THE SEISMIC EFFICIENCY OF BUCKLING-RESTRAINED BRACED FRAME STRUCTURES

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Abstract

The bracing systems have been considered a reliable solution for the seismic-resistant design of buildings, which has been widely applied in recent years. This article aims to investigate the performance of braced frame structures in the seismic-resistant design. Typical buckling restrained braced frames, represented by an approximate bilinear behaviour, are selected to perform nonlinear time-history analyses. The findings indicate that bracing systems are a potential solution for seismic-resistant design, as they significantly reduce the top displacement and internal force of the structures based on their dissipation capacities through inelastic behaviour. Furthermore, the performance of vertical bracing systems is recommended to calculate according to the distribution of shear forces along the height of structures, ensuring that they are effective solutions that meet the design philosophies.

Keywords: *Seismic-resistant design; braced frame structure; nonlinear behaviour; nonlinear time history analysis.*

1. Introduction

Earthquakes resulted in massive losses and destruction, notably in terms of infrastructure. In regions of high seismic risk, there is the additional challenge of construction structures to resist such extreme natural disasters. The field of structural engineering has evolved quite significantly over the past several decades in its approach to design of earthquake-resistant structures. Although it has been always and will remain the foremost intent of seismic codes to prevent sudden collapse and failure of structures under extreme events, the impetus for the field to come up with solutions that are more optimized and efficient has been markedly realized in recent years.

The performance-based seismic design, which was considered a structural approach, has been defined in many current standards and specifications [1-4]. It is an all-encompassing term used to describe the method in which the design criteria are based on achieving certain performance goals under various levels of seismic hazards. These performance goals may refer to criteria such as the lateral floor displacements,

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peak floor accelerations, or a target damage state of the building as a result of an earthquake [5, 6]. Accordingly, there are two overarching performance objectives in designing efficient earthquake-resisting structures: (i) adequate lateral stiffness to limit large displacements during the elastic response to minor and moderate earthquakes, and (ii) sufficient ductility to withstand large inelastic displacements under extreme earthquakes and prevent sudden collapse. Generally, the performance-based seismic design approach allows certain failure levels of structural components depending on the specified earthquake intensity in the design standard.

Although the performance-based design and its adoption in contemporary practice have proved useful and enabled increased reliability of the expected structural performance of constructions under seismic events, the increasing demand for optimization of the performance of structures in order to minimize the level of damage, economic loss, and repair costs will continue to push engineers to come up with better solutions.

Recently, the use of advanced anti-seismic devices for the seismic-resistant design of constructions has become increasingly popular in earthquake regions. The main difference between this technique and conventional structural methods is the possibility of higher energy dissipation capacities and/or a higher ductility value, replacing the ductility demand within the conventional structures.

Over the previous decade, the development of brace has been an important addition to the structural engineer's seismic design toolkit. A braced frame is considered a strong structural system commonly used in structures subject to lateral loads such as wind and seismic impacts [7-11]. The members in a braced frame are generally made of structural steel, which can work effectively both in tension and compression. These devices represent a major improvement in terms of rehabilitee and ductility over conventional structural systems [12]. The main advantage of these systems is their ductility and stable response under reversed seismic loading [7, 9, 10], that promise to not only capture the benefits provided by this system but also provide for improved system performance and greater design flexibility at a lower cost.

This paper aims to investigate the effects of bracing systems on the seismic response of a simple 2D frame structure. An overview of bracing systems and the design philosophies of braced structures are preliminarily outlined. A parametric study is then conducted on a simplified 2D frame structure, analyzed by SAP2000, in order to evaluate the efficiencies of bracing systems as a seismic-resistant design solution. To do so, the buckling restrained braced frame structures that represent the bracing systems are modelled by nonlinear link elements. The accelerograms of Kobe's earthquake, which are selected and scaled to match the target spectrum of Thanh Xuan, Hanoi, are employed as seismic impacts. The nonlinear time history analysis method is conducted to establish the seismic responses of braced structures. The top displacements, base shear forces, and bending moment at the bottom of columns are preferred to evaluate the effect of braces, which is accomplished through a comparison of obtained results between the conventional structure and braced structures.

2. Buckling-restrained braced frame structures

2.1. Overview of the braced structural systems

Steel bracing systems have been used for decades to brace structures against wind and seismic lateral forces. Over the years, our understanding of steel brace-frame behaviour has progressed. The use of steel bracing systems composed of tubular steel shapes, in X or V (chevron) configurations became increasingly popular after the 1970s [10, 13]. Research and post-earthquake observations demonstrated that conventional braces have very poor inelastic buckling behaviour and poorly defined post-yield tension overstrength that often result in connection failures. Consequently, numerous other code requirements have progressed and begun to focus on the inelastic behaviour of the braces, requiring capacity design of the devices.

(a) (b)

Figure 1. Examples of braced buildings: (a) John Hancock Center, Chicago, US, and (b) University Hall, University of Berkeley, California.

