JST&M 8(2025), 43 – 53
DOI: 10.57131/jstm.2025.8.7

Original scientific paper

DUCTILITY CAPACITY STUDY OF LARGE-SCALE, BUCKLING-RESTRAINED BRACES IN STEEL STRUCTURES

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ABSTRACT

One of the new methods of anchoring steel structures is the use of large-scale buckling-restrained braces (BRBs) on the lateral system of this type of structure. This study investigates the behavior of BRBs and compares them with buckling braces. In this study, a two-dimensional frame with four stories and four spans was taken and analyzed in eight different ways, and each in the form of buckling and buckling-restrained braces. The results show that making the braces buckling-restrained has a positive effect on increasing ductility and energy dissipation.

Keywords: ductility capacity; steel structures; large-scale buckling-restrained braces

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1. INTRODUCTION

The building of metal structures as a symbol of progress and development began in the 1880s with commercial and residential use. The construction of commercial buildings was initially a response to demand from the business community, who wanted to live as close to each other and in the city center as possible. This led to great pressure on horizontal space in the central areas of cities. As metal structures usually have a striking appearance, they are also used by businesspeople as advertising media. On the other hand, the business world and tourism are interested in building high-rise hotels in city centers due to the high number of visitors and favorable economic returns. The rapid increase in the urban population and the lack of space have also had an impact on the architecture of residential buildings. The increase in land prices, the need to limit the horizontal expansion of cities, and the preservation of agricultural land are among the factors that have influenced the development and construction of metal structures.

The analysis and design of metal structures is considered one of the most important fields in civil engineering. Throughout history, earthquakes have always been considered one of the natural disasters that have caused the most material and spiritual losses in human societies. Until a few hundred years ago, this attention was limited to the fear of earthquakes and the attempt to avoid them. But as human societies have progressed, and especially as civil engineering has progressed, they have always looked for a solution to deal with them or to control the damage they cause in the best possible way. Today, engineering science has concluded that by understanding this phenomenon and its effects, as well as by researching and studying appropriate construction methods, recognizing new materials and using new equipment, and studying the results of past earthquakes, solutions can be found to reduce the effects of earthquakes and the damage they cause in different regions [1].

A brief review of the damage caused to structures in past earthquakes has shown that steel structures are better and more economical than other structures due to the deformability of the materials and their ability to absorb energy. Therefore, the need to select devices to absorb lateral loads from wind and earthquakes so that the optimal shape with the fewest materials absorbs the most energy in the structure has been considered in advance to ensure optimal behavior and reduce damage to structural members.

With the emergence of a new form of braces, called large braces, in recent years, these braces are expected to have a different seismic behavior (in terms of stiffness, efficiency, and ductility) than previous braces due to their geometric shape [2]. In addition, the buckling of these braces improves the behavior of the structure in terms of stability and energy absorption capacity [3]. In contrast to conventional braces, the braces in these structures cover multiple floors and spans as one brace. Therefore, several bracing arrangements of a particular bracing shape (e.g., cross) are possible for each structure, and the results are compared in two cases of non-buckling (buckling-restrained) and normal (buckling) braces. The natural conditions of Turkey and the way buildings are constructed in this country make it necessary for the issue of protecting society from earthquakes to be taken seriously in every respect. With the advances in civil engineering sciences and the emphasis on the resistance of structures to lateral forces, the use of appropriate and reliable devices to cope with these forces becomes noticeable. A bracing system is usually used for this purpose.

Historically, bracing has been used for the lateral stability of most tall buildings in the world since the end of the 19th century [4]. Lateral resistance in braced frames is provided by diagonal members, which, together with the beams, form the web of a vertical truss system. In this system, the columns are the edges of the truss. Since the horizontal shear forces acting on the building are absorbed by the horizontal components of the axial tension or compression forces of the webs, the bracing system is very efficient and useful in absorbing lateral loads. The effectiveness of the bracing system in creating a laterally rigid structure and the use of minimal material have made it an economical form of construction for all types of buildings and at any height. Another advantage of diagonal bracing is that the beams are minimally affected by the lateral loads, so the design of the floor system can be designed and executed repeatedly in the floors, which makes economic sense [5]. However, the main weakness of this system is that the axial force in the vertical columns, which applies the lateral force, deviates from the uniform distribution in the ideal case. The main cause of this phenomenon is the importance of shear deformations in the behavior of the deep edge beams of the structure in this system and the invalidity of the assumption that the panels remain the same after bending; this leads to an increase in stress in the corner columns and a decrease in the middle columns of the wing and web panels [6].

