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Feasibility analysis of the application of restricted buckling braces as a response control system

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ABSTRACT

Peru is a country with high seismic activity, necessitating the implementation of seismic response control techniques in its buildings to enhance protection without incurring high costs. Although seismic response control systems are already in use, displacement-activated energy dissipators, such as buckling restrained braces (BRB), are not yet common in Peru, unlike in other countries where they are widely used. Therefore, the purpose of this study is to redesign a structural steel building using buckling restrained braces as a seismic response control system. Secondary objectives include analyzing the theoretical principles behind the design of these elements, determining the most appropriate configuration for the specified building, evaluating the proposed reinforcement through nonlinear analyses, and comparing performance differences with and without the use of BRBs. For this, both national and international standards such as the Peruvian seismic-resistant design standard E030, ASCE 7-16, AISC 341-16, and AISC 360-16, among others, were applied. The process began with an extensive compilation of information and bibliographic review, followed by the selection of the steel building for redesign with the new response control system. The main configurations of BRB suitable for the proposed analysis direction were explored and selected. Subsequently, the building design was initiated, starting with the sizing of the BRB cores and their verification under the Peruvian standard E030 through a linear dynamic analysis. The design was then evaluated by adjusting the force distributions of the BRBs in the other frame components. Finally, a comparison of the structural performance of the system with BRBs versus the original SCBF system was conducted through a nonlinear static analysis, concluding with a nonlinear dynamic Time-History analysis to verify the building's maximum responses, such as drifts, displacements, forces, and dissipated energy.

Keywords: BRB, redesign, structural steel, restricted buckling braces

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1. Introduction

Peru is a country characterized by its high seismic activity due to its proximity to the Pacific Ring of Fire. Different construction systems have been used in Peruvian construction over the years, one of the most used being confined masonry [1], even more so because of the good behavior presented and verified in previous earthquakes [2]. However, like any growing country, its development determines the construction of buildings with greater requirements for light or height, as well as load or functionality. In this sense, it is important that the construction systems to be used in Peru contemplate the condition that every building will be subject to earthquakes at some point in its useful life, even more so that this system will influence the seismic behavior of the structure [3].

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A construction system needs to implement the use of seismic response control techniques with which, without a high cost, protection against seismic response in buildings is increased [3], even more so if they are high since they are very flexible, have low damping and have a significant response to dynamic loads [4]. This must be accompanied by a reduction in damage after the earthquake through the control of deformations in the structure, such as the costs of repairs and rehabilitations, and additional protection is granted to the life and property of the users and investors of the buildings.

It is for this reason that it is imperative to implement seismic response control techniques in buildings to improve their protection without incurring high costs [5]. Restricted buckling bracing (BRB) is a structural device designed to improve the seismic resistance of buildings. They are composed of a steel core that is confined within a material jacket that prevents buckling under compressive loads. This configuration allows the BRBs to withstand both tensile and compressive cyclic loads efficiently [6], [7], providing greater energy dissipation capacity during an earthquake and improving the stability and structural safety of the building [8]. Although seismic response control systems are already in use, displacement-activated energy dissipators, such as buckling-restricted bracing (BRB), are not yet common in Peru, unlike in other countries where their use is widespread [9], [10].

The objective of this research is focused on the feasibility analysis of the application of restricted buckling stays as energy dissipators by means of a numerical model, the redesign of reinforcements of a structural steel building is carried out with the system of Special Concentric Frames between Supports (SCBF) and for the verification of the design non-linear dynamic and static analyses will be carried out. In this way, it is expected to promote the application of these devices as a reinforcement option for structures in Peru. Likewise, there are secondary objectives that involve analyzing the theoretical principles behind the design of these elements, determining the most appropriate configuration for the specified building, evaluating the proposed reinforcement through nonlinear analyses, and comparing the differences in performance with and without the use of BRBs.

To achieve these objectives, both national and international standards were applied, such as the Peruvian seismic resistant design standard E030, ASCE 7-16, AISC 341-16 and AISC 360-16, among others. The process began with extensive information gathering and literature review, followed by the selection of the steel building to be redesigned with the new response control system. The main BRB configurations suitable for the proposed direction of analysis were explored and selected. Subsequently, the design of the building began, starting with the dimensioning of the BRB cores and their verification under the Peruvian E030 standard through a linear dynamic analysis. The design was then evaluated by adjusting the force distributions of the BRBs on the other components of the frame. Finally, the structural performance of the system with BRBs was compared to the original SCBF system by means of a non-linear static analysis, concluding with a Time-History nonlinear dynamic analysis to verify the maximum responses of the building, such as drifts, displacements, forces and dissipated energy.

This article distinguishes itself from other similar works published in the literature by several key aspects. First, it addresses the feasibility and impact of the use of BRBs in the specific context of Peru, where their implementation is scarce, unlike other seismically active regions where their use is more common. Second, the study not only proposes a design with BRB, but also conducts a comprehensive comparison of structural performance with and without BRB, using nonlinear static and dynamic analyses. In addition, it provides detailed guidance on the optimal selection and sizing of BRBs, adapted to local conditions and Peruvian regulations, offering a practical and specific approach for engineers in the region. Finally, the adaptability of BRBs in existing buildings without the need for significant architectural changes is highlighted, which represents a considerable advantage in terms of costs and intervention times.

This research promotes the application of BRB as a reinforcement option for structures in Peru, given its effectiveness studied in the framework of other research in China [11], United States [12], [13], Japan [14], [15], Turkey [16] and Indonesia [17] among other countries. This is presented as an effective solution to improve the seismic response of buildings in a context of high seismic activity.

2. Research method

2.1. Methodology

First, an exhaustive compilation of information and bibliographic review of the restricted buckling brace (BRB) dissipators was carried out and its application, subsequently, the steel building was chosen to be redesigned with the new response control system. The main configurations of BRB were investigated and the most suitable one for the application will be chosen in this research.

Then, as in many engineering research, the focus corresponds to the quantitative type [18], because it makes measurements on the behavior of the phenomena that have occurred. In this case, structural behavior can be measured to determine the effectiveness of the structural system studied.

Next, the design of the building was started from a dimensioning of the BRBs, their verification with the Peruvian standard E030 with a static and dynamic linear analysis. The design was verified with the readjustment force distributions of the BRB in the other elements of the gantry.

The verification of the final design was carried out through a non-linear analysis as follows: by means of a non-linear static analysis it was compared with the original SCBF system and finally a non-linear dynamic analysis Time – History was carried out where the maximum response of the building was verified, i.e. drifts, accelerations and forces.

2.2. Theoretical foundations

Peru is a seismic country, so it is necessary to carry out innovation and research in new technologies, systems and structural elements that improve the seismic performance of a structure in terms of energy dissipation capacity, rigidity and resistance. It is for this reason that the designs are aimed at achieving structures with a

The ability to dissipate energy greater than the seismic demand for energy, in parallel the less resistant and rigid a building is, the less inelastic its behavior will begin with a smaller displacement [19]

Buckling Restrained Braces are part of the earthquake-resistant elements of a structure. They can be arranged, like conventional braces, in the shape of a "V", "inverted V", among others, they have the particularity of resisting similar stresses both in tensile and compression, this added to the behavior in a stable way after the state of creep of the steel core, gives a structure a better capacity of energy dissipation.

