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Review of Reinforced Concrete (RC) Structural Damage Models

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ABSTRACT: Earthquakes are sudden and devastating natural disasters, often triggering secondary disasters such as tsunamis and landslides, posing a significant threat to people's lives and property. Since earthquake prediction is still in the research stage, the majority of earthquakes cannot be accurately forecasted, and their occurrences are often unexpected. With the development of seismic design, scholars both domestically and internationally have summarized a large number of damage models to assess the damage levels of structures. Analyzing the advantages and disadvantages of various models allows for the selection of appropriate damage models in seismic design.

KEYWORDS: damage model, deformation, energy, degeneration, Park-Ang.

I. INTRODUCTION

In seismic design, one aspect is damage assessment. Damage is a very intuitive manifestation of structural failure, and it is necessary to evaluate structural damage through damage indices. It is inevitable to use certain damage indices for structural design. A damage index is a quantitative physical quantity that describes the extent of damage to components or structures, usually by quantitatively describing the variation of structural characteristic parameters [1]. The damage index for a component can be defined as the ratio of a cumulative quantity in the component response history to the corresponding limit of a specific index value, typically denoted as D . The damage index D has the following properties: when $D = 0$, the component is intact; when $D = 1$, the structure is completely destroyed; when D is between $[0,1]$, the component is at different levels of damage. Ou[2] summarized the relationship between damage indices and failure levels, as well as failure phenomena. By calculating the damage index, they determine the level of damage and subsequently assess the damage situation. Scholars at home and abroad have proposed various damage models to calculate damage indices, including single-parameter models and two-parameter models. Single-parameter models include deformation-based damage models, energy-based damage models, and degradation-based damage models. Two-parameter models combine the above parameters in pairs, forming deformation and energy-based damage models; deformation and degradation-based damage models; degradation and energy-based damage models.

II. SINGLE-PARAMETER DAMAGE MODELS

Before the 21st century, most of the damage models proposed by scholars both domestically and internationally were single-parameter damage models. They only considered one aspect that causes structural damage, and their expressions were relatively complex, which was not comprehensive enough for seismic design. The emergence of single-parameter damage models laid the foundation for the appearance of two-parameter damage models. The author categorizes the single-parameter damage models proposed by scholars into three types: deformation, energy, and degradation, each with its own advantages and disadvantages. The author believes that among these three types of damage models, energy-based damage models are the most important. The influence of energy dissipation under cyclic loading on component damage cannot be ignored.

(1) Deformation-based damage model

The scholar proposed two damage models based on the vibration study of a single material point system [3]:

$$D_e = D_e^m + D_e^p = \frac{\mu_{\max} - 1}{\mu_v} + \frac{1}{2} \sum_{i=1}^N \left(\frac{\Delta \mu_{pi}}{\mu_f} \right)^2 \left(1 - \frac{\Delta \mu_{pi}}{2\mu_f} \right) \quad (1)$$

$$D_e = D_e^m + D_e^p = \frac{\mu_{\max} - 1}{\mu_v} + \frac{1}{4} \sum_{i=1}^N \left(\frac{\Delta \mu_{pi}}{\mu_v} \right) \quad (2)$$

In the equation, D_e^m and D_e^p respectively represent the damages caused by maximum deformation and cyclic plastic deformation. μ_{\max} denotes the maximum plastic strain rate, μ_v represents the ratio of plastic strain to yield strain, and $\Delta\mu_{pi}$ stands for the plastic strain increment of the i th cycle.

This damage model considers damage indices for both maximum deformation and cyclic deformation, covering the entire process. However, calculating the damage induced by cyclic plastic deformation is challenging and not very convenient for design calculations.

(2) Energy-based damage model

Darwin et al. [4] proposed an energy-based damage model:

$$D = \sum_{i=1}^n \beta_i / D_0 \quad (3)$$

In the equation, n represents the number of cycles, β_i denotes the energy dissipation coefficient, defined as $\beta_i = E_{hi} / P_y \delta_y$, where E_{hi} is the energy dissipated by the i th half-cycle load, P_y is the yield strength of the component, and δ_y is the yield displacement of the component.

Darwin et al. considered the energy dissipation of components under cyclic loading to establish the damage model. Another characteristic of this damage model is that it only considers half of a load cycle. The energy dissipation under the entire cyclic loading is approximately twice that of the energy dissipation during the elastic stage of the component. Therefore, Darwin et al. made this consideration to focus only on half of the cyclic loading. This also reflects a limitation of the model: it does not consider the entire stage. In reality, seismic events are complex processes, and considering only the elastic stage may not fully represent the entire stage.

