New lateral load distribution pattern for seismic design of deteriorating shear buildings considering soil-structure interaction

Jiulin Bai, Huiming Chen, Junfeng Jia, Bohao Sun, Shuangshuang Jin

A R T I C L E   I N F O
Keywords:
Uniform damage
Lateral force distribution pattern
Soil-structure interaction
Modified I-K model
Optimization design

A B S T R A C T
The current code-conforming seismic lateral load patterns are implicitly derived based on the dynamic solutions of fixed-base elastic structural systems, without considering the effects of hysteretic characteristic and soil-structure-interaction (SSI). Consequently, such lateral force patterns may not be applicable for the seismic design of nonlinear deteriorating structural systems. In this study, the analytical model was constructed using the shear building model. The peak-oriented modified I-K model and sway-rocking (S-R) model were employed to simulate the deteriorating behavior and SSI effects, respectively. A practical optimization design procedure for optimal lateral load pattern was developed based on the uniform damage distribution. The influence of main parameters on the new lateral load pattern was comprehensively investigated, including the parameters of the S-R model and the peak-oriented modified I-K model, ground motion excitations, fundamental period, target ductility, damping ratio and so on. The quantified expression of the new lateral load distribution was proposed as a function of fundamental period, the target ductility, aspect ratio and shear wave velocity. The results show that the structures designed according to the proposed lateral force pattern experienced obviously less damage than the code-conforming pattern.

1. Introduction
The seismic design will be carried out in seismic zones to quantify the earthquake-induced loading effects applied on the structures and configure sufficient members to achieve strength, stiffness and ductility, for the desired seismic performance. The applied lateral seismic forces excited by ground motions are usually accounted for by equivalent lateral force (ELF) design procedure [1–5]. One of the most important issues in the ELF design procedure is to derive the vertical distribution of lateral force profiles. It is widely recognized that the structures designed by the current code-defined lateral force distributions will undergo large inelastic deformation in severe earthquakes. Due to the solution of lateral force distributions without considering the inelastic behavior [6–8], the utilization of these lateral equivalent forces will not lead to the optimum distribution of structural seismic performance [9–11]. This is due to the fact that there is a discrepancy between the earthquake-induced story shears and the shear patterns assumed in generally cases.

The post-earthquake investigation and structural seismic analysis demonstrate that the structural damage is not uniformly distributed under strong earthquakes [9,11], and local and soft-story mechanisms are usually induced [12]. Some components or stories are severely damaged while the other parts of the structure keep within elastic or low-damage range. As a consequence, the structural material potential over the building height is not fully exploited, and the seismic performance is not maximized. If the structural material is shifted from non-damaged or low-damaged parts to severely-damaged parts, a uniform-damage status can be obtained [10,11]. In such a condition, the material potential is fully exploited and the seismic performance is greatly improved since the global energy dissipation mechanism is developed, which is considered as the uniform-damage based design [7,8,10,11,14,15].

The need for obtaining the optimum structural response distribution or uniform-damage has given rise to the development of the new lateral load distribution patterns. Mohammadi et al. [16] have shown that the code-suggested strength distribution pattern does not lead to a uniform distribution

* Corresponding author.
E-mail address: jiajunfeng@bjut.edu.cn (J. Jia).
https://doi.org/10.1016/j.soildyn.2020.106344
Received 7 March 2020; Received in revised form 23 June 2020; Accepted 25 July 2020
0267-7261/© 2020 Elsevier Ltd. All rights reserved.
distribution of damage, and proposed a new strength distribution pattern as a function of structural period and target ductility. Moghaddam et al. [17] utilized the shear-building model to represent the seismic analysis model of concentrically braced steel frames, and presented an equivalent procedure to perform the optimization procedure for uniform deformation. Then, Moghaddam et al. [18] conducted the optimization design of shear-building models, and more adequate load patterns including triangular pattern, trapezoidal pattern, parabolic pattern and hyperbolic pattern, were presented with respect to the structural period and target ductility. Also, this analytical approach was further applied to the tall buildings and height-wise irregular buildings, and new load patterns using the function of the structural period and ductility demand was proposed [10,19,20]. Furthermore, Chao et al. [9] developed a new lateral force model based on the relative distribution of maximum story shears of the steel frame structures. Park and Medina [21] utilized the single-bay frames to perform the uniform damage design, and developed a new lateral force pattern which had a similar format with the IBC pattern [3].

