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Energy-factor-based damage-control evaluation of steel MRF systems with fuses

Ke Ke [*1,2] and Michael C.H. Yam [3a]

[1] *State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China*
[2] *College of Civil Engineering, Tongji University, Shanghai 200092, China*
[3] *Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*

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Abstract. The primary objectives of this research are to investigate the energy factor response of steel moment resisting frame (MRF) systems equipped with fuses subject to ground motions and to develop an energy-based evaluation approach for evaluating the damage-control behavior of the system. First, the energy factor of steel MRF systems with fuses below the resilience threshold is derived utilizing the energy balance equation considering bilinear oscillators with significant post-yielding stiffness ratio, and the effect of structural nonlinearity on the energy factor is investigated by conducting a parametric study covering a wide range of parameters. A practical transformation approach is also proposed to associate the energy factor of steel MRF systems with fuses with classic design spectra based on elasto-plastic systems. Then, the energy balance is extended to structural systems, and an energy-based procedure for damage-control evaluation is proposed and a damage-control index is also derived. The approach is then applied to two types of steel MRF systems with fuses to explore the applicability for quantifying the damage-control behavior. The rationality of the proposed approach and the accuracy for identifying the damage-control behavior are demonstrated by nonlinear static analyses and incremental dynamic analyses utilizing prototype structures.

Keywords: steel moment resisting frame system; structural fuse; damage-control; energy factor; single-degree-of-freedom system; evaluation approach

1. Introduction

Seismic resistant structures that are designed according to the conventional ductile based design methodology may experience distributed damages in all members after a major seismic event, leading to unacceptable cost for repairing works or even demolishing the entire structure. For instance, a steel moment resisting frame (MRF) structure or a steel MRF with buckling restrained braces designed following current provisions would have a high potential for being a total economic loss even based on the design based earthquakes with the expected permanent residual deformation (Erochko *et al.* 2011). In this regard, many efforts have been made in the field of enhancing the seismic performance of conventional seismic resistant systems. A practical

*Corresponding author, Professor, E-mail: 1keke@tongji.edu.cn
[a] Associate Professor, E-mail: michael.yam@polyu.edu.hk

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alternative is to install sacrificial energy dissipation fuses in a structure, which can provide plastic energy dissipation stably under seismic actions and protect the remaining structure from inelastic damages in the expected deformation range. For instance, the effectiveness of frictional sliding fuses for mitigating seismic damages of concrete infilled frames was investigated by Mohammadi-Gh and Akrami (2010). Kheyroddin *et al*. (2016) conducted experimental works on the behavior of weak reinforced concrete beam-to-column joints strengthened by fused steel props. In parallel with these research works, recent research interests have also been directed to innovative steel MRF systems equipped with energy dissipation fuses (Vargas and Bruneau 2009a, b), since the damage-control behavior (Wada *et al*. 1992, Connor *et al*. 1997, Ke and Chen 2014) that restricts plastic deformation within these fuses can enhance the seismic performance of the system and save repair efforts after a shock. For instance, when buckling restrained braces (Vargas and Bruneau 2009a, b), steel shear panels (De Matteis *et al*. 2003), or specialized fuse detail in the energy dissipation beams (Calado *et al*. 2013, Dougka *et al*. 2014a, b) are implemented in a steel MRF system and designed to dissipate energy before damaging of frame members, the encouraging performance is achieved with the stable energy dissipation of these fuses for their early yielding behavior. Further, when additional devices that can enhance the re-centering behavior are installed in the structure, such as shape memory alloy devices (Fang *et al*. 2014, Wang *et al*. 2015, Yam *et al*. 2015), the residual deformation can be further mitigated, and the desirable performance of a steel MRF structure can be achieved under seismic actions.

Although the design concept has been validated by extensive investigations, the expansion of these innovative steel MRF systems with fuses in practice still requires the quantification of the damage-control behavior considering an entire system for seismic resilience design (Cimellaro *et al*. 2010) motives. Importantly, an applicable approach to identify potential damage of frame members subjected to a ground motion retaining computational attractiveness and conceptual simplicity is in need. In the perspective of energy (Trifunac 2008), the damage-control behavior of steel MRF systems with fuses can be quantified with the energy balance of input of excitations and the energy absorption of the system without damaging (or only slightly damaging) of frame members, which can involve the feature of strength and deformation simultaneously. Recent research works (Leelataviwat *et al*. 2002, 2009, Jiang *et al*. 2010) also imply that the direct application of energy balance is rational for capturing the essence of structural responses subject to ground motions, and the quantity of energy is a reliable index for featuring the structural damage (Moradipour *et al*. 2015). The principal objectives of this study are to investigate the seismic response of steel MRF systems with fuses focusing on the energy factor determined from a modified energy balance equation and to develop an energy-based approach for structural damage-control evaluations. First, damage-control behavior of a steel MRF system with fuses is clarified based on recent laboratory investigations of typical steel MRF structures equipped with fuses, and nonlinear features are quantified. Based on the concept of damage-control single-degree-of-freedom (DC-SDOF) systems that can be used as the reliable tool for analyzing the seismic response of these structures, the energy factor is derived based on the modified energy balance equation. Then, nonlinear dynamic analyses of the DC-SDOF systems are performed with an ensemble of ground motions, and the energy factor response is studied. Recognizing the inconsistency of the energy factor determined from applying the conventional energy factor spectra of elasto-plastic systems in DC-SDOF systems with significant post-yielding stiffness ratio, a practical transformation approach is proposed to associate the energy factor of DC-SDOF systems with elasto-plastic systems. Subsequently, the energy balance equation is extended to structural systems to build a damage-control evaluation approach. A damage-control index is also derived. Lastly, the proposed approach is applied to two types of steel MRF with fuses, specifically, steel MRF systems with energy dissipation beams as fuses and steel MRF systems with steel slit walls as fuses. The accuracy of the approach for identifying damages in frame members under expected ground motions is validated by analyses of prototype structures.

2. Damage-control behavior of steel MRF systems with fuses and concept of DC-SDOF systems

For a steel MRF system installed with fuses, the damage-control behavior is realized by the inelastic deformation of fuse elements and the elastic deformation of the frame members under seismic actions. This behavior is reflected by the structural yielding sequence. A typical pushover curve and a hysteretic curve of the system are shown in Fig. 1. When the additional re-centering devices such as post-tension strings or shape memory alloy connections are not installed, the yielding sequence favorably accommodates a damage-control core (DCC) following the bilinear kinematic law with significant post-yielding stiffness ratio into the hysteretic curve. If the deformation is restricted in the DCC, plastic energy corresponding to damage is concentrated in the fuse elements, and the frame members can stay damage-free by deforming elastically within an expected deformation range. In this research, the displacement corresponding to the initial yielding of the frame members is defined as the resilience threshold. When the displacement is below this threshold, the system is functionally resilient, as the repair work can be easily accomplished by replacing damaged fuses. This behavior has been validated by recent experimental studies of representative systems, in particular, a steel frame with energy dissipation beams as fuses (Ke and Chen 2016) and a steel frame equipped with the steel slit wall (SSW) (Ke and Chen 2014) as illustrated in Figs. 2~4. For a pure steel MRF, pre-selected energy dissipation beams are expected to be the "fuse beams" by yielding prior to damaging of the remaining members, which can be realized by the proper determination of member sizes and strength grades of the material. The other system is the steel MRF system implemented with steel slit walls (SSWs), in which SSWs are designed to be the structural fuses. Experimental results show that the yielding sequence of the frame members and the fuse elements makes the energy dissipation beams and SSW functional fuses, and the DCC can be extracted from the hysteretic curve (Figs. 3(b) and 4(b)). In addition, the satisfactory agreement between the test curves and the bilinear kinematic model curves with significant post-yielding stiffness ratio validates the applicability of the theoretical model for quantifying the damage-control behavior of steel MRF with fuses.

