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Behaviour of Different Bracing Systems in High Rise 3-D Benchmark Building under Seismic Loadings

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Abstract: This paper presents the seismic behaviour of different bracing systems in high rise 20 storey 3-D benchmark steel building. A nonlinear static pushover analysis was carried out to on different braced 20 storey high rise 3-D benchmark steel building to capture the seismic response. In this study, five structural configurations were used: moment resisting frames (MRF), chevron braced frames (CBF), V-braced frames (VBF), X-braced frames (XBF), and zipper braced frames (ZBF). The primary goal of this study is to investigate the seismic behaviour of different bracing systems in a benchmark building under the different lateral load patterns. It is seen that the type of bracing system significantly influences the performance of high rise buildings. The seismic performance of the 20 storey benchmark building is measured in terms of the fundamental time period, capacity curve, storey displacement, and inter-storey drift ratio. It can be concluded from the study that the seismic resistance can be increased by use of the CBF, VBF, and ZBF than XBF and MRF.

Keywords: Seismic behaviour, high rise 3-D benchmark steel building, bracing systems, nonlinear pushover analysis, capacity curve.

1. Introduction

Moment resisting frames and braced frames have been commonly used as lateral load resisting structural elements in steel buildings. The different bracing systems include typical diagonal bracing, X-bracing, chevron bracing and V-bracing configurations, which connect the brace concentric to beam- column joint. Roeder and Popov proposed eccentric bracing, combining good features of moment resisting frame and concentric braced frame both [1, 2]. The seismic performance of chevron braced frames can be improved by redesigning the brace and floor beams to a weak brace and the strong beam system. This upgraded chevron braced frame result in an excellent hysteretic response [3]. Tremblay et al. studied seismic performance of concentrically braced steel frames, i.e. diagonal braced frame and X-braced frame [4]. Yang et al. proposed a design methodology for zipper braced frames to achieve good ductile behaviour [5]. The zipper braces activated buckling in all storeys except the top one [6]. Also, Nouri et al. investigated the concentric braced frames and proposed zipper braced to mitigate the vertical unbalanced force in case of chevron braced frame [7]. Similarly Patil et al. studied behaviour of different braced steel

buildings of different height for symmetric plan building [8].

In this research paper, an attempt is made to investigate the seismic behaviour of different braced systems in G+20 storey high rise benchmark building. An extensive analytical investigation of the seismic behaviour of different braced buildings has been undertaken by nonlinear static pushover analysis. An attempt has been made to assess the performance of different bracing systems under application of different invariant lateral load patterns in a nonlinear static pushover analysis, by using five structural configurations: moment resisting frames (MRF), chevron braced frames (CBF), V-braced frames (VBF), X-braced frames (XBF) and zipper braced frames (ZBF).

2. Example G+20 Benchmark Building

In this study, behaviour of different bracing systems in G+20 storey high rise benchmark building for lateral loads is investigated. Total 5 different bracing systems investigated using nonlinear static pushover analysis. Results of nonlinear static pushover analysis of benchmark high rise buildings are discussed in section 4. Plan and elevation of benchmark buildings are illustrated in Fig. 1. Dimensions of benchmark buildings, basement level height is 3.65m, ground level height is 5.49m, 2^{st} to 20^{th} level height is 3.96m and all bays with 6.10m width.

3. Nonlinear Static Pushover Analysis

Nonlinear static analysis is performed on benchmark buildings using different lateral load patterns to determine the effects of the lateral load on the global structural behaviour through the loaddisplacement curve. In this study, displacement controlled pushover analysis is carried out using SAP2000 v16 (Computer and Structures, Inc, Berkeley) software [9].



Figure 1: Plan and Elevation of G+20 Benchmark Building

The target displacement used for each building is 4% of the total height of the building (ATC-40) [10]. Indian codes were used to calculate different parameters [11-13]. The SAP2000v16 default hinge properties based on FEMA-356 criteria are

used for beams, columns and braces. Hinges are assigned at both the ends of each column, beam element and at mid-span of braces. For column, coupled (PMM) hinges, which yields based on the interaction of axial force and bi-axial bending moments at the hinge location, are used. P (axial) hinges are assigned for steel braces in tension/compression and M3 (moment) hinges are assigned to the beam elements [14].

