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Assessment of the Seismic Performance Improvement Effect of Shape Memory Alloys in Tall Buildings with Combined Shear Core and Peripheral Shear Walls

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Abstract

Over the past two decades, shape memory alloys (SMAs) have emerged as an effective approach for improving the seismic performance of structures. Their benefits are not limited to conventional low-rise systems, but also extend to high-rise buildings, where seismic demands and torsional effects are often more severe. Among the main advantages of SMAs are their ability to reduce structural irregularities and provide self-centering capacity, thereby enhancing post-earthquake performance. This study investigates the effect of SMA application on a high-rise building incorporating a central shear core and perimeter shear walls at the four corners. The structural response was evaluated under two conditions: one with conventional steel reinforcement and the other with SMA bars used as longitudinal reinforcement in the boundary elements of the shear core. To ensure a realistic seismic assessment, three acceleration time-history records were selected based on their compatibility with site conditions and regional seismicity. Although the studied building was geometrically regular, the results show that accidental torsion can still induce significant torsional irregularity in tall buildings. The findings indicate that incorporating SMA reinforcement substantially reduced torsional irregularity indices, improved the uniformity of lateral displacement distribution, and enhanced the overall torsional response of the structure. In particular, the maximum torsional ratio decreased from 1.349 to 1.187, shifting the structural behavior from significantly torsionally irregular to torsionally regular. Therefore, SMA reinforcement can be considered an efficient strategy for improving the seismic design of high-rise buildings.

Keywords: Reinforced Concrete Tall Buildings, Shear Core, Peripheral Shear Walls, Shape Memory Alloys, Torsional Irregularity, Self-Centering Behavior

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1. Introduction

Improving the seismic resilience of high-rise buildings has become an important research focus, leading to growing interest in smart materials such as shape memory alloys for enhancing structural response and self-centering capability. As building height increases, seismic performance becomes a critical design concern due to the combined influence of large structural mass, pronounced second-order effects, and heightened sensitivity to lateral displacements. In reinforced concrete tall buildings, commonly adopted structural systems include moment-resisting frames, dual systems integrating shear walls, and core-based structural configurations. Among these alternatives, the central shear core system is widely favored because it provides substantial lateral rigidity, efficiently limits lateral deflections, and demonstrates reliable behavior under seismic loading. Despite these advantages, several structural challenges persist. Concentration of stress and strain in critical zones of shear walls, plastic hinge development within boundary elements, and elevated interstory drift demands during strong earthquakes continue to threaten structural performance.

The impact of near-fault ground motions further intensifies these concerns. High-intensity, short-duration velocity pulses characteristic of such records can markedly increase displacement and ductility demands. Consequently, damage may localize within specific stories, residual deformations may become significant, and torsional responses may be amplified—particularly in buildings with geometric irregularities. Even in structures possessing regular plan layouts, the inclusion of accidental torsion in design considerations can elevate torsional demands and modify the vertical distribution of seismic forces. Accordingly, effective limitation of interstory drift, reduction of residual deformations, and improvement of torsional response are recognized as essential objectives in the seismic design and performance enhancement of tall buildings.

The limitations of conventional seismic-resistant systems in controlling residual deformations and post-earthquake damage have encouraged the adoption of advanced materials capable of providing both energy dissipation and self-centering capabilities. Accordingly, Shape Memory Alloys (SMAs) have been recognized as a particularly promising option because of their superelastic properties, capacity to sustain and recover large inelastic strains, and intrinsic energy dissipation capability. Under significant loading, these materials can return to their original shape while experiencing minimal residual deformation (Corbi et al., 2003). When incorporated into critical structural components, such features can help reduce strain concentration, restrict the spread of plastic hinges, and enhance the self-centering performance of the overall system. A large body of previous research has mainly examined the use of SMAs in moment-resisting frames, bracing systems, and structural connections. By contrast, their application in the shear walls of tall buildings, particularly with respect to torsional behavior and the overall response of central shear core systems, has been addressed far less extensively. In addition, most available studies have focused primarily on seismic performance indicators and have not fully explored the combined influence of different reinforcement arrangements and various levels of SMA implementation. In view of these gaps, the present study aims to assess the assessment of the Seismic Performance Improvement Effect of Shape Memory Alloys in Tall Buildings with Combined Shear Core and Peripheral Shear Walls

Recent advances in structural engineering have demonstrated the significant potential of Shape Memory Alloys (SMAs) for enhancing the seismic performance of reinforced concrete structures. Owing to their unique superelastic and self-centering characteristics, SMAs have been investigated in a wide range of structural components, including beams, columns, beam–column joints, moment-resisting frames, and shear wall systems. Early studies by Effendy and Liao (2006) explored the application of SMA bars as external reinforcement in low-rise reinforced concrete shear walls. Subsequently, Shokouhfar and Ghasemieh (2014) examined the use of SMA reinforcement in the critical regions surrounding eccentric openings in reinforced concrete shear walls. Palermo and Abdulridha (2016) investigated the replacement of conventional steel longitudinal reinforcement with SMA bars in reinforced concrete shear walls, while Mostafazadeh and Ghasemieh (2016) employed martensitic SMAs to provide both strengthening and prestressing effects within wall systems.

More recently, attention has shifted toward the implementation of SMAs in large-scale structural systems. Shamirani (2024) evaluated the seismic behavior of a reinforced concrete building with a dual moment frame–shear wall system reinforced with different SMA types, including NiTi, FeNCATB, and CuAlMn. Furthermore, Pourreza (2026) studied the effectiveness of SMA reinforcement in the longitudinal boundary elements of the central shear core in reinforced concrete tall buildings, considering different reinforcement arrangements and varying degrees of geometric irregularity. Despite these valuable contributions, the majority of previous studies have primarily focused on local component behavior or conventional shear wall systems. Comprehensive investigations addressing the influence of SMA reinforcement layouts on the torsional response and seismic performance of tall buildings with central shear core systems subjected to near-fault ground motions remain limited. Therefore, further research is required to evaluate the effectiveness of different SMA implementation strategies in improving the overall seismic resilience of such structures.

