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Numerical Study of a Buckling Restrained Brace (BRB) in Steel Structures and Comparison with a Convergent Ordinary Brace (OCB) Under Static and Dynamic Loading

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Abstract

Bulk metallic glass (BMG) has good mechanical strength, high hardness, wear resistance, and corrosion resistance with promising application in various industries. However, for the industrial production of BMG, the main issue is how to overcome limitations of joining with other materials. The present study focuses on solder processing at low operating temperature to avoid exceeding the recrystallization temperature. A feasible joining process for BMG was developed using lead-free solders. The BMG surface is pre-plated with copper, nickel, or titanium as a wetting layer. The reaction temperature is set between the glass transition temperature of BMG and the melting point of the solder. After a reflowing and aging process, the joint sample was examined using SEM, EDS, EPMA, and XRD. The Cu–Zr based BMG can be successfully joined with Sn-58Bi solder after plating Cu on the BMG surface. A diffusion layer was observed and the thickness increased with longer aging time. The main components of the diffusion layer are ZrO_2 and $Cu_{10}Zr_7$.

Abstrak

Kajian Numerik Penjepit yang Ditahan Menekuk (BRB) pada Struktur-struktur Baja dan Perbandingan dengan Penjepit Biasa yang Konvergen (OCB) dengan Pembebanan Statis dan Dinamis. Filosofi rancangan gedung-gedung tahan gempa bumi telah mengalami banyak perubahan dalam tahun-tahun belakangan ini. Banyak sruktur yang dirancang dengan metode-metode tradisional, dan juga pengembangan metode-metode analisis serta kemajuan kinerja kompuer yang signifikan, merupakan faktor-faktor yang memberi kontribusi pada perubahan-perubahan tersebut. Di dalam kajian ini, ketahanan sruktur baja yang dijepit diinvestigasi dengan menggunakan penjepit yang ditahan menekuk (*buckling restrained braces* (BRB)) dan dibandingkan dengan suatu penjepit biasa yang konvergen (*a convergent ordinary brace* (OCB)). Gedung-gedung dengan 5, 8, 10, dan 12 lantai yang rancangannya buruk diperkokoh dengan BRB dan kinerjanya diinvestigasi dengan menggunakan analisis statis dan dinamis non linier. Di dalam kajian ini, penguatan bagian-bagian struktur lainnya pada penjepit tersebut diinvestigasi. Hasil-hasilnya menunjukkan bahwa pengurangan sambungan plastis pada perpindahan ruang antara BRB k arah rangka-rangka pada pnjepit konvnsional lbih kcil karena menurunnya prilaku plastis sambungan dan distribusi prpindahan rlatif pada ruang antara.

Keywords: BRB brace, improvement, non-linear static analyses, non-linear dynamic analysis, reinforcement of steel structure

1. Introduction

Reducing the vulnerability of buildings against earthquakes has presented a major challenge to designers and practitioners. The importance of this issue is increasing because of building wear in earthquake zones, construction of buildings without standards and instead using the old design regulations, which has doubled in the past few decades. Therefore, seismic rehabilitation of existing buildings in terms of building construction engineering programs has been proposed. According to earthquake engineering science and advances in seismic design regulations, the question arises to whether the structures that have been designed based on the old regulations could meet the new provisions; otherwise the building must be strengthened to comply with the new regulations [1]. These changes may increase based on building importance, the addition of a stipulation to the conditions of the regularity (well-organization) of the building in the plan, changing the formulas of the building response factor (B), and the building behavior factor (R) for some structural systems, which changes the seismic lateral response forces. Therefore, the structures modeled according to the old regulations do not respond under the same conditions based on seismic provisions of steel structures, and they need to be strengthened [2].

A weakness of common frames is the difference between tensile and compressive strengths; consequently, the resistance declines under encountering cyclic loading. In a buckling restrained brace (BRB), the nucleus should be designed in a way that both compression and tension is acceptable. To prevent ultimate buckling in compression, the nucleus is placed within a steel tube and the space between the tube and steel nucleus is filled with mortar or concrete. Before pouring the mortar, a non-sticky mortar is placed in the empty space between the nucleus and mortar [3].

The main issue with conventional braced systems with a special concentric brace is the difference of tensional and compressive capacity such that in severe earthquakes when the compressive brace is buckled, tensional brace tolerates high non-elastic cycle deformations. As a result, in multi-story buildings braced with special concentric bracelets with decreasing hardness and resistances by buckling, the concentrated non-elastic lateral deformations in that story will increase [4–7].

Faghihmaleki *et al*. [8] compared the behavior of special concentric braced frames with buckling bracelets. Non-linear static analysis with periodical loading was performed on the frames. The results indicate a more formative and stable behavior of the buckling bracelet than a conventional bracelet. Additionally, the effect of the primary geometric defect is significant only in the initial displacement steps and of the percentage of strain hardening is greater, the structure shows greater sustainability against higher forces.

Ariyaratana and Fahnestock [9] investigated the reserve strength generated by members of the rigid brace in a lateral load-resistant system to improve the seismic performance of the buckling brace. These two modes with storage resistance can be used together or separately, which leads to system diversity.

Asgarian and Shokrgozar [10] presented the response modification factor of structures with buckling brace frames and in this study, the traction capability and response modification factor of buckling brace frames were investigated. using linear and non-linear static analysis, linear dynamics, non-linear dynamics on building models with different brace using OpenSees software. They surveyed the effect of parameters on response modification factors, such as the height of the building and the type of system brace. In this article, the behavior factor was determined for the brace systems. In conclusion, the behavior factor decreased by increasing the number of stories.

