Structural Engineering and Mechanics, *Vol. 52, No. 6 (2014) 1157-1176*
DOI: http://dx.doi.org/10.12989/sem.2014.52.6.1157

Energy-based damage-control design of steel frames with steel slit walls

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(Received August 19, 2013, Revised May 10, 2014, Accepted July 26, 2014)

Abstract. The objective of this research is to develop a practical design and assessment approach of steel frames with steel slit walls (SSWs) that focuses on the damage-control behavior to enhance the structural resilience. The yielding sequence of SSWs and frame components is found to be a critical issue for the damage-control behavior and the design of systems. The design concept is validated by the full-scale experiments presented in this paper. Based on a modified energy-balance model, a procedure for designing and assessing the system motivated by the framework regarding the equilibrium of the energy demand and the energy capacity is proposed. The damage-control spectra constructed by strength reduction factors calculated from single-degree-of-freedom systems considering the post stiffness are addressed. A quantitative damage-control index to evaluate the system is also derived. The applicability of the proposed approach is validated by the evaluation of example structures with nonlinear dynamic analyses. The observations regarding the structural response and the prediction during selected ground motions demonstrate that the proposed approach can be applied to damage-control design and assessment of systems with satisfactory accuracy.

Keywords: steel frame, steel slit wall, energy approach, damage-control, resilience, yielding sequence, experimental study

1. Introduction

Recent disasters indicate that the conventional ductility-based design philosophy may lead to significant economic penalty and costly repair work since inelastic deformation is expected to be sustained by the entire structure during ground motions. In some situations a building even had to be demolished for severe damage and large residual deformation. In view of sustainability in seismic engineering, the structural resilience (Bruneau and Reinhorn 2006) reflected by reduced failure probability and higher efficiency in recovery after hazard has become a critical issue, and the damage-control behavior (Connor *et al.* 1997) defined as concentration of inelastic deformation in a set of components or devices which are easy to be replaced or repaired after the event of earthquake is believed to be essentially effective in enhancing this feature, sparking an innovation of structural systems and design methodologies (Wada *et al.* 1992, Connor *et al*. 1997,

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http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

Pampanin 2012, Mansour *et al.* 2011, Shen *et al.* 2011).

As for the system of steel frame with steel slit walls (SSWs), it is significantly efficient in resisting seismic loads. With the slits distributing in the panel, the SSW can resist the lateral loading by bending behavior of a series of flexural links (Hitaka and Matsui 2003). Recently, more effort regarding the seismic behavior of SSWs and the system has been made, validating its applicability in engineering practice (Hitaka and Matsui 2006, Hitaka *et al.* 2007, Cortes and Liu 2011a, b). However, existing investigations and design approaches mostly concentrated on the ultimate state. Considering the resilience of the system, it is expected that the SSWs can develop inelastic deformation as the primary energy dissipative components while the frame members can remain elastic within a certain range since the repair work can be easily accomplished by replacing the damaged SSWs. One alternative to avoid the damage of frames is to apply pinned connections in frames (Cortes and Liu 2011a), but it inevitably increases the risk of collapse under extreme earthquake since no further energy dissipation can be provided by frame components. In addition, the release of rotation constraint in frame connections might result in significant sacrifice of stiffness and strength reserved in frames, which might increase the construction cost. Accordingly, it is believed to be more economical to make use of the stiffness and the energy dissipation of frames in the ultimate state, and a critical issue is to develop a practical approach in dealing with design and assessment of the system that focuses on the damage-control behavior.

The primary objective of this research is to accommodate the damage-control behavior into steel frames with SSWs. Critical issues presented consist of (1) the behavior of system as well as the feasibility verification of the design concept and (2) a practical approach focusing on design and assessment of the system regarding the damage-control behavior. Since the damage-control motive can be reflected by concentration of plastic energy in the SSWs, the feature of energy is used in this research, which has been demonstrated to be a more comprehensive index to evaluate the structural behavior (Housner 1956, Nakashima *et al*. 1996, Leelataviwat *et al*. 2002, 2009, Choi and Kim 2009, Taner Ucar and Duzgun 2012). Firstly, the design concept of the damage-control behavior reflected by the yielding sequence of SSWs and frames is investigated, and the related underlying theory is also explored. The behavior of the system is validated by full scale experiments of assemblies of the SSW with surrounding frames and results are reported herein. Subsequently, based on a modified energy-balance model, a practical approach regarding design and assessment of the damage-control behavior of the system is proposed. Considering the interaction of structural yielding sequence and ground motion properties, a damage-control spectrum based on a bilinear model is established by involving the post stiffness provided by frames. A quantitative damage-control index is also proposed. Lastly, three example structures are evaluated with the proposed approach and the accuracy is verified by nonlinear dynamic analyses.

2. Damage-control behavior of steel frames with SSWs considering yielding sequence

An alternative to accomodate the damge-control behavior into systems is to account for the yielding sequence explicitly. If the disposable SSWs are ensured to develop inelastic deformation before yielding of frame components (Fig. 1), damage can be sustained by SSWs within a certain range with deformation compatibility.

For an idealized model, the frame with SSWs as a damage-control system will exhibit a bilinear feature below the resilience threshold which is controlled by initial yielding of frame components. In the global elastic stage, the steel frame and SSWs behave elastically. In the subsequent stage,

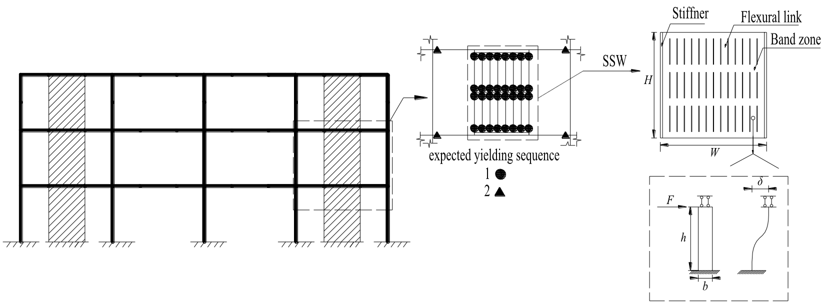
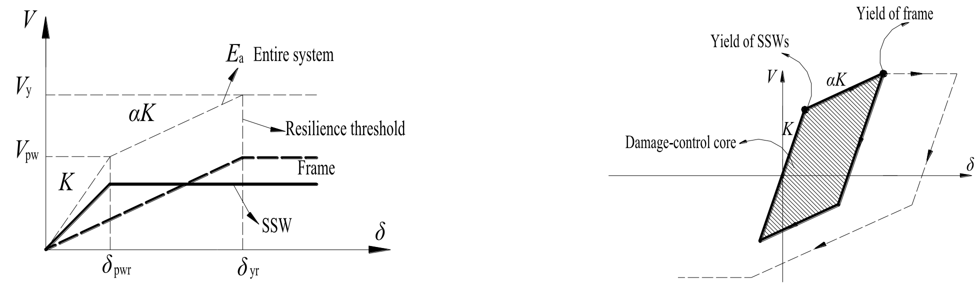


Fig. 1 The steel frame with SSWs and the expected yielding sequence



(a) Load-displacement curve of systems (b) The damage-control core

Fig. 2 Behavior and the damage-control core of frames with SSWs

the SSWs develop inelastic deformation and the steel frame still remains elastic. Accordingly, when the system is subjected to ground motions, the yielding sequence can favorably move plastic energy into the replaceable SSWs, reflecting as a "damage-control core" in hysteretic curves as shown in Fig. 2.

