NUMERICAL ANALYSIS OF THE EFFECTS OF DIFFERENT BEHAVIOR MODELS OF ISOLATORS ON THE SEISMIC RESPONSES OF MULTI-STORY BUILDINGS

Hai Dang Tran[1], Xuan Dai Nguyen[1,*], Van Tu Nguyen[1], Hoang Nguyen[1]

[1]*Institute of Techniques for Special Engineering, Le Quy Don Technical University*

Abstract

Seismic base isolation (SBI) is widely recognized as a highly effective solution for earthquake-resistant design, extensively implemented in high-seismicity regions, and increasingly adopted in areas with moderate seismic activity. While structural analysis software provides various behavior models to simulate SBI elements, the suitability of these models for specific analytical applications remains unclear. This study conducts a numerical analysis to assess the impact of different isolator behavior models - including equivalent linear, plastic Wen, bilinear, and rubber isolators - on the seismic response of isolated buildings. Nonlinear time-history analyses are performed on a typical seismically isolated building using the 1994 Northridge earthquake record, scaled to match the target spectrum. The seismic isolators are modeled using link elements with constitutive parameters corresponding to the selected models. Key response parameters, such as isolator behavior, lateral displacements, and base shear forces, are analyzed to compare the structural performance across different isolator models. The results indicate that nonlinear models (plastic Wen, bilinear, and rubber) yield comparable and realistic seismic responses, whereas the linear model significantly overestimates displacements and forces. These findings highlight the limitations of linear assumptions in seismic analysis and underscore the necessity of employing nonlinear models for a more accurate evaluation of structural behavior during earthquakes.

Keywords: *Seismic base isolation; hysteresis behavior; nonlinear time-history analysis; seismic isolation of multi-story buildings*.

1. Introduction

Tectonic plate movement and collision are the main causes of earthquakes, which are seismic events brought on by the abrupt release of stored energy within the Earth's crust. This energy release occurs when stress exceeds the strength of geological faults, generating seismic waves that propagate through the Earth's surface [1]. While tectonic activity is the predominant cause, other sources, such as nuclear explosions, can also induce seismic events. The consequences of earthquakes are far-reaching, affecting human populations, infrastructure, and economies, particularly in near-field regions

* Corresponding author, email: xuandai.nguyen@lqdtu.edu.vn
DOI: 10.56651/lqdtu.jst.v8.n2.954.sce

where ground motion is most intense. Historically, earthquakes have been among the most devastating natural disasters, resulting in extensive loss of life and infrastructure damage. The economic impact extends beyond immediate destruction, encompassing the costs of emergency response, containment, reconstruction, and long-term recovery efforts, which often face logistical challenges in severely affected areas.

Multi-story buildings, due to their considerable height and concentrated structural loads, are particularly vulnerable to the horizontal forces generated by seismic activity. The dynamic effects of earthquakes on these structures include intense vibrations, excessive stress accumulation, significant deformation, foundation displacement, structural damage, and, in extreme cases, progressive collapse. Ensuring the seismic resilience of multi-story buildings is critical to mitigating these risks and enhancing structural performance under earthquake loading.

To mitigate the effects of earthquakes, advanced seismic protection technologies have become integral to modern construction design. These methods aim to modify key structural parameters in the dynamic equation of motion, either by reducing seismic demands or enhancing structural resilience. Among these approaches, SBI has emerged as one of the most effective solutions for protecting multi-story buildings by decoupling the superstructure from ground motion [2]-[4]. The key advantages of this technique include:

Isolation mechanism: The core principle of SBI involves isolating the building from ground-induced vibrations, allowing it to move independently during seismic events. This significantly reduces the direct transmission of seismic forces to the structure.

Energy dissipation: Many seismic isolators incorporate high energy dissipation capabilities, effectively reducing vibration energy and limiting both internal forces and lateral displacements within the structure.

Restoring capacity: Earthquakes often induce large displacements that can lead to inelastic deformations in structural components. In addition to isolation and energy dissipation, seismic isolators offer great restoring properties, enabling the structure to return to its original position and functional state after an earthquake.

By integrating these features, SBI enhances the seismic resilience of buildings, minimizing structural damage and improving post-earthquake recoverability [4]-[7].

Before the 1980s, SBI was met with skepticism within the engineering community, with many considering it an impractical solution. However, over time, extensive research and successful applications have led to its widespread acceptance, as reflected in the growing number of journal articles, technical reports, workshops, and conferences on the subject [3], [8]. Currently, SBI remains an active field of study, with ongoing advancements in both new isolation systems and the enhancement of existing technologies, particularly elastomeric-based bearings. SBI has become a standard approach in bridge engineering, playing an essential role in protecting structures from seismic forces. It is now a key component of earthquake-resistant design, not only for new construction but also for the retrofitting of existing infrastructure. This technique has proven to be one of the most effective solutions for mitigating seismic effects, demonstrating its value not only in high-seismic regions but also in areas with moderate seismic activity [8]-[11].

Although SBI is widely recognized as an effective method for protecting structures against earthquake damage, the response of base isolators is inherently nonlinear. Their behavior deviates from a simple proportional force-displacement relationship, particularly under large seismic forces. Various modeling approaches have been developed to characterize the behavior of seismic isolation bearings, each with distinct advantages and limitations.

Generally, the bilinear model remains the most widely used approach for representing the nonlinear behavior of seismic isolators under earthquake loading [4], [11]-[16]. Despite its simplicity, it effectively captures the essential nonlinear characteristics of most conventional isolation devices [13]. Another widely recognized and extensively used hysteresis model is the Bouc-Wen model, renowned for its ability to simulate smooth hysteretic behavior with rounded transition curves. In this model, the shift from linear-elastic to inelastic response is governed by a set of parameters, allowing for a gradual and more realistic representation of the nonlinear transition. In addition, the equivalent linear model is often employed in simplified analyses to provide an approximate prediction of structural response under seismic loading [4], [8], [13].

