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同濟大學 TONGJI UNIVERSITY

Research Division on Bridge Earthquake Resistance
Towards Next-Generation Resilient Bridges

Time Varying Seismic Analysis of Costal Bridges Considering Durability Damages in Service Life

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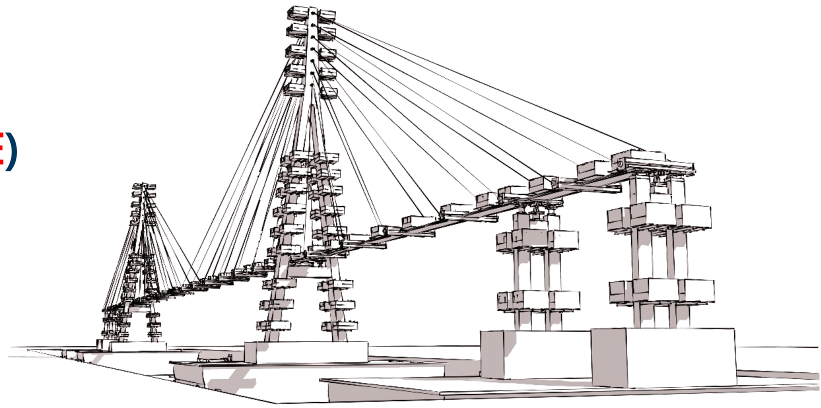


2026/06/06

Outlines

1. Background

2. Time Varying Seismic Fragility and Risk Analysis Method

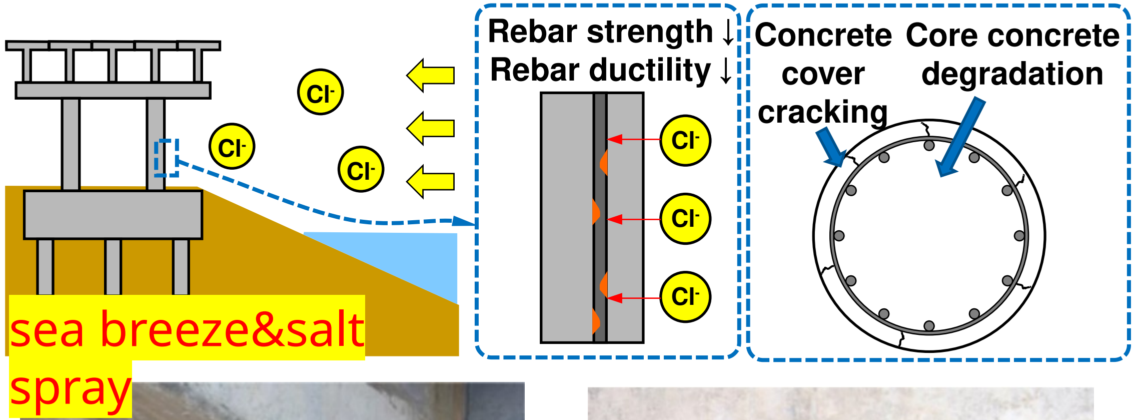
3. Uncertainty-Included Time Varying Bridge Modeling

4. Results and Conclusions

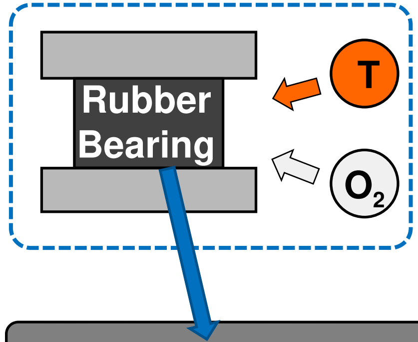
1. Background

➢ **Time Varying Service Condition of Costal Bridges**

Corrosion-induced deterioration in RC columns



Thermal oxidative aging and replacement of rubber bearings



Accel. thermal oxidation tests

Shear stiffness

↑ Rupture strain

Replaceable component

- Periodic replacement
- Reset of deterioration

A Scenario yet not fully studied: RC Column corrosion + rubber bearing aging + bearing periodic replacement

[1] Akiyama M, Frangopol DM, Ishibashi H. Toward life-cycle reliability-, risk- and resilience-based design and assessment of bridges and bridge networks under independent and interacting hazards: emphasis on earthquake, tsunami and corrosion. Structure and Infrastructure Engineering. 2019;16:26–50.
[2] Itoh Y, Gu HS. Prediction of Aging Characteristics in Natural Rubber Bearings Used in Bridges. Journal of Bridge Engineering. 2009;14:122–8.

