Challenge Journal of Structural Mechanics

Research Article

Performance-based seismic design of laterally braced steel frames

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ABSTRACT

Improving the performance of structural frames is one of the most important focuses of today's researchers. The total base shear capacity of the structural frames will increase by reaching the maximum number of plastic hinges. In this work, the effects of bracing system type on different heights of steel frames were investigated. Static pushover analysis was used to evaluate the performance of 4, 8, and 12-story steel frames with seven structural configuration systems. The results showed that the performance of braced frames increased significantly in terms of number of plastic hinges, total base shear and performance point compared to unbraced frames. The capacity curves were maximum in the one-story X-bracing, multi-story X-bracing, and single diagonal bracing systems.

ARTICLE INFO

Article history:
Received 21 April 2022
Revised 17 May 2022
Accepted 9 June 2022

Keywords:
Base shear
Braced steel frames
Capacity design
Performance-based seismic design
Plastic hinge

1. Introduction

Structures designed by seismic code procedures are expected to undergo large deformations in the inelastic range when subjected to strong earthquakes; however, seismic codes are still based on elastic methods. This procedure can cause unpredictable and weak response during strong earthquakes with inelastic activity unevenly distributed among structural elements by Lee et al. (2004). In capacity design, buildings are allowed to be damaged during strong earthquakes. The distribution of this damage is determined by the designer and necessary precautions are taken. In ductile behavior, plastic deformation is adopted in the design. The location and type of these damages are the most important elements of the capacity design and are affected by many factors such as the bracing and the stiffness of the members by Al-Safi et al. (2020). It is known that the stiffness matrix of any structure is given by Eq. (1).

$$[K] = \{F\}\{U\}^{-1} \qquad (1)$$

where $\{F\}$ is the external force, $[K]$ the stiffness matrix, and $\{U\}$ denotes the displacements. In other words, the lower the displacement, the greater the stiffness. Plastic hinge formation distinguishes the location of the building where greater potential damage can occur. In this arrangement, by reaching the maximum number of plastic hinges, theoretically, the building has the highest ultimate load. Otherwise, the building will collapse with less load and less plastic hinges. Achieving the maximum number of plastic hinges could be a new performance goal in seismic design. Higher rigid frames can be obtained by adding bracing systems. Many bracing systems have been proposed in the literature and the most commonly used bracing systems are multistory X-bracing proposed by Aninthaneni and Dhakal (2017), Yang et al. (2019), single diagonal Abou-Elfath et al. (2017), Sabouri-Ghomi and Payandehjoo (2017), Setyowulan et al. (2020), Zeng et al. (2019), V-bracing Kanyilmaz (2017), Salmasi and Sheidaii (2017), one story X-bracing Al-Safi et al. (2021), Jamkhaneh et al. (2019), Mahmoudi et al. (2019), Mashhadiali et al. (2016), concentric braced frames Banihashemi et al. (2015), Cesare et al. (2014), De Stefani et al. (2015), Hammad and Moustafa (2021), Mirjalali et al. (2019), Nezamisavojbolaghi (2020), and K-bracing Tajmir Riahi et al. (2020). In the above literature, there is a lot of research on the braced frames, but

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ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2022.04.002

most are finite element analysis (FEA) or experimental work with a limited number of stories and limited bracing systems; however, there is no study focus on the performance-based seismic design of these frames with a different bracing system and a different number of stories. This study aims to examine the performance-based seismic design of the most recommended bracing systems in the literature and to find the most effective bracing system for frames out of six bracing systems investigated in terms of plastic hinge number, base shear vs. displacement capacity curve, and performance point. For this purpose, 4, 8, and 12 story steel frames with six bracing configurations (K-bracing, inverted V- bracing, V- bracing, single-diagonal bracing, one story X- bracing, and multi-story X- bracing) were examined.

2. Research Methodology

2.1. Building information

In this study, steel frames with 4, 8 and 12-story were selected to represent low, mid, and high-rise frames. The frames selected were typically intermediate steel moment frame with Cd = 3 and R = 3.5. Frames have 4@4 m bays and a story height of 3.2 m. An approximate analysis was carried out to determine the dimensions of element's cross sections. Structural sections of all frames were designed according to AISC 360 (2016) and summarized in Table 1. Earthquake loads were calculated according to IBC (2020) and Class C soil was used. The spectral response acceleration parameters at short period, S_S, and at a period of 1s, S_1, are 0.36g, 0.17g, respectively. The dead load was accepted as 37 kN/m', live load = 8 kN/m', and finishing load = 6 kN/m'. A36 steel was used. Pushover analysis was performed using Sap2000 Software V22. Six types of bracing systems (Single diagonal, V-bracing, inverted V-bracing, K-bracing, multi-story X-bracing, and one-story X-bracing) compared to the unbraced frame on the number of plastic hinges, base shear vs. displacement capacity curve, and performance point (V, D) (Fig. 1(a-g)). The sections of the columns and beams were kept the same in all frames to investigate the effect of bracing configurations. The connections between beams and columns has been considered to be rigid.