The findings reported in these studies suggest that the integration of Shape Memory Alloys into structural components can markedly improve seismic performance. The use of SMA reinforcement has been associated with reduced interstory drift demands, improved torsional response, and decreased displacement concentration over the height of the structure. Furthermore, the superelastic behavior and self-centering capacity of SMAs play an important role in limiting residual deformations, increasing structural resilience, and enhancing post-earthquake serviceability after severe seismic events.

The seismic performance of tall buildings is strongly influenced by the distribution of mass and stiffness throughout the structure. Any imbalance in these parameters may generate torsional effects that significantly alter the lateral response of the building and increase deformation demands in critical structural elements. This issue becomes more pronounced in high-rise structures, where the combination of large lateral displacements, higher-mode effects, and dynamic amplification can lead to substantial torsional response during strong earthquakes. Therefore, the evaluation and control of torsional irregularity have become important considerations in the seismic design of tall buildings. According to Iranian Standard No. 2800, torsional irregularity is assessed based on the ratio of the maximum story displacement to the average displacement at the two ends of the same story. Depending on the magnitude of this ratio, buildings may be classified as having moderate or severe torsional irregularity, which can adversely affect their seismic performance and overall structural safety (Standard No. 2800, 2014). A ratio greater than 1.20 indicates significant torsional irregularity, while a value exceeding 1.40 corresponds to severe torsional irregularity. An increase in torsional irregularity is generally associated with larger lateral displacements and greater force demands in lateral load-resisting components, which may in turn increase the probability of nonlinear response, progressive damage development, and even overall structural instability. For this reason, the seismic design of reinforced concrete structures requires careful consideration of the distribution of stiffness and mass, together with adequate control of torsional behavior, to achieve the target performance levels specified in seismic codes. Previous studies on high-rise buildings with mass and stiffness irregularities at different elevations have likewise shown that such discontinuities can have a substantial effect on seismic behavior and on the displacement demands experienced by the structure.

In light of the above considerations, this study presents a comprehensive Assessment of the Seismic Performance Improvement Effect of Shape Memory Alloys in Tall Buildings with Combined Shear Core and Peripheral Shear Walls. To this end, Shape Memory Alloys (SMAs) were incorporated into the longitudinal reinforcement of shear walls through two different reinforcement configurations, and their effects on the overall seismic response of the structural system were systematically examined.

2. Technical Points

Tall buildings are widely regarded as key indicators of urban growth and technological progress in contemporary societies. Predominantly constructed in densely populated cities, these structures have become increasingly important as an effective response to population growth and limited land availability. Their considerable height, modern architectural form, and integration of advanced technologies distinguish them from conventional low-rise buildings.

From a structural engineering standpoint, the behavior of high-rise buildings is considerably more complex than that of shorter structures. Their large height, high slenderness, long fundamental vibration period, and greater sensitivity to dynamic actions result in response characteristics that are markedly different from those of low-rise systems. As the number of stories increases, lateral loads, particularly those induced by wind and earthquakes, become the dominant factors in structural design. Consequently, issues such as control of lateral displacements, limitation of interstory drift, floor acceleration, second-order (P–Δ) effects, soil–structure interaction, and overall structural stability assume critical importance (Salmanbay et al., 2005). In addition, an improper distribution of stiffness and mass along the building height may lead to deformation concentration in certain stories and may trigger soft-story or weak-story mechanisms, thereby significantly reducing seismic performance. Under near-fault ground motions, which are commonly characterized by strong velocity pulses, notable frequency content, and short effective duration, long-period structures such as tall buildings may be subjected to excessive displacement demands and substantial residual deformations. This condition not only endangers structural safety but also affects the post-earthquake functionality and serviceability of the building. Therefore, in the analysis and design of tall structures, nonlinear dynamic analysis and the careful selection of representative near-fault ground motion records are essential for obtaining a realistic estimate of structural response under severe seismic loading.

To provide sufficient lateral strength and stiffness, a variety of structural systems are used in tall buildings. These include moment-resisting frames, braced systems, shear walls, central shear cores, tubular systems, diagrid structures, and various combinations of these configurations, examples of which for reinforced concrete buildings are presented in Figure 1. Among these systems, shear core configurations have been widely employed, particularly in reinforced concrete high-rise buildings, because of their ability to provide considerable flexural and torsional stiffness simultaneously. As a result, they play an important role in controlling lateral displacements and reducing torsional effects. Despite these advantages, several factors may negatively influence the seismic performance of such systems. These include deformation concentration in critical regions of shear walls, the formation of extensive cracking, degradation of effective stiffness, and the occurrence of torsional irregularities caused by asymmetric distributions of mass or stiffness (Pourreza et al., 2026). Representative arrangements of shear core systems are shown in Figure 2.

