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Hybrid Testing of Isolated Nuclear Island Buildings Based on Model Updating Methods

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ABSTRACT

In this paper, based on the hybrid testing of model updating, the dynamic response of the isolation bearings of the experimental substructure and the numerical substructure of the nuclear island building under earthquake is obtained. The hybrid testing based on model updating is performed for the nuclear island building, with an LRB1000 used as the experimental substructure for dynamic loading. The numerical model of the upper structure and other isolation bearings is modelled in OpenSEES, while an unscented Kalman filter algorithm in MatLab to update the parameters of the isolation bearings in OpenSEES. For the experimental substructure, a high-capacity, high-speed seismic isolation loading platform was employed to conduct the hybrid testing on the LRB isolation bearings of the nuclear island building. The results show that in the hybrid testing of the seismically isolated nuclear island building, the deformation of the isolation layer coincides well with the numerical simulation results. This method effectively avoids experimental distortions caused by scaling in shake table tests and significantly improves the accuracy of the test results through model updating, confirming its necessity in seismic performance tests for isolation bearings. Moreover, it effectively replicates the dynamic characteristics of the upper structure and provides an accurate response of the LRB isolation bearings under seismic action.

INTORDUCTION

As the core component of nuclear power plants, the structural safety of nuclear island buildings under seismic actions is of paramount importance, directly impacting the safe operation of nuclear reactors as well as the protection of equipment and personnel (2020). Domestic and international studies have demonstrated that base isolation technology can effectively enhance the seismic safety of nuclear island buildings (2023).

In domestic and international research on base isolation, extensive studies have been conducted on base isolation experiments. Domestic scholars such as SHI Chencheng et al. (2022) performed numerical simulation analysis of the overall isolation of the Hualong nuclear island building using ANSYS finite element software; SHEN Chaoyong et al. (2012) conducted quasi-static tests on bridge isolation bearings; Chen Yan et al. (2023) carried out shaking table tests on the isolated structure of the nuclear island building, with results showing significant isolation effects when applying base isolation technology to scaled-down models. However, in purely numerical simulations, inaccuracies in model parameters and assumptions, as well as discrepancies between theoretical simplified models and real-world models, may lead to unreliable results. Quasi-static tests fail to simulate dynamic characteristics or accurately model velocity-sensitive parameters, making them unsuitable for evaluating the seismic capacity of large-scale structures. Shaking table tests are limited by the size and load capacity of the shaking table, often requiring large-scale model reductions that may cause experimental distortions.

Substructure hybrid testing technology has gained widespread application (2023). This methodology divides the structural model into a numerical substructure (simulated via finite element analysis) and a experimental substructure (experimentally loaded in laboratories), with dynamic analysis achieved

through boundary coordination and real-time data interaction. Recent advancements have particularly demonstrated its efficacy in seismic isolation bearing research. TANG Zhenyun et al. (2023) proposed a two-stage real-time substructure testing method for isolation structures to simultaneously simulate nonlinear behaviors of isolation layers and superstructures while mitigating errors from numerical modeling inaccuracies; LI Xiaolei et al. (2021) developed an adaptive time-delay compensation system for real-time hybrid testing to evaluate high-damping rubber isolation bearings' mechanical properties and structural responses; LANESE I [2012] implemented real-time dynamic hybrid testing for base-isolated structures. A critical challenge lies in updating numerical substructure parameters during testing, as physical loading alters system characteristics. To address this, Wang Tao et al. (2021) introduced an improved auxiliary unscented particle filtering algorithm for model updating; Zheng Jiayi et al. (2021) employed an unscented Kalman filter-based approach in friction pendulum isolation system studies; Du et al. (2022) validated online model updating techniques through hybrid testing on six-story frames with lead-rubber bearings, demonstrating enhanced simulation fidelity.
This study employs substructure hybrid testing methodology to mitigate experimental distortions arising from shaking table capacity constraints and large-scale model reductions, while implementing the Unscented Kalman Filter (UKF) algorithm for real-time updating of numerical substructure model parameters to ensure their accuracy during the testing process.