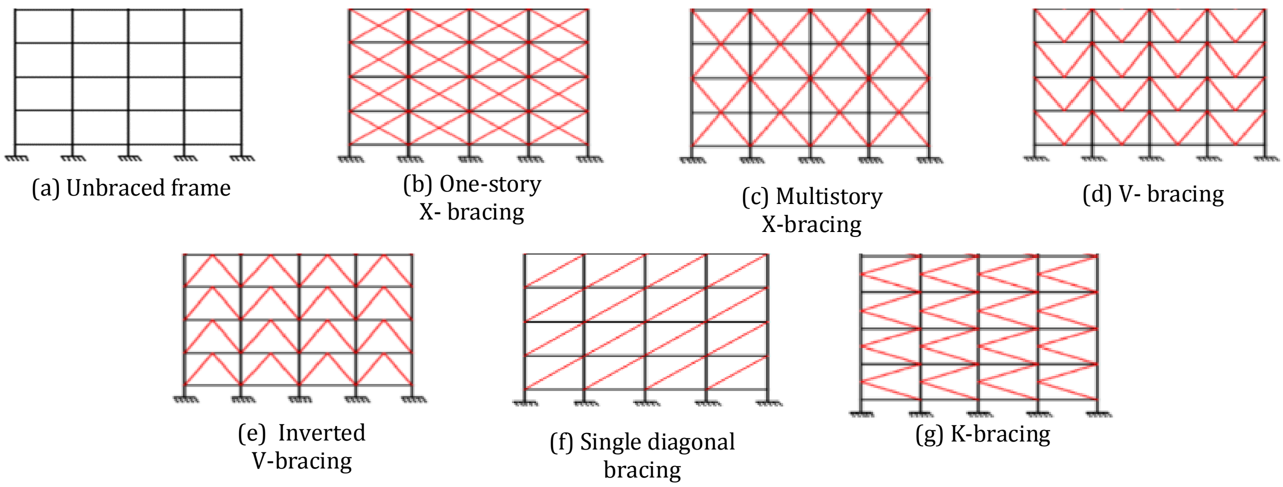

Fig. 1. Types of bracing systems used.

Table 1. Structural sections used in pushover analysis.

Building	Stories	Column	Beam	Bracing
4-story	1st -4th	HEB 350	IPE 330	2*L* 70 × 8 × 0
8-story	1st -2nd	HEM 600	IPE 330	2*L* 70 × 7 × 0
	3rd-4th	HEB 550	IPE 330	2*L* 70 × 7 × 0
	5th -8th	HEB 360	IPE 330	2*L* 50 × 6 × 0
12-story	1st -2nd	HEM 700	IPE 330	2*L* 70 × 8 × 0
	3rd -4th	HEM 650	IPE 330	2*L*70 × 8 × 0
	5th -8th	HEB 500	IPE 330	2*L*60 × 8 × 0
	9th -12th	HEB 360	IPE 330	2*L*60 × 8 × 0

2.2. Plastic hinge properties

The non-linear (M-θ) plastic hinge properties used in the examined frames are shown in Fig. 2. Moment and rotation values are normalized to the corresponding yield values. According to FEMA 356 (2000), the length of the plastic hinge regions is equal to half the section depth.

$$L_P = h/2 \quad (2)$$

where L_P is the length of plastic hinge, and h is the depth of the section.

Depending on the performance level chosen, a constant lateral drift should be applied at the top node of all frames. Lateral drift limits must meet the limits given in Table 2 (Naeim 2001). Assuming life safety performance level, lateral drift was calculated as 0.02 of the frame height, and base shear remained variable.

