Numerical Assessment on Behavior Factor of Concentrically Braced Irregular Steel Framed Buildings

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Abstract

In the design of an earthquake resistant structures using equivalent lateral force method, behavior factor has an important role to account reduction of linear elastic responses coming from energy dissipation and absorption of structures due to its non-linear behavior. Despite this, currently there is perceived gap and meagre of researches regarding the behavior factor components of concentrically braced steel framed structures accompanied by numerous plan and elevation irregular structural configurations. This research investigated the behavior factor for plan and elevation irregular concentrically braced steel framed structures and presented comparative behavior factor analysis in accordance with the Ethiopian seismic code provisions. Further various structural configurations namely setback and inclined frames were studied to get insight into response of a concentrically braced steel framed structures under seismic induced ground motion. ETABS 2018.0.2 finite element packaged software was used to perform the nonlinear static pushover analysis. Among from the analyzed and extracted behavior factor components on the concentrically braced steel frames, the over-strength component was found to be dominant than others. Even though, the Ethiopian seismic code provided a unique value of behavior factor, results of this research showed that the behavior factor differs with a variation in structural configurations. Furthermore, analysis results also indicated that the intrinsic behavior factor values for the proposed structural models exceeded values provided by the Ethiopian seismic code provisions. Those deviations range from 26.8% to 194.4% for setback and inclined frame respectively.

Keywords: *Behavior factor, Concentrically braced steel frames, Pushover analysis*

1. INTRODUCTION

1.1. General

Earthquake is a natural phenomenon, which causes the ground to shake violently thereby triggering landslides, creating floods, causing the ground to heave and crack and cause large-scale destruction to innocent lives and properties. Thus, it is necessary to predict the effect of strong earthquake induced excitation forces and structural elements which can easily dissipate the energy produced by the earthquake [1].

Among from the available materials and structural elements, structural steel, which is strong, light weight, ductile, and capable to dissipate energy through yielding is the most preferable material for design and application of earthquake resistant structures [2]. Moreover, concentrically braced structural steel frame is an efficient and common type of braced frame on which it is aligned concentrically at the joint [1].

Behaviour factor is a factor used for design purposes to reduce the forces obtained from a linear analysis. Thus, it is a critical factor which can easily account nonlinear responses of structures due to material and geometrical nonlinearity, structural type, and different safety factors during the design process. Furthermore, behaviour factor (R) has three major components; ductility dependent component, over-strength dependent component, and damping dependent component.

Despite the importance of behaviour factor on structures under ground motion induced excitation forces, many researchers investigated the effect of different parameters of steel structures prone to corresponding seismic actions.

According to [3], a behaviour factor for steel, RC, and masonry frames were conducted by [4-7]. [4] Evaluated the behavior factor of steel moment resisting frames using standard pushover method of analysis. The researchers compared the numerical analysis result with the values recommended by [3] and based upon the analysis results, [4] insisted that in contrary to the story numbers, the behavior factor was not affected by both the number of bays and lateral load patterns. In addition to this, it was found that, for most low-rise framed structures, the value of the behavior factor recommended by the [3] was underestimated. Likewise, [5] investigated the effect of different number of stories, spans, and lateral load patterns. In this study, components of behaviour factor on ordinary moment resisting steel frames were all assessed and compared with the upper limits of reference values of behaviour factor given by [3]. As a remarking point, the authors anticipated that the local ductility criterion comprised by a limit of induced axial load ratio was significant on ductility of column.

Moreover, Behavior factor for unreinforced masonry buildings for two different types of elastic horizontal spectra was also evaluated by [6] using a nonlinear static analysis. The results of the study revealed a result that, the behavior factor values obtained from the numerical analysis were higher than the values recommended by [3]. [7] Evaluated the behavior factor of the five, ten, and fifteen story plan regular and irregular RC moment resisting frames. The researcher deployed a nonlinear-dynamic (time-history) method of structural analysis, compared the numerical analysis results with the value recommended by [8] and claimed that those values were found to be overestimated and conservative. In addition, there was a significant difference in the results from two types of spectra.

By employing a nonlinear static pushover analysis [9-12] assessed behaviour factor and compared corresponding values in accordance with the Indian standard (IS1893). [9] Investigated the presence of regular and irregular steel ordinary moment resisting building frames. From the pushover analysis, maximum storey drifts, storey displacements, time periods, and mode of frequencies were extracted and it was insisted that further investigation on irregular structural configurations with corresponding individual local and global capacities are forwarded. [10] Evaluated the response of components of reduction factor including strength, redundancy, ductility, and damping values for high-rise reinforced concrete building. The study result elucidated the use of providing the code specified behaviour factor with the respective ductility and over strength factors.

