SEISMIC PERFORMANCE OF SUPERELASTIC BRACING SYSTEMS APPLIED TO STEEL FRAME STRUCTURES

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Abstract

Bracing systems have emerged as an effective solution for enhancing the resilience of steel frame structures under dynamic loads. Conventional steel bracings dissipate energy through bilinear hysteresis responses, ensuring structural safety but often resulting in significant residual displacements after strong earthquake impacts that necessitate costly maintenance and repairs. Shape memory alloys (SMAs), particularly superelastic alloys, have drawn interest due to their potential for both energy dissipation and self-centering capabilities. This study explores the use of SMA-based superelastic bracing systems in steel frame structures subject to seismic loading. Using nonlinear time-history analyses performed in ETABS, the study investigates the comparative response of conventional and superelastic bracing systems. The findings of this research suggest that SMA-based bracing systems may offer advantages in reducing column demands and residual displacements, indicating potential for further development in seismic design applications.

Keywords: *Bracing system; superelastic brace; shape memory alloy; nonlinear time-history analysis; seismic structural analysis*.

1. Introduction

The rapid economic, social, and technological development over the past decades has driven significant advancements in infrastructure, leading to the construction of large-scale buildings and facilities to meet growing societal and economic demands. However, this development has also increased the structures' vulnerability to dynamic impacts like windstorms and earthquakes. As seismic risks become more pressing, the need for effective structural design solutions that enhance resilience and minimize damage to structures has become important.

Current seismic design standards [1]-[4], classify earthquake-resistant solutions into two primary categories: conventional structural design approaches and modern techniques that incorporate energy dissipation devices. Conventional methods rely on a structure’s inherent strength, stiffness, and ductility to withstand seismic forces, effectively preventing collapse. However, while these methods provide essential protection capacity, they often

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DOI: 10.56651/lqdtu.jst.v8.n01.953.sce

lead to significant permanent deformations, necessitating costly repairs after an earthquake. In contrast, modern approaches employ advanced materials and technologies to enhance energy dissipation and improve restoring capabilities. These innovations significantly reduce residual displacements and structural damage, allowing buildings to remain functional both during and immediately after a seismic event.

In the present advanced seismic designs, the primary objective is to ensure both the load-bearing capacity and the energy dissipations of the structures. The structural system, therefore, must have sufficient strength and appropriate stiffness to control vibrations and inertial forces as well as limiting the excessive deformations/displacements. Additionally, a high energy dissipation capacity (in other words, the equivalent damping ratio) is essential for mitigating seismic effects. However, allowing inelastic deformations in the structure implies accepting a certain level of structural damage during earthquakes. If the structure is subjected to cyclic loading or seismic forces exceeding design standards, these deformations may become irreversible, resulting in structural failure or loss of functionality.

Over the last fifty years, advanced seismic design technologies have become a dominant trend in some high-seismic active regions in the world. These technologies incorporate mechanical or semi-mechanical devices into structural systems to enhance structural capacity under seismic impacts. Seismic-resistant design solutions are generally classified into three categories: passive damping, active damping, and semi-active damping. Among them, passive damping is the most widely used due to its cost-effectiveness, adaptability, and independence from external power sources [5]-[9].

The bracing system, which has been extensively studied and developed over several decades, is a vital component of passive damping mechanisms in seismic-resistant structural design, especially for frame structures. Seismic-resistant bracing systems were first researched in Japan in the 1970s to enhance structural elastic stiffness under strong earthquakes [10], [11]. Subsequently, their development expanded, especially in high-seismic regions, due to their superior energy dissipation capacity. Extensive theoretical and experimental studies have gained significant advancements, making them increasingly prevalent, particularly after the 1970s [12]-[17]. This technique provides an effective solution for structures subjected to significant lateral loads, such as wind, storms, and particularly earthquakes. These systems are typically constructed from steel, a material known for its exceptional tensile and compressive strength as well as its stability under cyclic loading.

Generally, the bracing system significantly enhances the structural performance and improves the overall ductility of the system compared to conventional designs. The most notable advantages of this solution are its superior ductility and stable performance under cyclic loads, such as earthquakes, which not only bring about technical efficiency but also design flexibility and significant economic benefits. As a result, bracing systems have been widely implemented in steel frame structures, especially in strong earthquake regions.

Among modern structural approaches, particularly in bracing systems, SMAs have emerged as a promising alternative to conventional steel due to their unique superelastic properties, which enable them to restore their original shape after deformation. SMA-based bracing systems offer superior energy dissipation and self-healing capabilities, making them an attractive solution for mitigating earthquake damage in steel-framed structures.

In recent years, bracing systems incorporating SMAs have become a prominent research focus in seismic-resistant design for steel frames. SMAs can undergo large deformations and fully recover their original shape upon unloading as a type of superelastic material with a high elastic modulus. This distinctive property makes them suitable for damping systems, paving the way for next-generation bracing solutions in earthquake-resistant structures. Recent studies have increasingly explored SMA applications in seismic design, particularly for steel frames. With their ability to endure significant deformations while fully recovering upon unloading, SMAs offer an innovative alternative to advanced damping systems. Their capacity to enhance energy dissipation, reduce vibrations, and prevent permanent structural damage by eliminating residual displacements makes them a highly effective solution for earthquake-resistant structures, especially in high-seismic regions.

