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# Structural Two-Parameter Exponential Damage Model Performance Analysis under Earthquake Excitation

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**Abstract**

On the basis of the earthquake damage assessment criteria and destroyed model, the inter-story drifts of the structure under rare earthquake are obtained through the capacity spectrum method, combining the nonlinear static analysis with the structural element's plastic hinges distribution, and the earthquake damage of structure is evaluated. In this paper the relationship between the hysteretic energy of the structure and the maximal displacement is used to get the structural hysteretic energy, which greatly improved the computational efficiency and this method has broad engineering application prospects.



*Keywords:* two-parameter earthquake damage model; Park-Ang criterion; Pushover analysis; inter-story cumulated energy; damage index.

## 1. Introduction

At present, it is considered that the principal effect of the earthquake amplitude first causes major damage to the structure beyond the linear stage, while the sustained time process of the strong earthquake causes reciprocating vibration leading to structural nonlinear response stage. This failure mechanism reflects that, this fact is caused by the combined effects of large amplitude of load and cyclic loading effect. It can explain the combined effects of the three elements of ground motion on structural damage[1].

## 2. Two parameter earthquake damage model

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Since the 20th century, researchers on how to quantitatively describe structural damage performance under earthquake excitation have resulted into publication of so-many research reports. In the field of this theory, the most widely used is the Park and Ang's [2] linear combination of seismic damage model of earthquake elasto-plastic deformation and the cumulative hysteretic energy.

The Park-Ang criterion is a structural element floor's damage evaluation criterion. To evaluate the floor damage index, the structure's floor ultimate displacement, the yielding displacement and yielding shear force can be obtained through the restoring force parameters of each floor's structural element and thereby calculate the structural inter-story damage index, which is defined as:

$$D_i = \frac{X_{im}}{X_{icu}} + \beta \frac{E_{ih}}{V_{iy} X_{icu}} \tag{1}$$

Where $X_{im}$, $E_{ik}$ are the maximum inter-story drift and inter-story cumulative energy of the i$^{th}$ floor under seismic action, respectively $V_{iy}$ is the i$^{th}$ floor's yielding shear force, $X_{icu}$ is the structure i$^{th}$ floor's damage ultimate displacement and $\beta$ is energy factor which generally varies between 0~0.85.

## 3. Simplified calculation method of damage model

### 3.1. Inter-story cumulative energy Eik

The equation of energy response of a single degree of freedom (SDOF) system when subjected to horizontal earthquake excitation can be written as [4]:

$$\int_0^t m\ddot{x}\dot{x}dt + \int_0^t c\dot{x}^2 dt + \int_0^t f_s \dot{x}dt = -\int_0^t m\ddot{x}_g \dot{x}dt \tag{2}$$

The above equation can be abbreviated (or rewrite) as follows:

$$E_K + E_D + E_Y = E_I \tag{3}$$

In literature [5], the relationship between the floor's elasto-plastic deformation energy and the maximum displacement is expressed as follows:

$$E_{ih} = \frac{1}{2} V_{iy} X_{iy} + (1 + 4\rho) V_{iy} (X_{im} - X_{iy}) \tag{4}$$

Wherein, $\rho$ Is hysteretic model correction factor ($\rho$ = 0.2).According to the practical frame's cross-sections and material strength standard, the shear bearing capacity of the i$^{th}$ floor is calculated in this article. The yielding shear force $V_{iy}$ of the frame structure is obtained by the following equation [6]:

$$V_{iy} = \frac{M_{ci}^t + M_{ci}^b}{h_i} \tag{5}$$

$M_{ci}^t$, $M_{ci}^b$ are bending moment at the top and bottom of the column i, which can be calculated in accordance and considering strong column-weak beam, strong beam-weak column and hybrid node principles, separately. According to structural seismic code requirements, the strong column weak-beam principle should be adopted for earthquake design [7].