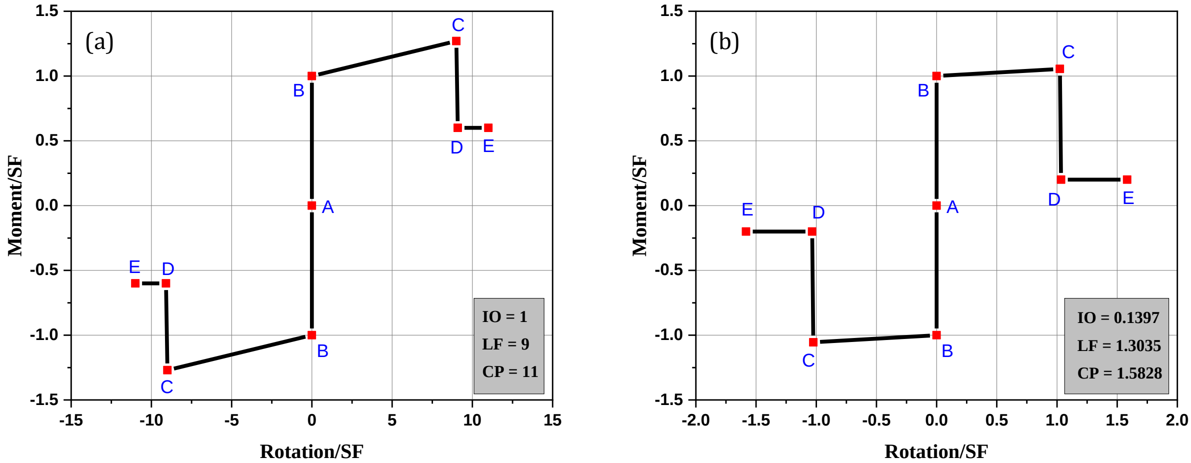

Fig. 2. Plastic hinge properties for (a) beams, and (b) columns.

Table 2. Deformation limits by Naeim (2001).

	Performance limit			
Interstory drift limit	Immediate occupancy	Damage control	Life safety	Structural stability
Maximum total drift	0.01	0.01-0.002	0.02	0.03 V_i/P_i

3. Results and Discussion

3.1. Plastic hinge formation

In this study, beam and column sections were kept the same in all configurations for comparison. The plastic hinges formed in the structural members (columns and beams) of braced and unbraced frames are shown in Figs. 3-5 and summarized in Tables 3-5. The performance of plastic hinges is classified into three levels as follows proposed by FEMA 356:

- “Immediate Occupancy (IO): Damage is light, and structure retains most of its original strength and stiffness. There may be minor cracking on the structural members”.
- “Life Safety (LS): Substantial damage to the structure and the structure may have lost a large portion of its strength and stiffness”.
- “Collapse Prevention (CP): Severe damage and little strength and stiffness remains. Building is unstable and is near collapse”.

In the 8- and 12-story buildings, the number of plastic hinges formed was higher in all braced frames compared to the unbraced frame. On the other hand, in low rise (4-story) frames, the number of plastic hinges increased in some bracing systems, while it decreased in others. Fig. 3 and Table 3 show that the maximum number of plastic hinges formed in 4-story frames are in V-bracing and then in inverted V-bracing. In this system, the performance levels remained "Life safety" as assumed, but the other systems were moved to the "Collapse prevention" performance level. Compared to the unbraced frame, the number of plastic hinges increased by 45% and 19% for V-bracing, inverted V-bracing systems, respectively.

In the mid-height frames (8-story), Fig. 4 and Table 4 show that, plastic hinges increased in all braced frames and the maximum number of plastic hinges was noticed in the inverted V-bracing system. The number of plastic hinges compared to the unbraced frame were increased by 32, 28, 22, 20, 20, and 18% for the inverted V-bracing, multistory X-bracing, V-bracing, one-story X-bracing, single diagonal bracing, and K-bracing, respectively. In addition, the final performance level of inverted V-bracing, V-bracing, and K-bracing remained life safety (LS) performance level; however, other bracing systems have moved to the collapse prevention (CP) performance level. This is the main reason for the increase seen in the capacity curves of these frames.

In the high-rise building, Fig. 5 and Table 5 show that, the behavior was similar to that of mid-rise buildings. All frames with bracing showed an increase in the number of plastic hinges compared to the unbraced frame. Moreover, single diagonal, multistory X-bracing, one-story X-bracing, and K-bracing were moved to the performance level of collapse prevention (CP), while other systems remained at the life safety (LS) performance level. Compared to the unbraced frame, the K-bracing, multistory

X-bracing, single diagonal, one story X-bracing, V-bracing, and inverted V-bracing systems showed an increase in the number of plastic hinges by 26, 25, 17, 12, 12, and 12%, respectively.

