Analysis of Seismic Load Bearing Capacity of Short Leg Shear Wall Based on Energy Dissipation

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***Abstract* — Understanding of the failure mode and the load carrying capacity of short leg shear wall structures under rare earthquake is a problem of the engineer's concern. Based on the energy principle, the seismic performance of high-rise short leg shear wall structure is analyzed by using the model of concrete damage plasticity, The damage of the structure under different seismic peak and the corresponding plastic damage energy can be obtained. The results show that the plastic energy dissipation can reflect the damage degree of the structure. The damage of the structure under the "resonance" excitation is studied. The damage state of the first two modes is obtained, which is the basic failure form of the structure, and the plastic damage energy of the corresponding basic failure mode is obtained, which is the ultimate bearing capacity of the first two modes. Based on the wavelet analysis principle, the input seismic wave is decomposed by wavelet transform. The seismic wave is decomposed into the wavelet band with the structure of the natural vibration frequency as the center. The plastic energy dissipation of the structure under seismic wavelet is obtained. A representation of the carrying capacity by the energy is proposed. The formula can be used to determine the safety performance of short leg shear wall structure under earthquake action.**

Keywords - short leg shear wall; plastic energy dissipation; load carrying capacity; safety performance

I. INTRODUCTION

Since the short leg shear wall structure system was put forward by academician Baisheng Rong [1], it has been increasingly developed in high-rise residential buildings. However, this architecture has not been tested in rare earthquake, and people know little about the injury and damage of the structure. Therefore, the research on the seismic performance of short leg shear wall has important significance. The damage of earthquake on the structure is actually a process of transmission, conversion and consumption of energy. The resistance ability to external forces of the structure is not only related to the lateral force resistance ability of the structure, but also the anti-deformation ability, therefore to estimate the seismic capacity of the structure reasonably, these influencing factors must be given comprehensive consideration. Scholars at home and abroad have done a lot of researches on the application in architectural structure based on the analysis methods of energy [2-5]. Fajfar [6-7] and other people made in-depth analysis of the elastic-plastic earthquake response of the structure, and the results showed that the energy consuming capacity of structure can reflect earthquake resistant behavior of structure synthetically, which is a comprehensive integrated indicator, but it is still very difficult to determine the ultimate aseismic capacity of the structure. The spectral distribution of seismic wave is wide, to study the impact of seismic wave frequency spectrum on structure input more subtly, scholars apply the wavelet theory into earthquake engineering field [8-9]. Architectural structure has its specific intrinsic frequency and mode of vibration, stimulation of different frequency band on the structure will lead to different structural response and bearing capacity. Based on energy principle, it studies the "resonance" ultimate bearing capacity of the structure and plastic damage under seismic wavelet action, and puts forward ultimate limit states expression based on plastic energy dissipation to determine the safety performance of short leg shear wall structure in earthquake.

II. ENERGY RESPONSE ANALYSIS OF STRUCTURE

A. Establishment of energy equation

Under horizontal earthquake action, the differential equation of motion of multi-degree freedom system is:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=-[M]\{I\}\{\ddot{x}_g(t)\} \quad (1)$$

Where $[C]$ is damping matrix; $[M]$ is lumped mass matrix; $[K]$ is stiffness matrix; $\{\ddot{x}_g(t)\}$ is ground movement acceleration; $\{x(t)\}$ is displacement row vector of the structure; $\{\dot{x}(t)\}$ is velocity row vector of the structure; $\{\ddot{x}(t)\}$ is acceleration row vector of the structure.

Respectively multiplied into the equation (1) with $\{x(t)\}^T=\left\{\frac{dx(t)}{dt}\cdot dt\right\}^T=\{\dot{x}(t)\}^T\cdot dt$, and then during the entire earthquake time t_0, to integrate on the time, then following energy balance equation is obtained:

$$\int_0^{t_0} \{\dot{x}(t)\}^T [M]\{\ddot{x}(t)\}dt + \int_0^{t_0} \{\dot{x}(t)\}^T [C]\{\dot{x}(t)\}dt + \int_0^{t_0} \{\dot{x}(t)\}^T \{F(t)\}dt = -\int_0^{t_0} \{\dot{x}(t)\}^T [M]\{\ddot{x}_g(t)\} \tag{2}$$