Chang *et al*. [11] performed a set of 3D non-linear time history analysis for six building samples. They used ordinary earthquakes and nearby areas, and three limit modes were considered. Using the definition of limit modes and relative displacement limit of the proposed story by FEMA356, they calculated the probability of the fracture. The pressure showed that the effect of the braced frames can be considerably changed with the ground and height movement of the building. Added bracing frames helps to reduce the story drift and decreases the fracture probability against conventional movements of the ground. This effect is especially obvious for a building with a low height. In comparison, the bending frame system has lower lateral displacement toward two modes of bracing for near ground movements.

Manfredi and Sarno [12] evaluated the performance of reinforced concrete structures and also investigated the seismic performance of reinforced concrete frames for gravity loads, which showed little lateral strength in their model. To solve this problem, they examined BRB frames and OCB frames using non-linear and dynamic static analyses and found that the lateral displacement was reduced in the model with BRBs.

In 2021, Akcelyan *et al*. [13] proposed a rate-dependent model for low-yield stress buckling restrained braces and a procedure for calibrating the input parameters of the new simulation model. They illustrated two different ways for non-linear frame analysis with the proposed model and validated the proposed model with component BRB experiments.

In 2020, Dong el al. [14] investigated full-scale glulam frames with BRBs under cyclic loading. They proposed two types of timber–steel interface connections, strong and stiff, to work with BRBs efficiently and proved the capacity design approach. The BRBs improved the glulam frames' strength, stiffness, and energy dissipation.

In 2021, Castaldo *et al*. [15] retrofitted an existing 3D RC structure using BRBs. They assessed the influence of the masonry infills on the seismic performance of the structure and evaluated the performance of the. Finally, demand hazard curves for the different EDPs and structural models were performed.

In this study, a braced steel structure resistance using BRB was compared with OCB. To do this, buildings with 5, 8, 10, and 12 floors that were poorly designed were reinforced with BRB and their performance was investigated using non-linear dynamic and static analyses.

2. Introducing the Structures

To survey the strengthening of the steel moment frame structures against earthquakes using BRB, 8 frames, including 4 frames with conventional dog bone-shaped braces and 4 frames with buckling dogbane-shaped braces with conventional similar sections were selected in 5, 8, 10, and 12 story buildings. The height of a story was 3.2 m and the distance between the columns in each frame was 4 m. Beam connection is simple and the column connection is the hinge. The chief system was loin and at last, all points move a story together. Therefore, there is no force and axial deformation. SAP2000 software Ver. 18 was used for modeling. The plan of the buildings is considered in the same form (Figure 1). Two lateral openings of peripheral frames have dog bone-shaped braces (Figure s2 and 3). Table 1 shows the sections used in the modeling. In addition, the building was considered completely regular in the plan and the usage of the building frames was residential. The beams and columns were ST37 steel with tension of F_y=2400 MPa. The maximum of allowed tension is $1/1F_y = 2640$. The loading of frames was based on ASCE7-16 regulation, Edition 2016 [16]. The structures are assumed to have been built in Tehran. This structure was built with average importance in an area with very high relative danger and on ш type soil [17]. In this research, the size of the nucleus and tube, and crust thickness of BRB were 153×19 (mm^2) and 3 mm, respectively. The central nucleus was considered to be smooth steel ST37 and the surrounding steel crust was high-strength steel ST52. Additionally, the concrete is the same usual concrete with compression strength of 21 MPa. There was 2.5 mm of empty space between the central nucleus and concrete/mortar in each side [18]. The mentioned distance is the same thickness of the separating layer so that the nucleus, under the effect of imposed force, enters higher modes, and, consequently, the buckling brace shows better behavior in cyclic loadings. The middle concrete and steel crust were in continuous contact [19],[20].

The frames studied in this research was designed by the allowed tension method based on the tenth subject of Iran building national regulation and seismic loading was based on the analytical static method because of AISC341-16 regulation, Edition 2016 [20]. By allocating plastic joints to the beams and columns of the brace, it was under non-linear static analysis and the level of their function was calculated based on the principles of factor method. While the frame cannot respond to the considerable function level, the frame allocating weaker sections was under linear static analysis and then non-linear static, which continued until displacement of the structure reaches the displacement of the target.

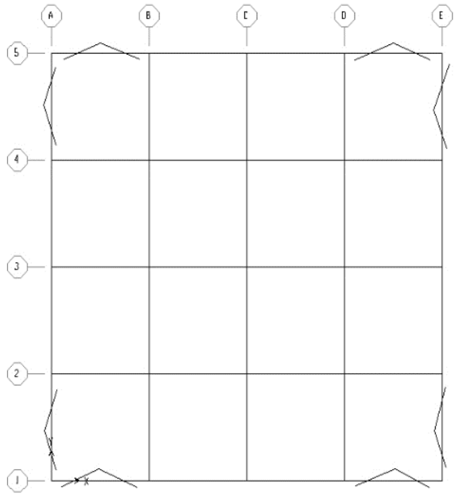


Figure 1. Plan of the Considered Frames

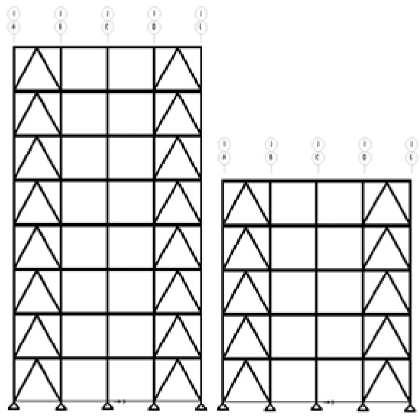


Figure 3. Eight and Five Story Buildings with Brace (Frame 1)

