Credibility of Estimating the Hysteretic Energy Demands of Concentrically Braced Steel Frames

Cuiling Ma

Abstract Earthquake happens frequently in China, and seismic design is of high importance for buildings. The energy-based seismic design method with clear conception has attracted attention of more and more researchers. One of the initial questions is how to determine the energy requirement. In this paper, the finite element software is used to analyze the time history of the concentrically braced steel frames designed according to the current codes and standards. The analysis shows that the cumulative demand obtained by time history analysis is similar to the estimated value. The hysteretic energy dissipation of the concentrically braced steel frames is of small top and big bottom along the height of the structure, and the energy dissipation of the floors below the height of H/3 (H is the height of the structure) is larger. Under rare earthquakes, the yield mode of structures designed according to the elastic design method of small earthquakes is uncontrollable, so it is necessary to study the design method based on energy behavior.

Keywords Concentrically braced steel frame · Hysteretic energy demands · Energy-based seismic design method

1 Introduction

Earthquake happens frequently in China. Several strong earthquakes, such as Wenchuan earthquake and Taiwan Chi-chi earthquake, have caused large casualties and property losses. Seismic design of buildings can effectively withstand the damage caused by earthquakes.

The performance-based seismic design is committed to clearly controlling the state of the structure under different earthquake intensity, so that the damage of the structure does not exceed the specific behavior of the expected strength earthquake, and has the expected level of reliability. Since this method was proposed, it has attracted wide attention [1–6, 8–12].

C. Ma (✉)
College of Urban Construction and Transportation, Hefei University, Hefei, China
e-mail: 415997243@qq.com

Y. Yang (ed.), *Advances in Frontier Research on Engineering Structures*, Lecture Notes in Civil Engineering 286, https://doi.org/10.1007/978-981-19-8657-4_16

The estimation of energy demands of multi-degree-of-freedom architectures is a key step in the research of energy-based seismic design methods. In this paper, examples of the concentrically braced steel frames designed in accordance with Chinese current norms and standards was used to evaluate the rationality of the equivalent velocity spectra of cumulative hysteretic energy established in Literature [7] in accordance with Chinese site classification for hysteretic energy demand estimation.

2 Design Overview

The elevation and plan layout of chevron concentrically braced steel frames ("CBSF" for short) are shown in Fig. 1.The seismic design parameters are as follows. Seismic fortification intensity is 8° (0.3 g), soil type II, site group 2,category C,50 years for the design working life. The bidirectional span is 7.8 m, and the storey height is 3.3 m, with 10 and 15 floors. In Fig. 1, dotted lines denote secondary beams, a span of 2.6 m, which are hinged to the primary beams. The measurements of the parapet are 1.1 m for height by 0.2 m for thickness. The thickness of outer wall is 0.2 m.

The dead and live loads of floor are 4.5kN/m^2 and 2.0kN/m^2 respectively, while the dead and live loads of roof are 5.0kN/m^2 and 2.0kN/m^2 respectively.Q235B.Steel supports and beams adopt welded I-shaped section members with flange as shear edge, steel columns adopt box section members, and rigid joints.

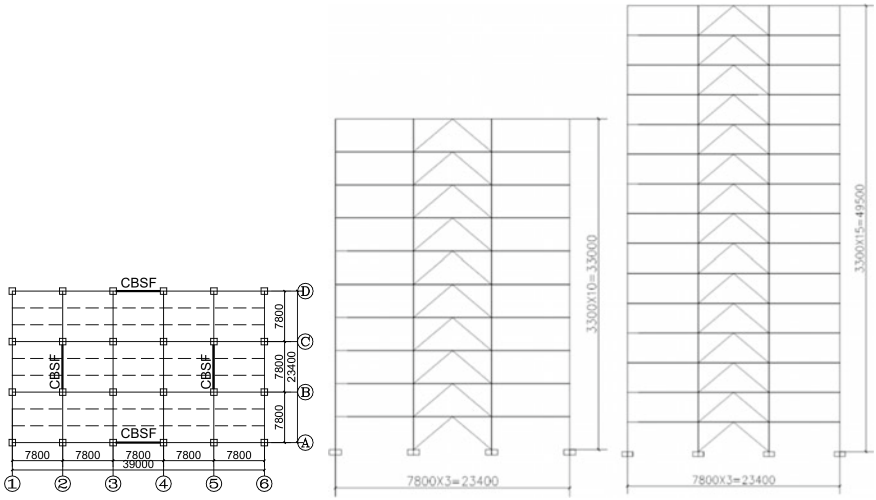


Fig. 1 CBSF plane view and elevation (unit: mm)