Despite the widespread application of various hysteresis models for simulating the nonlinear behavior of seismic isolators, comprehensive reviews and systematic comparative studies remain limited. Most existing research concentrates on individual models under specific loading conditions or structural configurations, often without offering a rigorous evaluation of their relative advantages, limitations, and suitability across a broader spectrum of scenarios. Common nonlinear response models – such as bilinear, Bouc-Wen, and rubber isolator models (e.g., those implemented in ETABS) – generally offer similar geometric representations. However, the influence of the curvature in the transition zone between linear and nonlinear behavior on the seismic response of structures has not been adequately examined. This gap in the literature underscores the need for a more comprehensive assessment of the accuracy, robustness, and practical applicability of these models, particularly within the framework of performance-based seismic design. Such investigation is especially critical for complex or safety-critical infrastructure, where predictive reliability and model relevance are essential.

2. Objective and methodology

The primary objective of this study is to investigate various seismic behavior models and evaluate their effects on the seismic responses of isolated building structures.

To achieve this goal, the study adopts the following methodology:

- Conducting a comprehensive review of typical seismic behavior models of isolators.

- Performing numerical analyses on a typical multi-story building model equipped with seismic isolators, considering different behavior models. The analysis focuses on key response parameters, including top-story displacement, base shear force, and the nonlinear behavior of the isolation system.

The findings will provide critical insights into the reliability of equivalent linear analysis methods compared to nonlinear approaches, offering valuable recommendations for engineers in the seismic design and analysis of isolated building structures.

3. Overview the behavior of seismic isolator

Currently, various behavior models are used to represent the nonlinear response of seismic isolators, each with distinct characteristics suited to different isolator types and accuracy requirements in the analyses. In the framework of this study, the authors focus on two primary groups of models: equivalent linear models and simple nonlinear models, include rubber isolator mode, bilinear model, and plastic Wen model that integrated in structural analysis software (i.e., ETABS [17]).

3.1. Equivalent effective linear model

The linear viscoelastic model represents the behavior of viscous bearing by combining an elastic spring and a viscous damper in parallel configuration, to simplify the simulation of nonlinear behavior of isolator, as shown in Fig. 1. As a result, this model is able to use for equivalent linear analysis such as simplified analysis method, spectral analysis method, etc. According to Fig. 1, this model is characterized by two key parameters: the effective stiffness (K_{eff}) of the spring and the equivalent viscous damping ratio (β_{eff}) of the damper, both evaluated at the design displacement (D_{max}).

Typically, these effective parameters are determined based on expected peak displacement responses (D_{max}), with the constitutive parameters (F_{max}) of the bilinear model derived accordingly (1):

$$K_{eff} = \frac{F_{\max}}{D_{\max}} \tag{1}$$

The energy dissipated in each cycle, represented by the area enclosed within the elliptical hysteresis loop (as shown in Fig. 1), is influenced by the maximum displacement. Since the initial expected displacement is not known in advance, it must be determined in accordance with the design spectrum and damping ratio defined by the standards. Consequently, an iterative procedure is commonly employed to estimate the performance parameters and seismic demands of isolated structures [8], [10], [13], [18].

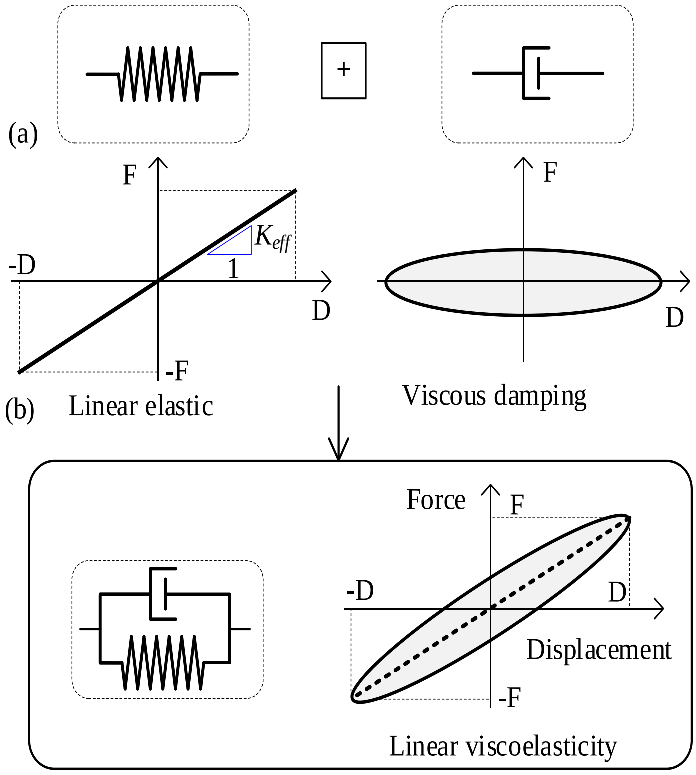

Fig. 1. Linear viscoelastic model: (a) diagrams; (b) component behavior.

