

The Performance of Concentrically Braced Frames (CBF) in Chevron V Brace and Diagonal Configuration by Considering Various Frame Heights

**Arief Panjaitan^{1*}, Purwandy Hasibuan¹, Rudiansyah Putra¹, Mochammad Afifuddin¹,
Muhammad Haiqal², Fakhran Adian³, Dwi Putroe Naulia³, Asraf Hazid³**

¹Civil Engineering Department, Faculty of Engineering, Syiah Kuala University, 23111, Indonesia

²Architecture Department, Faculty of Engineering, Syiah Kuala University, 23111, Indonesia

³Alumni of Civil Engineering Department, Syiah Kuala University, 2311, Indonesia

*Corresponding author: arief_panjaitan@usk.ac.id

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Abstract – Concentrically Braced Frame (CBF) is a structural system with high stiffness, so it is recommended to be implemented in earthquake-hazard areas. The stiffness in CBF is contributed by its diagonal component, which is called bracing. Bracing reduces lateral deformation on the frame system because of the earthquake and prevents heavy damage or failure of the structure. So far, several studies have been conducted. However, the effect of the frame height and the bracing configuration on the CBF performance has not yet been clarified. This study analytically investigated several models of CBF in Chevron V Brace and Diagonal configurations. Those models were prepared with different frame heights. The analyses were conducted by employing the cyclic load and considering yield displacement control in each model. The observation was emphasized on the load-displacement hysteresis curve, from which the performance of each model can be revealed. Three parameters of performance are evaluated: strength, stiffness, and dissipation energy. The analysis discovered that the Diagonal CBF performed better than the Chevron V Brace CBF by presenting a larger and more stable hysteresis curve, which is addressed to better energy dissipation. It is also discovered that reducing the frame height is suggested to enhance the CBF performance due to the earthquake.

Keywords: Concentrically Brace Frame (CBF), CBF configuration, cyclic load, hysteresis loop, structural performance, dissipation energy

Introduction

A seismic-resistant structure is required to be established in the earthquake-hazard area to ensure the strength of the building. Concentrically Braced Frame (CBF) is one of the seismic-resistant structures with high stiffness that comes from its diagonal component, bracing. In CBF, bracing is a component that dissipates earthquake energy to diminish the damage to structural components such as beams and columns. So far, several studies have been conducted. Deghan *et al.* (2020) investigated the seismic behavior of two-story and four-story Chevron Braced Frames. Those models were studied by means of a nonlinear cyclic pushover and nonlinear response history analysis methods.

Azad *et al.* (2017) analytically studied the seismic behaviors of several Concentrically Braced Frames (CBFs) configurations, i.e., X-braced, Split X-Braced, and V-Braced, under various nonlinear time histories. The CBF's configurations were designed according to the United States and Europe provisions. Rai and Goel (2003) presented an analytical study of seismic behavior and the future upgrading of Ordinary Steel Concentric Braced Frame (OCBF) structures by preventing brace member local buckling. Dicleli and Mehta (2007) studied the seismic performance of Steel Chevron V-Braced Frames with and without viscous fluid dampers (VFDs) as a function of the intensity and frequency characteristics of the ground motion and VFD parameters. Sen *et al.* (2017) examined the vulnerability of older V-braced CBF infrastructure with yielding beams. This research showed that brace yielding in tension is prevented due to beam deflection, but frame action mitigates the reduced brace resistance. Okazaki *et al.* (2013) conducted a large-scale shake table to examine the dynamic response of a steel concentrically braced frame. The test revealed excellent performance from the bracing connections. Elastic

deformation of the beam prevented the braces from developing their full tensile strength. Saloma *et al.* (2017) present Diagonal and V-braced steel Structure designs with pushover analysis following ATC40 guidelines. This study presented the capacity curve, the performance point, and the process of the plastic hinge until the collapse of the building.

Thongchom *et al.* (2022) proposed X-Bracing to enhance the damper shear strength, and its behavior is evaluated numerically and parametrically. To consider the parameters to predict the behavior of the damper, the required equations are proposed. Razak *et al.* (2018) reviewed the influence of various types of structural bracing on the structural performance of buildings. The study revealed effective structural bracing that is able to enhance structural performance due to lateral excitation. Leslie *et al.* (2013) provided a designer's view on asymmetric friction connections (AFC), their advantages and disadvantages, and how to consider their application in Concentrically Braced Frames (CBF).