Consequently, [11] deployed nonlinear method of structural analysis and investigated the behaviour factor for the braced and moment resisting steel framed structures. The researchers assessed behaviour factor of the aforementioned frames on the effect of various number of stories and bracing configurations. Then behavior factor values from the analysis were compared in accordance with the Indian standard provisions (IS1893). The result from the numerical computations revealed that as a number of stories decrease the behavior factor increases. Moreover [12] evaluated the behaviour factor by applying the nonlinear analysis for reinforced concrete high-rise moment resisting frames with different bay sizes and the post-processed results were compared in accordance with Indian standard (IS1893). The analysis result revealed that as the number of bays of building decreased the behavior factor also dropped.

Despite the efforts made by previous researchers on behaviour factor of framed structures under ground motion induced force excitations, there is a knowledge gap on effect of presence of different irregular structural configurations on concentrically braced moment resisting steel frames. To fill this meagre of researches, the present study contributes to the literature by employing a nonlinear static pushover analysis on a ten-storied concentrically braced steel framed structures with different irregularities including a down setback and 7.6º inclined irregular framed steel structures which are not covered by previous researchers. In addition to this, the output of this research can be used as an input in the modification and provision of behaviour factor values in the Ethiopian seismic code [8].

2. MATERIALS AND MODELING

Since the focus of this study is relied on steel structure, the major structural components i.e. beams, columns and bracings are all structural steel members with a steel grades of Fe430 and Fe510. All beams are IPE section, columns are HE sections and bracings are rectangular tubes. The formation of plastic hinge for the elements of the frame is required in the nonlinear static pushover analysis. Therefore, all the cross sections are class 1 (plastic) cross sections which can develop adequate plastic hinges in the formation of plastic mechanisms. All the models are 10 storied concentrically braced steel frames with a total height of 30m and a plan dimension of 20m x 20m. Those frames are also expected to be in zone 5 and ground type B. The criteria for structural irregularity in plan and elevation are employed in accordance with the Ethiopian seismic code [8] section 4.2.3. Description on layouts of the proposed five different structural configurations is elucidated in Figure 1-5.

a. Model 1 is a plan and elevation regular concentrically braced frame. In this study, this model is taken as control model. The Ethiopian seismic code [8] specified the behavior factor value as 4.

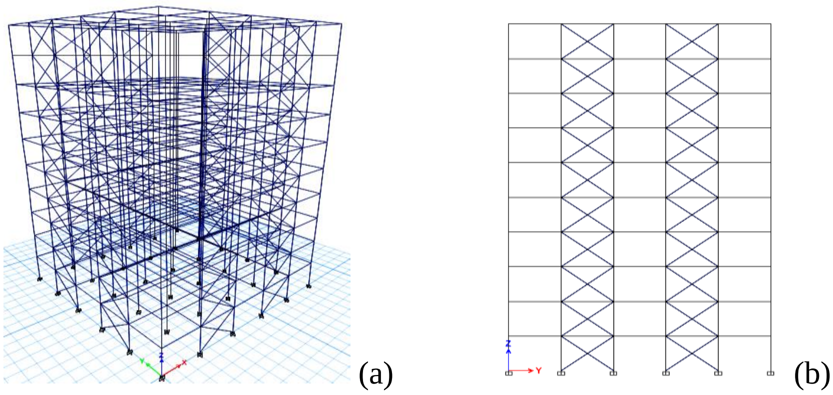


Figure 1. Model for regular in plan and elevation concentrically braced steel frame: (a) 3D; and (b) plane frame

b. Model 2 is a plan irregular and elevation regular concentrically braced frame. The Ethiopian seismic code [8] specified the behavior factor value as 4. According to article 4.2.3.2. (3) of [8], and when comapred to the control model, Model-2 had 16% plan irregularity

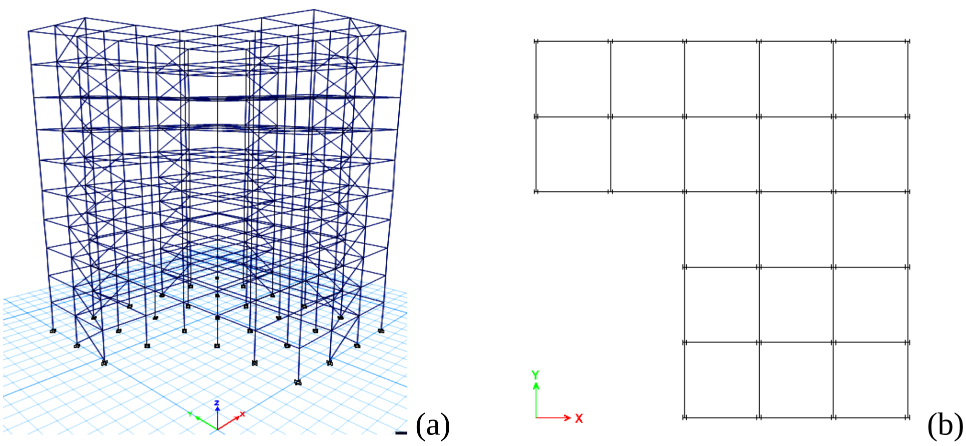


Figure 2. Model for plan irregular concentrically braced steel frame: (a) 3D; and (b) floor plan

c. Model 3 is a plan and elevation irregular concentrically braced frame with a setback of five top stories. The Ethiopian seismic code [8] specified the behavior factor value as 3.2. According to article 4.2.3.3. (5b) of [8], and when compared with the control model, Model 3 had 40% elevation irregularity