Basic mechanical properties of the strong column-weak beam node: structure beams yield before columns; axial force suffered can be ignored. The maximum moment of the beam within elastic stage is:

$$M_{eby} = W_n F_y \tag{6}$$

$$M_{c1} = \frac{i_{c1}}{i_{c1} + i_{c2}} \sum M_{eby}, \quad M_{c2} = \frac{i_{c2}}{i_{c1} + i_{c2}} \sum M_{eby} \tag{7}$$

According to the bending moment equilibrium of the node, the bending moments at the column both sides are obtain as follow:

$\sum M_{eby}$ is the sum of beam-ends yielding bending moment. $i_{c1}$, $i_{c2}$ the linear stiffness of the top and bottom column at the intersection of the same node:

The column yielding displacement is generally expressed as:

$$X_{yi} = \frac{V_{yi}}{D'}, \quad D' = \frac{12i}{h^2} \tag{8}$$

Wherein, $X_{yi}$, $V_{yi}$, $D_t$ are respectively the each floor's i[th] column yielding displacement, yielding shear force and column lateral stiffness.

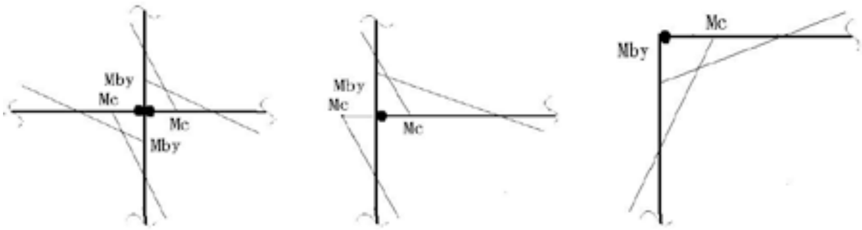



Fig.1.beam-column node moment at floor yielding stage.

Within the plastic stage, the maximum bending moment resulting in plastic hinge is express as:

$$M_{pb} = W_{pn} F_y \tag{9}$$

Where: $F_y$, yield strength of steel material; $W_n$, the beam section modulus;

The empirical equation of ultimate displacement of the column is express as:

$$X_{icu} = \frac{V_{pi}}{D'} \tag{10}$$

From steel structure design specifications [8], the plastic hinge bending moment of the beam $M_{pb}$ and the maximum bending moment at plastic stage $M_{eby}$ ratio are only related to cross-section geometry properties.

$W_{pn} / W_n$ Is call the cross-section shape factor *F*. for rectangular cross-section, *F* = 1.5.

*3.2. The maximum inter-story drift*

Based on finite element analysis software, an analytical frame structure model is established in this paper. The Pushover analysis is performed on the frame model for low stiffness direction and the maximum displacement response of the structure is obtained as:

$$X_{im} = \frac{X_i^b - X_i^a}{H_i} \tag{11}$$

$X_i^b$ Is the top floor displacement of the i[th] floor; $X_i^a$ is the base displacement of the i[th] floor and $H_i$ Is the i[th] floor high. When $X_{im} - X_{iy} < 0$, the structure is in elastic stage, D=0.

## 4. Numerical analysis example

On the basis of the strong column-weak beam fundamental design concept and using the Q235 steel material, a 10 storey steel frame model is established where the storey high is 4m. The finite element analysis software SAP2000 is used at the first stage to carry out the structural response under El-Centro wave, Tianjin wave and RGB, respectively, and combining SAP2000 with Matlab program the inter-story drift and floor damage index are evaluated. The structure floors damage indexs are presented in table 1.

Table 1.structure floors damage index

| Floors | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Tianjin | <0 | <0 | <0 | 0.054 | 0.137 | <0 | <0 | <0 | <0 | <0 |
| El-Centro | <0 | <0 | <0 | 0.028 | 0.170 | 0.241 | 0.289 | 0.289 | 0.262 | 0.217 |
| RGB | <0 | 0.050 | 0.149 | 0.321 | 0.365 | 0.412 | 0.441 | 0.424 | 0.327 | 0.153 |

It can be remarked that: the structure is almost “intact”, the structure reacts well when subjected to Tianjin wave. While partial damage appears at middle floors under El-Centro wave excitation. More severs structural damages are observed when the structure is subjected to artificial earthquake wave (RGB). According to literature [9], structure collapse definition and classifications criteria are defined and presented in table 2. The structure damage situation under the artificial wave is more deeply investigated and presented in table 3.

