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Parameter Identification of the Bouc-Wen Model Using Damage Index and Its Application to Seismic Response Prediction of RC Structures in Nuclear Power Plants

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1. Introduction

Accurate seismic response prediction is critical for the safety of critical infrastructure such as nuclear power plants (NPP). However, this remains challenging because strong ground motions induce significant changes in the dynamic characteristics of reinforced concrete (RC) structures. Once yielding occurs, nonlinear hysteretic behavior governs the response, characterized by stiffness degradation, strength deterioration, and pinching, all of which evolve with damage progression. The complexity of this behavior necessitates a hysteretic model with sufficient flexibility to represent stiffness degradation, strength deterioration, pinching, and other evolving characteristics during nonlinear response.

To represent such complex hysteresis, the Bouc–Wen model has been widely adopted due to its flexibility in simulating smooth nonlinear force–deformation relationships. Nevertheless, its limited capability to capture pinching and degradation has prompted the development of the Bouc–Wen–Baber–Noori (BWBN) model and its modified form (m-BWBN) [1], with the latter introducing yield strength as a direct calibration parameter. However, even with these advanced models, discrepancies between simulated and experimentally observed responses remain evident in the nonlinear range, indicating that a single parameter set may not adequately represent the evolving hysteretic behavior of RC structures.

To address these challenges, this study proposes a damage-state-based parameter identification framework that explicitly accounts for the progressive changes in hysteretic characteristics across damage levels. The accuracy of the proposed method is experimentally compared with that of a conventional m-BWBN model using cyclic loading test data, and the influence of these modeling approaches on seismic response prediction is further evaluated using seismic test results. By calibrating parameters separately for each state and applying them in seismic response prediction, the proposed method improves agreement with experimental results and enables a more realistic assessment of RC structure performance under severe ground motions.

2. Methods

2.1 Damage-State-Based Identification of m-BWBN Parameters

One of the most widely used approaches for defining damage states in RC structures is the Damage Index (DI) proposed by Park and Ang [2], which combines a deformation term based on the ratio of maximum to ultimate displacement with an energy term representing cumulative hysteretic energy. Because the index can produce non-zero values in the elastic range, Huang [3] revised the formulation so that the DI remains zero prior to yielding. Using this improved definition, DI values are calculated from displacement–force data and the response is classified into four damage states according to the thresholds in Park and Ang [4], as summarized in Table I.

Table I: Damage states defined based on Park and Ang damage indices

Damage Index	Damage state
0	No damage
0~0.2	Minor
0.2~0.4	Moderate
0.4~1.0	Severe
>1.0	Collapse

Typical m-BWBN parameters include the post-to-pre-yield stiffness ratio and shape/strength parameters governing loop curvature, pinching, and degradation. In practice, several of these parameters do not remain constant; instead, they evolve as nonlinearity intensifies and structural damage progresses. To address this limitation, a damage-state-based identification strategy is employed: the response is segmented by DI, and one model parameter is estimated for each damage state using a Genetic Algorithm. Identifying parameters for each damage state enables the m-BWBN model to adapt to degradation and produce accurate seismic response predictions at all damage levels.

2.2 Response Prediction Framework

Following parameter identification, the hysteresis model is used to predict the nonlinear seismic response of the RC structures. The equation of motion for ground motion is as follows.

$$m\ddot{u} + c\dot{u} + f_s(u, z) = -m\ddot{u}_g \qquad (1)$$

In this equation, m denotes the mass, c the viscous damping coefficient, $f_s(u, z)$ the restoring force describing the force–deformation relationship, and $\ddot{u}_g$ the ground acceleration. In this study, $f_s(u, z)$ is represented by the calibrated m-BWBN hysteretic model. For time integration, the Chen and Ricles (CR) algorithm is adopted due to its explicit update form, unconditional stability for positive damping, and accuracy comparable to the constant-average-acceleration Newmark method.

