Lifecycle-Oriented Seismic Design and Damage Identification for Bridges based on AI-Driven Methods

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Extended Abstract

Regional seismic analysis of bridges requires ground-motion inputs that are both compatible with design spectra and representative of real earthquake characteristics. In conventional engineering practice, recorded strong motions are selected directly or artificial motions are generated from code-specified spectra. However, artificial motions may not adequately preserve the frequency content, phase distribution, and non-stationary characteristics of real records, whereas direct use of recorded motions may lead to large deviations from the target response spectrum. In addition, when a large number of bridges in a region must be evaluated, nonlinear time-history analysis for every bridge and every ground-motion record becomes computationally expensive. This study proposes an AI-based regional seismic analysis framework that links seismic input generation, bridge response database construction, and rapid damage or performance assessment.

The proposed framework first develops an improved time-domain spectral matching algorithm to generate spectrum-compatible ground motions while retaining the physical characteristics of recorded accelerograms. Three improvements are introduced into the conventional matching procedure. First, a mismatch-based period subdivision sorting strategy is used. Instead of matching all periods in a fixed short-to-long sequence, the target period range is divided into several subdivisions, and the subdivisions with larger spectral mismatch are adjusted first. This strategy reduces mutual interference among added adjustment wavelets and improves convergence efficiency. Second, an adaptive convergence parameter selection method is adopted. The reduction coefficient of the off-diagonal terms of the response matrix and the relaxation parameter for wavelet amplitudes are determined

using the Whale Optimization Algorithm, which improves numerical stability and convergence speed. Third, a wavelet-based peak ground acceleration (PGA) correction algorithm is introduced after spectral matching. The dominant frequency component at the time instant of PGA is identified using synchro-squeezed wavelet transform, and a localized correction wavelet is added to restore PGA consistency without introducing velocity or displacement drift.

Based on the matched ground motions, a regional seismic performance analysis database is established for typical highway bridges. Because more than 95% of bridges in the target bridge population have fewer than five spans, a representative three-span continuous girder bridge is selected as the prototype. The structural and material parameters considered in the database include main span length, side span ratio, section width, deck slab thickness, bearing stiffness, pier height, pier diameter, pier wall thickness, elastic modulus, yield strength, concrete strength, reinforcement ratio, protection layer thickness, axial compression ratio, and mass coefficient. Although these parameters may follow normal, lognormal, or uniform distributions in actual bridge inventories, they are treated as uniformly distributed in the parametric sampling process to ensure broad and balanced coverage of the design space. Latin hypercube sampling is used to generate 10,000 bridge samples. For each sample, nonlinear time-history analyses are performed using seven matched ground motions, resulting in 70,000 bridge response analyses for database construction.

The main outputs of the database include bearing displacement demand, pier-bottom bending moment demand, pier-top displacement demand, pier-bottom flexural capacity, and pier-top displacement capacity. These response and capacity quantities provide the basis for demand-capacity comparison and seismic damage assessment. A typical bridge model used for database construction is illustrated in Figure 1. The database therefore establishes a direct link from seismic input to structural response and performance indicators, which is essential for training an efficient machine-learning surrogate model.

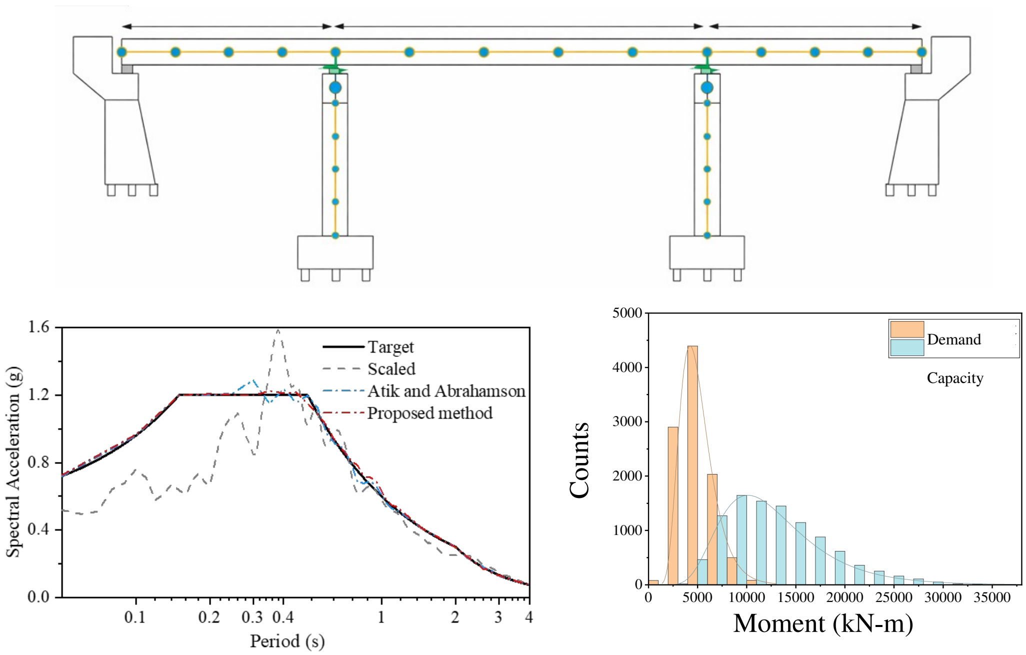

Figure 1- Typical three-span continuous girder bridge model and AI-driven algorithm.

An artificial neural network regression model is then developed as the surrogate model for regional seismic performance analysis. Feature engineering is conducted to remove parameters that do not contribute to specific response or capacity predictions, thereby reducing the risk of overfitting. The dataset is divided into a training set and a testing set with a ratio of 70% to 30%. Input variables are standardized to zero mean and unit variance to reduce scale effects among different design parameters. Five-fold cross-validation and grid search are used to optimize the model hyperparameters. The trained surrogate models show consistent performance for both training and testing datasets, indicating good prediction accuracy and generalization capability. The predicted values are close to the corresponding numerical-analysis results for key seismic performance indices such as bearing displacement demand and pier-bottom moment demand.

The proposed method is further demonstrated through the seismic design of a typical three-span continuous beam bridge. The initial design uses GBZJ400x400x99 (CR) plate rubber bearings, with stiffness of 2700 kN/m and displacement capacity of 71 mm. The predicted bearing displacement demand is 84 mm, which exceeds the capacity. After the bearing type is adjusted to GBZJ450x450x114 (CR), with stiffness of 2960 kN/m and displacement capacity of 82 mm, the predicted bearing displacement demand decreases to 77 mm. The pier-bottom moment demand and pier-top displacement demand of the adjusted bridge remain lower than their corresponding capacities. Therefore, the adjusted bridge satisfies the seismic design requirements. Compared with traditional single-bridge nonlinear seismic design, which may require several days of modeling and analysis, the trained surrogate model completes the seismic performance prediction in approximately 0.22 seconds, demonstrating its potential for large-scale regional bridge cluster assessment and rapid design iteration.

The study shows that the improved time-domain spectral matching algorithm can generate spectrum-compatible ground motions with high PGA consistency while preserving the non-stationary features of recorded earthquakes. The regional bridge response database provides a reliable data foundation for machine-learning-based seismic performance assessment. The AI-based surrogate model avoids repeated finite-element modeling and time-consuming nonlinear analyses, enabling rapid prediction of bridge seismic response and demand-capacity status. The proposed framework provides an efficient data-driven approach for regional bridge seismic analysis, damage assessment, and seismic design optimization.

Keywords: *seismic design; ground motion; damage identification; data fusion; artificial intelligence*