Note that the above derivation of new seismic load patterns has been focused on the fixed-base structures, i.e., without considering the soil-structure-interaction (SSI) effects. SSI has a significant effect on the seismic performance of structures, especially for the alluvium and soft soils by transforming the foundation stiffness and energy dissipation of the structural systems [22,23]. For this consideration, Ganjavi and Hao [24] developed an optimization algorithm of elastic soil-structure systems for uniform distribution of damage, and a new lateral load pattern was proposed as a function of the fundamental period of the structure, soil flexibility and structural slenderness ratio. Furthermore, the optimal lateral load pattern for seismic design of nonlinear shear-building considering SSI effects was developed by Ganjavi et al. [25]. Also, new lateral force patterns have been developed for considering the higher mode effects and increasing collapse resistant capacity, by Ganjavi and GholamrezaTabar [26], and Li et al. [27].

As can be seen, the majority of the developed new lateral load patterns for uniform damage distribution are derived based on the non-deteriorating bilinear shear spring model (e.g. Ref. [16–19,24–26]). It should be noted that the non-deteriorating model may be more applicable to the steel structures. For reinforced concrete (RC)-type structures, the strength and stiffness degradation, and pinching effect, will have a significant influence on the seismic performance of the system. Although the considerations of deteriorating structural model [21,27] and SSI effects [24,25] have been separately considered in the previous research, there is still a discrepancy between the current new lateral load patterns and the seismic design of deteriorating structural system for uniform damage considering SSI effect. Based on the above consideration, this study aims to develop a new lateral load distribution pattern of deteriorating shear buildings considering SSI effects. The comprehensive analytical model was constructed using the peak-oriented modified I–K hysteretic model to construct the shear building model, and the sway-rocking model [22,23] to consider the SSI effects. The optimization procedure for uniform damage distribution was developed. The effects of the key parameters on the new lateral load distribution pattern were systematically investigated. Based on the main affecting parameters, the quantified expression of the new lateral load distribution was proposed.

2. Analytical models and assumptions

Among the many structural analytical modes, the shear building model is commonly and widely used to simulate the nonlinear seismic response of multistory buildings. In this model, each story is modeled by a lumped mass which is connected by nonlinear springs to present the story lateral force resistance, and the rotational coupling among vertical structural components is negligible. In general, the multistory shear building model can present the structures where the story shear mechanism is expected, for example, a stiffer diagram to columns [24,28,29]. Due to the simplicity, easy operation, and reduction of computational effort, the shear building model is benefit for the parametric analysis of earthquake response. Therefore, the shear building model is employed in the present study since the structural parameters are modified in the optimization process, to obtain the optimum lateral force distribution pattern.

As mentioned before, the soil-structure-interaction (SSI) effect and deteriorating hysteretic behavior are considered in the whole structural system. The schematic diagram of the fixed-based model and SSI-based model are demonstrated in Fig. 1, where \(m_i\), \(c_i\) and \(f_i\) are the story mass, story damping and story stiffness of the \(i\)-th story, respectively. The models of superstructure and the SSI effect are described next.

2.1. Analytical model of superstructure

To reflect the hysteresis deterioration of structural models, the modified Ibarra-Medina-Krawinkler deterioration model (referred to as modified I–K model) developed by Ibarra et al. [30], and Lignos and Krawinkler [31], is employed to simulate the story hysteretic response of shear building models. The verification of modified I–K model has been performed by a large number of experimental data of steel and reinforced concrete structural members. The significant characteristic of modified I–K model is to capture the strength and stiffness deterioration, as well as pinching effect. Furthermore, the modified I–K model is capable of considering the case of member strength reducing to zero and the asymmetry of skeleton curves in positive and negative loading directions, as compared to the I–K model, which can achieve a better seismic response results. Therefore, employing the modified I–K model to construct the story shear-lateral displacement relationship, can not only account for the nonlinear characteristics, but also make the derived new lateral force pattern being more compatible with the deteriorated structural systems.

