Research Article

Seismic Energy Response of SDOF Systems Subjected to Long-Period Ground Motion Records

Yu Cheng, Yao-Rong Dong, Li Qin, Yuan-Yuan Wang, and Ye-Xue Li

1Hubei Key Laboratory of Power System Design and Test for Electrical Vehicle, Hubei University of Arts and Science, Xiangyang 441053, China
2Key Laboratory of C&PC Structures of the Ministry of Education, Southeast University, Nanjing 210096, China

Correspondence should be addressed to Yao-Rong Dong; yaorong099@163.com

Received 23 November 2020; Revised 3 March 2021; Accepted 10 March 2021; Published 23 March 2021

Academic Editor: Luigi Aldieri

To provide an important reference for the energy-based seismic design of long-period structures, the elastoplastic dynamic analysis program is employed to study the seismic energy response of single-degree-of-freedom (SDOF) systems under two types of typical long-period ground motions. Then, the influencing relationships of external and internal factors on the energy response spectra under near-fault pulse-like and far-field harmonic ground motions are analyzed one by one. Study results are obtained as follows: within the whole period, all the input energy, hysteretic energy and damping energy spectra of SDOF systems under near-fault pulse-like and far-field harmonic ground motions, are larger than those under common ground motions, even the seismic energy response under far-field harmonic ground motions is larger than that under near-fault pulse-like ground motions. From the aspect of energy concept, the energy response spectra and energy distribution rule of SDOF systems are evaluated based on the intensity and spectral distribution under near-fault pulse-like and far-field harmonic ground motions. If the ratio of hysteretic energy to input energy (RHEIE) is determined, the hysteretic energy which must be dissipated by a structure would be derived by the method of energy-based design. The input energy and hysteretic energy are mainly influenced by damping ratio and ductility coefficient, while the yield stiffness ratio exerts minor effects. It indicates that reasonable structural design parameters would contribute to the hysteretic energy of a structure itself.

1. Introduction

It has been found that there are long-period components with the extensive study on the characteristic of earthquake records [1–3]. With the development of high-rise structures, the earthquake records whose long-period components are rich would inevitably bring the resonance effect on these tall buildings with long vibration period. For example, the dynamic behavior of high-rise buildings under various long-period ground motions should be taken into account on the seismic design of the structure. The analytical results on test specimen subjected to long-period ground motions show that the cumulative ductility is four times greater than the design value, while the maximum story drift is almost the same as the design value [4]. The base-isolated high-rise buildings with long vibration period are easily in resonance with long-period components of earthquake records in Japan. The seismic design on these tall buildings with long vibration periods must be taken seriously [5]. Particularly, the effects of near-fault long-period ground motions on the nonlinear response of base-isolated long-period structures have been noticed in recent years [6, 7]. In short, the above situations about the effects on long-period structures subjected to long-period ground motions should not be ignored easily.

Currently, due to the simplicity of force and displacement conception in the engineering practice applications, the design methods based on force and displacement parameters have been discussed and applied over the past few decades [8–11]. However, these methods would not be applicable to the inelastic seismic design of buildings located in high-intensity seismic area. Housner [12] firstly proposed the concept of energy balance in the field of earthquake engineering. The energy-based seismic design method combines two most important design parameters of force
and displacement. It can reveal the nature of seismic response from the perspective of energy dissipation, and it can more fully reflect the impact on structures and the seismic capacity of structures under earthquake excitation [13–16]. At present, the energy-based approach has been proved to be effective and helpful to determine the seismic design of a structure under long-period earthquake excitation [17–21]. To reasonably evaluate the seismic energy response, it is necessary to define some relevant parameters from the energy balance, such as input energy, hysteretic energy, damping energy, the ratio of hysteretic energy to input energy, the ratio of damping energy to input energy, et al. The energy response spectra corresponding to these parameters can effectively be applied in the research on the seismic energy response of a structure under earthquake excitation.

A lot of work has been accumulated on the seismic input energy of a structure under long-period ground motions. The resonance effects between long-period ground motions and high-rise buildings can be produced easily. As a result, the seismic input energy is expected to be several times higher than that in the seismic design [22]. Chen et al. [23] thought that the seismic input energy of TOM wave is mainly distributed from 4 s to 10 s, and it is so easy to cause resonance effect on the prototype structures whose vibration period is about 9 s. To this end, the seismic energy response to the long-period structures under long-period ground motions has attracted great attention in academia. However, it is not comprehensive about the types of energy response spectra and influential factors, such as source nature, earthquake magnitude, source-to-site distance, propagation path, site condition, and the site effect of long-period seismic events [1, 24, 25]. In addition, the vibration period and damping ratio are two key factors influencing the dynamic behavior of long-period structures [26–29]. So, it is necessary to study the influence on seismic energy response affected by the dynamic characteristic of a structure itself.

Two types of ground motions in the existing earthquake records are considered as special long-period ground motions; besides one is near-fault pulse-like ground motions, and the other is far-field harmonic ground motions. This paper aims to investigate the seismic energy response of SDOF systems under near-fault pulse-like and far-field harmonic ground motions. As we all know, the improved pulse classification algorithm proposed by Shahi and Baker is frequently used to classify up to five potential pulses for each ground motion [30], and the selected ground motions in this paper are rotated in line with the orientation of the strongest potential pulse. Taking reliable long-period earthquake records as the research object, the elastoplastic dynamic analysis program is employed to study the seismic energy response of SDOF systems under two types of typical long-period ground motions. The main parameters are total input energy ($E_I$), cumulative hysteretic energy dissipation ($E_{H}$), damping energy dissipation ($E_D$), the ratio of hysteretic energy to input energy ($\lambda_H$), and the ratio of damping energy to input energy ($\lambda_D$). Then, the external and internal factors affecting the energy response spectra and energy distribution rule are analyzed one by one. It can provide an important reference for the energy-based seismic design of long-period structures subjected to long-period ground motions.

### 2. Energy Equation and Energy Principle

The dynamic equilibrium equation for elastoplastic SDOF systems under earthquake excitation is

$$m\ddot{x}(t) + c\dot{x}(t) + f(x(t)) = -m\ddot{\gamma}_g(t),$$

where $m$ is the mass of SDOF systems; $c$ is the viscous damping coefficient; $f(x(t))$ is the restoring force; $\dot{x}(t)$ and $x(t)$ are the acceleration, velocity, and displacement response relative to the ground, respectively; and $\ddot{\gamma}_g(t)$ is the ground acceleration at the moment of $t$.

