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Research Article

Retrofitting Reinforced Concrete Buildings by Using Steel Bracing

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Keywords

Steel bracing,
Pushover analysis,
Concentrically braced frame,
Eccentrically braced frame.

Abstract

Earthquakes have caused significant physical and psychological damage, with injuries and deaths often resulting from falling objects, flying glass, and collapsing walls. Existing reinforced concrete structures may not be seismically resistant due to their nonductile features. Strengthening is needed to reduce seismic risk and improve seismic performance. Among various methods, steel bracing is popular for strengthening structures, achieving resistance to lateral loads and maintaining lateral load stability. Steel bracing offers advantages over other methods, including lower costs, ease of construction, and reduced space requirements. The study compares the seismic performance levels, capacity curves, target displacement, elastic stiffness, base shear, and displacement of eccentric and concentric bracing types (V-bracing, Inverted V-bracing, and Diagonal Bracing) under different brace layout patterns. Using the SeismoStruct program, the best bracing seismic action will be determined for 3D-modeled buildings with four, six, eight, and fifteen stories. This study aims to comparatively analyze eccentric and concentric bracing types under various brace layouts for different building heights using SeismoStruct, in alignment with the 2018 Turkish Earthquake Code. Pushover analysis revealed that inverted-V concentric braced frames (CBF) significantly improved shear loads by about 87% in four-story buildings and maintained high performance in six, eight, and fifteen-story buildings.

1. Introduction

Earthquakes have caused significant damage and long-term health problems, necessitating the development of earthquake-resistant construction to minimise structural damage and injuries. Existing buildings often suffer from issues with seismic performance, requiring the development of seismic strengthening solutions. Strengthening techniques can help build stock by offering technological remedies for most seismic hazards while minimising vulnerability. Modern building materials, such as steel braces, are one of the key approaches to strengthening structures [1]. Steel bracing decreases lateral drift and damage to building structures due to increased stiffness, reducing lateral damage compared to a bare frame. Steel bracing offers advantages over bracing in terms of cost, ease of construction, space commitment, and ability to achieve required strength, stiffness, and stability. Retrofitted frames are braced with steel to achieve satisfactory levels of life safety. Therefore, it is crucial to investigate various strengthening techniques at different story levels to improve seismic performance and prevent earthquake disasters.

1.1. Literature Review of Previous Studies

The seismic behaviour of concentrically and eccentrically braced frames is crucial for maintaining capacity design standards. Previous research has examined

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the use of steel bracing to strengthen RC frames, using various programs.

Kamanli and Unal (2017) conducted a study using SAP2000 to compare load-displacement curves of specimens and assess the impact of strengthening methods on the structure's carrying capacity for lateral loads, stiffness, and energy loss [2]. Eskandari et al. (2017) investigated the seismic response of reinforced concrete braced frames (RC-BFs) to close-fault and far-fault movements, finding that the mean maximum drift of the frames was within acceptable bounds [3].

Somase et al. (2021) compared the performance of different types of bracing systems for reinforced concrete buildings, finding greater safety after using X and Inverted V-braced frames [4]. Ayaanle and Erdal (2020) evaluated the effectiveness of concentric bracing systems during seismic activities, finding X bracing to be the most effective [5].

Sadeghpour and Ozay examine the effectiveness of eccentric steel bracing in reinforced concrete frames through nonlinear static analysis. The authors analyse structures of varying heights and bracing positions, focusing on the impact of link beam length on retrofitted RC structures. The overstrength, ductility, and response modification factors of the eccentric steel bracing systems in RC frames with several stories were assessed using a nonlinear static pushover analysis [6].

Sadeghpour and Ozay explore efficient methods to estimate the Collapse Margin Ratio (CMR) using ANN, RSM, and ANFIS, avoiding time-consuming traditional methods like Nonlinear Static Analysis and Incremental Dynamic Analysis. Through 5016 IDA analyses on 114 RC frames, key parameters were studied. ANFIS demonstrated the highest accuracy and efficiency, followed by ANN, outperforming RSM [7].

1.2. Study Scope and Objectives

This study compares eccentric and concentric steel bracing systems for existing 3D RC buildings, using nonlinear analysis to determine performance levels, capacity curves, target displacement, elastic stiffness, base shear and displacement. The SeismoStruct program is used to determine the best bracing seismic action based on different patterns of building stories 4, 6, 8, and 15.

2. Behavior of RC Steel Braced Structures

Earthquakes are devastating events, causing ground shaking and costing significant money to repair and rebuild structures. Seismologists use computers and digital recorders to study earthquakes more closely [8, 9]. Bracing system design is crucial to prevent losses and withstand seismic forces. Load resisting systems, specifically those used to resist lateral loads, are essential for buildings to prevent earthquake damage.

2.1. Structural Integrity and System Reliability

Structural system reliability is the probability of a system functioning safely [10]. Performance-based design requires a comprehensive system-level assessment of dependability. Steel bracing systems, for example, are ductile and can carry greater loads due to redundancy and force redistribution options. Framed constructions limit drift and hinge development without causing damage [11].

2.2. Bracing System in Reinforced Concrete Structure

2.2.1. Steel Bracing

Bracing systems in reinforced concrete (RC) buildings are crucial for resisting lateral loads and absorbing axial loads from earthquakes. They increase stiffness and strength, are economical, easy to install, and can be arranged in eccentric or concentric connection styles, making them a popular choice for RC frames.

2.2.1.1. Concentrically Braced Frame

Concentric braced frames (CBFs) are structural systems used in RC buildings to resist seismic forces. They consist of diagonal braces parallel to the frame's plane, creating a stiff frame. The connections of CBFs should be stronger than the members themselves to maximize energy dissipation and prevent buckling [12]. These frames are designed to maintain the elastic phase during load administration and ensure connections are strong. Strength drift control is crucial during the designing stage, especially for tall buildings [13]. Concentric bracing can be arranged in various configurations, including Inverted V, Diagonal bracing, and V bracing as in Figure 1.

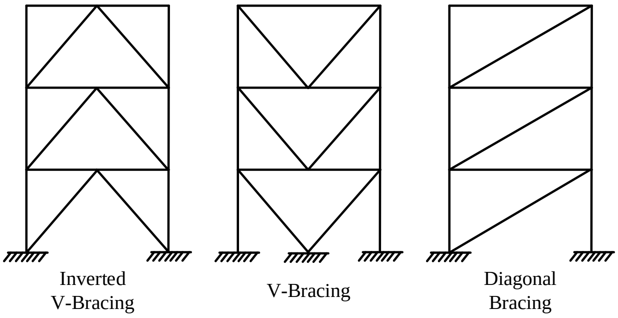


Figure 1. Define Concentric bracing frame types.

