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Damage-State-Based Bouc–Wen Approach for RC Structures in Nuclear Power Plants and Its Experimental Validation

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1. Introduction

Reinforced concrete (RC) structures in nuclear power plants (NPPs) are safety-critical components whose seismic performance directly affects plant safety and operational continuity. Accurate seismic response prediction of these structures is therefore essential for reliable performance assessment and safety assurance.

Under strong ground motion, RC structures exhibit highly nonlinear behavior characterized by stiffness and strength degradation, and pinching effects. These characteristics evolve progressively with accumulated damage, making consistent response prediction increasingly challenging.

Bouc–Wen class models are widely used to represent nonlinear hysteretic behavior [1-3]. However, conventional modeling approaches typically adopt a single parameter set throughout the entire loading history. As RC structures enter the nonlinear region, their structural properties and hysteretic characteristics evolve with damage progression. Therefore, representing the entire hysteretic response with a single parameter set becomes physically inconsistent, and the damage-dependent evolution of structural behavior should be considered.

To address this limitation, this study proposes a damage-state-based parameter updating framework for Bouc–Wen class models. The framework discretizes damage progression using a damage index and identifies distinct parameter sets corresponding to different damage states. The effectiveness of the proposed approach is validated through hybrid simulation, and its seismic response prediction performance is compared with that of a single-parameter model.

2. Methods

2.1 Damage State Definition

To quantify structural damage evolution, the modified Park–Ang damage index was adopted [4]. The damage index (DI) was calculated from displacement–force data by accounting for both maximum deformation demand and cumulative hysteretic energy dissipation. At each time step, the maximum displacement history and accumulated energy dissipation were updated to evaluate the instantaneous DI value.

The computed DI values were classified into four damage states according to the thresholds proposed by Park and Ang [5]. Through this classification, continuous damage progression was represented as discrete damage states for subsequent parameter identification.

2.2 Parameter Identification

Following damage state classification, the displacement–force data were segmented according to the corresponding DI intervals. The modified Bouc–Wen model (m-BWBN) parameters were then identified independently for each segment to capture damage-dependent hysteretic behavior.

A Genetic Algorithm (GA) [6] was employed to minimize an objective function based on force-displacement errors between experimental and simulated results. To account for the stochastic nature of GA, the optimization was repeated 100 times for each damage state. The solution with the minimum objective function value was adopted as the representative parameter set.

2.3 Response Prediction

Nonlinear seismic response prediction was conducted using the Chen & Ricles (CR) time integration scheme for nonlinear dynamic analysis [7]. During the time-history analysis, the DI was evaluated in real time. When the computed DI exceeded a predefined threshold, the model parameters were updated to the corresponding damage-state parameter set. To maintain physical consistency, only the parameters were updated, while the internal hysteretic state variables were continuously evolved without resetting, ensuring a smooth transition between damage states and preserving numerical stability. The nonlinear dynamic response was obtained through the time-history analysis incorporating the damage-state-dependent parameter updating scheme.

3. Hybrid Simulation Setup

To validate the proposed damage-state-based response prediction framework, a pseudo-dynamic hybrid simulation was conducted using two RC wall specimens. One specimen was tested under quasi-static cyclic loading for parameter identification, while the other was used in the hybrid simulation to evaluate seismic response prediction performance.

As illustrated in Fig. 1, the structural system was divided into analytical and experimental substructures. The analytical part was modeled as a lumped-mass single-degree-of-freedom (SDOF) system, and the RC wall specimen served as the experimental substructure to provide nonlinear restoring forces.

A lumped mass of 8.72 tons and a damping ratio of 0.07 were assigned to the analytical model. The system was intentionally tuned to achieve a first natural frequency of 5.8 Hz, closely matching the dominant frequency of a representative NPP auxiliary building. This frequency matching ensures that the dynamic characteristics of the target structure are appropriately represented.

During the hybrid simulation, ground acceleration was applied to the analytical substructure. The computed command displacement was imposed on the experimental specimen, and the measured restoring force was fed back to the analytical model to satisfy the dynamic equilibrium of the coupled system.

This configuration enables direct validation of the proposed framework under seismic conditions representative of NPP auxiliary structures.

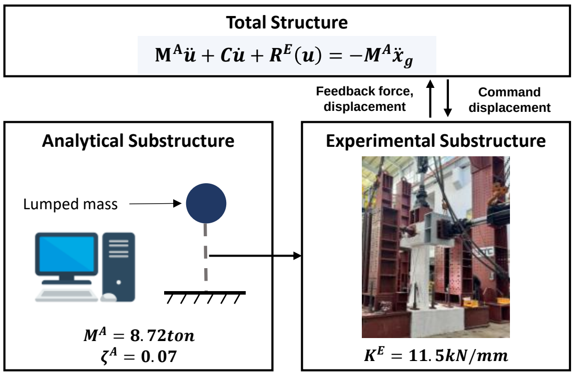
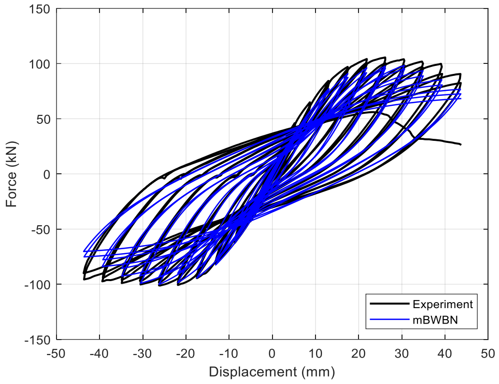