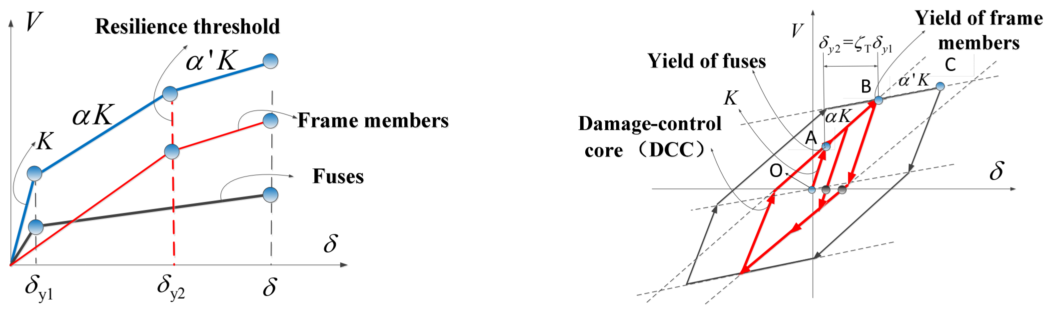
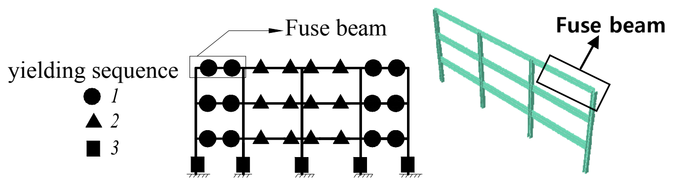
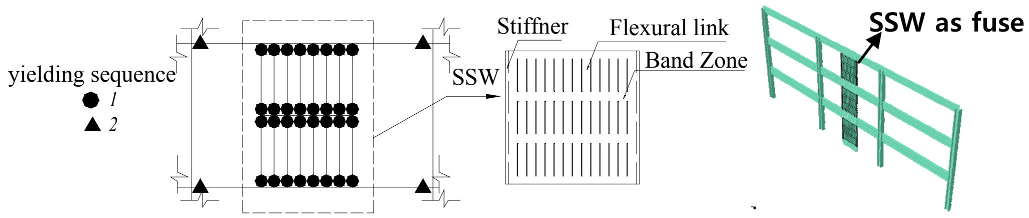


Fig. 1 Behavior and yielding sequence of steel MRF systems with fuses

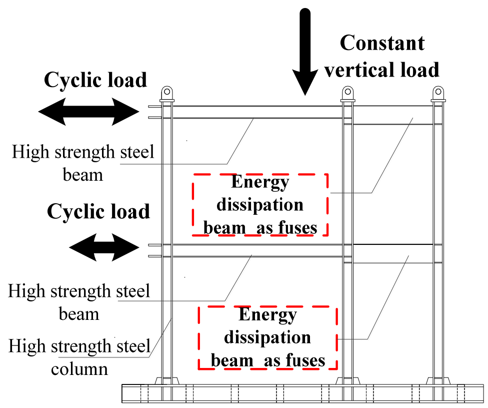


(a) Steel MRF system with energy dissipation beams as "fuse beams"

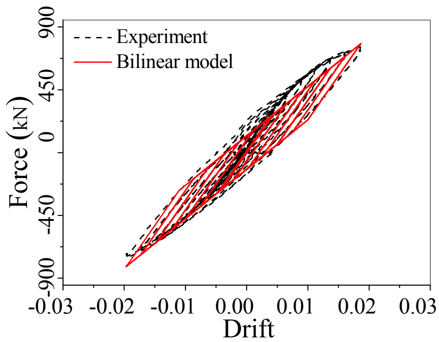


(b) Steel MRF system with SSWs as fuses

Fig. 2 Typical steel MRF systems with fuses



(a) Test specimen



(b) Experimental hysteretic curve as the damage-control core (DCC)

Fig. 3 Test specimen and results of steel MRF with energy dissipation beams as fuses

A single-degree-of-freedom system with the applicable hysteretic behavior (Li and Fahnestock 2012, Park 2013) can be used to reasonably evaluate the structural seismic response. Therefore, a bilinear oscillator with significant post-yielding stiffness ratio defined as the damage-control single-degree-of-freedom (DC-SDOF) system can be used to analyze seismic responses of steel MRF systems with fuses, since the ultimate state is not in the scope of this research. The post-yielding stiffness ratio (α) defined by the ratio of the post-yielding stiffness to the initial stiffness of the system can be introduced, as plotted in Fig. 5. Note that although the seismic response of bilinear system has been investigated extensively, most works, to a large extent, are limited to bilinear models of negligible post-yielding stiffness ratio (Zahrah and Hall 1984, Lee *et al.* 1999, Hatzigeorgiou 2010), information about systems of considerable post-yielding stiffness ratio which features the behavior of steel MRF systems with fuses below the resilience threshold, particularly research on the energy balance, is still limited. Thus, the necessity of this research is highlighted.

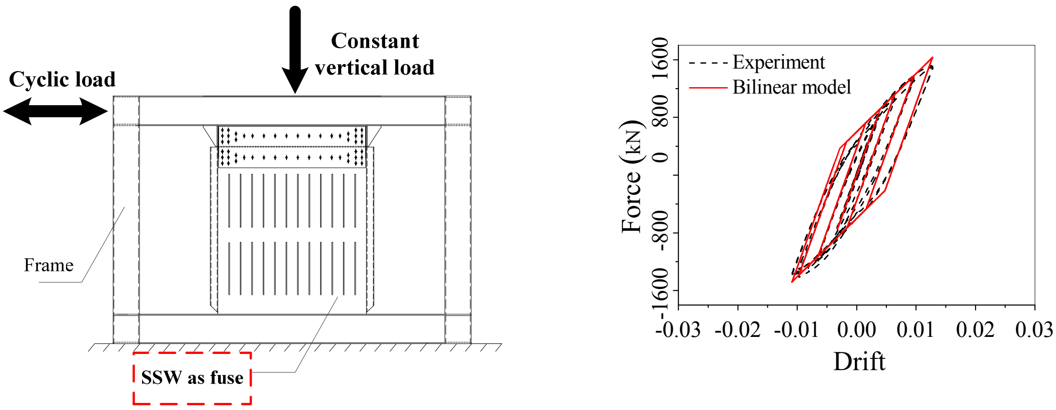
To quantify the yielding sequence and the damage-control behavior, a target sequence factor is defined and given by

$$\zeta = \frac{\delta}{\delta_{y1}} \tag{1a}$$

where δ_{y1} and δ are defined as the first yield displacement determined by yielding of the fuses and an expected target displacement, respectively. The target sequence factor at the resilience threshold is then given by

$$\zeta_{\mathrm{T}} = \frac{\delta_{y2}}{\delta_{y1}} \tag{1b}$$

where δ_{y2} is the second yield displacement determined by the initial yield point of the frame system. This index is defined to distinguish it from the concept of ductility because the latter is generally used for the ultimate state evaluation and is calculated with equivalency. Therefore, the sequence



(a) Test specimen

(b) Experimental hysteretic curve as the damage-control core (DCC)

Fig. 4 Test specimen and results of typical steel MRF with SSW as fuses

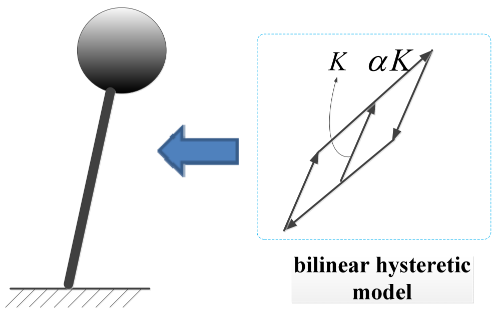


Fig. 5 Concept of damage-control single-degree-of-freedom (DC-SDOF) system

factor is introduced, and the shape of the DCC can be quantified with ζ_T denoting the resilience threshold and α.

3. Seismic Energy Balance And Energy Factor of a DC-SDOF system

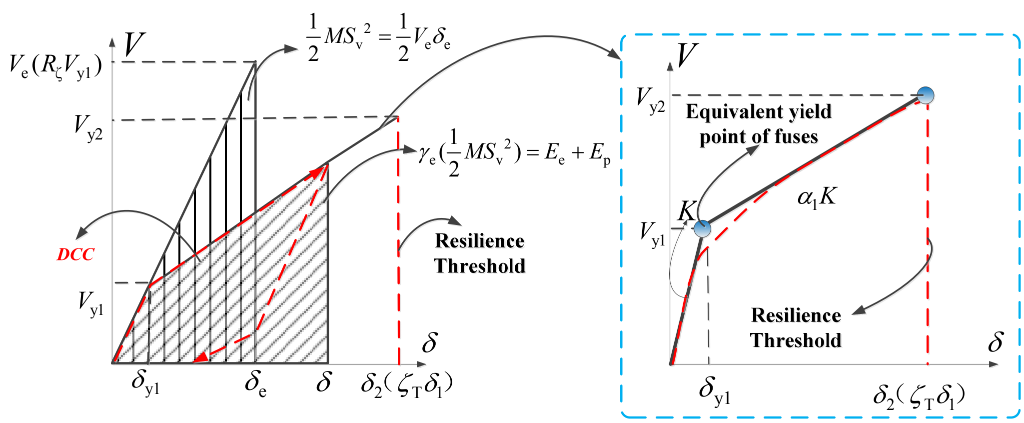
3.1 Energy balance of DC-SDOF systems

Essentially, the response of systems subjected to ground motions can be featured in terms of energy balance. Because available studies on seismic energy balance of systems are generally established based on an idealized model (Leelataviwat *et al*. 2009, Kharmale and Ghosh 2013, Pekcan *et al*. 2014, Wongpakdee *et al*. 2014) considering an elasto-plastic single-degree-of-freedom (EPSDOF) system of zero post-yielding stiffness, which may not be applicable for systems with fuses considering significant post-yielding stiffness ratio, a modified energy balance focusing on the DCC is established in this research. Specifically, a balance equation can be established based on the skeleton curve of the system associated with the corresponding elastic system plotted in Fig. 6. Note that although the actual nonlinear curve is not completely bilinear as inelasticity of a system develops progressively, the idealization can be achieved with tangent lines based on the displacement point denoting the resilience threshold (see Fig. 6(b)).