2.2.1.2. Eccentrically Braced Frame

Eccentric frames combine a bracing frame with a moment-resisting frame to provide a system with high elastic stiffness and inelastic response [14]. They resist lateral loads in high seismic areas due to their stiffness and ability to adapt during earthquakes. Figure 2 shows the link in the structure system for an eccentric beam. Link length, a beam section attached to the brace, allows the assembly to be connected to another brace or column. As the link length decreases, the frame becomes stiffer, approaching the stiffness of a Concentrically Braced Frame. Long links reduce the stiffness comparable to that of a moment frame by increasing the flexibility of the frame. The lateral stiffness of an eccentrically braced frame depends on the length ratio between the link and the beam [15].

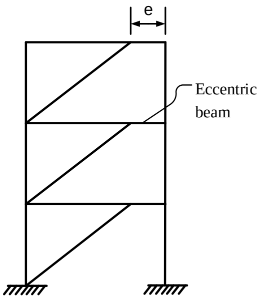
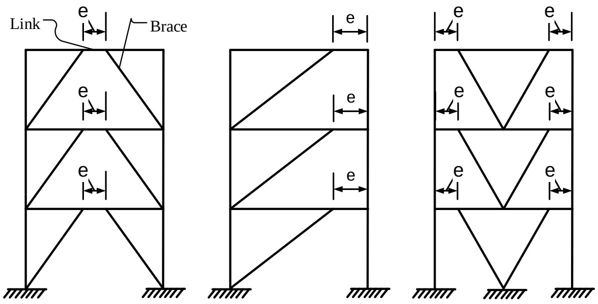


Figure 1. Define the link (e) on the structural system for an eccentric beam.

Eccentrically braced steel bracing in reinforced concrete buildings, arranged in different braced styles as shown in Figure 3.



Eccentric Inverted V-Bracing

Eccentric V-Bracing

Eccentric Diagonal Bracing

Figure 2. Eccentrically braced style. a) Eccentric Inverted V bracing, b) Eccentric Diagonal bracing, c) Eccentric V-bracing.

In eccentrically braced frames, a link (e) separates bracing members and columns, creating a weak spot for plastic deform and hinges, and distributing earthquake-generated energy.

According to AISC Code, links are calculated as:
Shear short links:

$$e < 1.6\ \frac{Mp}{Vp} \tag{1}$$

Where: Mp is Nominal plastic moment capacity, (N.mm), Vp is Nominal plastic shear capacity, (N), and e is Link length, (mm).

The plastic shear capacity is calculated as:

$$Vp = 0.6\ fy\ (d - 2tf)tw \tag{2}$$

Where: Fy is the specified minimum yield strength, d is the overall beam depth, and tw is the web thickness.

Plastic moment capacity is expressed as:

$$Mp = ZFy \tag{3}$$

Where: Z is the plastic section modulus [16].

3. Analysis Methods

The growth of seismic analysis due to software and electronic equipment has led to the use of advanced analytical, numerical, and experimental methods. Civil engineers face static, linear, and deterministic problems, and seismic codes offer practical strategies for earthquake analysis. This section discusses static pushover analysis and information on the 2018 Turkish Earthquake Code.

3.1. Static Pushover Analysis

3.1.1. Capacity Curve

The Capacity Curve or Pushover Curve represents the nonlinear behaviour of a structure, based on the horizontal displacement of the building's roof and the force exerted by it. This analysis transforms dynamic problems into static ones by calculating the interaction between base shear and displacements [17, 18]. A design seismic load generates a demand spectrum, which determines a structure's maximum inelastic capacity at a given damping ratio. Demand curves are formed by the response spectrum determined by earthquake zone, soil type, and damping level [19].

3.1.2. Plastic Hinges

Pushover analysis predicts collapses by obtaining hinges at weak points and following damage sequences. Hinges represent local force-displacement relationships under lateral loads [20]. Plastic joint load-carrying capacity depends on curvature and length, with ultimate rotations calculated based on joint length. Different criteria can result in different deformation capacities.

3.1.3. Target Displacement

Estimating damage and deformation patterns in a structure involves establishing a target displacement based on earthquake excitation. This displacement is then used to evaluate the structure's components and elements. According to an earthquake code target displacement can be calculated during adaptive pushover analysis, using parameters such as the control node, direction, and elastic response spectrum. The performance point is calculated by intersecting the target displacement with the elastic response spectrum.

3.1.4. Base Shear of the Lateral Forces

As a result of seismic activity, base shear estimates the maximum lateral force that will be exerted on a structure's base. It means the structure is subjected to monotonously increasing lateral loads until it reaches its peak response as shown in Figure 4.

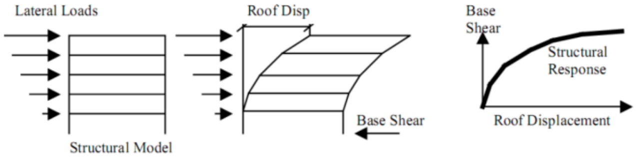
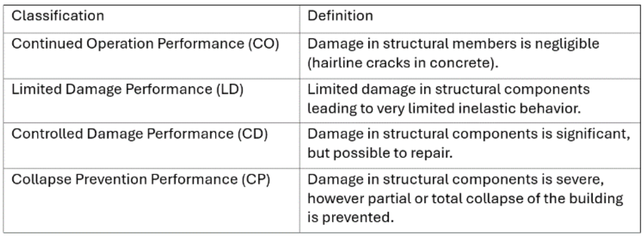


Figure 4. Roof displacement under lateral force on the structure base [21].

3.1.5. Performance Levels According to 2018 Turkish Earthquake Code

Figure 6 defines the building performance levels of the 2018 Turkish Earthquake Code.



Classification	Definition
Continued Operation Performance (CO)	Damage in structural members is negligible (hairline cracks in concrete).
Limited Damage Performance (LD)	Limited damage in structural components leading to very limited inelastic behavior.
Controlled Damage Performance (CD)	Damage in structural components is significant, but possible to repair.
Collapse Prevention Performance (CP)	Damage in structural components is severe, however partial or total collapse of the building is prevented.

Figure 6. Building performance level definition of the 2018 Turkish Earthquake Code [22].