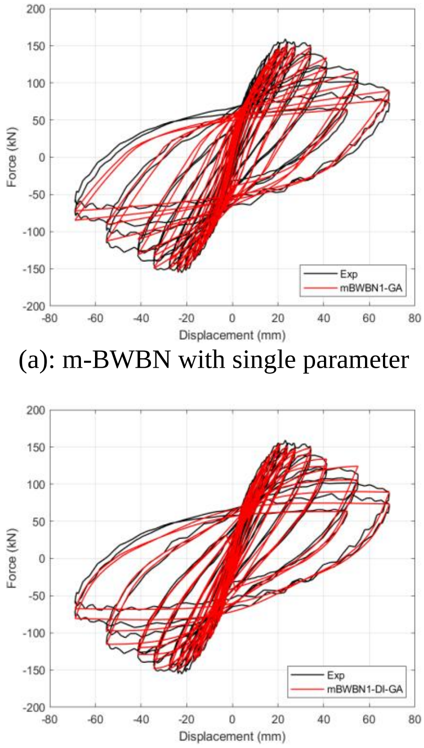
The nonlinear seismic response analysis is performed while adaptively updating the hysteretic model parameters according to predefined DI thresholds. At each time step, the current DI is computed from the simulated displacement–force history. When the DI exceeds the threshold for the next damage state, the corresponding parameter set, identified in the calibration stage, is applied to the hysteretic model. This procedure is repeated until the end of the simulation, ensuring that the model parameters remain consistent with the evolving damage condition of the structure.

3. Experimental validations

3.1 Parameter Identification Result

Fig. 1 presents a comparison between the cyclic loading test data of an RC column subjected to bi-axial loading from Chae [6] and the simulated responses obtained from both the single parameter m-BWBN model and the damage-state-based m-BWBN model.

To complement this visual comparison, Table II summarizes the quantitative evaluation using three metrics: relative RMSE, correlation coefficient, and energy dissipation error. Across all measures, the proposed method shows lower RMSE and energy dissipation error, and a higher correlation coefficient than the conventional model, confirming its enhanced predictive capability for cyclic loading behavior.



(a): m-BWBN with single parameter

(b): m-BWBN with damage-state-based parameters

Fig. 1. Comparison between experimental and force-displacement plots of RC columns (Chae)

Table II: Model evaluation based on relative RMSE, correlation, and energy dissipation error

Evaluation criteria	m-BWBN with single parameter	m-BWBN with damage-state-based parameters
Relative RMSE	12.75%	6.34%
Correlation coefficient	0.9919	0.9980
Energy dissipation error	8.96%	3.41%

3.2 Response Prediction Result

The proposed response prediction framework was validated against hybrid simulation results reported in Chae, which is a testing method that combines numerical and physical components to capture structural behavior under seismic loading. The tested specimen was identical to that used in the cyclic loading experiment and was subjected to a constant vertical load during the seismic test. The 1994 Northridge earthquake was used as the input ground motion, with its amplitude scaled to 0.2 of the original record. The numerical model of the tested RC structure was defined with an initial stiffness of k=15kN/mm, an effective mass of m=81.529 ton, and damping ratio of ζ=5%. Time integration for seismic response prediction was carried out using the CR algorithm, with the restoring force represented by the calibrated m-BWBN model described in Section 2.2. Both the single parameter and damage-state-based models were applied for this purpose, and their predictions were subsequently compared with the experimental results.

As shown in Table III, the maximum displacement prediction error was 20.3 % for the single parameter m-BWBN model, whereas the damage-state-based model reduced this error to 4.9 %, indicating improved accuracy in peak response estimation.

Table III: Comparison of maximum displacement between experimental results and model predictions

Methods	Maximum displacement	Error
Experiment results	17.11mm	-
m-BWBN with single parameter	20.58mm	20.3%
m-BWBN with damage-state-based parameters	17.94mm	4.9%

4. Conclusions

This study proposed a damage-state-based parameter identification method to enhance the accuracy of nonlinear behavior prediction for RC structures. Quantitative and qualitative comparisons confirmed that the proposed approach provides improved predictive capability over conventional single parameter models. The framework was further applied to seismic response prediction using the 1994 Northridge earthquake record, showing close agreement with the experimentally observed maximum displacement. Building on these results, future study will focus on validating the model's ability to reproduce the entire seismic response time history, thereby enabling a more comprehensive assessment of its predictive performance under strong ground motions.

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