RESEARCH ON COLLAPSE AND DAMAGE EVOLUTION OF REINFORCED CONCRETE FRAME STRUCTURE UNDER SEISMIC FORCE

Haiqing Liu[1,2], Xiaobo Chen [2] , Jing Yuan [3], Xueqing Wang [3]

[1] *Professor, College of Civil Engineering & Architecture, Liaoning Technical University, Fuxin, China*
[2] *Doctor, Institute of civil engineering & water conservancy, Dalian University of Technology , Dalian, China*
[3] *Doctor, College of Civil Engineering & Architecture , Liaoning Technical University, Fuxin, China*
Email: lhq2008@163.com, Xiaobo9017@163.com

ABSTRACT:

Elastoplasticity displacement time history response of the structure under seismic force is analyzed by nonlinear dynamic finite element method. The damage index of member is calculated by the improved double parameter damage model based on distortion and dissipation. The damage index of holistic structure is calculated with weighted method. The process of structure collapsing is defined quantificationally by damage index based on three-level seismic fortification objective. The analysis shows that the improved damage index model can describe the process of structure collapsing quantificationally and continuously. The damage evolution equations of beams, columns and holistic structure are fitted and the damage evolution rules of frame structure are studied. The damage evolution equations of the beam and the column based on the two variables of the number of layer and time are put forward. The damage evolution rules of holistic structure accord with the design principle of strong column and weak beam by the optimal fitted equation of the damage index.

KEYWORDS: damage index, structural collapse, seismic response, damage mode, damage evolution rule

1. INTRODUCTION

Earthquake disaster causes numerous casualties and buildings' collapse and lifeline project is seriously damaged. Loss of life and property is largely due to buildings' collapse when earthquakes occur. The study of the process of building collapsing under seismic force has important practical significance. With the seismic damage theory, structural damage under seismic force is described quantificationally by the calculation of damage index to study the whole process of RC structure collapsing. It provides the guidance to establish more reasonable structure design decision, effectually reduce probability of structure collapsing when earthquake occurs and take effective preventive measures. And it provides the theoretical base of disaster prevention and disaster reduction. The study of damage evolution rules of RC frame structure under seismic force has important theoretical significance to show the damage evolution essential of frame structure under seismic force.

2. COMPUTATIONAL MODEL OF DAMAGE INDEX

2.1. Computational Model of Member's Damage Index

The damage index of member can be defined ratio of one cumulant to limit permissible value of corresponding index, which is generally expressed by *D*. There is the common opinion on structural damage and failure mechanism under seismic force at home and abroad. It is the double parameter damage model based on the two controls parameters which are distortion and dissipation. That is,

$$D = f\left(\frac{X_m}{X_u}, \frac{E_h}{E_u}\right) \tag{2.1}$$

The double parameter damage models are commonly used that the seismic damage model based on linear combination of maximum distortion and cumulate hysteretic energy dissipation curves advanced by American scholar, named Park Y.J et al, the double parameter seismic damage model of brick structure advanced by Jiang Jinren and Sun Jingjiang, the seismic damage model of steel structure advanced by Academician Ou-Jinping and the double parameter seismic damage model advanced by Academician Wang-Guangyuan. In this paper, the double parameter damage index model is improved based on previous work. The improved model is expressed as follows:

$$D=(1-\beta)\frac{X_i-X_y}{X_u-X_y}+\beta\frac{E_i}{F_y(X_u-X_y)} \tag{2.2}$$

where, $0\leqslant\beta\leqslant1$. And β is the coefficient of linear combination and the same as $1-\beta$; X_i is the member's elastoplasticity distortion of each time step; X_y is the yield deformation; X_u is the limit distortion; F_y is the yield force of member; E_i is the cumulate hysteretic energy dissipation in the process of seismic force's action.
The improved double parameter seismic damage model accords with original definition of the damage index and is widely used. Both the maximal damage index and all the damage indexes in the whole process of seismic force's action can be worked out. The damage evolution rules can be studied preferably and the process of holistic structure collapsing can be described quantificationally.

2.2. Computational Model of Structural Damage Index

In this paper, the damage model of holistic structure is established with weighted average method which was applied by Park et al:

$$D=\sum(W_iD_i)/\sum W_i \tag{2.3}$$

Where, W_i is the damage weighted value of i member, which means the importance of i member in holistic structure. Park made W_i equal to D_i. It shows that the more seriously member damages the greater it contributes to the damage of holistic structure.