The nominal absorbed energy defined as the area under the monotonic pushover curve can be directly solved using Eq. (2)

$$E_a = E_e + E_p = \frac{1}{2}V_{y1}\delta_{y1} + (\zeta - 1)V_{y1}\delta_{y1} + \frac{1}{2}(\zeta - 1)^2 \alpha V_{y1}\delta_{y1} \tag{2}$$

where E_a is the nominal absorbed energy consisting of the nominal elastic energy (E_e) and the nominal plastic energy (E_p); V_{y1} is the shear force corresponding to the yield of the fuses. Note that for a structural system, this quantity can be associated with the reaction base shear of the system under lateral loads representing seismic actions (Leelataviwat *et al*. 2009). To relate ground motions to structural nonlinear behavior, the energy balance is established by introducing the



(a) The energy balance of DC-SDOF (b) Idealization of structural nonlinearity

Fig. 6 Energy balance of DC-SDOF system and idealization of the structural nonlinearity energy factor. Based on the premise that the frame members remain elastic, the energy balance quation is given by

$$\gamma_{\mathrm{e}}(\frac{1}{2}MS_{\mathrm{v}}^{2})=E_{\mathrm{e}}+E_{\mathrm{p}} \tag{3}$$

where γ_e, M, and S_v are the energy factor of the DC-SDOF system, the mass of the system and the pseudo-velocity, respectively. It is noted that the energy factor is an essential indicator for determining the energy balance. For an elastic system, the energy factor equals to unity and Eq. (3) comes down to the energy balance equation proposed by Housner (1956). For an inelastic system, the value of γ_e is not a constant value and depends on the interaction of structural nonlinearity and ground motions. For DC-SDOF systems, the energy factor can be calculated by

$$\gamma_{\mathrm{e}}=\frac{E_e+E_p}{\frac{1}{2}MS_v^{2}}=\frac{\frac{1}{2}V_{\mathrm{y1}}\delta_{\mathrm{y1}}+(\zeta-1)V_{\mathrm{y1}}\delta_{\mathrm{y1}}+\frac{1}{2}(\zeta-1)^{2}\alpha V_{\mathrm{y1}}\delta_{\mathrm{y1}}}{\frac{1}{2}V_{\mathrm{e}}\delta_{\mathrm{e}}}=\chi[2\zeta-1+\alpha(\zeta-1)^{2}] \tag{4a}$$

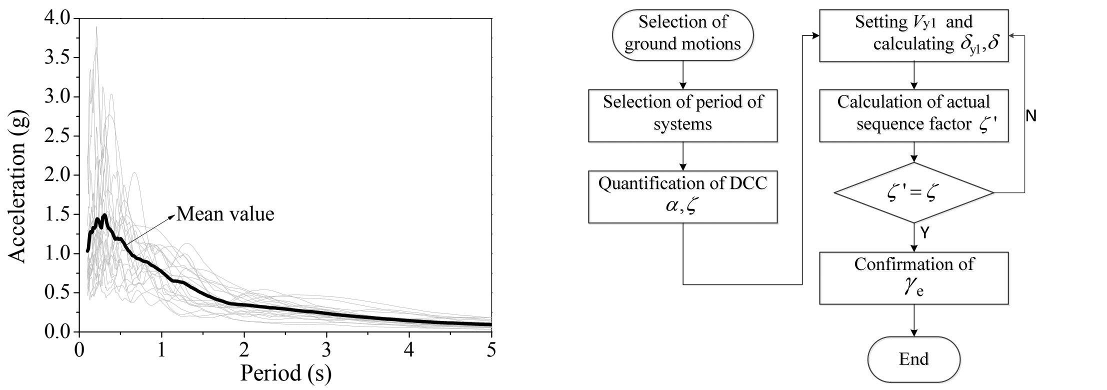
$$\chi=\frac{1}{R_{\zeta}^{2}} \tag{4b}$$

$$R_{\zeta}=\frac{V_{\mathrm{e}}}{V_{\mathrm{y1}}} \tag{4c}$$

where V_e and δ_e are the base shear and maximum displacement of the corresponding elastic system; χ is defined as the damage-control factor; R_ζ is the strength reduction factor of the DC-SDOF system.

3.2 The ground motion ensemble and analysis approach

In this study, an ensemble of 20 ground motion records (Fig. 7) is used. These records are derived from historical recordings or physical simulations and were also used in the original research of SAC projects (Shome *et al.* 1998). These ground motion data can be viewed as representative for Los Angeles with a 10% probability of exceedance in 50 years, considering the stiff soil site condition. Compared with the research work based on constant-strength spectra (Farrow and Kurama 2003), it is more instructive to study the seismic performance of the system on the same deformation level, which is similar to the construction of constant-ductility spectra, as damage-control behavior is generally restricted by the elastic deformation capacity of the steel MRF members. Also, because available research considering the elasto-plastic model or the bilinear model of a negligible post-yielding stiffness ratio is not suitable for featuring the nonlinearity of steel MRF systems with fuses below the resilience threshold, in this research, the response of systems is analyzed with a target sequence factor and a considerably large post-yielding stiffness ratio. The framework of calculating the energy factor is shown in Fig. 7(b). The analysis is carried out with a validated program BTESPEC (Ke *et al.* 2015). A damping ratio of 5% is assumed.



(a) Acceleration spectra (b) The framework of calculating the energy factor

Fig. 7 Acceleration spectra and calculation procedure of the energy factor

3.3 Energy factor spectra

Based on the derivation of the energy factor stated above and the selected ground motions, the energy factor spectra constructed by the mean values of γ_e are shown in Fig. 8. For comparison, energy factor responses of elasto-plastic single-degree-of-freedom (EPSDOF) systems are also analyzed and presented in the figure. Overall, the results imply that the energy factor of the system is sensitive to the shape of the DCC. According to the figures, γ_e significantly decreases when α increases in the short period region (i.e., period smaller than 0.5 s), while the trend is reversed for moderate and long period regions. This phenomenon can be conceptually explained by the shift of the "effective" period induced by inelastic action (Farrow and Kurama 2003). For a system with negligible post-yielding stiffness ratio in the short period (relative to predominant ground motion period) region, the elongation of the structural period will move the system into the energy-rich region, while for long-period systems, this effect may reduce the energy demand by pushing the system away from the energy-rich region. In contrast, systems with large post-yielding stiffness ratio will have the opposite trend, as the elongation of the structural period is constrained with increasing periods. For systems with very large post-yielding stiffness ratios, energy factors remain nearly constant at a value of unity. This is understandable because the system approaches a completely elastic system. For the influence of the target sequence factor, its variation will lead to an opposite trend in comparison with α. In addition, the impact of α will be amplified when ζ is significant. Importantly, for steel MRF systems which generally fall in the moderate and long period region, the energy demand denoted by the energy factor tends to increase with the post-yielding stiffness ratio increasing, which highlights the need for special cautions during design.

The universally used energy factor spectra (Leelataviwat *et al.* 2009, Kharmale and Ghosh 2013, Pekcan *et al.* 2014, Wongpakdee *et al.* 2014) derived from Newmark and Hall spectra (Newmark and Hall 1982) for EPSDOF systems are also plotted in Fig. 8. The results imply that although the designed energy factor spectra are applicable for EPSDOF systems and those with negligible post-yielding stiffness ratio (i.e., $\alpha < 0.3$), significant bias can be observed for DC-SDOF systems with significant post-yielding stiffness ratios, particularly when the sequence factor is also significant. In this regard, a modified formulation of the energy factor spectra is developed in this research, considering the moderate and long period systems, which are applicable for steel MRF systems. Essentially, the core of the modification is to transform the DC-SDOF system