Research on the application of SMAs in superelastic bracing systems for structural reinforcement remains limited in Vietnam. This is due in part to the country's location in a region with moderate seismic activity, as well as the relatively recent introduction of SMA-based technologies in structural engineering. This gap highlights the need for further investigation, analysis, and evaluation of SMA braces, which remain highly promising for development in seismic engineering.

2. Objective and methodology

The primary objective of this study is to investigate the feasibility of using SMA-based superelastic bracing systems in earthquake-resistant steel frames.

To achieve this goal, the following methodologies have been identified:

- An overview of seismic impact on building structures.

- Method of modeling the behavior of bracing systems in building structure models.

- Numerical analysis on a typical steel building model, comparison of the seismic performance of conventional steel bracing with SMA-based alternatives.

The findings provide insights into the potential advantages of SMA bracing in reducing column bending moments and preventing residual displacements, contributing to the development of more resilient and cost-effective seismic design solutions.

3. Calculation of seismic impact on structures

3.1. Horizontal acceleration response spectrum

The response spectrum parameters are defined by the maximum ground motion amplification due to structural responses, including accelerations, velocities, and displacements. These parameters are essential for evaluating earthquake impacts on structures, particularly in relation to seismic energy over a given displacement period.

According to the Vietnamese seismic design standard TCVN 9386:2012 [1], the elastic acceleration response spectrum is calculated as follows:

For the building with the natural vibration periods shorter than 4.0 seconds, the horizontal elastic response spectrum $S_e(T)$ is calculated using the following formula:

$$\begin{aligned}
&0 \le T \le T_B : S_e(T) = a_g S\left[1+(2.5\eta-1)T/T_B\right]\\
&T_B \le T \le T_C : S_e(T) = 2.5a_g S\eta\\
&T_C \le T \le T_D : S_e(T) = 2.5a_g S\eta\left(T_C/T\right)\\
&T_D \le T \le 4s : S_e(T) = 2.5a_g S\eta\left(T_C T_D/T^2\right)
\end{aligned} \tag{1}$$

The elastic displacement response spectrum $S_{de}(T)$ is derived from the elastic acceleration response spectrum using the following formula:

$$S_{de}(T) = S_e(T)\cdot\left(T/2\pi\right)^2 \tag{2}$$

For the natural vibration period longer than 4.0 seconds, based on Eurocode 8 [2], the elastic acceleration response spectrum is derived from the elastic displacement response spectrum $S_{de}(T)$ where the value of $S_{de}(T)$ is defined as follows:

$$\begin{aligned}
&T_E \le T \le T_F : S_{de}(T) = 0.025a_g S T_C T_D\left[2.5\eta+\left(\frac{T-T_E}{T_F-T_E}\right)(1-2.5\eta)\right]\\
&T_F \le T \qquad : S_{de}(T) = 0.025a_g S T_C T_D
\end{aligned} \tag{3}$$

where a_g ($a_g = \gamma_I \times a_{gR}$) is the design ground acceleration for soil class A, γ_I is the importance factor, a_{gR} is the reference peak ground acceleration, S is the soil factor, η is the damping correction factor which depends on the viscous resistance ξ (%), T is the vibration period of the structure.

T_B, T_C, T_D, T_E, T_F are the period limits of the acceleration response spectrum, which depend on the type of soil, are specified in the following Tab. 1:

Tab. 1. The parameters describing the elastic response spectra according to TCVN 9386:2012 [1]

Soil	**S**	**T_B**	**T_C**	**T_D**	**T_E**	**T_F**
A	1	0.15	0.4	2	4.5	10
B	1.2	0.15	0.5	2	5	10
C	1.15	0.2	0.6	2	6	10
D	1.35	0.2	0.8	2	6	10
E	1.4	0.15	0.5	2	6	10

3.2. Time-history analysis with accelerograms

TCVN 9386:2012 provides specific guidelines for the application of accelerogram in seismic analysis. Specifically, it requires most acceleration time histories to be scaled to match target response spectrum. Various methods for generating artificial acceleration time histories or calibrating actual ones have been extensively studied and applied by researchers such as D. V. Thuat [18], V. N. Anh [19], and N. X. Dai [20], [21].

On the other hand, for structures incorporating bracing elements, particularly superelastic braces, accurately modeling nonlinear behavior of these elements is essential. This enables a deeper understanding of their operational principles and optimizes their performance. Accordingly, time-history analysis provides the most effective approach for evaluating seismic performance, which is applied in this paper with calibrated accelerograms in accordance with current standards and recommendations [1]-[4], [22].

4. Braced frame modeling

In the structural system, beams and columns primarily carry vertical and horizontal loads, while the bracing system is responsible for reducing horizontal forces acting on the columns. In general, bracing configurations commonly include V-bracing, X-bracing, and K-bracing, which are strategically incorporated into rectangular structural regions to enhance stability and overall frame performance [23], [24].

Brace systems, serving as auxiliary components added to the initial structural system, increase the stiffness and improve the energy dissipation capacity of the entire structure. To simulate the behavior of braces, a nonlinear modeling is often employed by using the force-displacement relationship of the model in the form of hysteresis loops, typically bilinear hysteresis behavior [13], [14], [25], [26].

