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Seismic performance evaluation of steel frame-steel plate shear walls system based on the capacity spectrum method*

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Abstract: This paper presents some methods that the standard acceleration design response spectra derived from the present China code for seismic design of buildings are transformed into the seismic demand spectra, and that the base shear force-roof displacement curve of structure is converted to the capacity spectrum of an equivalent single-degree-of-freedom (SDOF) system. The capacity spectrum method (CSM) is programmed by means of MATLAB7.0 computer language. A dual lateral force resisting system of 10-story steel frame-steel plate shear walls (SPSW) is designed according to the corresponding China design codes. The base shear force-roof displacement curve of structure subjected to the monotonic increasing lateral inverse triangular load is obtained by applying the equivalent strip model to stimulate SPSW and by using the finite element analysis software SAP2000 to make Pushover analysis. The seismic performance of this dual system subjected to three different conditions, i.e. the 8-intensity frequently occurred earthquake, fortification earthquake and seldom occurred earthquake, is evaluated by CSM program. The excessive safety of steel frame-SPSW system designed according to the present China design codes is pointed out and a new design method is suggested.

Key words: Steel frame-steel plate shear walls (SPSW) system, Capacity spectrum method (CSM), Seismic demand spectrum, Base shear force-roof displacement, Seismic performance evaluation

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INTRODUCTION

The steel frame-steel plate shear walls (SPSW) structure, as a dual lateral load resisting system used in North America and Japan, is gaining acceptance and suitable for multi-story or high-rise building in high seismic regions (Berman *et al*., 2005; Sabouri-Ghomi *et al*., 2005). These walls are lighter and more ductile than reinforced concrete shear walls. As much as 50% of steel savings in structures have been achieved by employing the steel plate shear walls rather than a comparable moment-resisting frame (Caccese *et al*., 1993; Elgaaly, 1998). Whereas, the seismic performance evaluation of steel frame-SPSW system designed according to the current corresponding China design codes subjected to various amplitudes of ground motion should be noticed in order to design economical and safe structures.

Structural failures in recent earthquakes have exposed the weakness of current design procedures and shown the needs of new concepts and methodologies for the seismic performance evaluation of structures. The capacity spectrum method (CSM), a performance-based seismic analysis technique, which is first introduced by Freeman *et al*.(1975), can be used for a variety of purposes such as fast evaluation of a large inventory of buildings, design verification for new construction of individual buildings, and evaluation of an existing structure to identify damage states. In recent years, there have been substantial researches and discussions on the merits of inelastic

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response spectra and equivalent damped spectra and on the appropriateness of using damped spectra to represent inelastic response (Chopra and Goel, 1999). Fajfar (1999) developed the inelastic demand spectra and illustrated the application of the modified CSM by two examples. Wang *et al*.(2004) reviewed the basic principles and methods of the static elastio-plastic analysis in FEMA273/274 and in ATC240, and applied the Pushover analysis to evaluate the frame-shear wall structure designed according to China code for seismic design by using the software of ETABS.

The aim of present research is to assess the seismic performance of steel frame-SPSW system under various amplitudes of ground motion. The calculation program of CSM based on the standard acceleration design spectra derived from the China code for seismic design of buildings is made by means of MATLAB7.0 computer language. By applying CSM, the seismic performance of a dual lateral force resisting system of 10-story steel frame-SPSW designed according to the corresponding China design codes is evaluated under three different conditions of the 8-intensity frequently occurred earthquake, fortification earthquake and seldom occurred earthquake, respectively. The excessive safety of steel frame-SPSW system designed according to the China design codes is pointed out and many corresponding design suggestions for this dual system are proposed.

CAPACITY SPECTRUM METHOD

Transformation from standard acceleration design spectrum into seismic demand spectrum