Nowadays, the conventional convergent bracing system is the most common structural system for coping with seismic loads in steel structures, and its use is becoming increasingly popular due to its cost-effectiveness, simplicity of design, and ease of implementation. However, the damage caused by recent earthquakes such as the Loma Prieta, El Centro, and Kobe earthquakes to conventional convergent braced frames has raised concerns about the seismic performance of this system [7].

Conventional bracing undergoes large lateral deformations when subjected to lateral loads, whether from earthquakes or wind. When these deformations exceed a certain limit, they lead to structural and non-structural failure, and the safety and integrity of the structure are jeopardized. The failure is aggravated by the P-Δ effect, and the destructive deformations increase. To cope with such deformations, different types of elements and systems are used in steel frames [8].

Diagonal elements in conventional concentric bracing systems increase the stiffness and strength of the structure, but do not result in significant energy absorption in the structure during an earthquake. Most conventional bracing with different cross-sections, consisting of a single steel beam, is designed to resist both compression and tension forces. Buckling of these members depends on the slenderness factor λ [9]. Poor behavior after buckling, differences in tensile and compressive capacities, degradation of stiffness and strength under cyclic loading, and fatigue at low cycles are among the most important and fundamental problems in the performance of compression elements. When buckling occurs, the lateral stiffness decreases sharply and the stability of the frame is reduced, resulting in severe damage to structural and non-structural components and, in some cases, structural collapse. Conventional braces, therefore, have limited ductility and asymmetric energy cycles [10].

To overcome the above problems, new types of braces were developed in Japan about 30 years ago to improve the conventional braces and develop braces with more ideal elastoplastic behavior; this idea was first proposed by Yoshino et al. [11]. These braces were widely used in Japan after the Kobe earthquake in 1995. These braces are designed to prevent buckling of the braces by a suitable mechanism and allow yielding of the steel by compression. It is important that yielding does not occur locally and that it is appropriately and evenly distributed over the entire component so that the energy absorbed during a reciprocating load, such as an earthquake, reaches its maximum. While conventionally stiffened frames exhibit irregular behavior and tend to concentrate large deformations in one or more stories (thus forming a soft story), BRBs are much more stable in this respect. This does not necessarily mean that the relative displacement is less, but that the inelastic response of the frame is more uniform than the entire height of the structure. In the United States, buckling-resistant braces were first used in 2000. After engineers in the United States recognized the value of buckling-resistant bracing, a group of researchers from the California Society of Structural Engineers, in collaboration with the American Steel Institute, published proposed criteria for buckling-resistant bracing in 1999. These criteria were incorporated, with minor changes, into the NEHRP Proposed Seismic Criteria in 2003 and the American Steel Code of Practice in 2005 [12].

In order to predict the performance of a structure under seismic forces, a nonlinear time history analysis of earthquake data with acceptable reliability is required to represent various seismic characteristics such as amplitude, frequency content, duration, and so on. Therefore, the aforementioned analysis is complex, time-consuming, and impractical in most cases. To overcome these limitations, it is necessary to develop an evaluation method that is relatively simple but represents the main characteristics of the earthquake and the structure. It also reflects the change in inertial forces and the distribution of deformations resulting from the nonlinear behavior. Nonlinear incremental static analysis is one of the methods that can effectively help achieve this goal for some structures. Nonlinear incremental static analysis provides useful information about the nonlinear behavior of buildings during earthquakes. However, it should be noted that the interpretation of the results of this analysis requires engineering judgment despite the variety of earthquakes, the uncertainty of material properties, and the difficulties in modeling.

In this work, two-dimensional frames were subjected to nonlinear incremental static analysis, and the ductility values as well as the additional strength factor and the ductility reduction factor were calculated for large-scale and conventional non-buckling and large-scale and conventional buckling structures. All analyses were carried out using SAP2000 software.