4. Methodology

In this study, the selected 3D RC buildings were strengthened using eccentric and concentric bracing types (V-bracing, Inverted V-bracing, and Diagonal Bracing), under different brace layout patterns. The SeismoStruct program is used to determine the best bracing seismic action based on different patterns of buildings stories 4, 6, 8, and 15. 2018 Turkish Earthquake Code is used to compare the performance levels, capacity curves, target displacement, elastic stiffness, base shear and displacement.

4.1. SeismoStruct

SeismoStruct's large displacement performance considers geometric nonlinearities under static or dynamic loadings. A controlled node is the one with the highest applied load. SeismoStruct accounts for large displacements, rotations, and independent large deformations. The beam-column element has six degrees of freedom and six internal forces as in Figure 7.

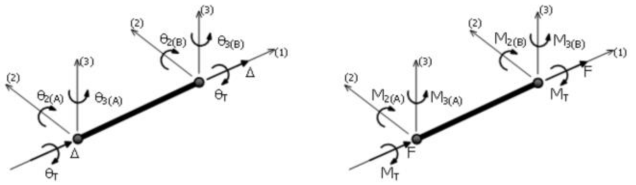


Figure 7. Beam-column local chord system [23].

SeismoStruct, an earthquake engineering tool, uses distributed inelasticity elements to represent beam-column behaviour, requiring individual fiber integration for nonlinear stress-strain behaviour as shown in Figure 8.

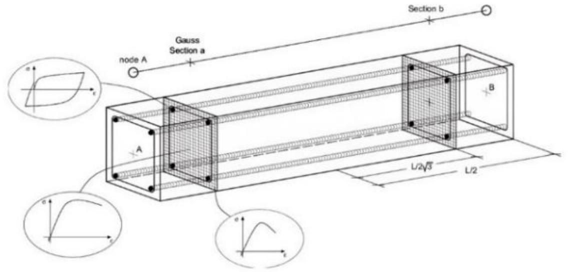


Figure 8. Discretization of a typical reinforced concrete cross-section [23].

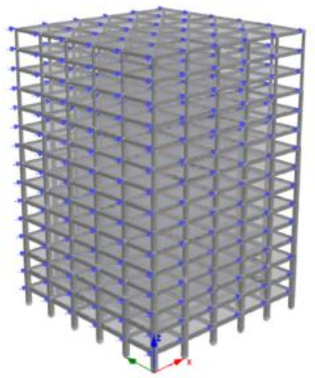
4.2. Performance Level Due to Turkish Code

The 2018 Turkish Earthquake Code combines performance levels and seismic action, with target displacements including Continued Operation Performance, Limited Damage Performance, Controlled Damage Performance, and Collapse Prevention Performance. Existing buildings are assessed based on the code's controlled damage target for the next 475 years under the DD-2 earthquake, with a return period of 475 years. Soil class C (ZC) soil and a 5% damping ratio for structures are used.

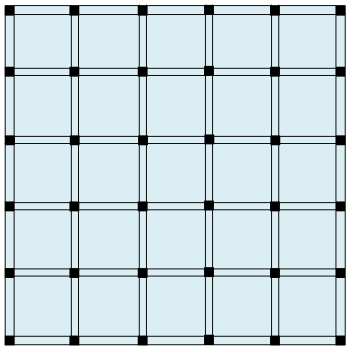
4.3. Modelling of the Frames

The frame section of three-dimensional reinforced concrete buildings designed by SeismoStruct, with heights of 4, 6, 8, and 15 stories. The building elements are designed as inelastic force-based plastic hinge frame element type (infrmFBPH) for concentric braces building and inelastic displacement-based frame element type (infrmDB) for eccentric braces building. The building's section fibers are 150.

For four-story buildings, the number of section fibers for columns is 62, with a Plastic-hinges length of 16.67%. For six-story buildings, the number of section fibers is 75, with a Plastic-hinges length of 16.67%. For eight-story buildings, the number of section fibers is 105, with a Plastic-hinges length of 16.67%. For fifteen-story buildings, the number of fiber sections is 139, 116, and 105, with a Plastic-hinges length of 16.67%. Figure 9 is an example of the 3D modelling for a fifteen-storey building, the 3D model was designed in the same way for 4, 6, and 8-storey buildings.



a) 3D view of fifteen-story plain building

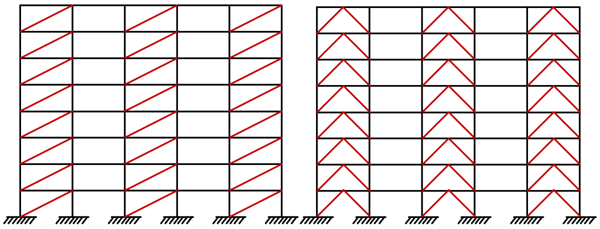


b) Plan of the fifteen-story building

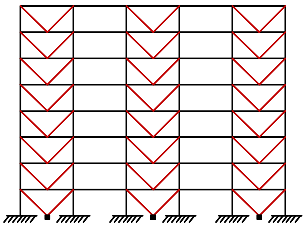
Figure 9 (a and b). Fifteen-story plan view.

4.4. Strengthening Braces Layout

Figures 10 to 15 show an example of the layout of different cases and braces for an eight-storey building. The design and braces employed for four, six, and fifteen-story buildings mirror those used for the eight-story structure.

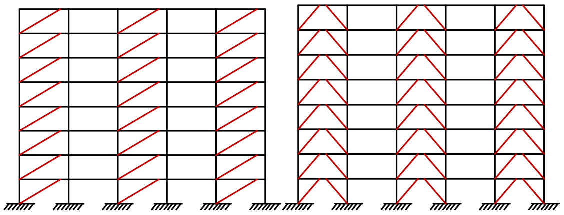


a) Diagonal brace b) IV- brace

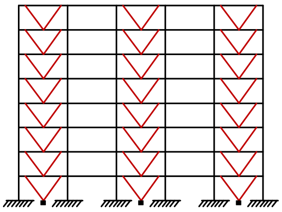


c) V-brace

Figure 10. First case (pattern 1) of concentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

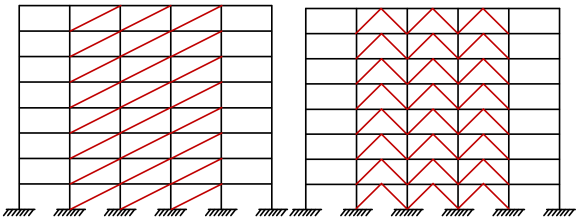


a) Diagonal brace b) IV- brace

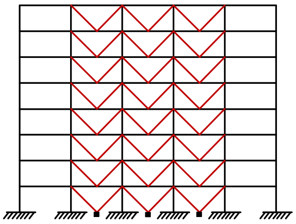


c) V-brace

Figure 11. First case (pattern 1) of eccentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