Generally, in the global structure, the beams and columns form the frame systems that carry vertical loads, meanwhile, the bracing system carries mainly the lateral loads. The resistance to horizontal forces is provided by two bracing systems, including vertical bracing and horizontal bracing. A vertical bracing system (main objectives within the scope of this study) is the bracing between column grid lines (in vertical planes) that provides load paths for the transference of horizontal forces to ground level. A horizontal bracing system is the bracing at each floor (in horizontal planes) that provides load paths for the transference of horizontal forces to the planes of vertical bracing.

Normally, the bracing system is geometrically configured in typical forms such as V-bracing, diagonal bracing, X-bracing (cross-bracing), K-bracing, etc., as shown in Figure 2. Trussing, or triangulation, is formed by inserting diagonal structural members into rectangular areas of a structural frame, helping to stabilise the frame [7, 10].

Cross-bracing (or X-bracing) uses two diagonal members crossing each other. These only need to be resistant to tension, one brace at a time acting to resist sideways forces, depending on the direction of loading. As a result, steel cables can also be used for cross-bracing.

K-bracing includes the braces connect to the columns at mid-height. It has more flexibility for the provision of openings in the facade and results in the least bending in floor beams. K-bracing is generally discouraged in seismic regions because of the potential for column failure if the compression brace buckles.

V-bracing includes two diagonal members forming a V-shape that extend downwards from the top two corners of a horizontal member and meet at a centre point on the lower horizontal member (left-hand diagram). Inverted V-bracing (right-hand diagram, also known as chevron bracing) involves the two members meeting at a centre point on the upper horizontal member.

Both systems can significantly reduce the buckling capacity of the compression brace so that it is less than the tension yield capacity of the tension brace. This can mean that when the braces reach their resistance capacity, the load must be resisted in the bending of the horizontal member.

Centric bracing is commonly used in seismic regions. It is similar to V-bracing but bracing members do not meet at a centre point. This means there is a space between them at the top connection. Bracing members connect to separate points on the horizontal beams. This is so the 'link' between the bracing members absorbs energy from seismic activity through plastic deformation. Eccentric single diagonals can also be used to brace a frame.

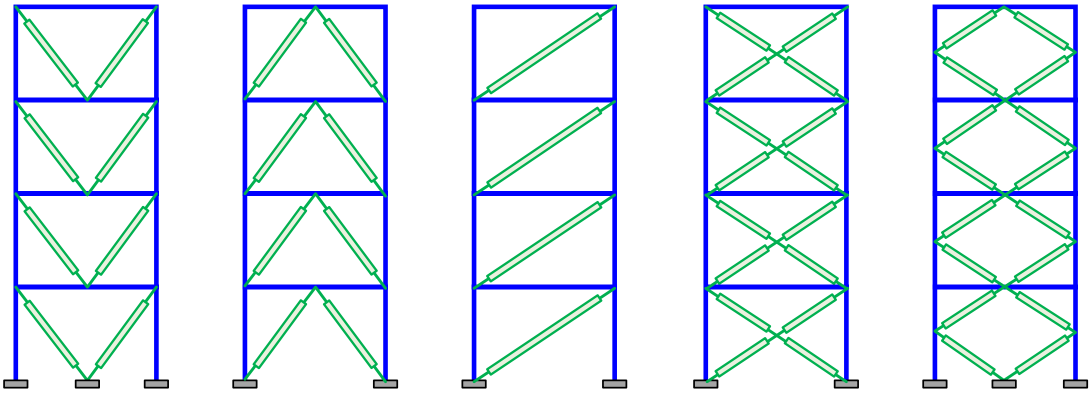

Figure 2. Typical braced frame configurations.

Buckling-restrained braced frame (BRBF) is a specific case of braced frame systems. Generally, the BRBF system has a global geometric configuration that is similar to a conventional concentrically braced frame, but its behaviour (i.e., force-displacement relationship) is distinctly different from those of a conventional one [13]. The most common BRBF systems are fabricated assemblies that consist of a steel core plate surrounded by a steel tube casting filled with grout or concrete. Figure 3 presents typical BRBF systems with their behaviour, where the BRBF yields axially in tension and compression, resulting in nominally symmetric cyclic response with strain hardening.