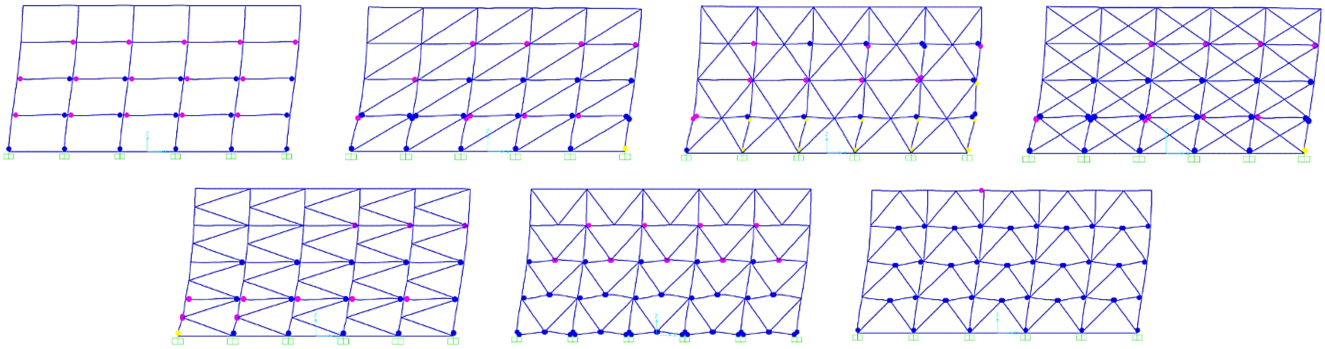

Fig. 3. Hinge severity legend for 4-story buildings.

Table 3. Final performance level calculations for 4-story buildings.

System type	Element	Total number of hinges	<IO (%)	<LS (%)	<CP (%)	>CP (%)	Performance level
Unbraced frame	Beam	25	60	40	0	0	LS
	Column	6	0	100	0	0	
Single diagonal bracing	Beam	19	42	58	0	0	CP
	Column	6	0	83	0	17	
Multistory-X bracing	Beam	16	38	63	0	0	CP
	Column	18	22	17	0	61	
One-story X-bracing	Beam	19	37	63	0	0	CP
	Column	9	11	78	0	11	
K-bracing	Beam	18	44	56	0	0	CP
	Column	8	25	63	0	13	
V-bracing	beam	39	23	77	0	0	LS
	column	6	0	100	0	0	
Inverted V-bracing	beam	31	3	97	0	0	LS
	column	6	0	100	0	0	

Table 4. Final performance level calculations for 8-story buildings.

System type	Element	Total number of hinges	<IO (%)	<LS (%)	<CP (%)	>CP (%)	Performance level
Unbraced frame	Beam	50	40	60	0	0	LS
	Column	0.0	0	0	0	0	
Single diagonal bracing	Beam	54	39	61	0	0	CP
	Column	6	0	83	0	17	
Multistory-X bracing	Beam	52	37	63	0	0	CP
	Column	12	0	83	0	17	
One-story X-bracing	Beam	54	37	63	0	0	CP
	Column	6	0	83	0	17	
K-bracing	Beam	53	34	66	0	0	LS
	Column	6	0	100	0	0	
V-bracing	beam	55	18	82	0	0	LS
	column	6	0	100	0	0	
Inverted V-bracing	beam	60	18	82	0	0	LS
	column	6	83	17	0	0	