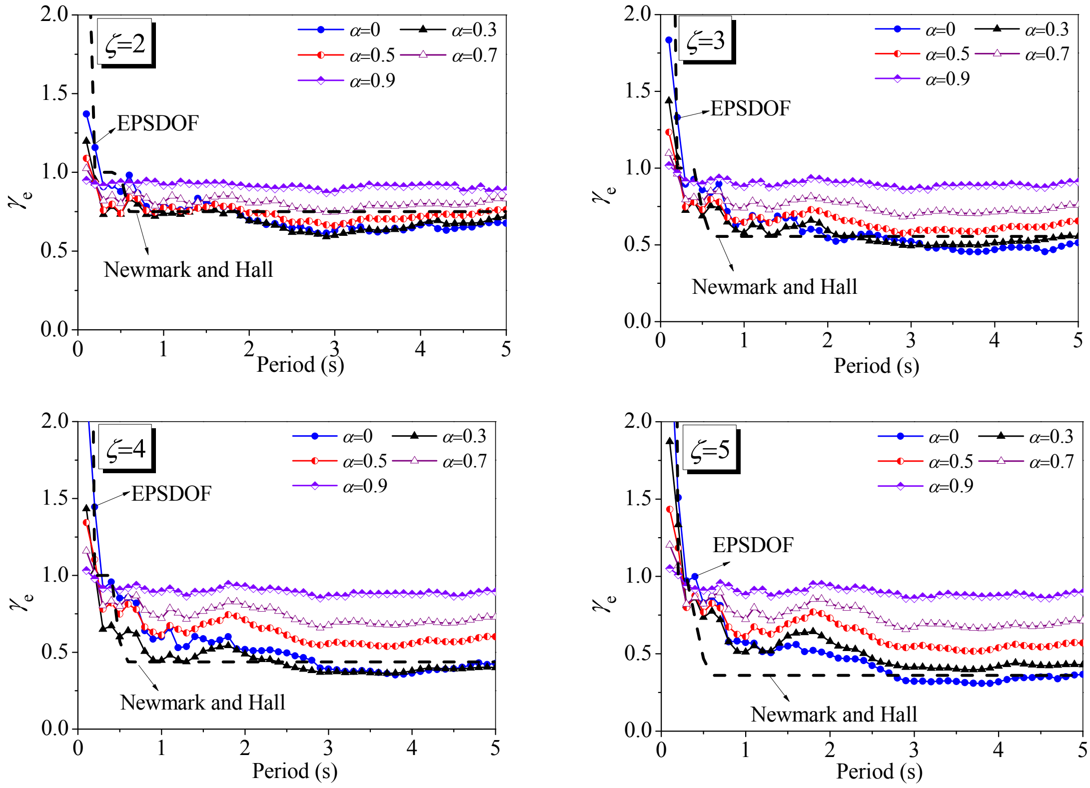


Fig. 8 Energy factor spectra and conventional design spectra

into an equivalent EPSDOF system. Specifically, as given in Fig. 9, for a DC-SDOF system with significant post-yielding stiffness ratio, an EPSDOF system with the identical energy absorption is used for calculation of the energy factor. Note that the rationality of the equalization lies in the equal-energy rule and equal-displacement rule of an EPSDOF system and a DC-SDOF system in the moderate period region and the long period region, respectively, which have been validated by the past research work (Ye *et al.* 2008) based on a large number of dynamic analyses. Accepting this statistical law, the strength modification reduction factor R_e can be determined by

$$R_{\rm e}=\zeta-\sqrt{\zeta^2-[\alpha(\zeta-1)^2+2(\zeta-1)+1]} \tag{5}$$

In addition, the equivalent yield force V_{ye} and the equivalent of ductility μ_e can be calculated by

$$V_{\rm ye}=R_e V_{\rm y1} \tag{6a}$$

$$\mu_{\rm e}=\frac{\zeta}{R_e} \tag{6b}$$

Substituting Eqs. (5) and (6) into Eq. (4), the damage-control factor can be expressed as

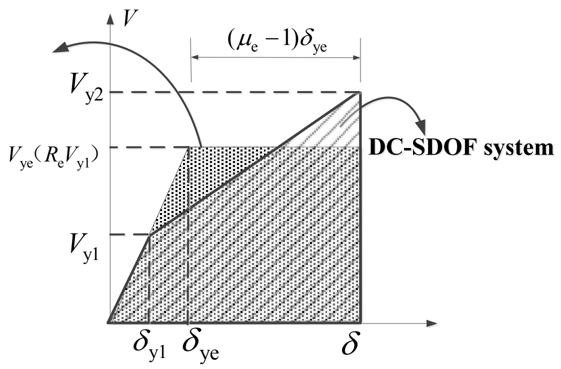


Fig. 9 Illustration of equivalent EPSDOF system

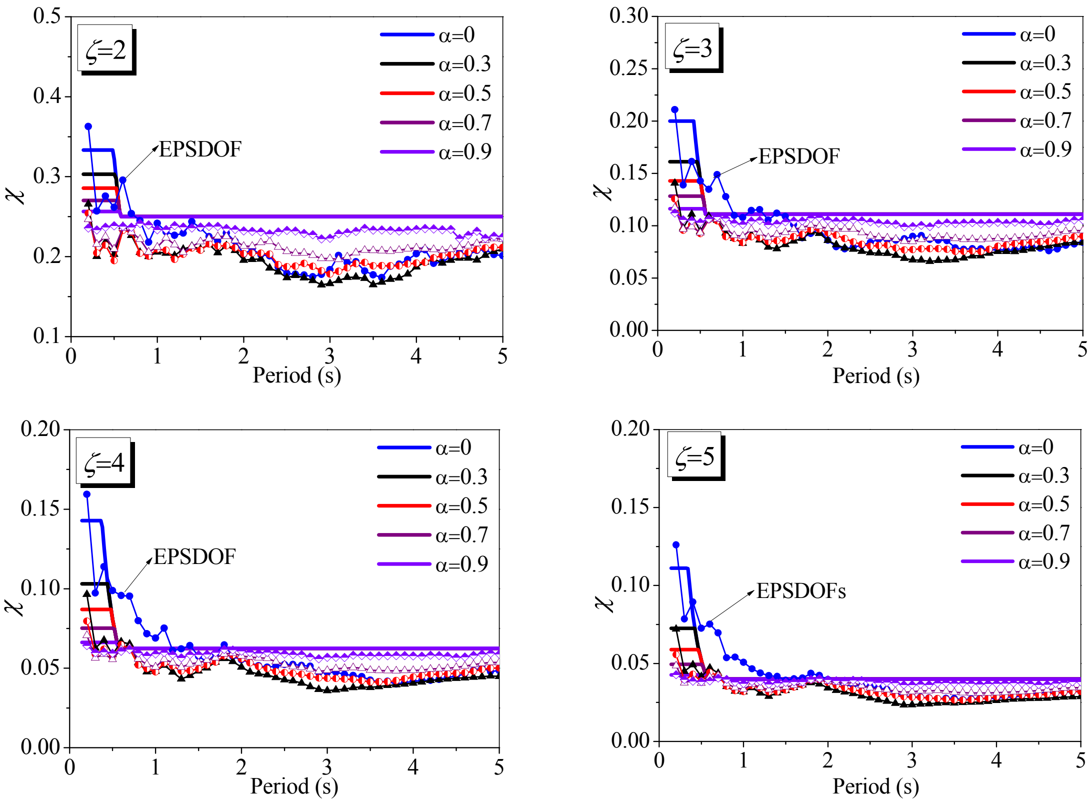


Fig. 10 Comparison of damage-control factor spectra

$$\chi = \frac{1}{R^2(T, \mu_e) R_e^2} \tag{7}$$

where R denotes the strength reduction factor of the transformed EPSDOF system, which can be calculated by applying the Newmark and Hall spectra. Therefore, the energy factor spectra of a

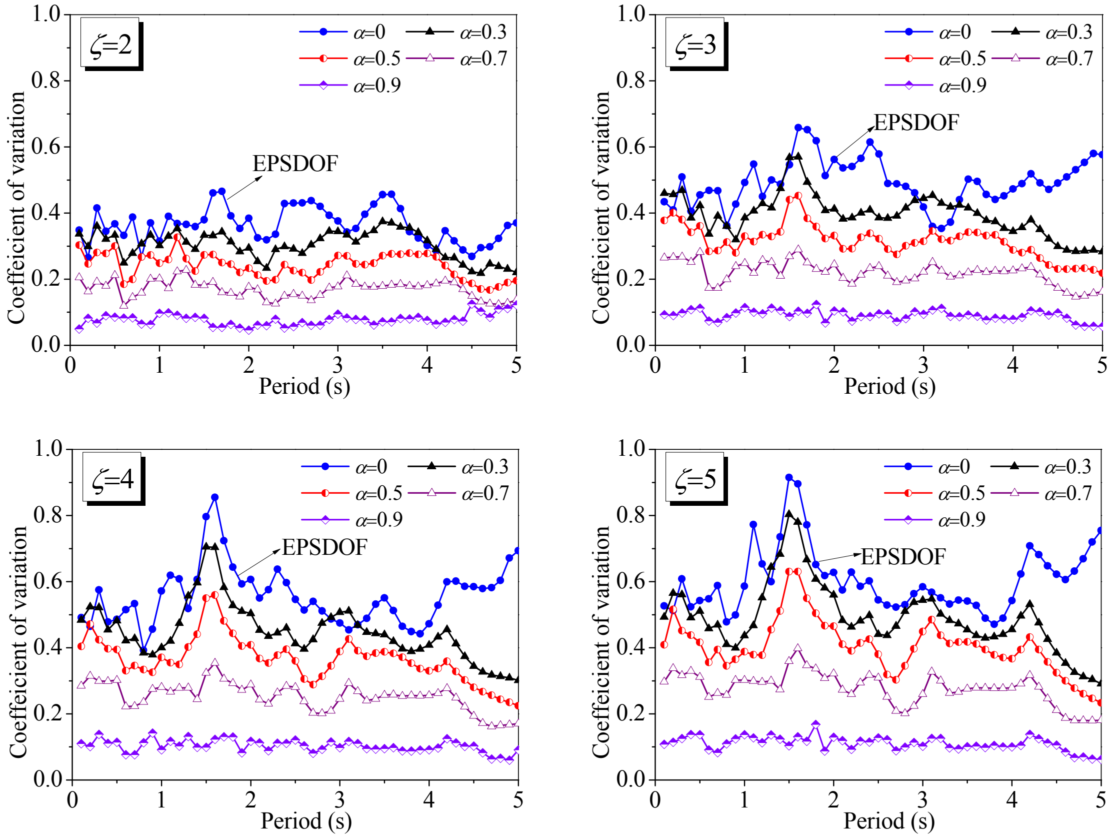


Fig. 11 Coefficients of variation of the energy factor

DC-SDOF system can also be calculated by solving the damage-control factor spectra and the shape of DCC by Eq. (4).