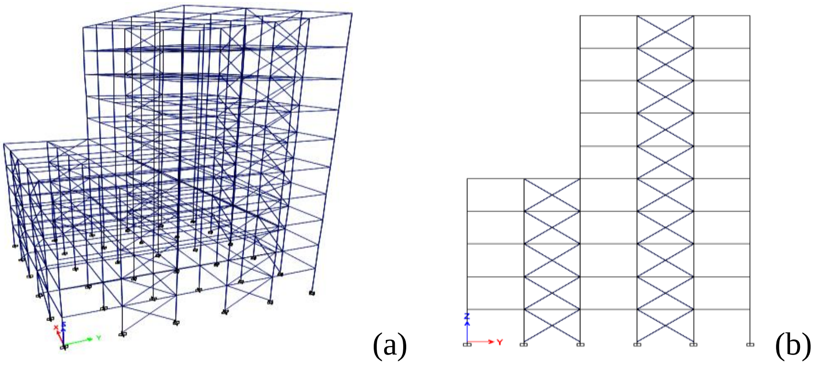


Figure 3. Model for plan and elevation irregular concentrically braced steel frame with a setback of five top stories: (a) 3D; and (b) plane frame

d. Model 4 is a concentrically braced frame with a down setback of two bottom stories in the y direction. The Ethiopian seismic code [8] specified the behavior factor value as 3.2. According to article 4.2.3.3. (5a) of [8], and when compared with the control model, Model 4 had 33.33% elevation irregularity

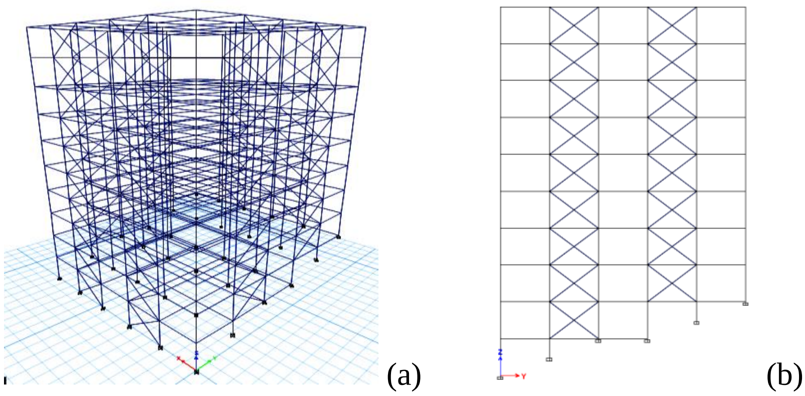
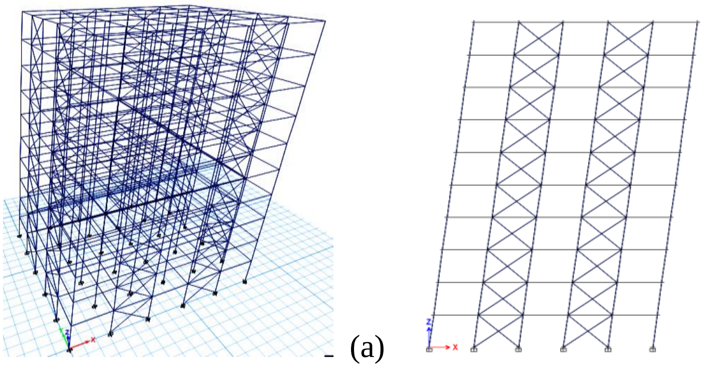


Figure 4. Model for concentrically braced steel frame with setback of two bottom stories in the y direction: (a) 3D; and (b) plane frame

e. Model 5 is an inclined concentrically braced frame with an inclination of 7.6° to the x-axis. The Ethiopian seismic code [8] specified the behavior factor value as 3.2.



(a) (b)

Figure 5. Model for inclined concentrically braced steel frame: (a) 3D; and (b) plane frame

3. METHODS

3.1.Loading

In the current study, the frames are analysed by taking into account the effect of a typical floor system on which the total dead and live loads on the floor system are all transferred to the beams in both directions of the frame. Table 1 listed the amount of gravity and live loads transferred to the exterior and interior beams.