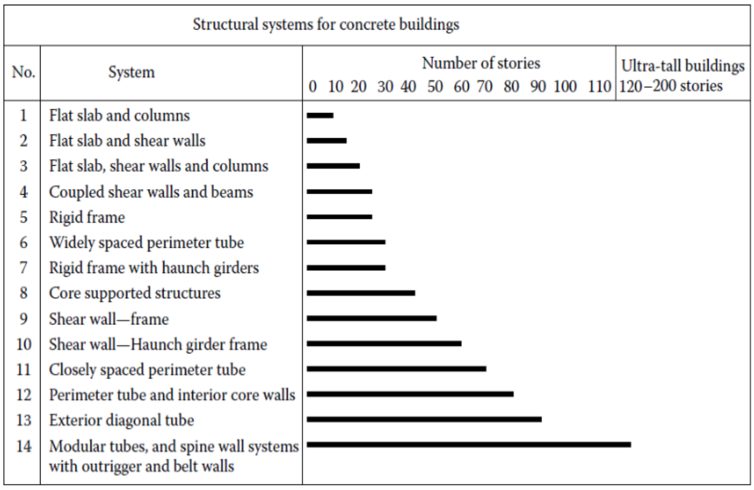


Figure 1. Different Structural Systems for Reinforced Concrete Buildings

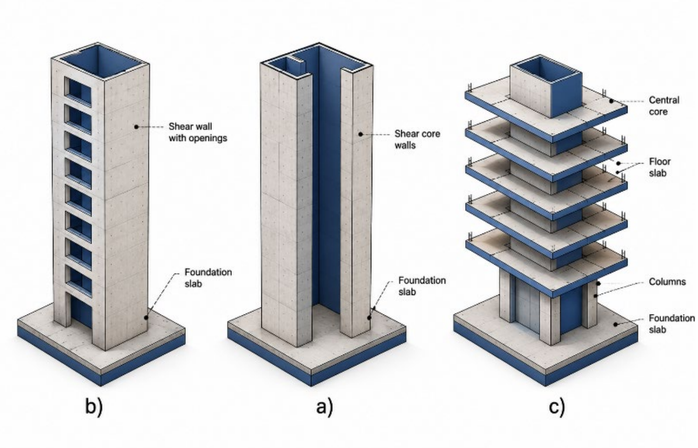


Figure 2. (a) Open core, (b) Semi-closed core with coupling beams, (c) Semi-closed core with floor diaphragms

A performance-based framework is therefore essential in the design of tall buildings, where meeting strength requirements alone is insufficient. In addition to adequate load-carrying capacity, careful attention must be given to key structural response indicators, including interstory drift, residual deformation, damage distribution, and the recentering ability of the system. Within this context, the proper choice of the lateral force-resisting system, the configuration of structural elements, and the optimization of stiffness distribution along both the plan and height of the building play a decisive role in attaining satisfactory seismic performance.

3. Shape Memory Alloys

Shape Memory Alloys (SMAs) constitute an advanced category of smart materials distinguished by their ability to regain their initial configuration after undergoing significant inelastic deformations. Due to their exceptional functional and mechanical characteristics, these alloys have emerged as a promising solution for enhancing the performance of reinforced concrete structures subjected to seismic loading. In comparison with traditional energy dissipation devices, SMAs provide several noteworthy benefits, including superior resistance to corrosion and cyclic fatigue, substantial energy dissipation capability, and the capacity to accommodate large strain levels, typically in the range of 8–10%, while maintaining minimal residual deformation. Another prominent feature of these materials is their ability to restore accumulated residual strains through thermally induced phase transformation, enabling the recovery of their original shape after unloading. This self-centering behavior significantly reduces permanent structural damage and post-earthquake repair demands, thereby improving the overall resilience and functionality of structures exposed to severe seismic events (Olander et al. 1932).

The phenomenon of super elasticity was first documented in 1932 when the Swedish scientist Ölander identified this distinctive behavior in a gold–cadmium alloy. This observation marked the earliest known evidence of the remarkable deformation recovery capability exhibited by certain metallic materials (Olander et al. 1932). Several decades later, a major breakthrough occurred when Buehler and his research team at the United States Naval Ordnance Laboratory discovered the shape memory effect in a nickel–titanium alloy. The newly developed material was subsequently designated as Nitinol, a name derived from its constituent elements and the laboratory in which it was developed (Buehler et al. 1963). Since then, Nitinol has become the most extensively studied and commercially adopted shape memory alloy, owing to its exceptional superelastic and shape recovery characteristics, which have enabled its widespread application across various engineering and technological fields.

The unique mechanical response of shape memory alloys is fundamentally attributed to their crystallographic characteristics and their ability to undergo reversible phase transformations. These materials primarily consist of two thermodynamically stable phases, namely martensite and austenite, each of which exists within a distinct temperature regime. The martensitic phase predominates at lower temperatures and is principally associated with the shape memory effect, enabling the material to recover previously imposed deformations upon thermal activation. Conversely, the austenitic phase becomes stable at elevated temperatures and is responsible for the superelastic behavior, allowing the alloy to sustain substantial strain levels and subsequently return to its original configuration with negligible residual deformation after unloading (Zarei et al. 2020). The manifestation of shape memory, super elastic phenomena is governed by the transformation temperatures that define the transition between these two phases. The interrelationship between phase transformation and mechanical response is commonly represented through temperature-dependent stress–strain curves, as illustrated in Figure 3.

