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# **A Review of Damage Performance Assessment of Reinforced Concrete Members Under Seismic Loads**

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**ABSTRACT:** The damage assessment of reinforced concrete members under seismic loading must take into account both displacement-induced damage caused by the 'peak effect' and cumulative damage caused by the 'duration effect'. This paper provides a systematic review of research progress on two-parameter damage models, focusing on the theoretical foundations and inherent limitations of both explicit and implicit models. Explicit two-parameter models, typified by the Park-Ang model, are concise in form and suitable for engineering applications; however, their linear superposition form fails to reveal the coupling mechanism between deformation and energy dissipation under variable-amplitude loading histories, and the definition of performance under damage states ( $D < 1$ ) lacks sufficient theoretical support; Implicit two-parameter models, using changes in structural properties such as stiffness and energy as indicators, possess clear physical significance and are easily verified through field testing; however, they struggle to establish a direct logical link between the damage state and the causes of damage. By comparing the applicability and theoretical shortcomings of these two model types, this paper suggests that future research should focus on elucidating the mechanisms by which varying displacement histories influence damage development. It proposes the development of novel assessment methods capable of reflecting the coupling relationship between deformation and energy dissipation, whilst establishing an intrinsic link between damage states and their causes, thereby providing a theoretical basis for enhancing the accuracy and reliability of structural seismic performance assessments.

**KEYWORDS:** Reinforced concrete; Seismic damage; Cumulative damage; Seismic performance assessment.

## **I. INTRODUCTION**

As research in earthquake engineering continues to advance, structural damage assessment has evolved from focusing solely on peak effects to taking cumulative damage effects into account. This is because low-cycle fatigue and plastic accumulation induced by prolonged seismic motion can significantly exacerbate damage to structural members. Consequently, the development of a two-parameter damage model capable of reasonably reflecting the coupled mechanism of displacement-exceedance damage and energy dissipation holds significant theoretical value and practical engineering importance.

Among various damage assessment methods, two-parameter damage models have attracted widespread attention due to their ability to account for both displacement-induced damage and cumulative damage simultaneously[1,2]. Depending on their mathematical formulation, these models can be classified into explicit and implicit two-parameter categories. Explicit two-parameter models, typified by the Park-Ang model, are characterised by their simplicity and ease of application in engineering[3]; implicit two-parameter models, on the other hand, use changes in structural properties such as stiffness and energy as indicators, offering clear physical significance and facilitating experimental verification[4,5]. Both types of models have their respective advantages and play important roles in seismic design and damage assessment[6,7].

This study addresses the issue of assessing the damage behaviour of reinforced concrete members under seismic loading by systematically reviewing the current state of research and theoretical shortcomings of both explicit and implicit two-parameter damage models. It focuses on analysing the mechanistic deficiencies of explicit models in handling displacement histories with varying amplitudes, as well as the theoretical shortcomings of implicit models

regarding the correlation between damage states and their causes. By comparing the applicable conditions and inherent limitations of the two model types, this study provides a theoretical basis for establishing more rational damage assessment methods.

## II. 'EXPLICIT' TWO-PARAMETER DAMAGE MODEL

Explicit two-parameter models assess the extent of damage by establishing an explicit functional relationship between the damage index and the structural macroscopic response (such as deformation and energy dissipation). The most representative of these is the Park-Ang damage model proposed by Park et al. in 1985[3]. Due to its concise form and clear physical significance, this model establishes a direct link between the damage index and the ductility coefficient, yield load, and reinforcement conditions (implied by the parameter  $\beta$ ), thereby enabling damage-based inverse design. Consequently, it has been widely applied and developed. However, its formal simplification also introduces inherent shortcomings in mechanistic interpretation.

Research by Feng et al. indicates that the ultimate deformation capacity of reinforced concrete columns is significantly influenced by the loading history, the root cause of which lies in the plastic accumulation in the stirrups and longitudinal reinforcement leading to buckling of the longitudinal reinforcement. This suggests that the so-called 'deformation damage term' in the model is, in essence, closely related to damage accumulation. Furthermore, the timing and magnitude of peak deformation during the loading history significantly influence the energy dissipation capacity of the member, indicating that the 'energy dissipation damage term' is also coupled with peak deformation. It is thus evident that the two damage mechanisms—deformation and energy dissipation—interact with one another, rather than being simply linearly superimposed[8].