The energy equation defined by the relative displacement of $x$ can be obtained and rewritten as follows:

$$\int_0^t m\ddot{x}(t)dx + \int_0^t c\dot{x}(t)dx + \int_0^t f(x(t))dx = -\int_0^t m\ddot{\gamma}_g(t)dx.$$  

(2)

The above energy equation can be rewritten as the following equation by substituting $dx = xdt$:

$$\int_0^t m\ddot{x}(t)\dot{x}(t)dt + \int_0^t c(\dot{x}(t))^2dt + \int_0^t f(x(t))\dot{x}(t)dt = -\int_0^t m\ddot{\gamma}_g(t)x(t)dt.$$  

(3)

where $E_K(t) = \int_0^t m\ddot{x}(t)x(t)dt$ is the kinetic energy; $E_D(t) = \int_0^t c(\dot{x}(t))^2dt$ is the damping energy dissipation; $E_{ES}(t) + E_H(t) = \int_0^t f(x(t))\dot{x}(t)dt$ is the elastic-strain energy dissipation and hysteretic energy dissipation; and $E_I(t) = -\int_0^t m\ddot{\gamma}_g(t)x(t)dt$ is the total input energy.

The above energy equation can be rewritten as follows:

$$E_K(t) + E_D(t) + E_{ES}(t) + E_H(t) = E_I(t).$$  

(4)

For elastoplastic SDOF systems, the energy dissipation capacity of a structure mainly depends on the cumulative hysteretic energy of $E_H$ and damping energy of $E_D$, and the hysteretic energy of $E_H$ accounts for a larger proportion. Therefore, the seismic design method based on the energy concept is to solve the cumulative hysteretic energy dissipation of $E_H$ in equation (4). And then, more details about the load-bearing capacity and plastic deformation capacity of a structure could be understood further. Combining relevant literatures [31, 32], the ratio of hysteretic energy to input energy (RHEIE) can be defined as the ratio of structural cumulative hysteretic energy dissipation to the total input energy of a structure ($\lambda_{HE} = E_{HE}/E_I$), while the ratio of damping energy to input energy (RDEIE) can be defined as the ratio of structural damping energy dissipation to the total input energy of a structure ($\lambda_{DE} = E_{DE}/E_I$). These two important parameters can be employed to reasonably evaluate the energy distribution rule of a structure under earthquake excitation.
3. Energy Response Spectra of SDOF Systems under Long-Period Earthquake Records

3.1. Selection of Long-Period Earthquake Records. Common ground motions refer to the particular ground motions where the Fourier amplitude is evenly distributed over a wide-frequency range. “Long-period ground motions” refers to the particular ground motions where the Fourier amplitude is concentrated in a narrow low-frequency domain. In this study, a lot of effective and reliable near-fault pulse-like and far-field harmonic ground motions are selected as the record databases of long-period earthquake records. The multiple earthquake damage indicates that the long-period ground motions have an amplification effect on the dynamic response of long-period structures, and they easily cause resonance-like action and serious damage to long-period structures. Therefore, it is necessary to compare the seismic energy response of long-period structures subjected to long-period and common ground motions. Tables 1–3 show more detailed information about near-fault pulse-like, far-field harmonic and common ground motion records, respectively. The particular distance from the fault rupture surface for near-fault pulse-like earthquake is within 20 km, and it includes obvious fliing-step and rupture-directivity effects. The particular distance from site soil to source for far-field harmonic earthquake is beyond 200 km, and its spectrum characteristics mainly rely on the observation station and the selection effects of site soil.

However, earthquake records obtained from seismic stations contain both ground vibration information purely caused by an earthquake and much complex interference. The long-period components of these interferences drift the baseline of earthquake time-history curve. To remove the effect of nonseismic factors, it is necessary to correct the baseline of earthquake time-history before it is used for a further study. The polynomial linear type is employed to adjust the baseline, and the high-pass filtering Butterworth type is used to correct the existed baseline drifting. The low-frequency components are considered as much as possible to be retained during the filtering correction process. In the Fourier amplitude spectrum analysis, the frequency range of 0-1 Hz is considered to be a low-frequency band. If the Fourier amplitude of ground motions is mainly concentrated in the low-frequency band and it is also satisfied for the judgment condition of equation (5), this particular ground motion is thought to be special long-period ground motions.

\[ \beta = \frac{\int_0^1 f(x)dx}{\int_0^1 f(x)dx} \geq 0.8, \]  \hspace{1cm} (5)

where \( f(x) \) is the function of Fourier amplitude spectrum and \( f \) is the cut-off frequency, and the value of \( f \) is 20 Hz in this paper.

Figure 1(a) illustrates the corrected acceleration time histories. Figure 1(b) displays the corresponding Fourier amplitude spectrum of partial ground motions listed in Tables 1–3 in a visual informative manner. The frequency distribution of long-period ground motions is concentrated in a relatively low-frequency (0.1–1.0 Hz) band, and common ground motions are concentrated in a relatively high-frequency (1.0–2.3 Hz) band.

3.2. Calculation of Various Energy Response Spectra. According to the above energy equation and energy principle, various energy response spectra on the total input energy, hysteretic energy dissipation, and damping energy dissipation are calculated, respectively. The damping ratio of 5%, the ductility coefficient of 3.0, and the yield stiffness ratio of 0.05 are initially assumed based on the bilinear restoring force model of SDOF systems.

Figure 2 shows the average energy response spectra of SDOF systems under three types of ground motions. The energy response spectra on input energy, hysteretic energy, and damping energy under three types of ground motions have experienced obvious three-stage process. All the energy response spectra increase in the short period. After passing through a peak in the medium-long period, they begin to decrease. And they have no obvious change in the long period. Within the whole period, all the energy response spectra under near-fault pulse-like ground motions are greater than those under common ground motions, and the peak values of input energy spectra under near-fault pulse-like and far-field harmonic ground motions are 4.8 times and 32.3 times of those under common ground motions, respectively. For near-fault pulse-like ground motions, all the energy response spectra slowly increase before 4 s, while they gradually decrease from 4 s to 10 s. And they tend to be stable when the vibration period of SDOF systems is beyond 10 s. For far-field harmonic ground motions, all the energy response spectra increase before 3 s, while they rapidly decrease after reaching the peak. And then they tend to be stable. The energy response spectra under far-field harmonic ground motions are greater than those under near-fault pulse-like ground motions within the whole period.