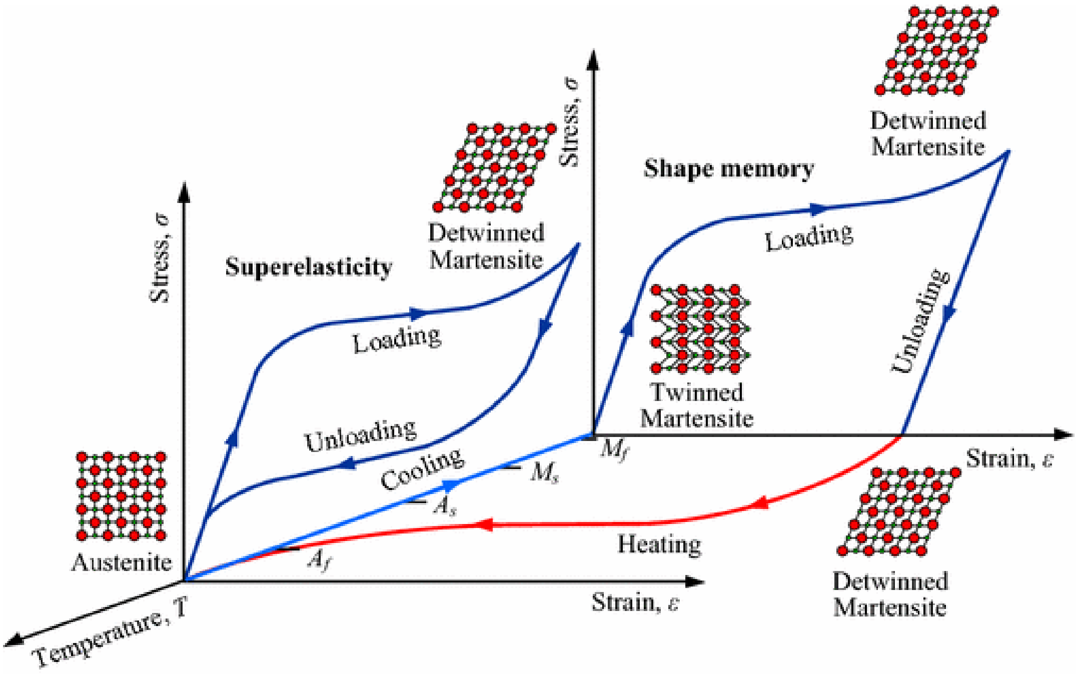


Figure 3. Mechanical Behavior of Shape Memory Alloys (SMAs)

The earliest practical applications of shape memory alloys were predominantly concentrated in the biomedical sector, where their unique functional properties facilitated their use in orthopedic implants, orthodontic devices, vascular stents, and various implantable medical components (Duerig et al. 1990). As research on these materials progressed and their exceptional capabilities became more widely recognized, their utilization extended far beyond medical engineering. Today, SMAs are employed in numerous technological and industrial disciplines, including mechanical systems, automotive engineering, aerospace structures, and a variety of consumer products such as eyeglass frames and portable electronic devices (Graesser et al. 1932; Hsu et al. 2000).

In the field of mechanical engineering, shape memory alloys have been extensively adopted in the development of thermally activated actuators and adaptive mechanical systems (Humbeeck et al. 1999). Their unique ability to undergo controlled shape recovery enables the conversion of thermal energy into mechanical work, making them particularly suitable for small-scale engines, smart actuation mechanisms, and other active control applications (Liang et al. 1992). This capability has significantly enhanced the attractiveness of SMAs for innovative engineering solutions requiring compact, reliable, and self-actuating components.

Given the distinctive characteristics of these alloys, their mechanical response must be described through precise and robust modeling frameworks. Accordingly, a wide range of constitutive models for shape memory alloys has been proposed in recent years. In general, these models can be divided into two main categories: phenomenological models and thermodynamic models.

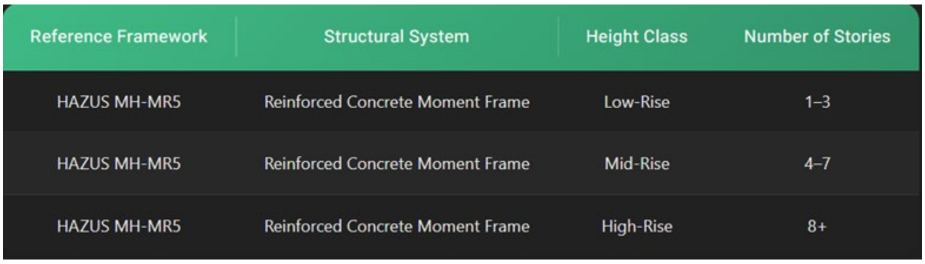
Phenomenological models are primarily formulated based on experimental observations and laboratory findings, and they are frequently expressed within a one-dimensional framework. Owing to their relative simplicity, these models have become particularly attractive for engineering practice, especially in structural engineering applications, where shape memory alloys are often employed as bars or wires. Representative examples of this class include the models introduced by Rogers et al., Ivshin et al., Lagoudas et al., and Auricchio. By drawing on experimental evidence, such models are capable of providing reliable predictions of the inelastic and superelastic deformation behavior of shape memory alloys in structural systems. In contrast, thermodynamic models are established on the fundamental laws of thermodynamics and energy conservation. These approaches seek to characterize the response of shape memory alloys through energy-based formulations and thermodynamic transformation mechanisms (Pourreza et al., 2026). Important contributions to this category include the studies conducted by Hong, Guo, and their collaborators. Compared with phenomenological approaches, thermodynamic models are generally better suited for advanced analyses and high-fidelity simulations, particularly under nonlinear thermo-mechanical loading conditions.

With the continual development of finite element analysis software, the behavior of shape memory alloys can now be modeled more effectively in practical engineering applications. For example, SeismoStruct offers the capability to simulate both the superelastic response and the shape memory effect of these materials, allowing engineers to predict with greater accuracy the performance of structures incorporating shape memory alloys under complex loading scenarios, including seismic actions. This feature supports the reliable and efficient use of these alloys in high-rise buildings and earthquake-resistant structural systems.

4. Modelling and Analysis

To investigate the seismic performance of tall buildings equipped with a central shear core and peripheral shear walls, a 15-story reinforced concrete model was selected and developed in accordance with the HAZUS-MH MR5 classification, as presented in Table 1, as a representative high-rise structural system. The model was designed and analyzed based on established code provisions to ensure the reliability and scientific validity of the results. Gravity and lateral loadings were assigned in accordance with the Iranian National Building Regulations (Parts 6 and 9) and the Iranian Seismic Design Code (Standard No. 2800, Fourth Edition). In addition, the dynamic response of the structures was evaluated through nonlinear time-history analysis using real near-fault earthquake ground motion records. The analytical procedure was conducted in accordance with the provisions of FEMA-356, along with other widely recognized international references.

Table 1. Classification of Reinforced Concrete Moment-Resisting Frames According to the HAZUS-MH MR5



Reference Framework	Structural System	Height Class	Number of Stories
HAZUS MH-MR5	Reinforced Concrete Moment Frame	Low-Rise	1–3
HAZUS MH-MR5	Reinforced Concrete Moment Frame	Mid-Rise	4–7
HAZUS MH-MR5	Reinforced Concrete Moment Frame	High-Rise	8+

The selected near-fault ground motion records were examined with due consideration of key site parameters, particularly soil classification and fault-to-site distance. The evaluation showed that the amplitudes of some accelerograms were either greater or smaller than those prescribed by the code-based design spectrum. Such differences can be attributed to the seismotectonic properties of the earthquake source as well as the governing local site conditions. Subsequently, the selected near-fault ground-motion records for Site Class II, along with the response acceleration spectra corresponding to the stronger horizontal component, are summarized in Table 2.