To validate the accuracy of the transformation for quantifying the energy factor of DC-SDOF systems based on the Newmark and Hall spectra, the mean damage-control factor spectra of DC-SDOF systems subjected to ground motions are compared with the counterparts determined by the proposed transformation approach associated with the Newmark and Hall inelastic design spectra indicated by solid lines, as given in Fig. 10. It is observed that the obtained damage-control factor spectra show satisfactory accuracy with conservative estimates of the damage-control factor from moderate to long period regions, which is believed to be applicable for design motives.

Considering the dispersion of energy factors, the coefficient of variation (COV) defined as the ratio of the standard derivation to the mean value is plotted against the period and given in Fig. 11. The results show that an increasing α can reduce the discreteness, as the COV of energy factors decreases considerably and almost remains constant at a relatively small value, regardless of the variation of the period. In contrast, increasing ζ values may lead to the opposite trend as the COV increases with increasing ζ. In general, a DCC with a significant post-yielding stiffness ratio is a favorable alternative to achieve the satisfactory seismic performance of a system, as a more stable energy balance mode is achieved for systems subjected to different ground motions.

4. Energy-based damage-control evaluation approach of steel MRF structures with fuses

4.1 Energy demand and energy capacity below the resilience threshold

Although the nonlinear dynamic analysis is a relatively more rigorous approach for analyzing the inelastic response of systems compared with other procedures, it is not efficient in engineering practice due to complicated computation efforts. An approach that retains the computational simplicity is still needed. Practically, for low-to-medium rise structures dominated by the fundamental vibration mode, the energy factor of the DC-SDOF system can be extended to structures as multi-degree-of-freedom (MDOF) systems, and the damage-control behavior can be evaluated and designed with nonlinear static analyses based on the energy balance considering provided ground motions. The underlying assumptions are as follows: (1) The modal shape remains constant after yielding of the fuses; (2) The effect of higher vibration modes on the structural seismic response is neglected. It is noted that for low-to-medium rise systems, past research works (Chopra and Goel 2002, Leelataviwat *et al*. 2009) based on these assumptions were demonstrated to be feasible with acceptable accuracy. Thus, these assumptions are adopted, and their rationality will be shown by the validation presented next.

Therefore, for MDOF systems, the nominal energy demand can be calculated and is given by

$$E_{\mathrm{d}}(\zeta)=\frac{1}{2}\gamma_{\mathrm{e}}(\zeta\ ,\alpha,\chi)M_1^{*}S_{\mathrm{v1}}^2 \tag{8a}$$

$$M_1^{*}=\Gamma_1^2 M_1 \tag{8b}$$

$$\Gamma_1=\frac{[\phi_1]^{\mathrm{T}}[m][1]}{[\phi_1]^{\mathrm{T}}[m][\phi_1]} \tag{8c}$$

where E_d, M_1^*, M_1. $\Gamma_{1,}$ $[m]$, $[\varphi_1]$ and S_{v1} are the nominal energy demand below the resilience threshold, the effective mass of the fundamental mode, the generalized mass of the fundamental mode, the modal participation factor of the fundamental mode, the mass matrix of the system, the mode shape vector of the fundamental mode and the pseudo-velocity of the fundamental mode, respectively. On the other hand, the nominal energy absorption for the fundamental mode can be derived and is given by

$$E_a(\zeta)=\begin{cases}\dfrac{\zeta^2 V_{\mathrm{y1}}u_{\mathrm{y1}}}{2\Gamma_1\phi_{\mathrm{r1}}} & (\zeta\le 1)\\[2ex] [\alpha(\zeta-1)^2+2(\zeta-1)+1]\dfrac{V_{\mathrm{y1}}u_{\mathrm{y1}}}{2\Gamma_1\phi_{\mathrm{r1}}} & (\zeta>1)\end{cases} \tag{9}$$

where V_{y1}, u_{y1}, φ_r, are the equivalent base shear corresponding to yielding of fuses, the equivalent roof displacement corresponding to yielding of fuses and the element of the fundamental modal vector at the roof, respectively. Note that to obtain these quantities, a pushover analysis considering the fundamental vibration mode is required (Chopra and Goel 2002, Leelataviwat *et al*. 2009). Hence, the corresponding nominal energy capacity at the resilience threshold can be calculated as $E_a(\zeta_T)$.

4.2 Energy-based damage-control index for low-to-medium rise structures

For low-to-medium rise structures, the evaluation of damage-control behavior can be conducted by considering the energy balance of the fundamental mode. Because damage-control behavior can be essentially represented by the achievement of the energy balance of nominal energy demand and the capacity below the resilience threshold, a damage-control index can be derived from Eq. (8) and Eq. (9) if $\zeta > 1$, given by

$$\psi = \frac{E_d(\zeta_T)}{E_a(\zeta_T)} = \frac{\Gamma_1 \phi_{r1} \gamma_e M_1^* S_{v1}^2}{[\alpha(\zeta_T - 1)^2 + 2(\zeta_T - 1) + 1] V_{y1} u_{y1}} \tag{10}$$

where ψ is defined as the damage-control index of the system. For systems that can achieve damage-control behavior, the energy balance can be correspondingly reached with the deformation below the resilience threshold, where $\psi < 1$. Because the damage-control index relates the ground motion property and structural nonlinearity, the working mechanism of systems clearly shows that frame members failure can be effectively avoided by sacrificing fuse elements. This is quantitatively indicated by a relatively lower value of the damage-control index. In the perspective of the energy response, a favorable energy balance mode is achieved, and the demand can be more easily reached with a lower deformation requirement. Meanwhile, plastic energy is completely moved to the fuse elements. Note that for cases with $\zeta \leq 1$, the system is in the elastic range.

4.3 Evaluation and design procedure

Based on the energy balance of the system, a practical evaluation procedure motivated by evaluation of the structural energy balance is established and is given in the flow chart shown in Fig. 12. During the preliminary design, the approach proposed by Vargas and Bruneau (2009a) can be adopted to design the fuses and frame members while the damage-control evaluation and

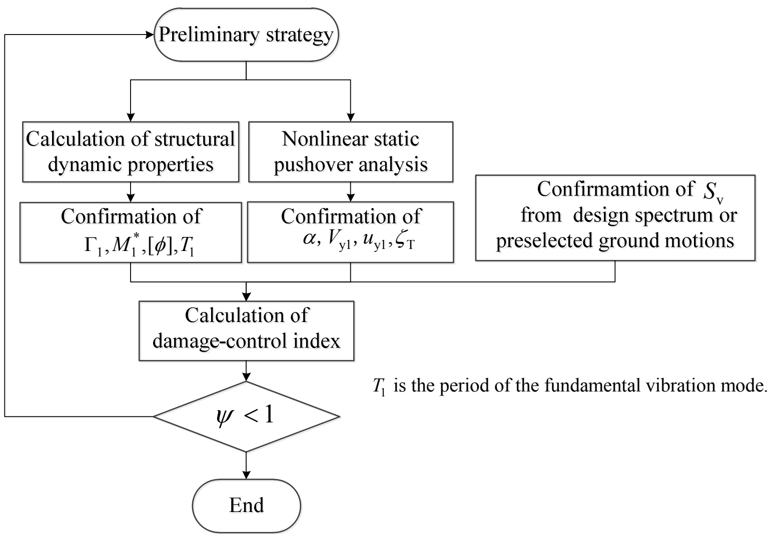


Fig. 12 Damage-control design and evaluation procedure of steel MRF structures with fuses

structural optimization can be conducted with the energy-based approach. Compared with theapproach motivated by separating the feature of displacement and force, the energy-based approach provides an alternative to evaluate the response with the energy-based index (ψ) with more flexibility as the deformation and strength are considered simultaneously.

By following the proposed procedure, the damage-control behavior can be evaluated and designed by conducting pushover analyses and adjusting the structural arrangement. It can also be used as a practical starting point for the optimization of structures with provided ground motions. In essence, the energy factor can be used to determine the peak response for identifying the occurrence of damage in frame members.