Where $\int_0^{t_0} \{\dot{x}(t)\}^T [M]\{\ddot{x}(t)\}dt$ represents the kinetic energy $E_k(t)$ at the end of an earthquake, $\int_0^{t_0} \{\dot{x}(t)\}^T [C]\{\dot{x}(t)\}dt$ is damping dissipation energy $E_d(t)$, the sum of cumulative hysteretic energy E_h and elastic strain energy E_e is expressed by the third item on the left of equation(2) $E_I(t) = -\int_0^{t_0} \{\dot{x}(t)\}^T [M]\{\ddot{x}_g(t)\}dt$ represents earthquake input energy, Eq.2 can be expressed as:

$$E_I(t) = -\int_0^{t_0} \{\dot{x}(t)\}^T [M]\{\ddot{x}_g(t)\}dt \tag{3}$$

Equation (2) and (3) shall be called the relative energy equation.

The total input energy of the seismic input structure in the energy equation is mainly borne by the damping energy dissipation and the hysteretic energy dissipation. The kinetic energy of the structure at the end of the earthquake is close to zero, and the structure will not collapse when the structure of the damping energy and hysteretic energy is enough to resist the total input energy of the earthquake. In general, if the damping has been determined, the seismic capacity of the structure is determined by the hysteretic energy of the structure.

B. Establishment of the Structural Model

This paper takes the short shear wall structure residential building on the twelve floor of building one as model construction, the total height of the structure is 35.1m, the story height of the first layer is 3.2m, and the rest story heights are all 2.9m. The wall limb thickness of shear wall is 200mm, the thickness of wall limb at axis C and axis J on first to fifth floor is increased slightly. The structure plan is shown in Fig.1. The strength grade of concrete of shear wall is C30 ~ C40, the strength grade of concrete of beams and boards is C30 ~C35. The rebar of shear wall adopts HRB335; the longitudinal steel of beam adopts HRB335 and the stirrup adopts HPB300. The building site category is class III, the seismic fortification intensity is 7 degree, the design earthquake group is the first group, the rare earthquake site characteristic period is 0.45s.

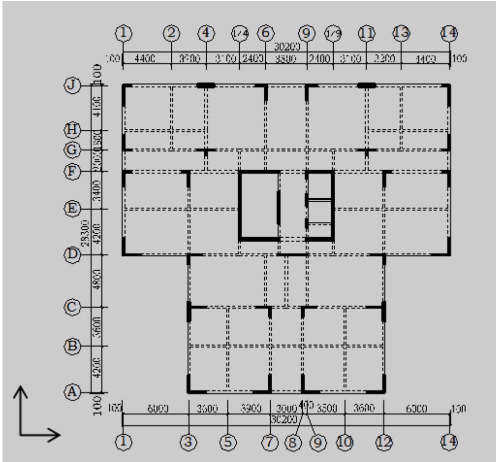

Figure 1. Standard planar diagram of structure

Concrete materials adopts concrete plastic damage model (CDP model) included in software ABAQUS, and the rebar adopts bilinear hardening model to simulate the relation. Because that under the influence of cyclic loading, there will be cracks and plastic deformation in the concrete structure or components, crack extension and plastic deformation will result in rigidity degeneration of concrete, damage factor can describe the rigidity degeneration at the unloading time well, and the damage factor is calculated according to the calculation parameters in literature [10]. Under the action of strong earthquake, shell elements can simulate the state of shear wall entering into plasticity, and the element is suitable to simulate large strain and deformation, therefore shear wall and floor adopts S4R element to simulate. Beam element has shear deformation stiffness, considering bending stress state at the same time, to simulate the beam column component of the beam and structure of Timoshenko with B31element. The damping ratio of this structure in earthquake adopts 0.05.

C. Analysis of the Energy Response of Structure under Different Vibration Amplitude

The acceleration peak value of EL-centro wave is adjusted to 220gal, 400gal and 620gal, and the time length is 20s. Table 1 shows the response values of the energy of the structure under the action of different acceleration peak at the end of the time.