Table 2. Recommended Near-Fault Ground Motion Records for Site Class II Soil Conditions (Barjoui Roshanpour et al. 2024)

Earthquake Record	**Year**	**Magnitude (Mw)**	**Source Distance (km)**	**Vs (m/s)**	**Duration (sec)**	**PGA Horizontal Components (g)**	
						PGA H1	**PGA H2**
"Big Bear-01"	1992	6.4	8	431	5.25	0.544	0.481
"Borah Peak_ ID-02"	1983	5.1	18	469	4.1	0.074	0.054
"Cape Mendocino"	1992	7	19	388	4.5	0.376	0.267
"Chuetsu-oki_ Japan"	2007	6.8	18	415	2.6	0.332	0.188
"Coalinga-05"	1983	5.7	11	475	4.2	0.217	0.193
"Helena_ Montana-01"	1935	6	3	594	4.05	0.161	0.156
"N. Palm Springs"	1992	7.2	17	397	4.35	0.223	0.217

In the present study, the analysis began with the selection of earthquake records, in which a set of near-fault ground motions was reviewed and three records with the highest peak horizontal acceleration values were chosen. These included the "Big Bear-01" record with a peak horizontal acceleration of 0.544 g, the "Cape Mendocino" record with a value of 0.376 g, and the "Chuetsu-oki, Japan" record with a value of 0.332 g. These records were then adopted as the primary candidates and subjected to scaling. Due to their comparatively high peak horizontal accelerations and their ability to represent near-fault seismic characteristics, they were ultimately used as the main input ground motions for structural modeling and analysis.

For the purpose of this study, a regular plan with dimensions of 45 m × 15 m was selected and located in Tehran, with a story height of 3.4 m, as illustrated in Figure 4. The investigated structure is a 15-story reinforced concrete building with a total height of 51 m, employing a dual lateral load-resisting system composed of moment-resisting frames, a central shear core, and peripheral shear walls. This structural model was considered representative of tall buildings. Moreover, the material properties, gravity loads, and story heights were kept identical in both reinforcement scenarios, namely the fully steel-reinforced model and the model incorporating shape memory alloy bars.

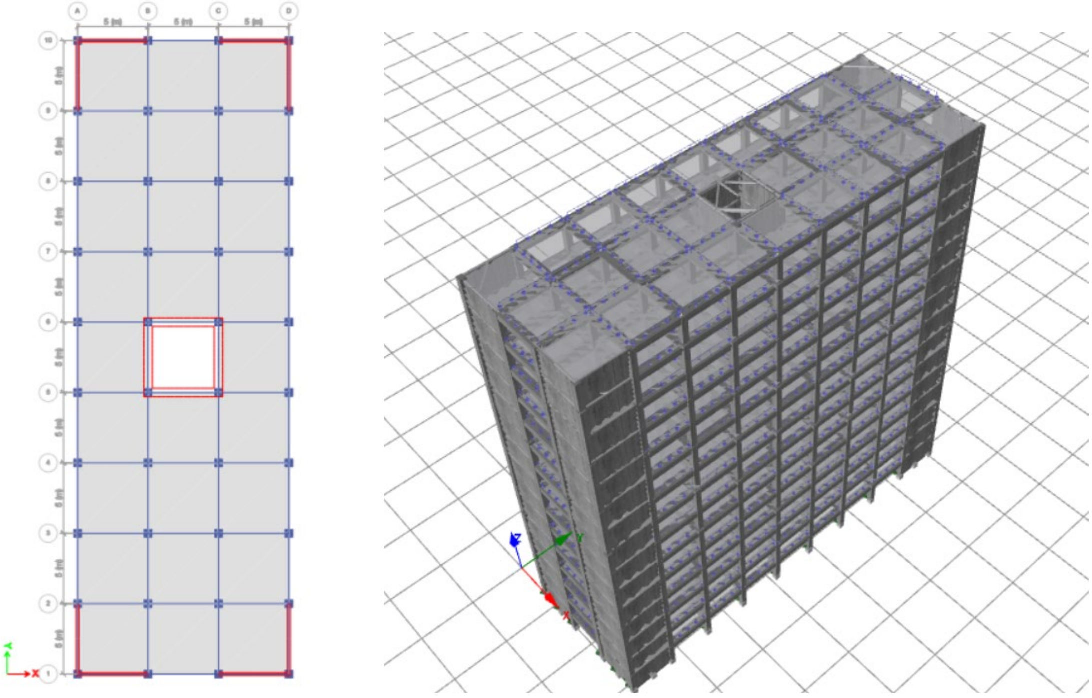


Figure 4. Geometrically Regular Plan Configuration

The material properties considered in the design and analytical procedures were selected in accordance with Table 3 and are summarized below.

Table 3. Material Properties Used in the Present Study

Material	Mechanical Property	Value
Concrete	Compressive strength (MPa)	30
	Tensile strength (MPa)	3
	Strain at peak stress (%)	0.20%
	Modulus of elasticity (MPa)	200,000
Steel	Yield strength (MPa)	400
	Strain hardening parameter (%)	0.50%
	Modulus of elasticity (MPa)	65,000
SMA	Austenite to martensite starting stress (MPa)	400
	Austenite to martensite finishing stress (MPa)	500
	Martensite to austenite starting stress (MPa)	300
	Martensite to austenite finishing stress (MPa)	100
	Superelastic plateau strain length (%)	7%

Furthermore, the cross-sectional dimensions selected for the lateral force-resisting components, including the columns, beams, and shear core, along with their reinforcement details, are listed in Table 4, which summarizes the geometric and strength properties of the structural members in full.