Figure 1 shows the bilinear behavior, representative for the cyclic behavior of a conventional brace system.

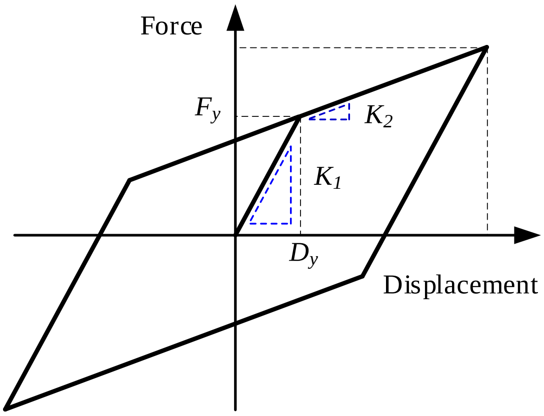

Fig. 1. Bilinear behavior model representing the conventional bracing element.

In Fig. 1, K_1 represents the initial elastic stiffness, K_2 denotes the post-elastic stiffness of the bracing element. The yield point is defined by the elastic limit force F_y and the yield displacement D_y.

Figure 2 shows the constitutive model of typical SMA brace element, represented by stress-strain flag-shaped hysteretic behavior. The loading phases include stiffness K_1 and K_2 and the unloading phases include K_3, K_4. Generally, it was assumed that the loading and unloading branches have different slopes (i.e., $k_1 \neq k_3$, $k_2 \neq k_4$). The elastic limits are determined at the displacement values of $\pm u_2$.

In the framework of this paper, the analyses were performed only with accelerograms that are automatically calibrated by ETABS software in frequency domain to match the elastic response spectrum defined in TCVN 9386:2012. For this study, the authors perform only one horizontal earthquake load component (the major component) acting independently in Ox-direction of the building. Consequently, the load combination is determined COM1 (0.9DL + 0.8LL + EQx + 0.3EQv).

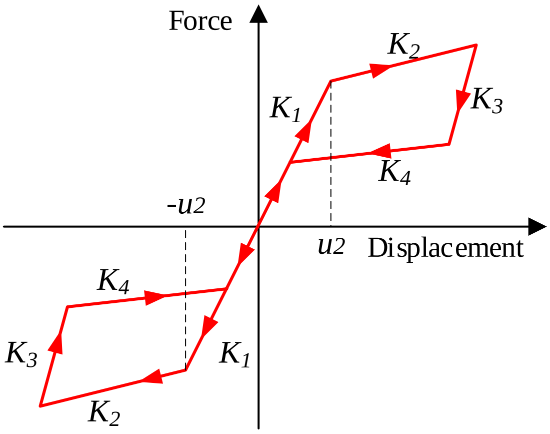

Fig. 2. Flag-shaped hysteretic behavior model representing the SMA bracing element.

5. Case study

5.1. Analytical model

In this study, the steel frame building structure is analyzed based on the model illustrated in Figs. 3, 4. The building features a square floor plan with four spans on each side, with the length of 9 m. The building consists of five stories, with each story having a height of 3.9 m. The dimensions of the structural elements are shown in Tab. 2.

The connection between the column bottom and the foundation is assumed to be bolted that is usually modeled as a semi-rigid link. However, in the framework of this analysis, the authors focus on capturing the nonlinear behavior of bracing elements. Therefore, it is assumed that the connection between the column and the foundation can be simplified as a pinned connection.

Tab. 2. Dimensions of the building structure

Structural name	**Material**	**Cross-section**			
		B	**H**	**Flange plate thickness**	**Web plate thickness**
Column (H)	S355	450	600	15	10
Primary Beam (H)	S355	300	750	15	8
Secondary Beam (H)	S355	200	500	15	8

In this study, the authors conducted analyses of two different types of bracing systems to evaluate the superiority of superelastic bracing systems utilizing SMA.

For the conventional bracing system, Buckling Restrained Braces (BRB) using S325 steel, the response exhibits a bilinear behavior, as illustrated in Fig. 1. Based on material properties and cross-sectional dimensions, the elastic stiffness K_1 was preliminarily calculated to be 110 kN/mm, the post-yield stiffness $K_2 = 1.1$ kN/mm ($K_2/K_1 = 0.01$), and the yield strength $F_y = 110$ kN.