3. DEFINING CRITERION OF STRUCTURAL COLLAPSE BASED ON SEIXMIC DAMAGE THEORY

Domestic and international scholars gave the different seismic damage limits according to the damage model which they put forward respectively, as shown in Table 3.1. There are two seismic damage objectives based on three-level seismic design of reinforce concrete structure according to the importance of structure to fit for structure seismic performance design in our country, as shown in Table 3.2. The damage index is related to the actual seismic damage in Table 3.1 and Table 3.2. The Structure damage under seismic force is described quantificationally according to the range of damage index.
Seismic force is described quantificationally according to the range of damage index.

Table 3.1 Damage index range of different damage rank

Damage extent	Basically undamaged	Slight damage	Middling damage	Serious damage	Collapse
Park		0～0.4		0.4～1.0	≥1.0
Niu -Ditao	0～0.2	0.2～0.4	0.4～0.65	0.65～0.9	≥0.9
Ou-Jinpijg	0～0.1	0.1～0.25	0.25～0.45	0.45～0.65	≥0.9
Liu-Boquan	0～0.1	0.1～0.3	0.3～0.6	0.6～0.85	≥0.85
Jiang-Jinren	0.228	0.254	0.42	0.777	≥1.0
Hu-Yuxian	0～0.15		0.2～0.4	0.4～0.6	0.8～1.0

Table 3.2 Three-level seismic fortification objective of reinforce concrete structure based on damage index

Seismic fortification level		Not damage after minor earthquakes	Repair after moderate earthquakes	Not collapse after major earthquakes	
Corresponding seismic damage rank		Basically undamaged	Slight and middling damage	Serious damage and collapse	
Allowable values of damage index	General structure		0.00～0.25	0.25～0.5	0.5～0.9
	significant structure		—	0～0.25	0.25～0.5

4. NUMERICAL SIMULATION ANALYSIS OF REINFORCED CONCRETE FRAME STRUCTURAL COLLAPSE

4.1 Project Profile

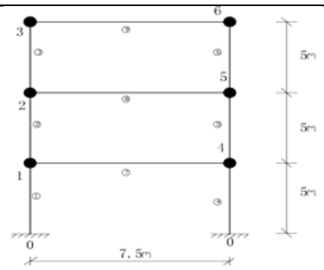
The calculation diagram of a three-layered RC frame structure is shown in Fig.1. The dimensions of members are shown in Table 4.1. The concrete grade is C30. The design value of concrete compression strength is 17.5N/mm^2. The concrete tensile strength is 17.5N/mm^2. The elasticity modulus of concrete is equal to 3×104 N/mm^2. Second grade reinforcement is adopted. The design value of tensile strength is 340N/mm^2. The elasticity modulus of reinforcement is equal to 2×105 N/mm^2. The mass of each layer is expressed respectively as m_1+m_4=5×103kg; m_2+m_5=5×103kg; m_3+m_6=3×103kg. The damping matrix [c] = λ[M], where λ = 0.6.

Table 4.1 Basic parameter of the three-layered reinforce concrete frame

Layer number	Floor height（m）	Girder span（m）	Sectional dimension (mm) Column	Sectional dimension (mm) Beam	Reinforcing bars (mm) Column	Reinforcing bars (mm) Beam
1	5	7.5	400×500	250×700	4 25	3 22
2	5	7.5	400×500	250×700	4 25	3 22
3	5	7.5	400×500	250×700	4 25	3 20

4.2 Numerical Simulation

The gradually amplificatory low-cycle cyclic load is imputed instead of seismic wave, as shown in Fig.2. *Nonlinear-Dynamic*, ourselves-developed nonlinear dynamic finite element calculation procedure is applied to calculate absolute displacement and relative displacement time history response of each layer peak, as shown in Fig.3 and Fig.4.



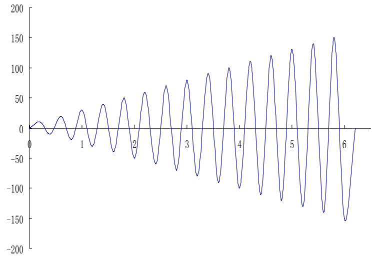


Fig.1 Frame calculation diagram

Fig.2 Low-cycle cyclic load

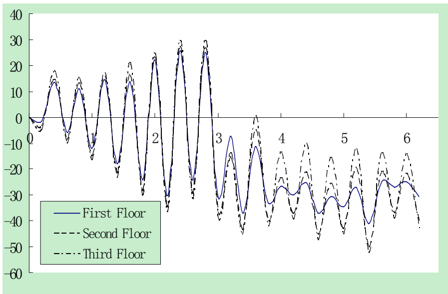


Fig.3 Absolute displacement time history curve of each layer peak

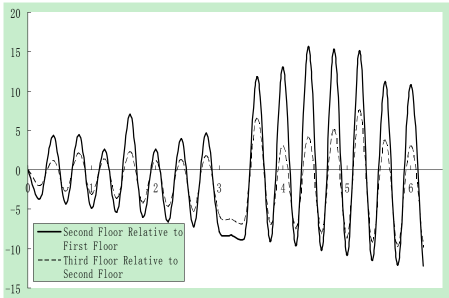


Fig.4 Relative displacement time history response response curve of each layer peak