The standard elastic design spectrum in China code for seismic design of buildings (GB 50011-2001, 2001) is defined as the relationship between the seismic influence coefficient α that is equal to the absolute maximum acceleration of single oscillator divided by the acceleration of gravity g and the natural period of vibration T. The horizontal seismic influence coefficient α is determined by

$$
\begin{aligned}
&\alpha=(10T\eta_2-4.5T+0.45)\alpha_{\max}, && 0\le T\le 0.1\ \text{s},\\
&\alpha=\eta_2\alpha_{\max}, && 0.1\ \text{s}\le T\le T_{\mathrm{g}},\\
&\alpha=(T_{\mathrm{g}}/T)^{\gamma}\eta_2\alpha_{\max}, && T_{\mathrm{g}}\le T\le 5T_{\mathrm{g}},\\
&\alpha=[\eta_2 0.2^{\gamma}-\eta_1(T-5T_{\mathrm{g}})]\alpha_{\max}, && 5T_{\mathrm{g}}\le T\le 6\ \text{s}. \quad (1)
\end{aligned}
$$

where α is the seismic influence coefficient, $\alpha_{\max}$ is the maximum of seismic influence coefficient, γ is the attenuation index in the descending branch of curve, η_1 is the modified coefficient of descent slope in the descending branch of line, η_2 is the modified coefficient of damping, T is the structural natural period of vibration, and T_{g} is the characteristic period of soil.

γ, η_1 and η_2 are individually given by the following expressions:

$$\gamma=0.9+\frac{0.05-\xi}{0.5+5\xi}, \quad (2)$$

$$\eta_1=0.02+(0.05-\xi)/8, \quad (3)$$

$$\eta_2=1+\frac{0.05-\xi}{0.06+1.7\xi}, \quad (4)$$

where ξ is the damping ratio of structure, and all other parameters have been defined previously.

The seismic demand spectrum is defined as the curve in the spectral acceleration-displacement response spectrum (ADRS) format obtained by the earthquake acceleration response of SDOF (single-degree-of-freedom) system with natural frequency distributed in some range under the given ground motion, in which spectral accelerations are plotted against spectral displacements for the period T. The demand spectrum represents the demands of the earthquake ground motion on the structure.

For an elastic SDOF system, the following relation applies,

$$S_{\mathrm{d}}=\frac{T^2}{4\pi^2}S_{\mathrm{a}}, \quad (5)$$

where S_{d} and S_{a} are values in the elastic spectrum of pseudo displacement and acceleration, respectively, corresponding to the period T and a fixed viscous damping ratio.

The standard elastic design spectrum can be transformed into the seismic demand spectrum by applying Eq.(5). For the 8-intensity frequently occurred earthquake with design fundamental acceleration of ground motion 0.3g, the first classification of design earthquake, 3.5 percent damping and site classification II, a typical smooth elastic design spectrum (Fig.1a) derived from China code for seismic design of buildings is converted to the seismic demand spectrum shown in Fig.1b.

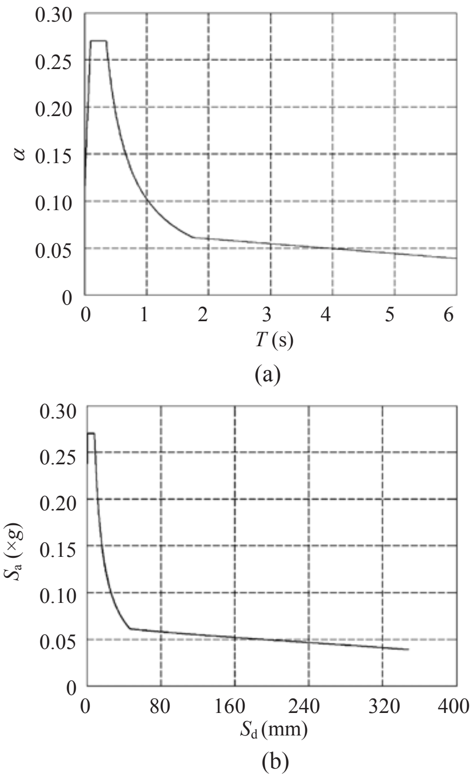


Fig.1 Response spectrum transformation. (a) Standard design spectrum; (b) Demand spectrum in ADRS format

Transformation from force-displacement curve into capacity spectrum

The capacity of structure is represented by a force-displacement curve obtained by non-linear static (Pushover) analysis subjected to the monotonic increasing lateral load up to the structural failure. The base shear forces and roof displacements are converted to the spectral accelerations and spectral displacements of an equivalent SDOF system, respectively. These spectral values define the capacity spectrum, which reflects the lateral deformation resisting capacity of structure. The lower building structure can be substituted for an equivalent SDOF system due to the first order vibration mode governing the whole earthquake response.

The CSM consists of the following steps:

(1) The base shear force-roof displacement curve of structure subjected to the monotonic increasing lateral inverse triangular load is achieved by Pushover analysis;

(2) The base shear force-roof displacement curve of structure (named capacity curve) is then transformed into the capacity spectrum of an equivalent SDOF system.