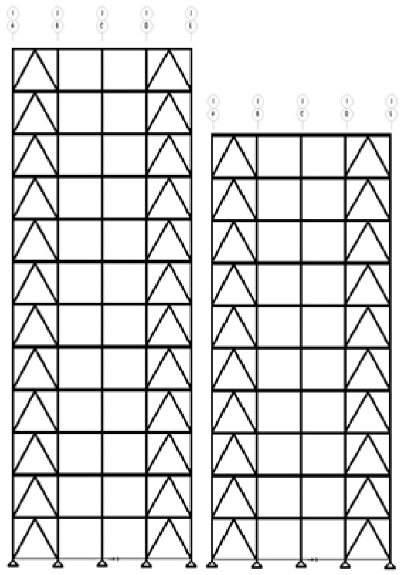


Figure 4. Twelve and Ten Story Buildings with Brace (Frame 1)

Gravitational loads on the building are dead and alive. The amount of dead load is based on executive details of chiefs and walls and the amount of alive loads is because of the usage of different parts of the building from ASCE7-16 regulation [16], and it is a linear load and based on the width of the loading surface of each frame that is 2 m, which entered on the beams of story. In this research, seven accelerometers were used to record the non-linear time history analysis of the earthquake because the minimum records required for dynamic analysis of time history was equal to seven records [17]. Table 2 shows the data for mapping acceleration. The acceleration of mappings had the following common features: (a) It is located in one classification of soil. (b) It is located in a nearly identical distance from the place of fault. (c) It has features of the areas far from the fault.

Table 1. The Sections used in the Modeling

Story	Column	Beam	OCB Brace
1	2IPE 600	2IPE 600	2UNP 400
2	2IPE 600	2IPE 600	UNP 380
3	2IPE 550	2IPE 550	UNP 350
4	2IPE 500	2IPE 500	UNP 350
5	2IPE 450	2IPE 450	UNP 320
6	2IPE 450	2IPE 450	UNP 320
7	2IPE 400	2IPE 400	UNP 300
8	2IPE 360	2IPE 360	UNP 280
9	2IPE 360	2IPE 360	UNP 260
10	2IPE 330	2IPE 330	UNP 260
11	2IPE 300	2IPE 300	UNP 240
12	2IPE 300	2IPE 300	UNP 200

Table 2. Data of Mapping Acceleration

Number	Year	Station Name	Earthquake Name	Earthquake Magnitude	PGA (g)
1	1979	Halles valley	Coyote Lake	5/74	0/0416
2	1984	Apeel 1E –Hayward	Morgan hill	6/19	0/0367
3	1989	Saratoga – Aloha Ave	Loma Prieta	6/93	0/3821
4	1994	LA – Hollywood Stor FF	Northridge	6/69	0/3354
5	1971	LA – Hollywood Stor FF	San Fernando	6/61	0/2101
6	1991	LOS ANGELES	SIERRA	5/61	0/2237
7	1980	Chihuahua	Victoria	6/33	0/1179

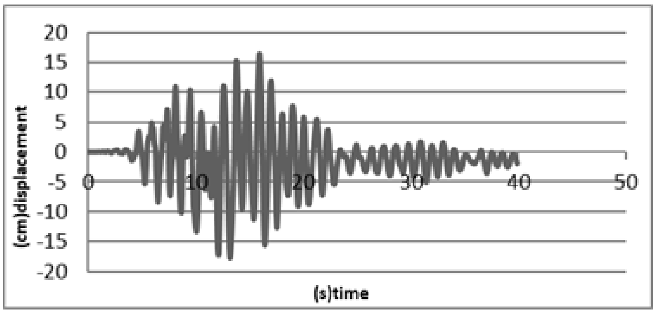


Figure 4. Acceleration of the Northridge Earthquake

Figure 4 shows a sample of mapping acceleration (Northridge earthquake) that used non-linear dynamic analysis. Table 2 lists other records.

For non-linear static analysis, all frames were pushed until displacement of the target. In this section, the factor method was applied for the displacement of the target. In this method, non-linear static analysis was conducted first and the base shear curve against the pushover curve was obtained. The displacement of the target can be obtained based on the pushover curve. In the frames were under steady lateral load pattern, the first mode was triangular. Alternatively, plastic deformations in the beams and columns of the bending frame under lateral loads of earthquakes appeared as plastic joints at the beginning and the end of the beams and columns. Plastic bending joints (M) were allocated at the end of the two beams. The axial-bending joint was allocated 0.475 and 0.525 along the beam and 0.05 and 0.95 along the height of the column. The axial plastic joint was defined for braces and located in the middle. Tables 2–4 list the function of frames.

3. Analysis of the Modeled Structures

Five Story Structure

Non-linear Static Analysis. For the non-linear static analysis of the five story structure, three lateral load patterns of triangular, steady, and first mode were used. For example, a five story frame with joints under the triangular lateral load pattern are displayed in Table 3.

As shown in Table 3, some joints pass from life safety (LS) are more limited in the OCB frame than in BRB, which indicates the weakness of this type of system.

In this section, graphs of the pushover of the structure under lateral load patterns are displayed in Figures 5–7. In a general, the number of plastic joints that passed from the LS limit was greater in the OCB mode and caused joints especially in the columns to decrease the OCB capacity of the horizontal area at the end of the graph and early submission.

The deformed form of the five story frame from pushover analysis is displayed in Figure 8.

According to Figure 8, joints in the frames with conventional brace have a greater limit than in joint column. In the frames with buckling brace the pressure will enter the columns and plastic joint is created because the brace is strong. To improve making plastic joints, the amount of immediate occupation (IO), LS, and collapse prevision (CP) are used. B indicates the stage before non-stop usage. C, D, and E are stages to complete destruction.