[20] explained that this is achieved by providing confinement to the brace by means of a confinement jacket, avoiding or reducing out-of-plane displacement as a result of buckling in the compression phase.

In addition, a material is provided that allows relative sliding with the least possible friction between the core and the confinement concrete because without this condition, in the tensile cycles there would be degradation of the concrete as a result of the friction between both materials [21].

This ensures that, in the compression phase, buckling occurs in high modes, thus achieving an even slightly higher compressive strength than in tensile strength. It should be noted that the steel core is the element that must take the axial load, while the entire confining system is arranged with the aim of providing lateral stability to the core and preventing buckling in low modes.

2.3. Overview of restricted buckling bracing

Buckle restrained braces consist of a ductile steel core, designed to deform under both tension and compression. To prevent buckling under compressive loads, this core is encased in a steel jacket, which can be hollow or filled with a material that confines the core. Figure 1 shows a schematic of a Buckling Restrictor Brace (BRB), which is used in structural engineering to improve the strength and stability of structures subjected to seismic or dynamic loads.

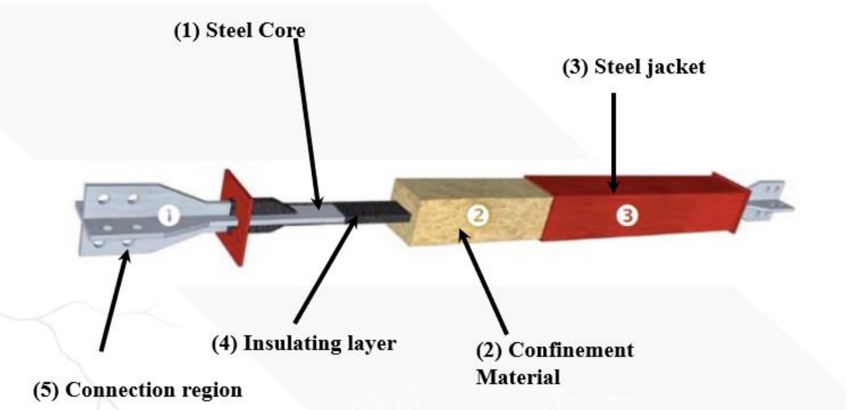

Figure 1. Components of restricted buckling bracing (BRB) according to [21]

The BRB is composed of the following components: the Steel Core, which provides the main resistance against applied loads and is designed to withstand both compressive and tensile loads; the Confinement Material, which surrounds the steel core and provides additional stability, preventing lateral buckling of the core under compressive loads; the Steel Jacket, which wraps around the confinement material and steel core, providing an additional layer of protection and confinement, helping to maintain the structural integrity of the BRB under extreme loads; the Insulating Layer, which sits between the steel core and the confinement material, providing thermal insulation and additional corrosion protection; and the Connection Region, which is the part of the BRB where it connects to the main structure, designed to efficiently transfer loads from the BRB to the structure and vice versa. The design and arrangement of these components ensure that the BRB can withstand significant seismic loads, improving the structure's ability to withstand warping and damage during a seismic event.

2.4. A case study

As can be seen from the figure, the floor plan of the building is 15m x 22m between axes. In the "x" direction, there are three Special Concentric Bracketed Frames (SCBF) as earthquake resistant elements; in the "y" direction there are four Special Concentric Bracketed Gantries (SCBF) to resist seismic stresses. The rest of the frames and beams are only to support the loads of gravity so all their connections to each other are articulated. The joists shown in the figure are referential only, all the slabs are reinforced in the X-X direction as shown in Fig 2.

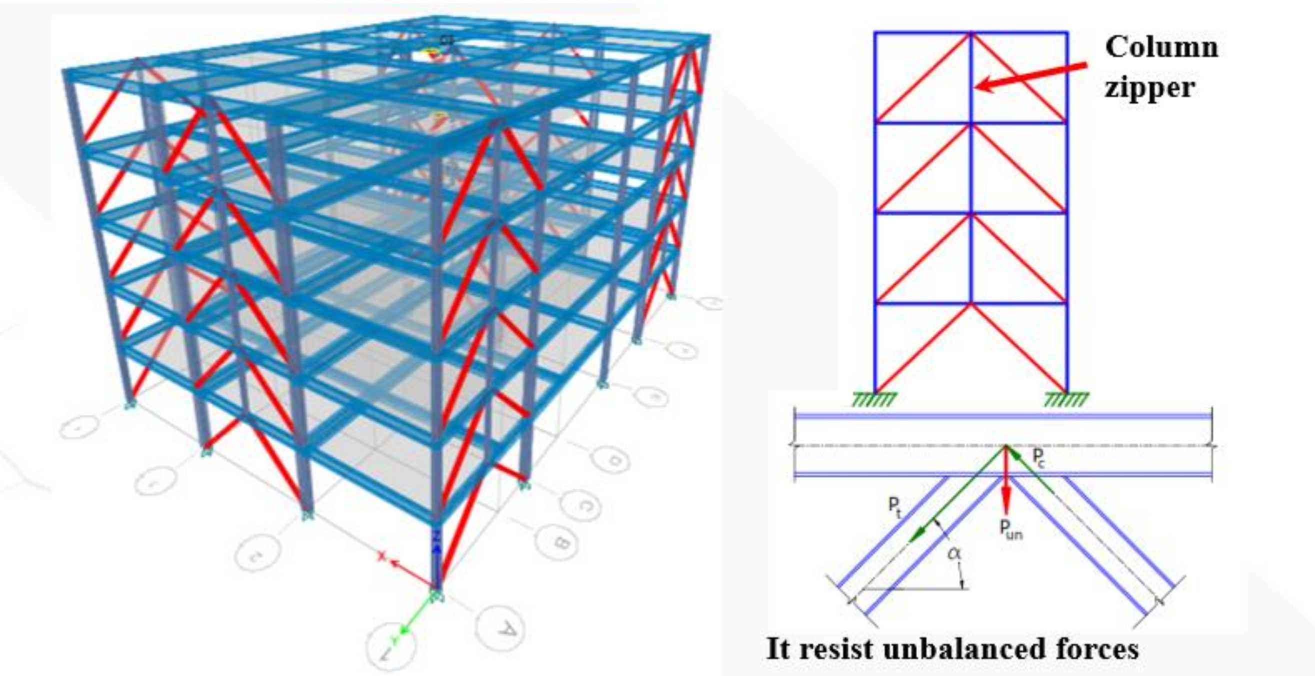

Figure 2. Model of structural steel building

Modeling Description:

1) Gr50 steel for beams, columns and braces (Fy=50 ksi, Fu=65 ksi)
2) Braces are modeled as articulated.
3) The beam-column connections are modeled as articulated.
4) The bases of the columns embedded in the foundation.
5) Rigid diaphragms on floors.