The transformation from the base shear force V_i and roof displacement Δ_i of each dot on the capacity curve into the spectral acceleration S_{ai} and spectral displacement S_{di} of an equivalent SDOF system is described by the following equations

$$S_{ai}=\frac{V_i}{M_1^*\cdot g}, \tag{6}$$

$$S_{di}=\frac{\Delta_i}{\Gamma_1\cdot X_{1,\mathrm{roof}}}, \tag{7}$$

$$\Gamma_1=\frac{\sum_{i=1}^{N}(m_i\cdot\phi_{i1})}{\sum_{i=1}^{N}(m_i\cdot\phi_{i1}^2)}, \tag{8}$$

$$M_1^*=\frac{\left[\sum_{i=1}^{N}(m_i\cdot\phi_{i1})\right]^2}{\sum_{i=1}^{N}(m_i\cdot\phi_{i1}^2)}, \tag{9}$$

where S_{ai} is the spectral acceleration (×g), S_{di} is the spectral displacement, V_i is the base shear force, Δ_i is the roof displacement, M_1^* is the structural modal mass of the first order vibration mode, Γ_1 is the first order mode-participation coefficient of structure, $X_{1,\mathrm{roof}}$ is the roof first order amplitude of vibration, m_i is the mass of the ith story in the structure, ϕ_{i1} is the first order amplitude of the ith story, N is the number of structural story, and g is the acceleration of gravity.

Seismic performance evaluation of structure

The fundamental principle of CSM, a performance-based seismic analysis technique, is to establish a uniform level of two spectral curves that are the seismic demand spectrum from the standard design response spectrum and the capacity spectrum from the base shear force-roof displacement curve of structure obtained by Pushover analysis, and to put these two spectral curves in one figure. The procedure compares the capacity of the structure with the demands of earthquake on the structure, and makes it possible to have a visual evaluation of how the structure performs when it is subjected to a given earthquake ground motion. The graphical intersection of the capacity spectrum and the demand spectrum, so-called performance point, approximates to the response of an equivalent SDOF system. No such intersection means that the structure has no enough earthquake resisting capability and needs to be re-designed. The spectral displacement at the performance point of an equivalent SDOF system is eventually converted back to the roof displacement of structure. The displacement of structure at the performance point is compared with the corresponding allowable values in all kinds of China design codes to evaluate the seismic performance of this structure.

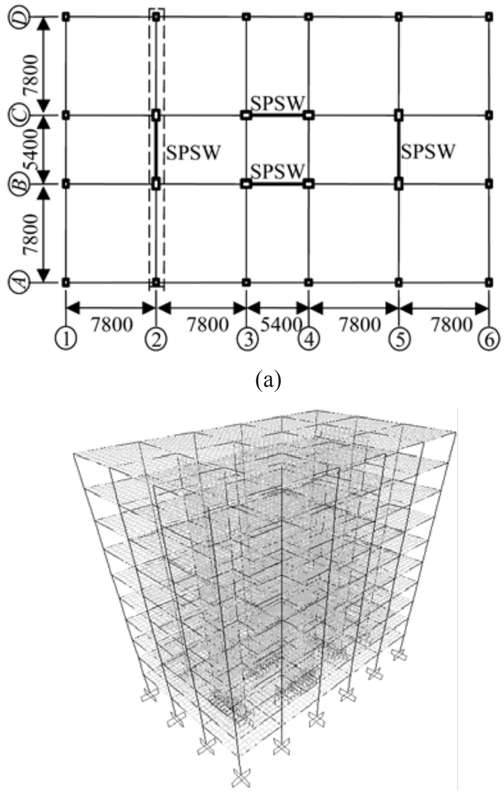
Once the performance point of an equivalent SDOF system is determined, the transformation of all quantities is performed by

$$Q = \Gamma_1 \cdot X_{1,\mathrm{roof}} \cdot Q^*, \tag{10}$$

where Q^* represents the quantities in the equivalent SDOF system (for example: force F^*, displacement U^*, and hysteretic energy $E_H{}^*$, if needed), and Q represents the corresponding quantities in the structure (for example: base shear V, top displacement U, hysteretic energy E_H). All other parameters have been defined previously.