2. MODELLING AND MATERIALS

The main functional principles of the operation of the BRB are to prevent the steel core from buckling, to allow the occurrence of compression yielding in it, and thus the possibility of absorbing energy in this component. This is achieved by encasing the entire length of the steel core in a sheathing filled with concrete or mortar. In this type of brace, the compressive load is carried by the steel core, and the concrete sheathing acts only as a lateral support to prevent buckling of the steel core, which causes the lateral distribution of internal pressure in the concrete sheathing. As a result, the buckling resistance of the core is greater than its yield strength, allowing the core to yield in both compression and tension, which significantly increases its energy absorption capacity. To prevent the axial compressive force of the steel core from being transferred to the concrete, this system gives the brace a high inelastic capacity, which absorbs more seismic energy and allows other components to remain within the elastic range. The difference in the behavior of conventional and buckling-resistant braces leads to different hysteresis behavior, which is shown in Figure 1. Different components of a BRB are depicted in Figure 2. As shown in Figure 3 in this study a total of eight two-dimensional 4-story frames are used which are braced with 4*4 X shape brace (covering four stories and four spans), 4*2 X shape brace (covering two stories and four spans), 2*2 X brace (covering two stories and two spans), K shape brace, diamond shape brace, V shape brace, 4*2 inverted V (∧)shape brace, and 1*2 ∧ shape brace, respectively. All these braces are designed and studied once as non-buckling and once as buckling states. The frames have 4 spans with a length of 6 meters and a height of 3.2 meters. The connection of the beam to the columns and the braces to the frame in these models is of the hinge type, and the supports are connected to the foundation in a fixed manner. The dead and live loads of the roof are $4 kN/m^2$ and $1.5 kN/m^2$, respectively, and the dead and live loads of the other floors are $4.7 kN/m^2$ and $2 kN/m^2$, in the given order. The mechanical properties of the steel material used in these analyses are listed in Table 1.

Table 1. Mechanical properties of materials used in models

Type	ρ	E	υ	σ_y (beams, columns)	σ_y (braces)
JIS-SN400	7830 kg/m^3	200 GPa	0.3	3500 kg/cm^2	2900 kg/cm^2

3. RESULTS AND DISCUSSIONS

Capacity curves obtained for these eight types of braces are shown in Figure 4. As it is observed, in all types of bracing, the area under the load-displacement curves is greater when non-buckling braces are used. Since the area under the curve represents the amount of energy dissipated by the structure, the greater the area under this curve, the greater the structure's ability to absorb and dissipate energy.

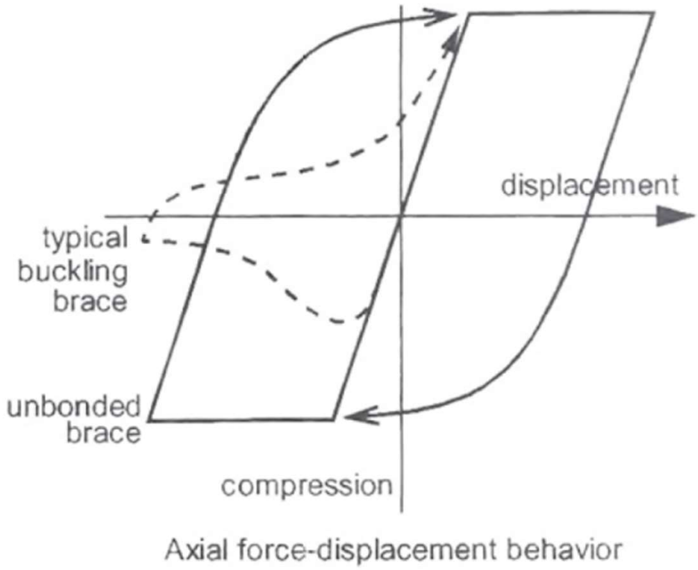

Figure 1. Comparison of load-displacement curves for BRBs and normal braces [3]