Required seismic demand parameters (E.030 2018):

1) Z=0.45 (Zone 4 of the seismic map of Peru).
2) U=1 (The structure will be considered to have a common use).
3) S=1 (S1 soil will be considered, so TP=0.4s and TL=2.5s)
4) R = 7 Special Concentric Bracketed Gantries (SCBF)
5) R = 8 Gantries with Restricted Buckling Braces (BRBF)

For the redesign with BRB, the same architecture and structural loads were maintained

3. Results and discussion

3.1. Sizing BRB cores using an iterative process

Fig. 3 shows a detail of reinforcement element connections, specifically a Gusset Plate, which is a reinforcement plate used to connect diagonals to structural frames. The main function of this plate is to distribute the loads and reinforce the joint at the critical points where the diagonals intersect other structural elements. In addition, Diagonal Braces are shown, which are structural elements designed to stabilize the structure against lateral displacements or dynamic loads, such as earthquakes. The working length and yield length of these brackets are indicated, suggesting that they are designed to withstand certain load levels before reaching a state of permanent deformation.

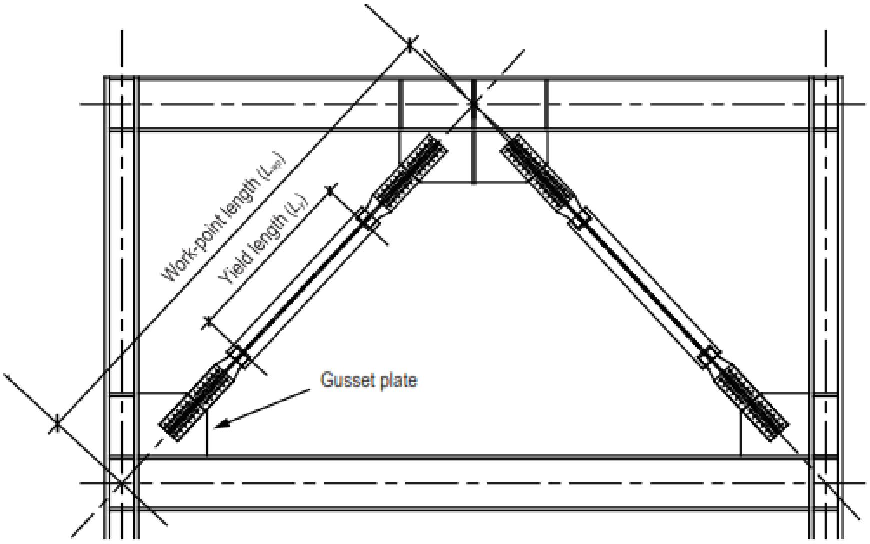

Figure 3. BRB System for X-X Steering: Chevron

Fig. 4 details reinforcement element connections with buckling restriction. It features a Buckling-Restrained Brace, a type of support specialized in preventing buckling under compressive loads, crucial for maintaining the structure's load capacity under seismic events. The structural elements to which the support is connected are also highlighted: Wide-Flange Beam and Column. These structural components, the column and the wide flange beam, provide vertical and horizontal support, respectively. As in the first figure, the working length and creep length are mentioned, which mark the extent to which the support can deform under load before a failure occurs.

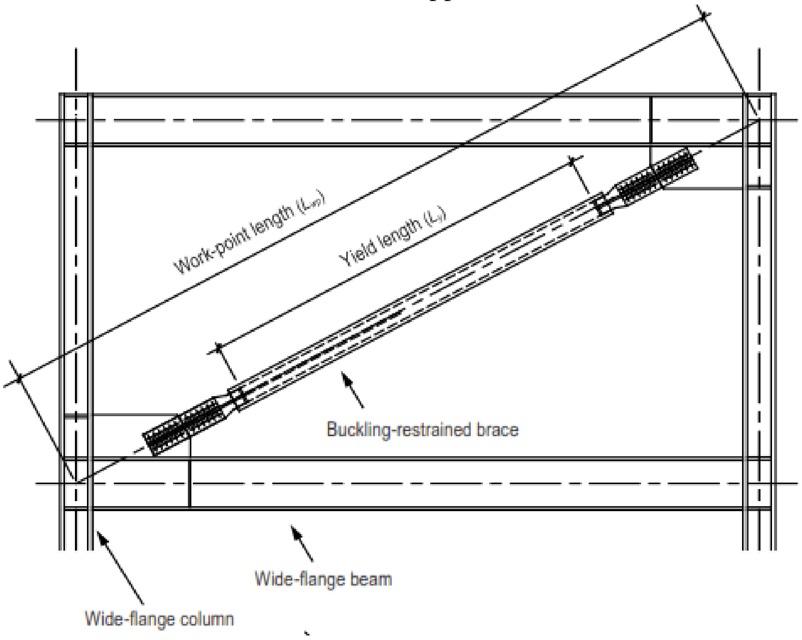

Figure 4. BRB System for Y-Y Direction: Single Diagonal

The figure 5 shows the BRB Design Procedure According to AISC 341.

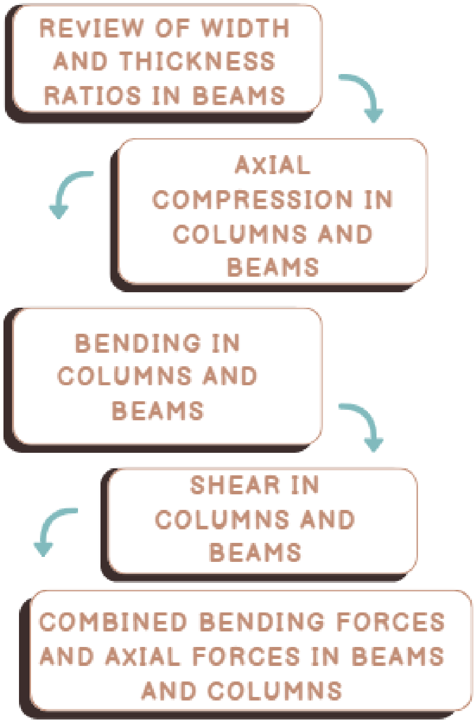

Figure 5. BRB design procedure according to AISC 341

The Table 1 provides detailed information on the strength of steel cores in a chevron design configuration. The table is organized into several columns, each describing a different aspect of the performance of these steel cores. The levels, which range from 1 to 5, indicate the floor level. The "Steel in²" column shows the area in square inches of the steel core used at each level, ranging from 1 in² to 4 in². The "Pu KIP" column represents the ultimate load in thousands of pounds force (KIP) that the cores were able to withstand before failing.