Table 4. Properties of the Designed Column, Beam, and Shear Wall Sections

Story Number	Columns	Beams	Shear Core Walls	Peripheral Shear Walls	Description
1 to 5	600×600 20-25	700×500 4-28 top 4-28 bottom	600×600 500-5000 56-28	600×600 200-5000 56-20	For Columns: Column dimensions (mm) Number of reinforcing bars – bar diameter (mm) For Beams: Beam dimensions: width × depth (mm) Number of reinforcing bars – bar diameter – reinforcement location (mm) For Shear Walls: Boundary element dimensions Length and thickness of the shear wall (mm) Number of reinforcing bars – bar diameter (mm)
6 to 10	500×500 16-25	600×400 4-28 top 4-28 bottom	500×500 400-5000 56-26	500×500 200-5000 56-18	
11 to 15	400×400 12-25	400×300 4-22 top 4-22 bottom	400×400 300-5000 56-22	400×400 200-5000 56-16	

To evaluate the structural response of the shear core and perimeter shear walls under different material conditions, two reinforcement schemes were considered for each analytical model. In the first Configuration, conventional steel reinforcement was used throughout all orthogonal shear walls. In the second Configuration, shape memory alloy reinforcement was employed only as the longitudinal reinforcement of the boundary elements in the shear core walls, while conventional steel reinforcement was retained in the remaining wall regions.

For the analysis, the finite element software SeismoStruct was employed, and the 2026 release developed by SeismoSoft was adopted as the numerical platform for the analyses. In SeismoStruct, reliable estimation of structural vulnerability and nonlinear member response depends on the accurate representation of both stiffness and inelastic behavior along the element length and over the section depth (SeismoSoft, 2026).

To satisfy this requirement, each member cross-section is discretized into a prescribed number of fibers. For conventional analyses, approximately 200 fibers are generally considered sufficient, whereas for more intricate cross-sections this number may increase to about 400. This fiber discretization is consistently applied along the member length, allowing the distribution of stiffness, strain, and damage to be captured with appropriate accuracy. Subsequently, the nonlinear stress–strain response of the section is determined from the interaction among the constituent fibers. For instance, a reinforced concrete beam may be divided into several zones, as illustrated in Figure 5, with a specific number of fibers assigned to each zone. This figure presents the implementation of fiber-based elements in the software and illustrates the procedure used to model the nonlinear behavior of structural sections.

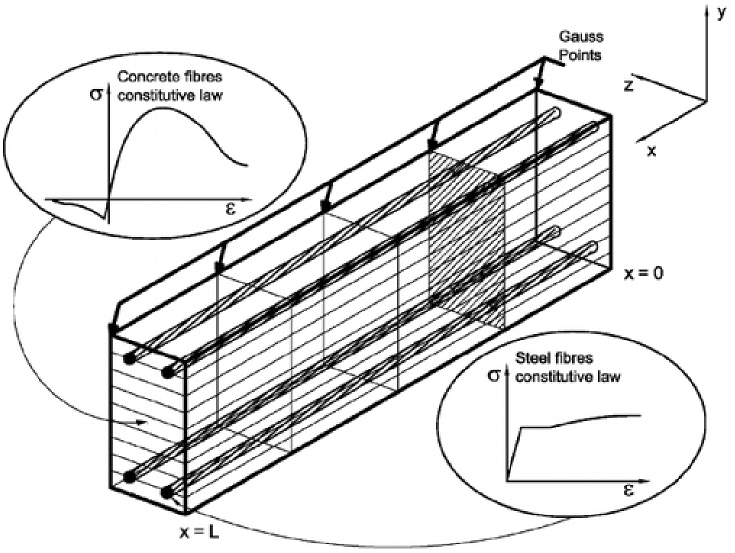


Figure 5. Fiber Elements in SeismoStruct Software (SeismoSoft. 2026)

Subsequently, the effect of incorporating shape memory alloys on the seismic response of the structures is examined. Particular attention is given to changes in key response parameters, especially displacements, interstory drifts, and seismic performance levels, relative to the case with conventional steel reinforcement. The results of this evaluation provide a basis for assessing the effectiveness of shape memory alloys in improving structural performance and mitigating structural vulnerability.

5. Outputs

To assess the influence of shape memory alloys on the torsional response of the structure, the story torsional ratio was examined for model shown in Figure 6 under two different reinforcement configurations of the orthogonal shear walls.

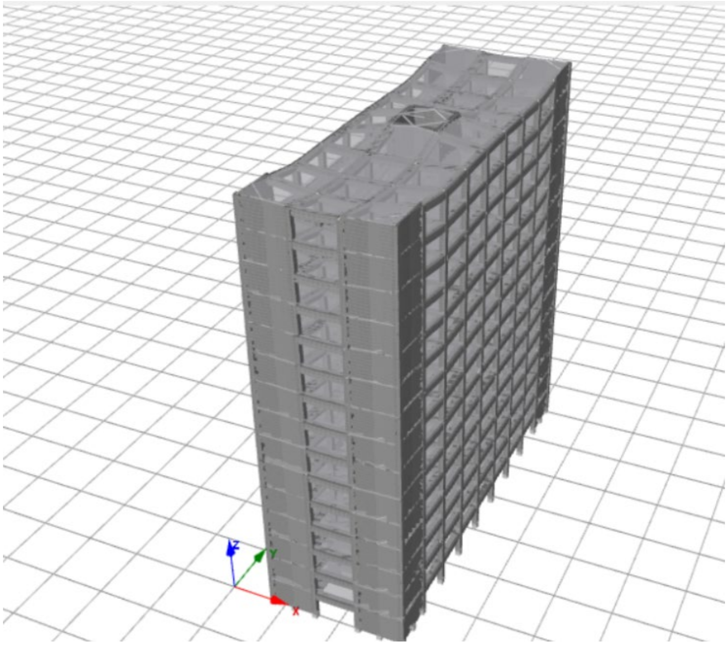


Figure 6. Deformed Shape of the Structure with a Geometrically Irregular Plan

In the first reinforcement configuration, all shear wall reinforcement was assumed to consist of conventional steel bars, and the corresponding story torsional ratios are presented in Table 5. The results indicate that the maximum torsional ratio occurs at the ground floor, reaching a value of 1.349. Based on the classification criteria of Iranian Standard No. 2800, torsional ratios within the range of 1.2 to 1.4 represent significant torsional irregularity. This finding suggests that lateral displacements are not uniformly distributed over the building plan, thereby increasing the contribution of torsional effects to the overall seismic response of the structure.