4. Seismic Energy Response Affected by External Factors

External and internal factors are the two main factors affecting the seismic energy response of SDOF systems. External factors mainly refer to the characteristics of earthquake excitation, while internal factors mainly refer to the dynamic characteristics of a structure itself. Since the earthquake record is a nonstationary random time-series with a wide-frequency band, the characteristics of earthquake excitation mainly include the nature of source, the earthquake magnitude, the source-to-site distance, the spreading path, and the site condition. The seismic energy response of elastoplastic SDOF systems that are studied is affected by the external factors of earthquake magnitude and site condition.
Table 1: Basic information of near-fault pulse-like earthquake records.

| No. | Earthquake events | Station component | M ($M_w$) | D (km) | S  |
|-----|-------------------|-------------------|-----------|--------|----|
| 1   | Northridge        | 1085_SCE018       | 6.7       | 5.2    | C  |
| 2   | Northridge        | 1085_SCE288       | 6.7       | 5.2    | C  |
| 3   | Northridge        | 1084_SCS052       | 6.7       | 5.3    | D  |
| 4   | Northridge        | 1084_SCS142       | 6.7       | 5.3    | D  |
| 5   | Northridge        | 1086_SYL090       | 6.7       | 5.3    | C  |
| 6   | Northridge        | 1086_SYL360       | 6.7       | 5.3    | C  |
| 7   | Northridge        | 1045_WPI046       | 6.7       | 5.5    | D  |
| 8   | Northridge        | 1045_WPI316       | 6.7       | 5.5    | D  |
| 9   | Northridge        | 1013_LDM064       | 6.7       | 5.9    | C  |
| 10  | Northridge        | 1013_LDM334       | 6.7       | 5.9    | C  |
| 11  | Northridge        | 1044_NWH090       | 6.7       | 5.9    | D  |
| 12  | Northridge        | 1044_NWH360       | 6.7       | 5.9    | D  |
| 13  | Northridge        | 1063_RSS228       | 6.7       | 6.5    | D  |
| 14  | Northridge        | 1063_RSS318       | 6.7       | 6.5    | D  |
| 15  | Northridge        | 1050_PAC175       | 6.7       | 7      | A  |
| 16  | Northridge        | 1050_PAC265       | 6.7       | 7      | A  |
| 17  | Northridge        | 1052_PKC090       | 6.7       | 7.6    | C  |
| 18  | Northridge        | 1052_PKC360       | 6.7       | 7.6    | C  |
| 19  | Northridge        | 949_ARL090        | 6.7       | 8.7    | D  |
| 20  | Northridge        | 949_ARL360        | 6.7       | 8.7    | D  |
| 21  | Northridge        | 1082_RO3000       | 6.7       | 10.1   | D  |
| 22  | Northridge        | 1082_RO3090       | 6.7       | 10.1   | D  |
| 23  | Northridge        | 960_LOS000        | 6.7       | 12.4   | D  |
| 24  | Northridge        | 960_LOS270        | 6.7       | 12.4   | D  |
| 25  | Northridge        | 1083_GLE170       | 6.7       | 13.3   | C  |
| 26  | Northridge        | 1083_GLE260       | 6.7       | 13.3   | C  |
| 27  | Northridge        | 1080_KAT000       | 6.7       | 13.4   | C  |
| 28  | Northridge        | 1080_KAT090       | 6.7       | 13.4   | C  |
| 29  | Northridge        | 1087_TAR090       | 6.7       | 15.6   | D  |
| 30  | Northridge        | 1087_TAR360       | 6.7       | 15.6   | D  |
| 31  | Northridge        | 953_MUL009        | 6.7       | 17.1   | D  |
| 32  | Northridge        | 953_MUL279        | 6.7       | 17.1   | D  |
| 33  | Northridge        | 1016_NYA090       | 6.7       | 18.5   | C  |
| 34  | Northridge        | 1016_NYA180       | 6.7       | 18.5   | C  |
| 35  | Northridge        | 1012_LA0000       | 6.7       | 19.1   | C  |
| 36  | Northridge        | 1012_LA0090       | 6.7       | 19.1   | C  |
| 37  | Chichi            | TCU068-EW         | 7.6       | 0.32   | C  |
| 38  | Chichi            | TCU068-NS         | 7.6       | 0.32   | C  |
| 39  | Chichi            | TCU065-EW         | 7.6       | 0.57   | D  |
| 40  | Chichi            | TCU065-NS         | 7.6       | 0.57   | D  |
| 41  | Chichi            | TCU052-EW         | 7.6       | 0.66   | C  |
| 42  | Chichi            | TCU052-NS         | 7.6       | 0.66   | C  |
| 43  | Chichi            | TCU102-EW         | 7.6       | 1.49   | C  |
| 44  | Chichi            | TCU102-NS         | 7.6       | 1.49   | C  |
| 45  | Chichi            | CHY080-EW         | 7.6       | 2.69   | C  |
| 46  | Chichi            | CHY080-NS         | 7.6       | 2.69   | C  |
| 47  | Chichi            | TCU103-EW         | 7.6       | 6.08   | C  |
| 48  | Chichi            | TCU087-NS         | 7.6       | 6.98   | C  |
| 49  | Chichi            | TCU120-EW         | 7.6       | 7.4    | C  |
| 50  | Chichi            | TCU136-EW         | 7.6       | 8.27   | C  |
| 51  | Chichi            | TCU136-NS         | 7.6       | 8.27   | C  |
| 52  | Chichi            | CHY006-EW         | 7.6       | 9.76   | C  |
| 53  | Chichi            | CHY006-NS         | 7.6       | 9.76   | C  |
| 54  | Chichi            | TCU138-NS         | 7.6       | 9.78   | C  |
| 55  | Chichi            | TCU063-EW         | 7.6       | 9.78   | C  |
| 56  | Chichi            | TCU063-NS         | 7.6       | 9.78   | C  |
| 57  | Chichi            | CHY029-EW         | 7.6       | 10.96  | C  |
| 58  | Chichi            | CHY029-NS         | 7.6       | 10.96  | C  |
| 59  | Chichi            | TCU100-NS         | 7.6       | 11.37  | C  |
| 60  | Chichi            | TCU116-EW         | 7.6       | 12.38  | C  |
4.1. Energy Response Spectra Affected by the Characteristic of Earthquake Excitation

4.1.1. Earthquake Magnitude. Taken as an example are the ground motions in the site class C of near-fault pulse-like earthquake records (listed in Table 1), and the selected earthquake records are classified as $M_W$ 6.7 and $M_W$ 7.6. Taken as an example are the ground motions in the site class D of far-field harmonic earthquake records, and the selected earthquake records are classified as $M_W$ 7.3, $M_W$ 8.0, and $M_W$ 9.0. Various energy response spectra on the total input energy, hysteretic energy dissipation, and damping energy dissipation are calculated under near-fault pulse-like and far-field harmonic ground motions, respectively. The damping ratio of 5%, the ductility coefficient of 3.0, and the yield stiffness ratio of 0.05 are initially assumed based on the bilinear restoring force model of SDOF systems.

The numbers of samples in each earthquake magnitude of near-fault pulse-like and far-field harmonic ground motion records are exhibited in Figure 3. Figures 4 and 5 illustrate the influence of earthquake magnitude on various energy response spectra under near-fault pulse-like and far-field harmonic ground motions, respectively. The damping ratio of 5%, the ductility coefficient of 3.0, and the yield stiffness ratio of 0.05 are initially assumed based on the bilinear restoring force model of SDOF systems.