Table 1. Strength of steel cores, Chevron Case

Level	Steel in2	Pu KIP	ØPn KIP	DCR %
1	1	17	34.2	50%
2	2	45	68.4	66%
3	3	58	102.6	57%
4	4	69	136.8	50%
5	4	68.2	136.8	50%

The column "ΦPn KIP" refers to the nominal load adjusted by a resistance factor Φ in KIP, this load being higher than the ultimate load, suggesting the application of an increase factor to encompass certain safety margins or expected behaviors under specific loads. In addition, the "DCR %" or Demand/Capacity Ratio in percentage, shows what percentage of the theoretical capacity was actually used during the tests. For example, a value of 50% indicates that the applied load was half of the adjusted rated load, while a higher value such as 66% indicates usage closer to the adjusted rated limit.

On levels with a steel area of 4 in² (levels 4 and 5), although the ultimate load varies (69 KIP vs. 68.2 KIP), the adjusted rated load remains constant at 136.8 KIP, as does the DCR % (50%). This suggests that, for a given cross-section, there is consistency in the adjusted rated load, but there may be minor variations in the actual ultimate load that the cores can withstand. On the other hand, level 2, with a steel area of 2 in², shows a DCR % of 66%, the highest in the table, indicating that the load capacity of these cores was used closer to their adjusted nominal limit compared to other levels. The resistance factor seems to increase the expected ultimate load (Pu KIP) to a safer nominal load (ΦPn KIP), providing a safety margin in practical application.

The iterative process for sizing BRB cores began with the selection of an initial profile based on the required stiffness and desired energy dissipation capacity. The design methodology proposed by AISC 341 was used [22], which involves the verification of the capacity of the members in two critical states: the forces induced by seismic action and the forces required due to the limit deformation of the BRBs, specifically at 2.0 Δbm.

This iterative process was based on the analysis of mezzanine displacements, ensuring that they did not exceed the limits established by [23]. The reset forces for BRBs, obtained when the strain reaches 2 Δbm, are presented in Table 2, which facilitates the final size selection of the steel cores for the Chevron and inverted 'chevron' V cases.

Table 2. Resetting forces obtained for brbs when strain reaches 2 ΔBm

Level	Asc	Pbx	△bx	△bm	2.0△bm	ε_{BRC}	Adjustment Factors		
	in2	k	in	in	in	%	ω	ω β	β
5	1.00	17	72.71	0.043	0.26	0.70%	1.165	1.214	1.042
4	2.00	45	72.71	0.056	0.34	0.93%	1.252	1.322	1.056
3	3.00	58	72.71	0.048	0.29	0.80%	1.204	1.261	1.048
2	4.00	69	72.71	0.043	0.26	0.71%	1.169	1.219	1.043
1	4.00	68.2	72.71	0.043	0.26	0.71%	1.165	1.214	1.042

Table 3 shows the force levels in Buckling-Restrained Braces (BRBs) for inverted V configurations, with data for yield forces (Pysc KIP), ultimate load (Pu KIP) and maximum capacity (Cmax KIP) increasing with each level, indicating greater support capacity in higher configurations. The stabilized values of Pysc at the lowest levels and the differences between Pu and Cmax indicate a design that incorporates safety margins to ensure structural integrity under severe loads, which is essential in areas of seismic activity.

Table 3. BRB resetting forces for inverted "Chevron" V-case

Level	Pysc KIP	Pu KIP	Cmax KIP
5	46	54	56
4	92	115	122
3	138	166	174
2	184	215	224
1	184	214	223

The design of columns and beams must be verified using two states: 1) By forces induced by the seismic shear at the base and 2) Due to the required forces caused by the limit deformation of the BRB (2.0 Δbm).

3.2. Final configuration with BRB

The final configuration with BRB was determined after completing the iterative sizing process. This configuration is illustrated in Figure 6, which shows the plan view, and in Figures 7 and 8, which show the views of the central E-E and perimeter 1-1 axes, respectively. The final arrangement of the BRBs was the result of a detailed analysis that sought to optimize both the building's seismic response and material efficiency. The restricted buckling bracing was distributed in a way that improved the overall strength and rigidity of the building, while staying within design requirements and architectural constraints [24].