1. Background

➢ Limitations of Current Time Varying Fragility Analysis

Probabilistic demand and capacity modeling

Traditional

$$P_f = \Phi\left[\frac{\ln(EDP) - \ln(LS)}{\sqrt{\beta_D^2 + \beta_C^2}}\right]$$

Time-invariant

$$\ln(EDP) = a + b\ln(IM)$$

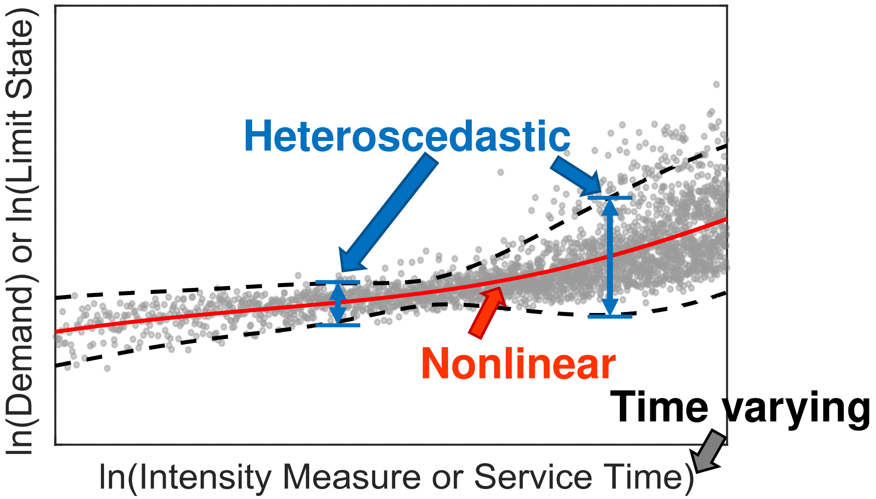
Engineering Demand Parameter

Linear

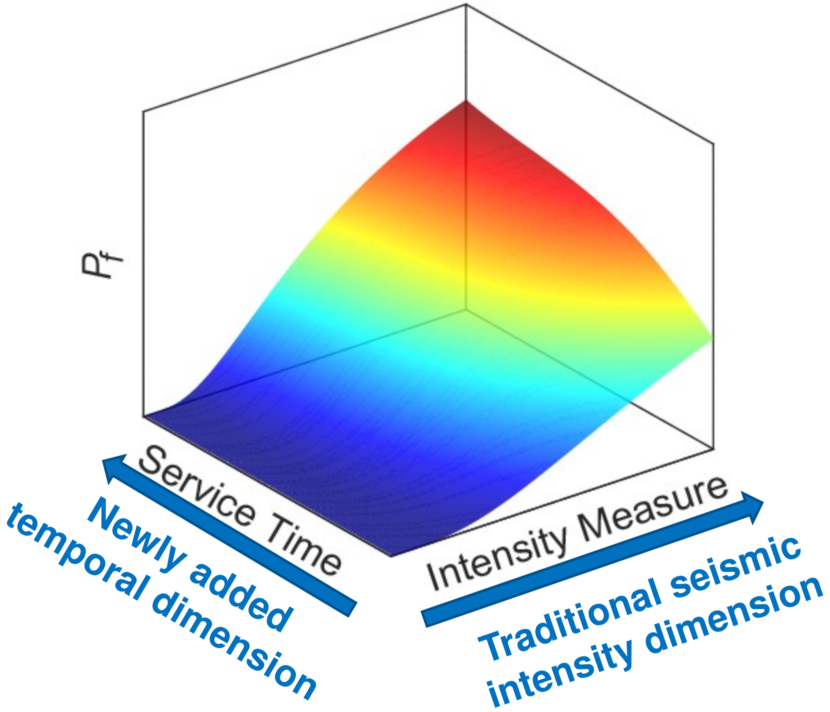
$$\beta_D = \sqrt{\frac{\sum_{i=1}^{N}[\ln(EDP_i) - [a + b\ln(IM)]]^2}{N-2}}$$