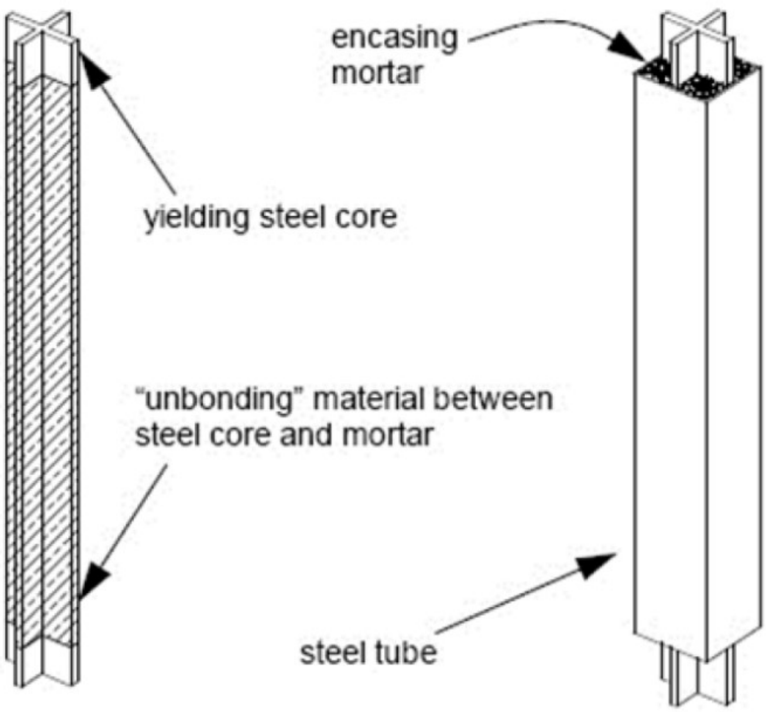

Figure 2. Different parts of the buckling restrained brace [3]