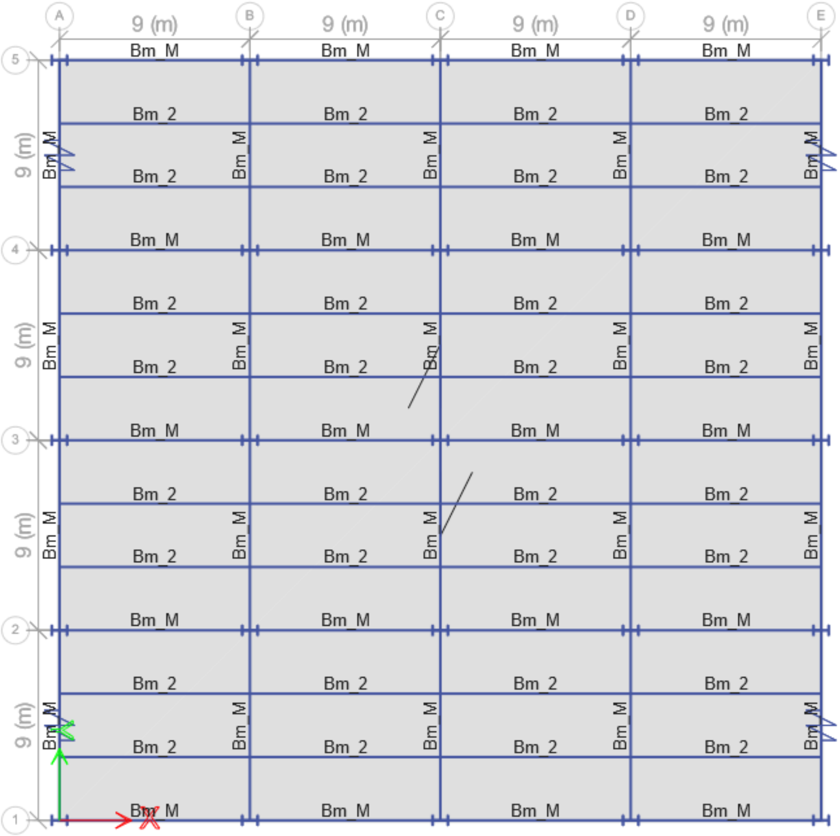

Fig. 3. Building floor plan.

For the superelastic bracing system, the authors referenced experimental results on Nickel-Titanium alloys. The behavior model of the bracing elements used in the analysis is shown in Fig. 5. To ensure a meaningful comparison of the performance of the two bracing systems using the same reference scale, the superelastic bracing system was calculated to match the yield strength of the conventional system ($F_y = 110$ kN). In practice, the stiffness and elastic limit of the hyperelastic braces can be easily adjusted by modifying its cross-sectional properties. This flexibility allows the analysis objective to be achieved without altering the fundamental nature of the research problem.

The behavior models in Fig. 5 were implemented as nonlinear spring elements (multi-plastic) in the ETABS software.

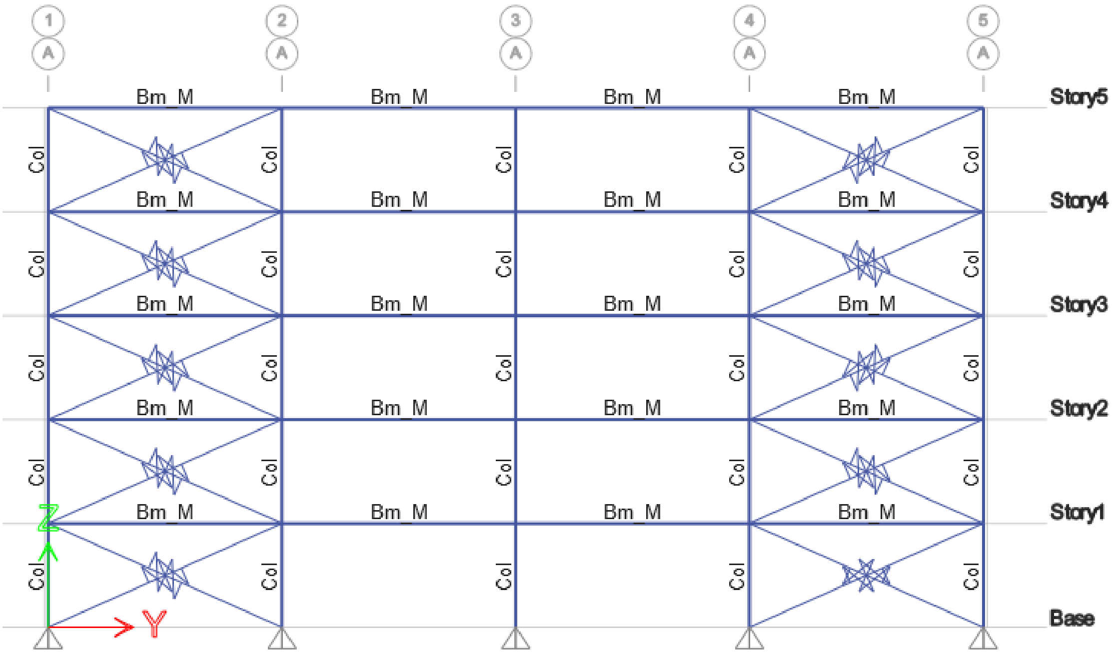

Fig. 4. Building elevation.