Homoscedastic

Our Study



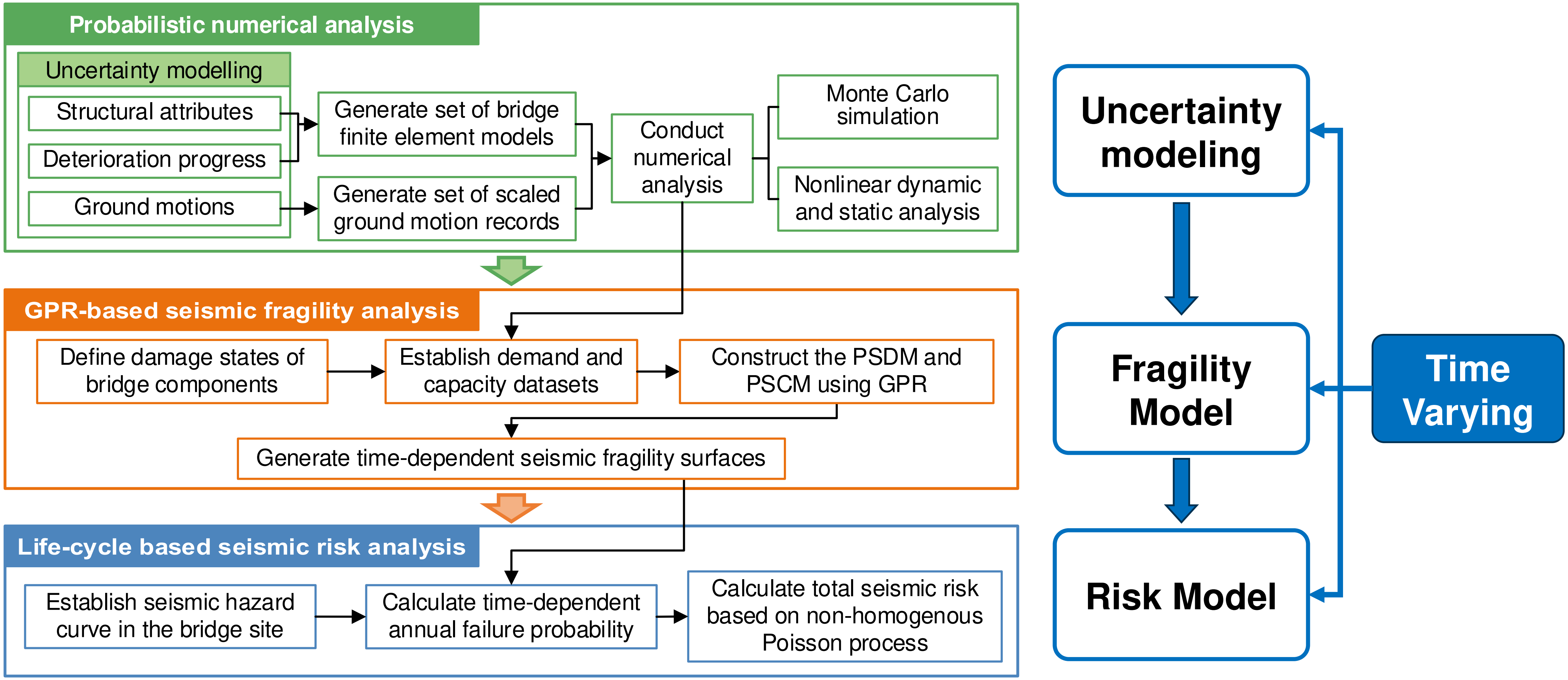
Time varying seismic fragility surface



Challenge: massive nonlinear analyses ➡ **Solution: machine learning-based surrogate model**

2. Time Varying Seismic Fragility and Risk Analysis Method

➢ **Time Varying Seismic Fragility and Risk Analysis Framework**



2. Time Varying Seismic Fragility and Risk Analysis Method

➢ Surrogate Modeling Approach: Gaussian Process Regression (GPR)

Gaussian process regression (GPR)

Output samples — Input samples — Gaussian process

$$\mathbf{y} = f^{GP}(\mathbf{x}) + \varepsilon, \quad f^{GP}(\mathbf{x}) \sim GP(m(\mathbf{x}), k(\mathbf{x}, \mathbf{x}'))$$