Table 1 shows that with the increase of the earthquake vibration amplitude, the total input seismic energy damping dissipation energy of the structure occupies slightly smaller proportion of the total input, but it is basically the same, the plastic energy dissipation occupies higher proportion in total input seismic energy. Fig.2 gives the tensile damage cloud chart of the structure at the final moment under different seismic peak, from Fig.2, we can know that the magnitude of the seismic wave amplitude is larger, and the more severer damage the expansion of damage region of the structure. Therefore, the damage degree of the structure in earthquake can be represented by plastic energy dissipation.

TABLE I ENERGY VALUE AT THE END OF EARTHQUAKE INPUTS(KN•M)

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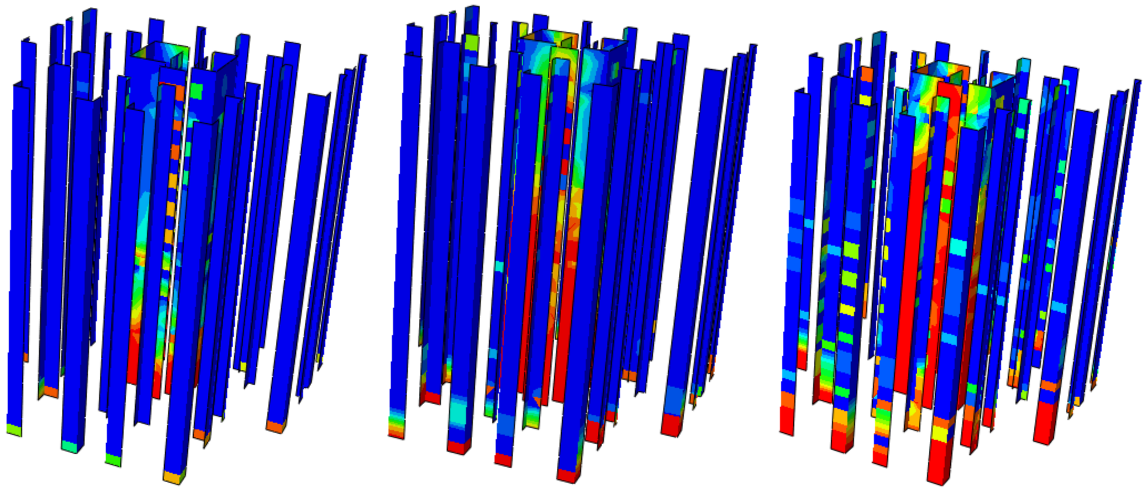
Acceleration peak	Total input energy	Damping energy dissipation	plastic energy dissipation	E_d / E_h (%)	E_h / E_I (%)
220gal	1931.70	1465.68	460.65	75.8	23.8
400gal	5285.21	3936.33	1340.27	74.5	25.4
620gal	11319.1	8082.61	3217.52	71.4	28.4



(a) 220gal (b) 400gal (c) 620gal

Figure 2. Final tension damage chart of wall under different seismic peak.

III. Confirmation of Resonance Ultimate Plastic Energy Dissipation

During the design,resonance phenomenon should be avoided, because the damages during resonance are most severe. This paper will study the ultimate plastic energy dissipation generated by the structure at resonance, it follows the concept of "resonance" of elastic system here, setting external excitation as simple form $\ddot{u}_g(t) = U_0 \sin\theta t$, when the frequency of external excitation is equal to the plastic energy dissipation obtained at resonant frequency at non- destructive state, in this paper, it is still called resonance plastic energy dissipation. In fact, because the structure enters into plasticity, the natural frequency of the structure will change. Table 2 lists the natural frequency of the first five stages of short shear leg wall structure.