The ①～③ member have the same damage to the ④～⑥ member because of structural symmetry, so the damage of the ①～③ member are only calculated. The damage indexes of each member in the different time step can be calculated according to the improved double parameter damage coefficient computational model and the structural damage coefficient computational model.

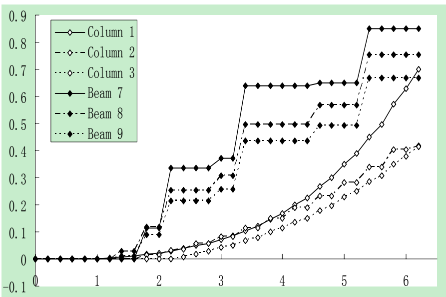


Fig.5 Each member's damage value curve of different time step

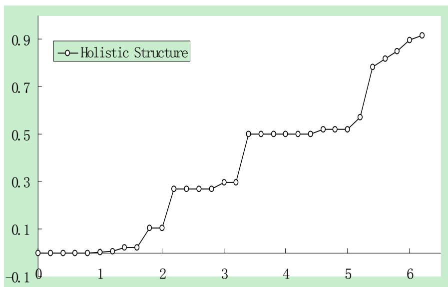


Fig.6 Holistic structural damage value curve of different time step

The damage indexes of members are compared by segistration and the holistic structural damage evolution curve is drawn simultaneously to compare the damage of each member more intuitively, as shown in Fig.5 and Fig.6.

4.3 Results Analysis

(1) Table 4.2 shows that the damage of beams is greater than that of columns during damage evolution. It corresponds with the actual design principle of strong column and weak beam. It means that when frame structures with strong column and weak beam enter the stage of large deformation, the secondary bearing members (beams) are damaged first and absorb seismic energy, then the vertical bearing members (columns) are damaged.

(2) Table 4.3 shows that the columns' damage values of bottom layer are larger than those of the second floor and the third floor. The main deformation of frame structure is shear deformation, so columns of bottom layer should be damaged seriously. Simulated result corresponds with the actual situation. The columns of bottom layer are damaged most seriously at 6.2s and damage index reaches 0.700487. Seen from the change ratio of columns' damage value between upper and lower layers, the change ratio of damage value from the third layer to the second layer is lesser than that from the second layer to the first layer while the members' damage values reach the maximum. It shows that the more frame structure has layers, the less columns' damage changes.

Table 4.2 Comparison of the damage value between beam and column in the same layer of the main time step

The number of layer	Bearing members	t=1s	t=2s	t=3s	t=4s	t=5s	t=6s
The first floor	Beam	0	0.11594	0.37207	0.64032	0.65025	0.84947
	Column	0.001	0.02251	0.07271	0.16737	0.34913	0.62945
The second floor	Beam	0	0.11743	0.37207	0.49800	0.56635	0.49424
	Column	0	0.01551	0.08280	0.14852	0.28352	0.40336
The third floor	Beam	0	0.08919	0.25862	0.43525	0.49424	0.66681
	Column	0	0	0.04153	0.11282	0.22853	0.37698

Table 4.3 Columns' damage values and change ratio of damage value between upper and lower layers of the main time step

Time / The number of layer	1s	2s	3s	4s	5s	6s
The first floor	0.000	0.022516	0.072716	0.167379	0.349193	0.629451
The second floor	0.000	0.01551	0.082804	0.148524	0.283528	0.403369
The third floor	0.000	0.0000	0.041534	0.11282	0.22853	0.376982
Change rate between the first layer and the second layer	+0	-31.1%	+12.18%	-11.26%	-18.8%	-57.06%
Change rate between the second layer and the third layer	+0	-100%	-49.84%	-24.04%	-19.4%	-6.5%

(3) Table 4.4 shows that the beams' damage values of bottom layer are larger than those of the second floor and the third floor. The beams of bottom layer are damaged most seriously at 6.2s and damage index reaches 0.849471. Seen from the change ratio of beams' damage value between upper and lower layers, the change ratio of damage value from the third layer to the second layer is greater than that from the second layer to the first layer while the members' damage values reach the maximum. It shows that the more frame structure has layers, the more largely beams' damage changes.