(3) Degradation-based damage model

Gulkan et al. [5] first employed the degradation of structural component stiffness to define the damage index:

$$D = K_0 / K_r \quad (4)$$

Where, K_0 and K_r respectively represent the initial stiffness and the secant stiffness corresponding to the maximum displacement of the structural component.

From this damage model, it can be observed that the degradation-based damage model only considers two states: one is the initial state and the other is the ultimate state. Compared to deformation-based and energy-based damage models, it is easier to derive the damage index and reduces computational complexity. However, by only considering two states, the damage index becomes discontinuous and fails to reflect the influence of the entire damage process.

From the above damage models, it can be seen that single-parameter damage models more or less lack comprehensive consideration of influencing factors, which may lead to inaccuracies in calculated damage indices. Consequently, this could affect the assessment of component damage and be highly disadvantageous for determining damage levels. The two deformation-based damage models mentioned in this paper did not take into account the influence of displacement amplitude on damage, as they did not introduce a parameter to correct for this effect. The influence of energy dissipation on the damage index cannot be ignored. Both deformation-based and stiffness-based damage models fail to consider this aspect. On the other hand, energy-based damage models do not consider the effects of loading sequence and displacement amplitude. Therefore, scholars have proposed dual-parameter damage models to address these limitations.

III. TWO-PARAMETER DAMAGE MODEL

Domestic and foreign scholars have realized that considering only one factor in damage is insufficient to describe damage indices. Therefore, they began researching two-parameter damage models. The so-called two-parameter damage model combines the factors considered in single-parameter damage models in pairs. Although this combination seems simple, it is derived through extensive experimentation. Two-parameter damage models mainly include deformation and energy-based damage models, deformation and degradation-based damage models, and degradation and energy-based damage models. Currently, the general consensus among scholars is that the primary factors influencing damage models are deformation and energy dissipation. Therefore, the author mainly discusses deformation and energy-based damage models, using the Park-Ang classical model as a reference and comparing it with other modified models at home and abroad.

(1) Deformation and energy-based damage model

Park and Ang [6,7], established a damage model based on a large number of reinforced concrete beam-column tests, which combines maximum deformation and accumulated hysteresis energy in a linear combination:

$$D = \frac{\delta_m}{\delta_u} + \beta \frac{\int dE}{F_y \delta_u} \tag{5}$$

In the equation, D represents the damage index of the structure; δ_m is the maximum deformation of the component or structure under seismic action; δ_u is the ultimate deformation of the component or structure under monotonic loading; F_y is the calculated yield strength; $\int dE$ represents the accumulated hysteresis energy; β is the coefficient representing the influence of cyclic loading. The specific expression for β is:

$$\beta = (-0.447 + 0.773\lambda + 0.24n_0 + 0.314\rho_t)0.7^{\rho_w} \tag{6}$$

In the equation, λ represents the shear-span ratio of the component. When λ is less than 1.7, it is taken as 1.7; n_0 is the axial load ratio. When n_0 is less than 0.2, it is taken as 0.2; ρ_t is the longitudinal reinforcement ratio. When ρ_t is less than 0.75%, it is taken as 0.75%; ρ_w is the volumetric stirrup ratio.

The classic Park-Ang model, widely applied, also exhibits several drawbacks as identified by existing research [8]: The model primarily relies on statistical analysis of experimental data without sufficient theoretical underpinning. Similarly, the calculation of the dissipation combination coefficient β lacks a theoretical basis. When the maximum deformation is reached and the component fails, the calculated value of D obtained from this model often exceeds 1 or even reaches 5, which is highly inconsistent with reality. The model only considers the influence of maximum plastic deformation, neglecting other non-elastic deformations on cumulative damage. It also fails to reflect experimental findings that suggest larger plastic deformations have a greater impact on component damage. The model fails to reflect the influence of cyclic amplitude changes during loading on the ultimate hysteresis energy of the component. It assumes that the ultimate hysteresis energy of the component is only related to the maximum displacement amplitude and is independent of the loading path, contrary to experimental results. Determining non-negative parameters is challenging. Despite empirical formulas provided by Park et al. to estimate combination parameters, their statistical dispersion remains significant.

(2) Park-Ang modified model

Niu [9] proposed a two-parameter damage model that combines nonlinearly the maximum elastoplastic deformation and the cumulative hysteresis energy during cyclic loading:

$$D = \frac{X_m}{X_u} + \alpha \left(\frac{E_h}{E_u} \right)^\beta \tag{7}$$

In the equation, α and β are combination coefficients, reflecting the different influences of structural deformation and energy dissipation on structural failure. For reinforced concrete structures, $\alpha=0.1387$; $\beta=0.0814$.