Table II Natural vibration frequency of short leg shear wall structure

Order number	1	2	3	4	5
Frequency(Hz)	1.0786	1.1951	1.2778	3.7938	4.0929

It uses natural frequency of translation of two order of X direction as research object, namely the first stage and fourth stage, to determine the resonance plastic energy dissipation of the structure. When the amplitude of exciting force is small, short leg shear wall structure will vibrate in elastic range firstly, when the external excitation frequency is equal to the natural frequency of the structure, resonance phenomenon will occur. With the increase of duration and amplitude, the resonance plastic strain of the structure increase correspondingly, and the damage of the structure increases gradually, when the damage of the structure is through the whole section, the structure is in failure state, then this paper call the corresponding plastic deformation energy here as resonance ultimate plastic energy dissipation, and the corresponding damage state resonance failure state. The final failure state is stipulated by man, with uncertainty, and there is no strict boundaries, therefore we believe that the failure state is a local site with comparatively severe damage, the damage state is determined through observing the damage condition. In this paper, Core area damage runs through, the condition of close to 50% of severe wall limb damage of peripheral shear wall is defined as failure state. Although with the increase of duration or magnitude, the energy is still increasing, in fact the structure is believed to be failured. Table 3 shows the corresponding resonance plastic energy dissipation of the structure under different frequency and the moment of occurrence.

Table III Natural vibration frequency of short leg shear wall structure

Order number	$\theta = \omega_1$			$\theta = \omega_4$		
Amplitude U_0	0.2g	0.22g	0.25g	0.6g	0.65g	0.7g
Resonance limit plastic energy dissipation E_{Hu} (kN·m)	3224.16	3278.82	3237.22	2274.67	2224.74	2240.23
Occurrence times	9.7s	5.3s	3.5s	9.2s	5.2s	3.3s
E_{Hu} average value(kN·m)	3246.73			2246.55		

Due to limitations of paper, it provides the first-order resonance collapse state with amplitude of the excitation of U_0=0.22g, as shown in Fig.3, after several trials, we found that the failure state occured at different moment with different amplitude were basically the same, and the plastic energy dissipation obtained was close. Mean value is used here as the first-order resonance ultimate plastic energy dissipation, represented by E_{Hu1}, namely E_{Hu1}=3246.73kN•m. This can also be seen as a corresponding ultimate bearing capacity at first-order resonance state. Excitation amplitude U_0=0.65g, the fourth-order resonance failure state is shown in Fig.4, using mean value as fourth-order resonance ultimate plastic energy dissipation, namely E_{Hu2}=2246.55J.

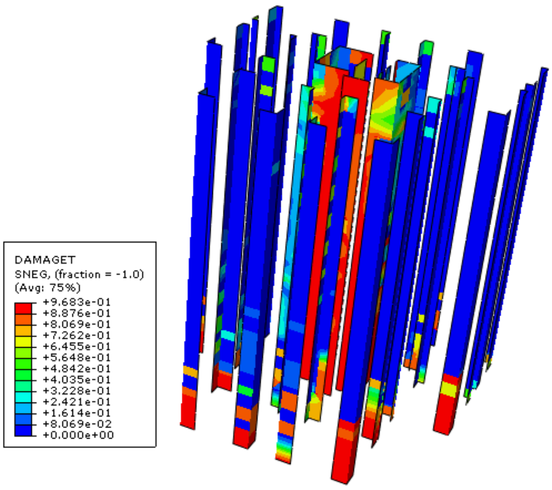


Figure 3. First order resonance failure state diagram of structure.

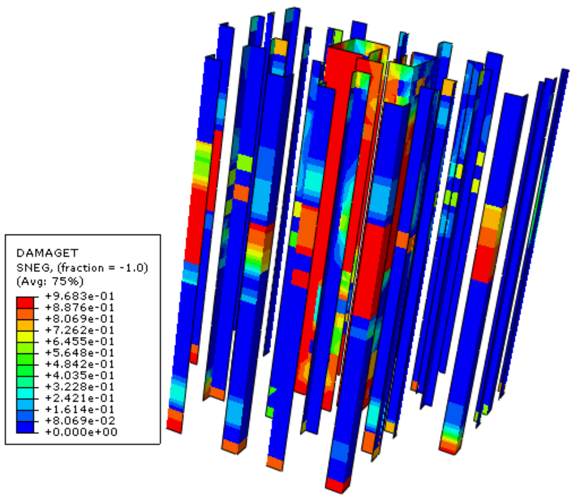


Figure 4. Fourth order resonance failure state diagram of structure.