2.1 The yielding sequence of steel frames with SSWs

For the motive of design, it is instructive to relate the yielding sequence of the system to parameters of structural components. For a system dominated by shear deformation, assuming that columns still remain elastic when beams yield, the yield drift of the frame can be estimated with the frame model (Choi and Park 2009) given by

$$\theta_{\mathrm{yi}} = (\lambda_{\mathrm{i}} + 1)\frac{M_{\mathrm{ybi}} l_{\mathrm{i}}}{6EI_{\mathrm{bi}}} \tag{1}$$

where E is the elastic modulus of steel. I_{bi} and l_{i} are the moment of inertia of beams and the distance between columns of spans in the ith story, respectively. θ_{yi}, $M_{\mathrm{yb}i}$ and λ_{i} are the yield drift of the frame, the yield moment of beams and the lateral deformation ratio of columns defined as the ratio of lateral displacement contributed by columns to that of beams, respectively. It is noted that λ_{i} is dependent on the stiffness of both columns and beams and ranges from 0.1 to 0.4 practically (Harris 2006). $M_{\mathrm{yb}i}$ can be obtained with the plain cross section assumption, expressed as

$$M_{\mathrm{ybi}} = W_{\mathrm{bi}} f_{\mathrm{yb}} = 2\frac{I_{\mathrm{bi}}}{d_{\mathrm{bi}}} f_{\mathrm{yb}} \tag{2}$$

where W_{bi}, f_{yb} and d_{bi} are the section modulus, the steel yield strength and the depth of beams in the *i*th story, respectively. Substituting Eq. (2) into Eq. (1), the yield drift of the frame is given by

$$\theta_{\mathrm{yi}} = (\lambda_{\mathrm{i}} + 1)\frac{f_{\mathrm{yb}} l_{\mathrm{i}}}{3Ed_{\mathrm{bi}}} \tag{3}$$

On the other hand, as SSWs deform with rotation of a set of flexural links in panels (Hitaka and Matsui 2003), neglecting the nonlinearity from initial yield to hinge and assuming that slits are uniformly distributed in SSWs, the yield drift of SSWs θ_{pwi} can be estimated as

$$\theta_{\mathrm{pwi}} = \frac{f_{\mathrm{yw}} h_{\mathrm{i}}}{2Eb_{\mathrm{i}}} \tag{4}$$

where f_{yw}, h_{i} and b_{i} are the yield strength, the height of flexural links and the width of flexural links of SSWs in the *i*th story, respectively. Accordingly, the drift of the frame and SSWs can be related by assuming that the system complies with deformation compatibility. To account for the yielding sequence, the story target sequence index is defined and given by

$$\zeta_{\mathrm{ti}} = \frac{\theta_{\mathrm{yi}}}{\theta'_{\mathrm{pwi}}} = (\lambda_{\mathrm{i}} + 1)\frac{2 f_{\mathrm{yb}} l_{\mathrm{i}} b_{\mathrm{i}} h_{\mathrm{si}}}{3 f_{\mathrm{yw}} h_{\mathrm{i}} d_{\mathrm{bi}} H_{\mathrm{i}}} \tag{5a}$$

$$\theta'_{\mathrm{pwi}} = \frac{f_{\mathrm{yw}} h_{\mathrm{i}} H_{\mathrm{i}}}{2Eb_{\mathrm{i}} h_{\mathrm{si}}} \tag{5b}$$

where θ'_{pwi}, H_{i} and h_{si} are the story drift corresponding to the yielding of SSWs, the height of SSWs and the story height in the *i*th story, respectively. Therefore, with proper design of frames and SSWs the damage-control behavior can be achieved by concentrating inelastic deformation in SSWs. As indicated by Eq. (5a), by adjusting the parameters of frame components and SSWs, a larger value of ζ_{ti} can be achieved.

For the entire system, the yielding sequence should be comprehensively studied considering the interaction of structural nonlinearity and ground motion properties. Although the actual yielding sequence caused by ground motions cannot be precisely predicted without nonlinear dynamic analysis, an approach retaining the practical simplicity will be presented next.

2.2 Experimental study

To investigate the damage-control behavior and the performance of the system, experiments with two full scale specimens (TFSSW1 and TFSSW2) incorporating the SSW and surrounding frame components were cyclically tested. Different boundary constraints were considered in two specimens. Specifically, the specimen TFSSW1 was intended to simulate the subassemblies when SSWs were located in the same bay from the bottom floor to the above floor while the specimen TFSSW2 corresponded to cases where SSWs were not arranged continually in vertical direction considering the flexibility of beams. The design of specimens was based on a practical project in china. To ensure the yielding sequence to achieve the damage-control behavior, the configuration

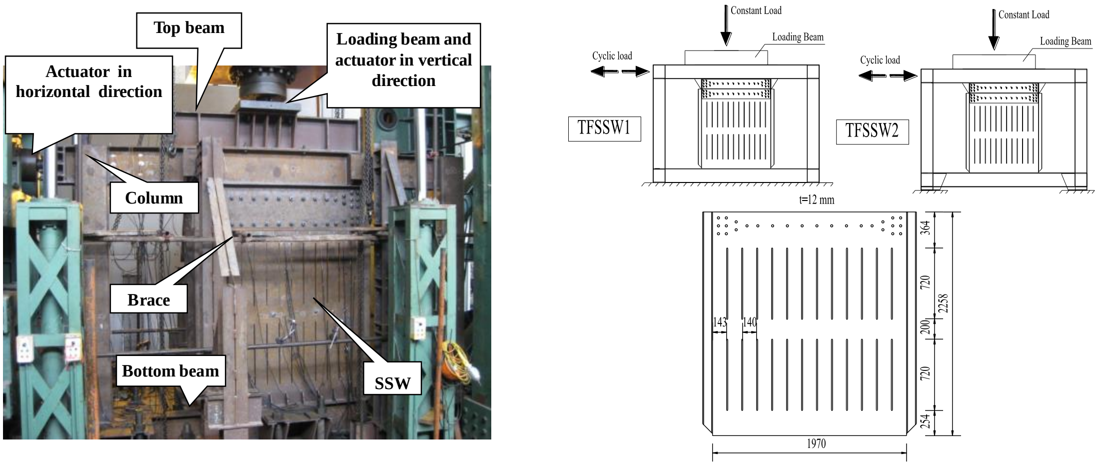


Fig. 3 Test setup and test specimens

Table 1 Dimension and section information of frames in specimens

Beam	Column	**l* (mm)	*h_s (mm)
H400×200×8×13	350×12	4400	2948

*h_s and *l* denote the story height and distance between columns of specimens, respectively.

Table 2 Average values of mechanical properties from coupon tests

Location	Yield strength (MPa)	Ultimate strength (MPa)
SSW	271.4	431.5
Beam flange	383.5	578.6
Beam web	430.7	590.5
Column	423.3	565.0

of the SSWs and the size of the frames were determined to achieve a calculated story target sequence index of 3. Specifically, the SSWs were designed to yield at the story drift of 0.002 and the frame were designed to initiate yielding at the story drift of 0.006. In addition, during the experiment the constant vertical load was considered as 350kN and 650kN for specimen TFSSW1 and TFSSW2, respectively (The value of 300kN was close to the accumulated live load on the bottom floor of a 30-story building).