Table 3. Joints in a Five Story Frame under Triangular Lateral Load Pattern

Type	Target Displacement	B	IO	LS	CP	C	D	E
OCB	5.578	1	7	0	0	1	5	0
BRB	4.47	0	1	0	0	0	0	0

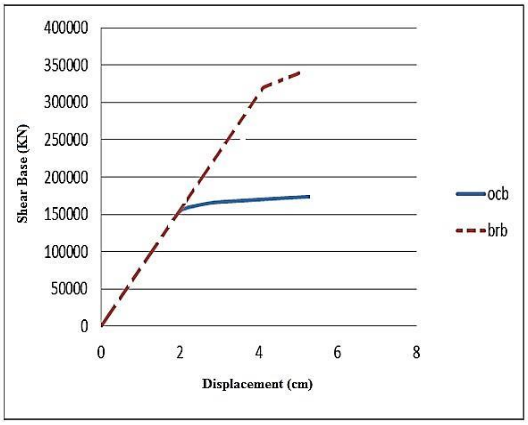


Figure 5. Base Shear Curve-displacement Under Triangular Lateral Load

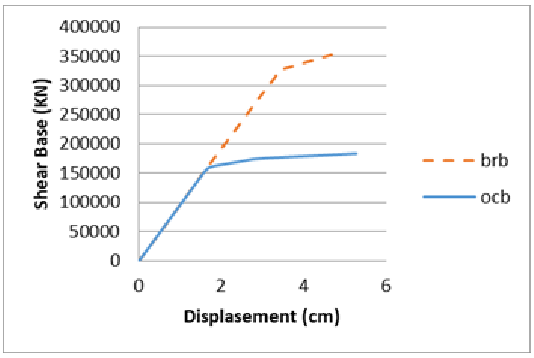


Figure 6. Base Shear Curve-displacement under Steady Lateral Load

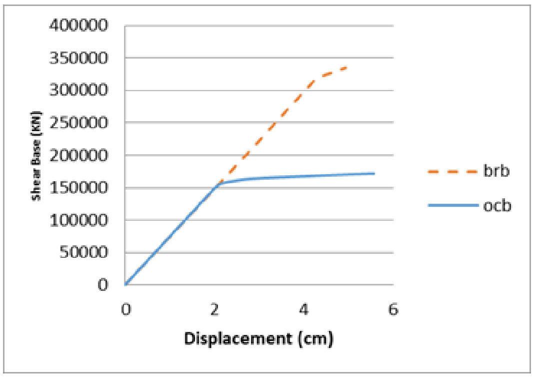
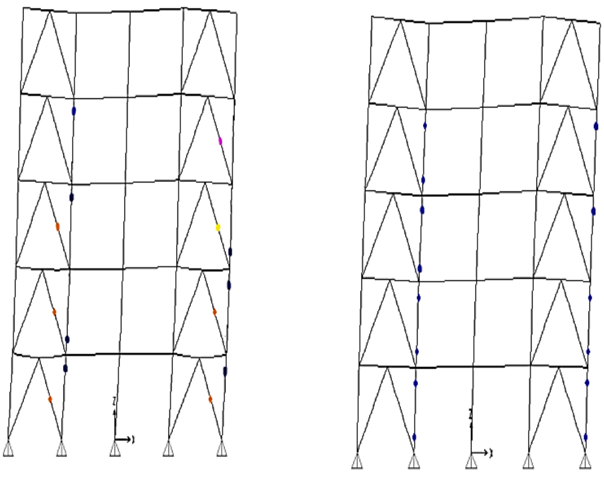


Figure 7. Base Shear Curve-displacement under the Lateral Load of the First Mode



(a) (b)

Figure 8. (a) Plastic Joints in the Structure with a (a) Conventional Brace and (b) Buckling Brace under Triangular Lateral Load

For non-linear dynamic analysis of the models, seven scaled earthquakes, of Coyote Lake, Morgan Hill, Northridge, Loma Prieta, Sierra Madre, San Fernando, and Victoria, were applied to evaluate the plastic joints of a five story frame.

Non-Linear Dynamic Analysis of a Five Story Structure

Scaling Mapping Acceleration. Acceleration of the selected mappings should be based on the method of AISC 341-16 regulation, Edition 2016 [14]: a) All mapping accelerations will be scaled as their maximum amount, which means their maximum acceleration equals g gravitation acceleration. b) The response spectrum of acceleration of each couple of scaled mapping accelerations is determined by a applying 5% damping ratio. c) Response spectrums of each couple of mapping accelerations are combined using a square root method and a combined spectrum will be made for each couple. d) The spectrums of the combined response of mapping acceleration couple are averaged and compared in the range of alternating times 0.2 T and 1.5 T with a standard spectrum. The scale coefficient is determined such that is in this range, the number of means in no mode will not be lower than 1.4, its peer amount in the standard spectrum. T is the time of the main alternate of the building. e) The factor of determined scale (Table 4), should be multiplied by the acceleration of scaled mappings in clause (a) and will be used in dynamic analysis.

The deformed form of five story frame from the non-linear time dynamic analysis is displayed in Figure 9. The number of joints under different mapping accelerations is displayed in five story frames in Table 5.