Kanvilmez (2017) studied stiffness parameters and post-buckling performances of double-angle bracings with bolted connections. The study revealed that extra stiffness and strength are provided by the contribution of the compression diagonal bracings. Unal and Kaltakci (2016) evaluated the behaviors of the types of Concentrically Steel Braced Frames (CBFs) defined in TEC-2007 under lateral loads. The CBF models that were tested analytically consist of two stories and one bay and are formed into two groups with scales of 1/2 and 1/3. To verify the accuracy of the analytic studies performed, the scaled-down Concentrically Steel Braced Frame test element made up of box profiles and the 1/3-scale reinforced concrete frame with insufficient earthquake resistance were tested individually under lateral loads.

Yang *et al.* (2019) examined the impact of the bracing configuration on the seismic response of a five-story prototype office building located in Vancouver, Canada, and disclosed that the different bracing configurations play an important role in sizing the structural member. Panjaitan *et al.* (2021) experimentally tested three bracing elements, i.e., single bracing, double sections bracing with batten plates, and double sections bracing with lacing, under cyclic load. The researchers discovered that double bracings with lacing performed better, as shown by higher dissipation energy than that of single and double bracings with batten plates.

Several past research works have elaborated on the behavior of the Concentrically Braced Frame (CBF). However, the performance of CBF in the Chevron V Brace and Diagonal Brace arrangements has not been clarified. This present study examined Chevron V Brace CBF and Diagonal CBF under cyclic load. The variation was made in the frame height. The analysis was conducted to determine a better CBF configuration due to earthquake load and to observe the effects of the frame height on the CBF performance.

Material and Method

Analyses were performed on six different models of Concentrically Braced Frames (CBF). The CBF was in Chevron V-Brace and Diagonal Brace arrangements, as demonstrated in Figure 1.

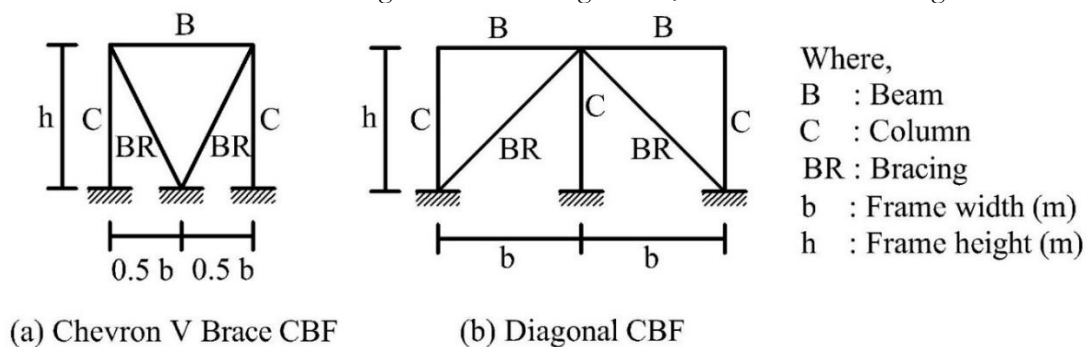


Figure 1. CBF models

Table 1. Mechanical properties of CBF component

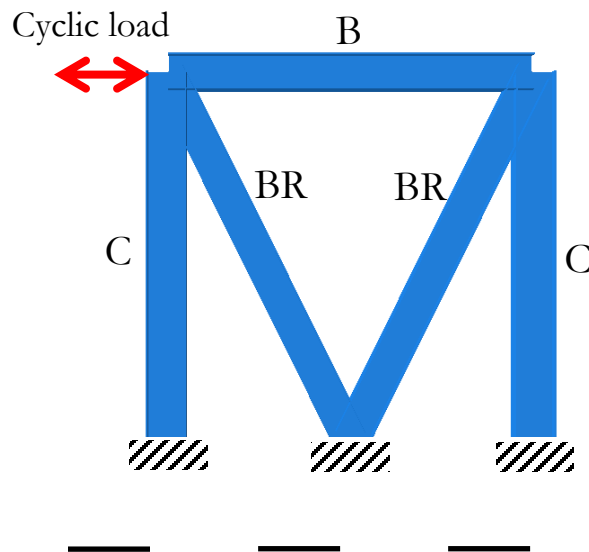
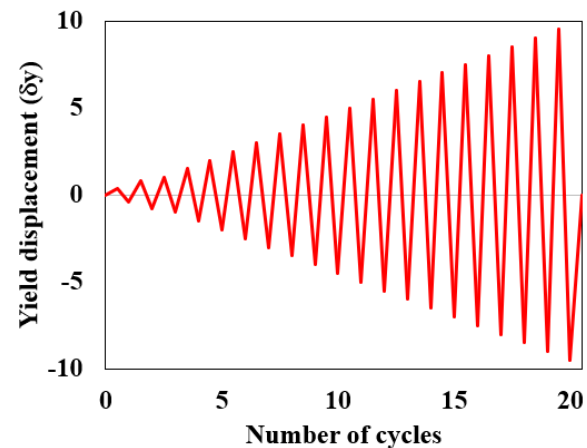
Steel grade`	Yield stress (MPa)	Ultimate stress (MPa)
BJ 37	240	370