3.2. Rubber isolator model

The rubber isolator model, available in ETABS software [17], is used to simulate nonlinear link elements representing rubber-based seismic isolators. This model captures the essential hysteretic behavior of rubber bearings, providing a practical approximation for structural analysis. As shown in Fig. 2, its hysteresis loop resembles that of a bilinear model; however, the transition between the elastic and plastic regions is smoother, reflecting the gradual stiffness degradation observed in real rubber isolators. Unlike simple bilinear models, where the transition is abrupt, this model ensures a more continuous representation of the force-deformation relationship. Additionally, ETABS automatically adjusts the transition curvature based on predefined parameters, limiting direct user control over this aspect. This feature simplifies implementation but may require calibration against experimental data to ensure accuracy in specific applications.

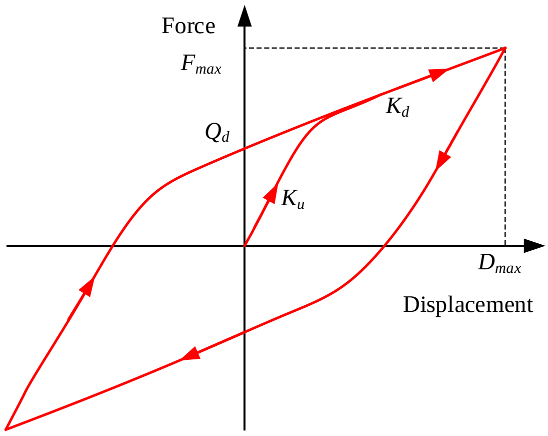

Fig. 2. Rubber isolator hysteresis model.

3.3. Bilinear model

The bilinear force-displacement model is considered an idealized, general theoretical representation of the behavior of typical SBIs. This model is defined by key parameters such as initial stiffness, post-yield stiffness, yield strength, and maximum displacement, is illustrated in Fig. 3. Due to its simplicity and computational efficiency, the bilinear model is widely used in nonlinear time-history analyses of isolated structures, where the deformation levels can vary significantly. By approximating the hysteretic response of SBIs with two distinct stiffness stages – an initial elastic phase followed by a post-yield phase – this model effectively captures the energy dissipation and flexibility provided by SBI systems. Despite its idealized nature, it offers a reasonable balance between accuracy and computational feasibility, making it a fundamental tool for seismic performance evaluation of isolators [2], [4], [8], [12], [19], [20].

The constitutive parameters of this model include: the characteristic strength (Q_d), the initial elastic stiffness (K_u), the post-elastic stiffness (K_d), the elastic limit (F_y), and the force maximum (F_{max}):

$$F_y = \frac{Q_d K_u}{K_u - K_d};\ F_{\max} = Q_d + K_d D_{\max} \tag{2}$$

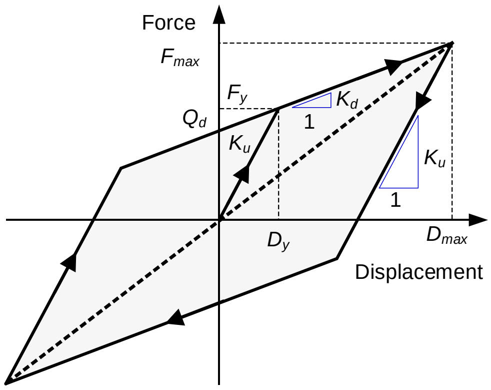

Fig. 3. Bilinear hysteresis model.

For this model, the initial elastic stiffness (K_u) is typically very high, as the yield displacement (D_y) is generally small, ranging from zero to just a few millimeters. While this high initial stiffness plays a minor role in the system's overall seismic response, its primary function is to provide rigidity under non-seismic loads, ensuring stability during service conditions. The initial characteristic strength (Q_d), and the post-elastic stiffness (K_d) are the most important system characteristics affecting its efficiencies as well as the performance of structures under large earthquakes. These parameters govern the energy dissipation capacity and flexibility of the system, directly affecting the seismic performance of the structure by controlling base shear, displacement demand, and overall stability [2], [4], [8].

3.4. Plastic Wen model

The Wen plastic model is widely used to simulate the nonlinear hysteretic behavior of materials and structural components. This model effectively captures the gradual transition between elastic and plastic deformation, making it suitable for representing the energy dissipation characteristics of seismic isolators, dampers, and other hysteretic systems. By adjusting key parameters, such as stiffness degradation and energy dissipation capacity, the Wen model provides a flexible and accurate representation of nonlinear response under cyclic loading conditions. The nonlinear force-displacement relationship is expressed by the following Eq. (3):

$$f = \alpha kd + (1-\alpha) f_y z \tag{3}$$

where k is the elastic constant, f_y is the yield force, α is the ratio of post-yielding stiffness and elastic stiffness, and z is an internal hysteretic variable. This variable has a range between $|z| \leq 1$, with the yielding surface represented by $|z| = 1$. The curvature of the transition position is defined by the factor "*r*", which is usually taken to between 2 and 20, as illustrated in Fig. 4.

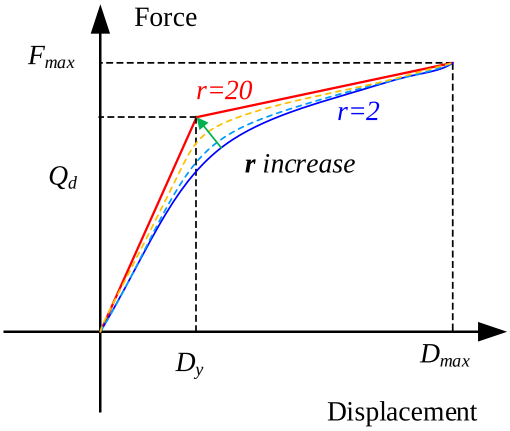

Fig. 4. Plastic Wen model.