The numbers of samples in each earthquake magnitude of near-fault pulse-like and far-field harmonic ground motion records are exhibited in Figure 3. Figures 4 and 5 illustrate the influence of earthquake magnitude on various energy response spectra under near-fault pulse-like and far-field harmonic ground motions, respectively. The damping ratio of 5%, the ductility coefficient of 3.0, and the yield stiffness ratio of 0.05 are initially assumed based on the bilinear restoring force model of SDOF systems.

The numbers of samples in each earthquake magnitude of near-fault pulse-like and far-field harmonic ground motion records are exhibited in Figure 3. Figures 4 and 5 illustrate the influence of earthquake magnitude on various energy response spectra under near-fault pulse-like and far-field harmonic ground motions, respectively. The damping ratio of 5%, the ductility coefficient of 3.0, and the yield stiffness ratio of 0.05 are initially assumed based on the bilinear restoring force model of SDOF systems.

4.1.2. Site Condition. Taken as an example are ground motions in $M_W$ 6.7 of near-fault pulse-like earthquake records, and the selected earthquake records are classified as the site class C and D. Taken as an example are ground motions in $M_W$ 8.0 of far-field harmonic ground motions, and the selected earthquake records are classified as the site class C and D. Table 1 shows the continued information of earthquake events and station components.

| No. | Earthquake events | Station component | $M$ ($M_W$) | $D$ (km) | $S$ |
|-----|-------------------|------------------|-------------|----------|-----|

Table 1: Continued.
Table 2: Basic information of far-field harmonic earthquake records.

| No. | Earthquake events | Station component | $M (M_w)$ | D (km) | S |
|-----|-------------------|-------------------|-----------|--------|---|
| 1   | Kumamoto          | EHM07-EW2         | 7.3       | 203    | D |
| 2   | Kumamoto          | EHM07-NS2         | 7.3       | 203    | D |
| 3   | Kumamoto          | EHM016-EW         | 7.3       | 213    | D |
| 4   | Kumamoto          | EHM016-NS         | 7.3       | 213    | D |
| 5   | Kumamoto          | SMNH09-EW2        | 7.3       | 233    | C |
| 6   | Kumamoto          | SMNH09-NS2        | 7.3       | 233    | C |
| 7   | Kumamoto          | EHM04-EW2         | 7.3       | 249    | D |
| 8   | Kumamoto          | EHM04-NS2         | 7.3       | 249    | D |
| 9   | Kumamoto          | HRS04-EW          | 7.3       | 260    | C |
| 10  | Kumamoto          | HRS04-NS          | 7.3       | 260    | C |
| 11  | Kumamoto          | KOCH13-EW2        | 7.3       | 285    | C |
| 12  | Kumamoto          | KOCH13-NS2        | 7.3       | 285    | C |
| 13  | Kumamoto          | OKYH06-EW2        | 7.3       | 333    | C |
| 14  | Kumamoto          | OKYH06-NS2        | 7.3       | 333    | C |
| 15  | Kumamoto          | TKS005-EW         | 7.3       | 360    | D |
| 16  | Kumamoto          | TKS005-NS         | 7.3       | 360    | D |
| 17  | Kumamoto          | TTR006-EW         | 7.3       | 404    | D |
| 18  | Kumamoto          | TTR006-NS         | 7.3       | 404    | D |
| 19  | Kumamoto          | OSK010-EW         | 7.3       | 454    | D |
| 20  | Kumamoto          | OSK010-NS         | 7.3       | 454    | D |
| 21  | Kumamoto          | NAR007-EW         | 7.3       | 490    | C |
| 22  | Kumamoto          | NAR007-NS         | 7.3       | 490    | C |
| 23  | Kumamoto          | KYTH04-EW2        | 7.3       | 523    | B |
| 24  | Kumamoto          | KYTH04-NS2        | 7.3       | 523    | B |
| 25  | Kumamoto          | MIEH03-EW2        | 7.3       | 557    | C |
| 26  | Kumamoto          | MIEH03-NS2        | 7.3       | 557    | C |
| 27  | Kumamoto          | MIEH07-EW2        | 7.3       | 587    | C |
| 28  | Kumamoto          | MIEH07-NS2        | 7.3       | 587    | C |
| 29  | Kumamoto          | AIC001-EW         | 7.3       | 620    | E |
| 30  | Kumamoto          | AIC001-NS         | 7.3       | 620    | E |
| 31  | Kumamoto          | AIC015-EW         | 7.3       | 654    | D |
| 32  | Kumamoto          | AIC015-NS         | 7.3       | 654    | D |
| 33  | Kumamoto          | GIFH24-EW2        | 7.3       | 683    | B |
| 34  | Kumamoto          | GIFH24-NS2        | 7.3       | 683    | B |
| 35  | Kumamoto          | NGNO04-EW         | 7.3       | 721    | D |
| 36  | Kumamoto          | NGNO04-NS         | 7.3       | 721    | D |
| 37  | Tokachi           | IUBH03-EW         | 8.0       | 206    | E |
| 38  | Tokachi           | IUBH03-NS         | 8.0       | 206    | E |
| 39  | Tokachi           | HKD130-EW         | 8.0       | 241    | C |
| 40  | Tokachi           | HKD130-NS         | 8.0       | 241    | C |
| 41  | Tokachi           | ABSH04-EW2        | 8.0       | 280    | C |
| 42  | Tokachi           | ABSH04-NS2        | 8.0       | 280    | C |
| 43  | Tokachi           | HKD151-EW         | 8.0       | 318    | D |
| 44  | Tokachi           | HKD151-NS         | 8.0       | 318    | D |
| 45  | Tokachi           | AOM018-EW         | 8.0       | 343    | C |
| 46  | Tokachi           | AOM018-NS         | 8.0       | 343    | C |
| 47  | Tokachi           | HKD025-EW         | 8.0       | 374    | D |
| 48  | Tokachi           | HKD025-NS         | 8.0       | 374    | D |
| 49  | Tokachi           | AKT013-EW         | 8.0       | 399    | C |
| 50  | Tokachi           | AKT013-NS         | 8.0       | 399    | C |
| 51  | Tokachi           | AKT018-EW         | 8.0       | 437    | D |
| 52  | Tokachi           | AKT018-NS         | 8.0       | 437    | D |
| 53  | Tokachi           | YMT001-EW         | 8.0       | 482    | E |
| 54  | Tokachi           | YMT001-NS         | 8.0       | 482    | E |
| 55  | Tokachi           | YMT015-EW         | 8.0       | 548    | E |
| 56  | Tokachi           | YMT015-NS         | 8.0       | 548    | E |
| 57  | Tokachi           | YMT020-EW         | 8.0       | 580    | E |
| 58  | Tokachi           | YMT020-NS         | 8.0       | 580    | E |

6 Advances in Civil Engineering
class C, D, and E. Various energy response spectra on the total input energy, hysteretic energy dissipation, and damping energy dissipation are calculated under near-fault pulse-like and far-field harmonic ground motions, respectively. A damping ratio of 5%, the ductility coefficient of 3.0, and the yield stiffness ratio of 0.05 are initially assumed based on the bilinear restoring force model of SDOF systems.