Table 1 Member sections of 10-story CBSF

Number of stories	Column sections		Beam sections		Brace section
	Interior column	Exterior column	Middle beam	Side beam	
1–3	□600*24	□600*20	H600*250*14*20	H600*250*14*20	H300*300*16*18
4–6	□500*22	□500*20	H600*250*14*18	H600*250*14*18	H250*250*10*12
7–9	□400*20	□400*18	H600*250*14*18	H600*250*14*18	H250*250*10*12
10	□400*20	□400*18	H600*250*14*18	H600*250*14*18	H250*250*10*12

Table 2 Member sections of 15-story CBSF

Number of stories	Column sections		Beam sections		Brace section
	Interior column	Exterior column	Middle beam	Side beam	
1–3	□700*24	□700*22	H600*250*16*20	H600*250*14*20	H300*300*18*20
4–6	□600*24	□600*22	H600*250*14*20	H600*250*14*20	H300*300*16*18
7–10	□500*24	□500*20	H600*250*14*18	H600*250*14*18	H250*250*10*12
11–14	□400*22	□400*18	H600*250*14*18	H600*250*14*18	H250*250*10*12
15	□400*22	□400*18	H600*250*14*18	H600*250*14*18	H250*250*10*12

3 Design Standards

Relevant provisions in current codes and standards, including "Standard for design of steel structures" GB 50017-2017, "Code for seismic design of buildings" GB 50011-2010, "Technical specification for steel structure of tall buildings" JGJ 99-2015, "Load Code for design of building structures" GB50009-2012,can provide guidance for design.

The seismic grade is three for 10-story building, and two for 15-story building, respectively. The damping ratio of CBSFs for elastic design under frequent earthquakes is set according to Code for seismic design of buildings, and the damping ratio is set as 0.05 for the energy analysis of structures under rare earthquake. The characteristic period value T_g is 0.40 s. The STS module in PKPM software and the finite element software SAP2000 were used to determine the beam, column and support sections of CBSFs as shown in Tables 1 and 2

4 Estimation of Structural Hysteretic Energy Demand

The cumulative hysteretic energy demand of multi-degree-of-freedom (MDOF) system, as shown in Table 3, can be obtained according to the existing formulas in

Table 3 Accumulated hysteretic energy demand

Example	Accumulated hysteretic energy demand of an equivalent SDOF system corresponding to the jth modeEh(ESDOF), j/kNm			Accumulated hysteretic energy demand of an MDOF Eh(MDOF)/kNm
	Eh(ESDOF), 1	Eh(ESDOF), 2	Eh(ESDOF), 3	
10-story CBSF	740.422	1172.438	708.081	1939.806
15-story CBSF	674.509	1557.067	1807.700	2356.936

Literatures [7, 11]. In order to obtain a better cumulative hysteretic energy demand of the structure, the sum of modal participating mass ratio should exceed 90%.

5 Time-History Analysis

Compared with static elasto-plastic analysis, time history analysis can reflect the structural response under earthquake. In this paper, the finite element software ABAQUS is used to analyze the elastic-plastic time history of frame structures. The beam elements (B31) are utilized to simulate the braces, columns, and beams. Considering the nonlinearity of the material, a bilinear follow-up strengthening model and Rayleigh damping model were used. The size of beam element grid is 0.2 m.