Table 2. Geometries of the CBF model

Notation	Configuration	Frame width (m)	Frame height (m)
C1	Chevron V Brace	4	3
C2	Chevron V Brace	4	4
C3	Chevron V Brace	4	5
D1	Diagonal	4	3
D2	Diagonal	4	4
D3	Diagonal	4	5

Table 3. Profile of CBF component

Notation`	Component	Section
B	Beam	IWF 400x300x16x10
C	Column	IWF 450x300x18x11
BR	Bracing	IWF 400x300x14x9

**Figure 2.** Cyclic loading application**Figure 3.** Loading schematic

All the components of CBF were made of BJ 37 steel, with the characteristics presented in Table 1. In the modeling process, the behavior of the material after reaching the yield point was assigned as the kinematic hardening rule. In kinematic hardening, the yield surface is allowed to translate in stress space with no change in size or shape, which means the yield surface remains the same shape and size but translates in the direction of yielding. The geometries of the CBF model are presented in Table 2. The table expresses that all CBF models have the same frame width of 4 m and various frame heights of 3 m, 4 m, and 5 m. Table 3 demonstrates the profile sections of CBF components. The table depicts that the column area section is wider than that of the beam and bracing. This sectional area arrangement shows that the design has followed the principle of the strong column and weak beam.