The numbers of samples in each site class of near-fault pulse-like and far-field harmonic ground motion records are exhibited in Figure 6. Figures 7 and 8 illustrate the influence of site class on various energy response spectra under near-fault pulse-like and far-field harmonic ground motions. The peaks of various energy response spectra under two types of long-period ground motions show a rising trend with the softer of site soil, and their increased amplifications even aggravate when the site soil softens. For near-fault pulse-like ground motions, the site condition has a great influence on various energy response spectra in the period range of 1–5 s. When the vibration period of SDOF systems is beyond 5 s, the site condition has little influence on the hysteretic energy and damping energy. For far-field harmonic ground motions, various energy response spectra are almost not affected by site condition in the short period of 0–1 s. They show a rising trend with the softer of site soil in the medium-long period of 1–10 s, and their increased amplifications are significant. When the vibration period of SDOF systems is beyond 10 s, their increased amplifications relatively get smaller.

4.2. Energy Distribution Rule Affected by the Characteristic of Earthquake Excitation. After obtaining the total input energy, hysteretic energy dissipation and damping energy dissipation, the ratio of hysteretic energy to input energy (RHEIE), and the ratio of damping energy to input energy

| No. | Earthquake events | Station component | M (M_w) | D (km) | S |
|-----|-------------------|-------------------|--------|-------|---|
| 61  | Tokachi           | FKSHE21-EW2       | 8.0    | 640   | C |
| 62  | Tokachi           | FKSHE21-NS2       | 8.0    | 640   | C |
| 63  | Tokachi           | NIGH11-EW2        | 8.0    | 687   | C |
| 64  | Tokachi           | NIGH11-NS2        | 8.0    | 687   | C |
| 65  | Tokachi           | NGNH128-EW2       | 8.0    | 763   | B |
| 66  | Tokachi           | NGNH128-NS2       | 8.0    | 763   | B |
| 67  | East Japan        | MYG005-EW         | 9.0    | 208   | D |
| 68  | East Japan        | MYG005-NS         | 9.0    | 208   | D |
| 69  | East Japan        | YMTT002-EW        | 9.0    | 236   | D |
| 70  | East Japan        | YMTT002-NS        | 9.0    | 236   | D |
| 71  | East Japan        | YMTTH12-EW2       | 9.0    | 256   | C |
| 72  | East Japan        | YMTTH12-NS2       | 9.0    | 256   | C |
| 73  | East Japan        | FJKH03-EW2        | 9.0    | 279   | D |
| 74  | East Japan        | FJKH03-NS2        | 9.0    | 279   | D |
| 75  | East Japan        | NIG009-EW         | 9.0    | 310   | E |
| 76  | East Japan        | NIG009-NS         | 9.0    | 310   | E |
| 77  | East Japan        | AOMH10-EW2        | 9.0    | 336   | D |
| 78  | East Japan        | AOMH10-NS2        | 9.0    | 336   | D |
| 79  | East Japan        | AOM019-EW         | 9.0    | 366   | E |
| 80  | East Japan        | AOM019-NS         | 9.0    | 366   | E |
| 81  | East Japan        | CHBH20-EW2        | 9.0    | 416   | A |
| 82  | East Japan        | CHBH20-NS2        | 9.0    | 416   | A |
| 83  | East Japan        | NIGH17-EW2        | 9.0    | 443   | C |
| 84  | East Japan        | NIGH17-NS2        | 9.0    | 443   | C |
| 85  | East Japan        | YMN010-EW         | 9.0    | 472   | C |
| 86  | East Japan        | YMN010-NS         | 9.0    | 472   | C |
| 87  | East Japan        | YMNHH13-EW2       | 9.0    | 500   | B |
| 88  | East Japan        | YMNHH13-NS2       | 9.0    | 500   | B |
| 89  | East Japan        | HKD102-EW         | 9.0    | 531   | D |
| 90  | East Japan        | HKD102-NS         | 9.0    | 531   | D |
| 91  | East Japan        | SZOH53-EW2        | 9.0    | 562   | B |
| 92  | East Japan        | SZOH53-NS2        | 9.0    | 562   | B |
| 93  | East Japan        | AIC005-EW         | 9.0    | 599   | D |
| 94  | East Japan        | AIC005-NS         | 9.0    | 599   | D |
| 95  | East Japan        | AIC003-EW         | 9.0    | 636   | E |
| 96  | East Japan        | AIC003-NS         | 9.0    | 636   | E |
| 97  | East Japan        | HKD030-EW         | 9.0    | 676   | D |
| 98  | East Japan        | HKD030-NS         | 9.0    | 676   | D |
| 99  | East Japan        | ABSH01-EW2        | 9.0    | 714   | B |
|100  | East Japan        | ABSH01-NS2        | 9.0    | 714   | B |
Table 3: Basic information of common earthquake records.

| No. | Earthquake events     | Station component | Magnitude ($M_w$) | Distance (km) | Site class |
|-----|-----------------------|-------------------|------------------|---------------|------------|
| 1   | Imperial Valley       | ELC000            | 5.0              | 34.98         | D          |
| 2   | Imperial Valley       | ELC090            | 5.0              | 34.98         | D          |
| 3   | Imperial Valley       | ELC180            | 6.59             | 6.09          | D          |
| 4   | Imperial Valley       | ELC270            | 6.59             | 6.09          | D          |
| 5   | Kobe                  | OKA000            | 6.9              | 86.94         | C          |
| 6   | Kobe                  | OKA090            | 6.9              | 86.94         | C          |
| 7   | Tabas, Iran           | TAB-L1            | 7.35             | 2.05          | B          |
| 8   | Tabas, Iran           | TAB-T1            | 7.35             | 2.05          | B          |
| 9   | Kern County           | TAF021            | 7.36             | 38.89         | C          |
| 10  | Kern County           | TAF111            | 7.36             | 38.89         | C          |
| 11  | Kern County           | PAS180            | 7.36             | 125.59        | C          |
| 12  | Kern County           | PAS270            | 7.36             | 125.59        | C          |
| 13  | Kobe                  | OSA000            | 6.9              | 21.35         | D          |
| 14  | Kobe                  | OSA090            | 6.9              | 21.35         | D          |
| 15  | Kobe                  | SHI000            | 6.9              | 19.15         | D          |
| 16  | Kobe                  | SHI090            | 6.9              | 19.15         | D          |
| 17  | Loma Prieta           | AGW000            | 6.93             | 24.57         | D          |
| 18  | Loma Prieta           | AGW090            | 6.93             | 24.57         | D          |
| 19  | Loma Prieta           | HCH090            | 6.93             | 27.6          | D          |
| 20  | Loma Prieta           | HCH180            | 6.93             | 27.6          | D          |
| 21  | Superstition Hill (B)| B-ICC000          | 6.54             | 18.2          | D          |
| 22  | Superstition Hill (B)| B-ICC090          | 6.54             | 18.2          | D          |
| 23  | Superstition Hill (B)| B-WSM090          | 6.54             | 13.03         | D          |
| 24  | Superstition Hill (B)| B-WSM180          | 6.54             | 13.03         | D          |
| 25  | Superstition Hill (B)| B-IVW090          | 6.54             | 23.85         | E          |
| 26  | Superstition Hill (B)| B-IVW360          | 6.54             | 23.85         | E          |

Figure 1: Continued.
(RDEIE) of SDOF systems could be calculated out under earthquake excitation. The energy distribution rule of elastoplastic SDOF systems studied is affected by the external factors of earthquake magnitude and site condition under near-fault pulse-like and far-field harmonic ground motions, respectively.

