Improved Park-Ang Damage Model for Reinforced Concrete Frame Structure

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Abstract

The improved form of the Park-Ang damage model for reinforced concrete (RC) structures is proposed for the problem that the upper and lower bounds of the original damage model are not convergent. The experimental database of reinforced concrete columns collected by the Pacific Earthquake Engineering Research Center (PEER) and the experiments completed by the authors are used to study the determination of the coefficients of the improved damage model. The damage index of the limit point calculated by the improved damage model is closer to 1, and the discreteness is obviously reduced. At last, the value of combination coefficient is recommended for ordinary RC members.

Keywords

Reinforced concrete; damage model; seismic damage; frame structure; damage index.

1. Introduction

Performance based structural design allows the structure to enter the nonlinear response stage under strong earthquakes, which means that the structure is allowed to undergo a certain degree of damage. In order to accurately assess the damage level of structure, cumulative damage index by some researchers to calculate the damage model of specific structure in the earthquake process, by the value of damage index reflect the damage degree of concrete structure or component.

Miner[1] proposed the damage index for metal structures, and for more than half a century, many scholars had done a lot of research work in this field, and put forward various damage index(Haluk & Altug [2]; Teran-Gilmore & Jirsa [3]). Park and Ang[4] proposed the damage model considering deformation and energy dissipation of reinforced concrete structures in 1945, which was widely adopted by scholars.

2. Model research

2.1 Improvement of damage model

Park-Ang damage model combined the deformation and the energy dissipation:

$$D_P = \frac{\delta_m}{\delta_u} + \beta \frac{\int dE}{f_y \delta_u} \tag{1}$$

In which, Dp is Park-Ang damage index, β is combined coefficient (recommended value is 0.05), δm is maximum deformation under dynamic loading, δu is ultimate deformation under monotonic loading, fy is yield strength, and $\int dE$ is cumulated dissipated hysteretic energy at the point of calculation.

Park-Ang damage model has been widely used because it reflects that the damage is caused by large displacement amplitude and low cyclic effect of seismic load. The model shows that the seismic parameters (amplitude, frequency spectrum and lasting time) play important roles in the structure damage. However Park-Ang damage model has some disadvantages: The damage index is not equal to 1 under monotonic load until failure; The structure shall be free of damage during repeated loading in the elastic stage, however damage index calculated by Eq.(1) is not equal to 0.

Considering these problems, the improved seismic damage model for reinforced concrete structures is proposed as follows:

$$D = (1-\beta)\frac{\delta_m}{\delta_u} + \beta\frac{\int dE}{f_y(\delta_u - \delta_y)} \quad (2)$$

Where, δy is yield displacement; fy(δu-δy) is energy dissipation for an ideal elastoplastic system under monotonic loading to failure; the detailed meanings of other parameters are the same as Eq.(1).

Under monotonic load until failure, energy dissipation of structures or components as an ideal elastoplastic system is $\int dE = f_y(\delta_u - \delta_y)$. And from the Eq.(2), we can get that the damage index is equal to 1. It shows that the damage index satisfies the convergence condition at the upper bound. The deformation of reinforced concrete members at cracking is very small compared with the ultimate deformation under monotonic loading, and the deformation before cracking is smaller. It can be assumed that the reinforced concrete members is in elastic state before cracking and the energy dissipation is negligible. As 1-β ranges between 0 and 1, the damage index of elastic stage calculated by Eq.(2) is closer to 0 compared with Park-Ang damage model. It suggests that the improved damage model can better satisfy the boundary conditions.

2.2 Experimental database

In order to establish the value of the combined coefficient of the damage model proposed in the paper, lots of test results need to be analyzed. The Pacific Earthquake Engineering Research Center(PEER), which is founded at the University of California, Berkeley and is funded by the National Science Foundation of the United States, establishes a detailed database of column experiments including the United States, Japan, New Zealand, Canada and other countries. The database is administered by Professor Marc Eberhard of University of Washington and is freely available to the world seismological engineering community.