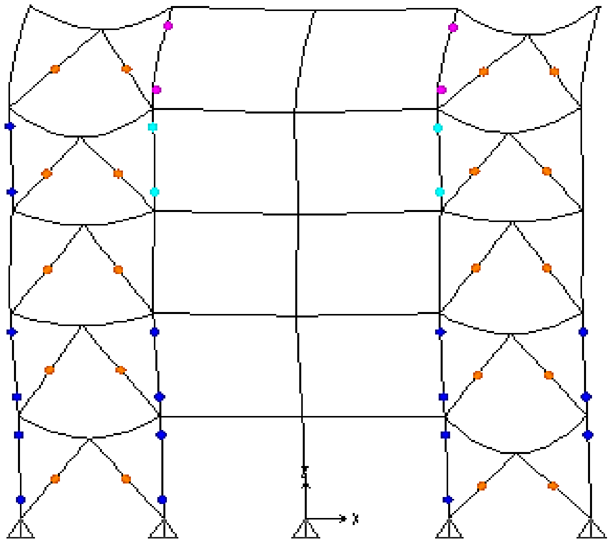
Based on Table 4, in the frames with conventional braces, more joints pass from the LS limit and there is the maximum of joints. By surveying Figures 14 to 20, the frames, the number of made joints in the columns with BRB braces that did not pass from LS limit, is greater than the frames with OCB brace because BRB transfers the force to the columns and creates more joints in this area. However, in the frames with OCB brace, the plastic joints are created first in the braces and then in the columns. The displacement and relative displacement of the story under non-linear time history is displayed in Figure 10.

Table 4. Scale Factor

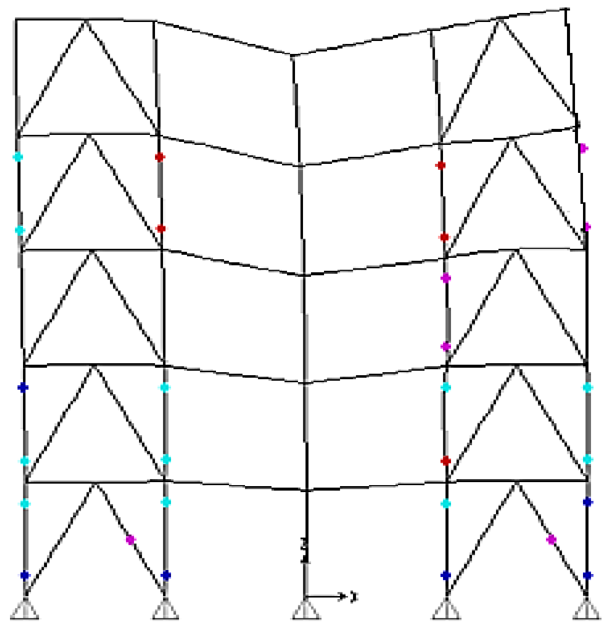
Story	5	8	10	12
SC Factor	0.53	0.565	0.682	0.72

Table 5. The Number of Joints under Different Mapping Accelerations of the Coyote Lake Earthquake in Five Story Frame

Type	B	IO	LS	CP	C	D	E
OCB	4	17	4	0	0	20	0
BRB	6	6	11	0	0	0	5



(OCB)



(BRB)

Figure 9. Plastic Joint in the Structure under the Coyote Lake Earthquake with a Conventional Brace and Buckling Brace

Based on the seven mapping accelerations applied to a five story structure with buckling braces, the displacement of stories with OCB and BRB had a decreasing trend. The relative displacement of the story in comparison with conventional braces had a special order and low changes were evident in each lower story.

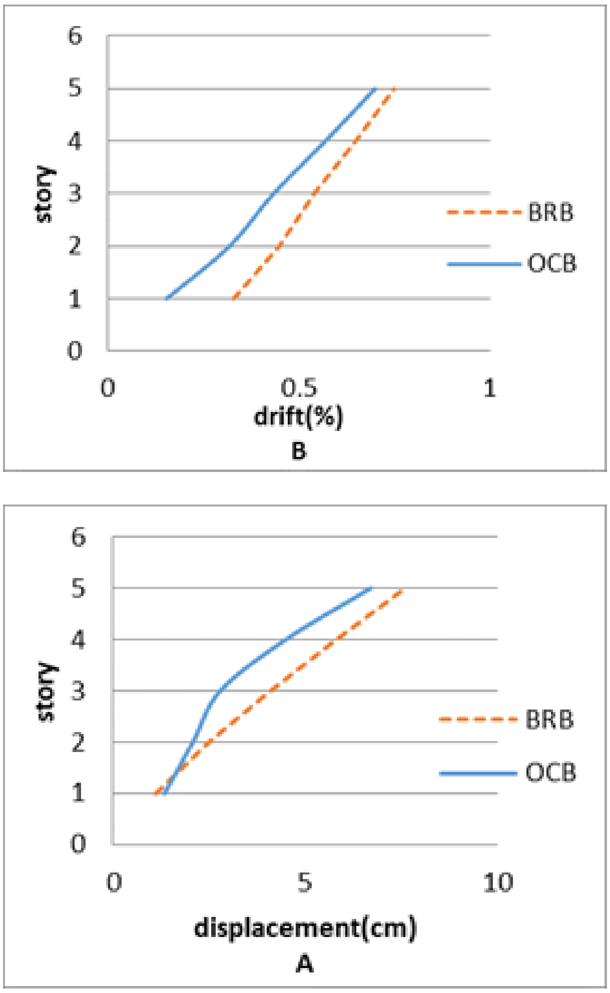


Figure 10. The Maximum of Displacement and Relative Displacement of Stories under the Coyote Lake Earthquake

Story Structure

Plastic Joints in an Eight Story Frame under Lateral Loads. In this section, also for determining the function of frames in making the plastic joint, (Table 6).

As shown in Table 6, as in the previous mode, some joints passing from the LS limit in OCB frame is greater than BRB, which shows a weakness of the system.