Earthquakes are sudden and random, and the corresponding structural ground motion response is also a random process, so it is necessary to select earthquake wave reasonably. In addition to the three elements of ground motion such as peak value, spectrum and duration, the energy factor should also be considered during wave selection. Earthquake waves were screened according to the principle of wave selection, and only one earthquake wave measured by the same seismic station in the same earthquake is selected. The earthquake waves used in the 10-story CBSF are P216, P322, P544, P735, P947, P951, P961, P1149, P1766, RSN2602E, respectively; The earthquake waves used in the 15-story CBSF are P735, P154, P836, P947, P951, P961, P850, P2714, RSN2361E, RSN2602N, respectively.

5.1 Comparison of Hysteretic Energy Analysis Value with Estimated Value

By using finite element software ABAQUS for time history analysis, the hysteretic energy demand of the structure under different far-field vibrations is extracted and the average value is taken as the analysis value. Finally, it is compared with the estimated value obtained by equations in Literatures [7, 11], as shown in Figs. 2–3.

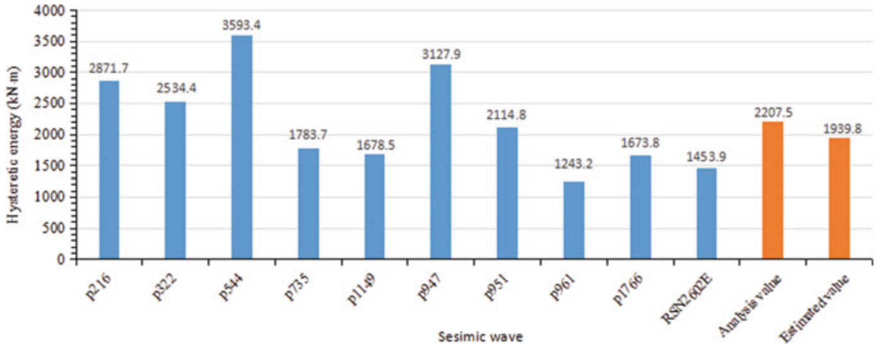


Fig. 2 Comparison of hysteretic energy analysis value with estimated value for 10-story CBSF

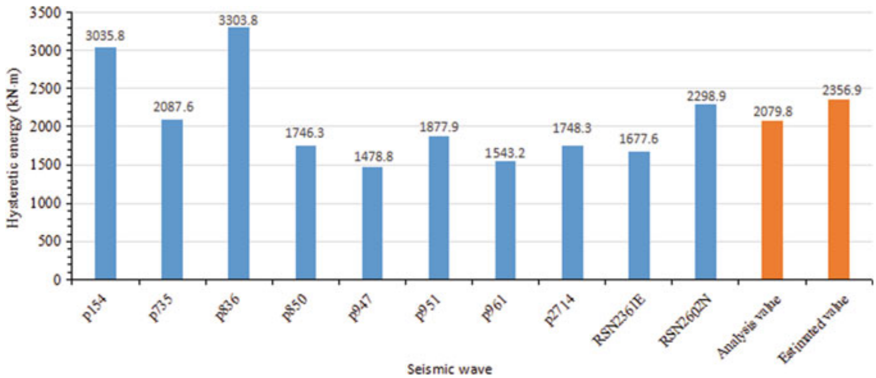


Fig. 3 Comparison of hysteretic energy analysis value with estimated value for 15-story CBSF

It can be seen from Figs. 2 and 3 that the hysteretic energy obtained by the same example under different earthquake waves is different, and there is a certain dispersion. The average value of hysteretic energy under the action of multiple seismic waves on the same example is basically consistent with the estimated value. The time-history analysis values of the 10-story and 15-story CBSF are 2207.5kN·m and 2079.8kN·m, and the corresponding estimated values are 1939.8kN·m and 2356.9kN·m, with errors of 13.8% and 11.7%, respectively. The analysis value of the 10-story CBSF is larger than the estimated value, which may be because the target ductility factor selected in the estimated calculation of hysteresis energy demand of the example is slightly smaller than the real target ductility, or the characteristic period of a seismic wave used in the analysis is close to the natural vibration period of the example structure, and resonance occurs.

