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Seismic performance analysis of frame and frame-shear wall structures based on energy balance

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Abstract. To explore the seismic performance of frames based on energy balance, based on the principle of energy analysis, the expression of energy relations of single degree-of-freedom system and the expression of energy response of multi-degree-of-freedom system are introduced. Based on the principle of energy analysis, the energy balance model is established, and a model for finite element analysis is set up. In addition, the traditional response spectrum is used to obtain the structure parameters. Entering the MIDAS finite element analysis software, the ability and performance of the frequently-seen earthquakes and rare earthquakes model are analyzed. Simulation experiments are carried out, and the results verified the validity of the above parameters. They are in line with the requirements of "High Standard", empirical formula and other requirements. The experimental results show that this method can effectively improve the seismic performance of reinforced concrete frame shear structures. At last, it is concluded that the structure can be well applied.

Key words. Energy balance, frame-shear structure, seismic performance.

1. Introduction

In the 1950s, Housner first proposed energy-based seismic design of structural thinking. He tried to use the energy analysis method to study the seismic response of the structure, that the structure of the earthquake response can be seen as a seismic energy input and dissipation process, as long as the damping and hysteretic energy dissipation capacity of the structure is greater than the earthquake input energy, structure can effectively resist the earthquake, and does not produce collapse. In the same time, Dr. George Housner explicitly proposed the concept of energy. The concept can better reflect the seismic intensity and spectral characteristics, and capture the inelastic deformation process of the structure under the action of strong earthquake from the input energy and dissipation of energy. The study of energy

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method becomes an important development direction to improve the traditional seismic design method [1]. In the 1980s, Japan's Akiyama systematically researched the energy-based seismic design method. Based on the research results of the SDOF system and the MDOF system, the idea and method of energy-based seismic design were proposed, and some of them were applied in the Japanese seismic code. From the late 1980s to the 1990s, Fajfar studied the ground motion intensity index and the energy input and distribution relationship of the SDOF system, and proposed the N2 design method for the concrete structure [2]. After 1990s, Fajfar and other scholars carried out a large number of studies on the seismic design method of the comprehensive consideration of the cumulative hysteretic energy dissipation and deformation. After 2000, Chou and Shen established the energy-based seismic design method of steel frame structure, and put forward the practical design flow.

Since the 1980s, Chinese scholars have begun to study energy-based seismic design methods. China's scholars have done a lot of research work in the energy input, distribution and the law of cumulative hysteretic energy dissipation of the SDOF system and MDOF system and the test of energy dissipation capacity of the structure and components. After many efforts of researchers, the foundation work of the energy law has been tending to improve, the corresponding design framework is basically mature, but there is no systematic design method.

2. Materials and methods

2.1. Energy method theory

For an idealized single-layer structure affected by horizontal seismic motion, it can be regarded as an ideal single-degree-of-freedom system. The quality of the system focus on a point of the end, the single degree of freedom or the multi-degree of freedom system will have the damping, and dissipate the structural energy. If it is assumed that the axial deformation does not occur at the end, the system will have three degrees of freedom in the analysis of the static force, namely: the horizontal line displacement and the rotation angle of the two nodes. In the dynamic analysis under horizontal ground motion, the single-degree-of-freedom system requires only an independent horizontal displacement to determine the position of the particle under the action of the horizontal inertial force. Therefore, the system has only one lateral displacement degree of freedom. The displacement u' of the particle relative to the original rest position can be regarded as the superposition of two parts, which are the rigidity lateral displacement u_{g} of the whole structure and the horizontal displacement u of the particle relative to the structure base produced by the inertia force

$$u' = u_g + u \tag{1}$$

Thus, it is easy to get a motion equation of single degree of freedom system, which can be expressed as

$$m\ddot{u}\,(t) + C\dot{u}\,(t) + f_{\mathrm{s}}\,(u,\dot{u}) = -m\ddot{u}_{\mathrm{g}}\,(t)\ . \tag{2}$$

Here, C is the viscous damping coefficient and $f_s(u, \dot{u})$ is the restoring force of the structure.

When the structure is still in the linear elastic deformation stage, the restoring force of the system can be expressed by the formula

$$f_s = Ku\,, \tag{3}$$

where K is the initial lateral stiffness of the system and u is the relative displacement of the system.