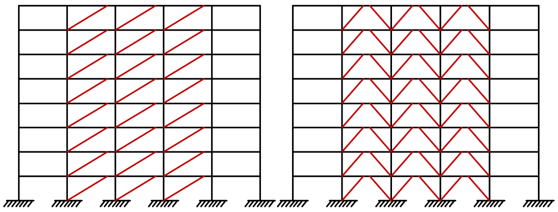


a) Diagonal brace b) IV- brace

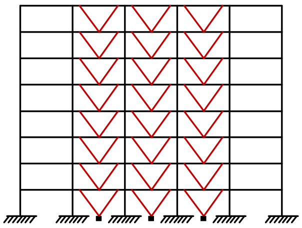


c) V-brace

Figure 12. Second case (pattern 2) of concentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

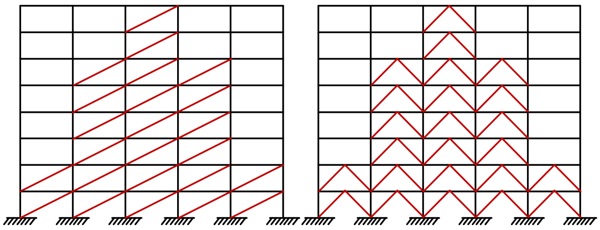


a) Diagonal brace b) IV- brace

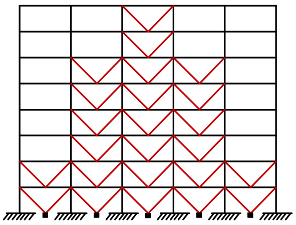


c) V-brace

Figure 13. Second case (pattern 2) of eccentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

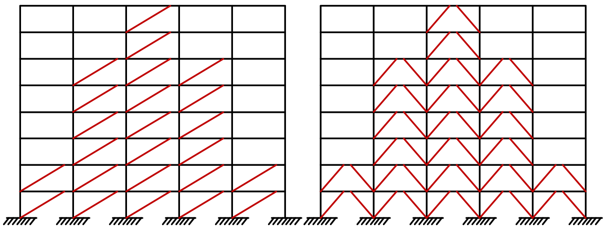


a) Diagonal brace b) IV- brace

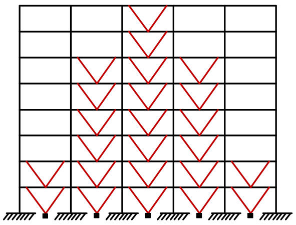


c) V-brace

Figure 14. Third case (pattern 3) of concentric braces for eight story building: a) Diagonal brace, b) IV-brace, and c) V-brace.



a) Diagonal brace b) IV- brace



c) V-brace

Figure 15. Third case (pattern 3) of eccentric braces for eight-story building: a) Diagonal brace, b) IV-brace, and c) V-brace.

4.5. Materials Properties

This part describes the properties of the materials used in the design according to 2018 Turkish Earthquake Code. It will describe concrete and steel for the RC part and the steel brace part. Figure 16 shows the Concrete stress-strain diagram, while Figure 17 shows Steel stress-strain diagram.

1) Concrete:

- Concrete strength (kPa): 33000
- Tensile strength (kPa): 2600
- Modulus of elasticity (kPa): $2.7x10^{8}$
- Strain at peak stress (m/m): 0.0022
- Specific weight (kN/m^3): 24

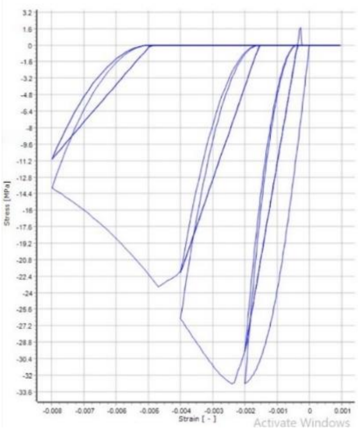


Figure 16. Concrete stress-strain diagram.

2) Steel and steel brace:

- Modulus of elasticity (kPa): $2x10^{8}$
- Yield strength (kPa): 250000
- Strain hardening parameter: 0.005
- Transition curve initial shape parameter: 20
- Transition curve shape calibrating coefficient, A1: 18.50
- Transition curve shape calibrating coefficient, A2: 0.15
- Isotropic hardening calibrating coefficient, A3: 0
- Isotropic hardening calibrating coefficient, A4: 1
- Fracture /buckling strain: 1
- Specific weight (kN/m^3): 78

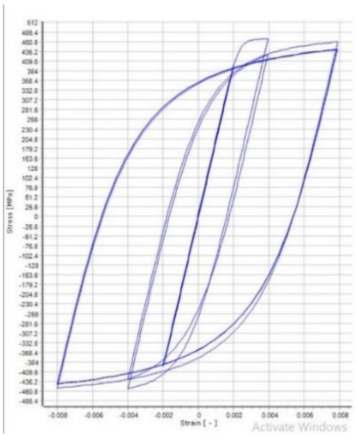


Figure 17. Steel stress-strain diagram (stl¬_mp)

5. Results and Discussions

The SeismoStruct program was used to analyze pushover in modelled buildings, determining the response of floors in terms of capacity curves, performance levels, base shears, displacements, and stiffness. The analysis was conducted on concentric and eccentric bracing frames based on their pattern design (Cases).

5.1. Capacity Curve

The capacity curve is a base shear-displacement diagram that illustrates structure behaviour after plasticity limitation, comparing different capacity curves for different bracing types and patterns (Case 1, Case 2, and Case 3). Figures 18 to 29 show the capacity curve of different cases (Patterns) for 4, 6, 8 and 15 storey buildings.

1) Four Story Building:

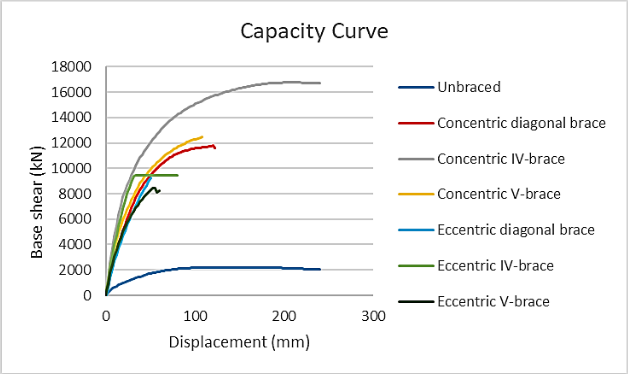


Figure 18. Base shear vs displacement (capacity curve) of Case 1 for four story building.