Under the second reinforcement configuration, SMA bars were incorporated as the longitudinal reinforcement within the boundary elements of the shear walls, while conventional steel reinforcement was retained in the remaining wall regions. The torsional irregularity ratios obtained for this configuration, reported in Table 5, indicate a maximum value of 1.187 at the ground floor. According to the classification limits specified in Iranian Standard No. 2800, this value corresponds to a torsionally regular condition. In comparison with the fully steel-reinforced model, the hybrid Steel-SMA configuration demonstrates a notable enhancement in torsional behavior, as evidenced by the reduced torsional irregularity ratio and the more balanced distribution of lateral response over the building height.

Table 5. Story Torsional Ratios for the two Reinforcement Configuration

Steel-SMA case	*	Full Steel case
Ratio	Story	Ratio
1.091	15	1.118
1.093	14	1.119
1.094	13	1.123
1.1	12	1.124
1.098	11	1.147
1.109	10	1.159
1.116	9	1.161
1.118	8	1.165
1.122	7	1.179
1.13	6	1.187
1.142	5	1.191
1.159	4	1.217
1.182	3	1.244
1.171	2	1.291
1.187	1	1.349

A comparative interpretation of the two reinforcement schemes suggests that the use of shape memory alloys in the shear core walls, especially at the boundary zones, can effectively decrease the story torsional irregularity ratio and lessen the detrimental influence of torsional imbalance. This improvement is reflected in a more favorable seismic behavior of the irregular structural system.

An evaluation of Figure 7 indicates that the story torsional ratios decrease progressively along the building height for both reinforcement schemes; however, the model incorporating SMA bars consistently exhibits lower torsional ratios at all story levels. In the lower stories, particularly from Story 1 to Story 5, the difference between the two configurations is more pronounced. The maximum torsional ratio in the fully steel-reinforced model occurs at the first story, with a value of 1.349, whereas the corresponding value in the Steel–SMA configuration decreases to 1.187. This reduction indicates that the use of SMA bars in the boundary elements of the shear core walls effectively mitigates torsional response in the most critical region of the structure, where seismic demand and lateral deformation concentration are generally higher. In the middle-height region, covering Stories 6 to 10, the torsional ratios of both models show a gradual decline. Nevertheless, the Steel–SMA model maintains lower values throughout this range, decreasing from 1.130 at Story 6 to 1.109 at Story 10. This trend demonstrates that the hybrid reinforcement scheme provides a more stable and controlled torsional response compared with the conventional steel configuration. A similar pattern is observed in the upper stories, from Story 11 to Story 15. Although the difference between the two reinforcement schemes becomes smaller at higher elevations, the SMA-reinforced model still shows consistently reduced torsional ratios. The values in this region remain close to 1.09–1.10, suggesting a more uniform distribution of lateral displacement across the plan.

To summarize, the results confirm that replacing conventional steel with SMA bars in the boundary elements of shear walls improves the torsional performance of the structure. The most significant improvement occurs in the lower stories, where the torsional demand is higher. Moreover, the reduction of the maximum torsional ratio from 1.349 to 1.187 shifts the structural response from a torsionally irregular condition toward a torsionally regular state according to the limits specified in Iranian Standard No. 2800.