Accordingly, the Wen plastic model shares similarities with the rubber isolator model in representing nonlinear hysteretic behavior. However, a key distinction lies in its simpler formulation, which allows for more straightforward control of the transition curvature between the elastic and plastic phases. This makes the Wen model particularly useful in simulations where ease of parameter adjustment is essential for accurately capturing the system's energy dissipation characteristics.

4. Case study

To evaluate the nonlinear seismic response, a series of numerical simulations are performed on a typical base-isolated building. The selected multi-storey building structure is designed to reflect typical residential buildings in urban areas that are highly susceptible to earthquake impacts. The analysis focuses on capturing the fundamental vibration mode of the structure, which serves as a key indicator of the effectiveness of the SBI system in reducing seismic forces and enhancing structural resilience.

4.1. Analytical model

The analyzed structure is a 15-story reinforced concrete building with a basement. The floor height is 3.9 meters for the upper stories and 3.6 meters for the basement. The floor plan consists of three bays in both the X and Y directions, analyzed using ETABS software, as illustrated in Fig. 5. The properties of structures, materials, and load distribution on the floor are presented in Tab. 1.

Tab. 1. Parameters of the selected building structure

Parameters		**Information**
Structural components	Beam systems	Main beams: 35 cm × 75 cm (width × depth)
		Sub-beams: 30 cm × 60 cm
		Foundation beams: 80 cm × 100 cm
	Columns	1st to 6th story: 100 cm × 100 cm
		7th to 11th story: 90 cm × 90 cm
		12th story to roof: 80 cm × 80 cm
	Other structural elements	Concrete wall thickness: 35 cm
		Floor slab thickness: 15 cm
		Basement floor slab thickness: 20 cm
Material properties		Concrete grade: C35/45 (as per EN 1993-1-1)
Loading conditions	Floor loading	Dead load: 100 daN/m²
		Live load: 200 daN/m²
	Roof loading	Dead load: 150 daN/m²
		Live load: 100 daN/m²

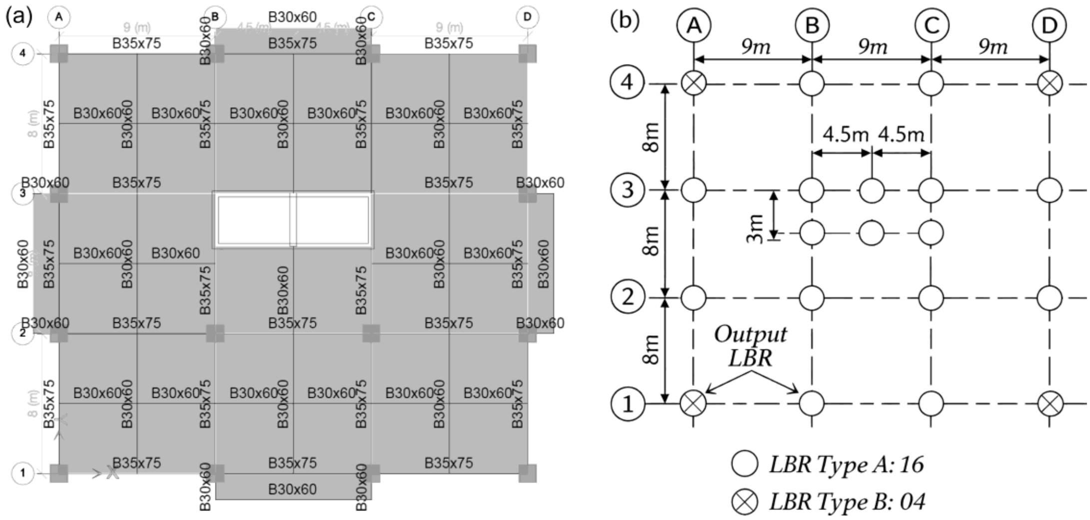

Fig. 5. The specific floor plan model of the building analyzed [21].

The building is designed to be supported on soil class C, situated in an area with a design ground acceleration of a_{gR} = 0.25 g, in accordance with Eurocode 8 [22]. Previous research has shown that for structures with long fundamental periods, such as base-isolated buildings, the seismic response obtained from nonlinear time-history analyses does not differ significantly whether earthquake records are scaled to match the elastic design spectra or the response spectra.

To ensure consistency between different seismic analysis approaches, the selected earthquake records are scaled to match the target spectrum defined by EC8, which considers 5% damping. This standardization allows for a uniform design methodology applicable to both spectral analysis (simplified equivalent linear method) and nonlinear time-history analysis. For this purpose, a set of historical ground motions has been chosen, as outlined in Tab. 2, and the spectra of the scaled records are presented in Fig. 6.

Tab. 2. Earthquake records selected for analyses

#	Earthquake, station	Nation, date	Mw	R (km)	PGA (g)
Acc1	Northridge, Castaic-Old Ridge Rte	US, 17-01-1994	6.7	41	0.568

The properties of isolators, represented by the constitutive parameters of the models, are detailed as follows:

Rubber isolator model:

Parameters	**Type A**	**Type B**
Initial elastic stiffness (kN/m)	65312	34188
Yield strength (kN)	210.000	110.250
Post yield stiffness ratio	0.048	0.048

Bilinear model:

Parameters	**Type A**	**Type B**
Initial elastic stiffness (kN/m)	65312	34188
Post elastic stiffness (kN/m)	3110	1628
Yield strength (kN)	210.000	110.250

Plastic Wen model:

Parameters	**Type A**	**Type B**
Initial elastic stiffness (kN/m)	65312	34188
Yield strength (kN)	210.000	110.250
Post yield stiffness ratio	0.048	0.048
Yield exponent	10	10

Equivalent linear model:

Parameters	**Type A**	**Type B**
Effective stiffness (kN/m)	4586	2400
Effective damping (kNs/m)	233.0295	121.9615

Accordingly, for the nonlinear models (i.e., rubber isolator model, bilinear model, and plastic Wen model), the values of elastic stiffness, post-elastic stiffness, and yield strength remain consistent across all cases.