The initial stiffness of the structure is represented by the stiffness of the beam, column and wall which the structure belongs, and can be obtained by a certain algebraic calculation. Under the action of rare earthquakes, the deformation of the structure may be in the elastic-plastic stage. In this process, the relationship between the restoring force and the displacement of the structure becomes very complex. In general, the restoring force will not correspond to the displacement value, but will depend on the deformation path and the deformation state, and can be expressed as

$$f_s = f\left(u, \dot{u}\right)\,. \tag{4}$$

In the theoretical study, the general mathematical model of restoring force which is simplified on the basis of the experimental data is adopted. The equation (2) can be understood as the system substrate is stationary, and a horizontal equivalent force $P = -mu$ is affected in the particle. Because the force is proportional to the quality of the system, the system quality is greater, the stronger the earthquake. The both ends of the motion differential equations (2) relatively displace u points to the particle, and the energy equation relative to the displacement can be obtained [3]

$$\int_0^u m\ddot{u}\,\mathrm{d}u + \int_0^u C\dot{u}\,\mathrm{d}u + \int_0^u f_s\,\mathrm{d}u = -\int_0^u m\ddot{u}_g\,\mathrm{d}u\,. \tag{5}$$

Since the displacement u is a function of time t, a differential relation $\mathrm{d}u = u\,\mathrm{d}t$ can be obtained, so that the integration of the displacement can be converted to the integration of time t, and the above relationship can be substituted into (3) to obtain the expression of the seismic response energy calculation of the single degree of freedom system:

$$\int_0^t m\ddot{u}\dot{u}\left(t\right)\,\mathrm{d}t + \int_0^t C\dot{u}^2\left(t\right)\,\mathrm{d}t + \int_0^t f_s\dot{u}(t)\,\mathrm{d}t = -\int_0^t m\ddot{u}_g\dot{u}\left(t\right)\,\mathrm{d}t\,. \tag{6}$$

$$E_I = \int_0^u m\ddot{u}_g\,\mathrm{d}u = -\int_0^t m\ddot{u}_g\dot{u}\left(t\right)\,\mathrm{d}t\,. \tag{7}$$

The equations on the left side of the above formula represent the different meanings, and the representing method is as follows:

Symbol E_K stands for the kinetic energy of the structure, that is given by the expression

$$E_{\mathrm{K}} = \int_0^u m\ddot{u}\,\mathrm{d}u = \int_0^t m\ddot{u}\dot{u}\,(t)\;\mathrm{d}t\,. \tag{8}$$

Quantity E_{D} is the damping dissipation energy of the structure, that is given as

$$E_{\mathrm{D}} = \int_0^u C\dot{u}\,\mathrm{d}u = \int_0^t C\dot{u}^2\,(t)\;\mathrm{d}t\,. \tag{9}$$

Symbols E_{S} and E_{H} denote the elastic deformation energy and inelastic hysteretic dissipation energy of the structure, respectively, that may be expressed as

$$E_{\mathrm{S}} + E_{\mathrm{H}} = \int_0^u f_s\,\mathrm{d}u = \int_0^t f_s\dot{u}\,(t)\;\mathrm{d}t\,. \tag{10}$$

So, at any time t, the relationship of the energy balance in the structure is

$$E_{\mathrm{K}} + E_{\mathrm{D}} + E_{\mathrm{E}} + E_{\mathrm{H}} = E_{\mathrm{I}}\,. \tag{11}$$

In mathematics, because the structure is a continuous medium, there should be infinite degrees of freedom, but in specific engineering practice, the structure is usually equivalent to the limited multi-degree-of-freedom system to analyze according to certain rules, and the specific expression is

$$[M]\,\{\ddot{u}\,(t)\} + [C]\,\{\dot{u}\,(t)\} + \{R\,(t)\} = -\,[M]\,\{r\}\,\ddot{u}_{\mathrm{g}}\,(t)\;, \tag{12}$$

where $[M]$ is the diagonal matrix of the concentrated mass, $[C]$ is the damping matrix of the structure, $\{R(t)\}$ is the restoring force matrix of the structure and $u(t)$, $\dot{u}(t)$, $\ddot{u}(t)$, respectively, represent the displacement vector, the velocity vector and acceleration vector of the particle of the structure. Symbol $\ddot{u}_{\mathrm{g}}(t)$ is the acceleration of the ground motion; conversion column vector, and consider the structure of the damping matrix, $\{r\}$ is the switching column vector, and the corresponding terms of the degree of freedom in the direction of action of the seismic inertial force is 1, and the rest is 0 [4].