Table 1. Unfactored distributed frame loading

Loads	Exterior Beams	Interior Beams
Live Load (kN/m)	8	10
Dead Load (kN/m)	15	18

In addition to this, to get the worst condition of the actions, the load combination rules were provided in accordance with the Ethiopian seismic code [8]. Equation 3.1-3.10 listed load combination formulas used for the analysis

$$DL + LL \quad (3.1)$$

$$1.35DL + 1.5LL \quad (3.2)$$

$$DL + 0.3LL \pm EQX1 \pm 0.3EQY1 \quad (3.3)$$

$$DL + 0.3LL \pm EQX1 \pm 0.3EQY2 \quad (3.4)$$

$$DL + 0.3LL \pm EQX2 \pm 0.3EQY1 \quad (3.5)$$

$$DL + 0.3LL \pm EQX2 \pm 0.3EQY2 \quad (3.6)$$

$$DL + 0.3LL \pm 0.3EQX1 \pm EQY1 \quad (3.7)$$

$$DL + 0.3LL \pm 0.3EQX1 \pm EQY2 \quad (3.8)$$

$$DL + 0.3LL \pm 0.3EQX2 \pm EQY1 \quad (3.9)$$

$$DL + 0.3LL \pm 0.3EQX2 \pm EQY2 \quad (3.10)$$

The effect of nonlinearity on evaluation of behaviour factor and seismic action are all determined and provided in accordance with the Ethiopian seismic code [8]. Likewise, the design seismic force and design of the frames is conducted by using a type-I elastic response spectrum.

3.2.Verification of designed frames

For ultimate and damage limit state verifications, interstory drift sensitivity coefficient and damage limitation requirement are evaluated in accordance with the Ethiopian seismic code [8] section 4.4.

a. **Ultimate limit states:**

In this study, the designed frames are verified against ultimate limit state requirements and an interstory drift sensitivity coefficient is computed by using equation 3.1

$$\theta = \frac{Ptot.\ dr}{V\,tot.\ h} \leq 0.10 \qquad 3.11$$

Where;

θ = Interstory drift sensitivity coefficient

P_{tot} = total gravity load at and above the story considered in the seismic design situation

V_{tot} = total seismic story shear at and above the story considered

h = interstory height

dr = design interstory drift

b. **Damage limit state:**

In addition to the ultimate limit state verifications, in the current study, the damage limitation requirement is also computed and considered into account by using the principle of presence and absence of non-structural elements with brittle and ductile materials fixed to the structure.

3.3. Nonlinear Static Pushover Analysis

In this study, a nonlinear static pushover analysis which is fully supported by [13] and [14] is employed and the response of all the plan and elevation irregular steel framed structural system are all evaluated by the corresponding strength deformation demands. Consequently, the displacement control pushover analysis and corresponding post-processed data is obtained by deploying the latest finite element analysis (FEA) packaged software ETABS 2018.0.2. The definition of plastic hinges in the frame elements is also carried out by ETABS 2018.0.2 hinge property module and is then confirmed by [14] and [15] guidelines.

Moreover, the capacity curve of the structure is plotted by employing a bi-linear idealization which easily provides the essential components including yield strength, pre-determined design strength, and ultimate displacement.

3.4. Behavior factor determination

Since an appropriate definition of the behavior factor is based on a ductility dependent component, an over strength-dependent component, and a redundant dependent component (see equation 3.12)

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$q = \frac{Ve}{Vd} = \frac{Ve}{Vu}\frac{Vu}{Vy}\frac{Vy}{Vd} = R\mu\, R\rho\, R\Omega = R\mu Rs$ ……………………..……………………...............3.12

Where, Ve, Vu, Vy and Vd correspond to the structure's elastic response strength, the idealized yield strength, the first significant yield strength and design base shear respectively.

This study comprised and analyzed all the components of behavior factor and made comparative study among each values of behavior factor against different structural configurations.

a. Ductility Factor

It is well known that, ductility is a very important property, especially when the structure is subjected to seismic loads. Thus, in the current study, ductility of each plan and elevation irregular concentrically braced steel framed structures are all determined according to [16] by taking alluvium site (see also equation 3.13-3.15).

$R\mu = \frac{\mu-1}{\Phi} + 1$ ……………………………………………..……………………………………..3.13

$\mu = \frac{\Delta m}{\Delta y}$ ……………………………………………..…………………………………………3.14

$\Phi = 1 + \frac{1}{12T-\mu T} - \frac{1}{5T}\exp[-2(lnT-0.2)^2$ ……………………………………………………….3.15

Where: Rμ is the ductility factor,

μ is displacement ductility ratio,

△m is the maximum deformation corresponding to the maximum base shear

Δy is the yield deformation and T is fundamental period of vibration of the building. Yield and maximum deformations are obtained from idealized bilinear pushover curve.

b. Over Strength Factor:

In this study, after it is made sure that the structure had reached its strength and deformation capacity. The sequential yielding of critical regions, material over strength, strain hardening, capacity reduction factors which are the sources of over strength (R_Ω) are all considered and computed by using equation 3.16

$R_\Omega = \frac{Vy}{Vd}$ ……………………………………….…………..………………………………...3.16

Where, V_y first significant yield strength; and Vd is the design base shear.

c. Redundancy Factor

It is obvious that, for seismic load resistance, it is a best practice to design buildings with a high degree of redundancy for seismic load resistance. In this study, the design of the five plan and elevation irregular concentrically braced steel framed structures were made to confirm redundancy criteria and typical values of redundancy factor is evaluated by the formula elucidated in equation 3.17

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$$Rp = \frac{Vu}{Vy} \quad \ldots\ldots 3.17$$

Where, Vu is the ultimate base shear and V_y first significant yield strength.