In contrast, the parameters of the equivalent linear model are derived from the bilinear hysteresis model in conjunction with the elastic response spectrum. These parameters typically the effective stiffness and damping ratio are determined through an iterative procedure designed to achieve convergence with the target design displacement. This iterative approach is implemented through self-developed programs in the Matlab programming language, previously validated and employed in the authors' earlier studies [11]-[13]. In practical applications, this approach enables the equivalent linear model to approximate the dynamic response of seismic isolators with reasonable accuracy under earthquake loading conditions [10].

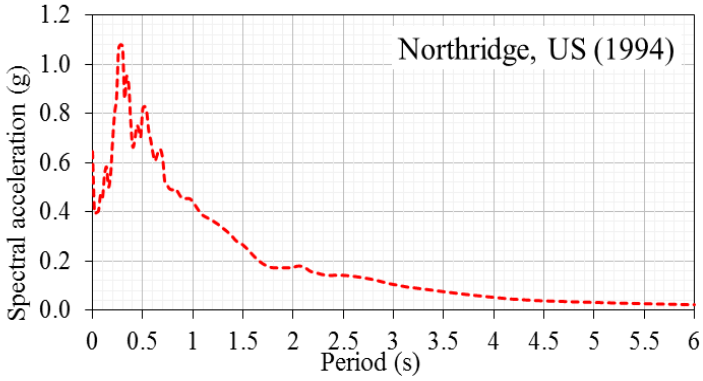

Fig. 6. Ground motion time history and spectral acceleration used for the study.

4.2. Results

As discussed above, the seismic response of seismic isolators, the top displacement, and the base shear force, are selected as key parameters to evaluate the impact of different SBI behavior models on the seismic performance of the building.

Figure 7 presents the hysteresis behavior of various isolator models under seismic loading conditions, including the rubber isolator, bilinear, plastic Wen, and equivalent linear models. Among these, the rubber isolator, bilinear, and plastic Wen models demonstrate similar cyclic responses, characterized by distinct nonlinear features such as stiffness degradation and energy dissipation through yielding. These models effectively capture the complex dynamic behavior of seismic isolators, especially in the post-elastic range, where nonlinearities dominate the response.

In stark contrast, the equivalent linear model – depicted by the magenta dashed line – exhibits a significantly different response profile. Specifically, it predicts substantially higher lateral displacements and corresponding base shear forces compared to the nonlinear models. This discrepancy arises despite the damping ratio in the equivalent linear model being calibrated to match the energy dissipation (i.e., the area enclosed by the hysteresis loops) of the nonlinear systems. The underlying limitation lies in the model's constant effective stiffness, which remains unchanged throughout the loading cycle. As a result, the equivalent linear model is inherently incapable of representing the nonlinear softening behavior observed in actual isolators during large deformations. Consequently, it continues to resist increasing displacement with a proportional rise in force, thereby overestimating the response in terms of both force demand and lateral displacement.

This finding has important implications for seismic design. On the other hand, the equivalent linear approach offers a simplified and computationally efficient means of estimating isolator behavior, and its conservative nature can contribute to enhanced safety margins. For instance, in early design stages or for structures where over-design is acceptable or even desirable – such as critical facilities – this model may serve as a useful tool. However, the results clearly demonstrate that this conservatism may come at the cost of realism and efficiency. By overpredicting displacements and forces, the equivalent linear model could lead to unnecessarily robust structural elements, increased construction costs, and suboptimal utilization of the isolator's energy-dissipating capacity.

Moreover, the inability to capture nonlinear softening may also obscure important dynamic effects, such as period elongation and reduced force transmission, which are essential benefits of base isolation systems. This misrepresentation can impair the designer's ability to assess performance accurately, particularly in performance-based seismic design frameworks where realistic response predictions are critical for achieving target performance levels without overdesign.

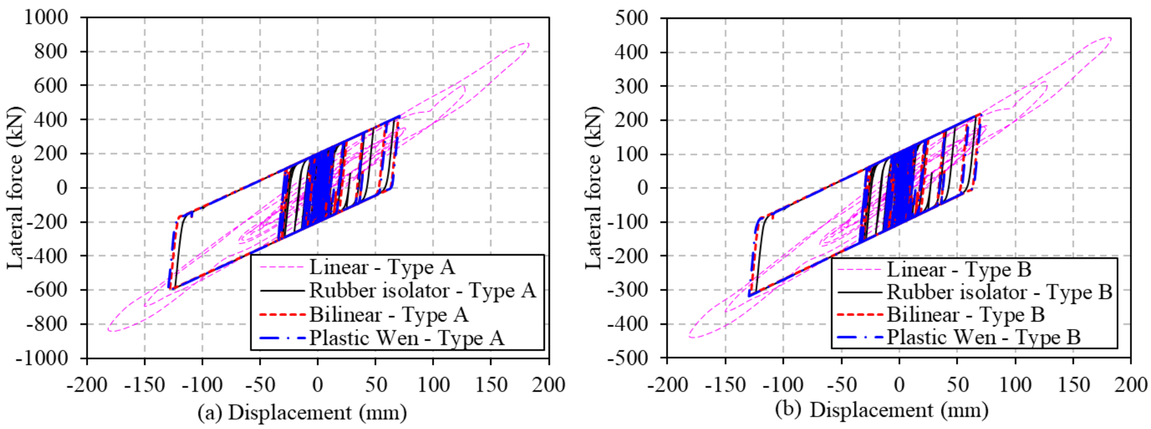

Fig. 7. Hysteresis behavior of different models of isolators.