When the earthquake continues to develop on the structure, the structure will enter the elastic-plastic stage, the stiffness matrix will change with time, and the specific performance is related to the position and the state of the each unit in their respective restoring force curve. Therefore, when solving differential equations, it is necessary to divide the whole seismic motion into a series of small steps of equal step length or different step length, and treat the structural parameters in each period as constants, and then use the stepwise integration method to solve.

In the structural analysis, the common step by step integration methods are linear acceleration method, the midpoint acceleration method, Marker β method and Wilson θ method [5]. In general, considering the aspects of stability and calculation accuracy of the model, the midpoint acceleration method or the Wilson's θ method are used to analyze the nonlinear dynamics of the multi-degree-of-freedom system.

Similar to the energy response equation of the single-degree-of-freedom system, the general form of the energy-response equation of the multi-degree-of-freedom system can be expressed as a matrix:

$$\int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} [M] \{\ddot{u}(t)\}\ \mathrm{d}t + \int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} [C] \{\dot{u}(t)\}\ \mathrm{d}t + \int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} \{R(u(t))\}\ \mathrm{d}t =$$

$$= -\int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} [M] \{r\}\, \ddot{u}_{\mathrm{g}}\, \mathrm{d}t\,. \tag{13}$$

The above equation can be abbreviated, and the simplified equation is:

$$E_{\mathrm{K}}(t) + E_{\mathrm{D}}(t) + E_{\mathrm{S}}(t) + E_{\mathrm{H}}(t) = E_{\mathrm{I}}(t)\ . \tag{14}$$

Now the energy of the ground motion input structure is

$$E_{\mathrm{I}}(t) = -\int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} [M] \{r\}\, \ddot{u}_{\mathrm{g}}\, \mathrm{d}t\,. \tag{15}$$

The kinetic energy of the structure is

$$E_{\mathrm{K}}(t) = \int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} [M] \{\ddot{u}(t)\}\ \mathrm{d}t\,. \tag{16}$$

The damping dissipation energy of the structure [6] is

$$E_{qrmD}(t) = \int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} [C] \{\dot{u}(t)\}\ \mathrm{d}t\,. \tag{17}$$

Elastic deformation energy and the hysteresis dissipation energy are

$$E_{\mathrm{S}}(t) + E_{\mathrm{H}}(t) = \int_0^{t} \{\dot{u}(t)\}^{\mathrm{T}} \{R(u(t))\}\ \mathrm{d}t\,. \tag{18}$$

As the nonlinear dynamic analysis process is very complex, the calculation is very large. So, in general, in the actual design and analysis, it is necessary to do corresponding simplify and assumptions to the structure to have better results in the application.

The energy-based seismic design method first establishes the seismic input energy spectrum. The empirical criteria based on the numerical analysis are the equal energy criterion, the maximum deformation criterion, the instantaneous energy criterion and the equivalent linearization method in geometry. The geometrical equivalent energy criterion considers that the elastic system and the elastic-plastic system are equal to the deformation energy obtained according to the geometrical calculation area in the uniaxial load-displacement curve. The maximum deformation criterion considers that the elasticity system is almost equal to the maximum deformation of the elastic-plastic system, is an empirical conclusion obtained based on seismic response time history analysis results [7]. The instantaneous energy criterion is an effective method to predict the maximum response of the elastic-plastic system based on the energy concept. According to the input energy in the time interval close to the fundamental period of the building structure, the unidirectional maximum deformation is determined, that is, the instantaneous input energy is transformed into the energy dissipation of uniaxial load-displacement to predict the maximum deformation. The equivalent linearization is a method suitable for the elastic system. It needs to assume that the damage distribution of the system is the same as that of the elastic system.

2.2. Establishment of analytical model of frame-shear structure

The engineering model is a part of the actual two-phase engineering under construction. The structure type adopts the cast-in-place reinforced concrete frame-shear wall structure, and the structure safety grade is the second level. The foundation design level is B level; the class of the building aseismicity is C-class, and the seismic fortification is 7 degree (0.15 g) [8]. The site soil is Class II, and the design seismic grouping is the first group. The seismic rating framework of the special-shaped column-frame shear-wall structure is the three-tier level.