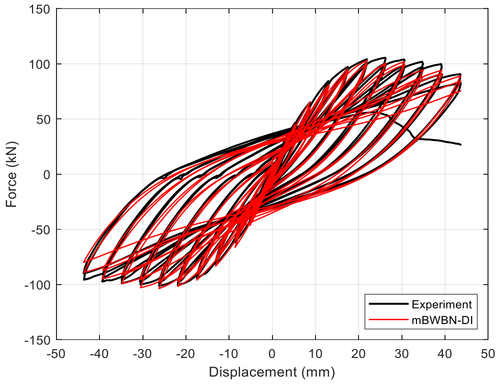
Fig. 1. Configuration of the hybrid simulation system

4. Results

Fig. 2 compares the cyclic loading test results with the simulated responses obtained from the single-parameter m-BWBN model and the proposed damage-state-based model. The proposed approach more accurately captures stiffness degradation and hysteretic evolution across progressive damage levels, particularly in the post-yield region. To complement this visual comparison, Table I summarizes the quantitative evaluation using three performance metrics: relative RMSE, energy dissipation error, and correlation coefficient. Across all measures, the proposed model achieves lower relative RMSE and energy dissipation error, along with a higher correlation coefficient, indicating improved agreement in reproducing cyclic nonlinear behavior.



(a): m-BWBN with single parameter



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

Fig. 2. Comparison between experimental and force-displacement plots of RC wall

Table I: 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	11.00%	8.17%
Correlation coefficient	0.9950	0.9973
Energy dissipation error	4.24%	2.15%

The effectiveness of the identified damage-state-dependent parameters was further evaluated through hybrid simulation under seismic excitation. The 1994 Northridge earthquake record was used as the input ground motion, and its amplitude was scaled to 2.0 times the original amplitude to induce nonlinear response. Table II presents the comparison between the experimental response and the numerical predictions. In terms of peak displacement, the proposed model reduces prediction error compared to the single-parameter approach. To further evaluate time-history prediction performance during critical nonlinear response phases, the RMSE was computed within the strong-motion duration defined by the Arias intensity 5–95% interval [8]. The proposed model shows a noticeable reduction in RMSE within this interval, indicating improved agreement with the experimental response during the most significant damage progression.

Overall, the results indicate that incorporating damage-state-dependent parameter evolution improves both cyclic response reproduction and seismic response prediction accuracy compared to the single-parameter model.

Table II: Comparison of peak displacement and strong-motion RMSE relative to hybrid simulation results

Method	Peak displacement	Peak Error	Strong-motion RMSE
Experiment results	21.67mm	-	-
m-BWBN with single parameter	25.06mm	15.6%	16.0%
m-BWBN with damage-state-based parameters	21.92mm	1.2%	9.0%

5. Conclusions

This study proposed a damage-state-based parameter updating framework for Bouc–Wen class models to improve seismic response prediction of RC structures in NPPs. By discretizing structural damage using the Modified Park–Ang damage index and identifying independent parameter sets for each damage state, the proposed approach accounts for damage-dependent evolution of hysteretic behavior. The identified parameters were validated through cyclic loading tests and hybrid simulation under the scaled 1994 Northridge earthquake record. The results showed improved agreement in both cyclic response reproduction and nonlinear seismic response prediction compared to the single-parameter model. These findings suggest that incorporating damage-state-dependent parameter evolution enhances the reliability of nonlinear dynamic analysis for safety-critical RC structures.

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REFERENCES

[1] Wen, Y. K, Method for Random Vibration of Hysteretic Systems. Journal of the Engineering Mechanics Division, 102(2), 249-263, 1976.

[2] Baber, T. T., & Noori, M. N, Random Vibration of Degrading, Pinching Systems. Journal of Engineering Mechanics, 111(8), 1010-1026, 1985.

[3] Kim, T., Kwon, O. S., and Song, J, Deep Learning Based Seismic Response Prediction of Hysteretic Systems Having Degradation and Pinching, Earthquake Engineering & Structural Dynamics, 52(8), 2384-2406, 2023.

[4] Huang, W., Qian, J., and Zhou, Z, Seismic Damage Assessment of Steel Reinforced Concrete Members by a Modified Park-Ang Model, Journal of Asian Architecture and Building Engineering, 15(3), 605-611, 2016.

[5] Park, Y. J., Ang, A. H., and Wen, Y. K, Damage-limiting Aseismic Design of Buildings, Earthquake Spectra, 3(1), 1-26, 1987.

[6] Goldberg, D. E, Genetic Algorithms, Pearson Education India. 2013.

[7] Chen, C., and Ricles, J. M, Development of Direct Integration Algorithms for Structural Dynamics Using Discrete Control Theory, Journal of Engineering Mechanics, 134(8), 676-683, 2008.

[8] Arias, A, A Measure of Earthquake Intensity, Seismic Design for Nuclear Plants, 438-483, 1970.