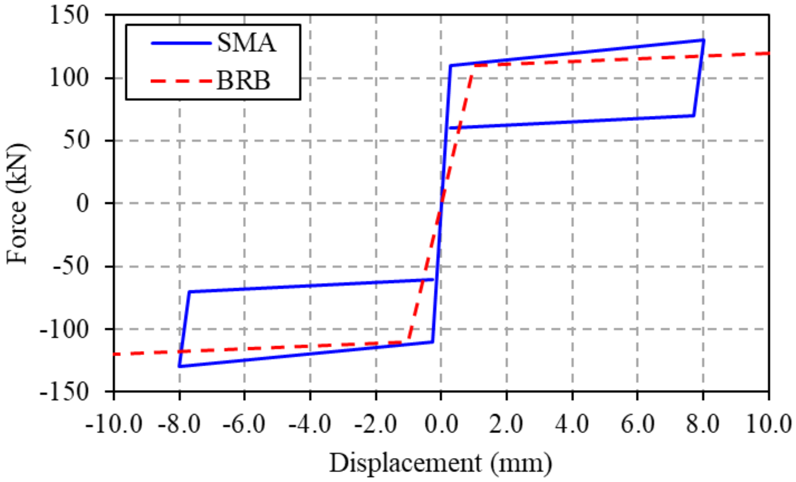

Fig. 5. Behavior models of conventional braces (BRB) and superelastic braces (SMA).

The applied load on the structure is seismic load, with the reference ground acceleration selected for Son La, Vietnam. To conduct time-history analyses, the authors employed available tools and data within the ETABS software to scale and calibrate acceleration records to match the target response spectrum.

5.2. Results and discussions

5.2.1. Results

The internal force results (bending moments in columns and beams), displacements (at the top of the structure), and the nonlinear behavior of the bracing elements were selected for investigation.

Comparison of bending moment in column structure between model using conventional brace and super elastic brace is shown in Figs. 6, 7, respectively.

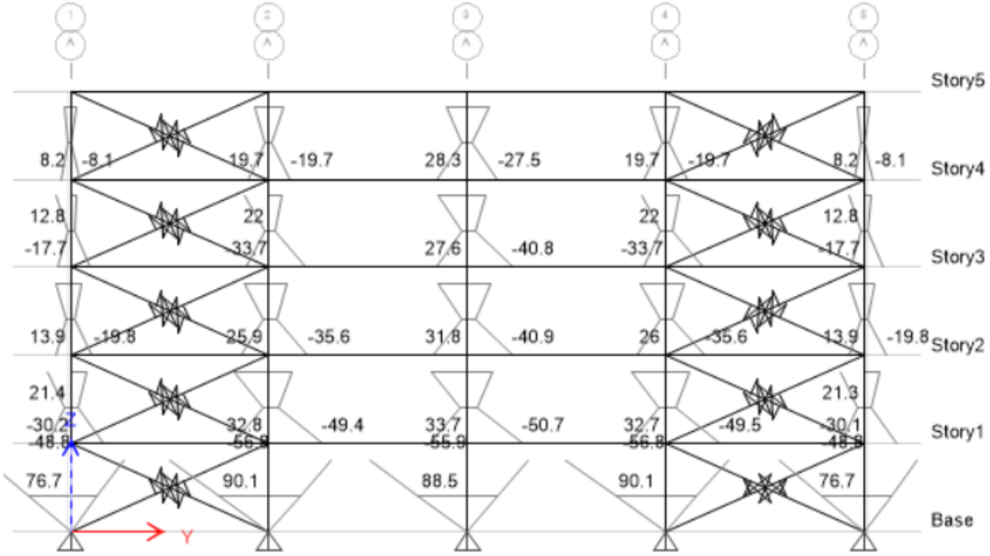

Fig. 6. Bending moments in columns with conventional bracing systems (kNm).

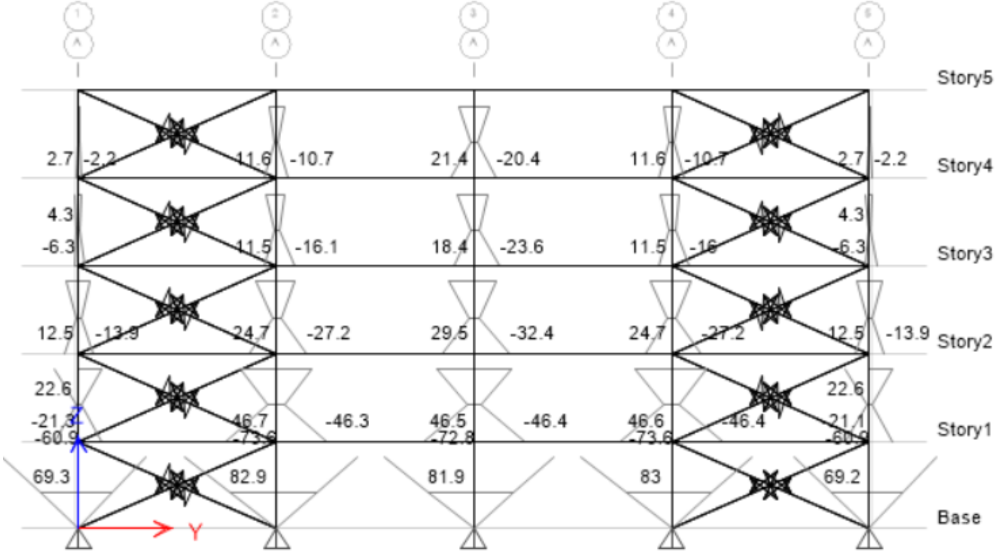

Fig. 7. Bending moments in columns with superelastic bracing systems (kNm).