Similarly, Fig. 8 presents the time-history responses of the structure in terms of top displacement and base shear force under seismic excitation. These results further reinforce the limitations of the equivalent linear model when compared to more advanced nonlinear modeling approaches. While the nonlinear models – such as the bilinear, rubber isolator, and plastic Wen – demonstrate more realistic behavior through moderated displacement demands and force responses, the equivalent linear model consistently overestimates both top displacement and base shear throughout the simulation period. These discrepancies have important design implications. In the context of performance-based seismic engineering, where accurate prediction of structural response is critical to meeting defined performance objectives, the use of an equivalent linear model could lead to design inefficiencies. For instance, the conservative nature of the model may result in oversized structural components, increased base shear demands, or excessive allowances for lateral displacements that are not truly representative of actual system behavior. This, in turn, can lead to cost inefficiencies and a misallocation of resources without corresponding improvements in safety or performance.

Therefore, while the equivalent linear approach may still be useful during preliminary design stages due to its simplicity and ease of implementation, its limitations must be carefully considered. For detailed dynamic analysis, particularly of structures employing seismic isolation systems, the use of nonlinear models is strongly recommended to ensure both accuracy in response prediction and reliability in design decisions. The findings underscore the necessity of incorporating nonlinear hysteretic behavior into structural models to capture the full spectrum of seismic response mechanisms, particularly in systems where isolator performance is a key component of the seismic protection strategy.

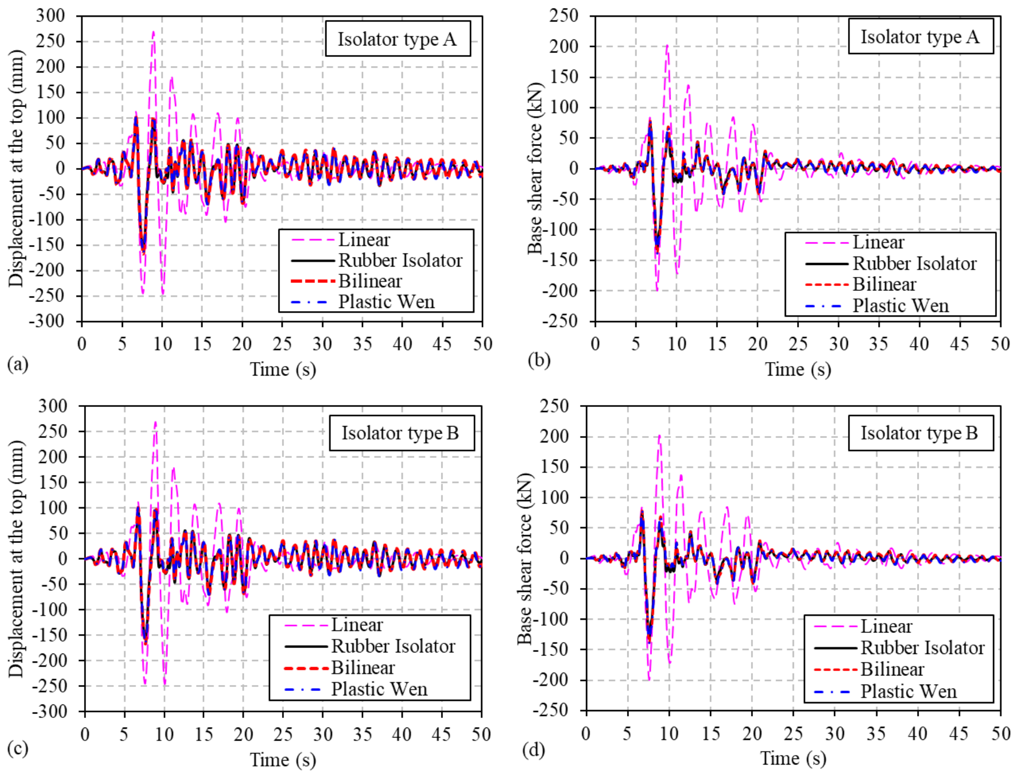

Fig. 8. Time-history responses of building: (a, c) top displacement, (b, d) base shear force.

The differences in obtained results are detailed in Tab. 3 and Fig. 9.

Tab. 3. Comparison of the seismic responses with different models of isolators

Model	**Displacement at the top (mm)**		**Base shear force (kN)**	
	max	**min**	**max**	**min**
Linear	269.6	-245.8	202.2	-199.8
Plastic Wen	103.3	-167.4	78.9	-138.6
Bilinear	102.2	-167.2	78.5	-138.1
Rubber isolator	97.5	-156.9	74.1	-132.1

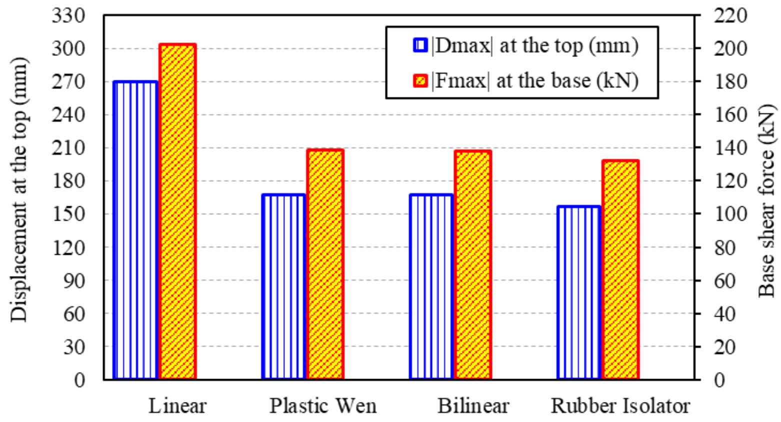

Fig. 9. Comparison of the peak responses of the structure with different models.