(4) Fig. 6 shows that the damage index of holistic structure exceeds 0.9 when t=6s. The holistic structural damage index comes within the extension of collapse according to table 2. It is judged that the structure is collapsing when t=6s according to table 1.

Table 4.4 Beams' damage values and change ratio of damage value between upper and lower layers of the main time step

Time / The number of layer	1s	2s	3s	4s	5s	6s
The first floor	0.000	0.115946	0.37207	0.640324	0.650257	0.849417
The second floor	0.000	0.117436	0.306803	0.498001	0.566359	0.754055
The third floor	0.000	0.089194	0.258626	0.435252	0.494242	0.666818
Change rate between the first layer and the second layer	+0	+1.2%	-17.54%	-22.23%	-12.73%	-11.23%
Change rate between the second layer and the third layer	+0	-24.04%	-15.7%	-12.6%	-19.4%	-11.57%

5. DAMAGE EVOLUTION ANALYSIS OF REINFORCED CONCRETE FRAME STRUCTURE

5.1 Fitting of evolution equations

In order to describe the damage evolution rules of members and structure preferably in the whole loading period, the damage evolution equations of each member and holistic structure are fitted by the mode of discrete data' fitting and the fitted curves of discrete damage values are obtained, as shown in Fig.7 to Fig.13.