5. Application of the approach to steel MRF structures with fuses

5.1 Example structures and implementation of the procedure

To validate the effectiveness of the proposed approach for quantifying the damage-control behavior subject to expected ground motions, a three-story steel MRF, a nine-story steel MRF and a three-story steel MRF with SSWs are used as examples. By following the preliminary design steps proposed by Vargas and Bruneau (2009a), the structures are modified based on two SAC steel MRF systems (3-story steel MRF and 9-story steel MRF in the LA area) (Gupta and Krawinkler 2000), but the same load condition is considered as the original structures. The post-yielding stiffness ratio (α) for the pure steel MRF systems are assumed to be 0.75 and the counterpart for the steel MRF with SSWs is selected as 0.7, as a relatively larger value of α (Nakashima *et al*. 1996, MacRae and Kawashima 1997) is believed to be more satisfactory in seismic performance improvement. However, this value needs to be confirmed by pushover analysis. ζ is selected as 8 for the steel MRF with SSWs and the value of 3 is considered for the pure steel MRF. It is noted that the reason for selecting different values of ζ for the steel MRF with SSW and the pure steel MRF lies in the fact that the SSWs generally yield at a relatively smaller drift as it can be controlled by the slit configuration, while less flexibility can be achieved for a pure steel MRF system. In particular, recognizing the fact that the yield drift of a general steel MRF is confined to a value around 1%, and a value of 0.125% was recommended for hysteretic dampers in a previous study (Nakashima *et al*. 1996), the initial value of 8 is selected for the ζ of steel MRF with SSWs. For the pure steel MRF systems, if the specialized detail is not employed, the yield drift of the fuse beams will be dependent on the material strength. Correspondingly, the value of ζ is assumed as 3, assuming that low yield steel will be adopted in the beams as fuses. The peak acceleration of ground motion is arbitrarily selected as 0.4 g, but in practice, this value should be considered based on the specific design purposes and practical seismicity.

The information about the member section of the three-story steel MRF and the three-story steel MRF with SSWs are shown in Fig. 13. The 9-story MRF is modified based on the original SAC prototype steel frame in LA area with the same sections and dimensions. It is noted that although the actual yielding sequence essentially depends on the relative strength and stiffness of the fuses and the primary steel MRF system, in this research the low-yield point (LYP) steel is considered as the material for structural fuses, which can provide more flexibility to adjust the structural yielding sequence. Recent investigations also indicate that systems with LYP steel components exhibit excellent performance with stable and redundant energy dissipation (Charney and Atlayan 2011, Atlayan and Charney 2014). For steel MRF systems with fuse beams, the fuse beams designed with LYP steel of a yield strength of 100 MPa are arranged in external bays in all stories. The remaining components of the system are designed to have a yield strength of 345 MPa. For the steel MRF system with SSWs, the SSWs are designed with the yield strength of 100 MPa and the frame components are designed with the yield strength of 345 MPa. The height and width of the flexural link (Hitaka and Matsui 2003, Ke and Chen 2014) are 800 mm and 188 mm, respectively. The thickness of the plate for the SSWs is 14 mm. Because the primary objective of analyzing these prototype structures is to validate the effectiveness of the proposed approach for damage-control evaluation, which does not depend on an optimized design, the optimization of the design is not further considered. The dynamic properties of the systems are given in Table 1. Structural models are established using ABAQUS. Specifically, for the frame members, the two-node linear beam elements in space, B31, are utilized for the models. For the SSWs, the four-node reduced integration shell elements, S4R, are utilized in the analysis models. To realize the connection of the SSWs and the frame beam members, the coupling interaction is assumed in the gusset plate region between the SSWs and the frame beams. In particular, all the nodes in the connection area are coupled through the "kinematic coupling", assuming that they have the same in-plane displacement. This assumption is rational since the connection area are stiffened by stocky cover plates having a significant in-plane rigidity, and the shear deformation is concentrated in the SSWs, as was observed in the previous tests (Ke and Chen 2014). For all the members, the elastic-plastic behavior of 2% hardening is considered. To rationally account for the seismic mass

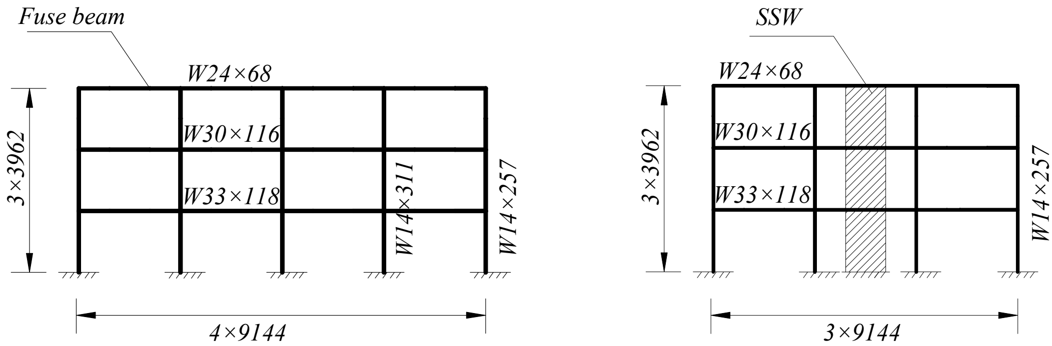


Fig. 13 Arrangement of components

Table 1 Dynamic properties of prototype structures

Structure	Story	Property (unit)	1st Mode	2nd Mode
Frame with fuse beam	3-story	Period (s)	0.93	0.32
		Modal effective mass (t)	1252.6	194.3
		Modal participation factor	1.27	0.42
Frame with fuse beam	9-story	Period (s)	2.21	0.83
		Modal effective mass (t)	3811.5	530.8
		Modal participation factor	1.37	0.54
Frame with SSW	3-story	Period (s)	0.68	0.23
		Modal effective mass (t)	874	115.4
		Modal participation factor	1.26	0.41

of the system, the uniformly distributed node mass in each floor is considered in the models. In particular, for the 3-story pure steel MRF, a total seismic mass of 437 t and 429 t is assigned to the roof floor and general floors, respectively. The counterparts for the 9-story steel MRF are 535 t and 435 t, respectively. For the steel frame with SSWs, the roof floor is assigned with the seismic mass of 353 t while the value of 321 t is distributed on the general floors. The determination of the seismic mass is based on the benchmark study conducted by Gupta and Krawinkler (2000). In the dynamic analyses, the Rayleigh damping of 5% considering the first two modes is assumed.

To demonstrate the effectiveness of the proposed procedure for identifying damages in the frame members subject to ground motions, both nonlinear static analyses and nonlinear dynamic analyses are performed based on the established numerical model. In particular, for the nonlinear static analyses, the gravity load is firstly applied to the structure as the first analysis step. Then the invariant lateral load distribution of the fundamental vibration mode of the structure (Chopra and Goel 2002, Leelataviwat *et al.* 2009) is applied and the corresponding parameters of the damage-control core can be determined, as the basis of the procedure. Similarly, for the nonlinear dynamic analyses, which are used to identify the actual damage levels in the frame members and validate the effectiveness of the approach, the gravity load is applied in the initial step. Subsequently, the ground motions are input in terms of acceleration, and the structural seismic response is analyzed. In these analyses, the incremental dynamic analyses are involved by using ground motions with various peak accelerations. Note that in the analyses the P-delta effect induced by the gravity load is not considered.