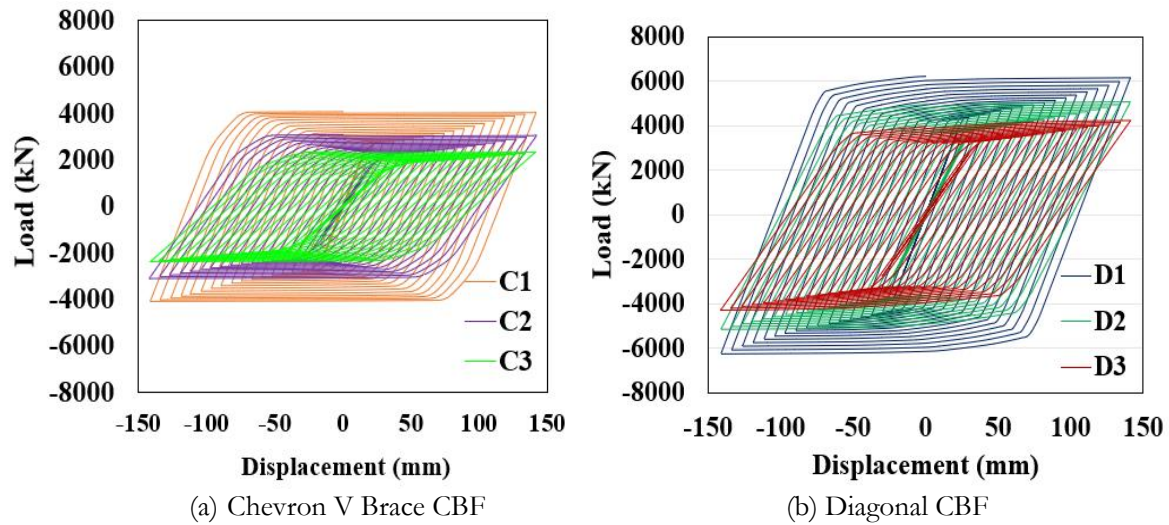


Figure 4. Load-displacement hysteresis curve

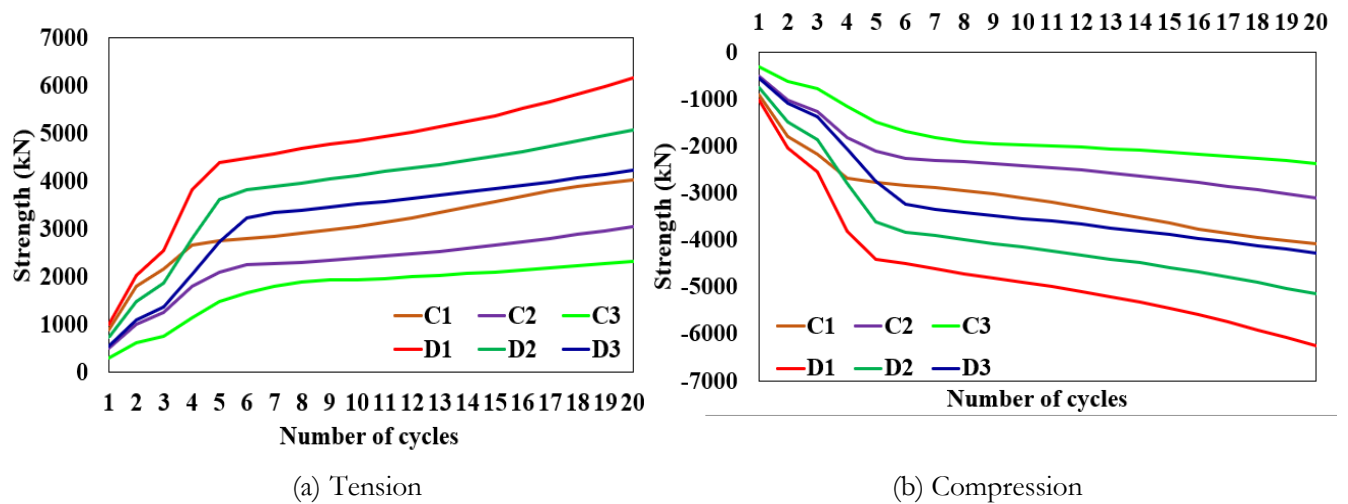


Figure 5. Strength

This study was analytically carried out using finite element software, i.e., Abaqus FEA (Ver. 6.13). The cyclic load was employed at the frame's upper-left corner, as outlined in Figure 2. Due to the employment of the cyclic load, the bracing will experience tension-compression axial forces.

Figure 3 illustrates a cyclic loading schematic with yield displacement (δ_y) controlled. In the first 3 cycles, the magnitudes of displacement control were taken lower than yield displacement, i.e., 0.4, 0.8, and 1.0 δ_y , to reveal the model behavior in the elastic range. Besides, the elastic displacement controls were employed to obtain the elastic stiffness of the models. At the inelastic condition, the increasing rate of 0.5- δ_y (0.5-yield displacement) was assigned to simulate the models. The magnitude of 1- δ_y was 15 mm, and this value was obtained from pushover analysis. To obtain a comprehensive result, 20 loading cycles were applied to the model.

Results

The load-displacement curves for the Chevron V Brace and the Diagonal CBF are expressed in Figure 4. The figure demonstrates the CBF frame with a shorter height having a larger area of the load-displacement hysteresis curve. Furthermore, the Diagonal configuration had a larger area of the load-displacement hysteresis curve than the Chevron V Brace CBF.

Figure 5 illustrates the strengths of the CBF for tension and compression. From the figure, the higher strengths were presented for the CBF frame with the shorter height. The highest strength is figured out in C1 for the Chevron V Brace and in D1 for the Diagonal. C1 performs the ultimate tension strength ($P_{u \text{ tension}} = 4040.4 \text{ kN}$) and the ultimate compression strength ($P_{u \text{ compression}} = 4072.8 \text{ kN}$). D1 exhibits the ultimate tension strength ($P_{u \text{ tension}} = 6162.2 \text{ kN}$) and ultimate compression strength ($P_{u \text{ compression}} = 6252.4 \text{ kN}$). If those values were clarified for other CBFs, the strength difference between the C1 and C3 is 73%. As for the diagonal configuration, the strength gap of 45 % is indicated for the difference between D1 and D3. Verification on C1 and D1 discloses that D1 exhibits a strength of 53 % higher than that of C1 at the 20th cycle. Investigation of the strengths at the tension and compression regions revealed that the strengths at the compression were higher than those at the tension, with a ratio of 1.53, which shows that the Bauschinger effect due to cyclic loading was obviously presented.