4.2.1. Earthquake Magnitude. Figures 9 and 10 illustrate the influence of earthquake magnitude on the energy distribution rule of SDOF systems under two types of long-period ground motions. For near-fault pulse-like ground motions, the distribution rule on total input energy is hardly affected by earthquake magnitude in the short period of 0–2 s. The RHEIE and RDEIE both decrease in the medium and long period. Particularly when the earthquake magnitude is $M_W$ 6.7, the decline of RHEIE and RDEIE reaches 62.5% and 40.4%. The total seismic input energy of a structure with medium or long vibration period mainly depends on the damping energy to dissipate. The low-magnitude near-fault pulse-like earthquake always induces less inelastic deformation, so it would mitigate the structural damage. For far-field harmonic ground motions, the decline of RHEIE reaches 33.6% at $M_W$ 7.3. The RHEIE varies within 60%–68% at $M_W$ 8.0 and $M_W$ 9.0. The hysteretic energy is the main way to dissipate the total seismic input energy of a structure under large magnitude far-field harmonic earthquake. However, the large magnitude far-field harmonic earthquake would exacerbate the structural damage due to the increased inelastic deformation. The RDEIE slightly grows with the increase of earthquake magnitude, and it does not significantly change along the vibration period of SDOF systems.

4.2.2. Site Condition. Figures 11 and 12 illustrate the influence of site class on the energy distribution rule of SDOF systems under two types of long-period ground motions. For near-fault pulse-like ground motions, the RHEIE and RDEIE both decrease in the site class C and D and the decline of RHEIE reaches 40% or so. The RHEIE in the site class D is slightly larger than that in the site class C, but the RDEIE is hardly affected by site class. For far-field harmonic ground motions, the RHEIE decreases in the site class C, D, and E. Specifically speaking, the decline of RHEIE in the site class C and D is about 30.5% and 28.8%, respectively. However, the RHEIE in the site class E is greatly different from that in above two types of site class in the period of

Figure 1: Basic property of partial earthquake records. (a) Acceleration time histories (s). (b) Fourier amplitude spectrum (Hz).
Figure 2: Energy response spectra. (a) Input energy. (b) Hysteretic energy. (c) Damping energy.

Figure 3: Numbers of samples in each earthquake magnitude. (a) Near-fault pulse-like ground motions. (b) Far-field harmonic ground motions.
5–16 s, even the maximum difference is up to 48.2%. The RDEIEs in the site class C, D, and E are within the fluctuation of 45%–55%.

5. Energy Response Spectra Affected by Internal Factors

Previous context has done much detailed analysis on the external factors. From the internal factors, the dynamic characteristic of a structure mainly include the damping model, the restoring force model, the damping ratio, the ductility coefficient, the second stiffness coefficient, and the yield displacement. The seismic energy response of elastoplastic SDOF systems are studied affected by the internal factors of damping ratio, ductility coefficient, and yield stiffness ratio.

5.1. Input Energy Spectra Affected by the Dynamic Characteristic of a Structure

5.1.1. Damping ratio. The ductility coefficient of 3.0 and the damping ratio of 0.02, 0.05, 0.1, and 0.2 are initially assumed based on the bilinear restoring force model. Figure 13 shows the influence of damping ratio on the input energy spectra under near-fault pulse-like and far-field harmonic ground motions. As the ductility coefficient of 3.0 keeps constant, the peaks on input energy spectra about two types of long-period ground motions slowly drop with the increase of damping ratio. As the damping ratio increases, the input energy spectra drop on the left side of demarcation point, while the input energy spectra grow on the right side of demarcation point. Compared with near-fault pulse-like ground motions, the specific period corresponding to the peak of input energy spectra tends to the short-period

**Figure 4:** Energy response spectra affected by earthquake magnitude under near-fault pulse-like ground motions. (a) Input energy. (b) Hysteretic energy. (c) Damping energy.
Figure 5: Energy response spectra affected by earthquake magnitude under far-field harmonic ground motions. (a) Input energy. (b) Hysteretic energy. (c) Damping energy.

Figure 6: Numbers of samples in each site class. (a) Near-fault pulse-like ground motions. (b) Far-field harmonic ground motions.
direction under far-field harmonic ground motions. As the ductility coefficient of 3.0 keeps constant, the input energy spectra under two types of long-period ground motions are almost not affected by damping ratio in the short period of 0–2 s. The influence of damping ratio on the input energy spectra of near-fault pulse-like ground motions is greater than that of far-field harmonic ground motions in the medium–long period of 2–7 s. On the contrary, the influence of damping ratio on the input energy spectra of near-fault pulse-like ground motions is less than that of far-field harmonic ground motions when the vibration period is beyond 7 s.

5.1.2. Ductility Coefficient. The damping ratio of 5% and the ductility coefficient of 1, 3, 5, and 8 are initially assumed based on the bilinear restoring force model. Figure 14 shows the influence of ductility coefficient on the input energy spectra under near-fault pulse-like and far-field harmonic ground motions. As the damping ratio of 5% keeps constant, the peaks on input energy spectra about two types of long-period ground motions continuously drop with the increase of ductility coefficient. As the ductility coefficient increases, the specific period corresponding to the peak of input energy spectra tends to the short-period direction more significantly under near-fault pulse-like ground motions than that under far-field harmonic ground motions. For two types of long-period ground motions, the input energy spectra are almost the same under different ductility coefficient in the short period of 0–2.8 s. The input energy spectra show a decreasing trend with the increase of ductility coefficient in the period range of 2.8–12 s. The input energy spectra of two types of long-period ground motions tend to be stable when the vibration period is beyond 12 s.
Figure 8: Energy response spectra affected by site class under far-field harmonic ground motions. (a) Input energy. (b) Hysteretic energy. (c) Damping energy.

