.

Table 1. Load–Displacement Response Comparison

Parameter	Conventional Steel System	SMA-Integrated System
Initial Stiffness	High	Moderate
Stiffness Degradation	Significant	Minimal
Residual Displacement	High	Very Low
Cyclic Stability	Decreasing	Stable
Symmetry of Response	Asymmetrical	Nearly Symmetrical

The SMA-integrated system shows improved stability and reduced permanent deformation compared to the conventional steel system.

4.3 Hysteresis Behavior and Energy Dissipation

The hysteretic response of the structure determines its energy dissipation capacity.

Table 2. Hysteresis and Energy Dissipation Characteristics

Parameter	Conventional Steel System	SMA-Integrated System
Hysteresis Shape	Pinched	Flag-shaped
Energy Dissipation (Initial)	High	Moderate
Energy Dissipation (Cyclic)	Degrading	Stable
Performance Degradation	Significant	Minimal
Self-Centering Capability	Absent	Present

Although steel shows higher initial energy dissipation, SMA systems maintain consistent performance over multiple cycles.

4.4 Residual Drift and Deformation

Residual drift is a key parameter influencing post-earthquake usability.

Table 3. Residual Drift Comparison

Parameter	Conventional Steel System	SMA-Integrated System
Maximum Drift	High	Moderate
Residual Drift	Significant	Very Low
Drift Recovery (%)	~10–20%	~80–90%
Post-Loading Configuration	Permanently Deformed	Nearly Original Shape

The SMA system demonstrates substantial improvement in deformation recovery, significantly enhancing structural usability.

4.5 Stress–Strain Behavior

The material response under cyclic loading is critical in understanding structural performance.

Table 4. Stress–Strain Characteristics

Parameter	Steel Material	SMA Material
Behavior Type	Elastic–Plastic	Superelastic
Permanent Strain	Present	Negligible
Recoverable Strain	Low	High (up to ~8%)
Cyclic Stability	Degrading	Stable
Fatigue Resistance	Moderate	High

SMA materials exhibit superior performance due to their ability to recover large strains without permanent deformation.

4.6 Effect of SMA Integration on Structural Performance

Table 5. Overall Structural Performance Comparison

Performance Parameter	Conventional Steel System	SMA-Integrated System
Plastic Hinge Formation	Early	Delayed
Stress Concentration	High	Reduced
Structural Damage	Significant	Minimal
Energy Dissipation	High (initial)	Stable (long-term)
Structural Recovery	Poor	Excellent

The integration of SMA elements improves overall structural resilience and reduces damage under seismic loading.

4.7 Summary of Results

The results clearly indicate that:

- SMA-integrated systems significantly reduce residual deformation
- Self-centering capability improves post-earthquake recovery
- Stable hysteretic behavior ensures consistent performance
- Structural damage is minimized compared to conventional systems

Overall, SMA-based systems transform conventional steel structures into **smart, adaptive systems** capable of both resisting and recovering from seismic events.

5. Conclusion

This study presented a comprehensive evaluation of the seismic performance of steel structures integrated with Shape Memory Alloys (SMAs) using a finite element-based analytical approach. The results clearly demonstrate that the incorporation of SMAs significantly enhances structural behavior under cyclic loading conditions compared to conventional steel systems.

The analysis showed that SMA-integrated systems exhibit **stable load–displacement response and flag-shaped hysteresis behavior**, which contribute to consistent energy dissipation and improved cyclic performance. Unlike conventional steel structures that experience permanent deformation due to plastic yielding, SMA-based systems display **superelastic behavior with minimal residual strain**, enabling effective self-centering capability.

A key outcome of this study is the substantial reduction in **residual drift**, which is one of the most critical parameters affecting post-earthquake usability. SMA-integrated structures were

able to recover a significant portion of deformation after unloading, thereby reducing structural damage and improving functionality. Additionally, the integration of SMA elements in critical regions such as beam–column connections and bracing systems delayed plastic hinge formation and reduced stress concentration, leading to enhanced structural resilience.

The findings also highlight that while conventional steel systems provide higher initial energy dissipation, their performance degrades under repeated loading cycles. In contrast, SMA-based systems maintain **stable and reliable performance**, making them more suitable for structures subjected to multiple seismic events. Furthermore, Fe-based SMAs offer a cost-effective alternative to NiTi alloys, improving the feasibility of large-scale implementation.

Despite the advantages, challenges such as high material cost, lack of standardized design guidelines, and limited practical applications must be addressed to facilitate widespread adoption of SMA-based systems. Future research should focus on the development of cost-efficient SMA materials, establishment of design codes, and large-scale experimental validation.

In conclusion, the integration of Shape Memory Alloys into steel structures represents a significant advancement in seismic engineering. SMA-based systems provide a transition from traditional damage-based design toward **resilient, recovery-oriented structural systems**, contributing to the development of sustainable and high-performance infrastructure in seismic regions.

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