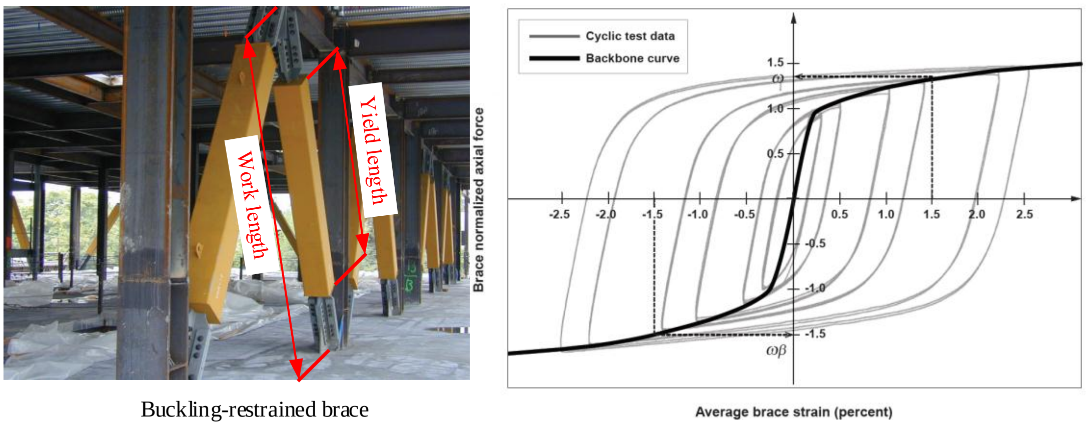

Figure 3. Typical BRB system and its force-displacement behaviour [13].

2.2. Design philosophies

The response of a braced frame is typically dominated by the behaviour of its bracing members. Under extreme lateral earthquake loading, in addition to increasing the lateral stiffness of the main structure, the braced experience several cycles of inelastic excursions. This behaviour has been investigated experimentally and analytically by several researchers.

Therefore, the design philosophy is that the bracing elements act as the primary seismic energy-dissipating components rather than adding the lateral stiffness. All the structural components are designed to resist the over-strength design action generated by yielding braces plus design gravity loading.

For braced structural systems, the seismic design concept translates into designing the braces to dissipate the energy induced by the earthquake through the inelastic deformation protecting the structural components that are considered non-dissipate from degradation. From the perspective of seismic-resistant design standards, this concept leads to the introduction and/or increase of the behaviour factor “q” that reduced the design seismic force demands.

Further, introducing damping devices in the global structure leads to an increase in the energy dissipation capacity of the structure. For these structures, the energy dissipation devices represent “sacrificial” elements that assume the role of energy consumers entirely by plastic deformations that occur in the devices. Therefore, the main structural elements remain essentially elastic at the expected strength. Further, from the point of view of the response spectrum, the increase in dissipation capacity, in other words, an increase in the viscous damping of the structure, offers a significant effect in reducing the impact of seismic load as well as the response of displacement of structures.

3. Analysis model - Case study

3.1. Structural modelling

In the framework of this parametric study, a simple 2D reinforced concrete frame is performed to investigate the effects of buckling restrained bracing systems on the seismic responses of structures. Accordingly, the considered frame layout consists of three bays and six stories: The external and the internal bays have spans of 6 m and 4 m, respectively. The story height is set to 3.6 m for all floors except for the ground floor, which is 4.0 m in height. The cross-section of outer span beam systems is 25 cm x 50 cm (width x depth) and that is 25 cm x 40 cm for inner span beams. The cross-section of columns is 25 cm x 40 cm. Grade of structural concrete: B25 (TCVN-5574:2018 [14]).

The objective of the analyses is to evaluate the effects of the bracing system on the seismic response of the frame structure, and it is suitable to be performed based on a simplified model. Accordingly, the bracing elements can be modelled by nonlinear link elements (bilinear force-displacement relationship), as shown in Figure 4.

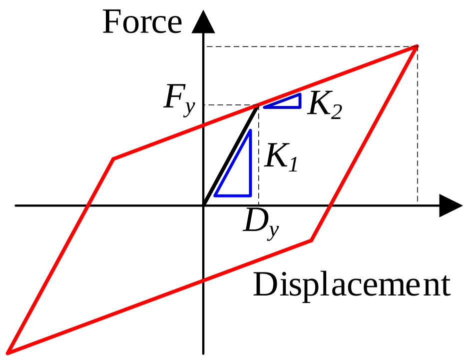

Figure 4. Representative force-displacement relationship of bracing system.

To achieve the research's objective, the models for parametric study are considered as follows:

The conventional structure is represented by a 2D frame without bracing systems, which is used to evaluate the effects of bracing systems. Model 1 is the 2D braced frame structure, in which, the bracing system is installed on the first-floor level. Model 2 is the 2D braced frame structure with a bracing system installed on the third-floor level. Model 3 is the 2D braced frame structure with a bracing system installed on the fifth-floor level. For all three models, the bracing systems used have the same properties (F_y = 22.5 kN, D_y = 1.5 mm, K_1 = 15 kN/mm, K_2 = 0.15 kN/mm) and their force-displacement relationship is illustrated in Figure 5.

In addition, the nonlinear behaviour of braced frame elements is strongly dependent on the shear force and the relative displacement between the two nodes of each element. Since the distribution of shear forces gradually decreases with the height of the structures, the performance of the braced frame elements, therefore, logically decreases with the height of the structure to conform to the optimal design criteria (i.e the stiffness and the elastic limit are decreased). In the framework of this study, the effects of bracing systems applied at all floor levels are also investigated, as shown in Figure 6. The properties of braced frame elements are preliminarily selected and applied for the structure as detailed in Table 1. Accordingly, every two stories are added bracing elements with the same properties. A total of three nonlinear link element types are employed.

