Research on seismic performance of existing frame structures reinforced with externally assembled energy consuming frame substructures

*Xiufeng Xu[1], Zi'ang Kong[2]

[1]Architectural Engineering Institute, Qingdao Huanghai University, Qingdao 266427, China;
[2]gad • Qingdao Branch of Zhejiang Greenton Architectural Design Co., Ltd., Qingdao 266000, China

E-mail:xuxiufeng2014@126.com,751961302@qq.com

Abstract. At present, a large number of aging frame structures in China are no longer capable of meeting the current seismic design requirements, and urgent seismic retrofitting is necessary. This study introduces an innovative retrofitting approach for enhancing the seismic resilience of existing frame structures by employing external energy-dissipating frame substructures. The method involves the strategic placement of I-shaped steel dampers or energy-dissipating hinge dampers at the joints of the external frames to augment the energy dissipation capabilities of structures. Utilizing a combination of experimental data from existing frame structures and damper tests, five finite element models were constructed to assess the seismic performance of various retrofit configurations, including pure prefabricated frame substructures, those reinforced with I-shaped steel dampers, and those with energy-dissipating hinge dampers. The findings demonstrate that the incorporation of energy-dissipating frames can lead to a significant increase in structural load-bearing capacity, ranging from 33% to 77%. Notably, the models featuring I-shaped steel dampers at the base and top of the external frames achieved the highest peak load-bearing capacity, while those with energy-dissipating hinge dampers at these locations exhibited the most pronounced hysteresis behavior, indicative of superior energy dissipation properties. Strain analysis of the models revealed that the majority of structural damage was localized to the dampers, effectively facilitating the control of damage during seismic events.

Keywords: energy-dissipating frame substructures; I-shaped steel damper; energy-dissipating hinge damper; seismic performance.

1 Introduction

In recent years, the frequency of seismic events has escalated, leading to numerous instances of structural failures, particularly the collapse or partial disintegration of frame structures. A significant proportion of the frame structures built in China during the 1980s and 1990s have been found to be non-compliant with current seismic design

Q. Gao et al. (eds.), *Proceedings of the 2024 7th International Conference on Structural Engineering and Industrial Architecture (ICSEIA 2024)*, Atlantis Highlights in Engineering 30,
https://doi.org/10.2991/978-94-6463-429-7_20

standards. This non-compliance poses a substantial risk to both human life and property safety during an earthquake, thus necessitating immediate attention and remedial measures. Traditional reinforcement methods for frame structures, such as increasing the cross-sectional area and replacing concrete, often encounter issues like frequent wet operations on-site, extended construction periods, and disruption to the normal use of buildings.

The external substructure reinforcement method does not require the relocation of instruments, equipment, or other items within the room during construction, and it does not affect the normal use of the structure, which is favored by many property owners. It mainly includes external precast prestressed frame reinforcement method[1], external steel frame, steel bracing, and steel bar reinforcement method[2], external parallel diagonal steel bar reinforcement method[3], and external buckling-restrained braced concrete frame reinforcement method[4]. The aforementioned studies indicate that external substructure reinforcement methods can improve the structural load-bearing pattern and enhance the overall seismic performance of the structure. However, the precast prestressed frame reinforcement has poor energy dissipation capacity. In contrast, external bracing significantly enhances both load-bearing and energy dissipation capacities, but there are issues such as stress concentration at the connection points between the bracing and the frame, as well as impacts on the building's view.

In recent years, scholars[5-6] have proposed energy-dissipating dampers for the connection of prefabricated frame beam-column joints. These dampers do not occupy external space of the structure and do not affect the building's view or daylighting. Moreover, they possess excellent seismic resistance and energy-dissipating shock absorption capabilities. Additionally, the dampers are designed to concentrate damage within the energy-dissipating plates, which simplifies the process of rapid post-earthquake restoration efforts.

Therefore, this study introduces energy-dissipating hinge dampers into the reinforcement of external substructures and proposes an innovative approach for the enhancement of prefabricated energy-dissipating frame substructures. Under seismic action, the soft steel in the damper first undergoes yielding and dissipating seismic energy, thereby reducing damage to the existing structure. Based on the existing research of frame test[7] and damper experiments[6], this study designs three types of reinforcement models for comparative analysis: an external pure reinforced concrete frame reinforcement model, an external I-beam damper frame reinforcement model, and an external energy-dissipating hinge damper frame reinforcement model. Initially, the Abaqus finite element software is employed to model the existing frame[8] and damper tests[7]. Under the premise of verifying the accuracy of the numerical models, structural reinforcement models are established to study their seismic performance.