TESTING DEVICE

The hybrid testing for the seismic isolation bearings utilized a high-capacity, high-speed spatial loading platform. The testing machine is equipped with two 2500 kN electro-hydraulic servo actuators in both horizontal (X and Y) directions, and four 10000 kN vertical (Z-direction) electro-hydraulic servo actuators. The hydraulic power unit supplies 3200 L/min of oil flow, supported by a 26000 L accumulator system. Integrated with a fully digital coordinated loading control system and a 36-channel data acquisition system, the platform achieves synchronized multi-axis loading.
The test machine features a working space of 3m×3m×4m, delivering 40000 kN compressive force and 20000 kN tensile force in the vertical direction with an 800 mm stroke and a maximum loading speed of 100 mm/s. Horizontally, it achieves dynamic loads up to 4000 kN, ±1000 mm displacement range, and peak velocities of 2000 mm/s.

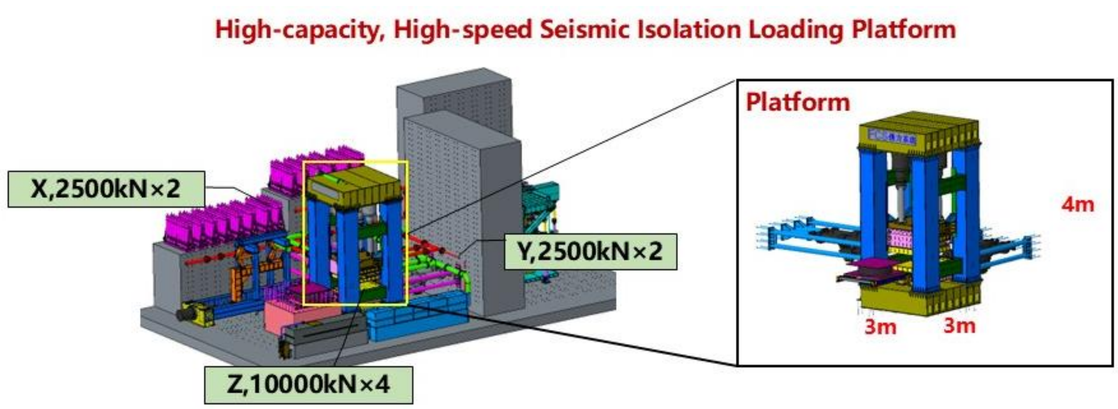


Figure 1. Space loading detection platform

TARGET STRUCTURE

This section introduces the experimental substructure (LRB1000) and numerical substructure in this hybrid testing study. It provides details on the parameters of the experimental substructure LRB1000, along with modeling and simulation analysis of the isolation layer and upper plant structure in OpenSees, which prepared for hybrid testing.

Isolation Layer

The target structure in this study focuses on a nuclear island building and its isolation layer, featuring dimensions of 30m (length) × 19m (width) × 40m (height). The seismic isolation system employs 32 lead rubber bearings (LRB) and 6 natural rubber bearings (LNR), all with a 1m diameter, arranged according to the layout configuration shown in Figure 2.

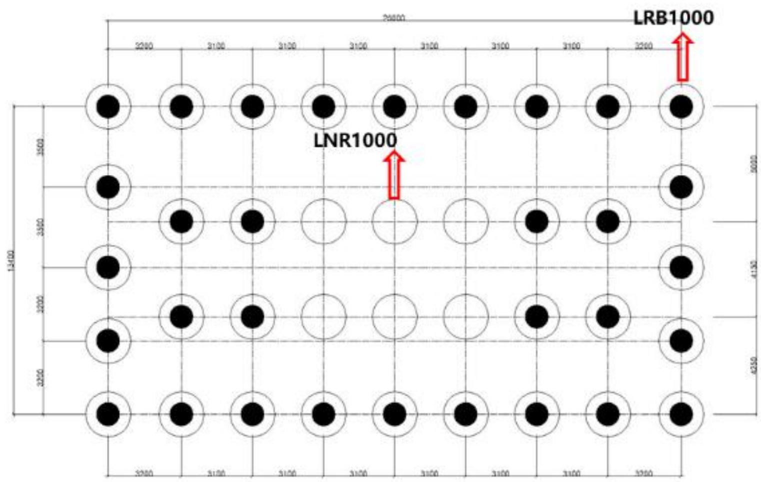


Figure 2. Nuclear island plant isolation system.