Table 6. Joints in an eight story frame under steady lateral load pattern

Type	Target Displacement	B	IO	LS	CP	C	D	E
OCB	12.38	0	4	0	3	0	7	0
BRB	13.25	0	12	0	2	0	0	0

Base Shear Curve-displacement under Lateral Load Patterns in an Eight Story Frame

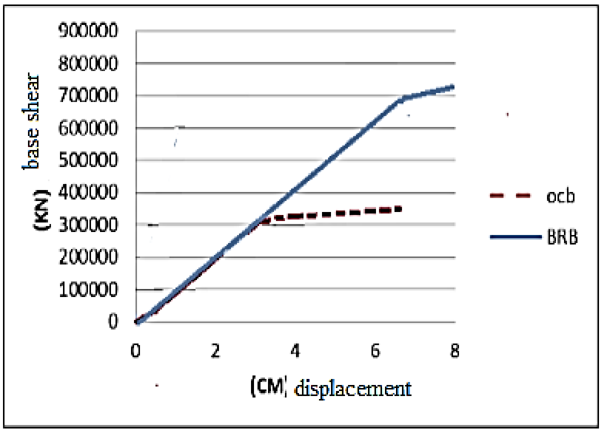


Figure 11. Base Shear Curve-displacement under Steady Lateral Load

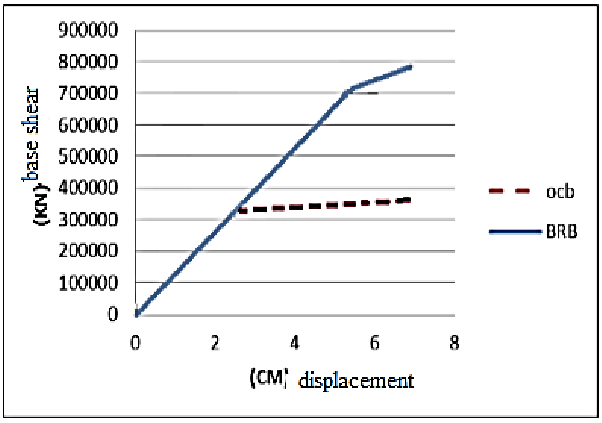


Figure 12. Base Shear Curve-displacement under Triangle Lateral Load

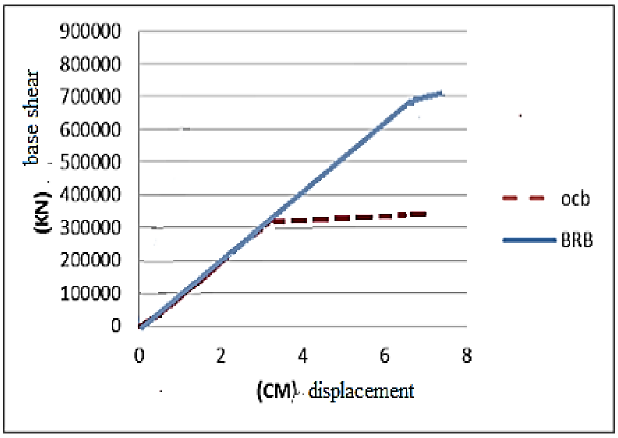


Figure 13. Base Shear Curve-displacement under Lateral Load of the First Mode

The Description of Non-linear Dynamic Analysis of 8 Story Structure

Displacement and Relative Displacement of an Eight Story Frame. Based on the seven mapping accelerations applied to an eight story structure, the displacement of story for OCB and BRB had a decreasing trend. Additionally, the relative displacement of the story in the buckling brace compared with conventional braces had a special order and there were few changes in each story toward the lower story.

Story Structure

Plastic Joints in a Ten Story Frame under Lateral Loads. As shown in Table 8, some joints that pass from the LS limit in the OCB frame are greater than the BRB, which indicates the weakness of this type of system.

Table 7. Joints under Mapping Acceleration of the Loma Prieta Earthquake in an 8 Story Frame

Type	B	IO	LS	CP	C	D	E
OCB	1	10	0	4	0	8	0
BRB	0	17	3	0	0	0	0

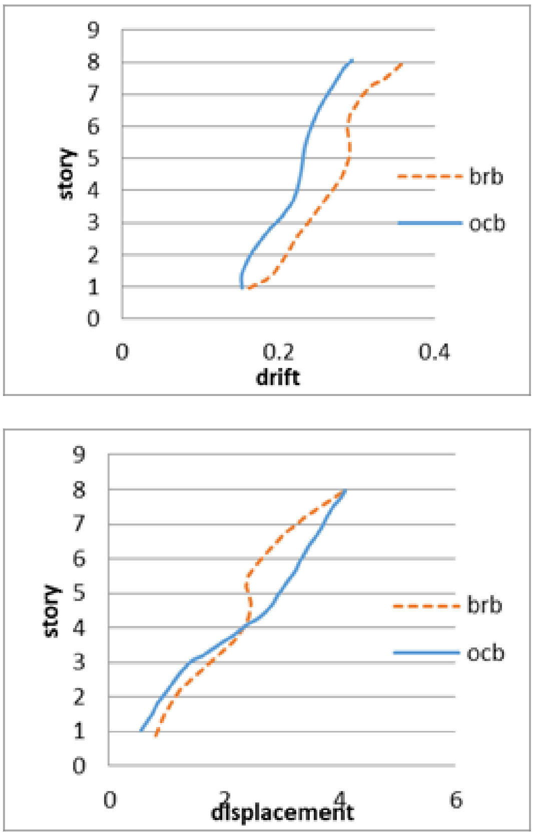


Figure 14. The Maximum Displacement and Relative Displacement of a Story under the Lome Prieta Earthquake

Table 8. Joints in Five Story Frame under Lateral Load Pattern of the First Mode

Type	Target Displacement	B	IO	LS	CP	C	D	E
OCB	1762	0	9	3	1	0	8	2
BRB	17.38	0	13	2	0	0	0	0