The specimens were instrumented with strain gauges and displacement transducers. The test setup and slits configuration of the SSW are shown in Fig. 3. The dimension and the section information of the frame are given in Table 1. Considering the yielding sequence of the system, the frame was composed of H-shaped beam and cold-formed square tubular columns with nominal yield strength of 345MPa while the SSW was designed with steel plate with nominal yield strength of 235MPa. The actual values of mechanical properties from coupon tests are given in Table 2.

The hysteretic curves of the specimens are shown in Fig. 4. During load cycles, localized yielding was detected at the story drift of 0.3% (cyclic amplitude of 10 mm) at the end of flexural links in SSWs. At the story drift of 0.7% (cyclic amplitude of 20 mm) the beam began to develop inelastic deformation in the flange as initiation of yielding was detected. The column initiated

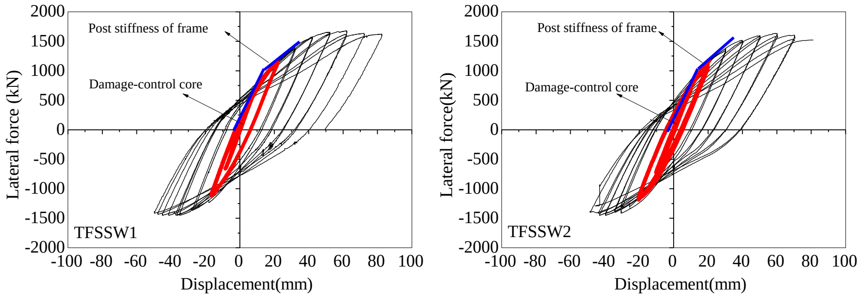
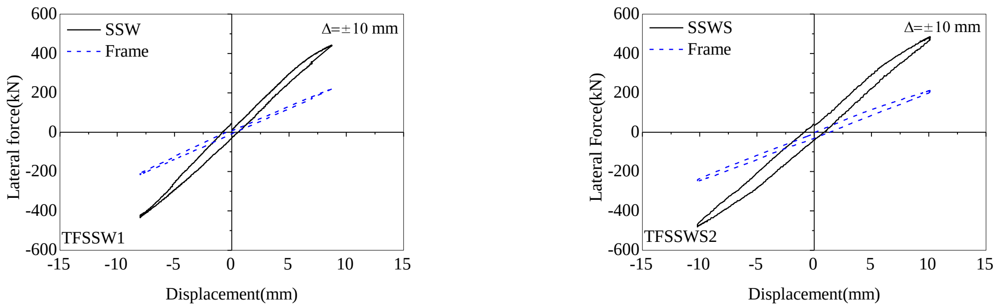
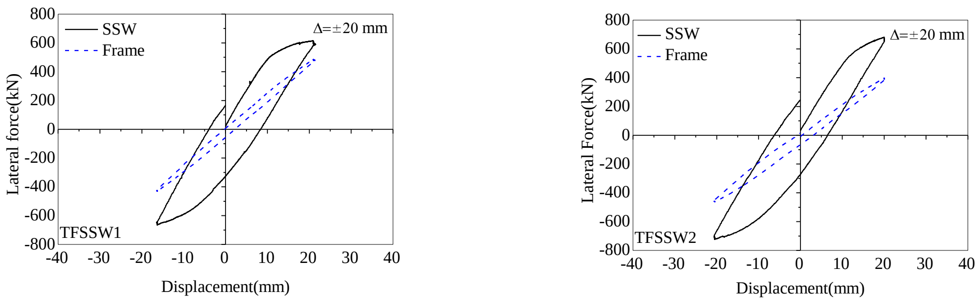


Fig. 4 Load-displacement curves of specimens



(a) 10mm amplitude



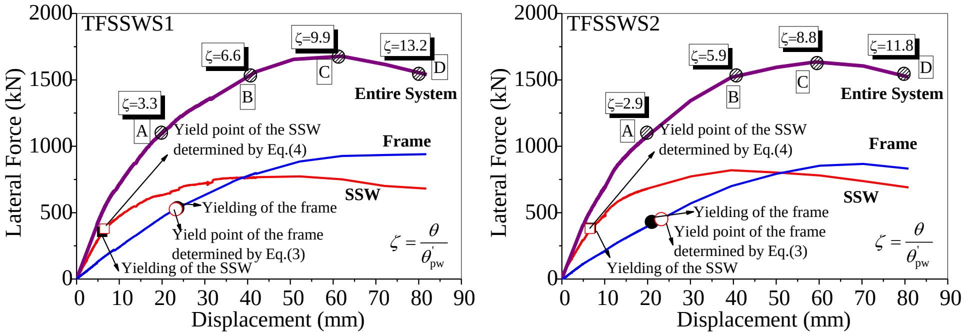
(b) 20mm amplitude

Fig. 5 Hysteretic loop of the frame and the SSW

yielding when the story drift was larger than 1% (cyclic amplitude of 30 mm), and the plastic hinges became visible at the story drift of 2% (cyclic amplitude of 60 mm). Accordingly, the damage-control behavior of the system was achieved by the observed yielding sequence and the damage-control core could be extracted from hysteretic curves.

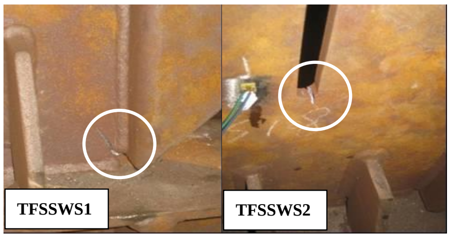
Based on the force equilibrium relationship and the strain gauges arranged on the column sections which deformed elastically during the entire load cycles, the lateral loads taken by the frame and the SSW can be calculated. Thus, the damage-control behavior and the yielding sequence can be further clarified and given by Fig. 5, demonstrating the design concept quite well.

Although this research focuses on the damage-control behavior of the system, it is instructive to clarify the behavior of the specimens after yielding of the frames. The skeleton curves of specimens in the push direction are shown in Fig. 6(a). The essential stages associated with the sequence index (ζ) defined as the ratio of the story drift (θ) to the story drift corresponding to the



(a) Skeleton curves of specimens

A: Initiation of out-plane deformation of flexural links in SSWs

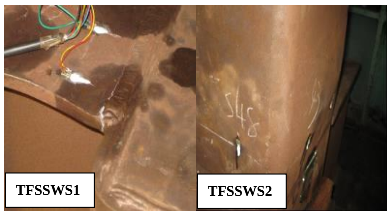


B:Initiation of fracture at slits and bottom of stiffener

C: Development of out-plane deformation of flexural links in SSWs

C:Inelastic buckling of beams

D:Extension of fracture at slits



D:Fracture at beam flanges and inelastic deformation of column base

(b) Damage or failure of specimens in essential stages

Fig. 6 General behavior of specimens

yielding of the SSWs (θ'_{pw}) are identified in the curves, and the associated damage or failure is depicted in the corresponding photos in Fig. 6(b). Over all, two specimens exhibited satisfactory synergetic behavior during the entire load cycles even after the frame began to develop inelastic deformation. Although the out-plane deformation of flexural links and fractures at slits were observed in the SSWs after yielding of frames, the global responses were still stable as the frames can also provide sufficient load carrying capacity. Both specimens reached the peak value of loading carrying capacity at the story drift of 2%, approximately, demonstrating the favorable seismic performance of the system. In addition, the yield points based on previous derivation are also calculated for comparison, as shown in Fig. 6(a). Specifically, the predicted yield points for the SSW and the frame are calculated by Eq. (3) and Eq. (4), respectively, considering the average yield stress from the coupon test. For the yield drift of frames, the lateral deformation ratio of columns is calculated considering the stiffness of beam and the column based on the theory of structural mechanics. Results indicate that the predication exhibits satisfactory accuracy.