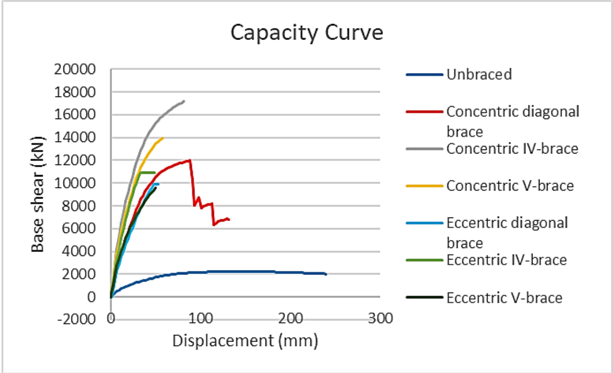


Figure 19. Base shear vs displacement (capacity curve) of Case 2 for four story building.

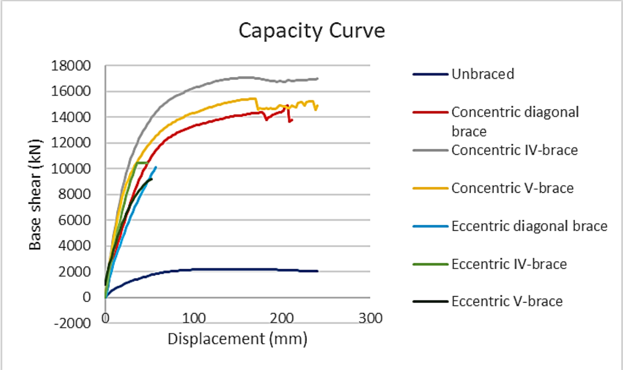


Figure 20. Base shear vs displacement (capacity curve) of Case 3 for four story building.

The pushover analysis revealed that adding braces significantly impacts a building's strength and stiffness. Braced buildings show better performance than unbraced ones, with the concentrically braced frame (CBF) inverted-V brace demonstrating the highest performance curve in Cases

1, 2, and 3. The concentric inverted-V brace was the best performance brace in all cases in a four-story building, increasing the base shear load by 87.12% compared to an unbraced structure. Eccentric braces (EBF) have a lower shear load and have larger stiffness and strength than concentric braces (CBF).

2) Six Story Building:

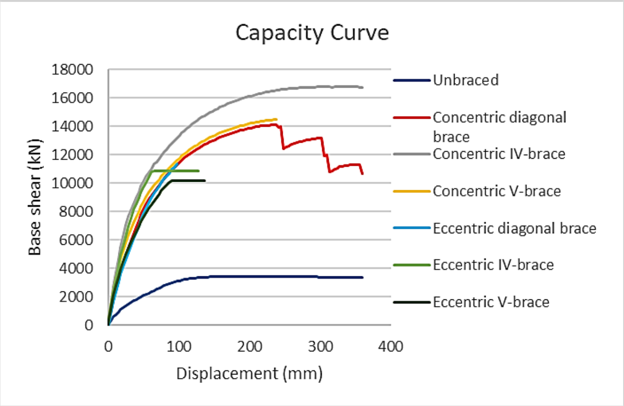


Figure 21. Base shear vs displacement (capacity curve) of Case 1 for six story building.

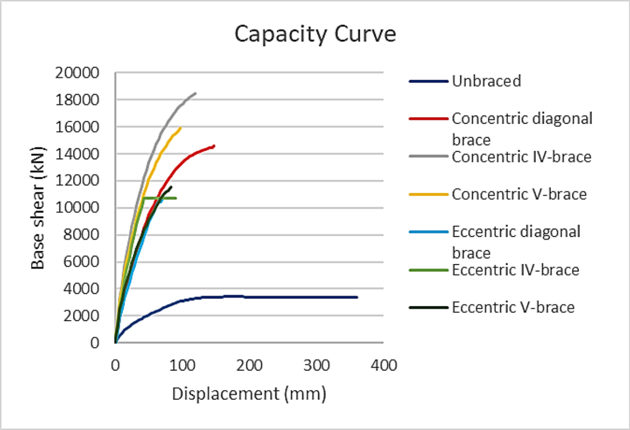


Figure 22. Base shear vs displacement (capacity curve) of Case 2 for six story building.

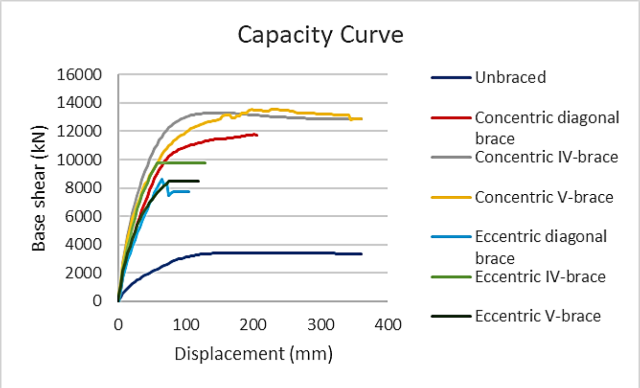


Figure 23. Base shear vs displacement (capacity curve) of Case 3 for six story building.

The study demonstrates that the concentric Inverted-V brace in Case 2 has the highest performance, increasing the shear load by 81.51% compared to an unbraced structure. In Case 1, the Inverted-V brace increased the shear load by 79.64%, while Case 3 saw a higher V brace by 74.80% compared to an unbraced structure.

3) Eight Story Building:

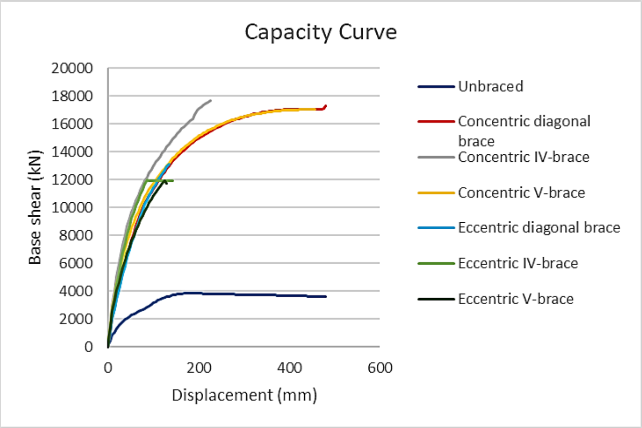


Figure 24. Base shear vs displacement (capacity curve) of Case 1 for eight story building.