Base Shear Curve-displacement under Lateral Load Patterns in a Ten Story Frame

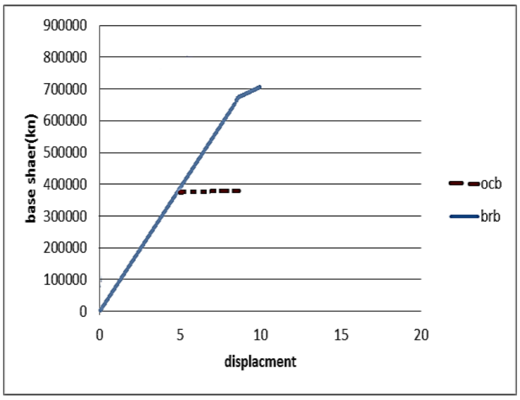


Figure 15. Base Shear Curve-displacement under a Steady Lateral Load

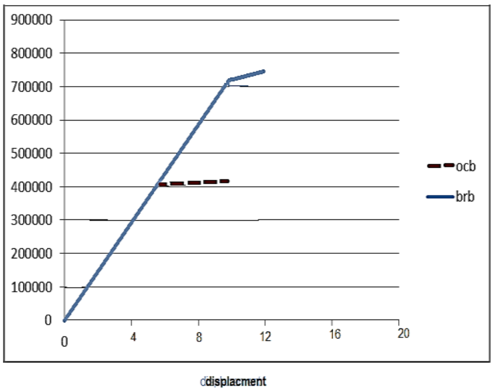


Figure 16. Base Shear Curve-displacement under the Triangular Lateral Load

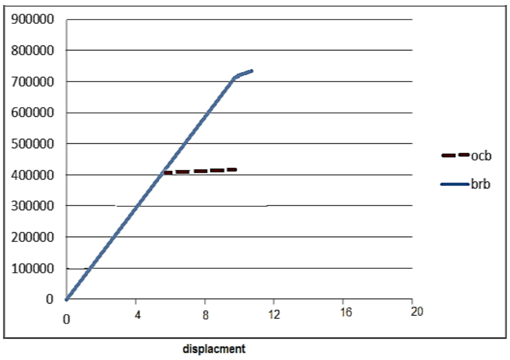


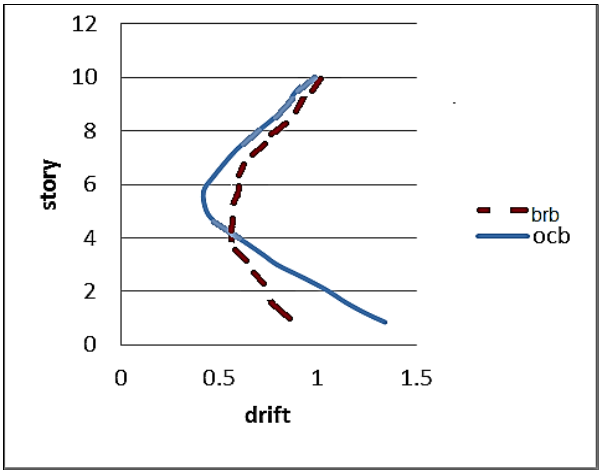
Figure 17. Base Shear Curve-displacement under the Lateral Load of the First Mode

Description of Non-linear Dynamic Analysis of a Ten Story Frame

Displacement and Relative Displacement of Ten Story Frame. Based on seven mapping accelerations applied to a ten story structure, the displacement of the story for OCB and BRB had a decreasing trend. In the relative displacement of stories in comparison with conventional braces has a special order and there are few changes in each story toward the lower story.

Table 9. Number of Joints under Mapping Acceleration of Morgan Hil earthquake in a Ten Story Frame

Type	B	IO	LS	CP	C	D	E
OCB	1	6	0	0	0	12	0
BRB	0	11	2	0	0	0	0



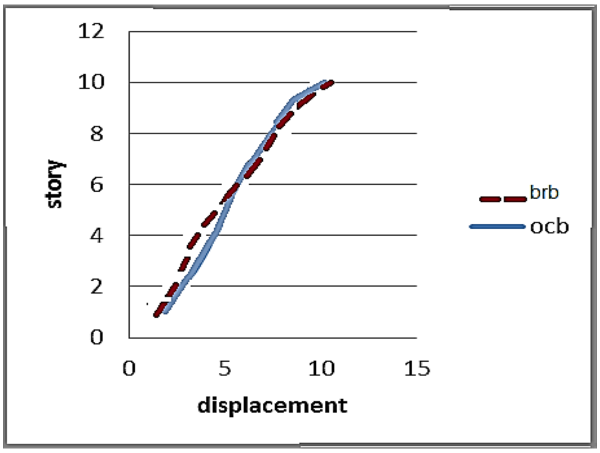


Figure 18. The Maximum Displacement and Relative Displacement of the Story under Morgan Hil Earthquake

Story Structure

Plastic Joints in a 12 Story Frame under Lateral Loads. As shown in Table 10, the number of joints that passes from the LS limit in the OCB frame is greater than BRB, which indicates the weakness of the system.