Note that the modified I–K deterioration model has three hysteretic responses, including bilinear, peak-oriented and pinched. In the three models, only the bilinear hysteretic model cannot capture the pinching effect, while the peak-oriented hysteretic model has fewer analysis parameters than that of the pinched model. Considering both the hysteretic characteristic and simplicity of the model, the modified I–K model with a peak-oriented hysteretic response is employed as the hysteretic model of the shear building structures. The backbone and hysteretic curves of the peak-oriented model are shown in Fig. 2. As can be seen from Fig. 2 (a), the skeleton curve has three segments, including the elastic section, hardening section and softening section. Also, \(K_e\), \(K_s\) (\(K_s = \alpha_s K_e\)) and \(K_c\) (\(K_c = \alpha_c K_e\)) are the elastic stiffness, hardening stiffness and softening stiffness, respectively, while \(\alpha_s\) and \(\alpha_c\) are the hardening stiffness coefficient and softening stiffness coefficient, respectively. Under the lateral seismic loading, the structure deforms elastically to yielding displacement \(\delta_s\), and then excurses into the hardening segment until the capping
point \( \delta_c \). At last, the structure goes into softening segment until the collapse point \( \delta_u \). Meanwhile, the hardening displacement \( \delta_h \) and softening displacement \( \delta_{hc} \) can be derived.

The hysteretic curve of the peak-oriented model is demonstrated in Fig. 2(b). The main parameters that control the characteristic of hysteretic curves include: elastic stiffness \( K_e \), yielding strength \( F_y \) and yielding displacement \( \delta_y \), hardening stiffness coefficient \( \alpha_h \), softening stiffness coefficient \( \alpha_s \), cyclic deterioration coefficient, deterioration rate, and so on. By changing these parameters, the peak-oriented models with different characteristics can be obtained. Tao investigated the influence of different model parameters and found that the softening stiffness, ductility capacity and cycle degradation coefficient were the most prominent parameters [32]. In this study, these three parameters are parametrically investigated.

1. Softening stiffness \( K_c \). Softening stiffness refers to the negative stiffness of the descending segment of the hysteretic curve. When the elastic stiffness \( K_e \) is determined, \( K_c \) is controlled by the softening stiffness coefficient \( \alpha_s \). In this study, \( \alpha_s = -0.1, -0.3 \) and \(-0.5\) were respectively selected to represent 'small softening stiffness', 'large softening stiffness' and 'great softening stiffness'.

2. Ductility capacity. The ductility capacity is defined as the displacement ratio of peak point to yielding point (i.e., \( \delta_c/\delta_y \)). By changing the ductility capacity, different hardening displacement can be obtained. In this paper, three \( \delta_c/\delta_y \) values with 2.0, 4.0 and 6.0 were selected to represent 'low-ductility', 'medium-ductility' and 'high-ductility', respectively.

3. Cycle degradation coefficient. In the modified I-K model, the cyclic degradation is mainly controlled by the cyclic degradation coefficients, including the strength deterioration \( \gamma_s \), post-capping strength deterioration \( \gamma_{sc} \), accelerated reloading softening deterioration \( \gamma_{se} \) and unloading softening deterioration \( \gamma_{se} \). More details about the definition and function of these cyclic degradation coefficients can be found in Ref. [30,31]. Different degradation coefficients can achieve the change of model degradation rate under cyclic loading. Three groups of cyclic degradation coefficients were employed to represent the slow degradation \( (\gamma_s = \gamma_{se} = \gamma_{sc} = \gamma_{se} = 50 \text{ and } \gamma_s = 100) \) and fast degradation \( (\gamma_s = \gamma_{se} = \gamma_{sc} = 25 \text{ and } \gamma_s = 50) \).

2.2. Soil-structure-interaction model

The soil-structure-interaction (SSI) is a very complicated process and many sources are included in the SSI effect: (1) change of the dynamic characteristic due to the yielding of superstructures; (2) reduction of the loading-carrying capacity of foundation due to the yielding of the soil and the foundation elements; and (3) gap between the soil and foundation under large deformation [33]. Considering all these interactions in the dynamic time history analysis will lead to a huge computational effort, even with the current high computational capabilities. In the numerical modelling, there are mainly two approaches to consider the SSI effects, including the direct analysis approach and substructure approach [34]. The direct analysis approach can address all the above-mentioned sources of SSI effects and require the specification of spatially three-dimensional variable input motions, which makes it difficult to be implemented and rarely used in practice due to the huge computational efforts. The substructure approach employs a series of springs and dashpots to represent the stiffness and damping between the soil and foundation interface. As a simplified substructure approach, the lumped parameter sway-rocking (S-R) method transforms the soil-foundation into mass-spring-dashpot model, and it is widely used in the analysis and research of SSI [22,23].