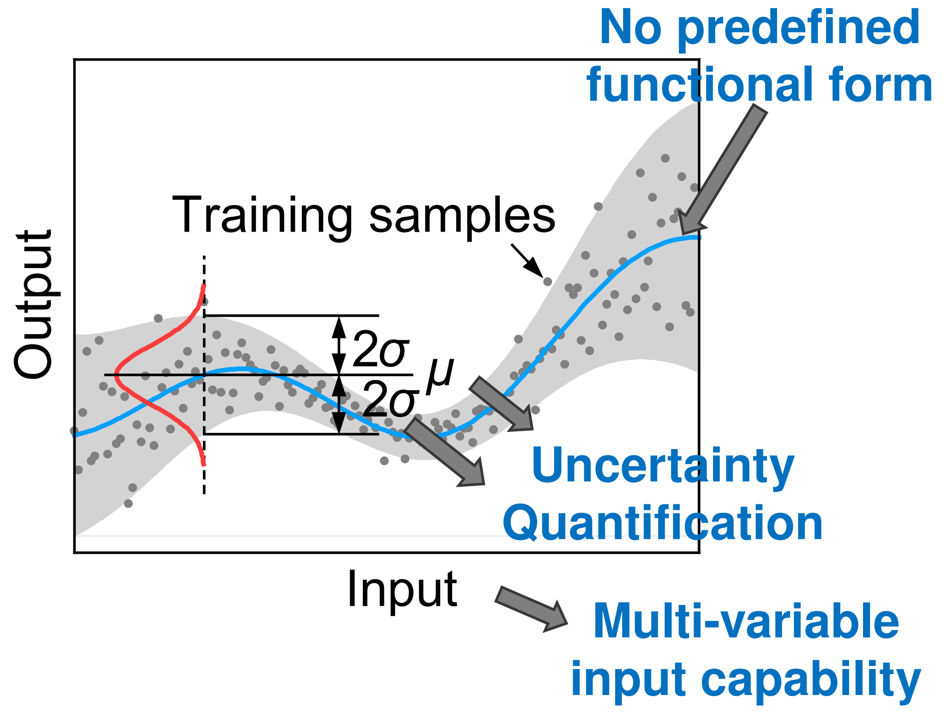
$$k(\mathbf{x},\mathbf{x}') = \sigma_f^2 \exp\left(-\frac{\|\mathbf{x}-\mathbf{x}'\|}{2\lambda^2}\right) + \sigma_n^2 \delta_{ij}$$

Squared exponential kernel

Hyperparameter optimizing

$$\begin{cases} \mathbf{y}_* \mid \mathbf{X}, \mathbf{y}, \mathbf{X}_* \sim N(\boldsymbol{\mu}_{\mathbf{y}_*}, \mathrm{cov}(\mathbf{y}_*)) \\ \boldsymbol{\mu}_{\mathbf{y}_*} = K(\mathbf{X}_*, \mathbf{X})[K(\mathbf{X}, \mathbf{X}) + \sigma_n^2 \mathbf{I}]^{-1} \mathbf{y} \\ \mathrm{cov}(\mathbf{y}_*) = K(\mathbf{X}_*, \mathbf{X}_*) - K(\mathbf{X}_*, \mathbf{X})[K(\mathbf{X}_*, \mathbf{X}_*) + \sigma_n^2 \mathbf{I}]^{-1} K(\mathbf{X}, \mathbf{X}_*) \end{cases}$$

Prediction $\mathbf{x} \rightarrow \mathbf{y}$



[1] Schulz E, Speekenbrink M, Krause A. A tutorial on Gaussian process regression: Modelling, exploring, and exploiting functions. Journal of Mathematical Psychology. 2018;85:1-16.