3. Energy-based damage-control design and assessment of the system

3.1 The energy balance of the system

As the system exhibits noteworthy features, the critical issue to be solved is a practical approach accounting for its damage-control behavior. Since firstly proposed by Housner (1956), the energy-balance concept has been widely applied to structural evaluation or design. Recently, the energy-balance equation based on elastic-perfectly plastic model was developed and extended to various structures for practical design applications (Lee and Goel 2001, Leelataviwat *et al*. 2009). In view of the energy balance regarding the damage-control behavior, the demanded energy will be provided by the elastic energy of the entire system as well as the plastic energy of SSWs, which can be used for design and evaluation.

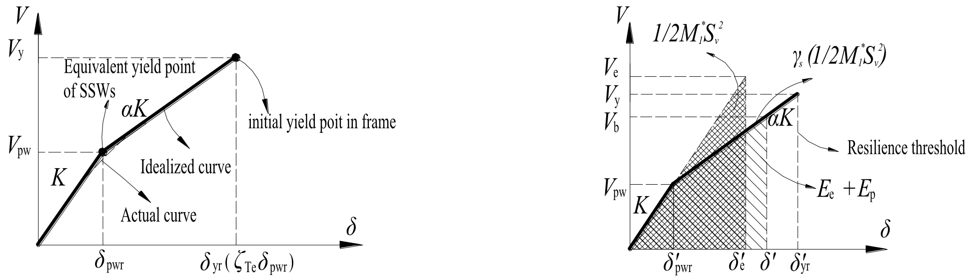
To consider the accuracy of the theory, it is necessary to clarify the underlying assumptions: (1) The structure is dominated by the fundamental mode and the effect of higher modes can be neglected; (2) The mode shape keeps constant in inelastic range. It is noted that these assumptions have been demonstrated to be feasible in low to medium rise structures and they are also the basic assumptions for the widely used pushover analysis for systems dominated by the fundamental mode (Krawinkler and Seneviratna 1998, Fajfar 2000, Chopra and Goel 2002). The accuracy and feasibility are validated by nonlinear dynamic analyses presented next in this paper.

Hence, for a system with the damage-control behavior reflected by the significant post stiffness provided by frame components as illustrated in Fig. 7, the energy-balance equation can be applied considering the energy factor and given by

$$\gamma_{\mathrm{s}}(\frac{1}{2}M_1^{*}S_{\mathrm{v}}^{2}) = E_{\mathrm{e}} + E_{\mathrm{p}} \tag{6}$$

where γ_{s} , M_1^{*} and S_{v} are the energy factor, the effective mass of the fundamental mode and the pseudo-velocity, respectively. The energy factor is defined as the ratio of the energy absorbed by the inelastic system to that of the corresponding elastic system under monotonic loading. E_{e} is the nominal elastic energy and E_{p} is the nominal plastic energy, which can be determined from the load-displacement curve. Therefore, the result of the left-hand side of Eq. (6) can be defined as the nominal energy demand, and the summation of the two components of the right-hand side of Eq. (6) leads to the nominal energy capacity. It is noted that the energy component does not include the cumulative effect of ground motions directly as it is calculated from skeleton pushover curve of the system, but it is still applicable in evaluating the seismic response (Newmark and Hall 1982, Leelataviwat *et al.* 2009, Jiang *et al.* 2010).

To account for the yielding sequence of the entire system, the target sequence index is defined



(a) Idealization of structural yielding sequence (b) Energy-balance of the equivalent SDOF system

Fig. 7 Illustration of the yielding sequence and energy balance of frames with SSWs

and given by

$$\zeta_{\mathrm{T}} = \frac{\delta}{\delta_{\mathrm{pwr}}} \tag{7}$$

where δ is the target roof displacement and δ_{pwr} is the equivalent yield roof displacement of SSWs which can be solved by idealizing the system with a bilinear curve (Fig. 7(a)). Specifically, δ_{pwr} can be confirmed with tangent lines combined with the resilience threshold as approximation and the resilience threshold is determined by the first yield point in the frame, implying that the frame is expected to be totally damage-free during ground motions. Although in structures SSWs will not yield simultaneously and δ_{pwr} is an equivalent feature, this approximation still leads to a conservative estimation. An equivalent target sequence index indicating the resilience threshold for the entire system can be determined as

$$\zeta_{\mathrm{Te}} = \frac{\delta_{\mathrm{yr}}}{\delta_{\mathrm{pwr}}} \tag{8}$$

where δ_{yr} is the yield roof displacement of the frame. When the displacement is below the resilience threshold, the entire system is resilient since the damage is concentrated in SSWs.

Based on the assumption that the system is dominated by the fundamental mode and the premise that the frame remains elastic, the energy-balance relationship can be extended to structural systems as multi-degree-of-freedom (MDOF) systems using equivalent single-degree-of-freedom (SDOF) systems (Leelataviwat *et al.* 2009) as shown in Fig. 7(b). As denoted by the definition of the energy factor, γ_{s} can be solved from Eq. (6) by

$$\gamma_{\mathrm{s}} = \frac{E_{\mathrm{e}} + E_{\mathrm{p}}}{\frac{1}{2} M_1^* S_{\mathrm{v}}^{\,2}} = \frac{\frac{1}{2} V_{\mathrm{pw}} \delta'_{\mathrm{pwr}} + \frac{1}{2} (V_{\mathrm{pw}} + V_{\mathrm{b}})(\delta' - \delta'_{\mathrm{pwr}})}{\frac{1}{2} V_{\mathrm{e}} \delta'_{e}} \tag{9}$$

where V_{pw}, V_{b} and V_{e} are the base shear corresponding to yield of SSWs, the base shear corresponding to the target roof displacement and the base shear of the corresponding elastic system, respectively. It is noted that V_{pw} ,V_{b} and V_{e} are identical to the base shear of the corresponding equivalent SDOF system (Chopra and Goel 2002). δ'_{pwr}, δ' and δ'_{e} are the displacements of the corresponding equivalent SDOF system (Fig. 7(b)), and can be calculated as follows