In this paper, the experimental data of 115 reinforced concrete columns in PEER database[5] are selected. Selection principle is as follows: the specimen is a reinforced concrete rectangular section column, and the failure mode is a flexural controlled failure. It has a complete hysteretic curve and is loaded to the failure of the component. All the selected test data contains specimen geometry, reinforcement form, material properties, loading mode and the relative position of specimen loading device, which lays the foundation for obtaining accurate hysteresis relations

The selected PEER database and the 13 reinforced concrete column beam tests completed by the author[6] of this paper together constitute the experimental database for determining the coefficients of the improved damage model. Limited to space, the detailed parameters of each test are not listed.

The distribution of characteristic parameters of the selected test data is shown in figure 1. It shows that the cylinder strength of the specimen concrete is 22.3~118MPa, the yield strength of longitudinal reinforcement is 335~587MPa, the yield strength of stirrups is 255~1424MPa, shear span ratio is 2.0~7.0, axial compression ratio is 0~0.8, Longitudinal reinforcement ratio is 0.7%~5.0%, volume tie ratio is 0.3%~7.7%. The basic parameters of the selected specimens cover the scope of the conventional building structure design and have a wide range of representativeness.

2.3 Determination of combination coefficient

There are 4 kinds of vertical loading models for the selected experimental data. Different vertical loading modes cause different P- effects, so the corresponding calculation method should be taken into account. The bending moment at the bottom of the column and the net shear force in the column are calculated according to the method recommended by the PEER database manua[7].

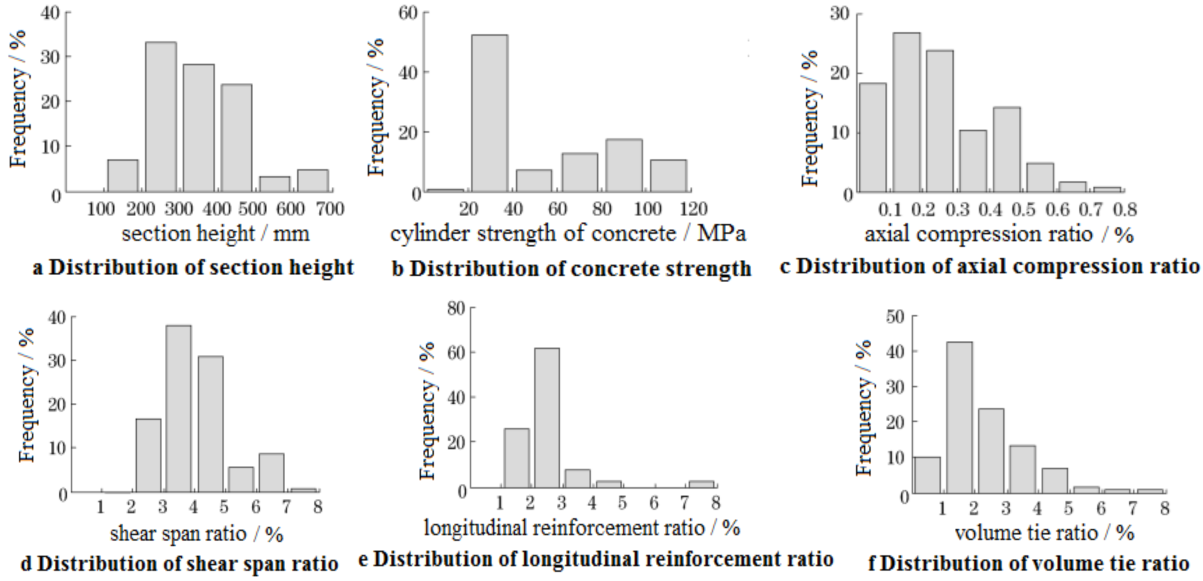


Fig.1 Parameter distribution of specimens

In order to determine the value of the combination coefficient, it is necessary to determine the yield displacement, the monotonic load limit displacement, the maximum displacement and cumulative energy dissipation at the failure point [8].