The nonlinear static pushover analysis, as described in FEMA-273 [15] and in FEMA-356 [14], is now being used as a standard tool to estimate seismic demands for buildings. Pushover analysis has played an important role in the development of performance-based earthquake engineering concepts in guideline documents and codes (e.g. ATC-40, 1996; FEMA-356, 2000) [10, 14]. Due to the fact that the lateral force profiles in static pushover analysis influence the structural response, different lateral load patterns have been utilized to represent the distribution of inertia forces imposed on buildings. In the past few years, several researchers have discussed accuracy and limitations of pushover analysis and proposed new various methods [16-19]. Some researchers have suggested to consider higher mode effects to overcome the shortcomings of a pushover procedure [20-21]. The researchers have addressed FEMA and modal pushover analysis with inelastic response history analysis in high-rise buildings [19-21]. The objective of this investigation is to study an improved pushover analysis procedure based on the invariant force distribution of different lateral load patterns in estimating seismic demands of buildings. The different lateral load patterns used in this study are as follows:

• Codal Lateral Load Pattern: Push 2

The codal lateral load shape represents the forces obtained from the predominant mode of vibration. Following equation is used to calculate codal load pattern [11]:

$$V_B = A_h W \tag{1}$$

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{i=1}^n W_i h_i^2} \tag{2}$$

Where V_B = design base shear as per IS1893 (Part-I): 2002 [11],

 h_i = height of the floor *i* measured from the base,

 Q_i = Lateral force at floor *i*,

 W_i = seismic weight of floor *i* and

n = number of storeys in the building.

• Elastic First mode Lateral Load Pattern: Push 3 The first mode load pattern is related to the first displacement mode shape (Φ) of vibration. The lateral force of a storey is proportional to the product of the amplitude of the elastic first mode and mass at the storey [8,13].

$$F_i = m_i \phi_i / \Sigma \ m_i \phi_i \tag{3}$$

Where Φi = amplitude of the elastic first mode of the storey.

• Multi-modal Lateral Load Pattern: Push 4

This lateral load pattern considers the effects of elastic higher modes of vibrations for a long period and characteristics of the structural behaviour. The contribution of first three elastic modes of vibration is considered to calculate the multimodal lateral load pattern.

• Uniform Lateral Load Pattern: Push 5

In this, the lateral force at a storey is proportional to the mass of the storey [8, 13].

$$F_i = m_i \,/\, \Sigma \,\, m_i \tag{4}$$

where F_i = lateral force at the *i*th floor, m_i = the mass at ith floor of the building.

4. Results and Discussion

Nonlinear static pushover analysis is performed using the calculated lateral load patterns on example different bracing systems in G+20 benchmark high rise buildings. The responses of different bracing systems are studied in terms of the fundamental period of vibration, base shear, roof displacement, storey displacement and interstorey drift ratio. The natural period of vibration is depicted in Table 1 for benchmark buildings. In addition, modal analysis of the example buildings is carried out to find the fundamental period of vibration derived by eigenvalue method. The



resulting fundamental period of vibration using eigenvalue analysis is reported in Table 1.

It is noticed from Table 1 that ZBF, and CBF shows reduced fundamental time period obtained by modal analysis. Besides this, the fundamental period obtained from the modal analysis is not close to that obtained from codal empirical equations for steel buildings.

Table 1: Period of vibration(s) of different bracing systems in G+20 Benchmark buildings

Codal	Modal analysis							
Period	MRF	CBF	VBF	XBF	ZBF			
2.4428	3.8208	2.2296	2.2391	2.2545	2.2244			

4.1 Capacity curves

The capacity curves, showing the relationship among base shear force and roof displacement, benchmark building of different invariable lateral load patterns is illustrated in Fig. 2. Table 2 depicts the base shear and roof displacement values of different bracing systems in a benchmark building for the different lateral load patterns evaluated from the nonlinear pushover analysis.

It is revealed from Table 2 that the Base shear changes with invariant lateral load patterns. ZBF and CBF show higher base shear than other structural systems in benchmark buildings. The 44% increase is observed in the base shear of ZBF than MRF for Push 2 load case. Similarly, 47%, 75%, 42% increase in base shear is seen for load case push 3, push 4, push 5 respectively.