Generally, from above expression the relation of both the formula proposed by [8, 15] is summarized in equation 3.18.

$$q = R = q_o \frac{\alpha u}{\alpha 1} = R\mu\, R\rho\, R\Omega = R\mu\, Rs \quad \ldots\ldots 3.18$$

where, $R_\rho = \alpha u/\alpha 1$ is the redundancy factor

Rs= $R\rho\, R\Omega$ is overstrength factor including redundancy and

$q_o = R\mu\, R\Omega$ is the basic behavior factor

4. RESULTS AND DISCUSSION

In this section, the results of nonlinear static (pushover) analysis are represented in the form of graph known as static pushover curve (capacity curve). The idealized bilinear force displacement curve which can easily map the capacity curve is given and are exhibited in Figure 6 - 10

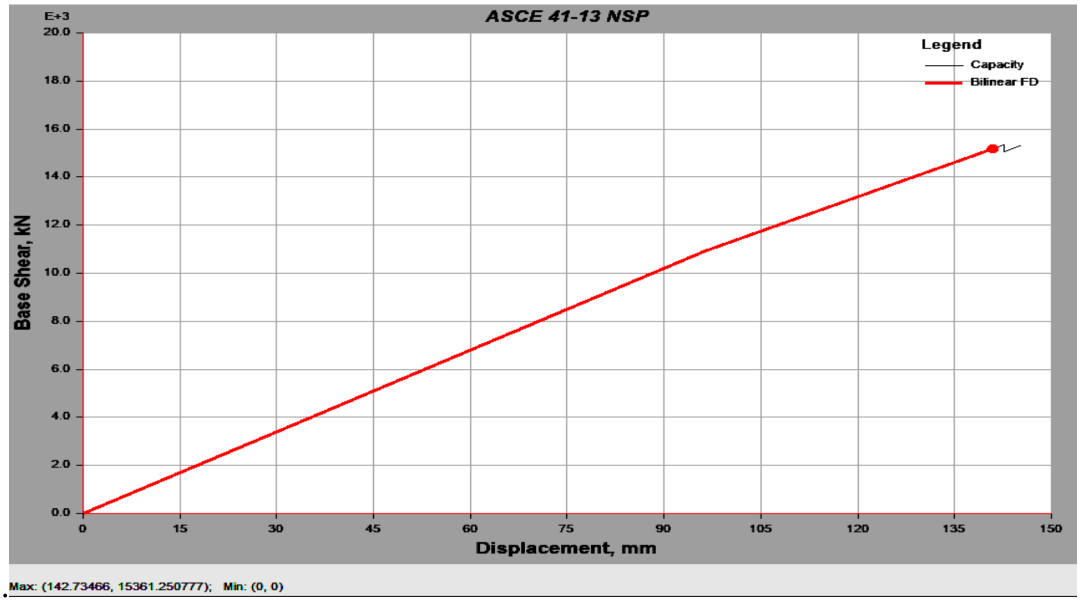

Figure 6. Capacity curve and bilinear idealization of plan regular frame model of plan regular concentrically braced steel frame

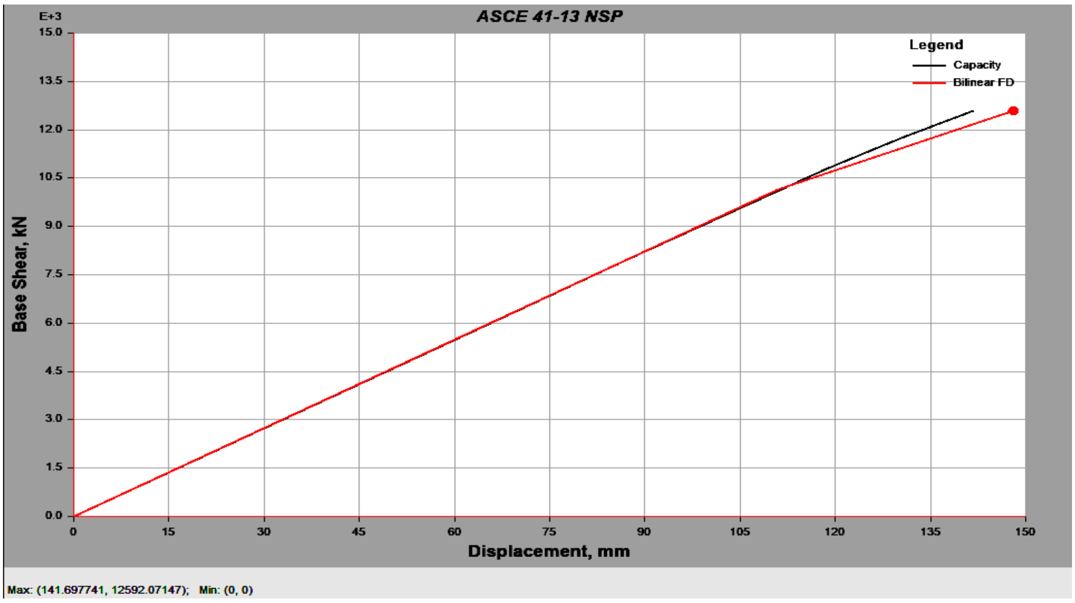

Figure 7. Capacity curve and bilinear idealization of plan irregular frame model of concentrically braced steel frame