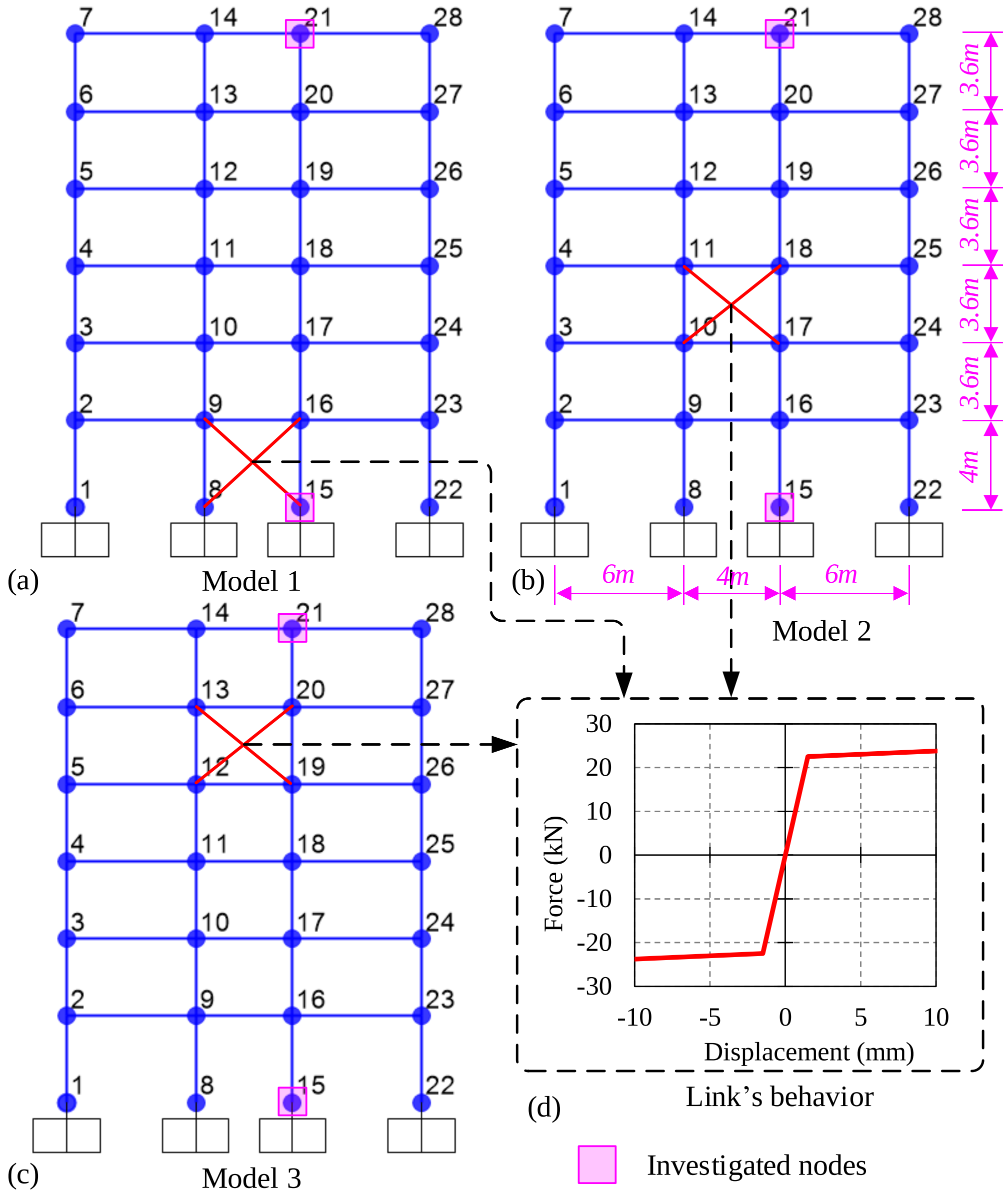

Figure 5. Models of 2D braced frame: (a) Model 1, brace on the first floor; (b) Model 2, brace on the third floor; (c) Model 3, brace on the fifth floor; and (d) Brace's behavior.