The SR model was shown in Fig. 1(b). In the SR model, there are two degrees of freedom (DOF): one horizontal (sway) DOF and one rocking DOF. For each DOF, the S-R model contains spring and dashpot coefficients. Since the structural engineers pay more attention to the seismic response of superstructure than the soil and foundation, the linear soil and nonlinear superstructure were assumed. Therefore, the spring and dashpot coefficients were obtained by employing the static elastic stiffness from the frequency-dependent impedance function of the soil [22,23]:

\[
K_h = \frac{8\rho V_s^2}{2 - \nu} \quad C_u = \frac{4.69 V_s \rho}{2 - \nu}
\]

\[
K_v = \frac{8\rho V_s^2}{3(1 - \nu)} \quad C_d = \frac{0.49 V_s \rho}{1 - \nu}
\]

where \( K_h \) and \( K_v \) are the stiffness in the horizontal direction and rocking direction, respectively; while \( C_u \) and \( C_d \) are the corresponding damping ratio; \( \rho \), \( V_s \), \( \nu \) and \( \nu \) are the soil density, shear wave velocity, equivalent radius of foundation and Poisson’s ratio, respectively. In this study, the soil density is set as 1800 kg/m³ and Poisson’s ratio is 0.4.

The S-R model is established in OpenSees platform [35]. The elastic material and viscous material were used to simulate the mechanical behavior of spring and dashpot, respectively. Zero-length elements were adopted to model the springs and dashpots in the horizontal and rotational directions. Moreover, in the S-R model, there are two important parameters, the shear wave velocity \( V_s \) and aspect ratio \( H/r \) where \( H \) is the total height of the structure. Accordingly, these two parameters mainly influence the stiffness of the soil and the shape of the structure. In this paper, the shear wave velocity \( V_s \) was set as 100 m/s, 200 m/s and 300 m/s respectively to represent three different types of soil: soft soil, medium-soft soil and hard soil. Furthermore, the aspect ratio was set as 1, 3 and 5 respectively to consider three different structural shapes: low, conventional and high. In order to study the influence of these two parameters on the optimum lateral force distribution pattern, a parametric study was carried out in the latter sections.
3. Optimization design procedure

3.1. Basic design principles

In order to establish shear-type structures using the peak-oriented modified I-K model considering SSI effects and develop the optimization design procedure to achieve the new lateral force pattern, some reasonable approximations were made in this paper.

(1) The floor mass was assumed to be the same along the height and the mass for each story can be specified (i.e., 100 tons in the present study). The story height was assumed as 3.6 m for each story. The yielding drift ratio was set as 0.3%, and that is to say, the yielding displacement \( \delta_y \) was 10.8 mm. Moreover, the target ductility \( \mu_t \) of structures under seismic loadings was considered as 1.0, 1.5, 2.0, 3.0, 4.0 and 5.0, a total of six cases.

(2) The fundamental period of structures was approximated as linearly with the story numbers. Usually, in the original design stage, the fundamental period \( T \) was calculated using \( T = 0.1 N \), where \( N \) was the total number of stories. In this study, eight original structures with 3, 5, 8, 10, 12, 15, 17 and 20 stories were used. As a result, the corresponding fundamental periods were 0.3 s, 0.5 s, 0.8 s, 1.0 s, 1.2 s, 1.5 s, 1.7 s and 2.0 s, respectively.

(3) The stiffness of the structures was assumed to be linearly distributed along the height and the stiffness remained unchanged during the optimization process. This assumption was made mainly based on the consideration that the peak-oriented modified I-K model could be applicable for the RC-type structures, and the optimization of RC structures mainly dealt with the component reinforcement design while the component sectional size kept unchanged. As a consequence, there was no obvious change in the stiffness of RC structures. In order to make the stiffness of structures unchanged, the period was adopted and the overall stiffness of the structures was iteratively scaled:

\[
K_{\text{total},1} = \left( \frac{T_0}{T_{\text{target}}} \right)^2 \cdot K_{\text{total},0}
\]

where \( K_{\text{total},1} \) and \( K_{\text{total},0} \) are the total stiffness of the optimized structure and original structure, respectively; \( T_0 \) is the fundamental period of the original structure and \( T_{\text{target}} \) is the target fundamental period of the optimized structure. Note that the total stiffness was the sum of the stiffness for all stories.