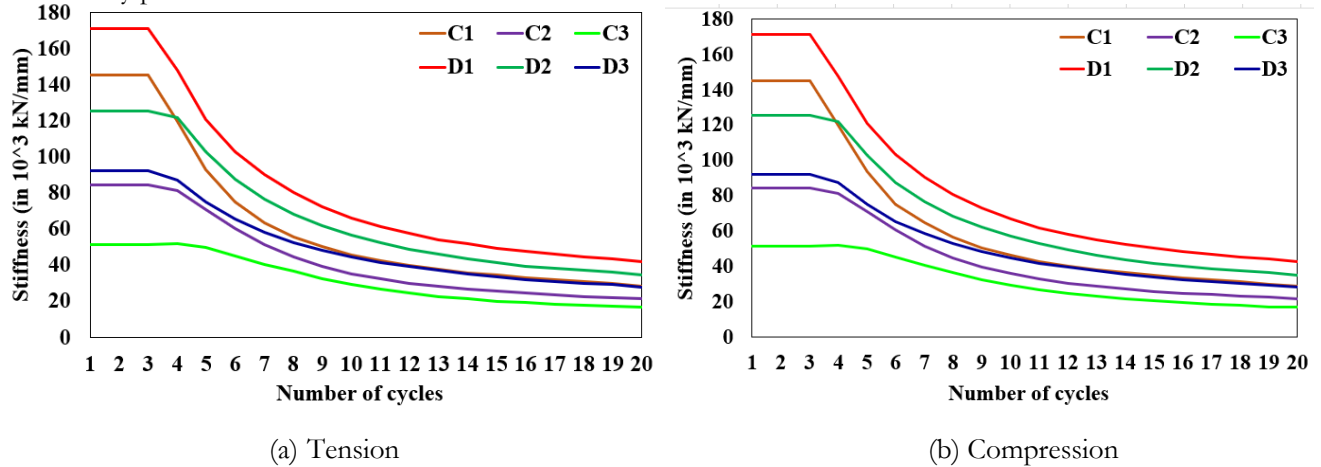


Figure 6. Stiffness

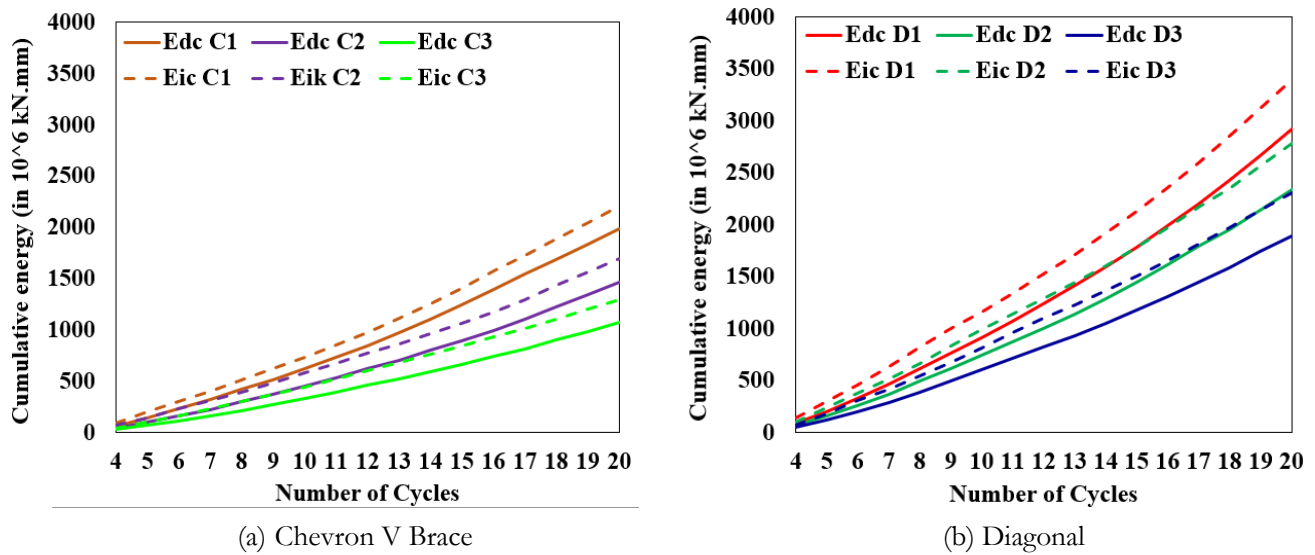


Figure 7. Cumulative energy

The stiffnesses of the CBF frame for each cycle are depicted in Figure 6. The figure shows the frame with the shorter height demonstrates a higher stiffness. The C1 exhibits the highest stiffness among other Chevron V Brace CBFs, and the D1 demonstrates the highest stiffness among other Diagonal models. The figure also shows that the first three cycles express constant stiffness values for all CBFs. As previously explained, those cycles were applied with values below $1-\delta_y$, so that the stiffness was identified at the elastic condition. Observing the highest inelastic stiffness at the 20th cycle, the C1 depicts the tension stiffness ($K_{\text{tension}} = 28503.6 \text{ kN/mm}$)

and compression stiffness ($K_{\text{compression}} = 28786.5 \text{ kN/mm}$). The D1 shows the tension stiffness ($K_{\text{tension}} = 41921.9 \text{ kN/mm}$) and compression stiffness ($K_{\text{compression}} = 42536.1 \text{ kN/mm}$). Verifying the C1 to C3 reveals a stiffness difference of 73%. Clarifying the D1 to D3 reveals a gap of 50%.