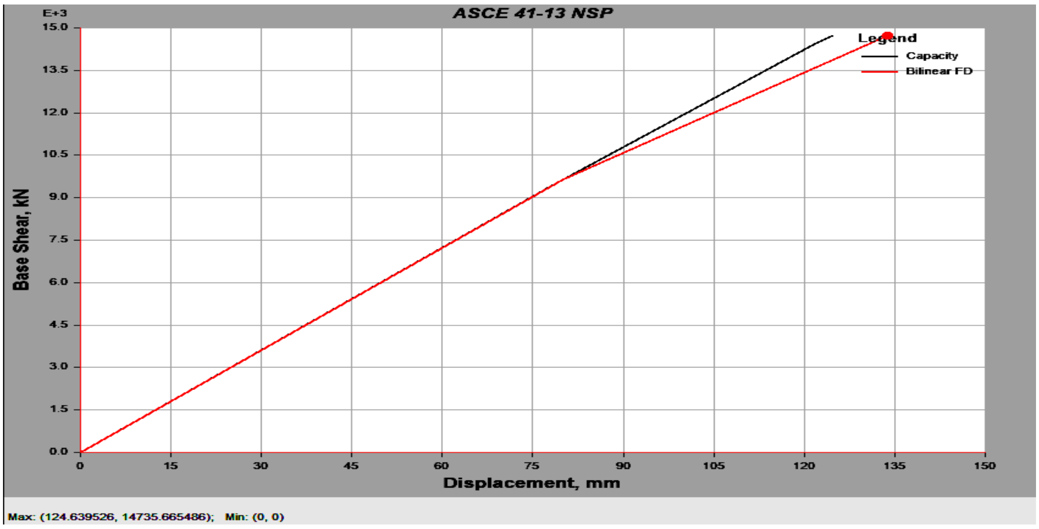

Figure 8. Capacity curve and bilinear idealization of plan and elevation irregular concentrically braced steel frame with a setback of five top stories

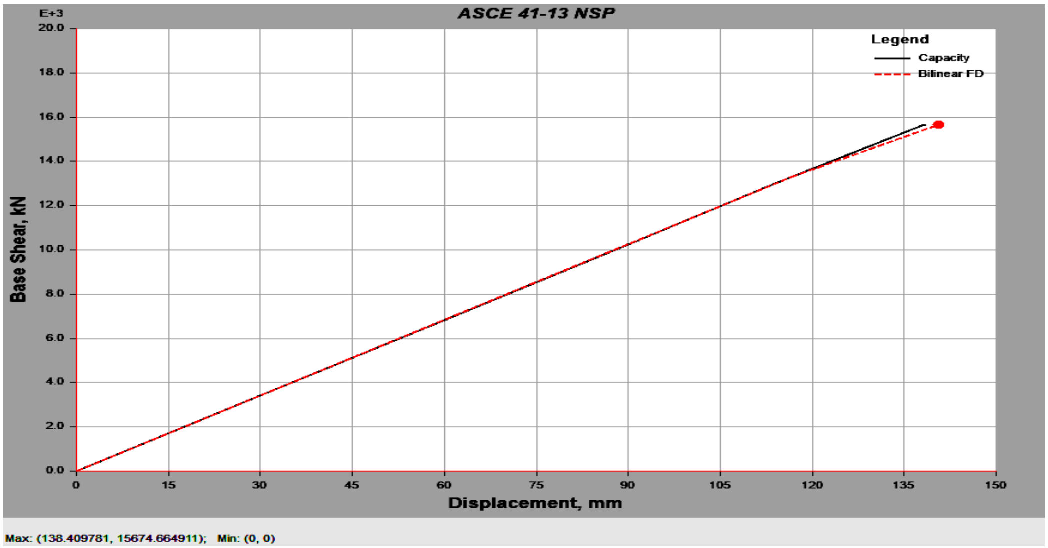

Figure 9. Capacity curve and bilinear idealization of down setback frame model of concentrically braced steel frame with setback of two bottom stories in the y direction