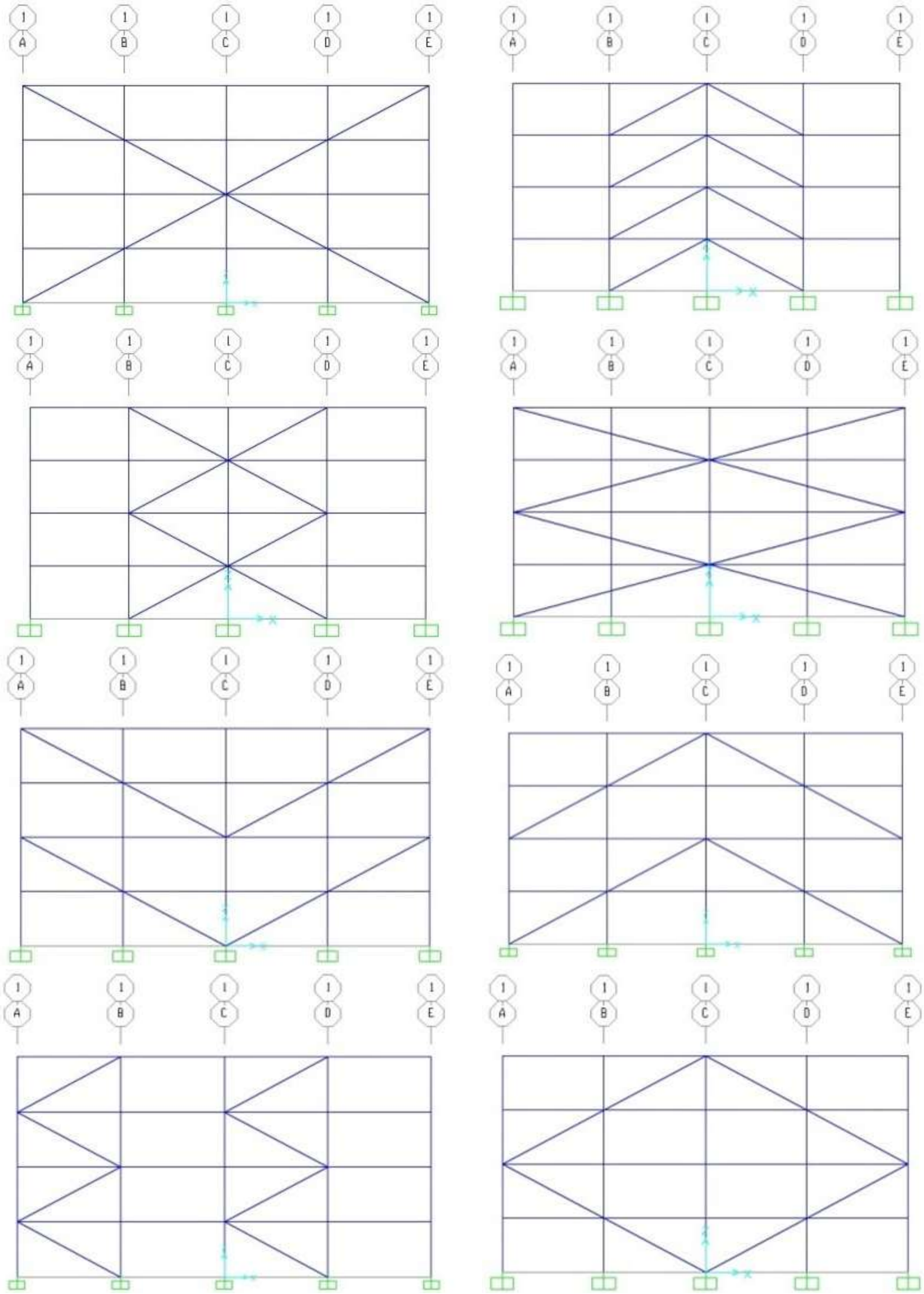

Figure 3. Eight different bracing models were used for analysis

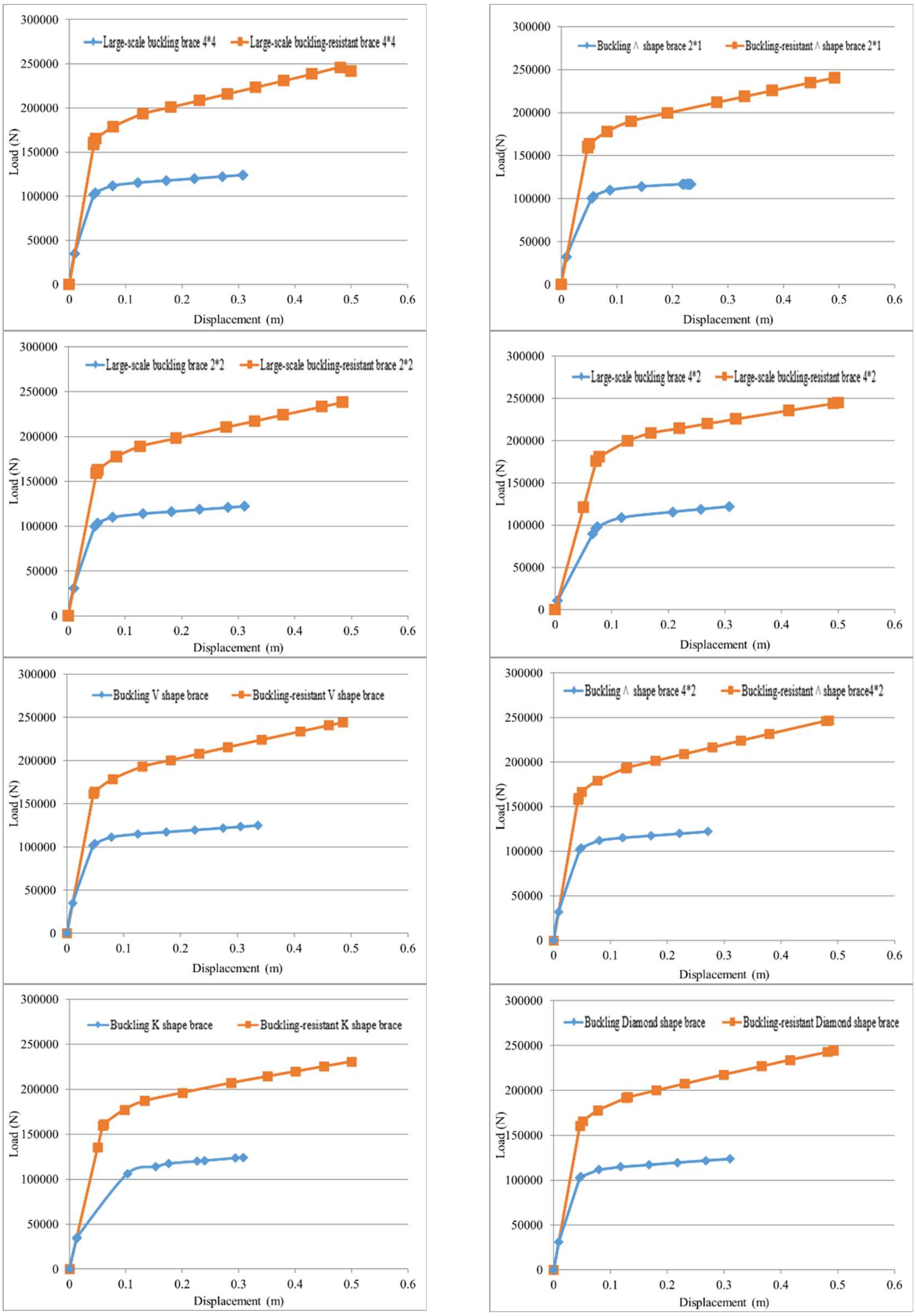

Figure 4. Load-displacement curve of different bracing models in buckling and non-buckling states

When a structure is subjected to large forces caused by an earthquake, it can dissipate the energy introduced by the earthquake to the extent of the area under the base-shear and lateral displacement curve if it behaves elasto-plastically. The greater this energy dissipation, the lower the vibrations of the structure and the less the structure can react to the vibrations caused by the earthquake. In this section, the trapezoidal integral method was used to determine the area under the load-displacement curves.