Figure 9: Energy distribution rule affected by earthquake magnitude under near-fault pulse-like ground motions. (a) RHEIE. (b) RDEIE.
5.2. Hysteretic Energy Spectra Affected by the Dynamic Characteristic of a Structure

5.2.1. Damping ratio. The ductility coefficient of 3.0 and the damping ratio of 0.02, 0.05, 0.1, and 0.2 are initially assumed based on the bilinear restoring force model. Figure 15 shows the influence of damping ratio on the hysteretic energy spectra under near-fault pulse-like and far-field harmonic ground motions. On the whole, the influence of damping ratio on the hysteretic energy spectra under two types of long-period ground motions is mainly reflected in the vicinity of the specific period corresponding to the peak. The influence of damping ratio on the hysteretic energy spectra is not significant in the short and long period. The peaks on hysteretic energy spectra under two types of long-period ground motions significantly drop with the increase of damping ratio. The specific period corresponding to the peak of hysteretic energy tends to the short-period direction under far-field harmonic ground motions. The hysteretic energy spectra under two types of long-period ground motions both reduce with the increase of damping ratio, and this property is manifested in the whole period range. It indicates that the damping ratio has a significant influence on the distribution rule of total input energy dissipation. The greater the damping ratio, the smaller the RHEIE (that is, the greater the RDEIE). Therefore, damping ratio plays an important role in the distribution rule of total input energy dissipation among the hysteretic energy and damping energy.

---

**Figure 10:** Energy distribution rule affected by earthquake magnitude under far-field harmonic ground motions. (a) RHEIE. (b) RDEIE.

**Figure 11:** Energy distribution rule affected by site class under near-fault pulse-like ground motions. (a) RHEIE. (b) RDEIE.
5.2.2. Ductility Coefficient. The damping ratio of 5% and the ductility coefficient of 1, 3, 5, and 8 are initially assumed based on the bilinear restoring force model. Figure 16 shows the influence of ductility coefficient on the hysteretic energy spectra under near-fault pulse-like and far-field harmonic ground motions. As the damping ratio of 5% keeps constant, the influencing rule of ductility coefficient on the hysteretic energy spectra under near-fault pulse-like ground motions is different from that under far-field harmonic ground motions. As the ductility coefficient increases, the peaks of hysteretic energy spectra drop under near-fault pulse-like ground motions, while the peaks of hysteretic energy spectra show a rising trend under far-field harmonic ground motions. The specific period corresponding to the peak both tends to the short-period direction under two types of long-period ground motions. For two types of long-period ground motions, ductility coefficient has little influence on the hysteretic energy spectra in the short period of 0–3 s, while the hysteretic energy spectra show a decreasing trend with the increase of ductility coefficient in the period range of 3–13 s. The hysteretic energy spectra are almost the same under different ductility coefficient, and the spectra values even tend to be stable when the vibration period is beyond 13 s.
5.2.3. Yield Stiffness Ratio. Bilinear restoring force models and stiffness degradation models are widely used for the hysteresis models of elastoplastic SDOF systems. The bilinear restoring force model is employed for this paper, and the yield stiffness ratio is the most important parameter influencing the bilinear restoring force models. The ductility coefficient of 3.0, the damping ratio of 5%, and the yield stiffness ratio of 0, 0.05, and 0.2 are initially assumed based on the bilinear restoring force model. Figure 17 shows the influence of yield stiffness ratio on the hysteretic energy spectra under near-fault pulse-like and far-field harmonic ground motions. As the ductility coefficient of 3.0 and damping ratio of 5% keep constant, the peaks of hysteretic energy spectra slightly grow with the increase of yield stiffness ratio under two types of long-period ground motions. As the yield stiffness ratio increases from 0, 0.05 to 0.2, the increasing amplitudes about the peaks of hysteretic energy spectra only reach 1.60% and 5.68% under near-fault pulse-like ground motions, while the increasing amplitudes about the peaks of hysteretic energy spectra only reach 3.96% and 7.30% under far-field harmonic ground motions.

In summary, the influence of yield stiffness ratio on the hysteretic energy can be neglected in the practical engineering application as the ductility coefficient and damping
ratio keep constant because yield stiffness ratio has little influence on the hysteretic energy under near-fault pulse-like and far-field harmonic ground motions.

6. Conclusions

The energy-based design method is used to evaluate the seismic energy response and energy distribution rule of elastoplastic SDOF systems under two types of special long-period earthquake excitation. The input energy, hysteretic energy, and damping energy are related to the characteristic of earthquake excitation and the dynamic characteristic of a structure itself, such as the earthquake magnitude, site condition, source-to-site distance, ductility coefficient, damping ratio, yield stiffness ratio, et al.

Within the whole period, all the input energy, hysteretic energy and damping energy spectra of SDOF systems under near-fault pulse-like and far-field harmonic ground motions, are larger than those under common ground motions, even the seismic energy response under far-field harmonic ground motions is larger than that under near-fault pulse-like ground motions. The peaks of input energy spectra, hysteretic energy spectra and damping energy spectra under long-period ground motions, show a rising trend with the
softer of site soil, and the increased amplifications even aggravate when the site soil gets softer. It is suggested to be related to the effects of filtering out the high-frequency components and amplifying the low-frequency components of soft site soil.

From the aspect of energy concept, the seismic energy response and energy distribution rule of SDOF systems are evaluated according to the intensity and spectral distribution under near-fault pulse-like and far-field harmonic ground motions. If the ratio of hysteretic energy to input energy (RHEIE) is determined, the hysteretic energy which must be dissipated by a structure would be derived by the method of energy-based design. The input energy and hysteretic energy are mainly influenced by damping ratio and ductility coefficient, while the yield stiffness ratio exerts minor effects. Therefore, the influence of yield stiffness ratio on the hysteretic energy can be neglected in the practical engineering application. It indicates that reasonable structural design parameters would contribute to the hysteretic energy of a structure itself.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

The present work was supported by the Doctoral Research Foundation of Hubei University of Arts and Science (nos. 2059070), Project of Hubei University of Arts and Science, Hubei Superior and Distinctive Discipline Group of “Mechatronics and Automobiles,” National Natural Science Foundation of China (no. 52074112), and Provincial Education Department Program of Hubei Province (no. D20182601). These supports were greatly appreciated.