2 Numerical simulation of frame and dampers

The experimental data for the RC frame, energy dissipation hinge damper, and I-beam damper are detailed in references [7] and [6], respectively. For the modeling process using Abaqus finite element software, the concrete structure is discretized with threedimensional 8-node reduced integration elements (C3D8R), and the reinforcement steel is represented by truss elements (T3D2). The reinforcement bars are embedded into the concrete matrix using the 'INSERT' feature. The Concrete Damaged Plasticity (CDP) model is employed to characterize the behavior of concrete, with its stress-strain relationship determined in accordance with Appendix C of the 'Code for Design of Concrete Structures(GB 50010-2015).' The steel reinforcement is modeled using the hysteresis model proposed by Fang Zihu [8], which accounts for the bond slip effect between the steel and concrete. The damper models are simulated using solid elements.

For the energy-dissipating hinge dampers, a 'surface-to-surface' contact is defined between the ear plates on either side of the damper. The pin is modeled by coupling the walls of the ear plate holes on both sides to distinct points and applying a 'coupling' configuration to the points where the walls of adjacent ear plate holes meet. A cylindrical coordinate system is established to allow rotational degrees of freedom around the axis. The boundary conditions and loading methods employed in the model correspond to those of the experimental setup. These models are depicted in Figure 1.

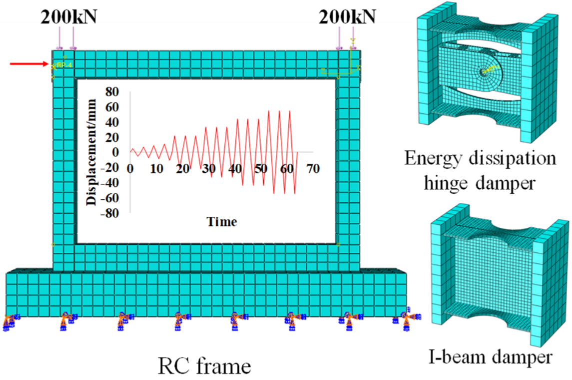
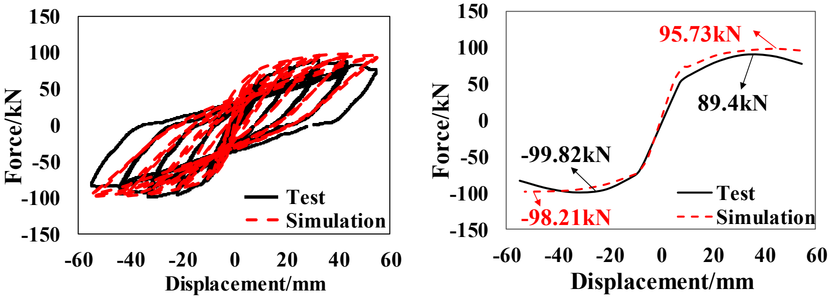
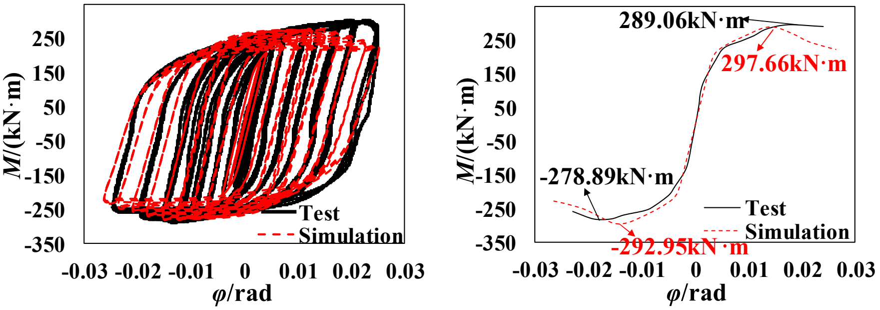