ENGINEERING DESIGN EXAMPLE

A dual lateral force resisting system of 10-story steel frame-SPSW structure is designed according to the China code for seismic design of buildings in a high seismic zone. The height of every story is 3.6 m, the each span length is 7.8 m for frames in both directions and 5.4 m for the infill panels. Fig.2a and Fig.2b show the building plan and 3D graph, respectively. This building is located in the region of a soil class II with fortified intensity of degree 8, the design fundamental acceleration of ground motion 0.3g and the first classification of design earthquake. The thickness of cast-in-situ reinforced concrete floor slab amounts to 100 mm and the concrete strength grade is C20. All frame beam-column connections are in the form of welded rigid joints. All beams and columns are grade Q235 steel. The LYP100 steel with the properties of extremely low yield strength of 100 MPa and high elongation is utilized in the infill panels. The uniform dead loads and live loads on the standard floors are individually taken as 4.02 kN/m^2 and 2 kN/m^2, however, 4.61 kN/m^2 and 0.5 kN/m^2 on the roofs, respectively.



(a)

(b)

Fig.2 Building scheme. (a) Plan (unit: mm); (b) 3D graph

The steel frame-SPSW system of the second axial line in Fig.2a is used as the analytical model shown in Fig.3. The maximum stress ratios of the beams and columns are individually approximately limited to 0.95 and 0.8 when the steel frames are designed by the design software STS, part of the software PKPM 2005, and the finite element analysis software SAP2000 according to corresponding China design codes. After the preliminary selection, step-by-step trail and being satisfied with the corresponding requirements in China design codes, the final sectional dimensions of the I-section beams and □-section columns are determined as follows: c_1: □700 mm×500 mm×30 mm×30 mm; c_2: □350 mm×350 mm×14 mm×14 mm; c_3: □600 mm×400 mm× 16 mm×16 mm; c_4: □300 mm×300 mm×14 mm×14 mm;

b_1: I400 mm×300 mm×12 mm×16 mm; b_2: I400 mm×300 mm×16 mm×20 mm; b_3: I500 mm×350 mm ×16 mm×20 mm. The thickness of each shear wall is 13 mm for the lower five stories and 12 mm for the upper five stories, respectively.

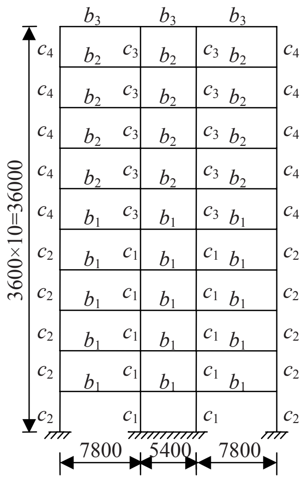


Fig.3 Analytic model (unit: mm)

The base shear force-roof displacement curve (Fig.4) of 10-story steel frame-SPSW system subjected to the monotonic increasing lateral inverse triangular load is obtained by applying the equivalent strip model (Sabouri-Ghomi and Roberts, 1992; Lubell *et al*., 2000) to stimulate SPSW and by using the finite element analysis software SAP2000 to make Pushover analysis. The distribution of structural plastic hinges at the roof displacement reaching 506.4 mm is shown in Fig.5.

The first order amplitude from bottom to top is obtained by using the software SAP2000 to carry out modal analysis: Φ=[0.06, 0.14, 0.24, 0.36, 0.48, 0.62, 0.77, 0.91, 1.05, 1.18], The modal mass and mode-participation coefficient for the first order amplitude of vibration are calculated as M_1^*=1499.7×10^3 kg and Γ_1=1.23, respectively. The transformation coefficient from the structural roof displacement into the spectral displacement of an equivalent SDOF system is $\Gamma_1 \cdot X_{1,\mathrm{roof}}$=1.45.