The basic modal analysis is carried out first to analyze the structural model, and the most original results of the structure are obtained, as shown in Tables 1–3.

Table 1. Structural eigenvalue analysis

Modal number	Frequency (Hz)		Cycle (s)	Allowable error
	Rad/s	Cycles/s		
1	6.7	1.0663	0.9378	0
2	7.7762	1.2376	0.808	0
3	8.1754	1.3012	0.7685	0
4	22.4687	3.576	0.2796	0
5	27.3295	4.3496	0.2299	0
6	28.271	4.4995	0.2222	0
7	44.6431	7.1052	0.1407	2.29E–82
8	56.8744	9.0518	0.1105	1.76E–68
9	58.3491	9.2866	0.1077	1.13E–67
10	74.1298	11.7981	0,0848	2.54E–54
11	98.6677	15.7034	0.0637	4.18E–29
12	101.4837	16.1516	0.0619	1.9E–25

The first mode of vibration of the structure is the translational motion in the X direction, the second mode is the translation in the Y direction, the third mode is the torsion, and the ratio of the first mode to the third mode is 73 %, which meets less than 90 % of the provisions [9]. In the first mode and the second mode, the stress at the top of the structure is the largest, and in the third mode, the stress at the corner of the structure is the largest.

Table 2. Parameters and quality of the mode of vibration

Modal number	TRAN-X		TRAN-Y		TRAN-Z	
	Quality (%)	Total (%)	Quality (%)	Total (%)	Quality (%)	Total (%)
1	71.0445	71.0445	0.1332	0.1332	0.0001	0.0001
2	0.4741	71.5186	67.3234	67.4566	0	0.0001
3	1.7839	73.3025	3.652	71.1086	0.0001	0.0002
4	14.1655	87.4681	0.0082	71.1168	0.0001	0.0002
5	0.0255	87.4936	10.6149	81.7317	0.0025	0.0027
6	0.0097	87.5033	3.9686	85.7003	0.0006	0.0033
7	5.5002	93.0035	0.0007	85.7009	0.0001	0.0034
8	0.0019	93.0054	1.1037	86.8046	0.0011	0.0046
9	0.0029	93.0083	4.7371	91.5417	0.001	0.0055
10	2.6485	95.6568	0.0005	91.5423	0.0003	0.0058
11	0.0053	95.6621	0.0726	91.6148	0.0002	0.006
12	0.0002	95.6623	3.1349	94.7497	0.7585	0.7645

Table 1. Structural eigenvalue analysis

Modal number	TRAN-X	TRAN-Y	TRAN-Z
1	97.2254	0.1823	0.0001
2	0.6695	95.0804	0
3	2.4784	5.0737	0.0001
4	99.1613	0.0576	0.0006
5	0.1744	72.5288	0.0169
6	0.0686	28.0642	0.0043
7	99.9584	0.012	0.0017
8	0.0324	18.711	0.0194
9	0.0513	82.8047	0.01690
10	99.5879	0.0203	0.0115
11	0.1452	1.9918	0.0053
12	0.0049	73.7291	17.8393

3. Results

3.1. Analysis of the displacement

Figure 1 shows the displacement of structure under the effects of Taft wave and E1 wave on frequent earthquakes, Fig. 2 then depicts the displacement of the structure under the effects of the Taft wave and El wave on rare earthquakes

The results show that the average displacement of the whole structure is 14.15 mm,