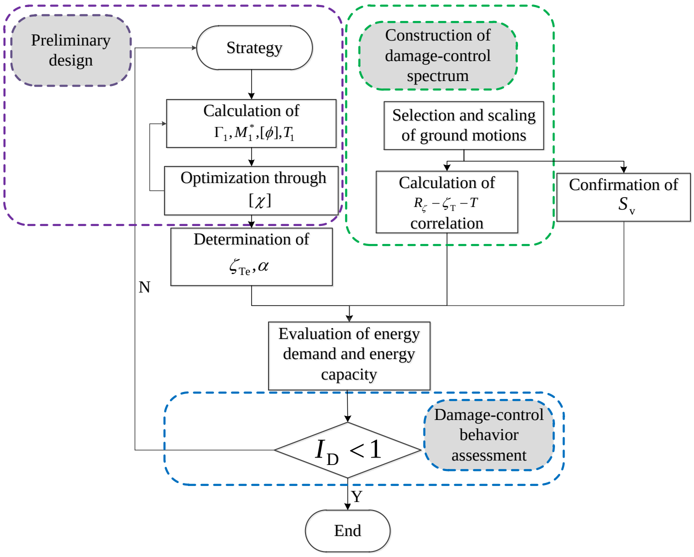


Fig. 8 Flow chart of energy-based damage-control design and assessment procedure of systems

$$\delta'_{pwr} = \frac{\delta_{pwr}}{\Gamma_1 \varphi_r} \tag{10a}$$

$$\delta' = \frac{\delta}{\Gamma_1 \varphi_r} \tag{10b}$$

$$\delta'_e = \frac{\delta_e}{\Gamma_1 \varphi_r} \tag{10c}$$

where Γ_1 , φ_r and δ_e are the participation factor of the fundamental mode, the roof element of the modal vector corresponding to the fundamental mode, and the maximum roof displacement of the corresponding elastic system, respectively. Therefore, with the application of the equivalent SDOF system, the energy factor for steel frames with SSWs can be determined by substituting Eq. (7) and Eq. (10) into Eq. (9) and given as follows

$$\gamma_s = \frac{2\zeta_T - 1 + \alpha(\zeta_T - 1)^2}{R_\zeta^2} \tag{11a}$$

$$R_\zeta = \frac{V_e}{V_{pw}} \tag{11b}$$

where R_ζ is the strength reduction factor and α is the hardening ratio defined by the post stiffness provided by the frame to the initial stiffness.

3.2 Practical procedure for energy-based design and damage-control assessment

Based on the energy balance and the yielding sequence of systems, a practical procedure that focuses on the design and assessment of the system can be determined consequently. The critical steps of the proposal are illustrated by the flow chart given in Fig. 8, and the details of the procedure are described as below.

3.2.1 Preliminary design of the system considering yielding sequence

In this step, the yielding sequence can be adjusted. Although it is not rigorous compared with nonlinear dynamic analysis, this step still provides practical starting point as the preliminary design step. For a structure with *r* stories, as the resilience threshold is determined by the first yield location in the frame, it is expected that SSWs in all stories can develop inelastic deformation sufficiently before yielding of the frame. Accepting the assumptions stated above, the displacement profile can be estimated with the modal vector of the fundamental mode (Harris 2006, Priestly 2003), and a sequence vector to optimize the yielding sequence of the system can be derived and given by

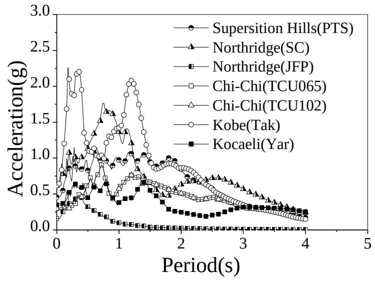
$$[\chi]=(\frac{\varphi_2-\varphi_1}{\zeta_{t1}\theta_{pw1}},\frac{\varphi_3-\varphi_2}{\zeta_{t2}\theta_{pw2}}....\frac{\varphi_r-\varphi_{r-1}}{\zeta_{tr}\theta_{pwr}})^{T} \tag{12}$$

where φ_i (i=1,2,3…r) is the element of the modal vector corresponding to the fundamental mode and $[\chi]$ is the sequence vector, which employs the influence of non-uniform distribution of the drift and the elastic deformation capacity of all stories. Iteration is generally needed to optimize the yielding sequence and an optimized design can be achieved with adjustment of structural components to attain a uniform distribution of elements in $[\chi]$. The recent proposed simplified models of SSWs and the structural analysis method (Hitaka *et al.* 2007, Cortes and Liu 2011) render this procedure viable. In addition, applications of steel with various strengths as well as flexibility of slits configuration also make the yielding sequence design flexible in engineering practice. It is noted that although this procedure is an estimation due to the influence of λ_i which is arbitrary and dependent on actual design, a conservative value can be used, while the equivalent target sequence index of the entire system can be confirmed with the pushover analysis.

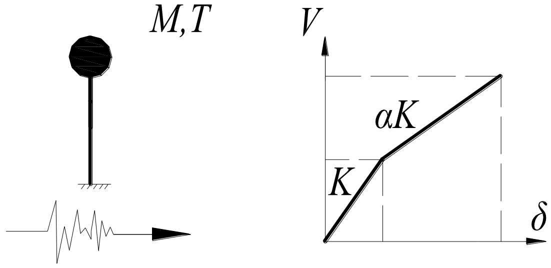
3.2.2 Construction of damage-control spectrum

As the energy factor is still dependent on the correlation between ζ_T and R_ζ, a R_ζ-ζ_T-T spectrum is needed. Compared with the conventional approach focusing on the ultimate state, the motive of damage-control design requires a more precise estimation of structural response for the purpose of resilience. Accordingly, in this study, based on a series of SDOF systems, the correlation of R_ζ-ζ_T-T defined as the damage-control spectrum is constructed incorporating the effect of the post stiffness as well as the yielding sequence of the system, and the target sequence index can be addressed in form of ductility. The damping ratio is assumed to be 5%. As the main purpose is to validate the presented theory and approach, in this research the damage-control spectrum is constructed based on a group of near-fault ground motions (Kalkan and Chopra 2011) scaled to PGA of 0.2g, and they are assumed to be representatives at a given site practically (Fig. 9).

The damage-control spectra corresponding to different values of α and ζ_T are illustrated in Fig. 10 with the mean values of strength reduction factors (R_ζ) calculated from selected ground motions. Compared with elastic-perfectly plastic systems, values of R_ζ are significantly larger in short period regions while the trend is reversed in long period regions. When the hardening ratio is sufficiently large, R_ζ almost remains constant regardless of period variation since it is getting nearer to totally elastic behavior. Considering that R_ζ is a square component in calculating the energy factor, it is believed to be more sensitive in the energy balance of structural systems. With