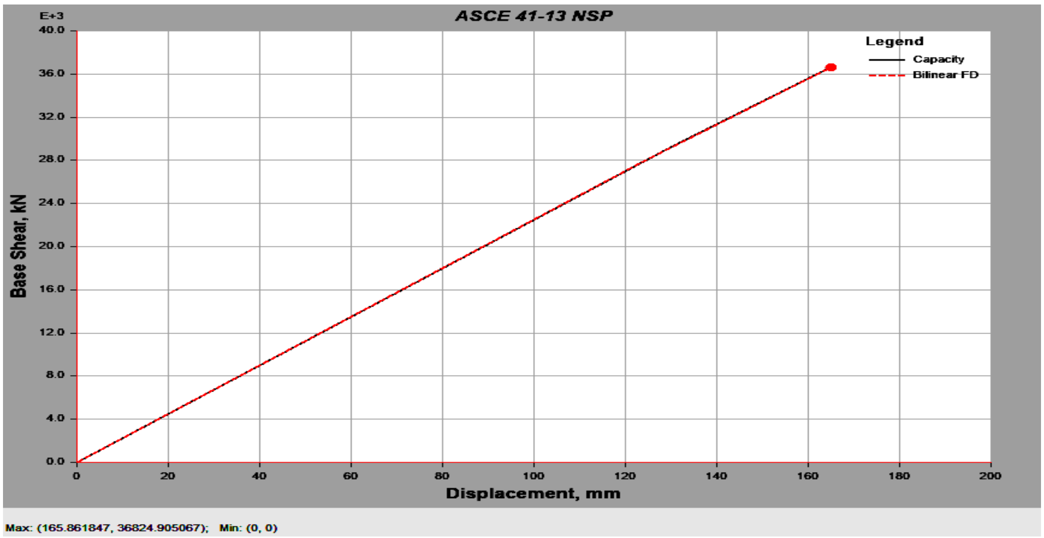

Figure 10. Capacity curve and bilinear idealization of inclined frame model of concentrically braced steel frame

The results of both analysis (Equivalent lateral force analysis method and nonlinear static (Pushover) analysis) are presented in a tabulated format on Table 2. These results are directly used for the determination of the behavior factor components. Design base shear (Vd) is taken from equivalent lateral force method and ultimate base shear (Vu), first yield base shear (Vy), roof displacement at ultimate point (Δm) and roof displacement at the first yield (Δy) are determined from the bilinear idealization of pushover curve

.Table 2. Equivalent lateral force and nonlinear static Analysis results

Designation	Vd (kN)	Vy (kN)	Vu (kN)	Δy (mm)	Δm (mm)
Plan Regular	3893.23	10910.9	15297.6	96.34	145.158
Plan Irregular	3106.86	10157.5	12592.1	110.975	141.698

Elevation Irregular	4040.9	13066.9	19744.8	108.245	193.169
Down Setback	4695.05	13280.5	15674.7	116.52	138.41
Inclined	5450.46	27762	36824.9	123.31	165.862

Table 3 illustrates the evaluation of behavior factor and its components for all frames. Among from the three components of behavior factor, the effect of over strength component is influential. Likewise, it is evident that the over strength reduction factor of inclined frame is larger than the other frames.

Table 3. Determination of Behavior Factor and its components

Designation	Rμ = (μ-1)/ϕ+1	Rρ = Vy/Vd	RΩ = Vu /Vy	Rs = Rρ*RΩ	R= Rμ*Rs	R (Code Value)	%age
Plan Regular	1.58	1.40	2.80	3.93	6.20	4	55.0%
Plan Irregular	1.32	1.24	3.27	4.05	5.34	4	33.4%
Elevation Irregular	1.89	1.51	3.23	4.89	9.24	3.2	188.7%
Down Setback	1.22	1.18	2.83	3.34	4.06	3.2	26.8%
Inclined	1.39	1.33	5.09	6.76	9.42	3.2	194.4%

Comparison of Evaluated Behavior factors

The determined behavior factors of the models and the corresponding value which are provided in the seismic code [8] are described in Figure 11. As shown in Figure 11, the behavior factor computed from nonlinear static pushover analysis is larger than the values provided by the Ethiopian seismic code [8]. The deviation ranges from 26.8% to 194.4% for setback and inclined frame respectively.