The Fig.3 and Fig.4 shows that, under the effect of the first-order frequency, the main damage part of the structure is the bottom of shear wall, and the bottom of core tube is destructed earliest and most severely, followed by peripheral wall limb with different degrees of damage. However, under the effect of the fourth-order frequency, core tube was damaged most severely, the middle-upper part of wall limb was destructed the most seriously with local damage at the bottom, which is different from the first-order failure state, indicating that there are different damage sites of the structure under different frequencies.

In comparison of the resonance of the two orders, the first-order resonance requires smaller ultimate stress amplitude to destruct the structure, the fourth-order resonance requires larger ultimate stress amplitude to destruct the structure, which is about three times that of the first order. Then compare the ultimate plastic energy damage degree when it is about to be destroyed, it can be seen from the comparison of the resonance of the two orders that frequency vibration of the first order is mostly likely to cause resonance destruction, outside force is the most "effective", the external loading amplitude required is the smallest and the structural distortion is the biggest. Plastic energy dissipation can reflect the carrying capacity of the structure in essence, thus we believe that using plastic energy dissipation to represent the corresponding loading stress at the collapse state of the structure is more accurate. High-order vibration takes bigger amplitude to generate destruction, but the corresponding plastic energy dissipation at destruction state is lower than the lower stages, therefore merely using the plastic damage energy as index to determine the damage is not correct, it should indicate which order of plastic energy dissipation it is.

IV. Wavelet Analysis of Seismic Wave and Bearing Capacity Expression

A. *Plastic Energy Dissipation of Seismic Wavelet*

The spectral distribution of seismic wave is wide, in order to find out frequency band that is the same as or similar to the natural frequency of the structure, it adopts wavelet analytic method to decompose the seismic wave into wavelet that can stimulate structure resonance. When processing seismic data, wavelet analysis concept was firstly introduced by geologist J.Morlet, and successfully be applied to the analysis of seismic signals. Wavelet analysis is a new time-frequency local changing analysis methods. Through transformation good local characteristics are obtained in time domain and frequency domain, which is the most important characteristic of wavelet analysis, and it can obtain all the details of signal time domain and frequency domain, to make good analysis of the energy distribution of signal at different frequency bands.

It adopts El-centro seismic wave, with the total length of 20s and sampling period of 0.02s. When using wavelet to make analysis of the earthquake energy response, the selection of wavelet basis function is very important in structural calculation. The selective principle of the basis function of wavelet: (1) appropriate support; (2) a large number of vanishing moment; (3) orthogonality and rapidity of calculation. Based on the above principles, this paper adopts Db5 wavelet to make wavelet analysis of the original seismic signal. The first natural frequency of the structure is 1.0786 Hz, so the largest size N=3 is selected, it produces 4 frequency bands, the first-order frequency is within A3 frequency band, the division of frequency band is seen in Table 4. Similarly, the fourth-order frequency of X direction translation is 3.7938 Hz, which is right in the frequency range of D3.

Table Ⅳ The Range of Every Frequency Bands

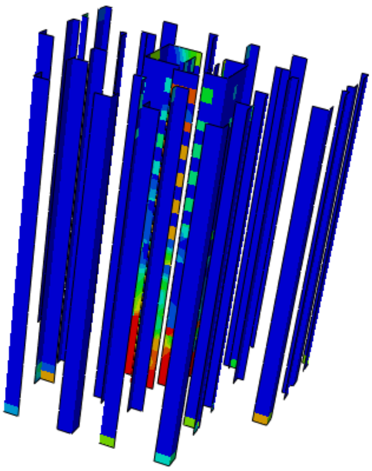
Band	D1	D2	D3	A3
Frequency range (Hz)	12.5~25	6.25~12.5	3.125~6.25	0~3.125

Input the reconstructed A3 and D3 wavelet after the decomposition of wavelet and EL-central earthquake original wave into ABAQUS software to calculate, it obtains the plastic energy dissipation of each wavelet at the final moment. The plastic damage of each wavelet obtained through ABAQUS calculation is seen in Table 5.