As shown in the figures, the bending moment in the column of the structure using SMA braces is smaller than that of the structure with BRB braces. This can be explained by the internal force distribution based on stiffness. Specifically, the stiffness of SMA braces, both in the elastic and post-elastic stages, is higher than that of BRB braces (Fig. 5). Consequently, for the same structural configuration and loading conditions, a larger portion of the internal force is carried by the SMA braces compared to the BRB braces, reducing the bending moment in the column structures.

A similar trend is observed for the bending moment in beams, as shown in Fig. 8 (BRB system) and Fig. 9 (SMA braces).

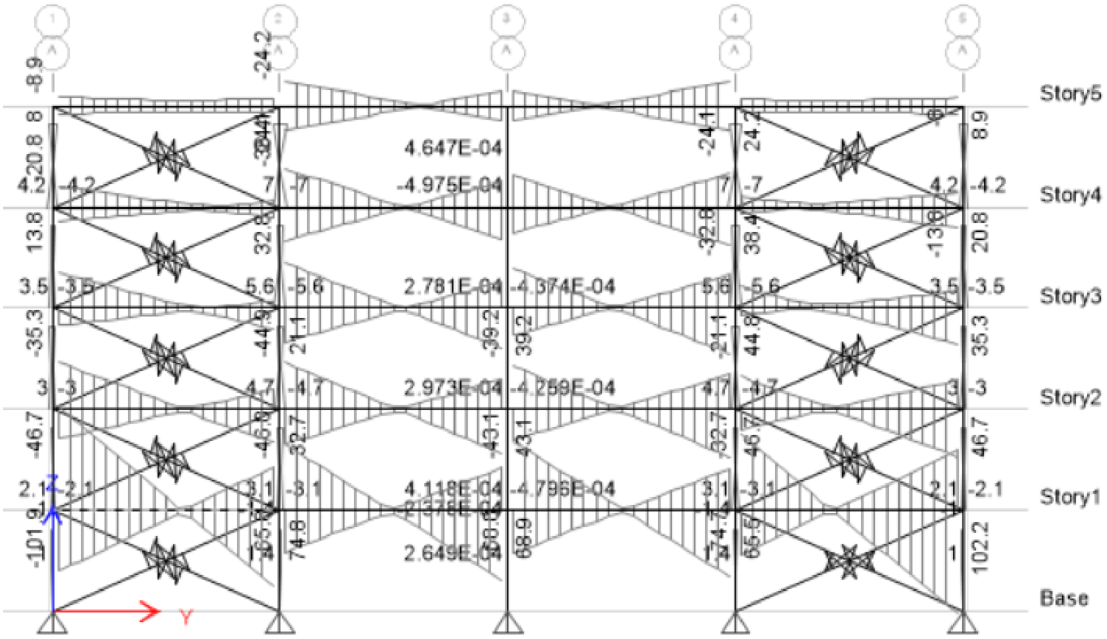

Fig. 8. Bending moments in beams with conventional bracing systems (kNm).

The time-history displacement at the top of the building is illustrated in Figs. 10a, 10c for BRB braces and SMA braces, respectively. The nonlinear responses of typical bracing element are plotted in Figs. 10b, 10d for BRB braces and SMA braces. As observed in the figure, the seismic response of braced elements exhibits nonlinear behavior, characterized by bilinear hysteresis loops in BRB braces and flag-shaped hysteresis in SMA braces. The results indicate that modeling braced elements using defined spring elements is appropriate and effectively meets the analysis objectives.