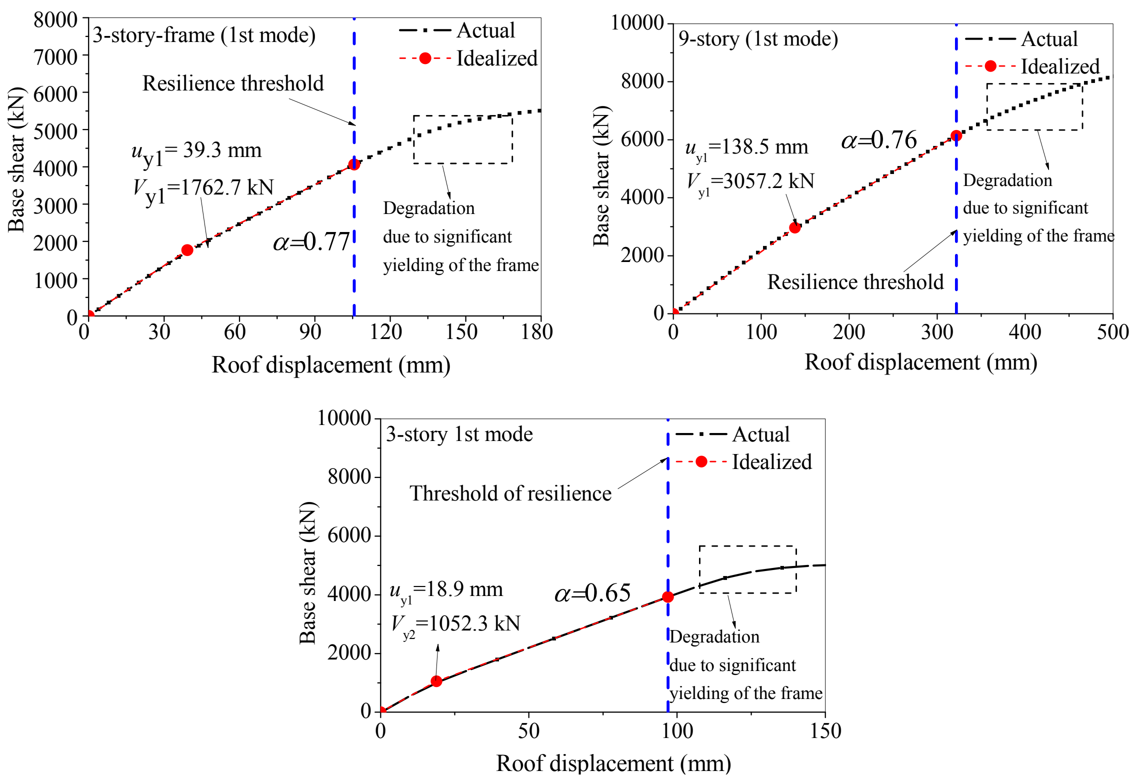


Fig. 14 Pushover curves of example structures

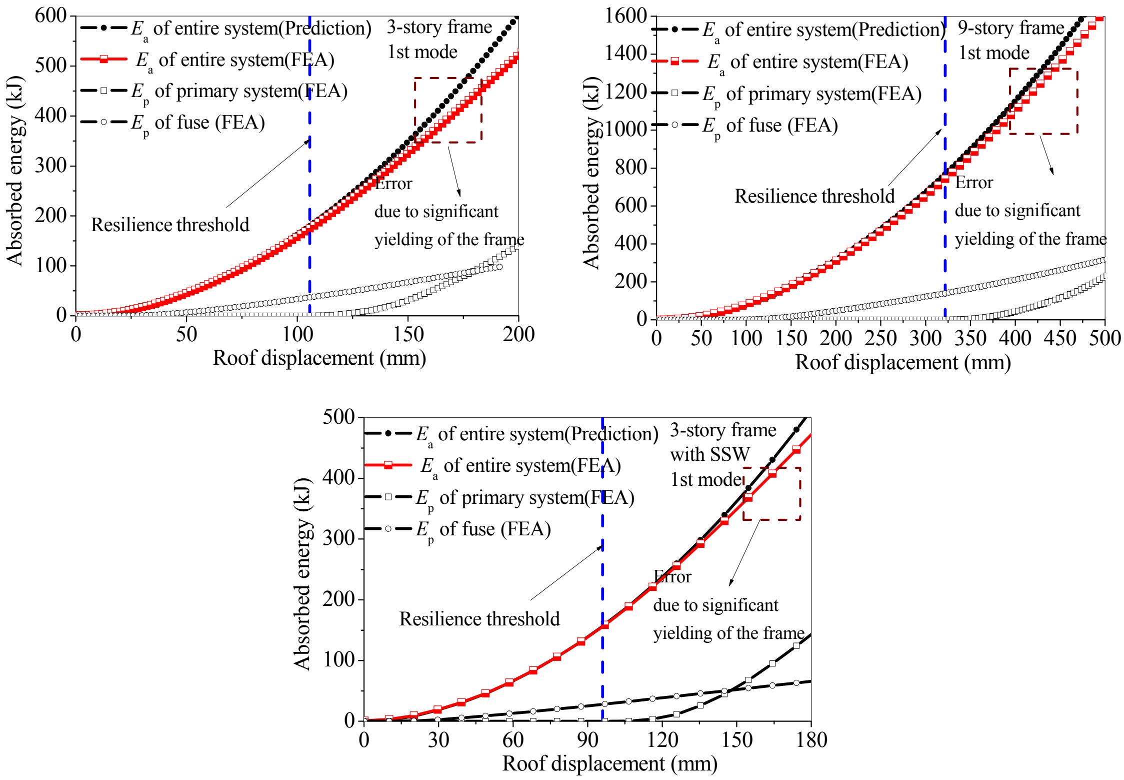


Fig. 15 Energy response curves of structures under pushover analysis

The pushover curves corresponding to the fundamental mode of the structures are shown in Fig. 14. In this study, the resilience threshold is selected that the frame is expected to have completely elastic behavior. Practically, the threshold can be chosen by considering specific design motives with the target displacement, as slight inelastic action in the frame may be acceptable, which is reflected by the almost constant post-yielding stiffness after the pushover curve going above the

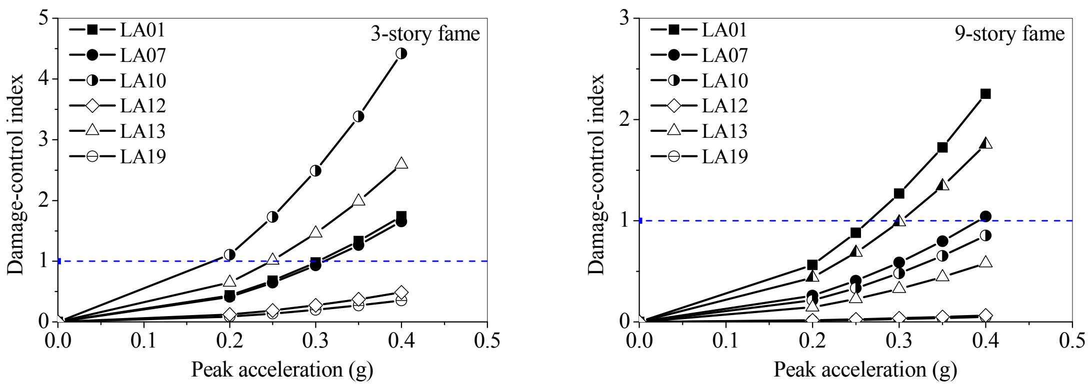


Fig. 16 Calculated damage-control indexes

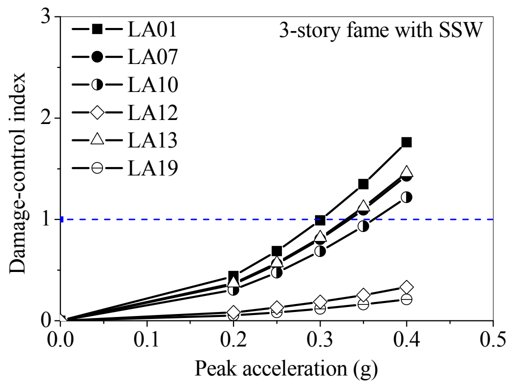


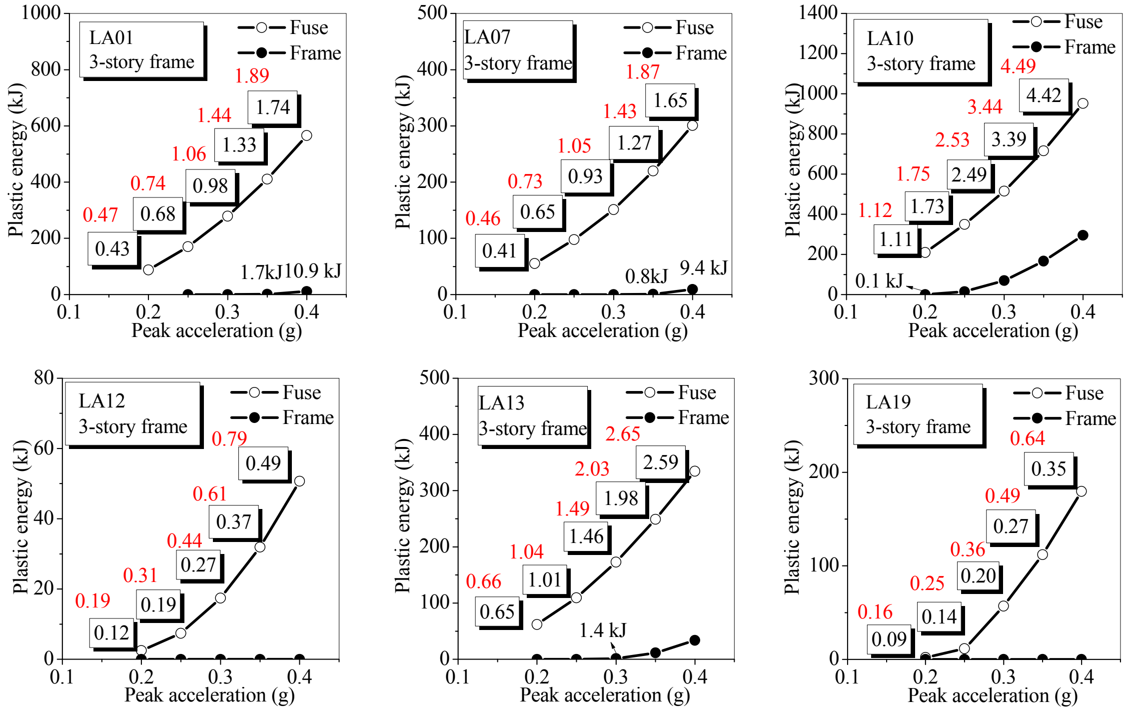
Fig. 16 Continued

defined resilience threshold in a certain deformation range. The absorbed energy responses of the systems under pushover analysis are illustrated in Fig. 15. The comparison of the calculated nominal absorbed energy determined by Eq. (9) and the analysis results extracted from numerical models implies that the proposed approach can provide satisfactory accuracy in computing the absorbed energy. The yielding sequence is indicated by the plastic energy distribution in the systems.