Table 1. Link element properties

Order	Link elements	K_1 (kN/mm)	K_2 (kN/mm)	D_y (mm)	Elastic limit (kN)
1	1, 2, 3, 4	15	0.15	1.5	22.5
2	5, 6, 7, 8	10	0.1	1.5	15.0
3	9, 10, 11, 12	5	0.05	1.5	7.5

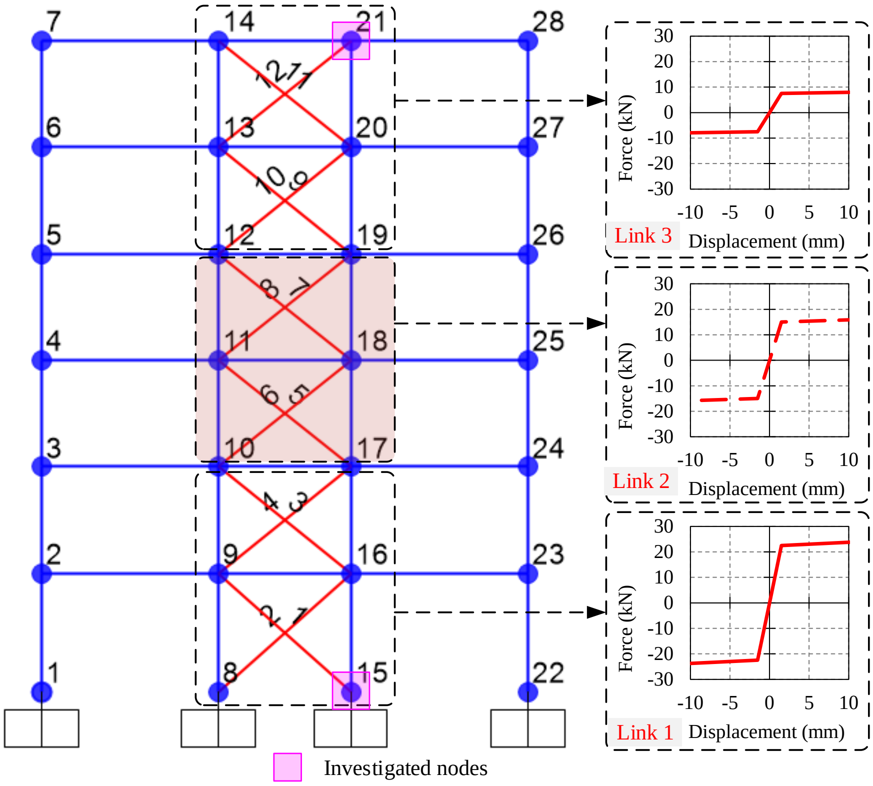

Figure 6. Model 4: 2D braced frame with a brace applied on all the floor.

3.2. Seismic actions

The seismic responses of the structure are investigated by using the acceleration ground motions of Kobe's earthquake, which is scaled to match the target spectrum of Thanh Xuan, Hanoi. The characteristics of the earthquake records are summarized in Table 2.

Table 2. Earthquake records were selected for analysis

Order	Earthquake	Mw	Hypocenter distance (km)	Component	PGA (g)
EQ1	Kobe, 1995-01-16, Nishi-Akashi, Japan	6.9	19.9	90°	0.509
EQ2				0°	0.503

Time-history accelerations are scaled by the method proposed by Dai Nguyen [15] and plotted in Figure 7(a) and 7(b) for two orthogonal components, respectively. The response spectra of scaled ground motions are plotted in Figure 7(c). As an observation, a good matching is found between the response spectra of the selected ground motions and the target spectra.

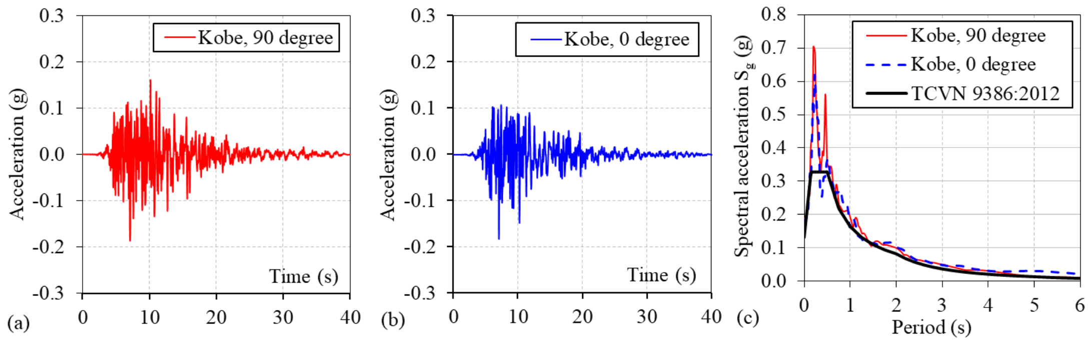

Figure 7. Scaled accelerations of Kobe's earthquake for analyses:
(a) component 90°, (b) component 0°, and (c) response spectra.

4. Results and discussion

Effects of bracing systems are evaluated through a comparison of the seismic responses of (i) the top displacement of structures (node 21), (ii) the shear force and the bending moment at the base of the column (node 15) between the braced frame structures and the conventional structure.