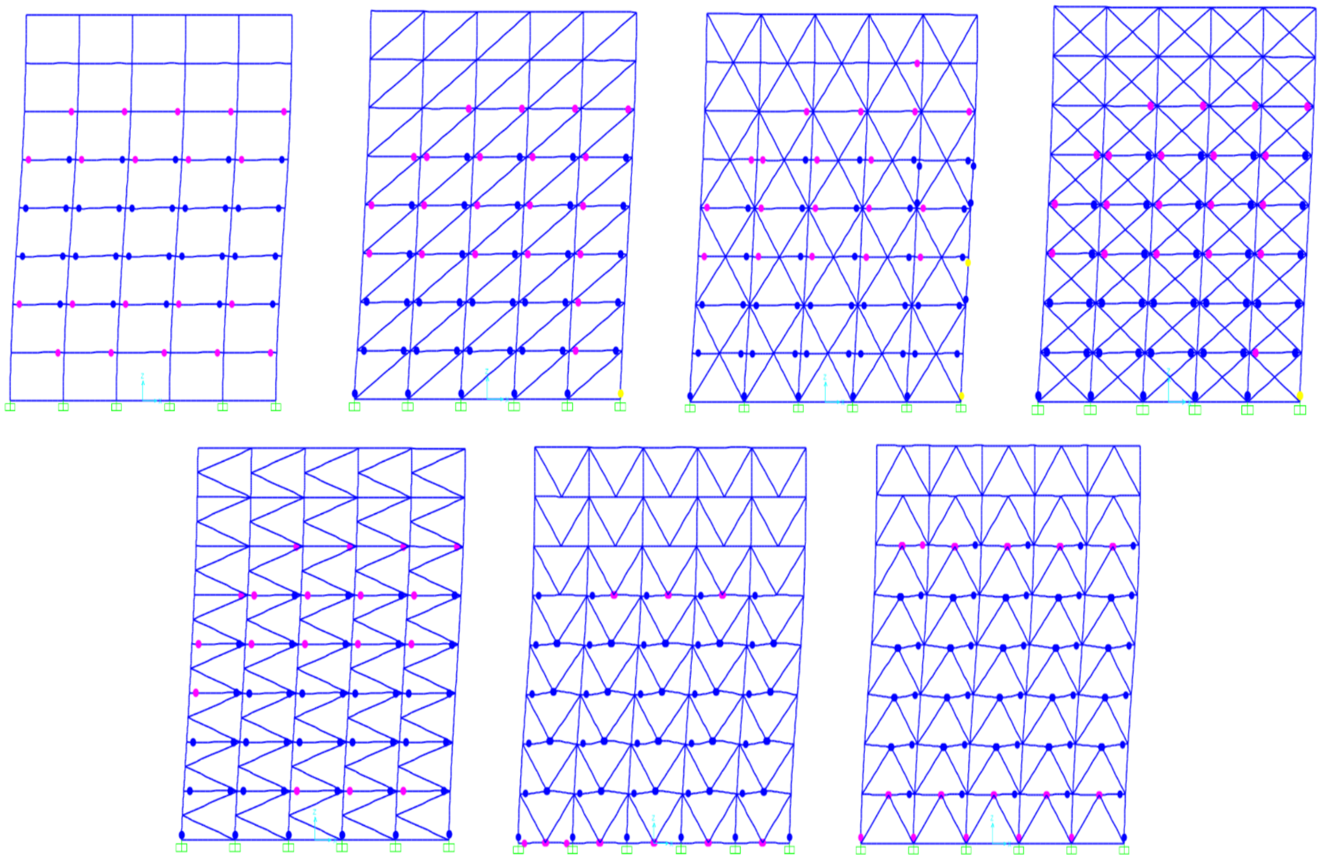

Fig. 4. Hinge severity legend for 8-story buildings.