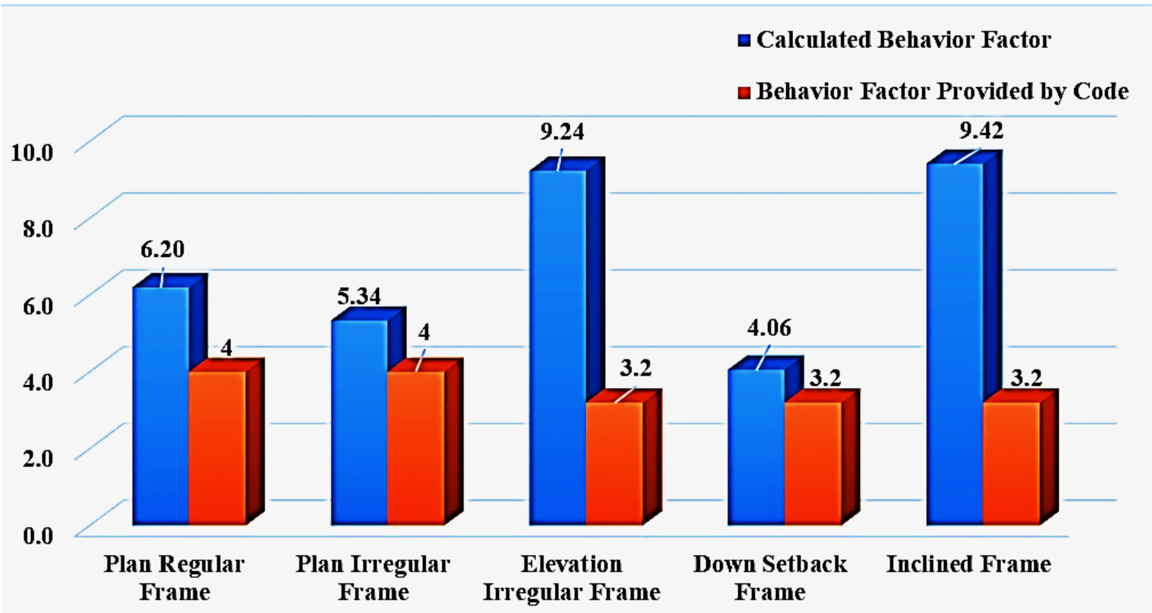

Figure 11. Comparison of Evaluated Behavior factors

5. CONCLUSION

In this paper, the behavior factor for plan and elevation irregular concentrically braced steel frames was evaluated. From the nonlinear static pushover analysis results, the following conclusions are made.

- The effect of over strength component was found to be dominant than others.
- Inclined frame revealed larger over strength factor component than other structural configurations.
- The behavior factor values provided by the Ethiopian seismic code ES EN (1998-1-2015) was less than the value obtained from the nonlinear static pushover analysis.

Finally, it is worth to forward a future research topic on investigating the behavior factor of concentrically braced steel framed buildings with further extended parameters.

REFERENCES

[1] Chen, W. F. & Scawthorn, C. 2003. *Earthquake Engineering Handbook*, Boka Raton,Florida, USA, CRC Press.

[2] Elnashai, A. S. & Sarno, L. D. 2008. *Fundamentals of Earthquake Engineering*, USA, John Wiley and Sons. Applied Technology Council 1995. Structural Response Modification Factors (ATC 19). Redwood City, California.

[3] EN 1998-1, Eurocode8: design of structures for earthquake resistance, Part 1: general rules, seismic actions and rules for buildings, European Committee for Standardization, CEN, 2004.

[4] Yahim, D., Branci, T., Bouchair, A. & Fourneley, E. 2016. Evaluation of Behavior Factor for Steel Moment-Resisting Frames. *International Scholarly and Scientific Research and Innovation*, 10**,** 5, pp. 398-403.

[5] Feraioli, M., Lavino, A. & Mandara, A. Behavior Factor for Seismic Design of Moment-Resisting Steel Frames. Proceeding of the 15th World Conference on Earthquake Engineering, 2012 Lisbon, Portugal.

[6] Manojlović, Dragan & Radujkovic, Aleksandra & Kocetov, Tatjana. 2018. Evaluation of the behavior factor of unreinforced masonry buildings. 6th International conference Seismic Engineering and Engineering Seismology, 2018 Kraljevo, Serbia

[7] Getahun Asres. 2018. Evaluation of behavior factor provision of ES EN for RC ductile regular and plan irregular building structures using nonlinear analysis (Master's thesis, Addis Ababa University, Addis Ababa, Ethiopia). Retrieved from *http://etd.aau.edu.et/handle/123456789/18269*

[8] ES-EN 2015. Design of Structures for Earthquake Resistance, Part-1:

General Rules, Seismic Actions and Rules for Buildings ES EN (1998-1-2015). Ethiopia: Ministry of Urban Development, Housing and Construction

[9] Siddiqui, M.A.M. & Azeem, M.A. . 2020. *Evaluation of Response Reduction Factor of Regular and Irregular Steel Moment Building Frames. International Journal of Applied Engineering Research***,** *15,3, pp 312 - 319.*

[10] P. Pawar. & M.V. Nagendra. 2020. Evaluation of Response Reduction Factor (R) for High Rise Buildings. *International Journal of Inovative Research in Technology (IJIRT)***,** 7,3, pp. 135-138.

[11] Swaminathan, A. & Thampan, P. V. 2017. Response Reduction Factor for Steel Frames. *International Journal of Scientific and Engineering Research,* 8**,** 4 pp. 113-116.

[12] Keerthi, S. & Philip, V. 2017. Evaluation of Response Reduction Factor Based on Redundancy for High Rise Buildings. *International Research Journal of Engineering and Technology (IRJET),* 04**,** 6, pp. 3161-3165.

[13] Federal Emergency Management Agency 2005. Improvement of Nonlinear Static Seismic Analysis Procedures (FEMA 440). Washington DC.

[14] Federal Emergency Management Agency 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356). *Washington DC.*

[15] American Society of Civil Engineers. 2014. Seismic Evaluation and Retrofit of Existing Buildings (ASCE/SEI 41-13). Reston, Verginia.

[16] Miranda, E. & V.Bertero, V. 1994. Evaluation of strength factor for earth quick resistant design. *Earthquake Spectra*, 10**,** 23, pp. 357-379.