Table 3 presents comparisons of seismic responses of the top displacement and the base shear forces between the conventional frame and the three braced frame models. Accordingly, the bracing system shows better performance in model 1 (braces are applied on the first floor) where the base shear force and the top displacement are considerably lower than those of the conventional frame. In other cases, the bracing systems seem to be ineffective, even having the opposite effect of increasing both the base shear force and the top displacement. These results may be caused by the bracing systems selected being too efficient for the demand of the structure. Specifically, the stiffness and the elastic limit of the device are too high, which increase significantly the stiffness of the global structure, resulting in a reduction of vibration period, and then the seismic response of acceleration (in other words, the base shear force) is increased. In addition, the device does not produce nonlinear behaviour, thus not providing a damping effect.

Table 3. Comparisons of seismic responses between the conventional frame and three specific braced frame models

Model	**Base shear force, node 15 (kN)**		**Lateral displacement, node 21 (mm)**	
	Max	***Min***	***Max***	***Min***
Model 1	29.73	-20.67	27.11	-22.82
Model 2	37.97	-29.77	29.47	-24.34
Model 3	40.17	-36.44	30.55	-27.33
Conventional frame	38.82	-37.07	29.32	-29.13

Figure 8 presents these comparisons of the response histories of considered structures subjected to EQ1.

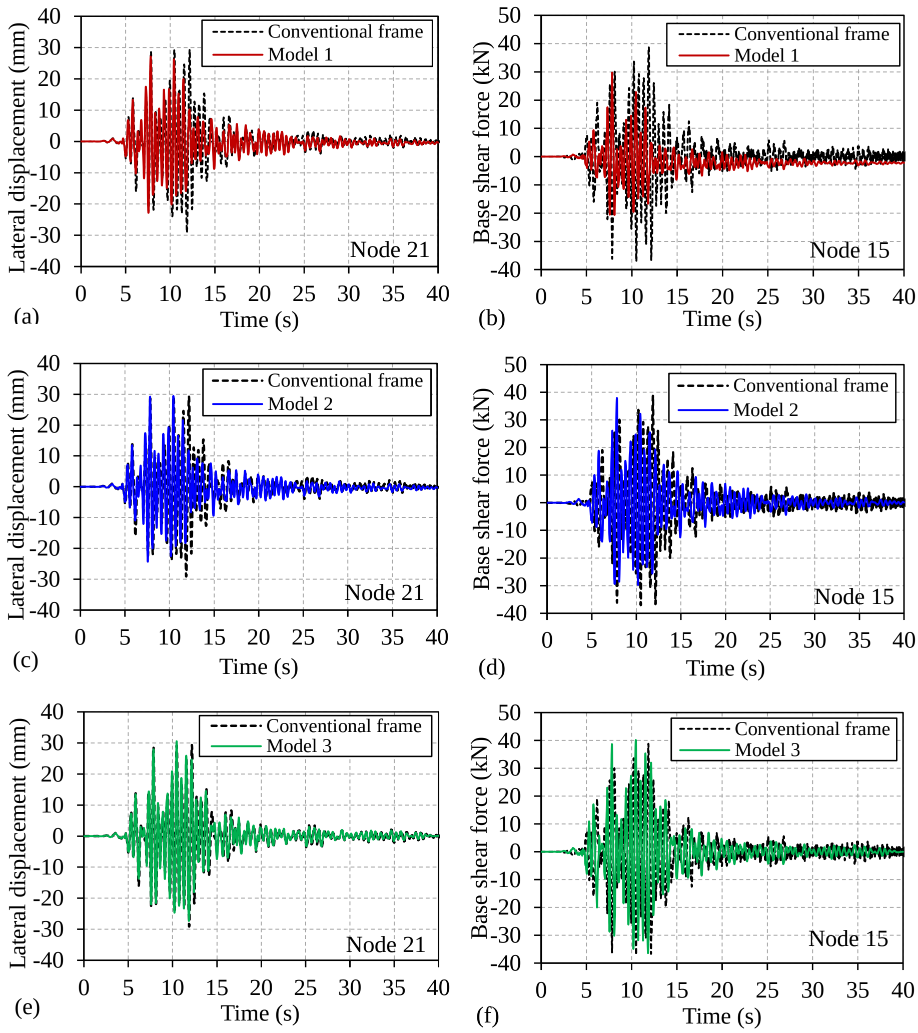

Figure 8. Response history of top displacements and base shear forces of considered models subjected to EQ1.

In Model 4, BRBFs were installed on all floor levels to evaluate their effects from the point of view of earthquake-resistant design. The obtained results, as detailed in Table 4, indicate high efficiencies of bracing systems that considerably reduce the top displacement, the base shear force, and the bending moment at the bottom of columns of the braced frame structure.

Specifically, the maximum displacement at the top of the braced frame structure is about 60% of the conventional frame (17.57 mm vs 29.32 mm for EQ1, and 19.91 mm vs 32.48 mm for EQ2). Meanwhile, the bending moment and the shear force at the base of columns of the braced frame are significantly reduced (about 56-70%) when compared with the conventional frame.