Figure 5 shows that among the non-buckling braces, the 4*4 X-shaped, the 2*2 X-shaped, and the diamond-shaped braces dissipate the most energy, respectively. Whereas, among the buckling braces, the 4*2 V-shaped, the 4*4 X-shaped, and then the diamond-shaped braces have the highest energy dissipation in the given order.

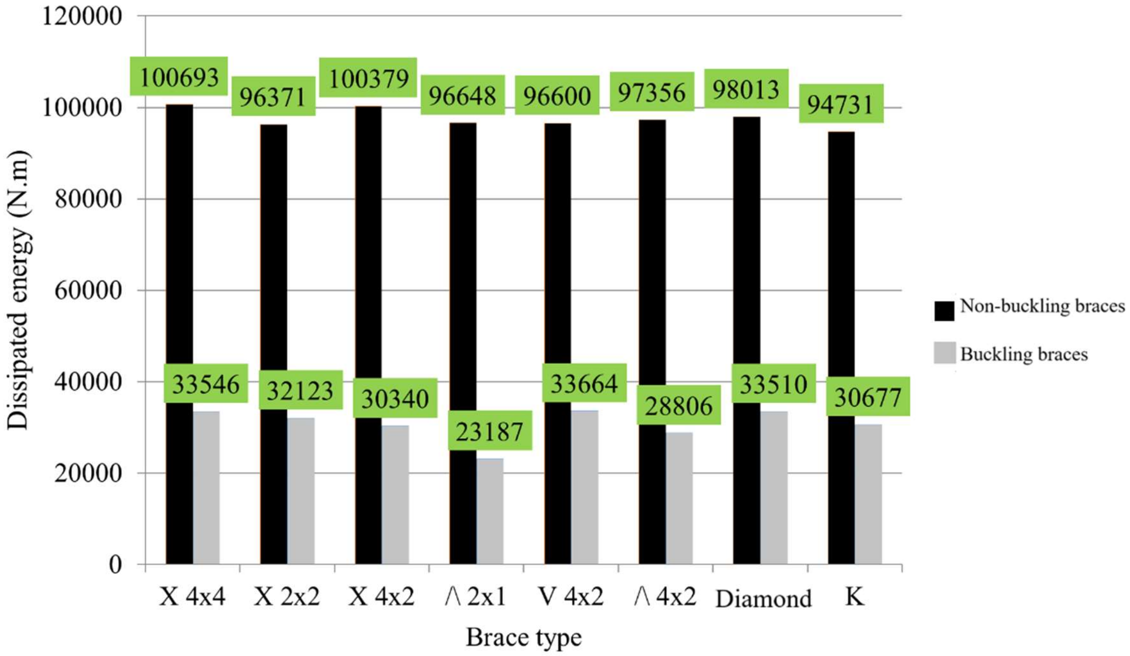

Figure 5. Dissipated energy magnitude of different bracing models in two buckling and non-buckling states

Ductile materials are materials that exhibit large strains while carrying a load. A ductile member must firstly be able to withstand sufficiently large non-reflexive deformations without significantly reducing its resistance, and secondly be able to absorb and dissipate a significant amount of seismic energy through stable behavior cycles. The ductility of flexural frames is defined as the ratio between the ultimate deformation of the frame end (Δu) and the displacement, such as the yield strength of the frame end (Δy), as:

$$\mu=\Delta u/\Delta y \qquad (1)$$

Ductility of the frames is calculated using the above equation. The obtained results are illustrated in Figure 6. These results show that all non-buckling braces have a higher ductility than buckling braces. Among the non-buckling braces, the 4*2 ∧ brace has the highest ductility. Then follow the diamond and 4*4 X braces with some lower ductility. The 4*2 brace has the lowest ductility among these braces. Among the buckling braces, the 4*4 X, 4*2 V, and 2*2 X braces have the highest ductility, respectively, and the 2*1 ∧ brace has the lowest ductility.