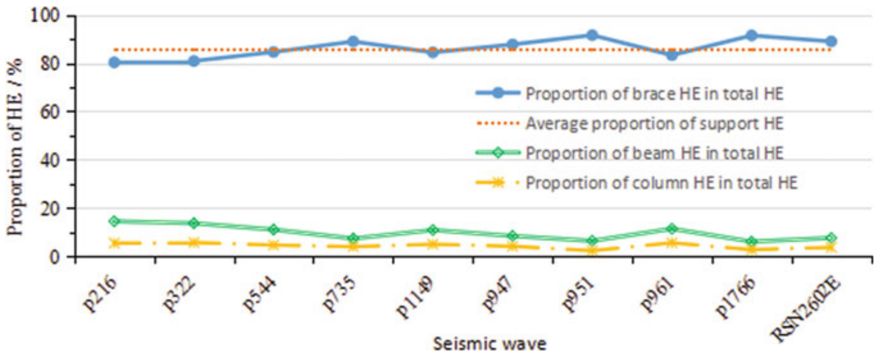


Fig. 4 Hysteretic energy distribution in 10-story CBSF components under different seismic waves

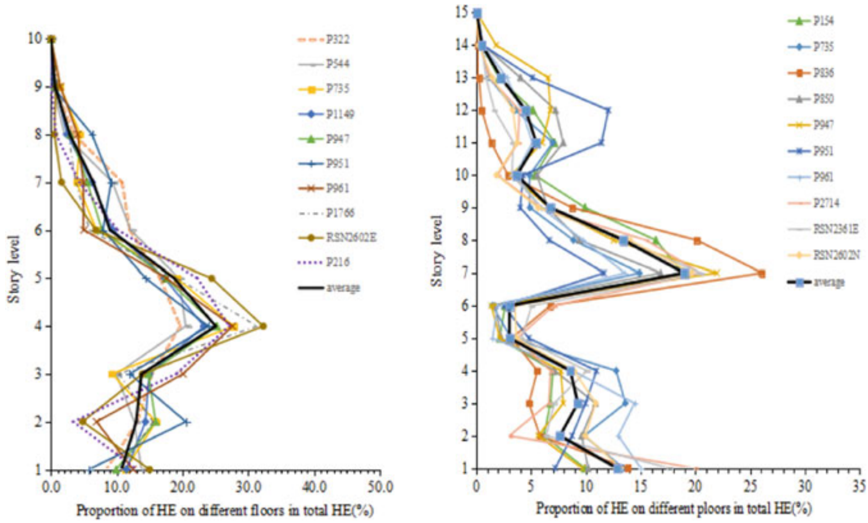
5.2 Distribution of Hysteretic Energy Dissipation in Different Members

Overall, the content in Sect. 5.1 of this paper can only judge the reliability of the relevant formulae in the Literatures [7, 11] to estimate the hysteretic energy demand value of the structure. The proportion of hysteretic energy of various components in different structures is different, resulting in different damage degrees of each component. Then, the distribution law of hysteretic energy among different components of each structure needs to be analyzed.

From Fig. 4, it can be seen that the distribution law of hysteretic energy among the components of the CBSFs is similar under different seismic waves, and the proportion for the 10-story CBSF is between 80.3 and 91.6%, with an average value of 85.8%.And the proportion for the 15-story CBSF is between 34.7 and 64.0%, with an average value of 47.2%. The ratio tends to decrease with the increase of structure layers. All components appear plastic deformation, resulting in different degrees of damage. Compared with the 10-story and 15-story CBSFs designed based on the energy design method in the Literature [13], the CBSFs designed in this paper according to the current codes are severely damaged under rare earthquakes, which is inconvenient to control. Therefore, it is necessary to seek more reasonable design method.

5.3 Interlayer Distribution Model of Hysteretic Energy

The distribution of hysteretic energy along the height of the structures can reveal whether there is obvious energy concentration, which provides a reference for the comprehensive evaluation of the seismic performance of the structure (Fig. 5).