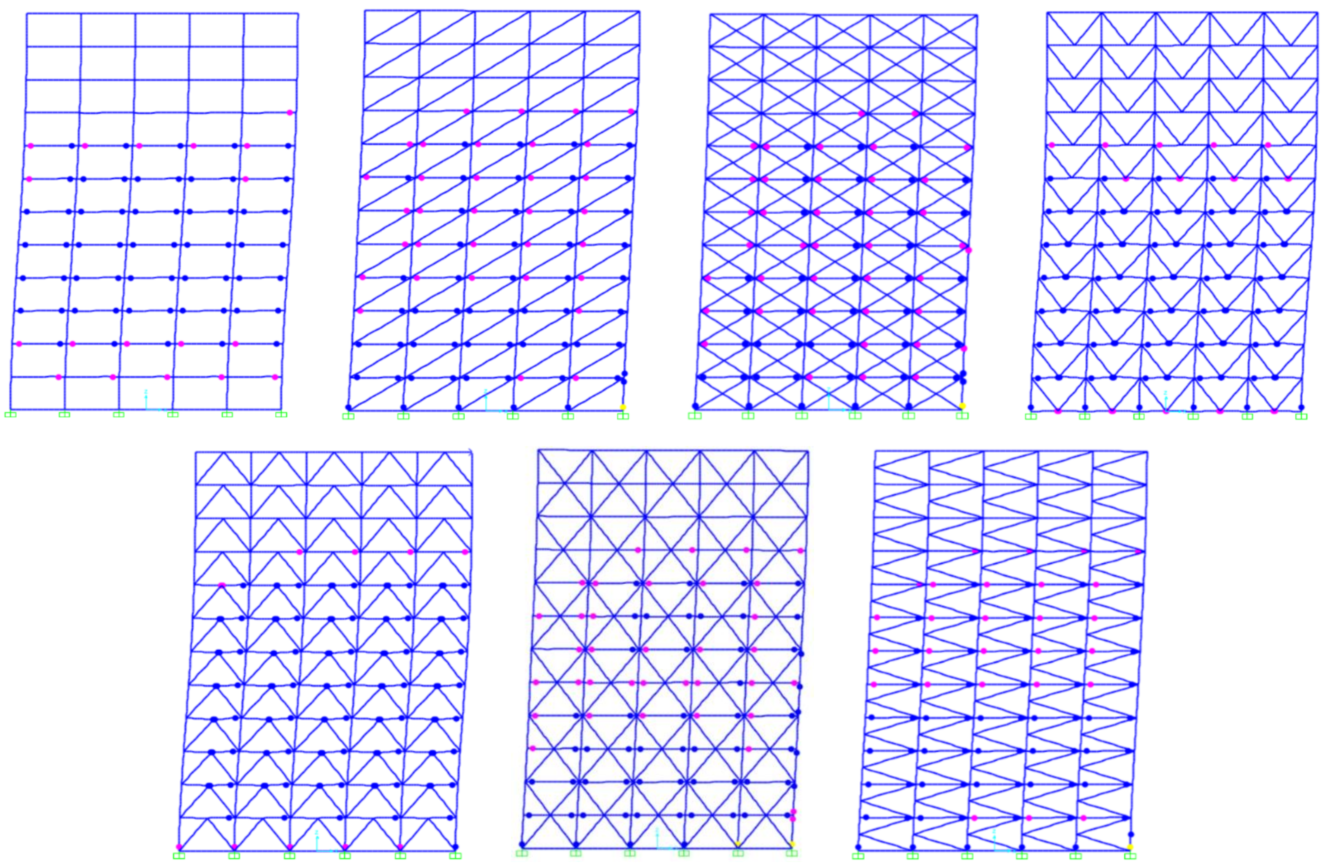

Fig. 5. Hinge severity legend for 12-story buildings.

Table 5. Final performance level calculations for 12-story buildings.

System type	Element	Total number of hinges	<IO (%)	<LS (%)	<CP (%)	>CP (%)	Performance level
Unbraced frame	Beam	76	24	76	0	0	LS
	Column	0	0	0	0	0	
Single diagonal bracing	Beam	82	40	60	0	0	CP
	Column	7	0	86	0	14	
Multistory-X bracing	Beam	82	41	59	0	0	CP
	Column	13	15	69	0	15	
One-story X-bracing	Beam	76	50	50	0	0	CP
	Column	9	22	67	0	11	
K-bracing	Beam	89	30	70	0	0	CP
	Column	7	0	86	0	14	
V-bracing	beam	79	18	82	0	0	LS
	column	6	0	100	0	0	
Inverted V-bracing	beam	79	6	94	0	0	LS
	column	6	83	17	0	0	

3.2. Capacity curves and performance point results

Static pushover analysis was performed to calculate the base shear vs. displacement capacity curves of all studied frames (Fig. 6). As mentioned in the previous section, the capacity curve is directly proportional to the number of plastic hinges forms. Fig. 6 clearly shows that the capacity curves of braced frames significantly increased. In low rise frames (Fig. 6a) single diagonal and one-story X-bracing systems showed the highest base shear values. In the single diagonal bracing, one-story X-bracing, multistorey X-bracing, K-bracing, V-bracing, and inverted V-bracing base shear was increased by 823, 820, 667, 221,107, and 59% in compassion to the unbraced frame. The reason for this increase is the transition of single diagonal, multistory X bracing, one-story X bracing and K bracing systems from LS performance level to CP performance level. Hence, the total plastic moment carried by these hinges increased; however, for the other systems the number of plastic hinges increased but the performance level remained the same. The capacity curves of the mid-rise (8-story) frames are shown in Fig. 6b and the maximum base shear value is observed in the multi-story X bracing system. Similar to low-rise frames this significant increase was because the performance level of these frames changed from LS into CP. The increase in base shear compared to the unbraced system was 502, 494, 492, 202, 97, and 64% for multistory X-bracing, one-story X-bracing, single diagonal, K-bracing, V-bracing, and inverted V-bracing systems. In high-rise (12-story) frames, base shear value was maximum in the one-story X-bracing system followed by the multistory X-bracing and single diagonal systems (Fig. 6c). In comparison with the unbraced frame, total base shear was increased by 517, 484, 481, 208, 103, and 68% for one story X-bracing, multistory X-bracing, single diagonal bracing, K-bracing, V-bracing, and inverted V-bracing systems, respectively.