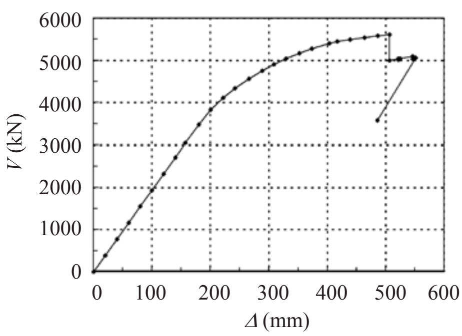


Fig.4 Base shear force-roof displacement

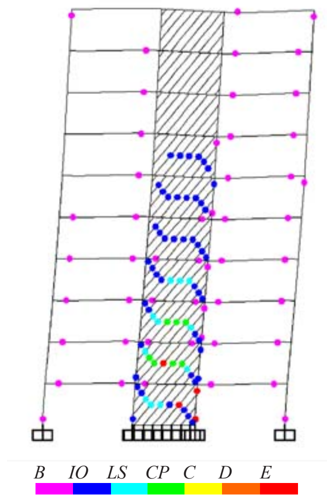


Fig.5 Distribution of plastic hinges

The program of CSM based on the standard design response spectrum in the China code for seismic design of buildings and the base shear force-roof displacement curve of 10-story steel frame-SPSW system obtained by Pushover analysis is made to evaluate the structural seismic performance by means of MATLAB7.0 computer language in this paper.

The values of the corresponding parameters of 8-intenstiy earthquake originating from the China code for seismic design of buildings are as follows. For the frequently occurred earthquake (so-called minor earthquake), the characteristic period of soil is T_g=0.35 s, the damping ratio of structure is ξ=0.035 and the maximum seismic influence coefficient is α_{max}=0.24. For the fortification earthquake (so-called moderate earthquake), T_g=0.35 s, ξ=0.035, α_{max}= 0.675. For the seldom occurred earthquake (so-called strong earthquake), T_g=0.4 s, ξ=0.05, α_{max}=1.2.

The seismic demand spectra under the three levels of 8-intensity earthquake and capacity spectrum of the equivalent SDOF system by using the calculated program of CSM are shown in Fig.6. The spectral displacements of the equivalent SDOF system at the three performance points are 38.4 mm, 105.8 mm and 219.2 mm under the minor earthquake, moderate earthquake and strong earthquake, respectively. The corresponding roof displacements of

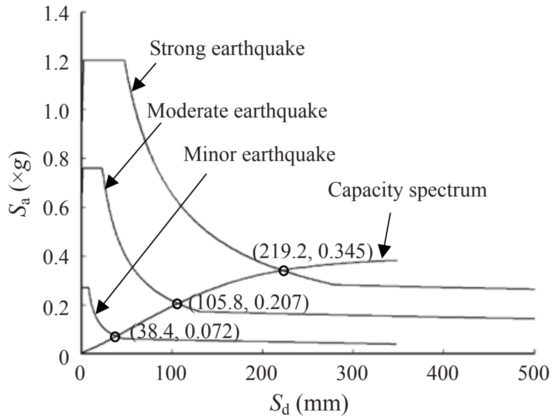


Fig.6 Seismic demand spectra and capacity spectrum

structure derived from the spectral displacements are 55.6 mm, 153.4 mm and 317.9 mm. As known from Fig.6, there exists the intersection between the seismic demand spectra and the capacity spectrum, which shows that the 10-story steel frame-SPSW system designed is strong enough to resist against these three levels of 8-intensity earthquake. However, the structure remains elastic under the 8-intensity moderate earthquake and only the shear walls yield, and most of the steel frame members still remain elastic even under 8-intensity strong earthquake. Furthermore, the bearing load at the performance point under the strong earthquake is far less than the ultimate bearing capacity of structure. At the mean time, the steel frame-SPSW as a dual lateral load-resisting system exhibits excellent ductility after reaching the maximum bearing value, that is to say, the bearing capacity of structure can still remain the ultimate level even if the structure endures very large deformations. This structural behavior with high ductility is not shown in Fig.4 because a large amount of plastic hinges are formed to unload the entire structure and the calculation is not convergent in the SAP2000 software when reaching the ultimate bearing capacity. Therefore, the performance of structure does not comply with the three-level earthquake resisting design principle of "undamaged under minor earthquake, repairable under moderate earthquake, non-collapse under strong earthquake". It also shows that the design of steel frame-SPSW system according to the present China codes is over safe.