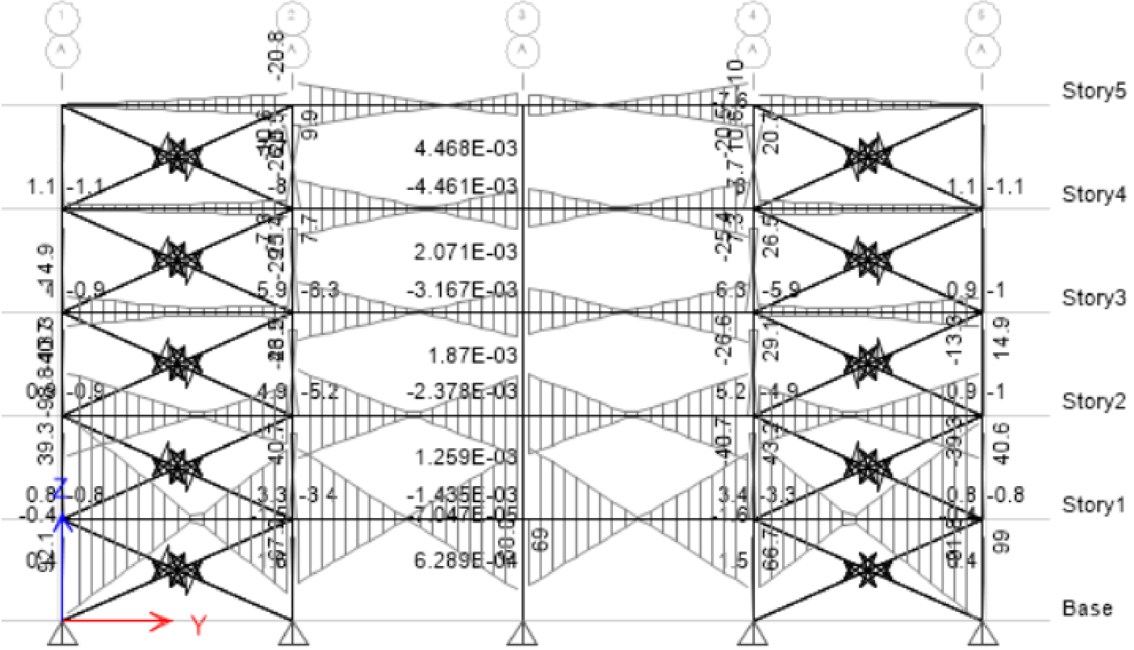

Fig. 9. Bending moments in beams with superelastic bracing systems (kNm).

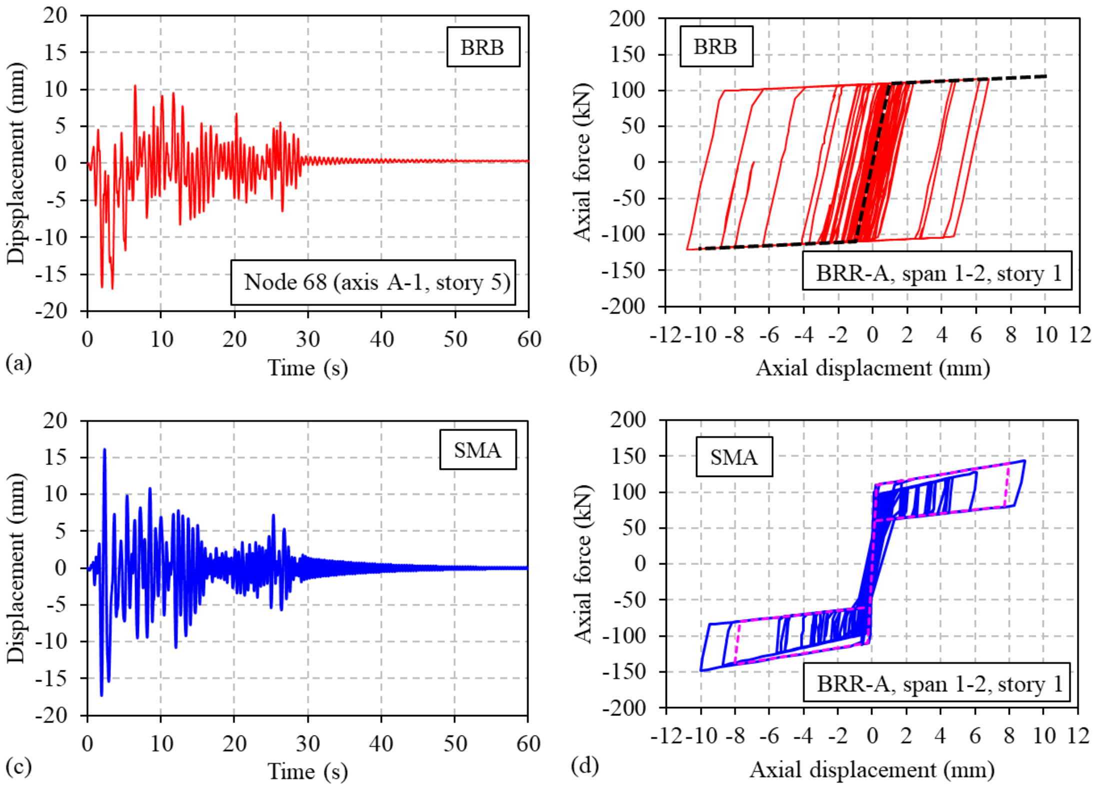

Fig. 10. Time-history response of bracing element.

On the other hand, as observed in Fig. 10, the BRB brace, characterized by a bilinear behavior model, exhibits significantly larger residual deformation compared to the SMA brace. As a result, structures incorporating BRB braces experience notable residual displacements, preventing them from fully returning to their original configuration after seismic events.

A detailed comparison of residual displacement values at the top of the first-floor column for both bracing systems is presented in Fig. 11. The structure utilizing BRB braces retain a considerable residual displacement of approximately 1 mm (over the peak displacement of 122 mm), whereas the structure with SMA braces demonstrates an almost negligible residual displacement. From a design perspective, these residual deformations compromise the structural integrity, necessitating repairs or even replacement following a strong earthquake to restore the structure's original performance state.

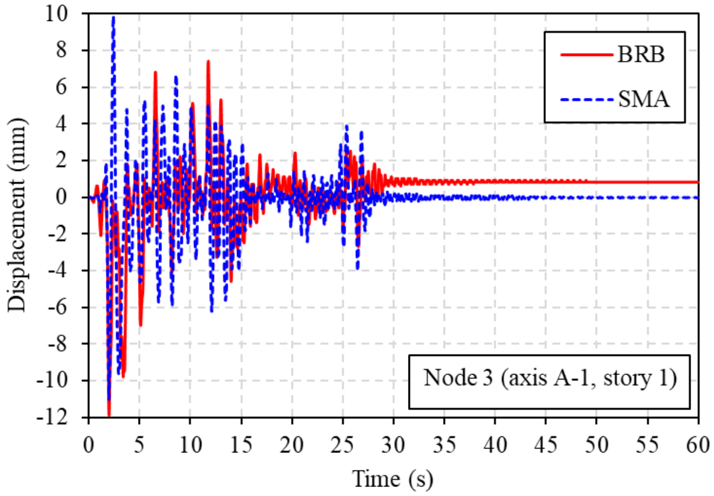

Fig. 11. Residual displacement of typical node of structure.