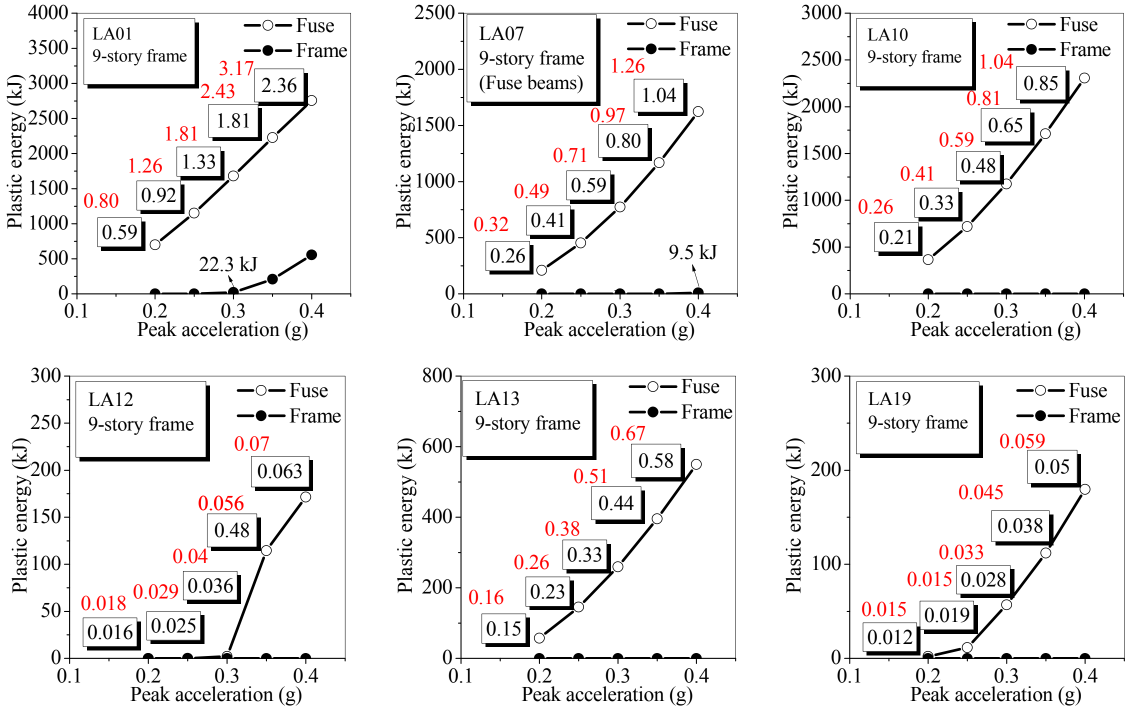
Representative damage-control indexes arbitrarily selected from the ground motion ensemble corresponding to selected ground motions with different scaled factors are calculated and plotted in Fig. 16. A quadratic function that relates the damage-control index to the peak ground motion acceleration (PGA) can be observed, which is also revealed by Eq. (10). However, for different structures, the indexes are quite different under the same series of ground motions, highlighting the significance of the interaction of the structural features and ground motion.

5.2 Verification by incremental dynamic analysis

The prototype systems are analyzed with the ground motions arbitrarily selected from the ground motions ensemble as stated above. In the incremental analyses, the PGA is scaled, and the value of 0.2 g, 0.25 g, 0.3 g, 0.35 g and 0.4 g is considered to be the five levels of acceleration. As the objective of this study is to validate the accuracy of the energy-factor-based approach for identifying the damage-control behavior, the plastic energy dissipation of the members is extracted as the primary quantity. The results of the plastic energy distribution and the corresponding damage-control indexes are shown in Fig. 17. In this research, to demonstrate the accuracy of the analysis algorithm and applicability of the transformation approach for featuring the energy factor, the energy factors are calculated considering an individual ground motion following the framework in Fig. 7(b) (values with shaded background) and the transformation approach (values in red). Generally, the results show satisfactory ability of the damage-control index to predict the damage of frame members even though in cases where inelastic deformation of the frame is very slight, as indicated by very small value of plastic energy dissipation in the frame members. Moreover, the tremendous potential of the transformation approach for practical applications is validated since the computed damage-control index determined by the transformation approach generally lies on the conservative side and is very close to the extracted value calculated following the framework.

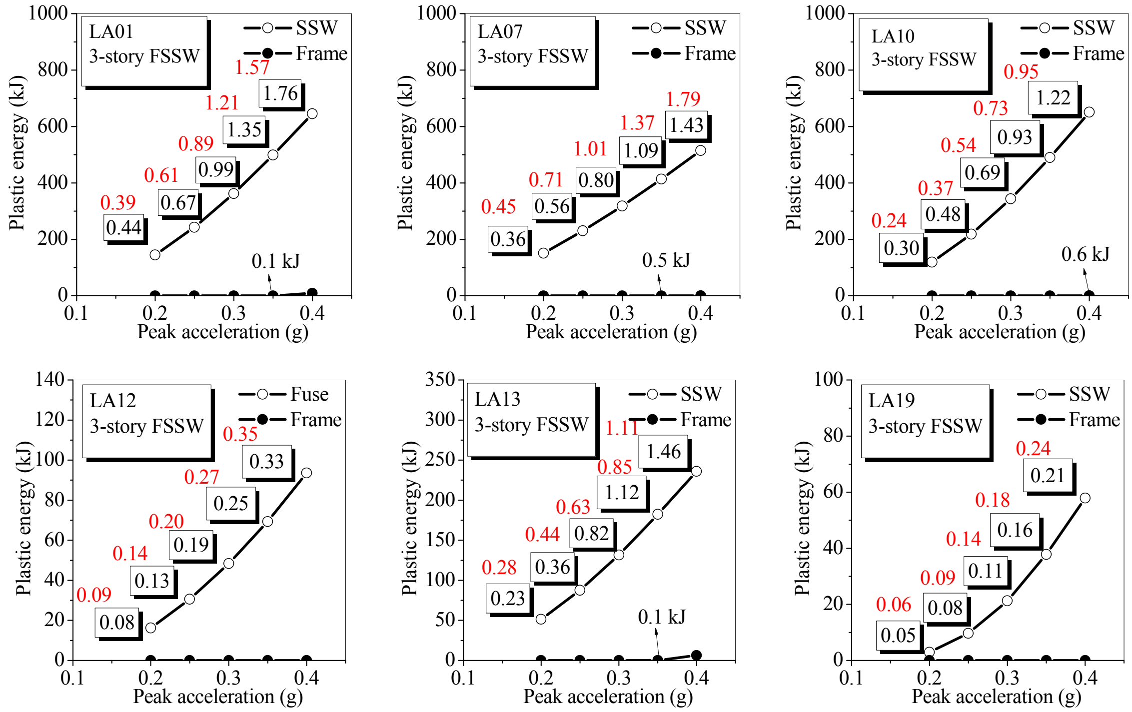


(a) 3-story frame



(b) 9-story frame

Fig. 17 Plastic energy distribution and corresponding damage-control indexes



(c) 3-story frame with SSWs

Fig. 17 Continued

According to the presented plastic energy response extracted from the incremental dynamic analyses of the prototype structures, it can be seen that the proposed energy-factor-based approach motivated by the energy balance concept can effectively identify the damage initiation of the frame members. The rationale behind the satisfactory effectiveness of the procedure lies in the accuracy of utilizing the energy factor of DC-SDOF systems to quantify the seismic response of low-to-medium rise structures dominated by the fundamental vibration mode. The proposed method puts forth an open discussion for the development of theoretical methods for analyzing the damage-control behavior of steel MRF systems with fuses below the resilience threshold. It is also validated by the results of the analyses in this research considering different steel MRF systems with fuses, the variation of damage-control shapes and representative ground motions with various PGA. The robustness of the proposed procedure can be further strengthened by the support of more experimental evidence (i.e., the results of shaking table tests), parametric study covering a wider range of parameters of the damage-control core, practical seismicity, and steel MRF systems with various energy dissipation fuses.

6. Conclusions

In this research, the energy factor of DC-SDOF systems representing the steel MRF systems with fuses is investigated for seismic resilience design, and a practical energy-based approach for damage-control evaluation is also developed. The main observations of this investigation are summarized as follows:

(1) The energy factor of the system is significantly influenced by the post-yielding stiffness ratio and the target sequence factor. The employment of a damage-control core of significant post-yielding stiffness ratio will favorably result in the stable seismic response of systems subjected to various ground motions, thus reducing the dependency on input excitations.
(2) The energy factor spectra directly developed based on EPSDOF systems is not applicable for steel MRF systems with fuses, particularly when the post-yielding stiffness ratio is significant. In this regard, a transformation method based on the conventional energy factor spectra is proposed, and it is validated to be rational for practical design and evaluation.
(3) The energy factor can be used to reasonably evaluate the damage-control behavior of low-to-medium rise structures considering the fundamental mode. The approach can be used to evaluate and optimize systems with nonlinear static pushover analysis with simple and efficient calculations.
(4) The energy responses extracted from an incremental dynamic analysis of different prototype structures show that the proposed approach exhibits satisfactory accuracy in damage-control behavior evaluation, and the approach is believed to be universal.

Although this research is constructed based on the fundamental vibration mode, it is applicable for quantification of damage-control behavior and resilience design considering low-to-medium rise structures. Importantly, this research is a significant ingredient in a complete energy-based design approach for steel MRF systems with fuses. Currently, research works considering the effect of higher modes and cumulative action is also in progress, and they will be helpful to provide full validation of the approach.

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