The corresponding drifts and lateral inter-story angles of each story at the different performance points under 8-intensity minor earthquake, moderate earthquake and strong earthquake are shown in Table 1. As known from Table 1, the structural maximum lateral inter-drift angles of 1/514 and 1/104 are far less than the elastic inter-drift limit angle of 1/300 and the elasto-plastic inter-drift limit angle of 1/50 derived from the present China code for seismic design of buildings under the frequently occurred earthquake and seldom occurred earthquake, respectively. Also, the structural maximum lateral inter-drift angle of 0.0053 under the moderate earthquake just approximately approaches the lower elasto-plastic inter-drift limit of 0.004~0.008 derived from General rule for performance-based seismic design of buildings (CECS 160:2004, 2004). Consequently, although the dual lateral force resisting system of 10-story steel frame-SPSW designed according to China code for seismic design of buildings and Appendix four of technical specification for steel structure of tall buildings (JGJ 99-98, 1998) meets the corresponding design requirements, the design method is not economic and does not sufficiently make use of the seismic performance with high ductility of the steel frame-SPSW system, which embarrasses the development of structural steel applied in the high-rise building.

Table 1 Drifts and inter-story angles of each story under the three earthquake levels

Story	Drifts (mm)			Inter-story angles		
	Minor	Moderate	Strong	Minor	Moderate	Strong
1	2.6	7.4	25.5	1/1385	0.0021	1/141
2	6.4	18.1	59.8	1/947	0.0030	1/105
3	10.9	30.9	94.3	1/800	0.0036	1/104
4	16.2	45.8	127.7	1/679	0.0041	1/108
5	22.0	62.0	159.5	1/621	0.0045	1/113
6	28.4	80.0	191.8	1/563	0.0050	1/111
7	35.1	98.8	222.5	1/537	0.0052	1/117
8	41.8	117.9	253.7	1/537	0.0053	1/115
9	48.6	137.1	285.3	1/529	0.0053	1/114
10	55.6	153.4	317.9	1/514	0.0045	1/110

The design method of structure according to China code for seismic design of buildings under the fortification-intensity earthquake is actually adopted to remain elastic under the frequently occurred earthquake, which means that the structural influencing coefficient R=2.8125 is used to reduce the design earthquake-induced force under the fortification-intensity earthquake. Based on the previous datum and analysis, it is suggested to adopt greater structural influencing coefficient in designing the steel frame-SPSW system (e.g., for the eccentrically braced steel frame system, the structural influencing coefficient derived from General rule for performance-based seismic design of buildings is R=1/0.25 =4). At the same time, the bearing shear stress of infill panel is specified in Appendix four of technical specification for steel structure of tall buildings to be less than the corresponding critical shear stress in plate buckling, which will have the infill panel designed to be the thick plate. In order to meet the requirement of dual lateral force resisting system, the corresponding sectional dimensions of frame beams and frame columns as the second defence system of seismic engineering are certainly increased, and so the design of steel frame-SPSW system will be over safe. As a result, the buckling of infill plate is suggested to be permissible so as to make full use of the post-buckling strength originated from the diagonal tension field carrying story shear formed in the wall, since the buckling of infill plate does not represent the whole structural failure and not significantly decrease the lateral bearing capacity of this dual system. Furthermore, the buckling of infill plate dissipates a vast amount of seismic energy to alleviate the earthquake action on other members of this dual system. Moreover, the steel with low yield strength and high elongation should be used as the material of infill panels.

CONCLUSION

Steel frame-SPSW structure is an innovative dual system capable of resisting against both wind and earthquake forces. CSM is a performance-based seismic analysis technique and can be used to evaluate the seismic performance of structure. This paper presented some methods that the standard acceleration design response spectra derived from China code for seismic design of buildings are transformed into the seismic demand spectra, and that the base shear force-roof displacement curve of structure is converted to the capacity spectrum of an equivalent SDOF system. The base shear force-roof displacement curve of a 10-story steel frame-SPSW designed according to the present China design codes subjected to the monotonic increasing lateral inverse triangular load is obtained by applying the equivalent strip model to stimulate SPSW and by using the finite element analysis software SAP2000 to make Push-over analysis. The seismic performances of the designed steel frame-SPSW system under the 8-intensity minor earthquake, moderate earthquake and strong earthquake have been evaluated by the program of CSM. Based on the previous datum and analysis presented in the paper, the excessive safety of this dual system has been pointed out, which does not comply with the three-level earthquake resisting design principle of “undamaged under minor earthquake, repairable under moderate earthquake, non-collapse under strong earthquake”. For designing the economic, rational and safe steel frame-SPSW system, a greater structural influencing coefficient is suggested to reduce the design earthquake-induced force under the fortification-intensity earthquake, and the buckling of infill plate is also suggested to be permissible so as to make full use of the post-buckling strength.

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