This study selects the corner-mounted LRB1000 bearing as the experimental structure shown as figure 3, with its complete mechanical performance parameters detailed in Table 1.

Table 1: Mechanical Performance Parameters of LRB1000.

Vertical Stiffness	kN/mm	4200
Equivalent Horizontal Stiffness(100%)	kN/mm	2.77
Equivalent Damping Ratio(100%)	%	24
Post-Yield Stiffness	kN/mm	1.67
Yield Force	kN	203
Total Rubber Layer Thickness	mm	186
Flange Thickness	mm	46
Total Bearing Height	mm	390

Figure 3. LRB1000 experimental structure.

Numerical Simulation

This study conducts dynamic analysis of the Nuclear Island Building in OpenSEES, employing a 3D shell element model for the superstructure and seismic isolation bearing elements with parameters derived from manufacturer-provided mechanical property tables. The ground motion input utilizes an artificial acceleration time history fitted to the RG1.60 modified spectrum, featuring 0.01-second intervals and a 25-second duration. The design seismic peak acceleration is set as tri-directional 0.30g.
Numerical simulation results indicate that the horizontal isolation layer's X and Y directional displacement time-history curves are presented in Figure 4, while the Z-directional force time-history curve is shown in Figure 5. The maximum horizontal displacement of the isolation layer, determined by comparing relative displacements between upper and lower nodes of the bearings, measures 179.5 mm. This value demonstrates compliance with dual code requirements: being less than 1.3 times the total rubber layer thickness of the bearings and under the 300 mm threshold, thereby satisfying all relevant seismic isolation specifications

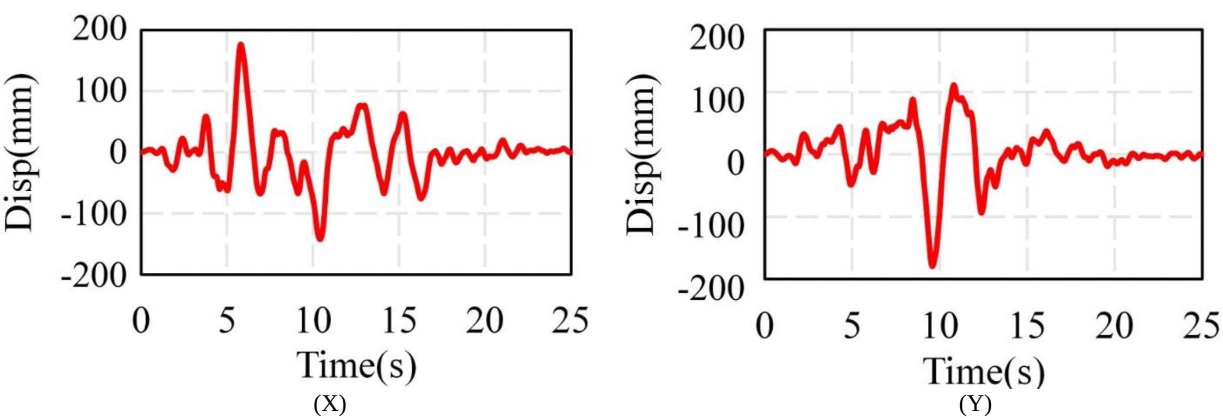


Figure 4. X\Y-Displacement time history curve.

The verification process employs distinct load factors for different stress states: 1.4× dead load for maximum compressive stress evaluation and 1.0× dead load for tensile stress assessment. The bearing contact area is calculated as the overlapping projection between the top and bottom surfaces at maximum horizontal displacement. Computational results indicate a maximum compressive stress of 11.14 MPa (below the 20 MPa limit) and a minimum compressive stress of 0.39 MPa (no tensile stress observed), fully compliant with code requirements.

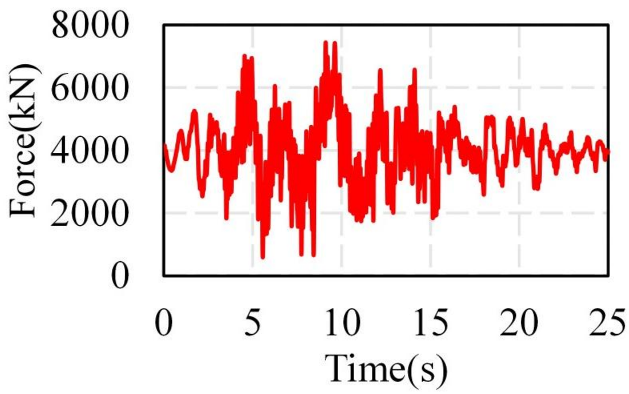


Figure 5. Z-Force time history curve.