Fig. 1. Finite element model

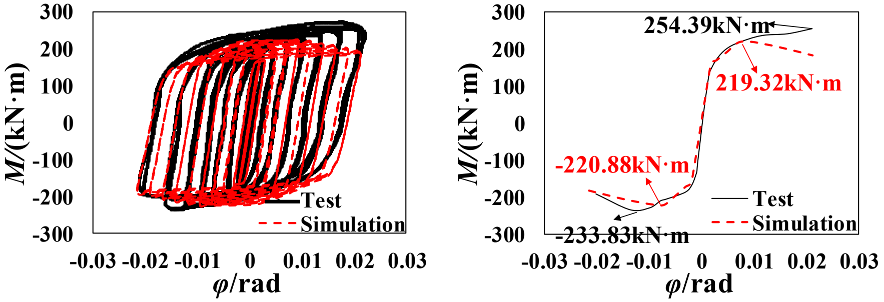
The comparison between the simulated hysteresis and skeleton curves and the experimental results is presented in Figure 2. The mean errors in the peak load capacity for both positive and negative directions are 4.35%, 4%, and 9.67%, respectively. That indicating a high level of accuracy.



(a) Hysteresis curve and skeleton curve of RC frame structure



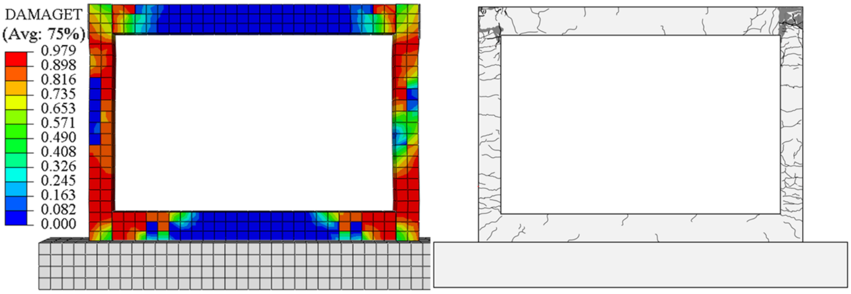
(b) Hysteresis curve and skeleton curve of I-shaped steel damper



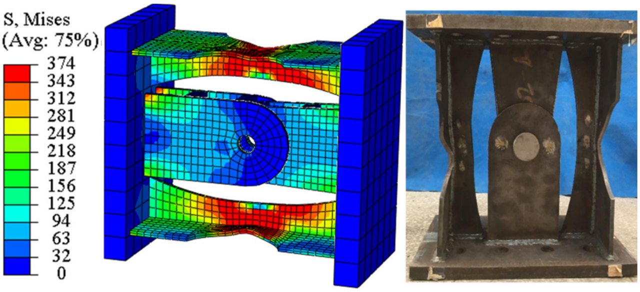
(c) Hysteresis curve and skeleton curve of energy-dissipating hinge damper

Fig. 2. Comparison between numerical simulation results and experimental results

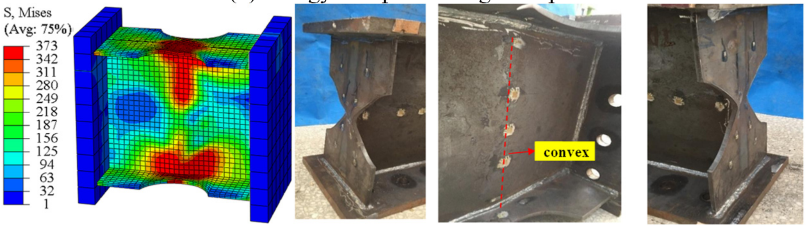
Figure 3 presents a comparison of the structural damage patterns derived from numerical simulations with those observed in experiments, showing a good agreement in the locations of structural damage. In conclusion, the numerical model can be utilized as a foundation for studying the seismic retrofit performance of external substructures.