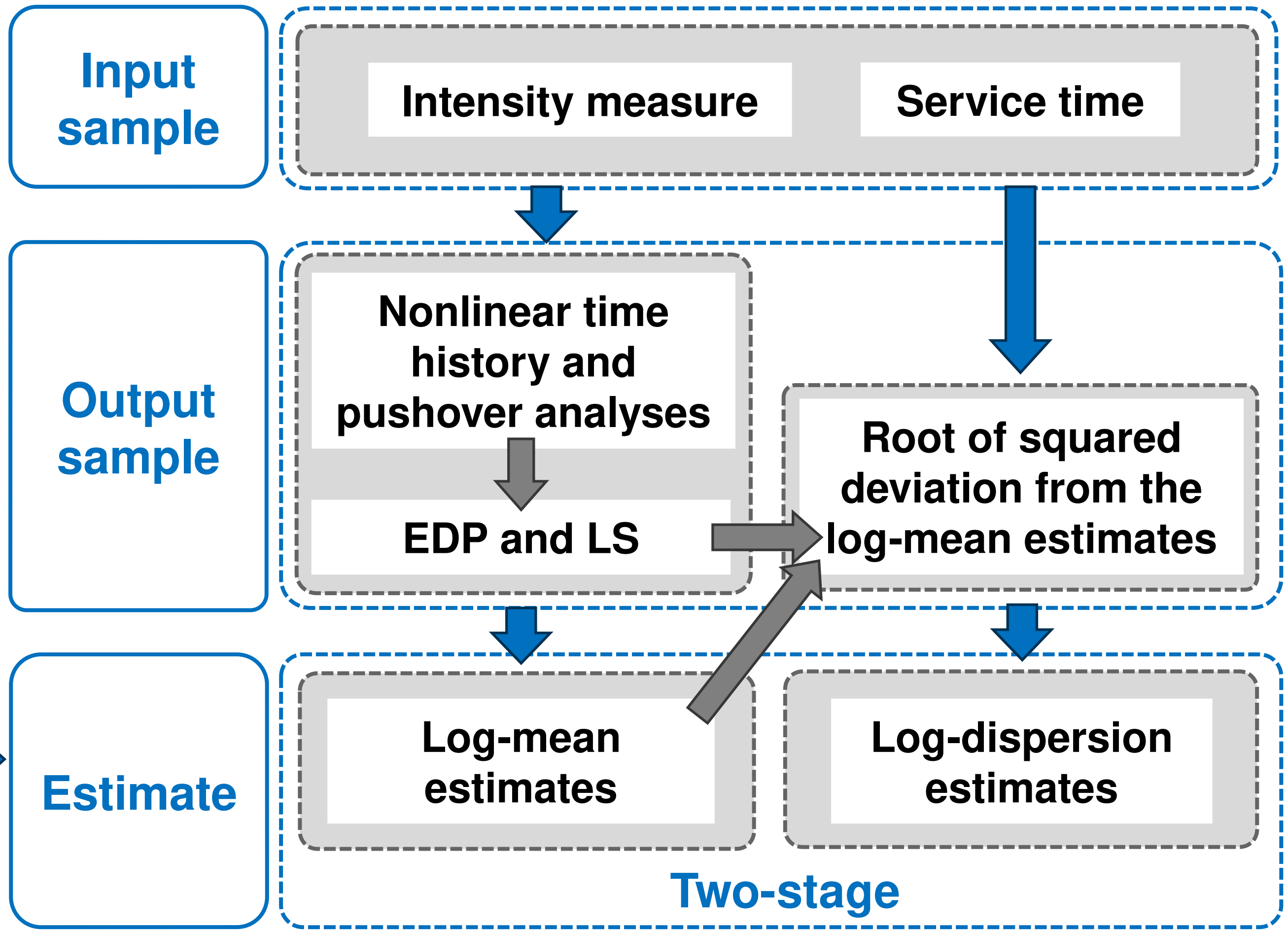
2. Time Varying Seismic Fragility and Risk Analysis Method

➢ GPR-Driven Seismic Demand and Capacity Modeling

GPR-driven time varying seismic demand and capacity model

$$\begin{cases} \ln(\mathbf{EDP})_* \mid \mathbf{X}_D, \ln(\mathbf{EDP}), \mathbf{X}_{D*} \sim N(\underbrace{\boldsymbol{\mu}_{\ln(\mathbf{EDP})_*}}_{\text{Log-mean estimate of seismic demand}}, \mathrm{cov}(\ln(\mathbf{EDP})_*)) \\ \boldsymbol{\beta}_{D*} \mid \mathbf{X}_D, \sqrt{(\ln(\mathbf{EDP}) - \boldsymbol{\mu}_{\ln(\mathbf{EDP})_*})^2}, \mathbf{X}_{D*} \sim N(\underbrace{\boldsymbol{\mu}_{\boldsymbol{\beta}_{D*}}}_{\text{Log-dispersion estimate of seismic demand}}, \mathrm{cov}(\boldsymbol{\beta}_{D*})) \\ \mathbf{X}_D = \{\ln(\mathbf{IM}), \mathbf{t}\} \end{cases}$$