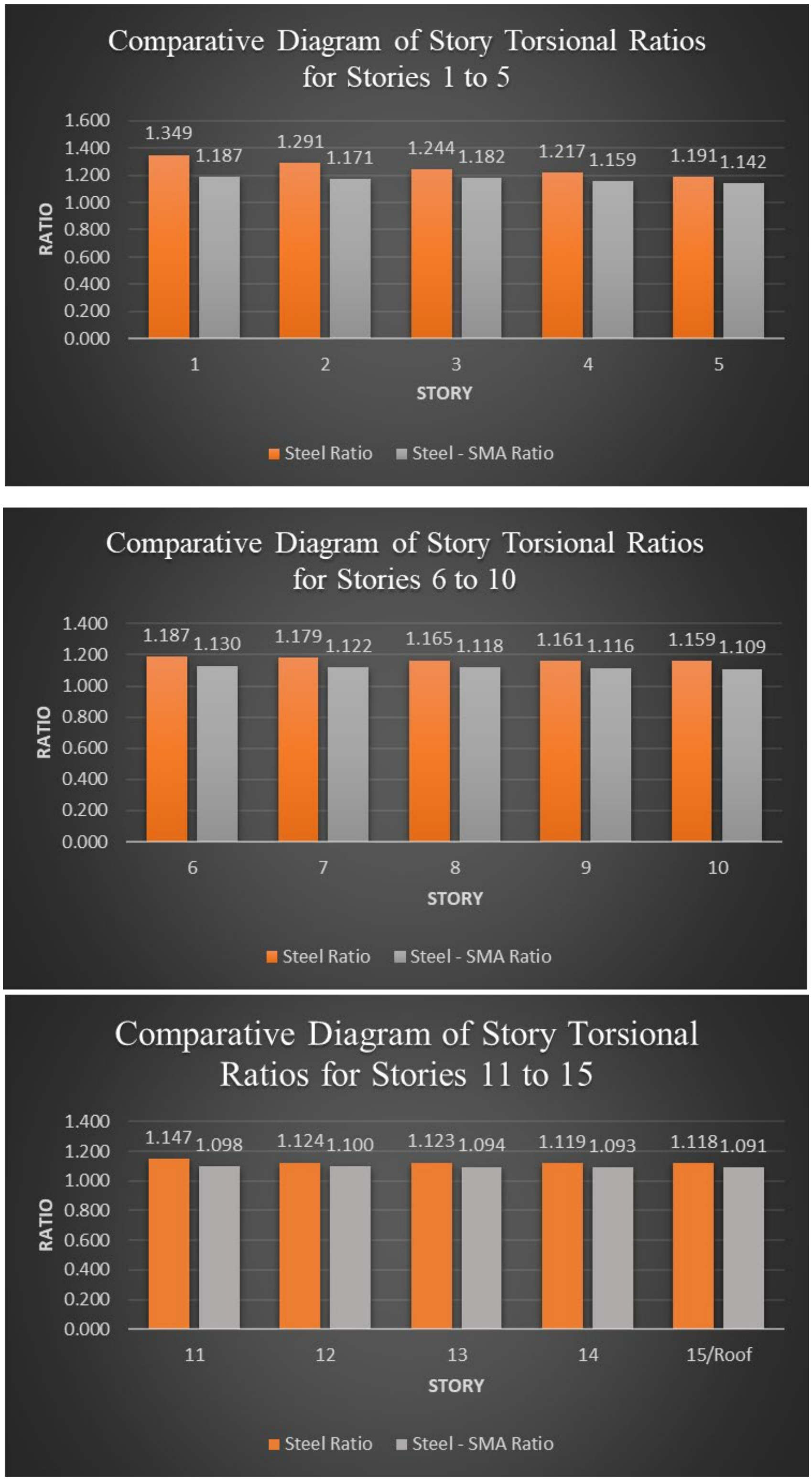


Figure 7. Comparative Diagram of Story Torsional Ratios

The observed improvement in torsional response can be mainly attributed to the unique mechanical characteristics of shape memory alloy (SMA) reinforcement, particularly its superelastic behavior and self-centering capability. When SMA bars are placed in the boundary elements of shear core walls, they are located in regions where high axial-flexural demands and inelastic deformation are expected during strong seismic excitation. In these critical zones, conventional steel reinforcement tends to accumulate residual strains after yielding, which may lead to permanent lateral displacement, uneven deformation distribution, and increased torsional effects. In contrast, SMA can undergo large recoverable strains and return toward its original configuration after unloading. This self-centering mechanism reduces the accumulation of residual deformation in the shear wall boundary regions and helps restore the lateral resisting system after each loading cycle. As a result, lateral displacements become more uniformly distributed across the plan, and the difference between the maximum and average story displacements is reduced. Since the torsional irregularity ratio is directly related to the nonuniformity of lateral displacement, the improved displacement compatibility provided by SMA reinforcement leads to lower torsional ratios.

Moreover, the superelastic response of SMA provides stable energy dissipation while limiting excessive plastic damage in critical wall regions. This behavior enhances the recentering capacity of the structural system and reduces the concentration of inelastic rotations near the base of the building, where seismic demands are typically more severe. Therefore, the incorporation of SMA bars in the boundary elements improves not only the torsional behavior but also the overall seismic resilience of the structure. In general, the reduction in torsional ratios observed in the Steel–SMA configuration can be explained by the ability of SMA reinforcement to control residual deformation, improve deformation compatibility, and provide a more balanced lateral response. These features confirm that the localized use of SMA in high-demand regions is an effective strategy for enhancing the seismic and torsional performance of tall reinforced concrete buildings.

6. Conclusions

This study investigates the influence of Shape Memory Alloys (SMAs) on the seismic behavior of tall Buildings with Combined Shear Core and Peripheral Shear Walls. Numerical models were developed in SeismoStruct and analysed using nonlinear time-history analyses under near-fault earthquake records. Two reinforcement schemes, including conventional steel reinforcement and SMA-reinforced boundary elements, were considered. The results showed that the use of SMA bars enhances seismic performance by reducing drift demands, improving torsional response, and limiting residual deformations. The main findings are presented as follows:

- The maximum torsional ratio at the first story decreased from 1.349 in the fully steel-reinforced model to 1.187 after replacing the longitudinal reinforcement of the shear core wall boundary elements with SMA bars. According to Iranian Standard No. 2800, this approximately 12% reduction changed the structural response from significant torsional irregularity to a torsionally regular condition, highlighting the effectiveness of SMA reinforcement in improving torsional behavior and achieving a more balanced lateral deformation pattern.

- The selective incorporation of shape memory alloy reinforcement into the longitudinal bars of the boundary elements delivered improved seismic performance relative to the conventional steel-reinforced configuration, while requiring a reduced amount of SMA material and resulting in lower additional construction costs. This finding further underscores the importance of optimizing the placement of SMA reinforcement within structural members Under near-fault ground motion records, characterized by intense velocity pulses and significant frequency content, the displacement demands imposed on the structure increased considerably. Nevertheless, the presence of Shape Memory Alloy reinforcement contributed to reducing the vulnerability of the structural system, particularly within critical story levels.
- In severe earthquakes, recorded ground accelerations may exceed the code-based design level. Although structural collapse may be prevented, large residual deformations can reduce post-earthquake functionality. In this regard, the self-centering behavior of shape memory alloys can help decrease permanent displacements and return the structure closer to its initial position, thereby improving seismic resilience and supporting the technical and economic justification for their use.
- The usage of shape memory alloy reinforcement improved the structural response under torsional irregularity by reducing the concentration of rotational demands along the building height. It also promoted a more balanced stiffness distribution and limited the localization of lateral displacements, resulting in a more uniform and stable seismic response.
- The results demonstrate that the application of shape memory alloys can be considered a promising seismic enhancement strategy, particularly for tall buildings. Owing to their re-entering capability and favorable energy dissipation characteristics, SMAs can effectively reduce structural damage, limit residual deformations, enhance structure self-centering and improve the resilience of the structural system.

7. References

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