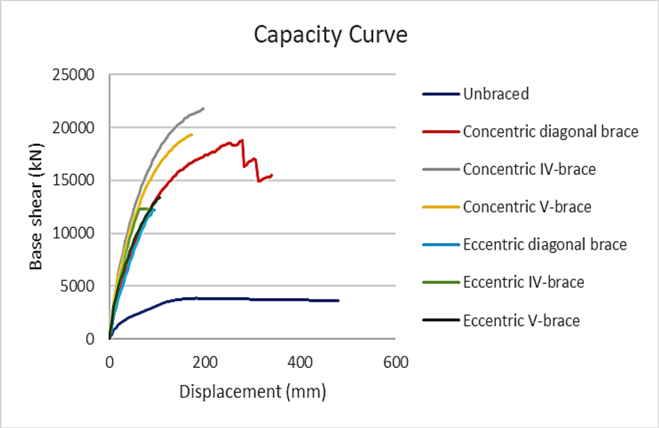


Figure 25. Base shear vs displacement (capacity curve) of Case 2 for eight story building.

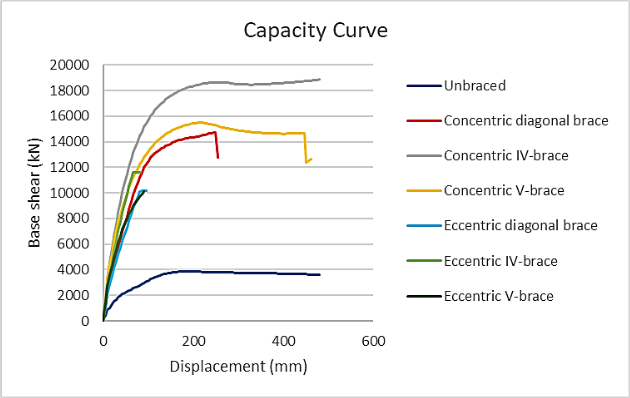


Figure 26. Base shear vs displacement (capacity curve) of Case 3 for eight story building.

Figures 24, 25 and 26 show that Inverted-V braces have the highest base shear load in Cases 1, 2, and 3 compared to an unbraced structure, with an increasing percentage of 78.17%, 82.31%, and 79.56%, respectively, with the best performance load in Case 2.

4) Fifteen Story Building:

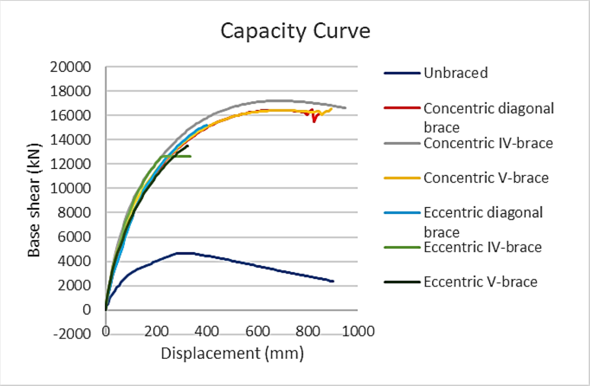


Figure 27. Base shear vs displacement (capacity curve) of Case 1 for fifteen story building.

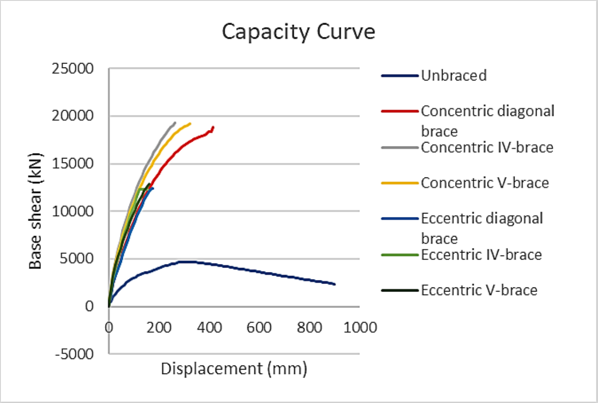


Figure 28. Base shear vs displacement (capacity curve) of Case 2 for fifteen story building.

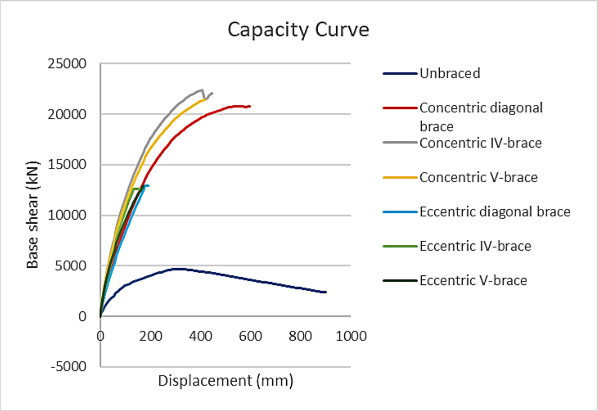


Figure 29. Base shear vs displacement (capacity curve) of Case 3 for fifteen story building.

The capacity curve for fifteen story building shows similarities, with the highest base shear load in Case 3 being the Inverted-V brace, increasing by 79.17%. Cases 1 and 2 also saw the highest load increase, with the Inverted-V brace showing the highest increase compared to an unbraced structure.

5.2. Performance Level

Table 1 shows the performance levels for various building heights (4, 6, 8, and 15 stories) braced and unbraced.