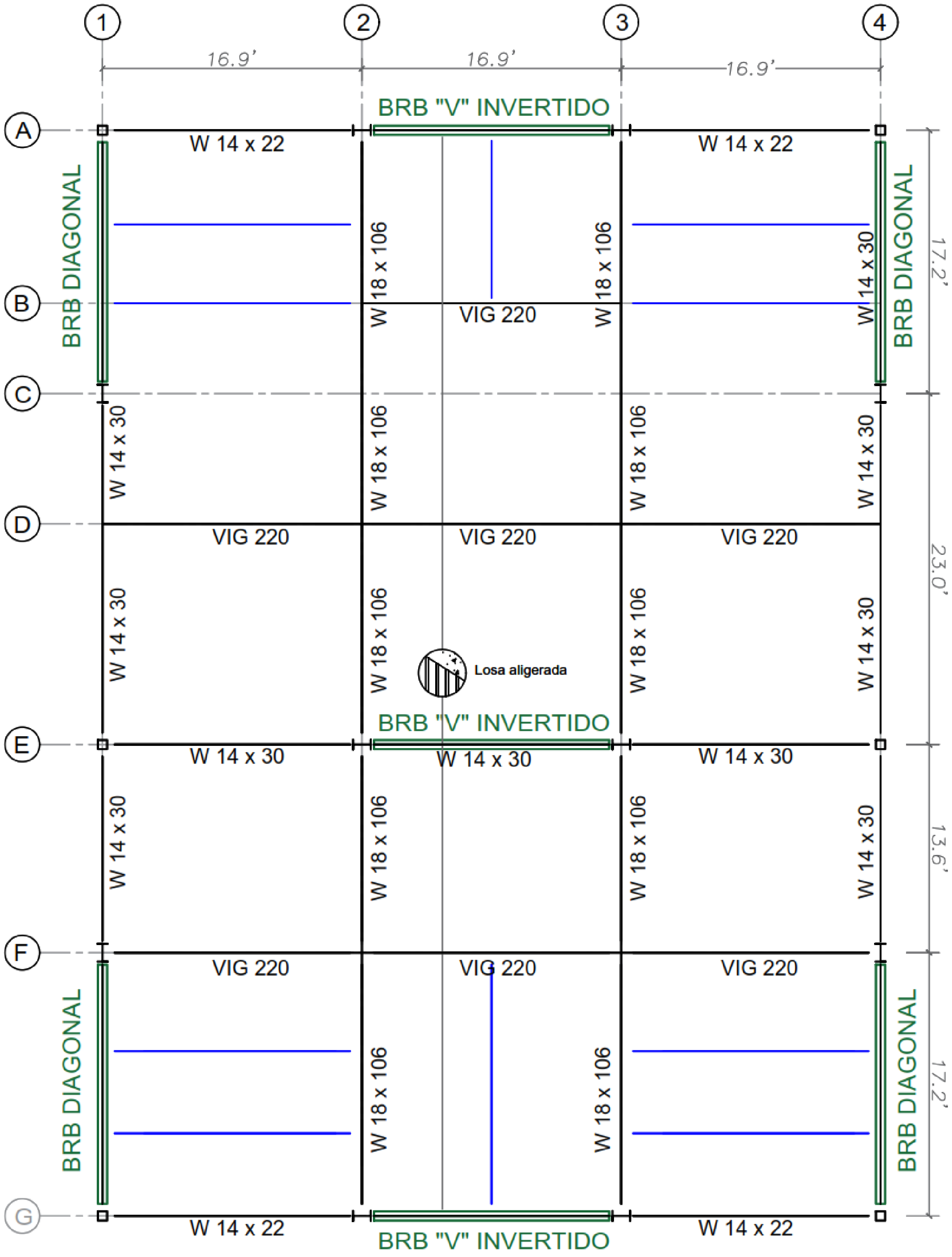

Figure 6. Plan View

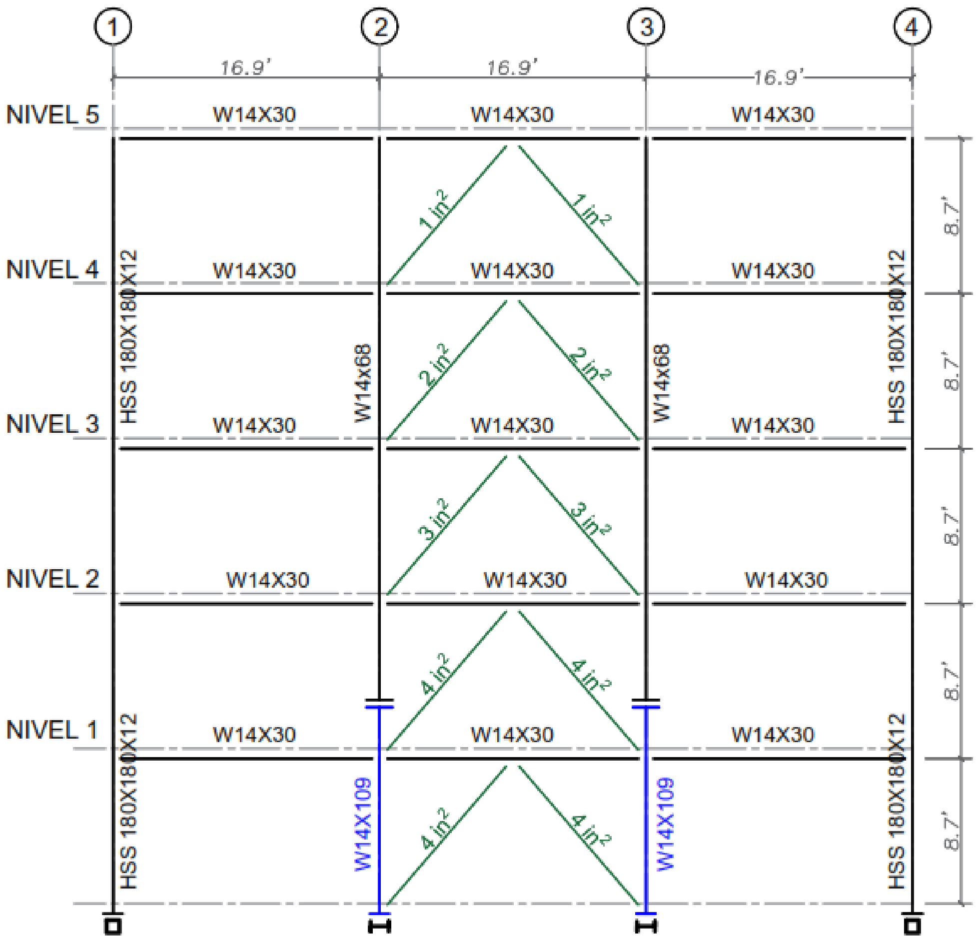

Figure 7. E-E central axis view

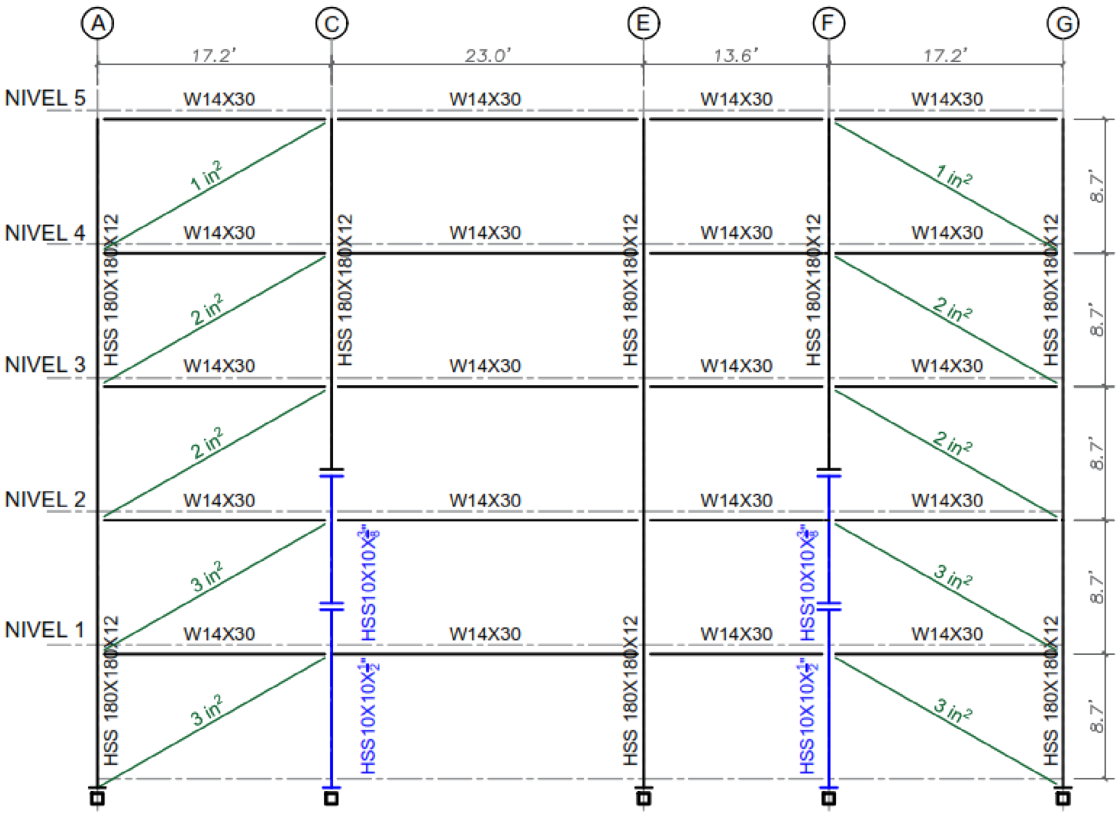

Figure 8. Perimeter axis view 1-1

3.3. Static nonlinear analysis

Nonlinear static analysis of the BRBF system revealed critical information about the structure's behavior under seismic loads. Using the analysis framework proposed by the VISION 2000 committee, occasional, rare and very rare earthquakes were evaluated. The capacity curves, shown in Figures 9 and 10 for the X-X and Y-Y directions respectively, indicated an adequate capacity of the structure to dissipate energy and limit deformations to acceptable levels. The capacity demand curves, Figures 9 and 10, confirmed that the designed BRBF system provides a significant margin of safety and performance, meeting advanced seismic design criteria and performance expectations under various load conditions [25]. It is presented below as Drift (%) and Shear at Base (%Weight)