Table 4. Comparison of seismic responses between the conventional frame and braced frame

Parameters		EQ1			EQ2		
		CF* (a)	BF** (b)	b/a (%)	CF* (c)	BF** (d)	d/c (%)
Displacement at the top	max	29.32	17.57	59.91	32.45	18.57	57.22
	min	-29.12	-13.97	47.97	-32.48	-19.91	61.29
Base shear force	max	38.82	22.03	56.76	37.80	23.91	63.25
	min	-32.48	-14.95	46.02	-38.77	-26.99	69.63
Bending moment at the base of columns	max	86.33	49.52	57.36	85.37	53.45	62.61
	min	-83.42	-33.79	40.51	-86.83	-60.83	70.06
*Conventional frame, ** Braced frame – Model 4							

Figure 9 presents the comparison of top displacement time-history between the braced frame structure and conventional structure. Accordingly, most peak response is significantly reduced.

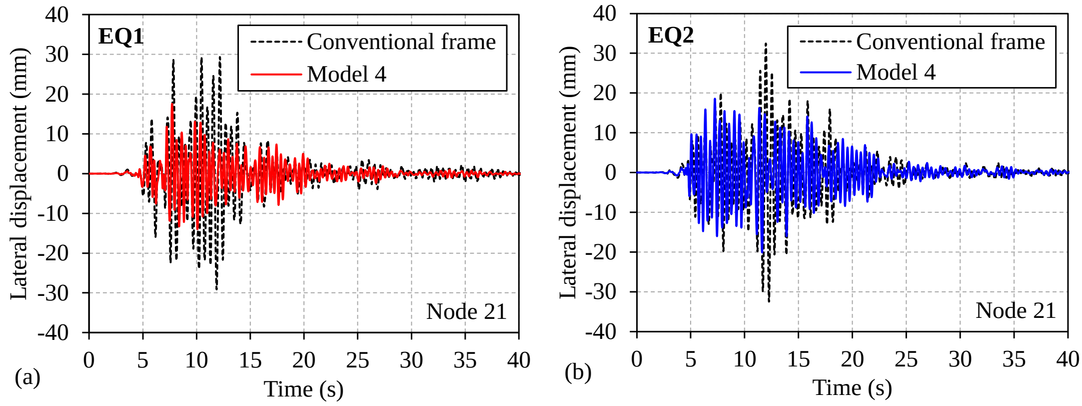

Figure 9. Comparison of the top displacement history between braced frame structures and conventional structure.

Figure 10 presents the comparison of response history for two models in terms of bending moment and base shear force at the bottom of columns. Similar results are obtained demonstrating that such applied braces offer a great effect on the seismic-resistant design of structures.