Additionally, the D1 experiences stiffness that is higher by 47% than the C1 at the 20th cycle, which reveals that the D1 has better stiffness than the C1. Figure 6 also confirms that the stiffness degrades with the continuation of the loading cycles, implying that the yield has spread on the brace components. Due to the yield condition, the CBF strength only slightly increases each cycle.

Figure 7 outlines the cumulative energy for the CBF in the Chevron V Brace (C) and Diagonal (D) models. The magnitudes of cumulative energy are not shown in the first three cycles. Due to the elastic condition, no areas of the load-displacement curve correspond to the zero-dissipation energy (E_d). Observation at the 20th cycle expresses that the C1 provides cumulative input energy (E_{ic} C1) that is greater than that of the C2 (E_{ic} C2) and the C3 (E_{ic} C3). The cumulative input energy of D1 (E_{ic} D1) is also noticed to be greater than that of D2 (E_{ic} D2) and D3 (E_{ic} D3). Similar patterns can be seen for cumulative dissipation energy (E_{dc}). The shorter frames have a higher cumulative dissipation energy than the taller frames.

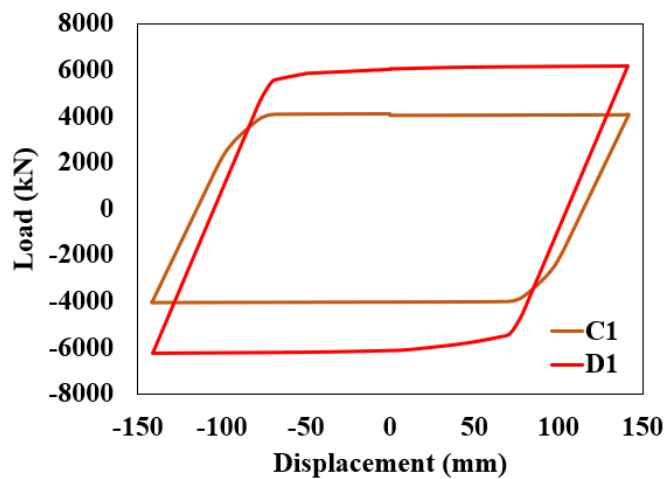
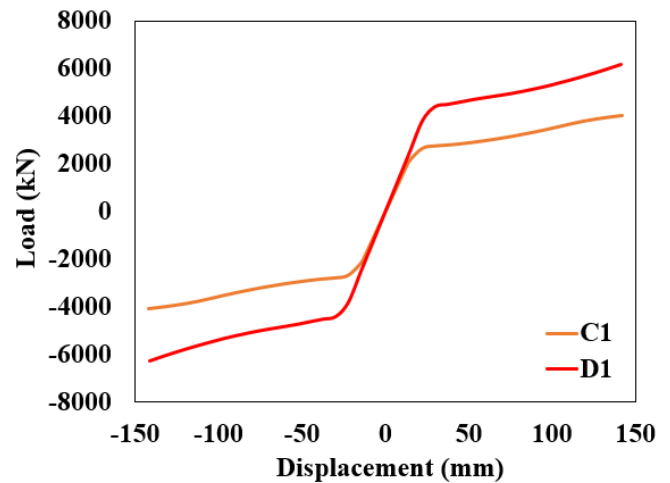
Tables 4 and 5 also recognize the efficiencies of dissipation energy. The efficiencies are monitored through the ratio of E_{dc} to E_{ic} . The higher E_{dc}/E_{ic} ratio is attributed to better dissipation energy efficiency, which means the model can absorb more available input energy (E_i). At the end of the 20th cycle, C1 has an E_{dc}/E_{ic} ratio of 90.3 %, more significant than the ratios of C2 (86.67 %) and C3 (82.7 %). The greatest E_{dc}/E_{ic} ratio is also validated in D1 (85.99%) than in D2 (84.04%) and D3 (81.31%). Confirming the dissipation energy efficiency in C1 and D1, it is found that the Chevron V Brace provides better results in dissipating energy than the Diagonal, which is specified by a higher E_{dc}/E_{ic} ratio in C1 at the end of the 20th cycle.