Table 1. Performance level of 4, 6, 8 and 15 -story building

			Performance level															
		Type of braces	Four story building				Six story building				Eight story building				Fifteen story building			
			CO	LD	CD	CP	CO	LD	CD	CP	CO	LD	CD	CP	CO	LD	CD	CP
		Unbraced				✓				✓				✓				✓
Concentric	Case 1	Diagonal brace		✓				✓					✓				✓	
		IV-brace	✓					✓					✓				✓	
		V-brace		✓				✓				✓				✓		
	Case 2	Diagonal brace		✓				✓				✓					✓	
		IV-brace	✓				✓				✓					✓		
		V-brace	✓				✓				✓				✓			
	Case 3	Diagonal brace	✓						✓			✓				✓		
		IV-brace	✓						✓			✓				✓		
		V-brace	✓					✓				✓			✓			
Eccentric	Case 1	Diagonal brace		✓			✓					✓				✓		
		IV-brace		✓				✓					✓				✓	
		V-brace		✓				✓				✓					✓	
	Case 2	Diagonal brace		✓				✓				✓				✓		
		IV-brace		✓				✓				✓				✓		
		V-brace			✓			✓				✓				✓		
	Case 3	Diagonal brace		✓				✓				✓				✓		
		IV-brace		✓				✓				✓				✓		
		V-brace			✓				✓			✓				✓		

Table 1 compares concentric and eccentric performance levels for different story heights. Unbraced buildings have CP, while added braces improve Continued Operation Performance, Controlled Damage Performance, and Limited Damage Performance. Concentric braces perform better than eccentric braces.

5.3. Target Displacement

Building displacement targets estimate structure damage and deformation patterns, considering target displacement and target point in accordance with the Turkish Earthquake Code. Table 2 shows target displacement performance with different patterns and braces.

Table 2. Target displacements of 4, 6, 8 and 15-story buildings.

Type of braces			Target displacement (m)															
			Four story building				Six story building				Eight story building				Fifteen story building			
			CP	LD	CD	Target point	CP	LD	CD	Target point	CP	LD	CD	Target point	CP	LD	CD	Target point
Unbraced			0.0453	0.1234	0.2099	0.1248	0.0435	0.1186	0.2018	0.1188	0.0653	0.1781	0.3029	0.1824	0.1153	0.3141	0.5345	0.3150
Concentric	Case 1	Diagonal brace	0.0112	0.0306	0.0521	0.0312	0.0177	0.0483	0.0822	0.0504	0.0394	0.1074	0.1827	0.1104	0.0732	0.1995	0.3394	0.1995
		IV-brace	0.0166	0.0427	0.0743	0.0432	0.0234	0.0639	0.1086	0.0648	0.0332	0.0905	0.1540	0.0912	0.0625	0.1704	0.2898	0.1710
		V-brace	0.0193	0.0526	0.0896	0.0528	0.0281	0.0766	0.1303	0.0792	0.0266	0.0725	0.1234	0.0768	0.0394	0.1073	0.1826	0.1140
	Case 2	Diagonal brace	0.0115	0.0313	0.0533	0.0336	0.0179	0.0488	0.0829	0.0504	0.0261	0.0711	0.1209	0.0720	0.0489	0.1333	0.2268	0.1425
		IV-brace	0.0084	0.0205	0.0357	0.0216	0.0141	0.0384	0.0654	0.0396	0.0208	0.0567	0.0964	0.0576	0.0386	0.1051	0.1789	0.1140
		V-brace	0.0088	0.0223	0.0389	0.0240	0.0127	0.0347	0.0591	0.0360	0.0187	0.0509	0.0867	0.0528	0.0334	0.0911	0.1551	0.0950
	Case 3	Diagonal brace	0.0111	0.0302	0.0514	0.0312	0.0311	0.0848	0.1443	0.0864	0.0304	0.0827	0.1407	0.0864	0.0530	0.1444	0.2456	0.1520
		IV-brace	0.0087	0.0208	0.0362	0.0216	0.0243	0.0663	0.1127	0.0684	0.0248	0.0675	0.1148	0.0720	0.0398	0.1084	0.1845	0.1140
		V-brace	0.0091	0.0217	0.0379	0.0240	0.0137	0.0374	0.0636	0.0396	0.0178	0.0486	0.0826	0.0528	0.0333	0.0907	0.1543	0.0950
Eccentric	Case 1	Diagonal brace	0.0110	0.0300	0.0510	0.0120	0.0163	0.0444	0.0755	0.0468	0.0211	0.0576	0.0980	0.0576	0.0463	0.1262	0.2147	0.1330
		IV-brace	0.0173	0.0472	0.0804	0.0472	0.0277	0.075	0.1283	0.0754	0.0307	0.0836	0.1423	0.0864	0.0713	0.1942	0.3304	0.1995
		V-brace	0.0112	0.0305	0.0519	0.0312	0.0296	0.0806	0.1371	0.0828	0.0272	0.0741	0.1261	0.0768	0.0670	0.1906	0.3243	0.1995

Case 2	Diagonal brace	0.0115 0.0312 0.0531	0.0336	0.0236 0.0642 0.1092	0.0648	0.0202 0.0549 0.0935	0.0576	0.0384 0.1045 0.1779	0.1045
	IV-brace	0.0099 0.0265 0.0458	0.0288	0.0194 0.0528 0.0899	0.0528	0.0177 0.0481 0.0819	0.0481	0.0334 0.0909 0.1547	0.0950
	V-brace	0.0096 0.0263 0.0447	0.0264	0.0179 0.0488 0.0830	0.0504	0.0176 0.0479 0.0815	0.0480	0.0316 0.0861 0.1465	0.0950
Case 3	Diagonal brace	0.0107 0.0291 0.0495	0.0312	0.0227 0.0618 0.1051	0.0648	0.0206 0.0560 0.0953	0.0576	0.0414 0.1129 0.1920	0.1140
	IV-brace	0.0105 0.0274 0.0478	0.0288	0.0279 0.0759 0.1292	0.0759	0.0180 0.0490 0.0834	0.0528	0.0351 0.0956 0.1626	0.1045
	V-brace	0.0098 0.0261 0.0453	0.0264	0.0257 0.0700 0.1191	0.0720	0.0185 0.0505 0.0859	0.0528	0.0323 0.0881 0.1499	0.0950

Unbraced buildings in four-story buildings have a high target displacement of 0.1248, with concentric Inverted-V brace (IV-brace) being the best system. Most eccentric braces have Limited Damage Performance, while concentric braced frames are more efficient. In six-story buildings, diagonal brace is the best eccentric performance system, while concentric braces show better performance. In eight-story buildings, concentric case 2 for IV and V-brace systems perform best, while in fifteen-story buildings, concentric V-brace systems achieve Continued Operation Performance and Limited Damage Performance.

5.4. Elastic Stiffness

Table 3 shows elastic stiffness performance with different patterns and braces.

Table 3. Elastic Stiffness of 4, 6, 8 and 15- storey building.