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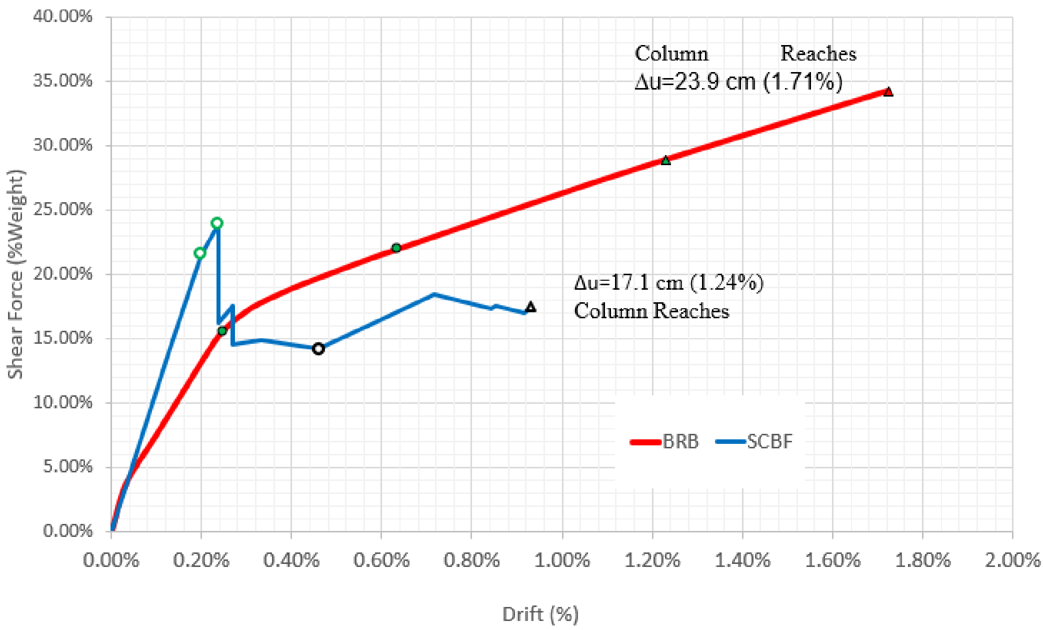

Figure 9 – Capacity Curve X-X Direction

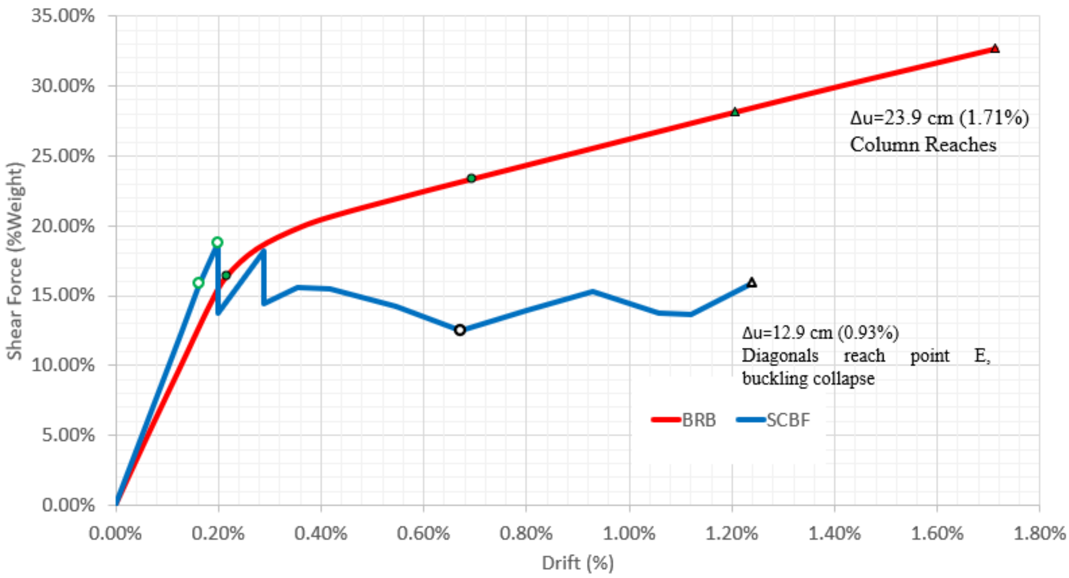

Fig. 10 – Y-Y Direction Capacity Curve

The performance analysis of the BRBF system was carried out according to the VISION 2000 committee, it will be considered an occasional, rare and very rare earthquake, respectively as shown in Figure 11 and Figure 12.