TESTING SYSTEM

This section primarily introduces a model-updating hybrid testing approach. The study implements Unscented Kalman Filter (UKF) technology to dynamically update parameters of the seismic isolation bearing LRB1000 in OpenSEES. Additionally, it proposes a hybrid testing control system based on OpenSEES-OpenFresco-LabVIEW for a six-degree-of-freedom compression-shear testing machine.

Hybrid Testing of Model Updating

This study employs a hybrid testing framework where the corner LRB1000 bearing serves as the experimental substructure, while the superstructure nuclear island building and other isolation bearings are modeled in OpenSEES as numerical substructures. The implementation integrates MATLAB with OpenSEES to execute an unscented Kalman filter (UKF) algorithm for parameter identification and updating, requiring the establishment of a shadow model in OpenSEES that replicates the experimental substructure's mechanical property behavior. The targeted updating parameter set for the LRB1000 bearing includes its OpenSEES modeling parameters: yield strength (f_y), post-yield stiffness ratio (α), shear modulus (G), and bulk modulus (K_b).

The hybrid testing framework for model updating in this study is illustrated in Figure 6. Firstly, OpenSEES inputs ground motion and performs dynamic computation for the current step to obtain boundary conditions at the upper bearing nodes. These boundary conditions are then simultaneously transmitted to both the shadow model for dynamic simulation and the experimental substructure for physical loading. Upon completion of both the shadow model's computation and the experimental substructure's loading, the X and Y directional restoring forces from the two models are compared. If the difference in either horizontal direction exceeds the predefined threshold of 15 kN, the Unscented Kalman Filter (UKF) algorithm in MATLAB initiates parameter updates for the isolation bearing set. Following successful UKF execution, the updated parameter group is implemented into the numerical substructure's bearing elements. Finally, the experimentally derived boundary conditions are fed back into OpenSEES's numerical substructure to advance the dynamic computation to the next step, completing the iterative process.

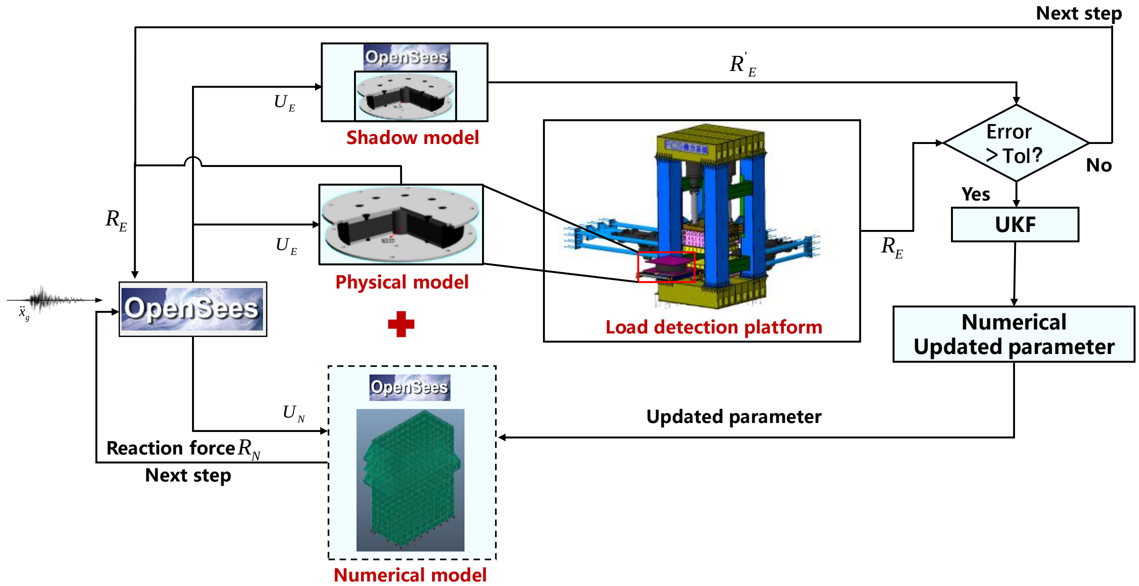


Figure 7. Hybrid testing of isolation bearing for model updating.