(4) For the shear-type structure, the story shear can be easily obtained from the seismic analysis. The lateral force distribution pattern can be further calculated:

\[
S_i = \begin{cases} 
V_i - V_i(i < n) \\
V_i(i = N) 
\end{cases} 
\]

\[
F_i = \frac{S_i}{V_{\text{base}}} 
\]

where \( V_i \) is the story shear force at the \( i \)-th story, \( S_i \) is the earthquake-induced lateral force applied at the \( i \)-th story, \( n \) is the story number, \( F_i \) is the lateral force distribution pattern and \( V_{\text{base}} \) is the base shear.

(5) In order to consider the most likely earthquake action applied on the structures, seismic excitations were employed to perform the
Soil Dynamics and Earthquake Engineering 139 (2020) 106344

5

nonlinear dynamic analysis. 21 artificial ground motions were generated using the SIMQKE software [36], to match the Chinese code spectrum in severe seismic hazard level [5]. Fig. 3 shows the pseudo-acceleration spectra of 21 ground motions and their comparison with the target code spectrum. It can be observed that good consistency between the code spectrum and generated ground motions was achieved.

3.2. Optimization variables and objective functions

Based on the previous design principle, the stiffness of the structure
presented in Fig. 13. As can be seen, when the target ductility was relatively small ($U_t = 2.0$), the material ductility ability had little effect on the lateral force distribution pattern. While for a large target ductility ($U_t = 4$) as shown in Fig. 13 (b), the influence of material ductility capacity on the lateral force distribution pattern would increase significantly. Especially, when the target ductility of the structure was large and the material ductility ability of the material was small ($\dot{\delta}_C/\dot{\delta}_S = 2.0$), the material ductility ability has a more significant effect on the lateral force distribution patterns. For practical purposes, the material ductility ability was set as medium ductility, i.e., $\dot{\delta}_C/\dot{\delta}_S = 4$.

4.10. Effect of material cycle degradation rate

The structures with $U_t = 5.0$, $T_{fix} = 1.0$ s, $H/r = 3.0$ and $V_t = 100.0$ m/s, subjected to GM1 seismic excitation were employed to investigate the influence of material cycle degradation rate. The lateral force distribution pattern for slow, medium and fast cyclic degradation rate of materials were compared in Fig. 14. As can be seen, the influence of the lateral force distribution patterns was small for different material cyclic degradation rates, and nearly no difference could be found. Therefore, in the present study, the material cyclic degradation rate was set as the medium-speed degradation.

5. Verification of optimization design for new lateral load distribution pattern

By employing the proposed optimization design approach, the new lateral force distribution pattern of shear-type structures considering the SSI effect, can be derived. Also, the derived lateral force distribution pattern is compared with the code-based lateral force pattern (GB50011 [5]):

\[
F_i = \begin{cases} 
\sum_{j=1}^{m_i} h_j (1 - \delta_h) & i < n \\
\sum_{j=1}^{m_n} h_j (1 - \delta_h) + \delta_n & i = n 
\end{cases}
\]  

(9)

where $h_i$ is the story height and $\delta_h$ is the additional force applied at roof floor.

The analytical result of structure with $T_{fix} = 1.0$ s, $U_t = 1.5$, $H/r = 3$, $V_t = 200$ m/s, under GM1 seismic excitation is shown in Fig. 15. It can be seen that the lateral force distribution pattern obtained by optimization design, was obviously different from that of code-based lateral force. In this case, the lateral force distribution in the lower part of the structure increased compared to the code-based lateral force distribution, and kept nearly constant in the middle stories.

In order to verify the effectiveness of the lateral force distribution pattern obtained by the optimization design method proposed in this paper, the shear-type structure was designed according to the derived optimum lateral force distribution pattern and code-based pattern, by considering the same total strength of the structure. The structure of $T_{fix} = 1.0$ s, $U_t = 1.5$, $H/r = 3.0$ and $V_t = 200$ m/s was used. The comparison of the story ductility of structures subjected to GM1 seismic excitation was presented in Fig. 16. As can be seen, the structure designed by the optimum lateral force distribution pattern can achieve the uniform story ductility distribution along the height.

However, for the structure design using the code-based pattern, the story ductility was obviously not uniformly distributed and concentrated at the 1st and 9th story where the ductility was much larger than that of other stories. This indicated the structures designed using the new lateral force distribution pattern can improve the seismic response. Therefore, the optimization design approach and derived optimum lateral force distribution pattern can be effective for achieving uniform-damage seismic response.