In this study, the performance point was evaluated according to the FEMA 440 Displacement Modification, FEMA 356 Coefficient Method, FEMA 440 Equivalent Linearization and ATC-40 Capacity Spectrum methods (Tables 6-8). The results show that the performance point of the bracing systems increases the base shear value corresponding to a decrease in the roof displacement. This showed that the stiffness of the braced frame was greater than that of the unbraced frame. Thus, the number of plastic hinges and capacity curves also increased.

Table 6. Performance point results for 4-story buildings.

System type	ACT-40 Capacity spectrum		FEMA356 Coefficient method		FEMA440 Equivalent linearization		FEMA440 Displacement modification	
	V (kN)	D (mm)	V (kN)	D (mm)	V (kN)	D (mm)	V (kN)	D(mm)
Unbraced frame	712.74	42.92	1155.25	69.67	712.75	42.92	1377.87	83.13
Single diagonal bracing	1038.39	9.63	2214.59	19.70	1057.90	9.80	2040.33	18.21
Multistory X-bracing	1045.24	11.89	2056.07	22.79	1045.25	11.89	1698.78	19.18
One-story X-bracing	1042.78	9.67	2155.73	19.20	1054.99	9.78	1961.03	17.53
K-bracing	1003.15	21.19	1715.43	36.19	1005.52	21.24	1660.71	35.04
V-bracing	1055.99	14.87	1698.36	28.03	1055.99	14.87	1544.01	24.67
Inverted V-bracing	1001.64	32.48	2413.19	68.18	1470.15	42.52	1517.24	43.52

Table 7. Performance point results for 8-story buildings.

System type	ACT-40 Capacity spectrum		FEMA356 Coefficient method		FEMA440 Equivalent linearization		FEMA440 Displacement modification	
	V (kN)	D (mm)	V (kN)	D (mm)	V (kN)	D (mm)	V (kN)	D(mm)
Unbraced frame	805.30	84.81	1204.33	127.09	805.30	84.81	1204.33	127.09
Single diagonal bracing	1721.64	41.39	2766.90	65.43	1756.43	42.19	2929.68	69.17
Multistory X-bracing	1702.77	42.18	2599.38	63.16	1702.77	42.17	2656.81	64.45
One-story X-bracing	1709.22	41.07	2172.38	51.72	1722.99	41.51	2798.64	66.10
K-bracing	1284.75	55.42	1908.70	82.16	1285.39	55.45	1949.70	83.92
V-bracing	1486.54	47.13	2111.51	71.66	1486.54	47.14	2137.28	72.69
Inverted V-bracing	1159.96	67.10	2537.95	125.76	1574.99	84.95	2537.95	125.76