Table 2: Base shear and roof displacement of different bracing systems in benchmark building

Different	t Push 2 load case		Push 3 load case		Push 4 load case		Push 5 load case	
Bracing	Base	Roof	Base	Roof Disp.	Base Shear	Roof Disp.	Base Shear	Roof Disp.
Systems	Shear (kN)	Disp. (m)	Shear (kN)	(m)	(kN)	(m)	(kN)	(m)
MRF	43425	1.9651	45007	1.9107	27505	0.7464	53695	1.5560
CBF	61123	1.1706	64693	1.4697	45741	0.0246	73711	0.9150
VBF	60829	1.1455	65356	1.5042	46386	0.0298	74839	0.9703
XBF	59470	1.5005	61362	1.5718	51411	0.2235	72320	1.2168
ZBF	62562	1.1859	66482	1.5396	48352	0.0260	76208	0.9858

4.2 Storey displacement

The storey displacements of different bracing systems in a benchmark building corresponding to different invariant lateral load patterns in pushover analysis are illustrated in Fig. 3. It is revealed from Fig. 3, trend in the similarities and/or in the variations of the different invariant lateral load patterns is reflected in the storey displacement profiles of the buildings. Storey displacement demand prediction of codal and elastic first mode load patterns is observed nearly same compared to the other lateral load patterns. The MRF buildings, as depicted in Fig. 3, show higher storey displacements than other systems as it is most ductile structural system. CBF, VBF, and ZBF show lesser storey displacement for all load cases. It is seen from Fig. 3 that XBF shows higher storey displacement than CBF, VBF, and ZBF.





4.3 Inter-storey drift ratios

The inter-storey drift ratios of different bracing systems in benchmark buildings corresponding to different invariant lateral load patterns in pushover analysis are illustrated in Fig. 4. Inter-storey drift ratio is higher in MRF than CBF, VBF, XBF, and ZBF for all lateral load cases. It is observed that inter-storey drift ratio is higher at the lower storey height of buildings. CBF, VBF and ZBF show less inter-storey drift ratio for all load cases. It is observed from inter-storey drift ratio of building that CBF, VBF and ZBF are more preferred than XBF and MRF.





5. Conclusions

In this study an attempt is made to assess the seismic response parameters of different bracing [1]. systems to examine the seismic behaviour of each system. The conclusions of this study can be summarized as follows.

- 1. Seismic response of CBF, VBF and ZBF benchmark building is nearly similar in terms of base shear. Seismic response of these systems is considerably higher than MRF and XBF.
- 2. CBF and VBF show lower storey displacement and inter-storey drift ratio indicating that these systems have strength and stiffness. ZBF also shows nearly similar storey displacement and inter-storey drift ratio.
- 3. The trend of the invariant lateral load patterns is reflected on seismic response of the benchmark buildings. Codal and elastic first mode lateral load patterns show similar results.
- 4. ZBF, VBF and CBF have higher seismic response depending on different seismic parameters such as fundamental time period, base shear, roof displacement, storey displacement, and inter-storey drift ratio than XBF and MRF.
- 5. CBF and VBF are most suitable bracing systems in highrise benchmark building so as to increase seismic resistance.

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References

- Roeder, C.W., Popov E.P., "Eccentric braced steel frames for earthquakes", Journal of the Structures Division, ASCE, Vol. 104, No. 3, pp. 391-411, 1978.
- [2]. Hjelmstad, K..D., Popov E.P., "Characteristics of eccentrically braced frames", Journal of Structural Engineering, ASCE, Vol. 110, No. 2, pp. 340-353, 1984.
 <u>http://dx.doi.org/10.1061/(ASCE)0733-</u> 9445(1984)110:2(340)
- [3]. Rai, D.C., Goel, S.C., "Seismic evaluation and upgrading of chevron braced frames", Journal of Constructional Steel Research, Vol. 59, pp. 971-994, 2003. <u>http://dx.doi.org/10.1016/S0143-</u>