For Eq.2 when the damage index D=1, the combined coefficient can be determined as follows:

$$\beta = \frac{f_y(\delta_u - \delta_m)(\delta_u - \delta_y)}{\delta_u \int dE - \delta_m f_y(\delta_u - \delta_y)} \tag{3}$$

And it is necessary to determine the yield displacement, the ultimate displacement under monotonic load, the maximum displacement and cumulative energy dissipation at the failure point. Among them, the yield displacement is determined according to the force displacement skeleton curve obtained by experiment [9]. The yield displacement is determined by the method in Figure 2, and the corresponding yield load is taken the average value of the maximum net horizontal load reached in the two loading directions. The criteria used by the researchers in the database to determine the failure of components are not exactly the same. Considering the flexural failure morphology, the maximum displacement is the smaller one of the relative displacement of the skeleton curve drops by 15 and the displacement of longitudinal steel bar during buckling or breaking. The ultimate displacement under monotonic load is determined by the method proposed by the International Federation for Structural Concrete [10].

By analyzing the selected database, the average of the combination coefficients is 0.035, the standard deviation is 0.13, and the coefficient of variation is 89%. The high discreteness of the combination coefficient reflect the complexity of the damage performance of reinforced concrete structures.

For verifying the accuracy of the improved damage model, the damage index is calculated for each experiment in the database using the improved damage model (β=0.03) and Park-Ang damage model (β=0.05). The calculation results are shown in Fig.3.

The average damage index of the failure point calculated by the improved damage model is 1.02, the standard deviation is 0.23, and the coefficient of variation is 21%. The average damage index of the failure point calculated by Park-Ang damage model is 1.42, the standard deviation is 0.63, and the coefficient of variation is 47%. Results shows that the damage index of the limit point calculated by the improved damage model is closer to 1, and the discreteness is obviously reduced.

Considering the characteristics parameters in most reinforced concrete structures (such as axial compression ratio, shear span ratio, stirrup lateral constraints etc.) are in the normal range, the coefficient of the improved damage model is taken as a constant value. In this paper, the coefficient of the rectangular reinforced concrete member, which is mainly flexural and has a good lateral restraint, is preferable to 0.03.

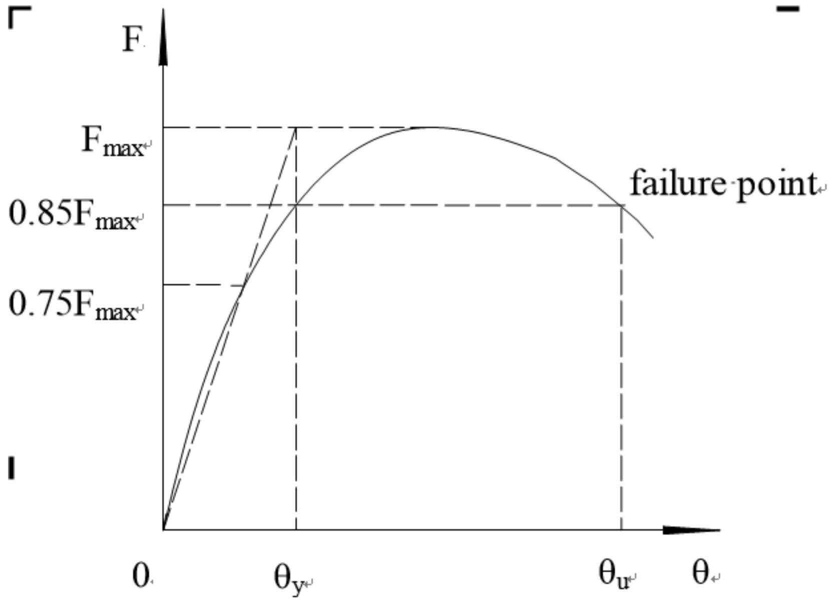
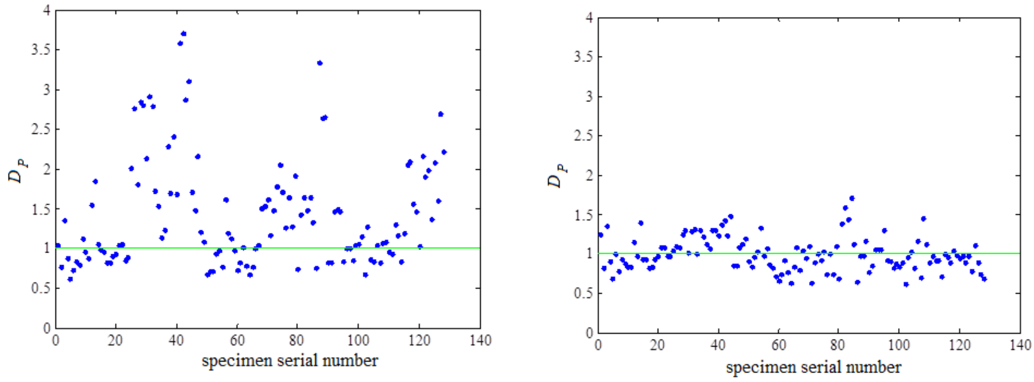