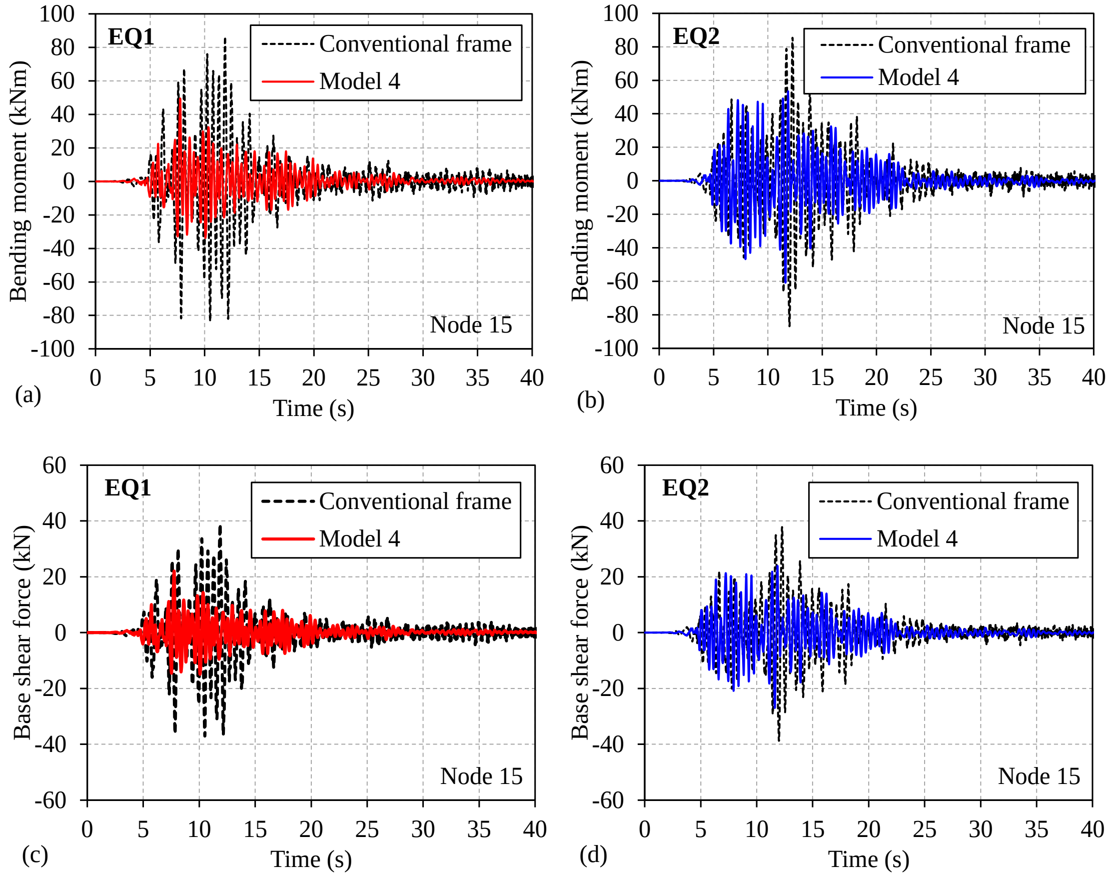

Figure 10. Comparison of the bending moments and base shear forces between braced frame structures and conventional structure.

From the above remark, the reduction of force and displacement can be explained from the point of view of vibrational energy. Accordingly, the nonlinear behaviour of the bracing system contributes significantly to the dissipation of the vibration's energy of structures, resulting in a reduction in the accumulated strain energy in the frame structure, the displacement, and the shear force in the structure.

To clarify this observation, Figure 11 plots the nonlinear force-displacement relationship of typical bracing elements. Accordingly, the degree of nonlinearity of bracing systems decreases as the mounting position height increases, even if its performance has been selected appropriately. This obtained result is consistent with the distribution of shear forces along with the height of the structure and the design of bracing systems according to the height of structures is necessary.

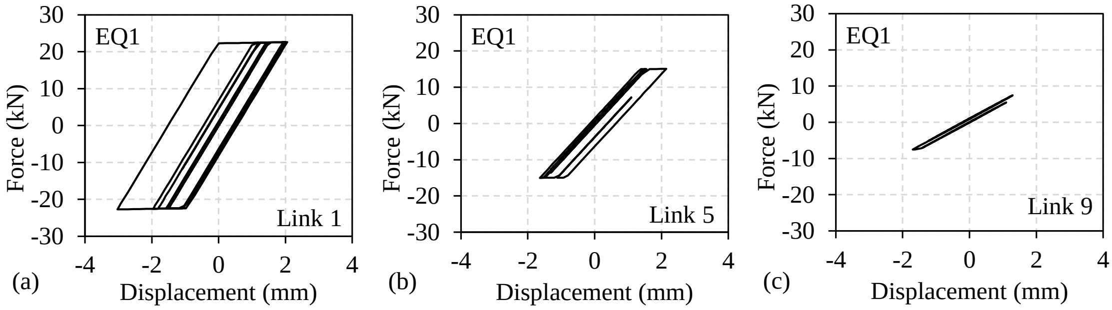

Figure 11. Force-displacement response of bracing elements.

5. Conclusion

The overall purpose of the present study was to investigate the effects of buckling-restrained bracing systems on the seismic response of braced structures, which are conducted through a parametric study of several 2D frame structures subjected to earthquakes. The obtained results show that the bracing systems are highly effective in seismic-resistant design where the shear force and bending moment at the bottom of columns and the top displacement are significantly reduced (up to 70%) compared with the conventional structure. The design of BRBF systems with nonlinear behaviour shall be based on the horizontal force distribution to improve the seismic capacity of the devices. Specifically, the performance of BRBF should decrease with the increase of the height of structures.

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NGHIÊN CỨU KHẢO SÁT HIỆU QUẢ KHÁNG CHẤN CỦA KẾT CẤU KHUNG GIẰNG

Nguyễn Xuân Đại, Nguyễn Văn Tú, Nguyễn Thành Đồng, Trần Việt Đức

Tóm tắt: *Bài báo nghiên cứu khả năng của hệ kết cấu khung giằng trong thiết kế chống động đất. Hệ thống khung giằng điển hình, được biểu thị bằng mô hình gần đúng dạng song tuyến tính, được lựa chọn để phân tích. Kết quả chỉ ra rằng, hệ thống giằng cung cấp giải pháp hiệu quả cho thiết kế chống động đất khi làm giảm đáng kể chuyển vị đỉnh và nội lực của kết cấu dựa vào khả năng tiêu tán năng lượng của chúng thông qua các ứng xử phi tuyến. Hơn nữa, đối với hệ thống giằng thẳng đứng, hiệu năng của chúng được kiến nghị tính toán tương ứng với sự phân bố lực cắt theo chiều cao của kết cấu nhằm làm cho chúng trở thành giải pháp hiệu quả đáp ứng các triết lý thiết kế.*

Từ khóa: Thiết kế chống động đất; kết cấu khung giằng; ứng xử phi tuyến; phân tích phi tuyến theo lịch sử thời gian.

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