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Technical note

Seismic energy factor of self-centering systems subjected to near-fault earthquake ground motions

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ABSTRACT

This research focuses on the seismic energy factor of self-centering systems. Based on energy balance concept, the energy factor of self-centering systems is derived. To clarify the influence of hysteretic parameters on the energy factor, nonlinear dynamic analyses of flag-shaped single-degree-of-freedom systems are performed. An ensemble of near-fault earthquake ground motion records is used as excitations. Numerical evaluations considering different combinations of hysteretic nonlinear parameters including the post-yielding stiffness ratio and ductility factor are performed. A comparison with the widely used design spectra is also made. The dispersion of analyses results is also presented. Results indicate that the energy factor of self-centering systems is appreciably influenced by nonlinear parameters (the ductility factor and post-yielding stiffness ratio). Results of this study are instructive for the revelation of the energy balance mode of self-centering systems, and they can be helpful to enhance and improve the current procedures based on energy balance concept.

1. Introduction

A fundamental issue of inelastic seismic design lies in proper quantification and application of seismic demand indices in design procedures. On the one hand, as force and displacement are of conceptual simplicity for engineering applications, design approaches established based on these features have been explored in past decades, such as the widely applied force-based procedures based on strength reduction factors [1–4] and displacement-based procedures based on displacement factors [5–8]. On the other hand, since it was firstly proposed by Housner [9], the energy balance concept has been extended to structural design and evaluation in earthquake engineering for capturing the essence of the seismic response. Recently, to consider the inelasticity of systems, a modified energy balance equation [10] was established based on the elasto-plastic single-degree-of-freedom (SDOF) system. Specifically, an energy factor accounting for the interaction of ground motion properties and systematic nonlinearity was introduced into the balance equation. Based on this demand index, the peak seismic response can be assessed, and the cumulative effect can be further evaluated when necessary. More importantly, it is convenient to associate this factor with indices of strength and deformation (e.g. strength reduction factor and ductility factor), making it attractive for practical applications. In this respect, extensive research works have been made and the derived energy factor has been applied to plastic design and evaluation of various structures [11–16]. For instance, based on the energy factor of an elasto-plastic system, Sahoo and Chao [11] derived the design base shear for buckling-restrained braced frames and developed a design procedure. Jiang et al. [15] used the energy factor to determine the energy demand of systems and developed an energy based multi-mode pushover analysis procedure. Pekcan et al. [16] designed innovative truss girder frame systems with the energy factor derived from Newmark and Hall spectra [2]. However, since the seismic energy factor is essentially influenced by hysteretic behavior and ground motion properties simultaneously [17], it is instructive and necessary to explore the effect of various hysteretic features for more rational estimates.

The objective of this note is to investigate the seismic energy factor of self-centering systems [18–22]. In recent decades, the excellent seismic performance of the system with negligible residual deformation has been validated experimentally [18,19]. When the ambient building resistance is not significant [20], the SDOF system with flag-shaped hysteretic feature can be used to quantify the structural seismic response, which is also verified by past research works [21,22]. First, the energy balance is established and the energy factor is derived considering the flag-shaped hysteretic nature of the system. Subsequently, a large amount of nonlinear dynamic analyses are performed to investigate the influence of hysteretic nonlinear parameters on the energy factor. The dispersion is also analyzed. Results are compared

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with the conventional model and its limitation is also clarified. Results of this research indicate that the energy factor of self-centering systems can favorably unite the strength and deformation, and the influence of hysteretic parameters is appreciable.

2. Energy balance concept and energy factors of self-centering systems

Structural seismic behavior can be reasonably evaluated by SDOF systems with applicable hysteretic features. Therefore, SDOF systems following the flag-shaped hysteretic law can be used to analyze the seismic response for self-centering structures. For instance, Christopoulos et al. [21] have investigated the seismic response of flag-shaped SDOF systems considering the strength factor, the ductility factor, the cumulative energy and the acceleration response with variation of hysteretic parameters. Specifically, nonlinear parameters of a flag-shaped SDOF system are quantified in Fig. 1(a). The ductility factor (μ_s) is defined by the ratio of the maximum target displacement (δ_T) to the yield displacement (δ_y); the post-yielding stiffness ratio (α) is defined by the ratio of the post-yielding stiffness after yielding to the initial stiffness (K); the energy ratio (β) is denoted by the ratio of the vertical height of the flag in terms of strength to the yield strength (V_y).

Based on the hysteretic feature, the energy factor can be derived by applying the energy balance concept (Fig. 1(b)). By associating an inelastic system with the corresponding elastic system, the energy balance equation can be established and given by

$$\gamma\left(\frac{1}{2}MS_v^2\right) = E_e + E_p \tag{1}$$

where γ, M, S_v, E_e and E_p are the energy factor, the mass of the system, the pseudo-velocity, the nominal elastic energy and the nominal plastic energy, respectively. The energy factor essentially denotes the ratio of the nominal energy absorbed by an inelastic system under monotonic loading to that of the corresponding elastic system.