Despite the overall similarity in nonlinear hysteretic behavior and structural time-history responses among the three nonlinear isolator models namely, the plastic Wen, bilinear, and rubber isolator models distinct differences are evident in their predicted displacement and base shear demands. Specifically, the plastic Wen model consistently yields the largest top displacement and lateral force responses, followed by the bilinear model. In contrast, the rubber isolator model produces the lowest response values across the same loading conditions.

In the authors’ view, these differences stem primarily from the mathematical formulation and parameterization of the models, particularly with regard to how stiffness degradation, yield strength, and energy dissipation are represented. The curvature of the force-displacement transition zone plays a critical role in governing the isolator's dynamic stiffness and the rate at which energy is dissipated during cyclic loading. Models with sharper transitions or limited energy dissipation mechanisms may underpredict inelastic deformation, whereas those with more gradual softening can lead to conservative, and sometimes excessive, displacement estimates.

From a modeling perspective, these findings highlight the importance of selecting an appropriate hysteresis model that aligns with the physical behavior of the isolation system being simulated. While all three models are capable of representing nonlinear isolation behavior to a certain degree, their predictive accuracy and suitability can vary depending on the specific performance objectives and characteristics of the isolator material. Careful calibration and validation against experimental data or high-fidelity simulations are essential to ensure meaningful and reliable results in seismic design applications.

5. Conclusion

This study investigates the influence of different seismic isolator models on the seismic response of base-isolated buildings through nonlinear time-history analysis. Four modeling approaches (i.e., equivalent linear, plastic Wen, bilinear, and rubber isolator models) are examined to evaluate their impact on structural performance. A detailed 3D model of a 15-story building is analyzed using the 1994 Northridge earthquake record, scaled to match the Eurocode 8 target spectrum. The following preliminary conclusions are drawn from the investigation:

- Plastic Wen, bilinear, and rubber isolator models exhibit similar seismic responses, reinforcing the importance of accurately modeling the nonlinear behavior of seismic isolators.

- The equivalent linear model significantly overestimates displacements and lateral forces compared to nonlinear models, highlighting its limitations in capturing realistic isolator behavior under seismic loading.

- The results emphasize the necessity of nonlinear modeling in the analysis and design of seismic isolators, ensuring more reliable performance predictions and enhanced structural safety.

This study strongly advocates for the adoption of nonlinear models in SBI design, as they provide greater accuracy and better insights into the dynamic behavior of isolated structures. Further research is needed to incorporate axial stiffness effects of isolators and the effects of all three components of earthquake motion. These factors will provide a more comprehensive understanding of isolator behavior and improve the accuracy of structural performance assessments under seismic loading.

Acknowledgement

This article is a significantly revised and expanded version of the conference paper [23] presented at "The 20th Annual Scientific Conference of Young Researchers – 2025", held at Le Quy Don Technical University in April 2025.

References

[1] S. L. Kramer, *Geotechnical Earthquake Engineering*. Prentice Hall, 1996.

[2] AASHTO, *Guide Specifications for Seismic Isolation Design*. American Association of State Highway and Transportation Officials Washington, D.C., 2014.

[3] G. P. Warn and K. L. Ryan, "A review of seismic isolation for buildings: historical development and research needs", *Buildings*, Vol. 2, pp. 300-325, 2012. DOI: 10.3390/buildings2030300

[4] F. Naeim and J. M. Kelly, *Design of Seismic Isolated Structures: From Theory to Practice*. John Wiley & Sons, the United States of America, 1999.

[5] R. L. Mayes, L. R. Jones, T. E. Kelly, and M. R. Button, "Base isolation concepts for seismic bridge retrofit", *Lifeline Earthquake Engineering: Performance, Design and Construction*, ASCE, pp. 67-81, 1984.

[6] M. C. Constantinou, A. Whittaker, Y. Kalpakidis, D. Fenz, and G. P. Warn, "Performance of seismic isolation hardware under service and seismic loading", Technical Report No. MCEER-07, 12, 2007.

[7] G. P. Warn and K. L. Ryan, "A review of seismic isolation for buildings: historical development and research needs", *Buildings*, Vol. 2, pp. 300-325, 2012. DOI: 10.3390/buildings2030300

[8] I. Buckle, M. Constantiou, M. Dicleli, and H. Ghasemi, *Seismic isolation of highway bridges*, MCEER, University at Buffalo, the State University of New York, 2006.

[9] JSSI, The Japan Society of Seismic Isolation. [Online]. Available: https://www.jssi.or.jp/english/. [Accessed Feb. 18, 2025].