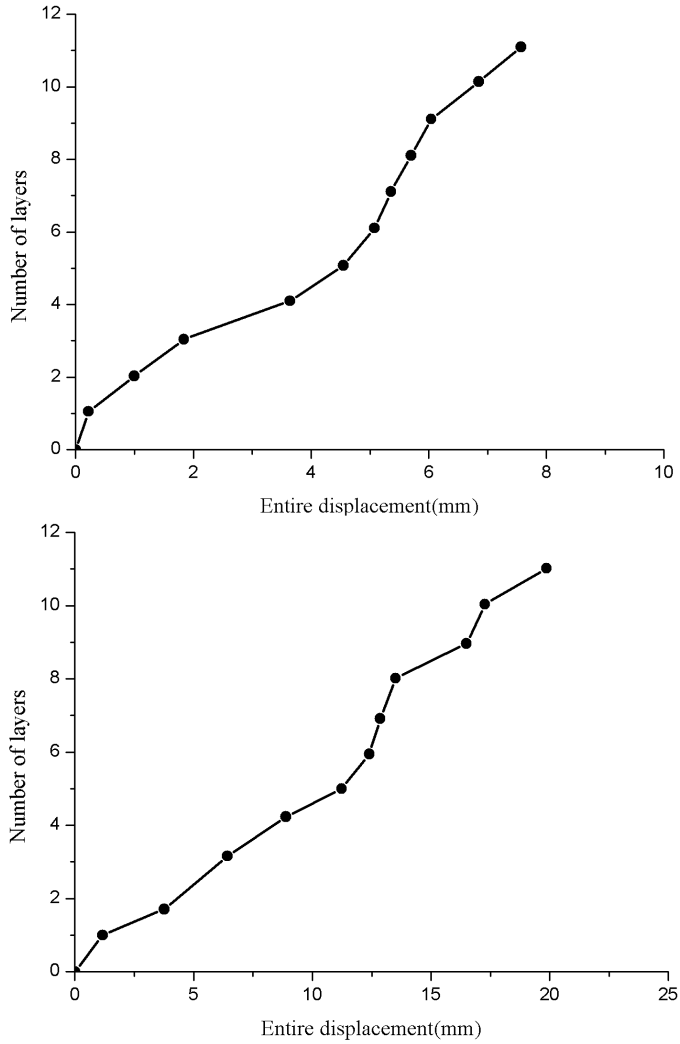

Fig. 1. Displacement of structure under the effects of Taft wave (up) and EL wave (bottom) on frequent earthquakes

which is in accordance with the specification. Comparing the floor displacement map, we can see that although the structure is subjected to different seismic waves, the response of the structure is similar. The structure is mainly composed of bending deformation in 1–4 layers, shear deformation in 5–8 layers and bending deformation in 9–ll layers [10]. Under different seismic waves, the displacements and deformations of the structures are different. The displacements of the EL waves are much larger, which is determined by the structural dynamic characteristics and the spectral characteristics of seismic waves. Overall, the overall deformation of the structure shows bending and shearing state. Therefore, it can be deduced that the displace-

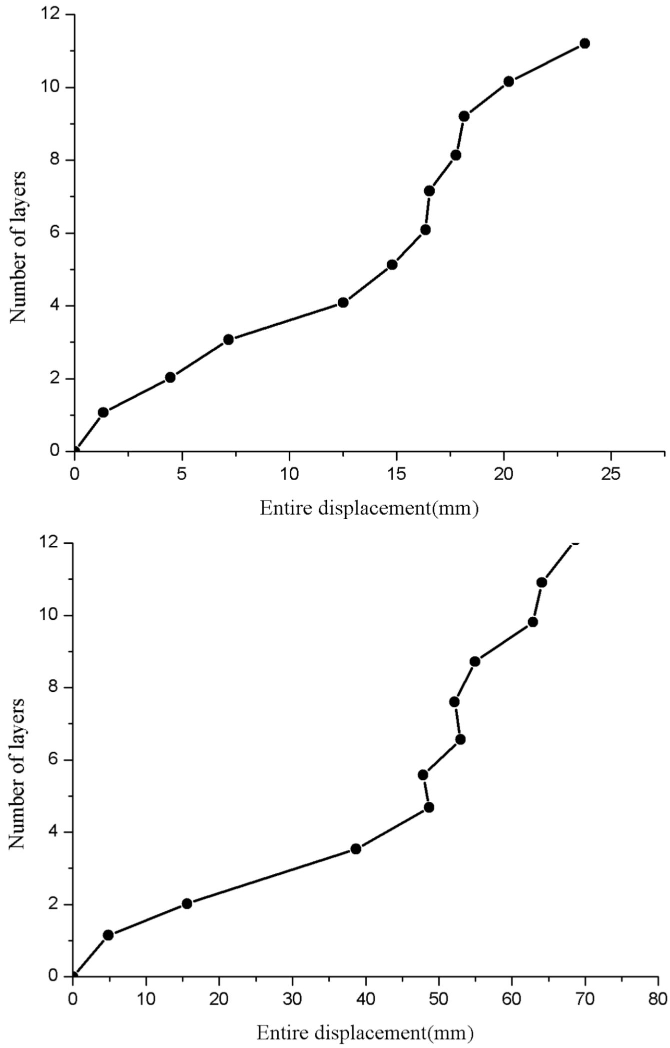

Fig. 2. Displacement of structure under the effects of Taft wave (up) and EL wave (bottom) on rare earthquakes

ment of frame-shear-wall structure under different seismic waves is different, but the deformation is uniform.