Implementation of untraced Kalman Filter algorithm in OpenSEES

In this study, the Unscented Kalman Filter (UKF) algorithm was implemented for parameter updating, utilizing restoring forces obtained from the experimental substructure to determine the necessity of updating parameters in the numerical substructure. The algorithmic implementation was specifically realized through a collaborative framework integrating MATLAB and OpenSEES, which required secondary development of OpenSEES to achieve customized computational workflows and data exchange functionalities.
This study implemented secondary development in OpenSEES by adding functional codes: setParameter defines the names of updatable parameter variables, updateParameter assigns new values to these parameters, tryonestep executes trial analyses, and revertToLastCommit restores the shadow model to its previous state post-analysis.
In MATLAB, develop a UKF program for parameter updating, and establish numerical substructure and experimental substructure shadow models in OpenSEES with initial parameter values. After completing the loading of the experimental substructure in the previous step, transmit the obtained boundary conditions as observations back to MATLAB. Simultaneously, calculate the current step's 2n+1 Sigma points (where n is the number of parameters requiring updates) using the mean and variance of the parameters from the previous step, with Sigma points representing parameter sets. Update each parameter set corresponding to the Sigma points into the shadow model of the experimental substructure for trial computations (tryonestep), obtaining the shadow model's restoring forces. Then, use the revertToLastCommit function to revert the structure to the previous step's state and proceed with trial computations for the next parameter set. After completing trial computations for all 2n+1 parameter sets, compare each group's restoring forces with the true restoring force values obtained from experimental substructure loading to determine the current step's parameter mean and variance. Input the updated parameters into the shadow model, update them into the numerical substructure via the updateparameter function, and execute the next analysis step using the runonestep function.

OpenSEES-OpenFresco-LabVIEW control system

In hybrid testing, after the numerical substructure completes finite element analysis, the obtained control commands must be transmitted to the actuator control system to regulate actuator loading through the actuator control system. Simultaneously, upon completion of each loading step, the restoring forces from the experimental specimen must be returned to the numerical substructure for subsequent dynamic equation calculations. This study proposes an integrated OpenSEES-OpenFresco-LabVIEW command-control system to achieve data communication between the OpenSEES numerical substructure and the physical loading system.

The entire system hardware consists of a personal PC, a shear-compression testing machine controller, and a shear-compression testing machine. The personal PC and the testing machine controller are connected via an Ethernet cable using a customized TCP/IP communication protocol to transmit control commands to the testing machine control system. Upon receiving control signals, the testing machine control system drives the actuators of the loading system to perform triaxial loading. Communication among the components is illustrated in Figure 7.