(a) Acceleration spectrum of ground motions



(b) SDOF system considering post stiffness

Fig. 9 Construction of damage-control spectrum

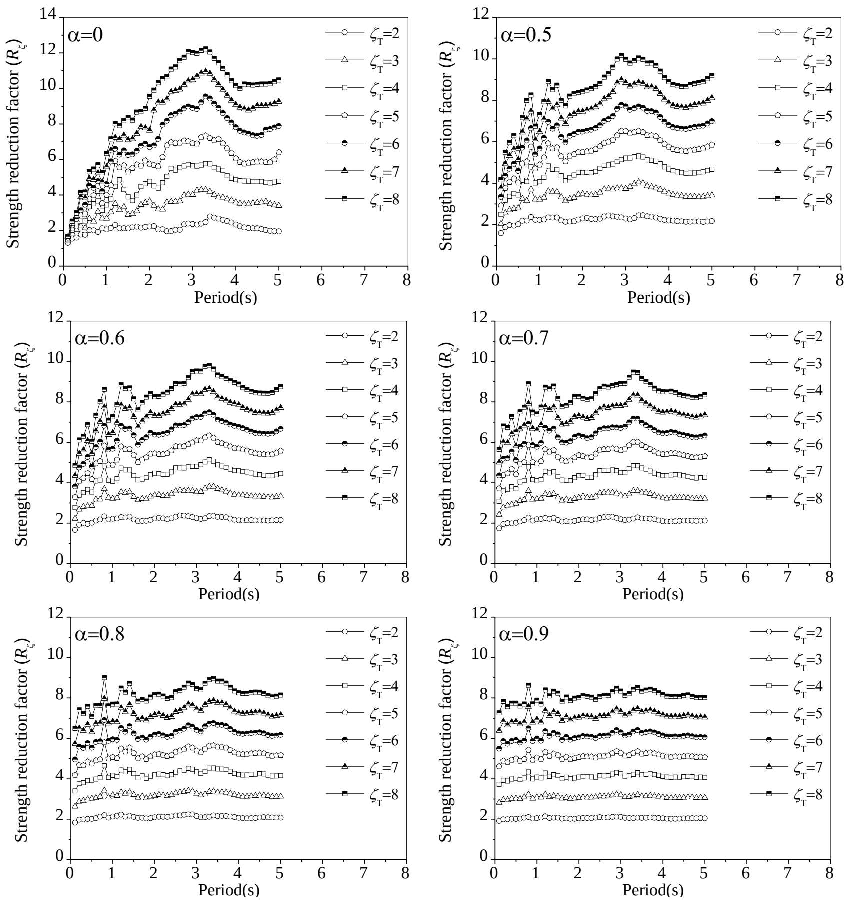


Fig. 10 R_ζ-ζ_T-T correlation considering post stiffness

the correlation of R_ζ and ζ_T, the energy factor can be determined consequently.

3.2.3 Damage-control behavior assessment

As the damage-control behavior can be reflected in the perspective of energy equilibrium, a damage-control index defined as the ratio of the nominal energy demand of the inelastic system to

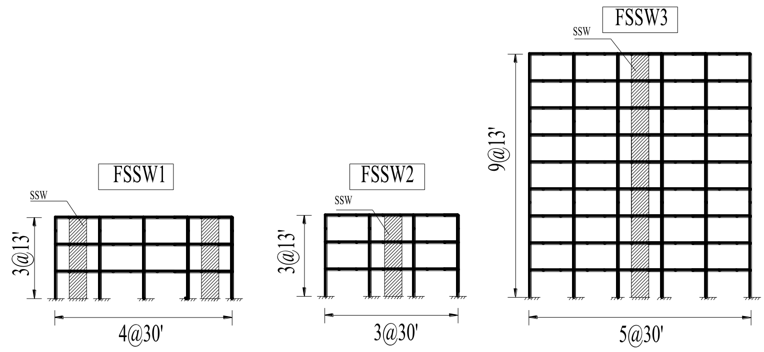


Fig. 11 Example steel frames with SSWs

Table 3 Beam and column sections of frames

	FSSW1 and FSSW2			FSSW3		
Story	Exterior Column	Interior Column	Beam	Exterior Column	Interior Column	Beam
1	W14×257	W14×311	W33×118	W14×370	W14×500	W36×160
2	W14×257	W14×311	W30×116	W14×370	W14×455	W36×160
3	W14×257	W14×311	W24×68	W14×370	W14×455	W36×135
4	-	-	-	W14×283	W14×370	W36×135
5	-	-	-	W14×283	W14×370	W36×135
6	-	-	-	W14×257	W14×283	W36×135
7	-	-	-	W14×257	W14×283	W30×99
8	-	-	-	W14×233	W14×257	W27×84
9	-	-	-	W14×233	W14×257	W24×68

that of the nominal energy capacity at the resilience threshold can be constructed and given by

$$I_{\mathrm{D}} = \frac{[2\zeta_{\mathrm{Te}} - 1 + \alpha(\zeta_{\mathrm{Te}} - 1)^2] M_1^* S_v^2}{2R_\zeta^2 E_a} \tag{13}$$

where I_{D} and E_{a} are the proposed damage-control index and the nominal energy capacity of system at the resilience threshold, respectively. Following the assumptions stated above, the nominal energy capacity, which is identical to the absorbed energy of the equivalent SDOF system at the resilience threshold, can be obtained by calculating the work done by applied forces. This can be determined from pushover analysis and given by

$$E_a = \frac{S}{\Gamma_1 \varphi_r} \tag{14}$$

where S is the area covered by pushover curve below the resilience threshold. When the solved index is smaller than 1, indicating that the nominal energy capacity is larger than the nominal energy demand at the resilience threshold, the system is resilient to achieve the damage-control behavior and the plastic energy corresponding to damage is concentrated in SSWs.

As revealed by Eq. (13), the damage-control behavior is essentially dependent on the yielding

Table 4 Constitution of steel slit walls in models

	H_i(mm)	W_i(mm)	b_i(mm)	h_i(mm)	t_i(mm)
SSW	3000	2000	188	800	14

Table 5 Dynamic properties of example structures

Model	*T_1 (s)	*T_2 (s)	M_1* (t)	participation mass ratio of fundamental mode
FSSW1	0.597	0.204	1175.6	0.99
FSSW2	0.678	0.230	874	0.99
FSSW3	1.968	0.728	3650	0.81

* T_1 and T_2 are the periods of fundamental mode and second mode, respectively.

sequence, the post stiffness and properties of the input ground motions. This will be validated by case studies presented next.

4. Application of the approach to example structures

4.1 FEA model of buildings

In this section, three steel frames with SSWs are established with ABAQUS, in which the frame are modeled with beam elements and SSWs are constructed with shell elements. These structures are preliminarily designed based on the Code for seismic design of buildings (GB50011) (2010). Important features used to conduct the design are Group 1, site Ⅳ and seismic precautionary intensity of 7. It is noted that the yielding sequence does not directly depend on the relative strength of SSWs and frame components because they work as a parallel system and comply with the deformation compatibility. Accordingly, in the preliminary design a displacement-based procedure based on the derivation stated above is used to determine the size and strength of the components to achieve the expected yielding sequence. All beams are assumed of yield strength with 250 MPa and all columns are assumed to be 345 MPa. SSWs are installed with assumed yield strength of 100 MPa. The configuration of SSWs regarding the aspect ratio of flexural links and the slits length is chosen based on the recommended range proposed by Cortes and Liu (2011b), and the yield drift of SSWs is determined based on the recommended value of Nakashima *et al.* (1996). The sections of frame components is modified based on the frames used by Gupta and Krawinkler (1999). The arrangement of example structures are indicated in Fig. 11. The section information and constitution of SSWs are given in Table 3 and Table 4. An elastic-plastic behavior of 2% hardening is considered and a damping ratio of 5% is considered for the fundamental and the second mode. The connections of the frame and SSWs are assumed to be elastic. In this analysis the nonlinearity of gravity load is not considered (Chou and Uang 2003). Because the objective is to validate the accuracy of the assessment approach which is not dependent on particular structural design, it is assumed that the arrangements of example structures are rational.