3.2. Analysis of the structure energy

The input structure model of the Tianjin, Taft and EL waves under the rare earthquake are taken to calculate the energy response of the above structure, at the same time, the peak value of seismic wave acceleration was taken as 2209, and the seismic response time was calculated as 20 s [11]. The analysis results of the total energy time history is respectively shown in Figs. 3 and 4.

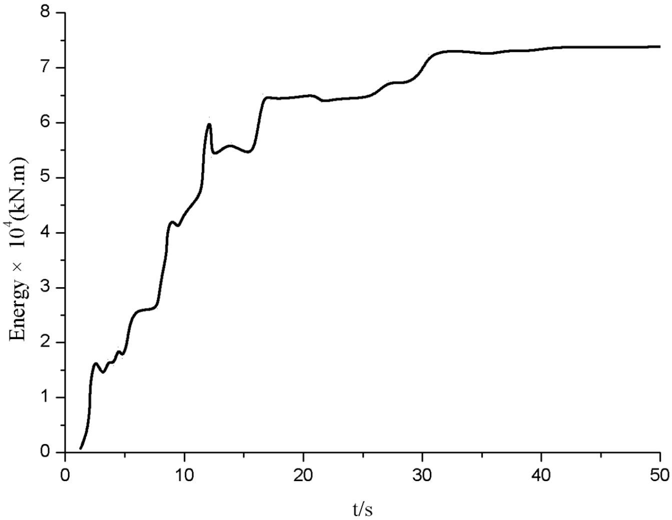

Fig. 3. Time history of Taft wave energy

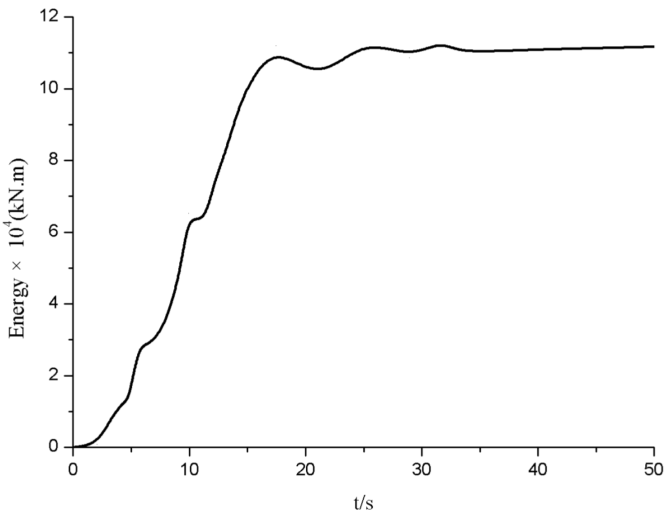

Fig. 4. Time history of EL wave energy

From the figure, we can see that although the seismic wave intensity and the duration are the same, the energy response of the structure is also quite different. The total energy basically increases and the shock increases. The time history curve of the total energy increases continuously in the beginning, which corresponds to the concentrated area of the seismic wave intensity.

From the comprehensive analysis of the effects of the frequent earthquake and rare earthquake on the structure, it can be concluded that the deformation curve of the whole structure under the action of multiple earthquakes is curved scissors type. And the displacement of the top layer of the structure is relatively large, because the mass and the rigidity setting is smaller. So the layout of the structure cannot ignore the rational layout of the top structure [12]. Under the action of rare earthquakes, the interlayer displacement value of the bottom layer of the structure shows the maximum value, and it is most likely to yield first. Through comparison and analysis of the wave energy, the following conclusions can be drawn: the total energy input of the structure under the action of rare earthquakes increases with oscillation, and the energy has a rapid growth section, which is usually located in the concentration section of the seismic wave intensity. Because of the waveforms of the seismic waves and the structure, the results of this paper show that although the peak of acceleration and the duration of earthquake are the same, the energy response of the structure is very different. Under the action of earthquake, the energy of the input structure is finally balanced by damping energy dissipation and non-elastic hysteretic energy dissipation. On the contrast of energy dissipation, the damping energy dissipation of the structure is smaller than that of the non - elastic hysteretic energy. Under the action of Taft wave and EL wave, the input energy and energy dissipation of the earthquake will reach the maximum value quickly and will not increase again in the later period, which reflects that the response of the structure to earthquake is reduced, the strength and rigidity of the structure depredate, while hysteresis loop area decreases.