Specifically, the nominal absorbed energy of a flag-shaped SDOF system is computed by

$$E_a = \left(\frac{1}{2}V_{y1}\delta_{y1}\right)[1 + 2(\mu_s - 1) + \alpha(\mu_s - 1)^2] \tag{2}$$

where E_a = nominal absorbed energy of the flag-shaped system in the inelastic range. It is noted that although the definition of E_a does not direct to a physical quantity, it can favorably unite the strength and deformation, and the covered area of the skeleton pushover curve is also implemented in various pushover approaches [10,15].

On the other hand, the absorbed energy of the corresponding elastic system, when it reaches the peak displacement, can be calculated as

$$E_{ae} = \frac{1}{2}MS_v^2 = \frac{1}{2}V_e\delta_e \tag{3}$$

where E_{ae} = absorbed energy of the corresponding elastic system; V_e = maximum strength of the corresponding elastic system and δ_e = maximum displacement of the corresponding elastic system.

Based on the definition stated above, following the procedure presented by Leelataviwat et al. [10], the energy factor of a flag-shaped SDOF system is obtained and given by

$$\gamma = \chi(T;\xi;\ \mu_s;\alpha;\beta)\left[2\mu_s - 1 + \alpha(\mu_s - 1)^2\right] \tag{4}$$

$$\chi = \frac{1}{R_y^2(T;\ \xi;\ \mu_s;\ \alpha;\ \beta)} \tag{5}$$

$$R_y = \frac{V_e}{V_y} \tag{6}$$

where χ = damage-control factor and it can be expressed by the strength reduction factor (R_y); T = structural period and ξ = damping ratio. As can be seen, the value of the defined damage-control factor still depends on the interaction effect of structural hysteretic behavior and ground motions. Note that although the cumulative effect is not directly employed when quantifying the energy factor, the research work [21] suggests that for self-centering systems with energy dissipation mechanisms, the cumulative absorbed energy is generally not significant for structural failure since damages are concentrated in replaceable devices with redundant energy dissipation capacity. However, the cumulative effect can still be considered by applying the energy factor as a given parameter in cases where the accumulated damages are indeed significant and expected to be quantified.

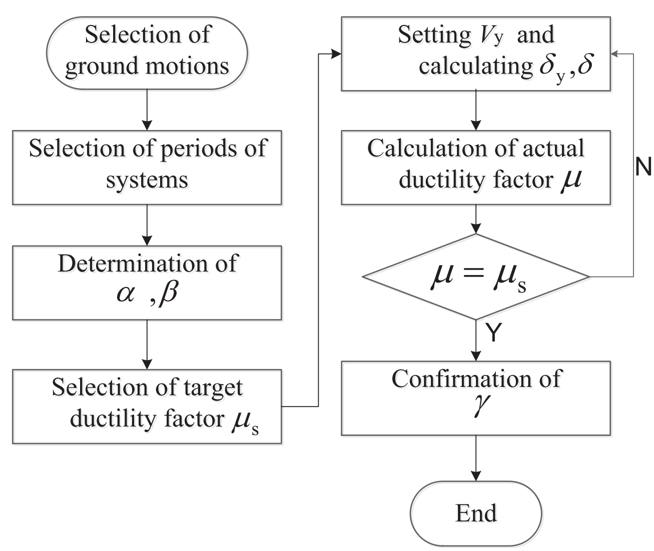

Fig. 2. Flow chart of computation of energy factors for self-centering systems.

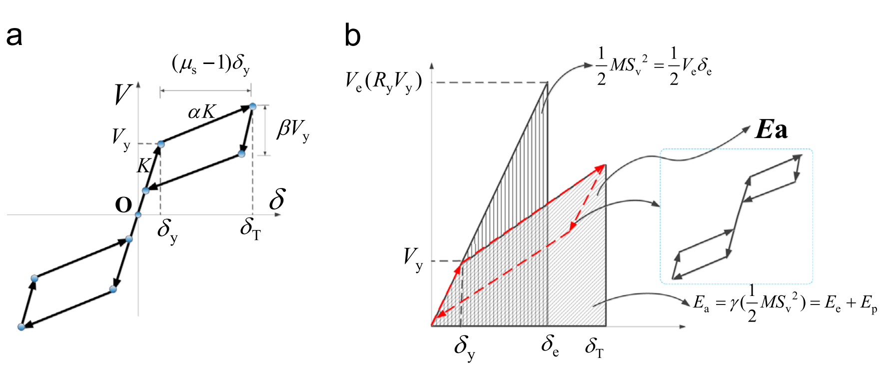

Fig. 1. Hysteretic features and the energy balance of self-centering systems.