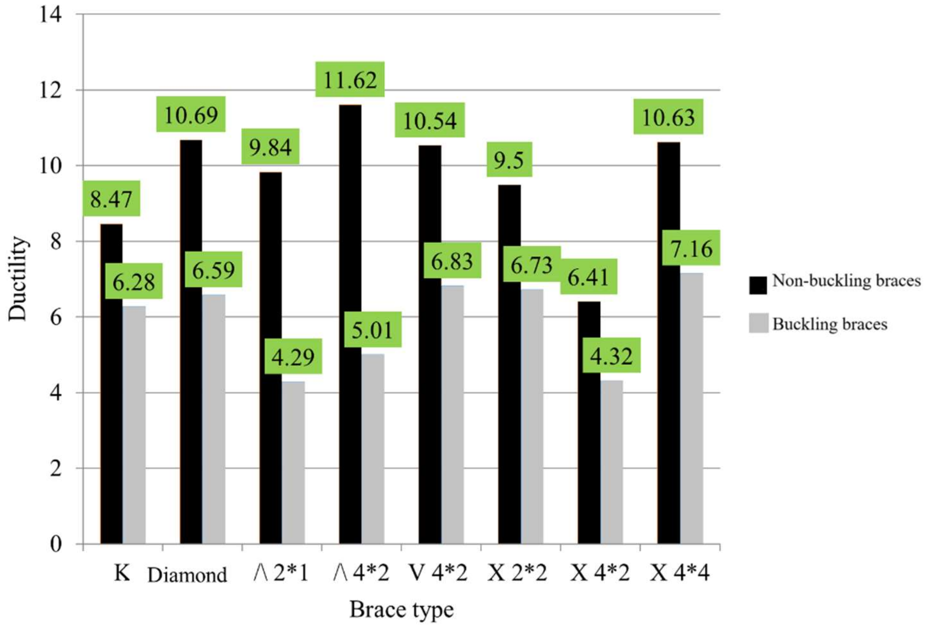

Figure 6. Ductility magnitude of different bracing models in two buckling and non-buckling states

In this study, the ductility reduction coefficient (Rμ) is also calculated using three common methods: Newmark-Hall [6], Krawinkler–Nassar [7], and Vidic [8], and the results are compared to each other. For a structure with a single degree of freedom, Newmark-Hall is calculated as follows:

$R_{\mu}=\sqrt{2\mu-1}$, $T \leq 0.5$ sec (2)
$R_{\mu}=\mu$, $T \geq 0.5$ sec (3)

where μ is ductility and T is the natural period of the structure. In the Krawinkler–Nassar relationship ductility reduction coefficient is calculated as:

$R_{\mu}=[c(\mu-1)+1]^{(1/c)}$ (4)
$c=(T^{n}/T^{n+1})+(b/T)$ (5)

where n is an exponent that adjusts the influence of period on the coefficient c. Here, c is an empirical coefficient obtained from regression analysis based on earthquake records, and b is another empirical parameter related to structural and seismic characteristics. Finally, the Vidic method proposes the following relations:

$R_{\mu}=(M-1)\times(T/T_0)+1$ if $T\leq T_0$ (6)
$R_{\mu}=\mu$ if $T>T_0$ (7)

where M is a ductility-related parameter, often representing the ductility demand, which is the ratio of maximum to yield displacement. T_0 is the reference period, often used as a threshold to differentiate short-period and long-period behaviour. The $R\mu$ results obtained from these three approaches are compared in Figure 7. In design codes, the structures are designed in such a way that none of them exceeds the elastic stage. Otherwise, plastic hinges will form in them. As a result, the overall stiffness of the structure decreases, but it is still able to resist until the formation of hinges causes a mechanism, and the stiffness of the structure tends to zero. At this stage, when the ductility capacity has also reached its limit, the structure is destroyed.