(a) FC frame



(b) Energy dissipation hinge damper

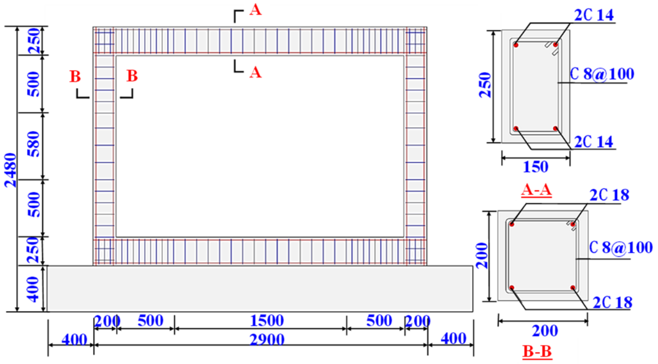


(c) I-beam damper

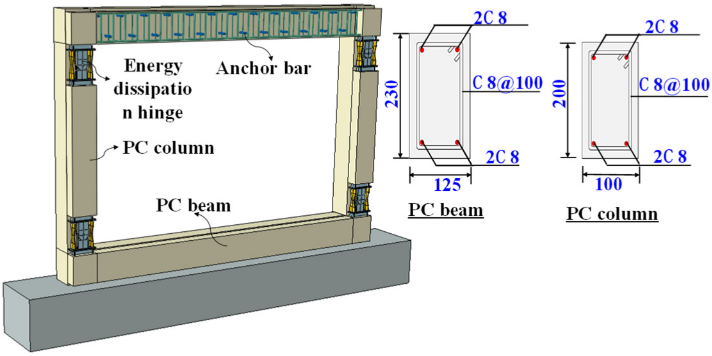
Fig. 3. Comparison of structural damage between numerical simulation and experimental results

3 Reinforcement scheme design

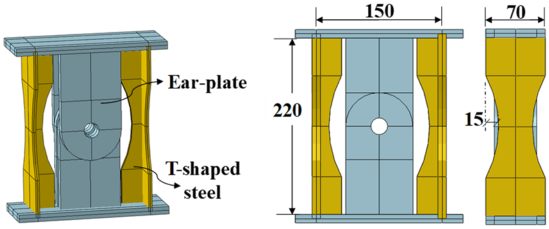
Taking the framework structure discussed in the previous text as the object of reinforcement, this study designs five reinforcement models. Model1 represents an externally bonded pure reinforced concrete frame; Model2 and Model3 are assembled frames equipped with external energy dissipation hinge dampers, Model 2 features dampers positioned at the column bases and beam ends, while Model 3 incorporates dampers at the column bases and column tops; Model 4 and Model5 are assembled frame with external I-beam dampers, the distinction between the two models is that Model 4 places the I-beams at the column bases and beam ends, while Model 5 positions the I-beams at the column bases and column tops. The reinforcement model is illustrated in Figure 4. The external frame is anchored to the existing structure using HRB400 rebar as anchor bolts, each with a diameter of 20mm. The T-shaped steel of the hinge dampers are composed of Q235 mild steel, with the remainder of the components made from Q355 steel. The I-shaped dampers are uniformly fabricated from Q235 steel. The thickness of the web and flange of T-shaped steel and I-shaped steel is 10mm.