Table 2.Park-Ang model damage criterion and classification

| Damage level | Intact | Slight damage | Moderate damage | Severe damage | Collapse |
|---|---|---|---|---|---|
| Park-Ang | | 0~0.4 | | 0.4~1 | >1 |
| Improved | < 0. 1 | 0.1~0.25 | 0.25~0.4 | 0.4~4 | >4 |

Table 3.structure inter-story damage under artificial wave (RGB)

| Floors | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Damage index | <0 | 0.050 | 0.149 | 0.321 | 0.365 | 0.412 | 0.441 | 0.424 | 0.327 | 0.153 |
| Damage level | Intact | Intact | Intact | Moderate | Moderate | Severe | Severe | Severe | Moderate | Slight |

From table 3 it can be seen that the 6th, 7th and 8th floors reached the “severe damage level”, which should be strengthened consider during structure design and assessment. The 4th, 5th and 9th floors are evaluated at “moderate damage level”; while other floors are almost “intact” or have “slight damage”.

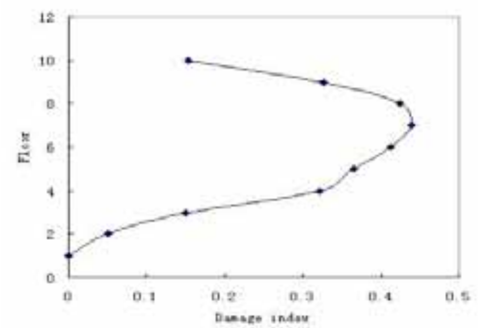
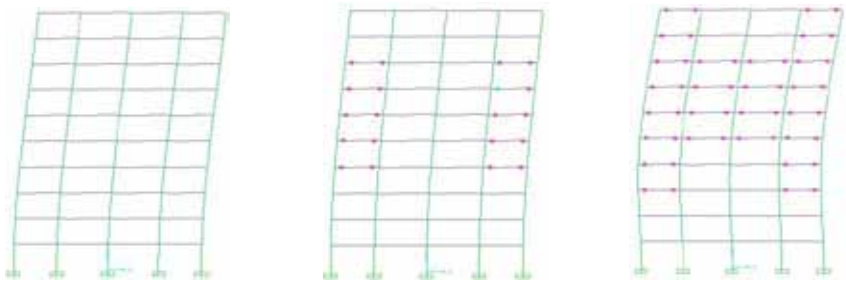



Fig.2. structure inter-story damage index distribution under artificial wave

Figure 2 shows the inter-story damage index distribution of the structure when subjected to the artificial earthquake wave and it can be easily seen the structure damage changes: weak floors are mainly observed in the middle of the structure; and with the increased earthquake damage intensity, the trend has extended to the upper and bottom. Therefore, during high rise buildings design, engineers must properly set up strengthening floors, to avoid unnecessary human casualties and economic losses.

The nonlinear static pushover analysis's plastic hinges distributions of the structure are shown in figure3.



(a)Tianjin wave (b) El-Centro wave (c) artificial wave

Fig.3. plastic hinge distribution:

According to the plastic hinges distribution of nonlinear static analysis, when the structural members achieved the performance point, the floors 5 to 8 beams where certain extent of plastic hinge appeared have presented moderate damage; The $3^{th}$, $4^{th}$, $9^{th}$ and $10^{th}$ floors' beams have relatively small injuries. This is consistence with the structure inter-story damage index assessment.

## 5. Conclusion

This paper presents a simplified calculation method of the structural damage model, and a comparative analysis with the plastic hinges distribution results of the sophisticated finite element model. Similar results are obtained in this analysis, proving the usefulness and reliability of the proposed method. This method of calculation greatly simplifies the computational work of the Park-Ang model, and plays an active role on the earthquake failure mechanism investigation.

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