Table 4. Cumulative energy for Chevron V Brace CBF

Cycle number	Displacement controlled (δ_y)	C1			C2			C3		
		E_{dc}	E_{ic}	Ratio of E_{dc} / E_{ic} (%)	E_{dc}	E_{ic}	Ratio of E_{dc} / E_{ic} (%)	E_{dc}	E_{ic}	Ratio of E_{dc} / E_{ic} (%)
		(10^6 kN.mm)	(10^6 kN.mm)		(10^6 kN.mm)	(10^6 kN.mm)		(10^6 kN.mm)	(10^6 kN.mm)	
1	0.4	0	0	0	0	0	0	0	0	0
2	0.8	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0
4	1.5	63109.33	96013.50	65.73	44752.78	66756.39	67.04	28563.30	42847.04	66.66
5	2	140958.08	197409.28	71.40	96470.91	143717.99	67.13	66737.02	99765.15	66.89
6	2.5	232940.84	302865.78	76.91	159745.07	232478.58	68.71	108971.71	161684.98	67.40
7	3	323716.99	406978.18	79.54	225566.25	312806.11	72.11	157855.65	230421.17	68.51
8	3.5	417845.22	512365.37	81.55	299165.97	397259.93	75.31	210581.05	303919.63	69.29
9	4	517452.77	618617.60	83.65	376703.68	487291.72	77.31	267351.36	375952.75	71.11
10	4.5	620312.01	729237.12	85.06	455771.76	579833.91	78.60	328624.01	446990.41	73.52
11	5	732366.66	850138.24	86.15	534767.60	671341.35	79.66	394369.35	523984.54	75.26
12	5.5	846665.13	974075.39	86.92	624323.76	768722.62	81.22	460447.76	601460.44	76.55
13	6	974617.96	1112817.43	87.58	708251.14	860323.24	82.32	526446.63	679068.36	77.52
14	6.5	1105971.05	1255891.15	88.06	801118.74	961613.03	83.31	597976.08	763173.76	78.35
15	7	1248066.89	1410628.52	88.48	895580.04	1065157.15	84.08	667960.70	845409.78	79.01
16	7.5	1399794.42	1574760.54	88.89	996564.85	1176267.28	84.72	746354.52	935152.52	79.81
17	8	1545094.53	1729962.41	89.31	1105554.10	1296202.32	85.29	818456.28	1015017.34	80.63
18	8.5	1690764.00	1885091.42	89.69	1228559.20	1431244.15	85.84	900451.66	1105578.69	81.45
19	9	1840147.50	2044486.56	90.01	1347262.77	1561813.88	86.26	988129.85	1202601.14	82.17
20	9.5	1992021.07	2205896.37	90.30	1469678.90	1695770.74	86.67	1072325.75	1296621.99	82.70

Table 5. Cumulative energy for Diagonal CBF

Cycle number	Displacement controlled (δ_y)	C1			C2			C3		
		E_{dc}	E_{ic}	Ratio of E_{dc} / E_{ic} (%)	E_{dc}	E_{ic}	Ratio of E_{dc} / E_{ic} (%)	E_{dc}	E_{ic}	Ratio of E_{dc} / E_{ic} (%)
		(10^6 kN.mm)	(10^6 kN.mm)		(10^6 kN.mm)	(10^6 kN.mm)		(10^6 kN.mm)	(10^6 kN.mm)	
1	0.4	0	0	0	0	0	0	0	0	0
2	0.8	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0
4	1.5	94501.87	141759.67	66.66	69307.69	103966.58	66.66	50864.64	76300.65	66.66
5	2	203338.98	298905.70	68.03	162271.17	242600.65	66.89	122075.15	183121.58	66.66
6	2.5	328493.97	456705.50	71.93	257446.58	374432.02	68.76	205222.28	306936.95	66.86
7	3	469192.60	636227.25	73.75	371907.24	514251.32	72.32	290947.97	420879.09	69.13
8	3.5	613154.06	827293.34	74.12	492873.73	669957.35	73.57	392870.91	544288.08	72.18
9	4	762779.39	999406.50	76.32	616284.76	832863.46	74.00	500199.69	676760.46	73.91
10	4.5	910765.16	1161298.06	78.43	741680.49	992458.35	74.73	603536.79	819169.05	73.68
11	5	1075111.30	1340774.80	80.19	869591.48	1136832.98	76.49	712300.03	961154.33	74.11
12	5.5	1241960.62	1524476.90	81.47	1002698.64	1287363.17	77.89	823388.13	1100923.93	74.79
13	6	1415229.27	1716115.70	82.47	1142979.99	1443973.43	79.16	936518.42	1230658.01	76.10
14	6.5	1601308.94	1922429.89	83.30	1292323.88	1609295.06	80.30	1054287.84	1365310.43	77.22
15	7	1786597.42	2128694.49	83.93	1452706.88	1787761.94	81.26	1177337.09	1505844.06	78.18
16	7.5	1989928.13	2355937.20	84.46	1615744.55	1969790.92	82.03	1306318.94	1652134.86	79.07
17	8	2205016.15	2596419.66	84.93	1795702.83	2171018.86	82.71	1449123.48	1812891.33	79.93
18	8.5	2431459.13	2850380.18	85.30	1956820.27	2353162.79	83.16	1592063.00	1973462.44	80.67
19	9	2670986.24	3117903.37	85.67	2144167.84	2564164.08	83.62	1741139.91	2141851.48	81.29
20	9.5	2923027.49	3399099.40	85.99	2341543.15	2786336.36	84.04	1890154.44	2310425.10	81.81