974X(03)00006-3

- [4]. Tremblay, R., "Inelastic seismic response of steel bracing members", Journal of Constructional Steel Research, Vol. 58, pp. 665–701, 2002. http://dx.doi.org/10.1016/S0143-974X(01)00104-<u>3</u>
- [5]. Yang, C.S., Leon, R.T., DesRoches R., "Design and behavior of zipper braced frames", Engineering Structures, Vol. 30, pp. 1092-1100, 2008.

http://dx.doi.org/10.1016/j.engstruct.2007.06.010

- [6]. Yang, C.S., Leon, R.T., DesRoches R., "Pushover response of a braced frame with suspended zipper struts", Journal of Structural Engineering, ASCE, Vol. 134, No.10, pp.1619-1626, 2008. <u>http://dx.doi.org/10.1061/(ASCE)0733-9445(2008)134:10(1619)</u>
- [7]. Nouri, G.R., Kalesar, H.I., Ameli, Z., "The applicability of the zipper strut to seismic rehabilitation of steel structures", World

Academy of Science, Engineering and Technology, Vol. 58, pp. 402-405.

- [8]. Patil, D.M., Sangle, K.K., "Seismic behaviour of different bracing systems in high rise 2-D steel buildings", Structures, Vol.3, pp. 282-305, 2015. <u>http://dx.doi.org/10.1016/j.istruc.2015.06.004</u>
- [9]. CSI, SAP2000, Integrated finite element analysis and design of structures basic analysis reference manual. Berkeley (CA, USA): Computers and Structures; 2015
- [10]. ATC-40, Seismic evaluation and Retrofit of Concrete Buildings. Applied Technical Council, 1996; 1.
- [11]. IS: 1893-2002, Criteria for earthquake resistant design of structures: part–1 general provisions and buildings, Bureau of Indian Standards, New Delhi.
- [12]. IS: 875 (Part 2):1987, Code of practice for design loads (other than earthquake) for buildings and structures: part 2 imposed loads, Bureau of Indian Standards, New Delhi.
- [13]. IS: 800-2007, General construction in steel-code of practice, Bureau of Indian Standards, New Delhi.
- [14]. FEMA 356, Prestandard and commentary for the seismic rehabilitation of buildings, FEMA 356 Federal Emergency Management Agency 2000, Washington DC.
- [15]. FEMA 273, NEHRP guidelines for the seismic rehabilitation of buildings, Rep. FEMA 273 Federal Emergency Management Agency 1997, Washington DC.
- [16]. Krawinkler, H., Seneviratna, G.D.P.K., "Pros and cons of a pushover analysis of seismic performance evaluation", Engineering Structure, Vol. 20 (4-6), pp.452-464, 1998. <u>http://dx.doi.org/10.1016/S0141-0296(97)00092-8</u>
- [17]. Elnashai, A.S., "Advanced inelastic static (pushover) analysis for earthquake applications", Journal of Structural Engineering and Mechanics, Vol. 12, No. 1, pp. 51-69, 2001. <u>http://dx.doi.org/10.12989/sem.2001.12.1.051</u>
- [18]. Chopra, A.K., Goel, R.K., "A modal pushover analysis procedure for estimating seismic demands for buildings", Earthquake Engineering Structural Dynamics, Vol. 31, No. 3, pp. 561-582, 2002. http://dx.doi.org/10.1002/ege.144
- [19]. Goel, R.K., Chopra, A.K., "Evaluation of modal and FEMA pushover analyses: SAC buildings", Earthquake Spectra, Vol. 20 No.1, pp. 225-254, 2004.

http://dx.doi.org/10.1193/1.1646390

- [20]. Poursha, M., Khoshnoudian, F., Reza, A., Moghadam, S., "Assessment of conventional nonlinear static procedures with FEMA load distributions and modal pushover analysis for high-rise buildings", International Journal of Civil Engineering, Vol. 6, No.2, pp.142-157, 2008
- [21]. Poursha, M., Khoshnoudian, F., Moghadam, S., "A breakthrough in estimating the seismic

demands of tall buildings", The 14th World Conference on Earthquake Engineering, Beijing, China, 2008.

[22]. <u>http://quiver.eerc.berkeley.edu:8080/</u> Visited, 15 Oct. 2014.