References

[1] K. Koketsu and H. Miyake, "A seismological overview of long-period ground motion," Journal of Seismology, vol. 12, no. 2, pp. 133–143, 2008.
[2] I. Takewaki, S. Murakami, K. Fujita, S. Yoshitomi, M. Tsuji, and M. Tsuji, "The 2011 off the Pacific coast of Tohoku earthquake and response of high-rise buildings under long-period ground motions," Soil Dynamics and Earthquake Engineering, vol. 31, no. 11, pp. 1511–1528, 2011.
[3] Y. Cheng and G. L. Bai, "Basic characteristic parameters and influencing factors of long-period ground motion records," Journal of Vibration, vol. 19, no. 7, pp. 5191–5207, 2017.
[4] Y.-L. Chung, T. Nagae, T. Hitaka et al., “Seismic resistance capacity of high-rise buildings subjected to long-period ground motions: E-Defense shaking table test,” Journal of Structural Engineering, vol. 136, no. 6, pp. 637–644, 2010.
[5] T. Ariga, Y. Kanno, and I. Takewaki, “Resonant behaviour of base-isolated high-rise buildings under long-period ground motions,” The Structural Design of Tall and Special Buildings, vol. 15, no. 3, pp. 325–338, 2006.
[6] F. Mazza, M. Mazza, and A. Vulcano, “Nonlinear response of r.c. framed buildings retrofitted by different base-isolation systems under horizontal and vertical components of near-fault earthquakes,” Earthquakes and Structures, vol. 12, no. 1, pp. 135–144, 2017.
[7] F. Mazza, “Base-isolation of a hospital pavilion against in-plane-out-of-plane seismic collapse of masonry infills,” Engineering Structures, vol. 228, Article ID 111504, 2021.
[8] R. S. Jalali and M. D. Trifunac, “A note on strength-reduction factors for design of structures near earthquake faults,” Soil Dynamics and Earthquake Engineering, vol. 28, no. 3, pp. 212–222, 2008.
[9] A. K. Chopra and C. Chintanapakdee, “Inelastic deformation ratios for design and evaluation of structures: single-degree-of-freedom bilinear systems,” Journal of Structural Engineering, vol. 130, no. 9, pp. 1309–1319, 2004.
[10] Y.-R. Dong, Z.-D. Xu, K. Zeng, Y. Cheng, and C. Xu, "Seismic behavior and cross-scale refinement model of damage evolution for RC shear walls," Engineering Structures, vol. 167, pp. 13–25, 2018.
[11] Y.-R. Dong, Z.-D. Xu, Q.-Q. Li, Y.-S. Xu, and Z.-H. Chen, “Seismic behavior and damage evolution for retrofitted RC frames using hauunch viscoelastic damping braces,” Engineering Structures, vol. 199, Article ID 109583, 2019.
[12] G. W. Housner, “Limit design of structures to resist earthquake,” in Proceedings of 1st World Conference on Earthquake Engineering, vol. 5, pp. 5.1–5.13, Berkeley, CF, USA, July 1956.
[13] C.-M. Uang and V. V. Bertero, “Evaluation of seismic energy in structures,” Earthquake Engineering & Structural Dynamics, vol. 19, no. 1, pp. 77–90, 1990.
[14] P. Fajfar and T. Vidic, “Consistent inelastic design spectra: hysteretic and input energy,” Earthquake Engineering & Structural Dynamics, vol. 23, no. 5, pp. 523–537, 1994.
[15] G. Ghodrati Amiri, G. A. Darzi, and J. Vaseghi Amiri, “Design elastic input energy spectra based on Iranian earthquakes,” Canadian Journal of Civil Engineering, vol. 35, no. 6, pp. 635–646, 2008.
[16] A. Benavent-Climent, F. López-Almansa, and D. A. Bravo-González, “Design energy input spectra for moderate-to-high seismicity regions based on Colombian earthquakes,” Soil Dynamics and Earthquake Engineering, vol. 30, no. 11, pp. 1129–1148, 2010.
[17] S. Szniszewski and T. Krauthammer, “Energy flow in progressive collapse of steel framed buildings,” Engineering Structures, vol. 42, pp. 142–153, 2012.
[18] C. Zhai, Z. Chang, S. Li, Z. Chen, and L. Xie, “Quantitative identification of near-fault pulse-like ground motions based on energy,” Bulletin of the Seismological Society of America, vol. 103, no. 5, pp. 2591–2603, 2013.
[19] K. Ke, G. Chuan, and S. Ke, “Seismic energy factor of self-centering systems subjected to near-fault earthquake ground motions,” Soil Dynamics and Earthquake Engineering, vol. 84, pp. 169–173, 2016.
[20] S. Pathak, A. Khennane, and S. Al Deen, “Energy formulation for seismic collapse assessment of RCC structures: improvements in performance design,” in Proceedings of Australian Earthquake Engineering Society 2017, Canberra, Australia, November 2017.
[21] D. Deniz, I. Song, and J. F. Hajjar, “Energy-based sideways collapse fragilities for ductile structural frames under earthquake loadings,” Engineering Structures, vol. 174, pp. 282–294, 2018.
[22] I. Takewaki and K. Fujita, “Earthquake input energy to tall and base-isolated buildings in time and frequency dual domains,” *The Structural Design of Tall and Special Buildings*, vol. 18, no. 6, pp. 589–606, 2009.

[23] Q.-j. Chen, W.-z. Yuan, Y.-c. Li, and L.-y. Cao, “Dynamic response characteristics of super high-rise buildings subjected to long-period ground motions,” *Journal of Central South University*, vol. 20, no. 5, pp. 1341–1353, 2013.

[24] L. D. Decanini and F. Mollaioli, “Formulation of elastic earthquake input energy spectra,” *Earthquake Engineering & Structural Dynamics*, vol. 27, no. 12, pp. 1503–1522, 1998.

[25] H. Sucuoğlu and A. Nurtug, “Earthquake ground motion characteristics and seismic energy dissipation,” *Earthquake Engineering and Structural Dynamics*, vol. 24, no. 9, pp. 1195–1213, 1995.

[26] H. Akiyama, “Collapse modes of structures under strong motions of earthquake,” *Annals of Geophysics*, vol. 45, no. 6, pp. 791–798, 2002.

[27] N. Fukuwa and J. Tobita, “Key parameters governing the dynamic response of long-period structures,” *Journal of Seismology*, vol. 12, no. 2, pp. 295–306, 2008.

[28] Y. Cheng, G. Bai, and Y. Dong, “Spectrum characterization of two types of long-period ground motions and seismic behavior of frame-core wall structures under multidimensional earthquake records,” *The Structural Design of Tall and Special Buildings*, vol. 27, no. 16, p. e1539, 2018.

[29] J. Li, H. Zhou, and Y. Ding, “Stochastic seismic collapse and reliability assessment of high-rise reinforced concrete structures,” *The Structural Design of Tall and Special Buildings*, vol. 27, no. 2, p. e1417, 2018.

[30] S. K. Shahi and J. W. Baker, “An efficient algorithm to identify strong-velocity pulses in multicomponent ground motions,” *Bulletin of the Seismological Society of America*, vol. 104, no. 5, pp. 2456–2466, 2014.

[31] H. Choi and J. Kim, “Energy-based seismic design of buckling-restrained braced frames using hysteretic energy spectrum,” *Engineering Structures*, vol. 28, no. 2, pp. 304–311, 2006.

[32] Z. F. Liu and P. S. Shen, “Evaluation of hysteretic energy to input energy ratio in tall hybrid structures,” *Journal of Earthquake Engineering and Engineering Vibration*, vol. 29, no. 2, pp. 73–78, 2009.