The main difference between the damage model proposed by Niu and other damage models lies in that their two parameters are derived from the structural design parameters and real earthquake disaster surveys, which is more reliable compared to general models or model parameters derived from experiments. However, its limitation is that this model is only applicable to frames with small height-to-width ratios and strong beam-weak column frames. The reason is that most houses in the 1950s and 1960s were of this type, while modern buildings are mostly high-rise structures, making this model inapplicable.

Chen et al. [10] proposed a modification to address the problem of convergence between the upper and lower bounds in the Park-Ang damage model for reinforced concrete structures.

$$D = (1-\beta) \frac{\delta_m}{\delta_u} + \beta \frac{\int dE}{f_y (\delta_u - \delta_y)} \tag{8}$$

$$\beta = \left(0.023 \frac{L}{h} + 3.352n_0^{2.35} \right) 0.818^{\alpha \rho_{sx} f_{yw} / f'_c} + 0.039 \tag{9}$$

In the equation: β is the combination coefficient, where $0 < \beta < 1$; for rectangular reinforced concrete members subjected primarily to bending with good lateral confinement of transverse reinforcement, β can be taken as 0.1; δ_y is the deformation at yield; $f_y(\delta_u - \delta_y)$ represents the energy dissipated by the ideal elastoplastic system when loaded monotonically to failure; L is the length of the specimen; $n_0 = N/f'_c A_g$ is the actual axial load ratio, where N is the axial force, f'_c is the uniaxial compressive strength of concrete cylinders, and A_g is the cross-sectional area of the specimen; h is the height of the specimen section; ρ_{sx} is the area reinforcement ratio parallel to the loading direction; f_{yw} is the yield strength of the lateral reinforcement; α is the effective confinement coefficient.

Compared to the Park-Ang model, the damage index D of this model is closer to 1.0 when the specimen reaches the failure point in the experiment, and in the elastic stage, the energy dissipation is 0. At this stage, the model is closer to 0, indicating that this model effectively corrects the upper and lower bounds of the Park-Ang model. However, β is determined based on a large number of beam-column test data, making it not applicable to other components. Moreover, the formula by Chen does not reflect the influence of displacement amplitude on damage, nor does it consider the effect of loading direction on damage.

Kunnath et al. [11] proposed a model that describes the damage index based on the rotation angle of the component:

$$D = \frac{\theta_m - \theta_y}{\theta_u - \theta_y} + \beta \frac{E_h}{M_y \theta_u} \quad (10)$$

In the equation, θ_m and θ_u respectively represent the maximum rotation of the plastic hinge at the end of the component and its ultimate value; θ_y is the recoverable rotation after unloading; M_y is the yield moment; E_h is the hysteresis energy. The Park-Ang model does not consider the influence of recoverable deformation after unloading on cumulative damage, which is elastic deformation. Therefore, Kunnath-Reinhorn and others corrected this weakness by subtracting the recoverable rotation after unloading. This correction addresses the issue of the Park-Ang model having a non-zero damage index in the elastic stage. They also modified the yield force to the yield moment, considering both force and deformation's effects on damage. However, they did not address the convergence problem of the upper and lower bounds of the Park-Ang model.

While the Park-Ang model is the most classical, it has several shortcomings. Scholars at home and abroad have made various corrections to it, including correcting the deformation term's deficiencies using elastoplastic deformation and yield deformation, simultaneously correcting energy terms using two parameters, and adjusting the deformation term by subtracting the recoverable rotation. However, each correction model focuses only on one aspect, and these scholars did not realize the coupling relationship between deformation and energy dissipation, which is not reflected in the Park-Ang model. No scholar has proposed a correction model addressing this aspect. In future research, experimental designs can be devised to investigate this aspect, conduct corresponding experiments, and propose new correction models.

IV. CONCLUSION

Single-parameter damage models only consider one factor in damage, with hysteresis energy having the greatest impact on component damage. Since only one factor influencing damage is considered, the resulting damage index often does not correspond well with reality. Consequently, scholars both domestically and abroad have established dual-parameter damage models, which comprehensively consider two aspects of damage, resulting in computed results that better match real-world scenarios. Models that simultaneously consider the effects of deformation and energy on component damage are the most common and best reflect component failure. Whether single-parameter or dual-parameter, the majority of models are currently developed through mathematical modeling based on experimental data obtained from damage tests on concrete beams and columns in laboratories. These data are then statistically analyzed to derive mathematical models. In the author's opinion, experimental data are limited, and many parameters used in the models lack physical significance and theoretical basis, resulting in models lacking generality. When such models are applied in real-life situations and cause damage, the consequences can be severe. The integration of damage models with actual damage investigations from earthquakes requires further research, and relevant theoretical studies should also be promoted simultaneously.

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