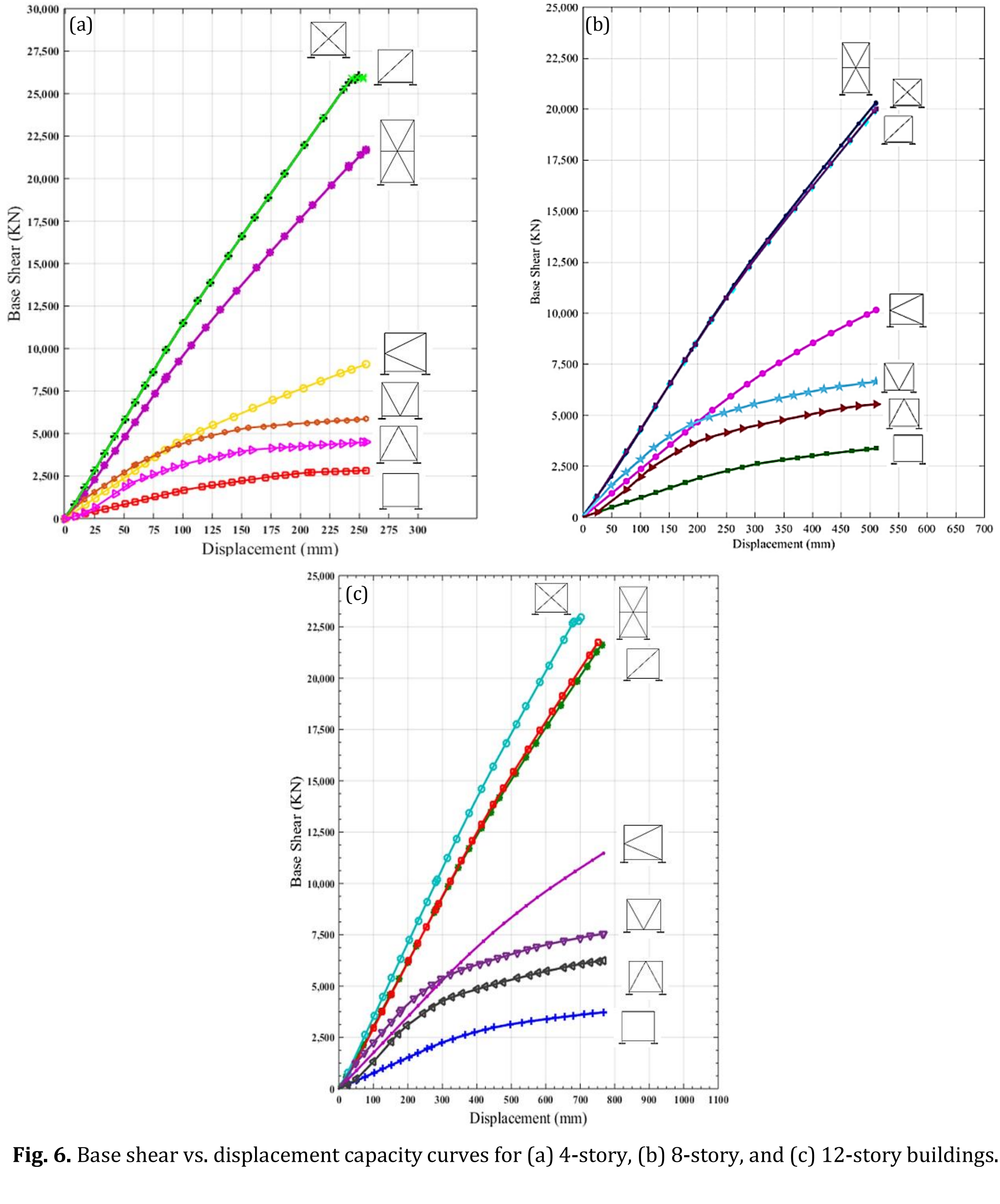

Fig. 6. Base shear vs. displacement capacity curves for (a) 4-story, (b) 8-story, and (c) 12-story buildings.

Table 8. Performance point results for 12-story buildings.

System type	ACT-40 Capacity spectrum		FEMA356 Coefficient method		FEMA440 Equivalent linearization		FEMA440 Displacement modification	
	V (kN)	D (mm)	V (kN)	D (mm)	V (kN)	D (mm)	V (kN)	D(mm)
Unbraced frame	734.98	121.04	1181.57	194.94	734.99	121.04	1181.57	194.94
Single diagonal bracing	1441.73	60.79	2860.02	117.30	1603.81	97.33	2860.02	117.30
Multistory X-bracing	1434.92	64.56	2550.19	107.87	1461.74	65.62	2250.19	107.87
One-story X-bracing	1595.66	59.07	2809.42	101.04	1680.15	61.99	2809.42	101.04
K-bracing	1120.08	80.29	1873.74	133.61	1145.37	82.08	1873.74	133.61
V-bracing	1242.75	64.81	1947.55	109.69	1283.65	67.37	1947.55	109.69
Inverted V-bracing	982.08	95.03	2452.69	197.05	1413.12	123.83	2452.69	197.05

4. Conclusions

In this study, a total of six bracing configurations were investigated based on the number of plastic hinges formed, the capacity curve and performance points. The following conclusions can be drawn from the study:

- Bracing members are important to resist lateral loads and, in this study, all braced frames showed a higher base shear as well as a greater number of plastic hinges compared to the unbraced frame.
- Multi-story X-bracing, one-story X-bracing, and single diagonal bracing systems have the highest capacity. Thus, the increase in the base shear for the 4-story, 8-story, and 12-story frames was 823%, 502%, and 517%, respectively.
- According to the FEMA 440 displacement modification, FEMA 356 coefficient method, FEMA 440 equivalent linearization, and ATC-40 capacity spectrum methods, the performance point of the bracing systems has a large base shear corresponding to a small roof displacement. This indicates that the rigidity of the braced frame is greater than the unbraced frame.

For future studies, performance-based design can be investigated on different joint types or different support types.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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