4. Conclusion

Although this paper does not fully express the superiority of energy method and there are still some deficiencies, from the overall view, the energy analysis results are basically consistent with the actual situation of the project. And the results obtained are similar with those of existing methods, which suggests that it has a certain reference value. Energy based seismic design methods focus on the failure modes of structure and control of energy dissipation mechanisms, so the seismic performance of structures can be better understood as a whole. At the same time, in that the cumulative damage effect of structure is taken into account, so it can make necessary and reasonable supplement for the design of the structure bearing capacity and that based on displacement. And it is proved to be currently comparatively perfect seismic design method based on the performance. The reinforced concrete frame structure system is a widely used structural system in practical engineering. As a result, it is of great significance to study the seismic design of reinforced concrete frame shear structures based on energy.

References

[1] F. Ren, Y. Zhou, G. Chen, J. Liang: *Experimental study on seismic performance of concrete-filled steel tabular frame-shear wall structure with buckling-resistant braces.*

Structural Design of Tall & Special Buildings *24* (2015), No. 1, 73–95.

[2] M. Surana, Y. Singh, D. H. Lang: *Seismic performance of concrete-shear-wall buildings in India*. Ice Proceedings Structures & Buildings *169* (2016), No. 11, 809–824.

[3] H. Jiang, X. Liu, L. Hu: *Seismic fragility assessment of RC frame-shear wall structures designed according to the current Chinese seismic design code*. Journal of Asian Architecture & Building Engineering *14* (2015), No. 2, 459–466.

[4] J. Seo, J. Hu, B. Davaajamts: *Seismic performance evaluation of multistory reinforced concrete moment resisting frame structure with shear walls*. Sustainability *7* (2015), No. 10, 14287–14308.

[5] Z. Dang, X. Liang, K. Li, H. Zhao: *Seismic design of reinforced concrete frame-shear wall structure based on yield point spectra*. Tumu Gongcheng Xuebao/China Civil Engineering Journal *48* (2015), No. 6, 25–35.

[6] H. A. D. S. Buddika, A. C. Wijeyewickrema: *Seismic performance evaluation of posttensioned hybrid precast wall-frame buildings and comparison with shear wall-frame buildings*. Journal of Structural Engineering *142* (2016), No. 6, paper 04016021.

[7] M. Surana, Y. Singh, D. H. Lang: *Seismic performance of shear-wall and shear-wall core buildings designed for India codes*. Advances in Structural Engineering (2014), 1229–1241.

[8] M. Surana, Y. Singh, D. H. Lang: *Seismic characterization and vulnerability of building stick in hilly regions*. Natural Hazards Review (2017), No. 7.

[9] F. Zhang, X. Li, Q. Xu, C. Gong, X. Chen, Q. Liu: *Experimental study on seismic behavior of frame-rocking wall structure*. Jianzhu Jiegou Xuebao/Journal of Building Structures *36* (2015), No. 8, 73–81.

[10] J. Y. Lu, L. N. Yan, Y. Tang, H. H. Wang: *Study on seismic performance of a stiffened steel plate shear wall with slits*. Shock and Vibration (2015), paper 689373.

[11] M. Zeynalian: *Numerical study on seismic performance of cold formed steel sheathed shear walls.*. Advances in Structural Engineering *18* (2015), No. 11, 1819–1830.

[12] C. Yuan, J. Hao, C. Fang, C. Fan, N. Han: *Experimental study on seismic behavior of semi-rigid steel frames with multi-ribbed grid composite steel plate shear wall structure*. Jianzhu Jiegou Xuebao/Journal of Building Structures *36* (2015), No. 4, 16–24.

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