The Park-Ang model attempts to comprehensively account for factors other than the core indicators through an empirical parameter  $\beta$ , in order to maintain its simple linear expression. However, the determination of the  $\beta$  value is typically based on the context of member failure ( $D \geq 1$ ), and fails to reveal the coupling mechanism between deformation and energy dissipation at an analytical level; that is, it does not address the underlying mechanisms by which variable-amplitude loading histories influence the damage development process. Consequently, whilst the model has proven to be reasonable and effective in defining the failure state ( $D=1$ ) of a member under variable-amplitude loading, it still lacks sufficient theoretical support and experimental validation when used to define performance under damage states ( $D < 1$ )[9].

To address these shortcomings, scholars both domestically and internationally have proposed various modified models[10,11]. These works are undoubtedly of great significance for refining the Park-Ang model. However, most of these modifications remain limited to parameter adjustments or formal optimisation, and have not fundamentally addressed the influence mechanism of the amplitude-displacement history on the damage development process. Consequently, whilst such modifications have made progress in enhancing the rationality and accuracy of the model as a 'failure criterion', whether its rationality and applicability as a 'quantitative damage indicator' have been fundamentally improved remains to be further explored theoretically and demonstrated in practice.

## III. 'IMPLICIT' TWO-PARAMETER DAMAGE MODEL

Unlike explicit models, implicit two-parameter models do not establish a direct ratio between damage and the effects of external loads; instead, they describe the extent of damage indirectly based on changes in the structure's intrinsic properties (such as stiffness, energy and strength) before and after damage[5].

As these indicators are relatively convenient to calculate and measure, implicit models are increasingly being applied in the quantitative analysis of damage. For example, Loh et al. found a good correlation between the decay of structural stiffness and damage characteristics; Qu Zhe et al. proposed a seismic design method based on the control of structural damage mechanisms, utilising the reduction in stiffness of structural members; and Wang Xinling et al. classified the development of damage into three stages based on changes in relative structural stiffness. In terms of energy, Fajfar proposed an equivalent ductility coefficient damage model that accounts for the effects of low-cycle fatigue; Hindi et al. developed a damage model that takes into account strength degradation effects[4].

The advantage of implicit damage models lies in their clear physical significance; they enable the quantitative assessment of structural damage at different levels, and the assessment results can be readily verified through testing[6]. However, the limitations of such models are equally pronounced. Their primary shortcoming lies in the lack of in-depth exploration of the logical relationship between 'damage state' and 'damage cause'. As damage expressions often fail to establish a direct link between structural requirements (such as seismic action) and structural performance (such as load-bearing capacity), these models are more frequently regarded as a post-processing tool for non-linear analysis results, and thus have certain limitations in directly guiding structural seismic design and damage assessment[12,7].

#### IV. CONCLUSION

This paper reviews two typical two-parameter damage models used in the assessment of the damage behaviour of reinforced concrete members under seismic loading. The main conclusions are as follows:

1. Explicit two-parameter models, typified by the Park-Ang model, offer the advantages of simplicity and ease of engineering application. However, their linear superposition form fails to accurately reflect the coupling mechanism between deformation and energy dissipation damage. In particular, when dealing with variable-amplitude loading histories, the model still lacks sufficient theoretical support for defining performance under damage conditions ( $D < 1$ ).
2. Implicit two-parameter models, which use changes in structural characteristics such as stiffness or energy as indicators, have the advantages of clear physical significance and ease of verification through field testing. However, their damage expressions struggle to establish a direct link between demand and capacity, and lack a direct logical connection to the causes of damage.

In summary, the future development of seismic damage models should focus on thoroughly elucidating the mechanisms by which 'variable-amplitude displacement histories' influence the damage development process. An ideal damage model should build upon the engineering applicability of explicit models whilst drawing on the clear physical significance of implicit models. It should establish a novel assessment method capable of reflecting the coupling mechanism between deformation and energy dissipation, and of establishing an intrinsic logical link between damage states and damage causes, thereby further enhancing the accuracy and reliability of structural seismic performance assessment.

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