4.2 Assessment of the damage-control behavior

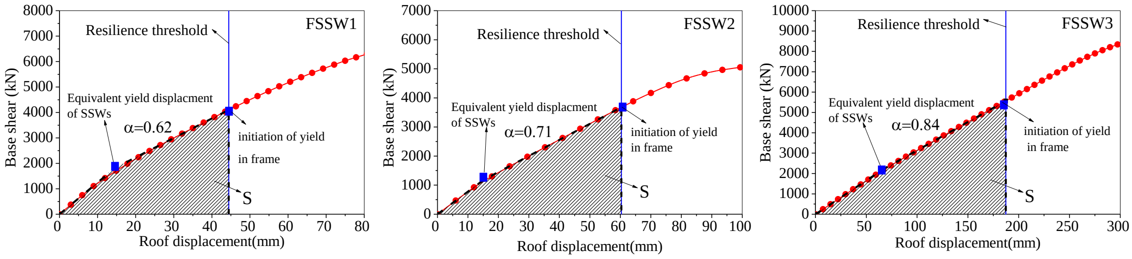


Fig. 12 Pushover curves of structures

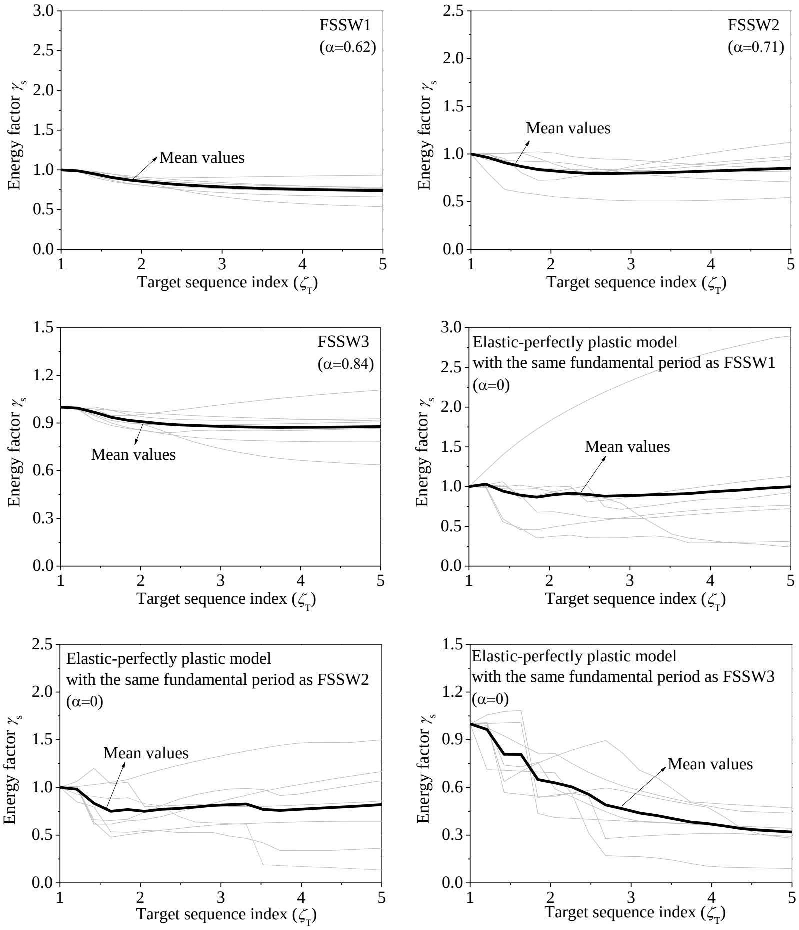


Fig. 13 Comparison of the energy factors determined from different models

To confirm the equivalent target sequence index of the system, pushover analysis is carried out considering the fundamental mode. The pushover curves of structure are given in Fig. 12 and dynamic properties are given in Table 5. The nominal energy capacity can be calculated accordingly by Eq. (14) with the areas (S) covered by the pushover curves illustrated by shaded parts in Fig. 12.

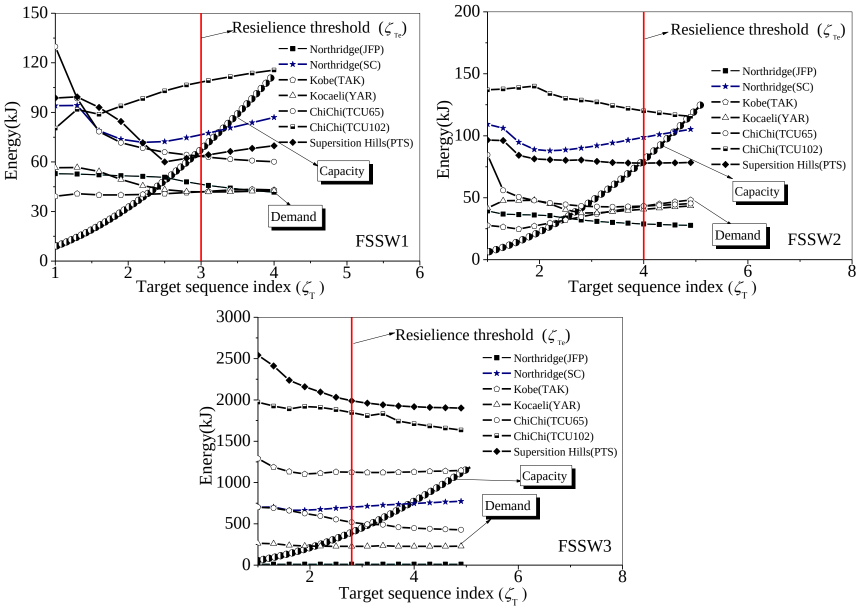


Fig. 14 Correlation of the nominal energy demand and the nominal energy capacity

Considering the significance of the post stiffness, it would be instructive to make comparison of the system with the post stiffness and the conventional idealized elastic-perfectly plastic model. In this study, based on the elastic dynamic properties of example structures, energy factors of elastic-perfectly plastic models of the identical fundamental period as that of the example structures are also determined to evaluate the sensitivity of the post stiffness, and the results are plotted in Fig. 13.

As indicated by the results calculated from selected ground motions, in most cases the example structures of relatively larger post stiffness will hold a higher requirement of the nominal energy demand as implied by larger mean values of energy factors compared with the elastic-perfectly plastic models. On the other hand, it is observed that the elastic-perfectly plastic systems may lead to a remarkable increase of dispersion regarding the energy factors. In contrast, the dispersion of energy factors for systems with relatively larger post stiffness during different ground motions is not significant, which indicates that a more stable energy balance mode is achieved. This phenomenon essentially implies that systems employing yielding sequence and post stiffness will improve the structural seismic behavior since the dispersion caused by the interaction of ground motions and structural nonlinearity can be reduced.