Fig.2 Definition of yielding and ultimate displacements



(a) Results of Park-Ang damage model (b) Results of the improved damage model

Fig.3 Comparison of damage index of specimen failure point

3. Conclusion

In this paper, the improved damage model is proposed for the problem that the upper and lower bounds of the park damage model are not convergent. The experimental database of reinforced concrete columns collected by the Pacific Earthquake Engineering Research Center (PEER) and the experiments completed by the authors are used to study the determination of the coefficients of the improved damage model. The damage index of the limit point calculated by the improved damage model is closer to 1, and the discreteness is obviously reduced. For facilitating the practical application of engineering design, the coefficient of the rectangular reinforced concrete member, which is mainly flexural and has a good lateral restraint, is preferable to 0.03.

Acknowledgements

The financial support from the National Natural Science Foundation of China under Grants No.50708081 and 90815029, Key Project of Chinese National Program for Fundamental Research and Development (2017CB714202), and Young Talents Innovation Program of Binzhou University (BZXYQNLG201602), are gratefully acknowledged.

References

[1] Miner M A. Cumulative damage in fatigue. Journal of Applied Mechanics, 1945, 12 (3):159-164.
[2] Haluk S, Altug E. Energy-based hysteresis and damage models for deteriorating systems. Earthquake Engineering and Structural Dynamics, 2014, 33(1): 69-88.
[3] Teran-Gilmore A, Jirsa J O. A damage model for practical seismic design that accounts for low cycle fatigue. Earthquake Spectra, 2015, 21(3): 803-832.
[4] Park YJ, Ang AHS. Mechanistic seismic damage model for reinforced concrete. Journal of Structural Engineering, 1985, 111(4): 722-739.
[5] PEER structural performance database. Berkeley: Pacific Earthquake Engineering Research Center, 2003, http://nisee. Berkeley. edu/spd.
[6] Jianbo Zheng, Huanjun Jiang, Linzhi Chen. Experimental study on seismic damage mechanisms of reinforced concrete beams and columns. Proceedings, the Eighteenth National Academic Conference on Structural Engineering, Guangzhou, China, 2016, pp:214-218.
[7] Berry M, Parrish M, Eberhard M. PEER structural performance database user's manual. Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2004.
[8] Yang Deqiang, Yan Changwang, Liu Shuguang. Seismic damage analysis of steel bone super high strength concrete column concrete beam joints based on energy method [J]. Journal of Disaster Prevention and Mitigation Engineering, 2017(01):17:24.
[9] Ding Xiaoyan, Pan Zhihong. Study on plastic hinge model of earthquake damaged concrete frame structure [J]. Earthquake Resistant Engineering and Retrofitting, 2016(06):48-54.
[10] FIB. Displacement-based seismic design of reinforced concrete buildings. International Federation for Structural Concrete, 2004.