Elastic stiffness (KN)																			
Type of braces	Unbraced	Concentric									Eccentric								
		Case 1			Case 2			Case 3			Case 1			Case 2			Case 3		
		D -brace	IV-brace	V-brace	D -brace	IV-brace	V-brace	D -brace	IV-brace	V-brace	D -brace	IV-brace	V-brace	D- brace	IV-brace	V-brace	D -brace	IV-brace	V-brace
Four story building	93125.35	342286.57	545625.26	451865.47	375953.17	620913.22	542964.29	363871.44	569379.88	539820.25	338452.07	480013.98	391112.98	373931.76	514911.75	454878.43	350868.07	468471.55	426283.23
Six story building	73275.50	256639.88	376981.00	325280.65	289189.94	452847.27	420487.20	262388.34	383129.26	367618.34	257034.53	335833.70	291589.92	283314.44	379163.65	355431.79	253560.01	317912.90	300705.33
Eight story building	75689.43	224445.55	310288.43	278554.43	253664.99	378472.78	356775.79	234033.72	339688.90	324357.89	223421.45	277876.93	260362.37	252935.41	317658.10	320771.67	231026.27	281408.02	280582.34
Fifteen story building	41160.97	116118.89	144260.17	134418.28	137944.95	189177.54	179753.50	132691.45	179009.42	171840.46	117993.67	133946.33	129269.26	138253.59	163106.55	169892.89	129253.18	153057.50	156892.68

Stiffness is crucial for earthquake resistance, and bracing systems can increase it. Unbraced buildings have the lowest stiffness at 93125.35 kN, which can be increased by adding a bracing system. Concentrically braced systems have higher stiffness than eccentrically braced ones. Inverted V-braces in four storey building have the highest elastic stiffness, increasing by 82.93%, 85%, and 83.64%, respectively in case 1,2 and 3 compared to unbraced system. This finding is also mentioned by Kafeel, Birendra, and Prasenjit Saha in their paper [24].

5.5. Base shear and displacement

Table 4 shows Base shear and displacement of 4, 6, 8 and 15- storey building.

Table 4. Base shear and displacement of 4, 6, 8 and 15-story buildings.

Base shear (kN) and displacement (m)										
Type of braces			Four story building		Six story building		Eight story building		Fifteen story building	
Unbraced			2214.56	0.0608	3416.19	0.0885	3855.65	0.1010	4657.06	0.1753
Concentric	Case 1	Diagonal brace	11766.52	0.0590	14113.65	0.1131	17284.96	0.1871	16466.92	0.3220
		IV-brace	16757.07	0.0766	16776.59	0.1144	17663.03	0.1318	17213.09	0.2989
		V-brace	12503.27	0.0581	14503.14	0.1093	17034.14	0.1651	16544.30	0.3172
	Case 2	Diagonal brace	11962.30	0.0494	14609.61	0.0866	18738.42	0.1505	18838.59	0.2676
		IV-brace	17187.46	0.0454	18479.53	0.0709	21792.84	0.1113	19294.82	0.1825
		V-brace	13929.60	0.0375	15928.98	0.0636	19329.36	0.1024	19219.48	0.2039
	Case 3	Diagonal brace	14904.71	0.0873	11763.64	0.0812	14746.77	0.1132	20812.38	0.3061
		IV-brace	17075.77	0.0601	13295.60	0.0613	18859.85	0.1156	22362.55	0.2382
		V-brace	15444.84	0.0650	13554.52	0.0881	15485.18	0.0957	21394.43	0.2440
Eccentric	Case 1	Diagonal brace	9234.78	0.0415	11334.24	0.0733	13145.60	0.1002	15213.85	0.2588
		IV-brace	9451.64	0.0257	10824.93	0.0466	12000.89	0.0645	12635.89	0.1559
		V-brace	8444.38	0.0363	10157.63	0.0624	11943.53	0.0860	13503.33	0.2108
	Case 2	Diagonal brace	9874.35	0.0398	10779.64	0.0570	12177.47	0.0743	12434.84	0.1400
		IV-brace	10874.37	0.0272	10705.93	0.0366	12289.03	0.0520	12259.69	0.1025
		V-brace	9586.83	0.0359	11524.65	0.0573	13393.59	0.0734	12865.70	0.1189
	Case 3	Diagonal brace	10131.81	0.0475	8640.17	0.0539	10192.88	0.0691	12898.03	0.1540
		IV-brace	10424.87	0.0300	9753.07	0.0439	11607.65	0.0556	12604.19	0.1104
		V-brace	9223.24	0.0370	8506.30	0.0498	10094.66	0.0596	12939.17	0.1280

The structure should withstand lateral loads to prevent stresses. The unbraced building has the lowest lateral load capacity at 2214.56 kN and 0.0608 m displacement. The highest load is for concentric IV-brace (Case 2), with a percentage of 87.12% increase. As Rishi, Abhay, and Vivek mentioned in their study, inverted V-braces demonstrate the best performance [25].

6. Conclusions and Recommendations

6.1. Conclusion

The analysis conducted using the SeismoStruct program on various building models has demonstrated the significant impact of bracing systems on building performance, particularly in resisting lateral loads and improving structural stiffness. Braced buildings consistently outperformed unbraced ones across multiple metrics, including capacity curves, performance levels, target displacements, elastic stiffness, and lateral load capacities. The pushover analysis revealed that concentric braced frames (CBF) with inverted-V braces achieved the highest performance in all cases (1, 2, and 3), significantly increasing shear loads by approximately 87% in four-story buildings compared to unbraced system and maintaining high performance across six, eight, and fifteen-story buildings. Adding braces improved the performance levels from Collapse Prevention (CP) in unbraced buildings to Continued Operation (CO), Controlled Damage (CD), and Limited Damage (LD) in braced structures, with concentric braces consistently outperforming eccentric ones.

The implementation of concentric and eccentric bracing systems, particularly the inverted-V brace, has proven to be highly effective in enhancing the seismic performance of buildings. Braced buildings showed reduced target displacements, indicating lower deformation and damage under seismic loads, with concentric inverted-V braces consistently achieving the highest performance with the lowest target displacements. Bracing systems notably increased the elastic stiffness of buildings, with concentric inverted-V braces providing the highest stiffness increases across all building heights, contributing to greater resistance against lateral loads. In summary, concentric braces, especially in the inverted-V configuration, delivered superior results in terms of strength, stiffness, and overall structural integrity, making them a preferable choice for improving the resilience of buildings in earthquake-prone areas.

6.2. Further Research Stages and Remarks

Future research should explore various types of braces to improve retrofitting efficiency of RC structural elements, addressing unfavorable arrangement and reducing strengthening costs, focusing on stability and non-linearly unsymmetrical structures.

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