To associate the demand with the capacity of the systems during ground motions, the energy balance relationship of example structures can be directly illustrated by the nominal energy demand curves and the nominal energy capacity curves as shown in Fig. 14. For nominal energy demand curves, they are results of the left-hand side of Eq. (6) and the values of the energy factor varying with the target sequence index. For the nominal energy capacity curves, they are determined from the pushover curves by calculating the work done by applied forces associated with the target sequence index. As can be seen, the damage-control behavior check can be clarified by intersection point of the demand curves and the capacity curves below the resilience threshold determined by the equivalent target sequence index. For systems that can sustain damage in SSWs to achieve the damage-control behavior, the intersection of the nominal energy demand curves and the nominal energy capacity curves can be obtained under the equivalent target sequence index, indicating that the systems can provide redundant energy absorption capacity required by input ground motions before the frame develops inelastic deformation. Comparatively, for systems that cannot achieve the damage-control behavior, there will be no intersection point obtained below the resilience threshold, implying that the frame is expected to develop inelastic deformation to reach the energy balance. It is should be noted that although in general the nominal energy demand will decrease with the development of inelastic deformation, there are cases in which the demand increases as the sequence index becomes larger, which was also observed by Jiang *et al*.(2010), and it is believed to be a characteristic of near-fault ground motions with fling-step pulses.

4.3 Verification of the proposed approach

The calculated damage-control indexes given by Eq. (13) and the plastic energy dissipated by the frames calculated by nonlinear dynamic analyses are compared and plotted in Fig. 15 (No plastic energy is dissipated by frames in cases where I_D<1). As a parametric study, the damage-

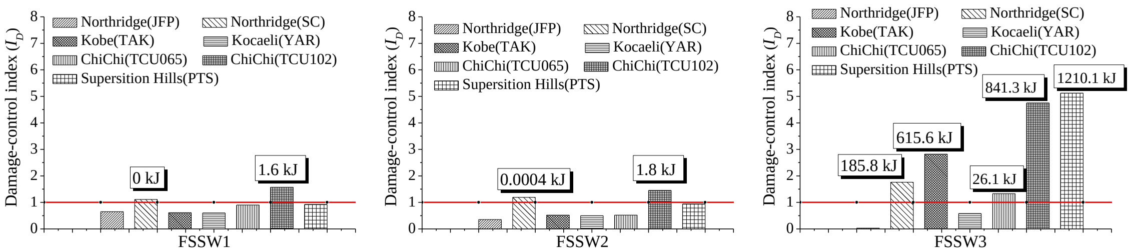


Fig. 15 Damage-control index and plastic energy extracted from nonlinear dynamic analyses

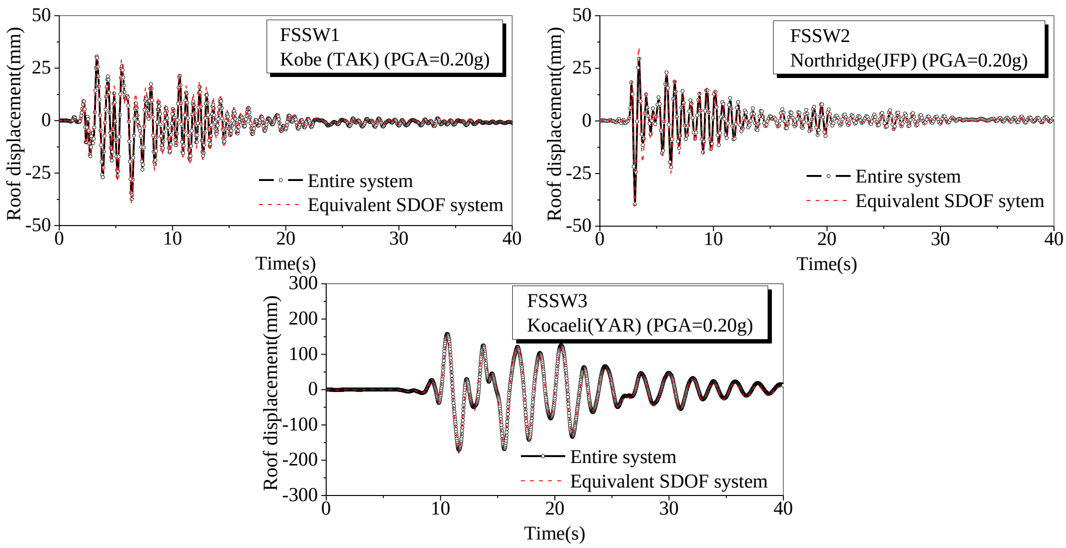


Fig. 16 Roof displacement response from nonlinear dynamic analysis of example structures and the ones from equivalent SDOF systems

control indexes are calculated corresponding to the selected ground motions respectively. The results indicate that the damage-control index can be used to estimate the damage-control behavior and reflect the damage severity with satisfactory accuracy. Practically, the resilience can be further enhanced to design the frame with more flexibility and increase the number of SSWs to maintain the required stiffness.

To validate the applicability of the assumptions used in this research, nonlinear dynamic analyses are carried out based on the equivalent SDOF systems with the feature of the fundamental mode (the effective mass, the base shear corresponding to yield of SSWs, the period and the post stiffness respectively). The displacement responses are compared with that of structural systems and plotted in Fig. 16. The results imply that the equivalent SDOF systems based on the fundamental mode can simulate the response of entire system quite well even in the inelastic range, demonstrating the applicability of assumptions adopted in this study.

As the approach provides satisfactory accuracy in evaluating the response, retaining the calculation simplicity, it is believed to be applicable in design of the system with higher efficiency before conducting the nonlinear dynamic analysis, particularly for low to medium rise systems dominated by the fundamental mode. Parameters of frame components and the SSWs can be adjusted to achieve the damage-control behavior during expected ground motions.

It is noted that the primary motive of defining the resilience threshold with the target that the frame keeps totally elastic is to validate the accuracy of the proposed approach, and it is believed to be feasible in regions of low or moderate seismicity. For regions of high seismicity, an alternative to ensure the damage-control behavior is to employ low-yield point steel as SSWs and high strength steel as frame members with slender sections to ensure the expected yielding sequence. This concept has been validated theoretically and experimentally in recent research (Wada *et al.* 1992).

5. Conclusions

This study focuses on damage-control design and assessment approach of steel frames with steel slit walls (SSWs). Analyses and experiments are carried out to verify the proposed theory and concepts. The results show that the damage-control behavior can be realized with explicit consideration of the yielding sequence by adjusting the structural components. The developed procedure based on the energy-balance considering the interaction of systematic nonlinear behavior and ground motions can account for the damage-control behavior quantitatively with provided input excitations. The comparison of the responses of three example structures and the prediction of the proposed approach shows attractive accuracy, demonstrating the applicability of the proposed approach. The energy responses of systems also imply that systems employing yielding sequence and post stiffness behave more stably compared with conventional elastic-perfectly plastic systems.

In essence, the system of steel frames with SSWs can be designed and assessed with a more rational approach, incorporating the damage-control behavior. Furthermore, compared with conventional approach focusing on the ultimate state considering the ductility, the approach is also believed to be more precise. Though the proposed approach in this research is established based on the fundamental mode with assumptions, it is thought to be applicable in evaluating low to medium rise buildings, retaining attractive efficiency before performing the nonlinear dynamic analysis. In addition, as the approach regarding the damage-control behavior check is established considering the dynamic properties of system, it is also believed to be applicable in various structures for damage-control assessment and resilience enhancement.

Acknowledgments

This research is supported by National Science Foundation of China (Grant No.51038008).

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