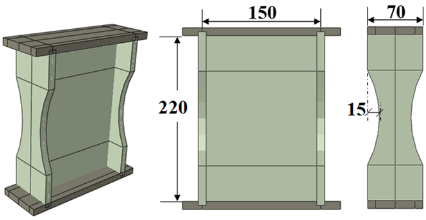
(a) Unreinforced frame structure model



(b) Reinforcement Model3 for external substructure



Energy dissipation hinge damper



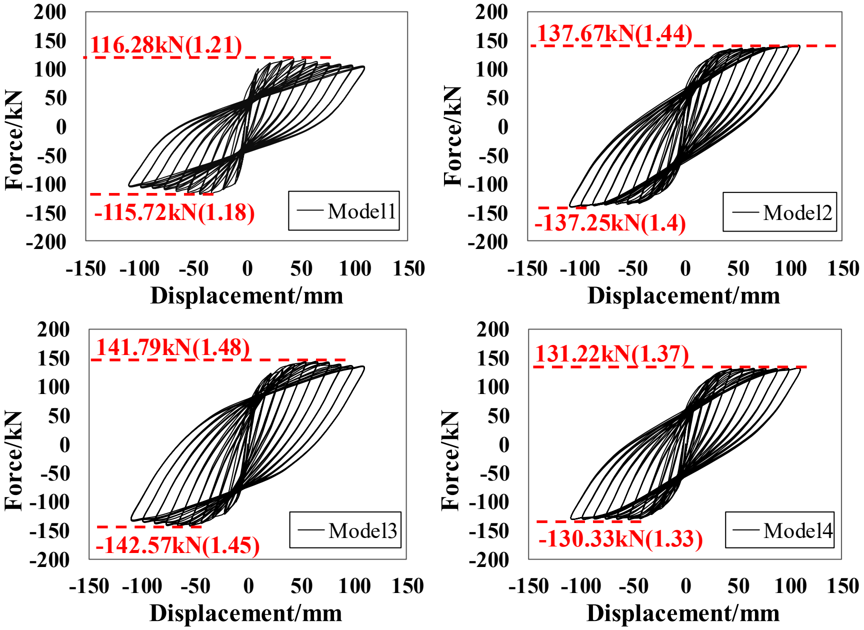
I-beam dampers

(c) The geometric dimensions of dampers

Fig. 4. Reinforcement model of external substructure

4 Analysis of seismic performance of reinforced structures

External substructure reinforcement models are established employing the same methodology as utilized for the RC frame and damper models. 'Surface-to-surface' contact was meticulously defined between the existing and external frames, characterized by a friction coefficient of 0.8. The existing RC frame was subjected to vertical and horizontal loads, with an axial load of 200kN per column, the axial compression ratio is approximately 0.3. The hysteresis and skeleton curves for these models are detailed in Figure 5, the numbers in parentheses represent the ratio of the peak bearing capacity of the reinforced model to the peak bearing capacity of the RC frame in Figure 2 (a). It can be seen that the compared with the externally attached pure reinforced concrete frame structure, the load-bearing capacity of the externally attached energy dissipation hinge damper frame structure and the I-shaped steel frame structure is significantly improved, about 1.33-1.77 times that of the RC frame structure. Among them, Model 5(featuring I-shaped steel dampers at the base and top of the external frame columns) has the highest bearing capacity. From the perspective of energy consumption, the hysteresis curve of Model 3(set the energy dissipation hinge damper at the column base and top) is the most full, indicating the best energy consumption capacity.



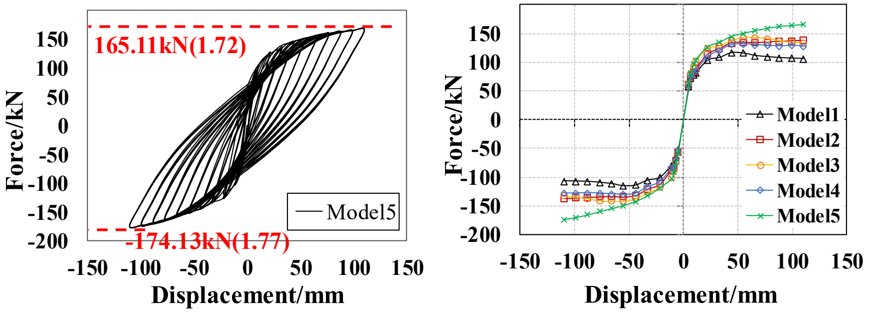


Fig. 5. Hysteresis curves and comparison skeleton curves of each model

The cumulative damage strain cloud diagrams of Model 2 and Model 4, presented in Figure 6 under a loading displacement of 44mm (approximately 1/42 radians), reveal that the strain is primarily concentrated on the dampers' weakened flanges. This pattern is consistent across Model 3 and Model 5, underscoring the effectiveness of the proposed external prefabricated energy-dissipating frame substructures in achieving the objective of controlled structural damage.