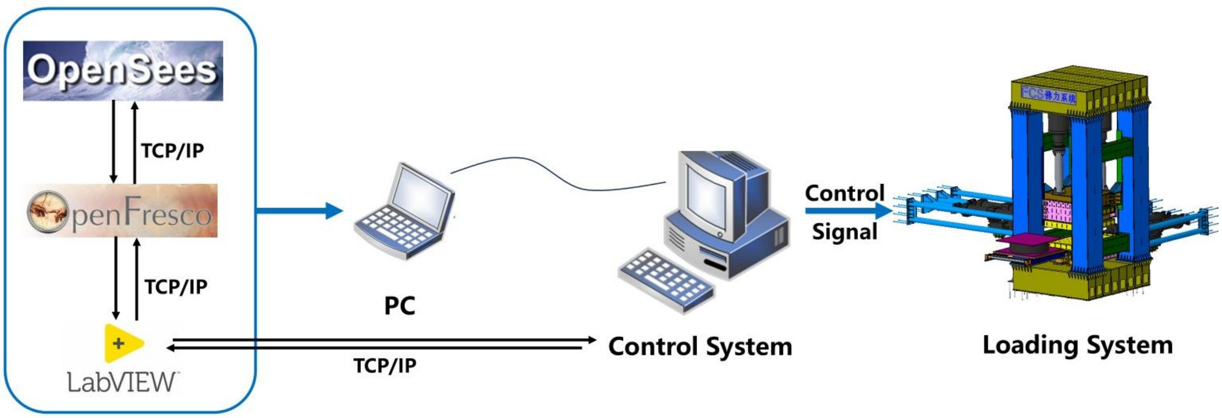
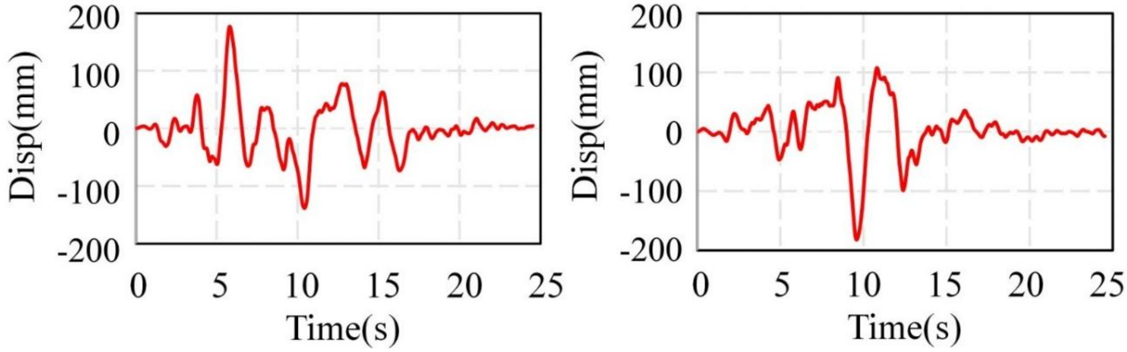


Figure 7. OpenSEES-OpenFresco-LabVIEW Flowchart for communication.

In a personal PC, the OpenSEES finite element simulation software is employed for dynamic finite element solving. The OpenFresco middleware processes boundary conditions between numerical and experimental substructures, retrieving loading commands for the experimental substructure. The LabVIEW hybrid testing control software, a self-compiled LabVIEW-based application, manages the hybrid testing workflow: it receives experimental substructure loading commands from OpenFresco, performs coordinate transformations to derive control instructions for the physical testing apparatus (shear-compression testing machine), and transmits these instructions via a customized protocol to the testing machine controller and control software for physical loading. Simultaneously, it acquires the testing machine's responses (force or displacement), applies coordinate transformations, relays the data to OpenFresco, and ultimately feeds it back to OpenSEES for subsequent dynamic computational analysis.

RESULT

The displacement time-history curves of the isolation layer in the X- and Y-directions, obtained from hybrid testing with model updating of the isolated bearings, are shown in Figure 8. The maximum displacement occurred in the X-direction, with a peak displacement response of 186 mm. According to the code requirements, the horizontal displacement control criteria for the isolation layer stipulate that the maximum horizontal displacement must be less than 1.3 times the total thickness of the rubber layer and not exceed 300 mm. Thus, the displacement meets the code requirements.



(X) (Y)

Figure 8. X\Y-Displacement time history curve.

The vertical compressive stress time-history curve of the bearing is shown in Figure 9. The maximum compressive stress experienced by the bearing is 9.75 MPa, which is below the code-specified maximum limit of 20 MPa. Additionally, no tensile stress conditions occurred under seismic excitation, fully satisfying the code requirements.