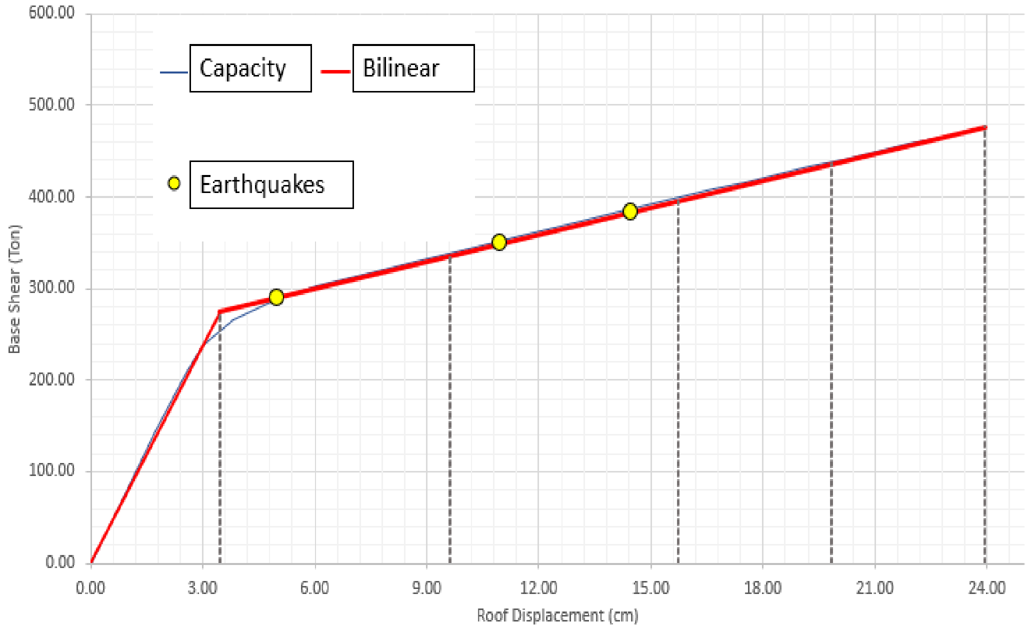

Fig. 11 – Capacity Demand Curves X-X Directions

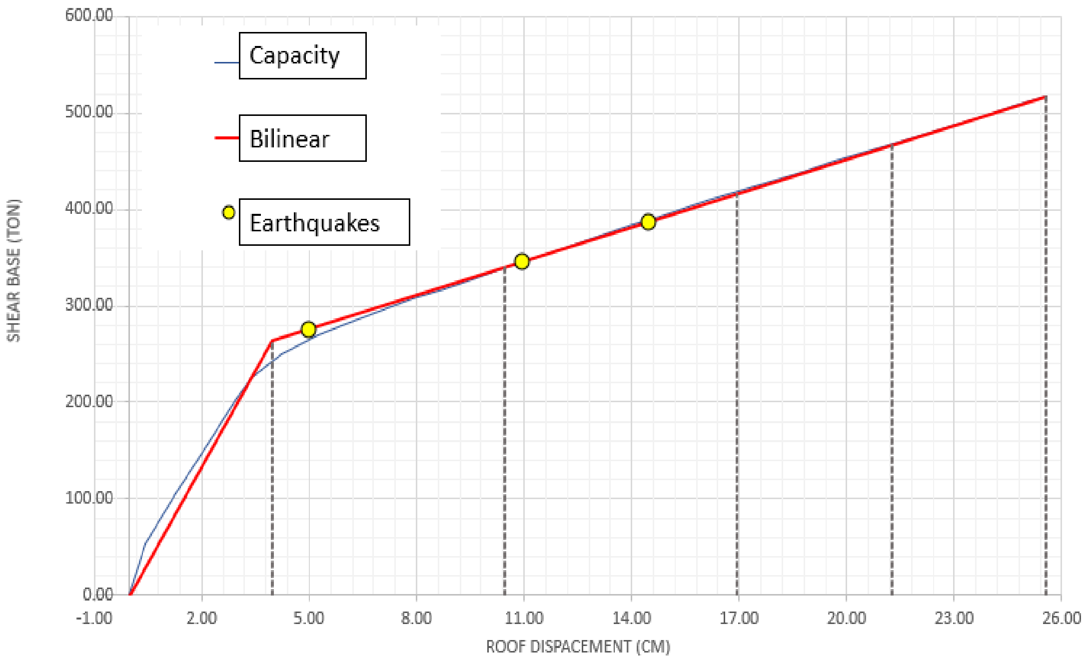

Fig. 12 – Capacity demand curves, Y-Y directions

3.4. Dynamic nonlinear analysis (DNA)

Inelasticities are expected to be concentrated in bracing [26]. For this reason, the other structural elements must remain elastic (subsequent verification):

1. Damping equal to 3% of the critical for steel structures.
2. Iterative Method of Numerical Integration [27]
3. Eight registers were used, with which accelerated grams compatible with the response spectrum of the E030 standard were generated

The result of the dynamic nonlinear analysis are shown in Figure 13 and Figure 14.