(a)10-story (b) 15-story

Fig. 5 Proportion of interlayer HE of CBSFs in total HE under different seismic waves

The hysteretic energy dissipation values of the same example under different seismic waves are different, and the maximum relationship is three times. The distribution patterns of hysteretic energy among the same support structure with different layers are similar but not identical. As the number of structural layers increases from 10 to 15, the proportion of hysteretic energy consumption in the upper floors increases, which is mainly due to the influence of high-order mode. It also indicates that the equivalent velocity spectrum of hysteretic energy and the mode superposition method of multi-degree of freedom structure can consider the energy carried by high-order mode. The hysteretic energy dissipation of the concentrically braced steel frames is of small top and big bottom along the height of the structure, and the energy dissipation of the floors below the height of H/3 (H is the height of the structure) is larger. The hysteretic energy dissipation of different examples is not a single linear distribution along the height direction of the structure, and the hysteretic energy dissipation at the variable section is accompanied by a sudden change.

6 Conclusion

The reliability of the hysteretic energy spectrum and mode shape superposition methods in the existing literatures to estimate the energy demand of braced steel frames is evaluated in this paper. Firstly, the member sections of the CBSFs are determined for elastic design method according to the current codes, and the hysteretic energy demand value of examples is obtained by using the relevant formula. Then, 10 seismic waves are selected based on certain principles, and the cumulative hysteretic energy dissipation under different seismic waves through time history analysis. At the same time, the distribution of hysteretic energy along the height of the structure and the distribution law of each member are studied. The results show that the cumulative hysteretic energy demand obtained by time history analysis is basically consistent with the estimated value. The hysteretic energy dissipation of the concentrically braced steel frames is of small top and big bottom along the height of the structure, and the energy dissipation of the floors below the height of H/3 is larger.

Acknowledgements This research is funded by the 2020 Excellent and Top-notch University Talent Cultivation Program (No. gxyq2020068) and the 2021 Scientific Research Program for Talents in Hefei University (No. 21-22RC39)

References

1. Berg GV, Thomaides SS (1960) Energy consumption by structures in strong-motion earthquakes. In: Proceedings of the second world conference on earthquake engineering, vol 2, pp 681–697
2. Chopra AK, Goel RK (2002) A modal pushover analysis procedure for estimating seismic demands for buildings. Earthquake Eng Struct Dyn 31(3):561–582
3. Chopra AK, Goel RK (2004) A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings. Earthquake Eng Struct Dyn 33(8):903–927
4. Ghosh S, Collins KR (2006) Merging energy-based design criteria and reliability-based methods: exploring a new concept. Earthquake Eng Struct Dyn 35(13):1677–1698
5. Housner GW (1956) Limit design of structures to resist earthquakes. In: Proceedings of the 1st world conference earthquake engineering, Berkeley
6. Liu ZF, Zhao P, Chen K (2017) Cyclic pushover analysis method based on the seismic energy dissipation course characteristics. World Earthquake Eng 33(2):39–45
7. Ma CL, Gu Q, Sun GH (2019) Mathematical expression of design hysteretic energy spectra based on Chinese soil type. Math Probl Eng 11:1–10. https://doi.org/10.1155/2019/3483516
8. Ma HW, Yang JY, Pan CQ (2022) Energy-based seismic design method for energy-dissipation steel frame. Build Struct 52(5):55–62
9. McKevitt WE, Anderson DL, Cherry S (1980) Hysterretic energy spectra in seismic design. In: Proceedings of the 2nd world conference on earthquake engineering, vol 7, pp 487–494
10. Prasanth T, Ghosh S, Collins KR (2008) Estimation of hysteretic energy demand using concepts of modal pushover analysis. Earthquake Eng Struct Dyn 37:975–990
11. Sun GH, Gu Q, He RQ, Fang YZ (2012) Evalution of seismic energy of steel frames based on energy spectrums. China Civ Eng J 45(5):41–48
12. Uang CM, Bertero VV (1990) Evaluation of seismic energy in structures. Earthquake Eng Struct Dyn 19(1):77–90
13. Zhang HD (2016) Energy-based seismic design method of chevron concentrically braced steel frame under far-field earthquake. Master Degree Thesis of Suzhou University of Science and Technology