PROBABILISTIC MODELING OF POST-EARTHQUAKE VERTICAL LOAD-CARRYING CAPACITY LOSS OF BRIDGE COLUMNS UTILIZING BAYESIAN UPDATING

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Extended Abstract

Post-earthquake rescue efficiency and transportation network recovery heavily depend on the emergency passage functionality of bridges, which is governed by the residual vertical load-carrying capacity (RVLC) of bridge columns. Residual displacement has been validated as an effective on-site indicator for RVLC degradation, whilst its relationship with capacity loss features strong stochasticity and heteroscedasticity. Conventional deterministic regression models only capture average trends and fail to quantify uncertainty; generic numerical models often carry systematic biases, while real-world post-earthquake measured samples are extremely scarce. To tackle these issues, this study develops a Bayesian probabilistic framework for evaluating and updating the correlation between residual drift ratio and vertical capacity loss, supporting rapid and reliable post-earthquake structural performance assessment.

The proposed methodology integrates two key components: Bayesian heteroscedastic Beta regression (BBR) and a Prior Relaxation-based Bayesian incremental updating strategy. For the bounded capacity loss ratio ($L \in (0,1)$), Beta distribution is adopted as the likelihood function to characterize complete conditional probability distribution, avoiding information loss from data binarization in traditional methods. A bi-exponential function serves as the mean function to fit the nonlinear trend between residual drift ratio and capacity loss, while a cubic B-spline is employed as the precision function to capture heteroscedasticity, namely, the uncertainty variation with residual displacement. Bayesian inference is implemented via Markov Chain Monte Carlo (MCMC) sampling with the No-U-Turn Sampler (NUTS), generating posterior distributions that provide both point estimates and uncertainty quantification.

To address systematic bias in generic numerical models and extreme data scarcity, the Prior Relaxation updating strategy is proposed. Instead of directly using the posterior of the simulation-based baseline model as the prior for incremental update, this method takes the mean and standard deviation of baseline posterior as prior parameters and introduces a relaxation factor λ to inflate prior variance. A larger λ reduces confidence in the prior model, granting more flexibility for the model to adapt to sparse real data. This design balances the inheritance of numerical simulation knowledge and correction from field measurements, enabling effective model calibration with minimal samples.

For dataset generation, a finite element model of circular-section reinforced concrete single-column bridge piers is established in OpenSeesPy, considering uncertainties in structural parameters (e.g., pier geometry, material properties, axial load ratio) and ground motion inputs. Incremental Dynamic Analysis (IDA) combined with Pushdown analysis is conducted to obtain 3,889 valid (residual drift ratio, capacity loss ratio) sample pairs. A biased dataset is further constructed by adjusting the axial load ratio to simulate systematic deviations between generic models and real structures, used to validate the bias correction performance.

Validation results demonstrate that the BBR model outperforms the classical Maximum Likelihood Estimation (MLE) in fragility analysis. By retaining full distribution information of continuous capacity loss data, BBR generates more accurate exceedance probability curves under multiple damage thresholds (5%, 20%, 35%, 50%) and adapts better to non-uniform sample distribution and high damage thresholds. In the sparse data scenario (only 10 measured points), the Prior Relaxation updating strategy achieves remarkable correction effects: with λ=20, the root mean square error (RMSE) relative to the benchmark is only 0.0433, far superior to standard Bayesian update (λ=1, RMSE=0.2737), small-sample MLE (RMSE=0.4027) and non-informative prior Bayesian inference (RMSE=0.0871). The relaxation factor effectively mitigates over-constraint from biased priors and avoids overfitting of small samples, realizing rapid calibration of generic models.

This study contributes a feasible probabilistic solution for post-earthquake bridge column capacity assessment. The pre-built generic prior model via numerical simulation can be quickly updated with a handful of field-measured residual displacements after earthquakes, generating high-precision site-specific capacity models. The framework provides explicit uncertainty quantification and robust fragility assessment results, offering critical decision support for post-earthquake rescue, traffic recovery and structural reinforcement. Limitations include that the current model is only validated for circular single-column RC piers, and the relaxation factor selection relies on engineering judgment. Future research will extend the method to multi-column bents and complex bridge systems, and develop an adaptive approach for determining the relaxation factor.

Keywords: *Residual bearing capacity; Residual drift ratio; Fragility analysis; Bayesian updating.*