5.2.2. Discussions

Table 3 presents a detailed comparison of the typical cases analyzed. The analysis results show that, for the same elastic limit, the superelastic bracing system exhibits superior performance compared to conventional bracing systems. Specifically, it achieves an approximately 20% reduction in bending moments within the columns, which in turn decreases bending moments in the beams. This leads to an overall improvement in structural stability, as evidenced by a noticeable reduction in the displacement at the top of building.

Tab. 3. Comparison of the seismic response between BRB braces model and SMA braces model

Comparison criteria		**Conventional bracing systems**	**Superelastic bracing systems**
Beam axis A, Span 1-2, 1st floor	M_{max} (kNm)	74.8	92.1
	M_{min} (kNm)	**-101.9**	-98.8
Column at 1st floor, Axis A-1	M_{max} (kNm)	**76.7**	62.6
	M_{min} (kNm)	-48.8	-36.9
Top displacement	(mm)	**17.3**	17.0
Displacement at 60s	(mm)	**0.3**	0.0016

Moreover, the integration of superelastic bracing systems significantly enhances the structural resilience by effectively eliminating residual displacements. Unlike conventional bracing systems that exhibit residual deformations due to the nonlinear response of the structure, superelastic braces with their unique properties allow the structure to be restored to its initial state. This restoring behavior not only minimizes post-earthquake repair costs but also ensures the immediate functionality of the building, making it a highly promising solution for seismic-resistant design.

6. Conclusion

In this study, the investigation of the effectiveness of superelastic bracing systems based on Shape Memory Alloys (SMA) in steel frame structures subjected to earthquake loading was conducted. The results obtained demonstrate that these advanced bracing systems may offer significant advantages over the conventional systems, including high elastic stiffness and exceptional restoring capabilities. These properties may contribute to a notable reduction in bending moments within columns and effectively eliminate residual displacements, enhancing overall structural stability and resilience under seismic impacts.

The results of this research may provide a fundamental knowledge on the behavior of SMA bracing and promised foundation for further in-depth studies and experimental validations, paving the way for the wider application of these systems in seismic-resistant design. By improving structural performance and post-earthquake recoverability, this study highlights the potential of SMA-based bracing as one of innovative and effective solutions for the design and construction of buildings in earthquake regions.

Acknowledgement

This research is funded by the Research Fund of the General Department of Logistics - Engineering, Vietnam Ministry of National Defense under the grant number “ĐTNCN.01/2025/TCHC-KT-HVKTQS”.

This paper is a significantly revised and expanded version of the conference paper presented at “The 20th Annual Scientific Conference of Young Researchers – 2025”, held at Le Quy Don Technical University in April 2025.

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HIỆU NĂNG CHỐNG ĐỘNG ĐẤT CỦA HỆ THANH GIẰNG SIÊU ĐÀN HỒI ÁP DỤNG CHO KẾT CẤU NHÀ KHUNG THÉP

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Tóm tắt: Hệ thống thanh giằng thường được sử dụng để tăng cường khả năng phục hồi của kết cấu khung thép chịu tác động của tải trọng động. Các thanh giằng thép thông thường tiêu tán năng lượng thông qua ứng xử phi tuyến với mô hình dạng vòng trễ song tuyến tính, giúp duy trì tính toàn vẹn của kết cấu nhưng có thể dẫn đến các dịch chuyển dư đáng kể sau các sự kiện động đất mạnh. Hợp kim ghi nhớ hình dạng (SMA), đặc biệt là những hợp kim thể hiện hành vi siêu đàn hồi, đã thu hút sự quan tâm do tiềm năng phân tán năng lượng và khả năng tự hồi phục của chúng. Nghiên cứu này khám phá việc sử dụng các hệ kết cấu thanh giằng siêu đàn hồi bằng hợp kim SMA áp dụng cho các kết cấu khung thép chịu động đất. Các phân tích phi tuyến theo lịch sử thời gian được thực hiện bằng phần mềm ETABS để so sánh và đánh giá hiệu quả của thanh giằng siêu đàn hồi so với thanh giằng thông thường. Kết quả cho thấy, thanh giằng siêu đàn hồi SMA mang lại hiệu quả cao trong việc giảm đáng kể mô men uốn trong cột và chuyển vị dư, mang lại giải pháp đầy hứa hẹn trong thiết kế công trình chịu động đất.

Từ khóa: *Hệ thanh giằng; thanh giằng siêu đàn hồi; hợp kim ghi nhớ hình dạng; phân tích phi tuyến theo lịch sử thời gian; phân tích công trình chịu động đất.*

Received: 15/03/2025; Revised: 27/05/2025; Accepted for publication: 25/06/2025

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