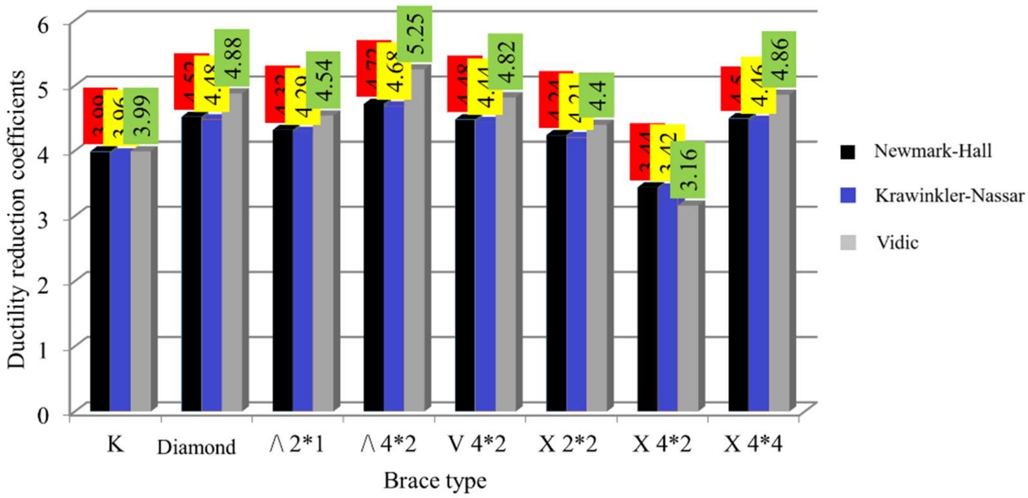

Figure 7. Ductility reduction coefficient values of different bracing models in non-buckling state using Newmark-Hall, Krawinkler-Nassar, and Vidic methods

During this process, the structures withstand additional resistance, which was not considered in the original design of the structure, and is referred to as additional resistance. This Increased resistance coefficient (Ω) is calculated as:

$$\Omega = V_y / V_s \tag{8}$$

where V_y is the force corresponding to the total yield strength of the structure, and V_s is the force corresponding to the formation of the first plastic hinge in the structure. Due to the proximity of the values of V_y and V_s, all values for the additional resistance coefficients are close to each other. The values of these coefficients for non-buckling braces are slightly larger than their values for buckling braces. Figure 8 indicates that the highest Ω value for non-buckling braces is for 4*4 X, followed by 4*2 ∧ and K braces, and the lowest value is for 4*2 V brace. Whereas for buckling braces, the highest value of Ω is for 4*2 ∧, K, and 2*2 X braces respectively, and the lowest value is for 4*2 V brace.

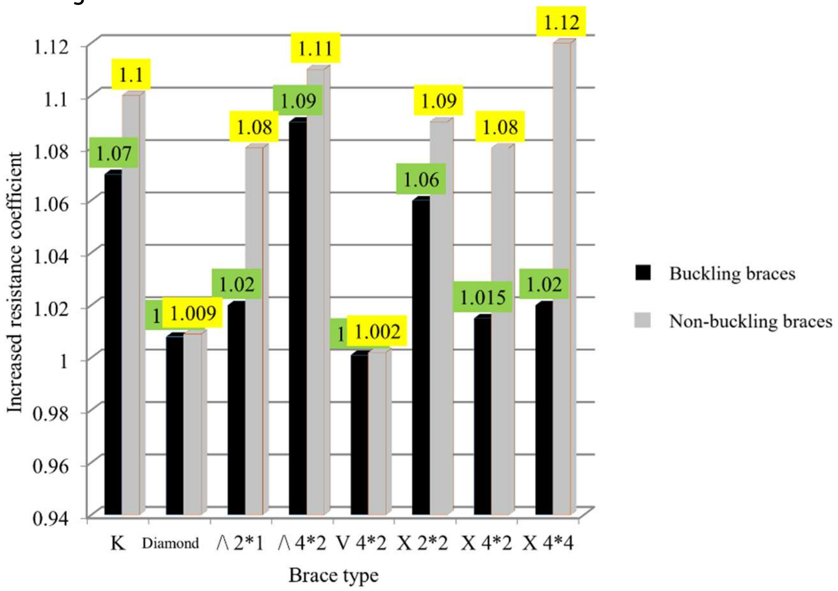

Figure 8. Increased resistance coefficient values of different bracing models in two buckling and non-buckling states

4. CONCLUSION

Due to the importance of load distribution and understanding the real behavior of a braced system under lateral earthquake forces in structures, the effect of buckling in bracing systems is investigated in this paper and compared in two buckling-resistant and buckling-unrestrained conditions for different models. Non-buckling braces have high energy dissipation, ductility, and a high behavior coefficient compared to buckling braces. The scaling of the brace has a favorable effect on the ductility and energy absorption of the structure. Among the non-buckling braces, X and diamond braces exhibit the highest energy dissipation. Among the buckling braces, X, V, and diamond braces have the highest energy dissipation. The ∧ , V, and diamond braces have the highest ductility of the non-buckling braces. The highest ductility among the buckling braces is shown by the 4*4 X- and V-shaped braces.

Conflicts of Interest

The authors declare no conflict of interest.

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