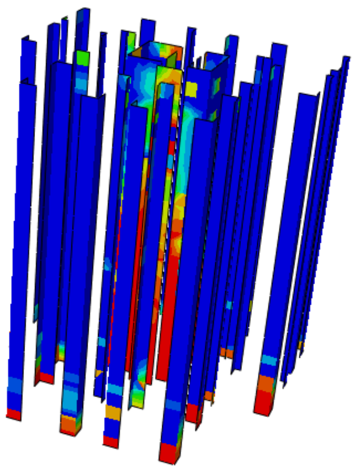
Table Ⅴ Plastic Damage Energy of Various Wavelet(kN•m)

Band / Acceleration peak	A3	D3	Original wave
220gal	390.48	229.24	460.65
400gal	1124.09	278.82	1340.27
620gal	2824.95	481.94	3217.52

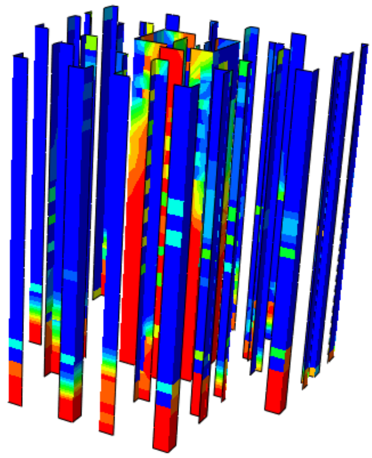
From the Table 5 can know wavelet analysis of seismic wave energy mainly determined by the low frequency band , and can be seen the sum of two frequency band energy value is greater than the energy of the original wave, so it can be seen that wavelet analysis does not accord with the principle of superposition. Figure 5 shows the tensile damage of the A3 wavelet with different amplitudes.



(a) 220gal



(b) 400gal



(c) 620gal

Figure 5. Tension damage chart of A3 wavelet

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The contrast between Figure 2 and 5 shows that tension damage cloud chart with the input of A3 wavelet is basically the same with the damage cloud chart with the input of original wave, combined with Table 5, we can get that theenergy of frequency band A3 occupies a larger proportion of original wave, structural damage is mainly controlled by the wavelet A3 of first-order frequency, so the structure failure mode under this seismic wave action is similar to the first-order failure mode.

B. *Structure Bearing Capacity Expression*

Based on the above analysis, it proposes the expression of the limit state of carrying capacity (see equation (4)), which is expressed by the plastic energy dissipation.

$$\begin{cases} E_{H1} \le E_{Hu1} \\ E_{H2} \le E_{Hu2} \end{cases} \tag{4}$$

Satisfying the equation (4) means that the structure is safe, or the structure may collapse.

Using the equation (4) to estimate the safety performance of the structure under different amplitude, the calculation results are shown in Table 6.

TABLE VI STRUCTURE SAFETY PERFORMANCE JUDGMENT

Acceleration peak	E_{H1} (kN·m)	E_{Hu1} (kN·m)	Safety performance	E_{H2} (kN·m)	E_{Hu2} (kN·m)	Safety performance
220gal	390.48	3246.73	Safe	229.24	2246.55	Safe
400gal	1124.09	3246.73	Safe	278.82	2246.55	Safe
620gal	2824.95	3246.73	Safe	481.94	2246.55	Safe

Table 6 shows that the structure is secure with 200gal and 400gal earthquake action, but the 620gal earthquake action is very close to resonance ultimate plastic energy dissipation, and the structure is close to failure state, in severe damage degree.

V. CONCLUSION

Through time histroy analysis of the dynamic elastic plastic of the short leg shear wall structure in the earthquake, it comes to the following conclusions:

(1) Plastic energy dissipation can reflect the carrying capacity of the structure in essence, thus we believe that using plastic energy dissipation to represent the corresponding loading stress at the collapse state of the structure is more accurate. High-order vibration takes bigger amplitude to generate destruction, but the corresponding plastic energy dissipation at destruction state is lower than the lower stages, therefore merely using the plastic damage energy as index to determine the damage is not correct, it should indicate which order of plastic energy dissipation it is.

(2) Different excitation frequencies cause different damage states, aim at the short leg shear wall structure studied in this paper, the first-order failure state mainly has severe damage at the bottom, the second-order failure state is mainly in the middle part. Divide the seismic wave into different sub wave bands for structure damage analysis, it can reflect the essence of earthquake damage.

(3) It proposes ultimate limit states expression shown by plastic energy dissipation, this formula can be used to determine the safety performance of short shear wall structure during earthquake.

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