**Figure 8.** Load-displacement envelope curve**Figure 9.** Load-displacement backbone curve

The load-displacement envelope curve is presented in Figure 8. The envelope curve is derived from the load-displacement curve's largest area. The discussion is made for C1 and D1 since both CBFs noticeably provide the best performance in the Chevron V Brace and Diagonal models. From Figure 8, it is pointed out that D1 has a bigger envelope than C1.

A study on the backbone curve for buckling restrained brace (BRB) CBF was conducted by infilling mortar into the PVC pipe. The pipe infilled by the mortar was the BRB. The backbone curve shows that the inelastic stiffness significantly increases with the pipe diameter enlarging (Moestopo and Andarini, 2019). Figure 9 shows the load-displacement backbone curve for C1 and D1. The figure specifies a slight difference in the elastic stiffness indicated by the overlapped line. This result exhibits that the influence of the bracing configuration, i.e., two braces in one or two spans, on the elastic stiffness is negligible. On the contrary, the D1 is observed to have higher inelastic stiffness than the C1. This result confirms that the arrangement of the two braces in two spans (D1) increases the inelastic stiffness compared to that of the two braces constructed in one span (C1).

Discussion

In CBF, the brace is the component that is prone to buckle. Accordingly, the steel damper is installed in the brace to produce a larger, more stable hysteretic curve (Bakhshayesh *et al.*, 2021). Figure 4 demonstrates the larger area of the load-displacement curve in a shorter CBF, meaning that a shorter CBF frame performs greater energy dissipation (or performance) than a taller CBF. The larger hysteretic curve was also characterized in Diagonal models, indicating that the Diagonal performed better than the Chevron V Brace CBF.

Figure 5 exhibits the strength of the CBF models. The higher strength is specified on the frame with the shorter height. The behavior is highly expected since the braces installed in a more gentle slope arrange the shorter height frame. This slope arrangement made the brace perform a higher strength. The stiffness of CBF models is presented in Figure 6. The figure reveals that the Diagonal has a better stiffness than the Chevron V Brace. The Diagonal composed of braces set in a more gentle slope results in higher CBF strength, leading to higher stiffness.

The position influence of the brace's cross-sectional area on the CBF performance was also studied (Zola *et al.*, 2017). Figure 7 illustrates the cumulative dissipation energy of the CBF models. The figure shows that shorter frames produce better dissipation energy than taller frames. The better dissipation energy is also characterized in Diagonal than the Chevron V Brace CBF. This behavior is possibly indicated due to the brace arrangements. The gentle slope of braces increases the brace's strength in the same applied displacement. Accordingly, the load-displacement hysteretic curve contributes to the larger cumulative dissipation energy.

Figure 8 reveals that the bigger envelope in D1 indicates that the D1 produces better dissipation energy than the C1. This behavior is presented since the D1 experiences a higher strength in each cycle than the C1. Figure 9 expresses that the D1 performs the inelastic stiffness, which is higher than the C1, which indicates that D1 is better at reducing the damages due to the earthquake.

Conclusion

This research analytically investigated the performance of two different CBF configurations, i.e., the Chevron V Brace and the Diagonal CBF. The variation was made in the CBF height. Observation of the performance indicators, i.e., strength, stiffness, and energy dissipation, revealed that the frame with the shorter height exhibited better results than that of the taller frame. It was also disclosed that the Diagonal CBF was better than the Chevron V-brace CBF, which is indicated by the considerable difference in performance parameters. Despite these results, the Chevron V Brace model was superior in dissipation energy efficiency than the Diagonal, characterized by a greater ratio of cumulative dissipation energy to cumulative input energy. Confirming these results, it is discovered that establishing the Diagonal CBF with two braces in two spans (a diagonal brace arrangement in a span) can be suggested as one solution to prevent heavy damage and failure to the building due to the earthquake.

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