[10] V. T. Nguyen, N. Q. Vu, and X. D. Nguyen, "Application of seismic isolation for multi-story buildings in moderate seismicity areas like Vietnam", *Journal of Physics: Conference Series*, 1706, 012119, 2020. DOI: 10.1088/1742-6596/1706/1/012119

[11] X. D. Nguyen and L. Guizani, "Optimal seismic isolation characteristics for bridges in moderate and high seismicity areas", *Canadian Journal of Civil Engineering*, Vol. 48, pp. 642-655, 2020. DOI: 10.1139/cjce-2020-0058

[12] V. T. Nguyen and X. D. Nguyen, "Effects of ground motion spectral shapes on the design of seismic base isolation for multi-story building according to Eurocode 8", *Innovative Infrastructure Solutions*, Vol. 6, pp. 1-13, 2021. DOI: 10.1007/s41062-021-00507-y

[13] X. D. Nguyen and L. Guizani, "On the application limits and performance of the single-mode spectral analysis for seismic analysis of isolated bridges in Canada", *Canadian Journal of Civil Engineering*, Vol. 49, pp. 1747-1763, 2022. DOI: 10.1139/cjce-2020-0749

[14] V. N. Thuyet, S. Deb, and A. Dutta, "Mitigation of seismic vulnerability of prototype low-rise masonry building using U-FREIs", *Journal of Performance of Constructed Facilities*, Vol. 32, 2018. DOI: 10.1061/(ASCE)CF.1943-5509.0001136

[15] M. Dicleli and M. Karalar, "Optimum characteristic properties of isolators with bilinear force–displacement hysteresis for seismic protection of bridges built on various site soils", *Soil Dynamics and Earthquake Engineering*, Vol. 31, pp. 982-995, 2011. DOI: 10.1016/j.soildyn.2011.03.005

[16] N. R. Manzo and M. F. Vassiliou, "Simplified analysis of bilinear elastic systems exhibiting negative stiffness behavior", *Earthquake Engineering & Structural Dynamics*, Vol. 50, pp. 580-600, 2021 DOI: 10.1002/eqe.3347

[17] ETABS: Integrated Finite Element Analysis and Design of Structures, Computer and Structures Inc., California, 2018.

[18] X. D. Nguyen, V. T. Nguyen, and H. Nguyen, "Evaluation of applicability of seismic base isolation for bridges according to Vietnamese codes", *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*, 2022, pp. 217-225. DOI: 10.1007/978-981-16-7160-9_21

[19] CSA-S6, *CSA-S6-19, Canadian highway bridge design code*, Canadian Standards Association, 2019.

[20] ECS, *Eurocode 8: Design of structures for earthquake resistance. Part 2: Bridges*, European Committee for Standardization Brussels, 2005b.

[21] V. T. Nguyen and X. D. Nguyen, "Seismic responses of multi-story building isolated by lead-rubber bearings considering effects of the vertical stiffness and buckling behaviors", *IOP Conference Series: Materials Science and Engineering*, Vol. 1030, 2021. DOI: 10.1088/1757-899X/1030/1/012080

[22] *Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General rules, seismic actions and rules for buildings*, European Committee for Standardization Brussels, 2005a.

[23] H. D. Tran, X. D. Nguyen, V. T. Nguyen, H. Nguyen, and Q. T. Dinh, " Numerical analysis of the effects of different behavior models of isolators on the seismic responses of multi-story buildings", *Tuyển tập công trình Hội nghị Khoa học các nhà nghiên cứu trẻ lần thứ XX - năm 2025*, 2025.

PHÂN TÍCH SỐ ẢNH HƯỞNG CỦA CÁC MÔ HÌNH ỨNG XỬ KHÁC NHAU CỦA GỐI CÁCH CHẤN ĐẾN PHẢN ỨNG ĐỘNG ĐẤT CỦA NHÀ NHIỀU TẦNG

Trần Hải Đăng[1], Nguyễn Xuân Đại[1], Nguyễn Văn Tú[1], Nguyễn Hoàng[1]

[1]*Viện Kỹ thuật công trình đặc biệt, Trường Đại học Kỹ thuật Lê Quý Đôn*

Tóm tắt: Gối cách chấn được xem là giải pháp hiệu quả trong thiết kế kháng chấn, được ứng dụng rộng rãi ở các khu vực có động đất mạnh và ngày càng được áp dụng ở khu vực động đất trung bình. Mặc dù phần mềm phân tích kết cấu hiện nay cung cấp nhiều mô hình ứng xử khác nhau để mô phỏng sự làm việc của gối cách chấn, nhưng sự phù hợp của các mô hình này trong phân tích vẫn còn chưa rõ ràng. Bài báo tiến hành phân tích số đánh giá ảnh hưởng của các mô hình ứng xử khác nhau của gối cách chấn – bao gồm mô hình tuyến tính, mô hình dẻo Wen, mô hình song tuyến tính và mô hình gối cao su – với phản ứng động đất của kết cấu nhà nhiều tầng. Các phân tích lịch sử thời gian được thực hiện đối với kết cấu nhà cách chấn điển hình bằng cách sử dụng giản đồ gia tốc động đất Northridge năm 1994, được khớp phổ phản ứng. Gối cách chấn được mô hình bằng phần tử lò xo với các tham số cấu thành tương ứng với các mô hình được khảo sát. Các thông số chính của phản ứng kết cấu, gồm ứng xử gối cách chấn, chuyển vị đỉnh và lực cắt đáy của công trình được sử dụng trong phân tích để so sánh phản ứng của kết cấu với các mô hình gối cách chấn khác nhau. Kết quả cho thấy, các mô hình phi tuyến (mô hình dẻo Wen, mô hình song tuyến tính và mô hình gối cao su) cho kết quả tương đồng nhau, trong khi mô hình tuyến tính đưa ra các kết quả quá cao về lực và chuyển vị. Kết quả này làm rõ những hạn chế của việc sử dụng mô hình tuyến tính tương đương và nhấn mạnh sự cần thiết phải sử dụng các mô hình phi tuyến để đánh giá chính xác hơn ứng xử của kết cấu cách chấn chịu tác dụng của động đất.

Từ khóa: *Gối cách chấn đáy; mô hình trễ phi tuyến; phân tích phi tuyến lịch sử thời gian; kết cấu nhà nhiều tầng cách chấn*.

Received: 16/03/2025; Revised: 23/12/2025; Accepted for publication: 26/12/2025

❑