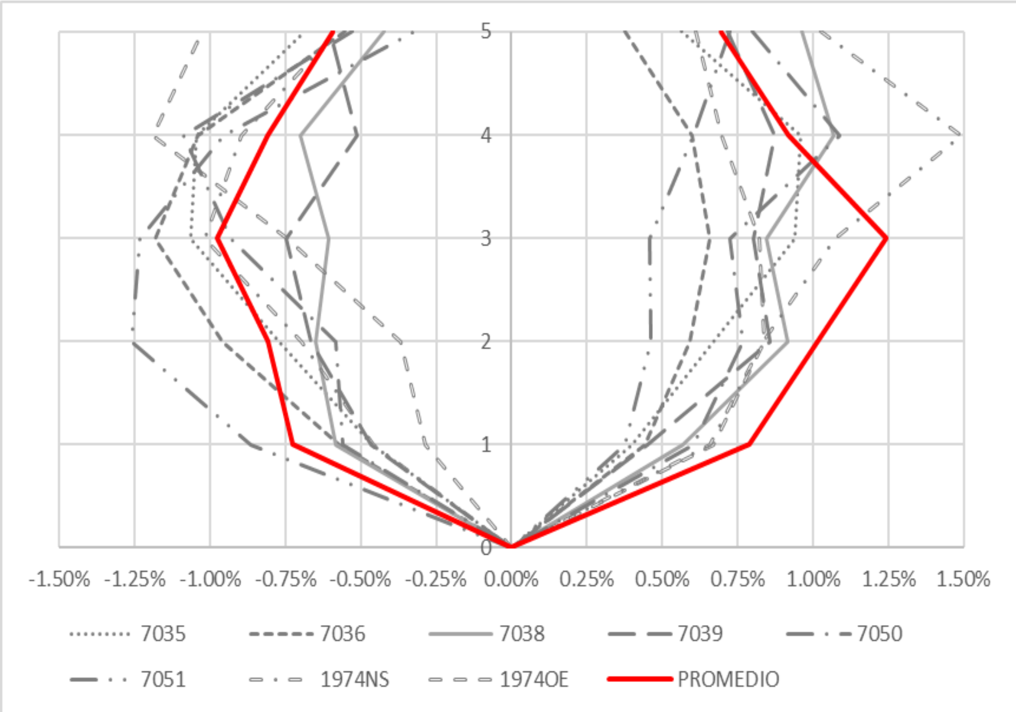

Fig. 13 – DNA mezzanine drifts in XX direction

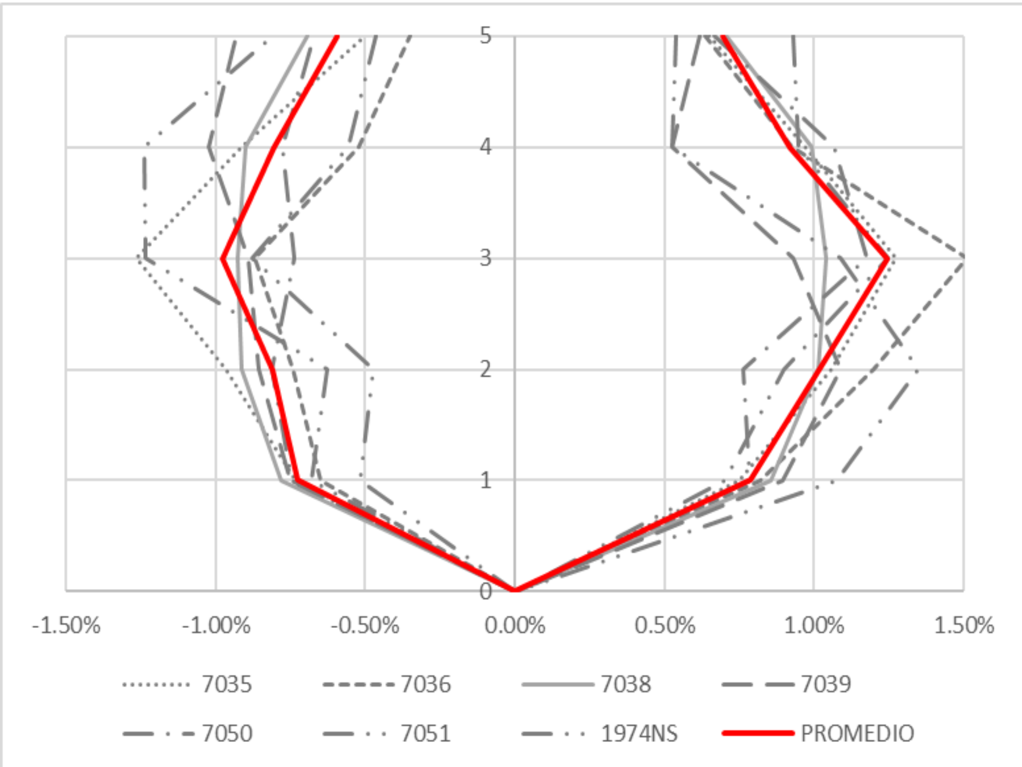

Fig. 14 – DNA mezzanine drifts in the YY direction

3.5. Optimization criteria used to select BRB configurations and their impact on overall structural design and performance

The optimal selection and configuration of the buckle-restricted bracing (BRB) was based on several key criteria to maximize structural performance and material efficiency. First, an iterative process was carried out to size the BRB cores, starting with the selection of an initial profile based on the required stiffness and desired energy dissipation capacity. This process was guided by the design methodology proposed by AISC 341, which involves the verification of the capacity of the members in two critical states: the forces induced by seismic action and the forces required due to the limit deformation of the BRBs, specifically at 2.0 Δbm.

The selection of the final configuration of the BRBs was based on the comparison of the reset forces obtained when the deformation reached 2Δbm and the verification that the mezzanine displacements did not exceed the limits established by the Peruvian E030 standard. In addition, the force distributions of the BRBs in the other components of the frame were adjusted to ensure proper load distribution and avoid excessive stress concentrations.

The impact of these optimization criteria on overall structural design and performance was significant. The optimized configuration of the BRBs improved the building's ability to dissipate energy and limit deformations during seismic events, reducing the forces transmitted to primary structural elements, such as columns and beams. Not only does this improve structural safety and occupant protection, but it also contributes to the sustainability of the building by minimizing damage and the need for post-earthquake repairs.

3.6. Discussion

The results of the study highlight the effectiveness of BRBs in improving the seismic response of the redesigned building. Through nonlinear dynamic analyses, a significant reduction in maximum drifts and accelerations experienced by the structure under seismic loads was observed compared to the original SCBF system. One of the most relevant aspects identified was the ability of BRBs to efficiently dissipate energy, which is reflected in the reduction of forces transmitted to primary structural elements such as columns and beams. This feature is essential for limiting damage during earthquakes, providing greater protection to the infrastructure and its occupants.

Additionally, the adaptability of BRBs in existing buildings was verified, where their implementation could be carried out without significant changes in the building's architecture. This represents a considerable advantage in terms of cost and intervention times compared to other structural reinforcement techniques. The study also highlights the importance of an appropriate configuration of the BRBs, which depends on the specific characteristics of the building and the seismic demands of the region. The proper selection and sizing of these devices are crucial for achieving the desired performance, as demonstrated in the analyses performed, where optimized configurations led to better results in terms of seismic response reduction.

The environmental impact and sustainability considerations associated with the use of BRBs versus other seismic response control techniques are also crucial aspects that need to be addressed. BRBs, designed to deform in both tension and compression, offer superior durability and require fewer maintenance interventions over the life of a structure compared to other seismic reinforcement systems. This reduces the need for frequent replacement and thus the generation of construction waste. In addition, BRBs can be manufactured using recycled materials such as UHPFRC filler [28] and lightweight aggregates derived from tires [29], which reduces the consumption of natural resources and the carbon footprint associated with their production. The implementation of BRBs can, therefore, contribute significantly to the sustainability of construction projects, while also improving structural safety.

The use of BRB heatsinks in current projects in Peru faces very high costs due to the import of these devices and the need for skilled labor for their installation. In addition, most BRB devices are patented and only three companies, Nippon Steel Engineering Co, Core Brace and Star Seismic, supply them in Latin America. To reduce these costs, it is recommended in future research to carry out experimental tests using local materials and technology, which could significantly reduce the manufacturing costs of these devices.

Although the results are promising, further studies are necessary to evaluate the long-term behavior of systems incorporating BRBs under different seismic scenarios. Additionally, it would be beneficial to expand the research to include experimental tests that complement the numerical analyses, providing a stronger basis for the validation of the models used and the hypotheses formulated.

4. Conclusions

A high R = 8 factor can be considered for future BRB designs, this is because BRBF systems are more efficient, BRBF systems are more flexible than conventional CBF systems and can in some cases be governed by boundary drifts rather than force requirements. This value should be accompanied by a coefficient (Cd=5) to that established in ASCE 7-16 [30], since if the provisions of the E030 standard (0.75R = 6) were used, these braces could be oversized. This would result in unnecessary additional costs as well as high transfer forces on beams, columns and connections.

Likewise, it was verified through seismic records that the BRB dissipators are in an inelastic state, allowing the other elements of the frame, i.e. the beams and columns, to continue in an elastic state. In this way, the proper behavior and validation of the proposed design is checked.

Restricted buckling bracing can be implemented in an existing building, particularly because it can be adapted to the rigidity and strength of a constructed building. Particular interest is in the verification of the transmission of axial loads in columns and beams that generate BRBs, as was the case of this research.

Future studies should explore the long-term maintenance requirements of Buckling Restrained Braces (BRBs) and assess their performance across various seismic events. This will help in understanding the sustainability and reliability of BRBs in enhancing seismic resilience over time. Such research could provide crucial insights for optimizing the design and implementation of seismic response systems in earthquake-prone regions.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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Author contributions

Conceptualization: Alan Orellana, Eugenio Orellana and Victor Andre Ariza Flores; Methodology: Alan Orellana, and Victor Andre Ariza Flores; Software: Alan Orellana and Eugenio Orellana; Validation: Alan Orellana and Eugenio Orellana; Formal Analysis: Alan Orellana, Eugenio Orellana; Investigation: Alan Orellana, Eugenio Orellana, and Victor Andre Ariza Flores; Resources: Alan Orellana, Eugenio Orellana, and Victor Andre Ariza Flores; Data Curation: Alan Orellana and Eugenio Orellana; Writing – Original Draft: Victor Andre Ariza Flores; Writing – Review & Editing: Alan Orellana and Eugenio Orellana; Visualization: Alan Orellana, Eugenio Orellana, and Victor Andre Ariza Flores; Supervision: Victor Andre Ariza Flores; Project Administration: Alan Orellana.

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