6. New lateral load distribution pattern

In order to apply the optimum lateral force distribution pattern to practical engineering, the data fitting technique was employed to obtain the fitting formula of the optimum lateral force distribution pattern. Basically, the lateral force distribution pattern was a function of the story relative height $\bar{H}$ defined as the ratio of story height to the total structural height. Furthermore, based on the previous extensive parametric studies, it can be found that the key factors affecting the optimum lateral force distribution patterns are the fundamental period $T_{fix}$, the target ductility $U_t$, aspect ratio $H/r$ and shear wave velocity $V_t$. Therefore, the five factors were taken as the dependent variables of the formula, and the formula was fitted by 1stOpt software. The expression of the lateral force distribution pattern is:

\[
F_i = \frac{p_1 + p_2 \ln(T_{fix}) + p_3 \ln^2(T_{fix}) + p_4 T + p_5 T^2}{1 + p_6 \ln(T_{fix}) + p_7 \ln^2(T_{fix}) + p_8 \ln(T_{fix}) + p_9 T + p_{10} T^2}
\]  

(10)

Note that in the above formula $p_1$-$p_{10}$ are the coefficients. These coefficients are related to the target ductility $U_t$, aspect ratio $H/r$ and shear wave velocity $V_t$, and the values of these coefficients are demonstrated in Table 1. Also, the fundamental period $T_{fix}$ can be approximated based on the story number.

In order to verify the accuracy and effectiveness of the fitting formula proposed in this paper, three different groups of dependent variables were selected, and the fitting values of the optimum lateral force distribution pattern were compared with the actual values, as shown in Fig. 17. It can be seen that the fitting values of the three cases match well with the actual values on the whole, and the difference between the fitting value and the actual value is also small for each story. Meanwhile, the correlation coefficient for the fitting formula is larger than 0.99, which indicates that the proposed formula has high fitting accuracy and can be used in practical application.

It should be noted that the $P-\Delta$ effect was not accounted for in the derivation of new lateral load distribution. For seismic design of structures, the $P-\Delta$ effect should be considered to provide the lateral resistance, to make sure the structure stand despite the vertical forces are now eccentric with respect to the axis of the columns. Therefore, the design lateral load should be able to simulate the seismic action calibrated by the equilibrium with the bending produced by the vertical force in connection with the story drift [37]. The objective of the developed new lateral load distribution is to determine the floor relative lateral force, and the specific value of story lateral forces can be calculated by considering the equivalent story force derived by $P-\Delta$ effect.

Moreover, the developed new lateral force pattern was derived based on the state of uniform story damage distribution of shear-type structures, by employing the optimization design. As a matter of fact, due to the development of local damage, concentration of local deformation and modification of the geometry of the frame, the story damage of building structures under strong earthquakes is not easy to distribute uniformly [9,11,13,15,38]. However, this feature was neglected in the study. Therefore, developing a more rational seismic lateral force load pattern by employing the seismic response of real structural systems, will be more investigated in the future study.

7. Conclusions

Based on the shear-type structural model, the peak-oriented modified I-K hysteretic model and sway-rocking (S-R) soil-structure interaction model were established to construct the analytical model. Based on the uniform-damage concept, the optimization design procedure was developed, and the new lateral force distribution pattern was proposed. Some conclusions can be made in this paper:

(1) The optimization design procedure can be effective to make the story ductility uniformly distributed along the height. The
convergence parameter $\alpha$ has effects on the optimization speed and convergence stability, which is also accompanied by the target ductility $U_t$. It is suggested that the convergence parameter $\alpha$ should be taken as 0.08 to 0.2 when $U_t < 3$ and 0.02 to 0.04 when $U_t \geq 3$.

2. The fundamental period of structure $T_{fu}$, target ductility $U_t$, shear wave velocity $V_s$, aspect ratio $H/r$ have a great influence on the new lateral force distribution pattern. While the softening stiffness, material cyclic degradation velocity, material ductility ability and damping ratio have little effect on the new lateral force distribution pattern.

3. The structures designed using the proposed equation can achieve a reduced seismic performance and better seismic damage distribution, compared with the structures designed by traditional methods.

Author statement

Jiulin Bai: Methodology, Supervision.
Huiming Jia: Conceptualization, Supervision.
Bohao Sun: Software, Modelling, Analysis.
Shuangshuang Jin: Software, Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 51978109 and 51778024) and the Fundamental Research Funds for the Central Universities (No. 2020CDJQY-A065).

References