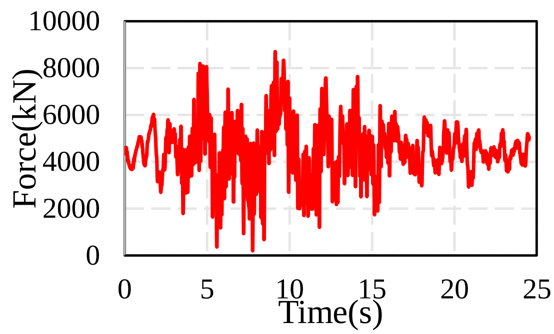
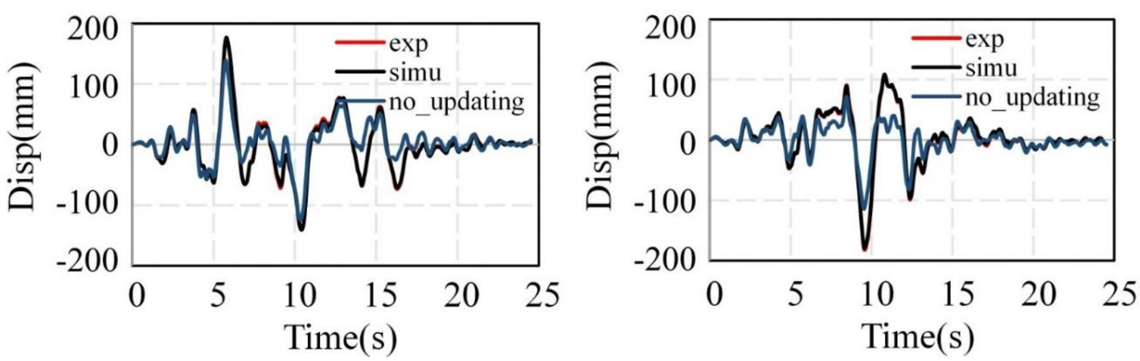


Figure 9. Z-Force time history curve.

The displacement time-history curves of hybrid testing results, numerical simulation results, and non-updated parameter results in the X- and Y-directions are compared in Figure 10, while the hysteretic curves of the bearings are compared in Figure 11. The numerical simulation results were derived from finite element simulations using relatively accurate bearing parameters obtained after offline updating.



(X) (Y)

Figure 10. Displacement time history curve comparison.

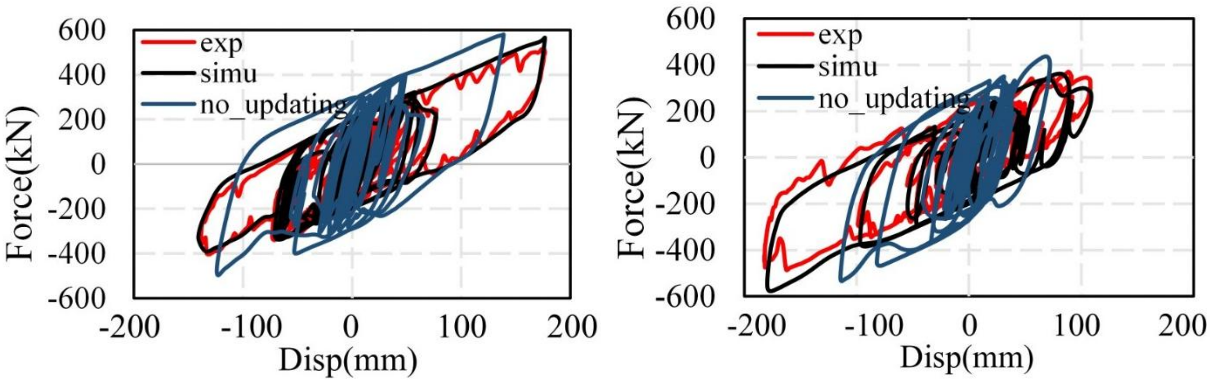


Figure 11. Hysteresis curve comparison.

The displacement time-history curves and hysteretic curves of the bearing under non-updated models exhibit significant differences compared to those from hybrid testing with model updating. At the same moment, the displacement discrepancy in the X- and Y-directions reaches 78.3 mm, with a 65.6 mm difference in peak values. These results demonstrate substantial deviations in X- and Y-direction displacements when parameters remain unupdated, highlighting the critical role of model updating in hybrid testing for isolated bearings.

CONCLUSION

This study employed a hybrid testing method based on the unscented Kalman filter algorithm for model updating of isolated bearings. A large-tonnage, high-speed seismic isolation spatial loading testing platform was utilized to conduct numerical simulations and bidirectional hybrid testing on lead-core rubber isolated bearings in the nuclear island building. The following conclusions were drawn:

1. The effectiveness of substructure hybrid testing: By employing the hybrid testing method, the limitations of scaled-down model distortion in shaking table tests were avoided, enabling a comprehensive seismic performance evaluation of the isolation layer and superstructure of the nuclear island building.
2. The large-tonnage, high-speed seismic isolation spatial loading testing platform utilized in this study accurately simulated the dynamic behavior of isolation bearings under seismic excitation, providing reliable technical support for experimental research on isolation technologies.
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