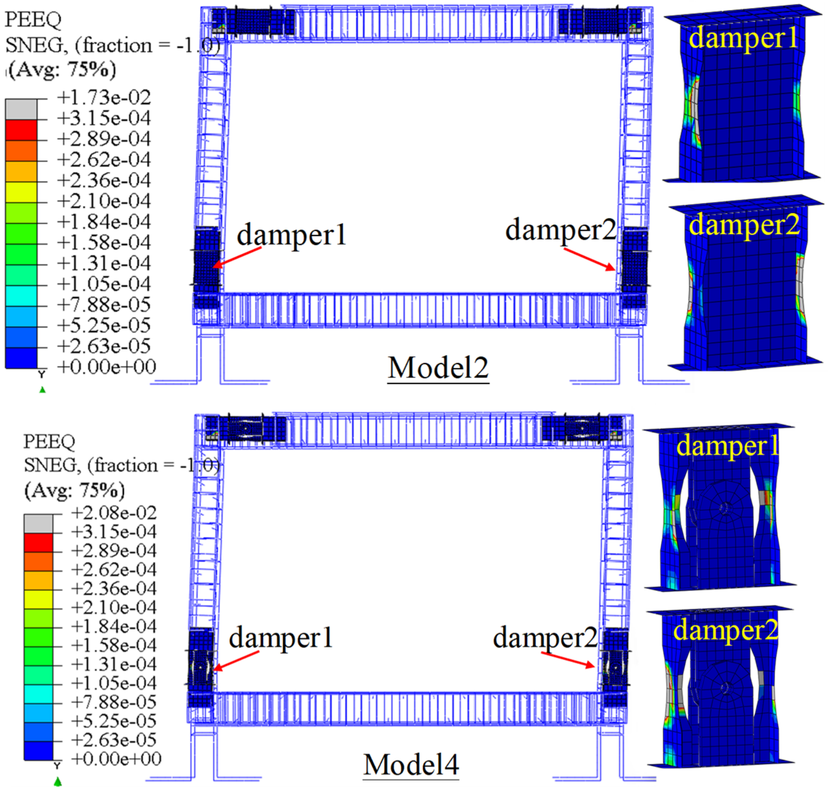


Fig. 6. Strain cloud map of Model2 and Model4

5 Conclusions

This paper proposes a method for reinforcing existing frame structures with externally attached prefabricated energy-dissipating frame substructures. Numerical simulation studies have led to the following conclusions: the structural damage is primarily concentrated on the dampers, allowing for controllable damage; the externally attached energy-dissipating hinge damper frame and I-beam frame substructures can increase the load-bearing capacity of the existing frame structures by 1.33 to 1.77 times. Among them, installing I-beam dampers and energy dissipation hinge dampers on the column base and top of the external frame can respectively obtain larger bearing capacity and energy dissipation capacity. During engineering reinforcement, energy dissipation hinge dampers or I-beam dampers can be selected according to actual needs.

Acknowledgment

Development Plan of Youth Innovation Team in Colleges and Universities of Shandong Province（2021KJ110）

References

1. Ryotaro K, Hiroyasu S, Qu Z, et al.(2019) Precast Prestressed Concrete Frames for Seismically Retrofitting Existing RC Frames. Engineering Structures, 184: 345–354. https://doi.org/10.1016/j..2019.01.110
2. Harayama K, Kawamoto T, Inai E, et al.(2012) An experimental Study of a Seismic Retrofitting Method with Framed Steel Brace Systems Partially and Concentrically Jointed with Anchors. Proceedings of the 15th World Conference on Earthquake Engineering. Tokyo, Japan. https://www.iitk.ac.in/nicee/wcee/article/WCEE2012_1846.pdf
3. Xu C X.(2013) Experimental Study on Bond Behavior of Main Bars in R/C Column with Emergency Retrofit by External Prestressed PC Rods. Magazine of the Korea Institute for Structural Maintenance and Inspection, 17(1):60-65. (in Korean) https://koreascience.kr/article/JAKO201314652522944.page.
4. Cao X Y. Wu G, Feng D C, et al.(2020) Research on the Seismic Retrofitting Performance of RC Frames Using SC-PBSPC BRBF Substructures. Earthquake Engineering & Structural Dynamics, 24 February. https://doi.org/10.1002/eqe.3265.
5. Xia T.Y.(2018) A Study on Joint Semi-Rigidity in Fabricated Concrete Frame with Replaceable Energy Dissipation Connector. Nanjing: Southeast University. (in Chinese)
6. Liu, R.Y, Wei C.G, Wu Y.X, etal. (2023) Hysteretic Performance of Fabricated Damage-controllable Steel Hinges. Journal of Water Resources and Architectural Engineering, 21(3):165-171. (in Chinese) DOI:10. 3969/j. issn. 1672 − 1144. 2023. 03. 024.
7. Cao X.Y, Wu G, Feng D.C, etal.(2019) Experimental and Numerical Study of Outside Strengthening with Precast Bolt-Connected Steel Plate–Reinforced Concrete Frame-Brace. J. Perform. Constr. Facil., 33(6): 04019077. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001351.

8. Fang Z.H, Zhen Y, Li X.P.(2018) Steel Hysteretic Model of Reinforced Concrete Structures[J]. Engineering Journal of Wuhan University, 51(7): 613-619. (in Chinese) DOI:10.14188/j.1671-8844.2018-07-008.