（1）Damage evolution fitted equations of columns：

Column 1： $$D(t) = 8.142e^{-15.68/t} \quad (5.1)$$

Column 2： $$D(t) = 2.346e^{-10.69/t} \quad (5.2)$$

Column 3： $$D(t) = 4.17e^{-14.42/t} \quad (5.3)$$

（2）Damage evolution fitted equations of beams：

Beam 7： $$D(t) = 0.06507t^3 - 0.006997t^2 \quad (5.4)$$

Beam 8： $$D(t) = 0.04888t^3 - 0.004688t^2 \quad (5.5)$$

Beam 9： $$D(t) = 0.0412t^3 - 0.003794t^2 \quad (5.6)$$

（3）Damage evolution fitted equation of holistic structure：

$$D_z(t) = 2.028e^{-25.52/t} \quad (5.7)$$

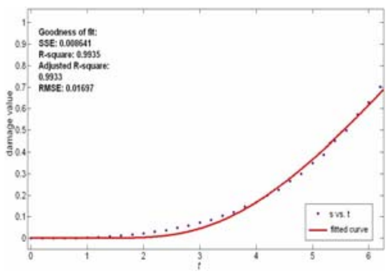


Fig.7 Damage evolution fitted curve of column 1

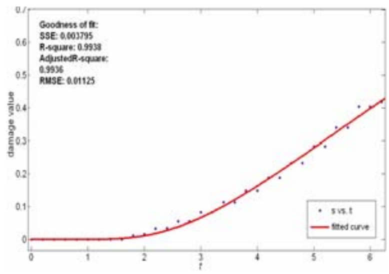


Fig.8 Damage evolution fitted curve of column 2

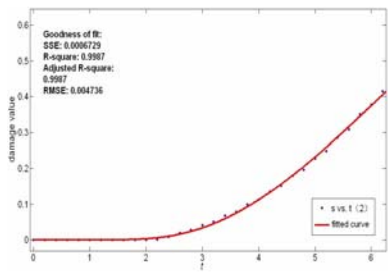


Fig.9 Damage evolution fitted curve of column 3

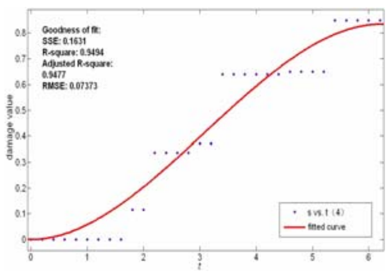


Fig.10 Damage evolution fitted curve of beam 7

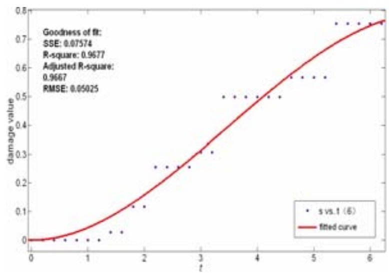


Fig.11 Damage evolution fitted curve of beam 8

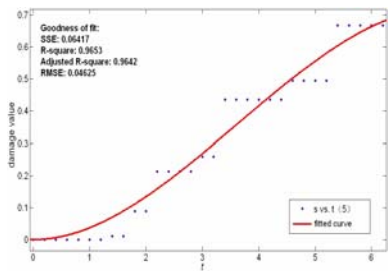


Fig.12 Damage evolution fitted curve of beam 9

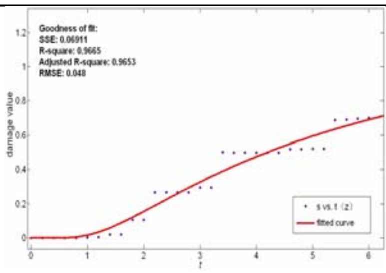


Fig.13 Damage evolution fitted curve of structure

5.2 Damage Evolution Equations Based on the Two Variables of Number of Layers and Time

The evolution equations of columns and beams are divided into two categories based on the thought of normalization and the number of layer is introduced into the damage evolution equation as a parameter to deduce the damage evolution equations of columns and beams based on the two variables of the number of layer and time.

（1）Damage evolution equations of beams：

$$D(f,t) = (0.0158 f^2 - 0.0712 f + 0.1205) \times t^2 + (-0.002 f^2 + 0.0093 f - 0.0143) \times t^3 \quad (5.8)$$

（2）Damage evolution equations of columns：

$$D(f,t) = (1.218 f^2 - 7.896 f + 15.09) e^{(1.235 f^2 - 2.445 f - 14.47)/t} \quad (5.9)$$

Where, $D(t)$ is the damage index of member based on time parameter; $D_Z(t)$ is the damage index of holistic structure based on time parameter; $D(f, t)$ is the damage index of member based on the two parameters of time and the number of layer; f is which layer the member is.

The collapse of columns plays the decisive role under seismic force. The collapse of the vertical bearing members (columns) is the major cause of the collapse of holistic structure. So the damage evolution rules of holistic structure are the same to those of columns, which accord with exponential law of development.

6 CONCLUSIONS

(1) By the improved computational model of damage index the maximal damage index can be calculated, and the damage index of holistic structure can be calculated continuously to describe the whole process of holistic structure collapsing.

(2) The evolution equations of columns and beams are deduced based on the two variables of the number of layer and time adopting the thought of normalization. The damage evolution rules of the two members are studied, which is a good preparation for further studying those of more types and multi-span structure.

(3) The improved model and the analysis theory correspond with the actual design principle of strong column and weak beam by comparison between the damage evolutions of each member.

REFERENCES

[1] Shen Jvmin, Zhou Xiyuan, Gao Xiaowang. (2000). Seismic Engineering. China Architecture and Building Press, Beijing, China.

[2] Xing Jun. (2004). Numerical Simulation of the Process of Reinforced Concrete Framework Collapsing under Seismic Force. Hebei University of Technology, Tianjin, China.

[3] Yu Haiyang. (2004). Research on Seismic Damage Model of Reinforced Concrete Structure. Chongqing University, Chongqing, China.

[4] Park Y.j. AngA.H.S. (1985). Mechanistic Seismic Damage Model for Reinforce Concrete. Structure Engrg ASCE **111: 4**, 722-739.

[5] Park Y.j. AngA.H.S. Wen Y.K. (1985). Seismic Damage Analysis of Reinforce Concrete Building. Structure Engrg ASCE **111:4**, 740-757.

[6] Jiang Jinren, Sun Jinjiang.(1987).Seismic Damage Model of Brick Structure**.** Earthquake engineering and engineering vibration **7:1**, 20-34.

[7] Ou Jinping, Niu Ditao, Wang Guangyuan. (1990). Fuzzy Dynamical Reliability Analysis and Design of Multi-storey Nonlinear Aseismic Steel Structure**.** Earthquake engineering and engineering vibration **10:4**, 27-37.

[8] Wang Guangyuan. (1999). Practice Method of Seismic Optimal Design of Engineering Structure and System. China Architecture and Building Press, Beijing, China.

[9] Ou Jinping, He Zheng, Wu Bin, Qiu Fawei. (1999). Seismic Damage Performance- based Design of Reinforced Concrete Structures**.** Earthquake engineering and engineering vibration **19:1**, 21-30.

[10] An Dongmei, Tan Bangben.(1994). Isotropic Damage Model in Concrete An Dongmei. Journal of Hunan University **22:4**, 109-114.

[11] Liu Haiqing, Chen Xiaobo, Wang Xueqing. (2008). Numerical Simulation of Collapsing of Reinforced Concrete Framework using damage index. Journal of Natural Disasters **17:2**