Table 10. Joints in 12 story frame under triangular lateral load pattern

Type	Target Displacement	B	IO	LS	CP	C	D	E
OCB	18.37	1	7	0	4	1	2	0
BRB	18.2	0	10	0	0	0	4	0

Base Shear Curve-displacement under Lateral Load Patterns in 12 Story Frame

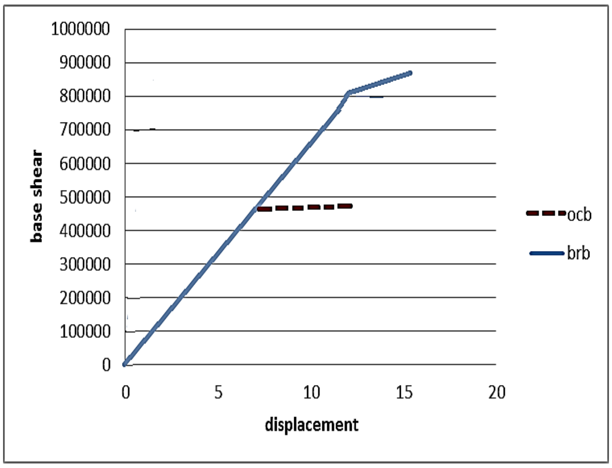


Figure 19. Base Shear Curve-displacement under the Triangular Lateral Load

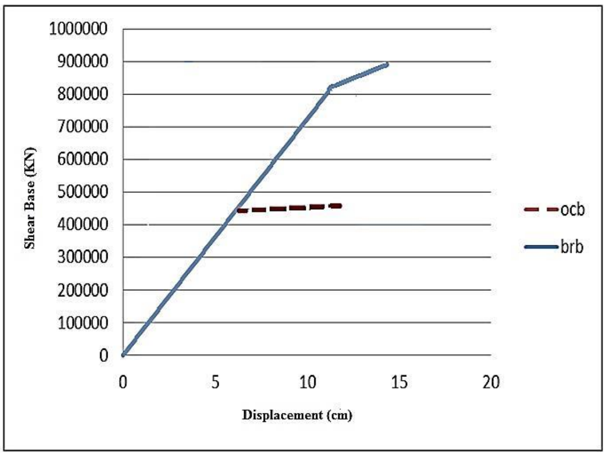


Figure 20. Base Shear Curve-displacement under Steady Lateral Load

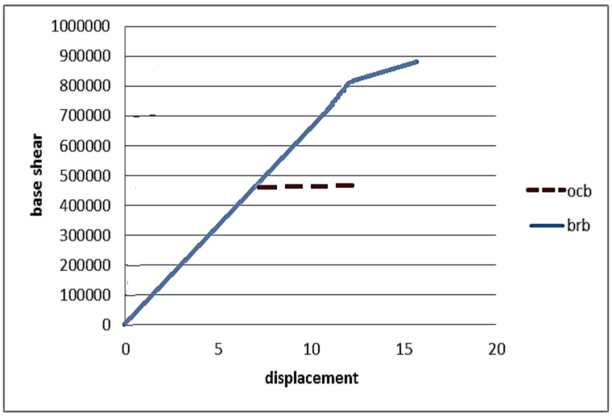


Figure 21. Base shear curve-displacement under the Lateral Load of the First Mode

Table 11. Number of Joints Under Mapping Acceleration of the Northridge Earthquake in a 12 Story Frame

Type	B	IO	LS	CP	C	D	E
OCB	0	21	0	4	0	8	0
BRB	1	11	1	0	0	5	0

Displacement and Relative Displacement of the 12 Story Frame

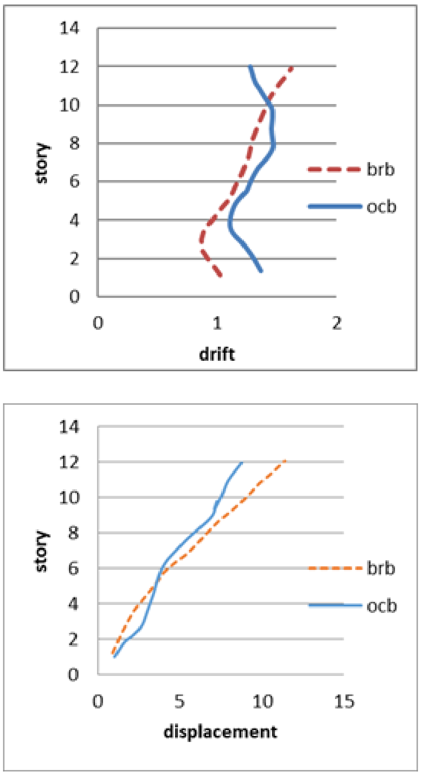


Figure 22. Displacement and Relative Displacement of the Story under the Northridge Earthquake

Description of Non-linear Dynamic Analysis of a 12 Story Frame. Based on the number of joints under mapping acceleration (Tables 7, 9 and 11), in the frames with conventional braces, more joints pass from the LS limit. Additionally, in the frames with BRB brace, the number of made joints that did not pass from LS limit was more toward the frames with OCB brace and the trend of making plastic joints was based on the columns with the braces with fewer stories. The use of a BRB caused the transfer of force to the columns and produced more joints in this area. In the frames with OCB brace, the trend of making plastic joints was first observed in the braces and then in the columns.

Based on the seven mapping accelerations applied to the 12 story structure, the displacement of stories for OCB and BRB had a decreasing trend. The relative displacement of stories compared with conventional braces has a special order and there were few changes in each story toward the lower story.

4. Conclusion

In this study, the strengthening of structures against earthquakes were surveyed using buckling braces and were analyzed using non-linear static and non-linear dynamic analyses. Their function was investigated and compared with conventional braces. The following results were obtained: (a) Buckling braces with a hysteresis curve had the same behavior in traction and pressure, which caused an increase in plasticity and more energy absorption of the structure. The BRB presented and optimized behavior. (b) The BRB system can be considered a desirable alternative for designing a seismic load system because of the very high plasticity and the suitable lateral hardness. (c) Buckling braces act in most cases as a fuse and prevent the submission of main members of the structure such as the columns. (d) In all different types of lateral load, with increasing elevation (or story), the base shear increase and the level of performance of the structure decreases in the structures modeled with 5, 8, 10 and 12 floors. (e) In general, because of decreasing plastic joints in BRB compared with the frames with the conventional brace, the displacement of the story was less because of the distribution of the relative displacement in the story.

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