$$\begin{cases} \ln(\mathbf{LS})_* \mid \mathbf{X}_C, \ln(\mathbf{LS}), \mathbf{X}_{C*} \sim N(\underbrace{\boldsymbol{\mu}_{\ln(\mathbf{LS})_*}}_{\text{Log-mean estimate of capacity}}, \mathrm{cov}(\ln(\mathbf{LS})_*)) \\ \boldsymbol{\beta}_{C*} \mid \mathbf{X}_C, \sqrt{(\ln(\mathbf{LS}) - \boldsymbol{\mu}_{\ln(\mathbf{LS})_*})^2}, \mathbf{X}_{C*} \sim N(\underbrace{\boldsymbol{\mu}_{\boldsymbol{\beta}_{C*}}}_{\text{Log-dispersion estimate of capacity}}, \mathrm{cov}(\boldsymbol{\beta}_{C*})) \\ \mathbf{X}_C = \{\mathbf{t}\} \end{cases}$$



2. Time Varying Seismic Fragility and Risk Analysis Method

➢ Time Varying Seismic Fragility and Risk Modeling

GPR-driven time varying seismic demand and capacity model

$$\begin{cases} \ln(\mathbf{EDP})_* \mid \mathbf{X}_D, \ln(\mathbf{EDP}), \mathbf{X}_{D^*} \sim N(\boldsymbol{\mu}_{\ln(\mathbf{EDP})_*}, \mathrm{cov}(\ln(\mathbf{EDP})_*)) \\ \boldsymbol{\beta}_{D^*} \mid \mathbf{X}_D, \sqrt{(\ln(\mathbf{EDP}) - \boldsymbol{\mu}_{\ln(\mathbf{EDP})_*})^2}, \mathbf{X}_{D^*} \sim N(\boldsymbol{\mu}_{\boldsymbol{\beta}_{D^*}}, \mathrm{cov}(\boldsymbol{\beta}_{D^*})) \\ \mathbf{X}_D = \{\ln(\mathbf{IM}), \mathbf{t}\} \end{cases}$$

Log-mean estimate of seismic demand

Log-dispersion estimate of seismic demand

$$\begin{cases} \ln(\mathbf{LS})_* \mid \mathbf{X}_C, \ln(\mathbf{LS}), \mathbf{X}_{C^*} \sim N(\boldsymbol{\mu}_{\ln(\mathbf{LS})_*}, \mathrm{cov}(\ln(\mathbf{LS})_*)) \\ \boldsymbol{\beta}_{C^*} \mid \mathbf{X}_C, \sqrt{(\ln(\mathbf{LS}) - \boldsymbol{\mu}_{\ln(\mathbf{LS})_*})^2}, \mathbf{X}_{C^*} \sim N(\boldsymbol{\mu}_{\boldsymbol{\beta}_{C^*}}, \mathrm{cov}(\boldsymbol{\beta}_{C^*})) \\ \mathbf{X}_C = \{\mathbf{t}\} \end{cases}$$

Log-mean estimate of capacity

Log-dispersion estimate of capacity

GPR-based time varying seismic fragility model

$$P_{\mathrm{f}}(\mathrm{DS} \mid \mathbf{X}_D, \mathbf{X}_C) = \Phi\left[\frac{\boldsymbol{\mu}_{\ln(\mathbf{EDP})_*} - \boldsymbol{\mu}_{\ln(\mathbf{LS})_*}}{\sqrt{\boldsymbol{\mu}^2_{\boldsymbol{\beta}_{D^*}} + \boldsymbol{\mu}^2_{\boldsymbol{\beta}_{C^*}}}}\right]$$

Life-cycle based total seismic risk model

$$H(IM) = k_0 IM^{-k_1}$$

$$v(\mathrm{DS} \mid t) = \int_0^{\infty} P_{\mathrm{f}}(\mathrm{DS} \mid IM = im, t) \left| \mathrm{d}H(im)/\mathrm{d}im \right| \mathrm{d}im$$

$$P(\mathrm{DS} \mid t_r) = 1 - \exp\left[-\int_{T-t_r}^{T} v(\mathrm{DS} \mid \tau)\mathrm{d}\tau\right]$$

$$= 1 - \exp\left[-\sum_{\tau = T - t_r}^{t_r/\Delta t} v(\mathrm{DS} \mid \tau)\Delta t\right]$$

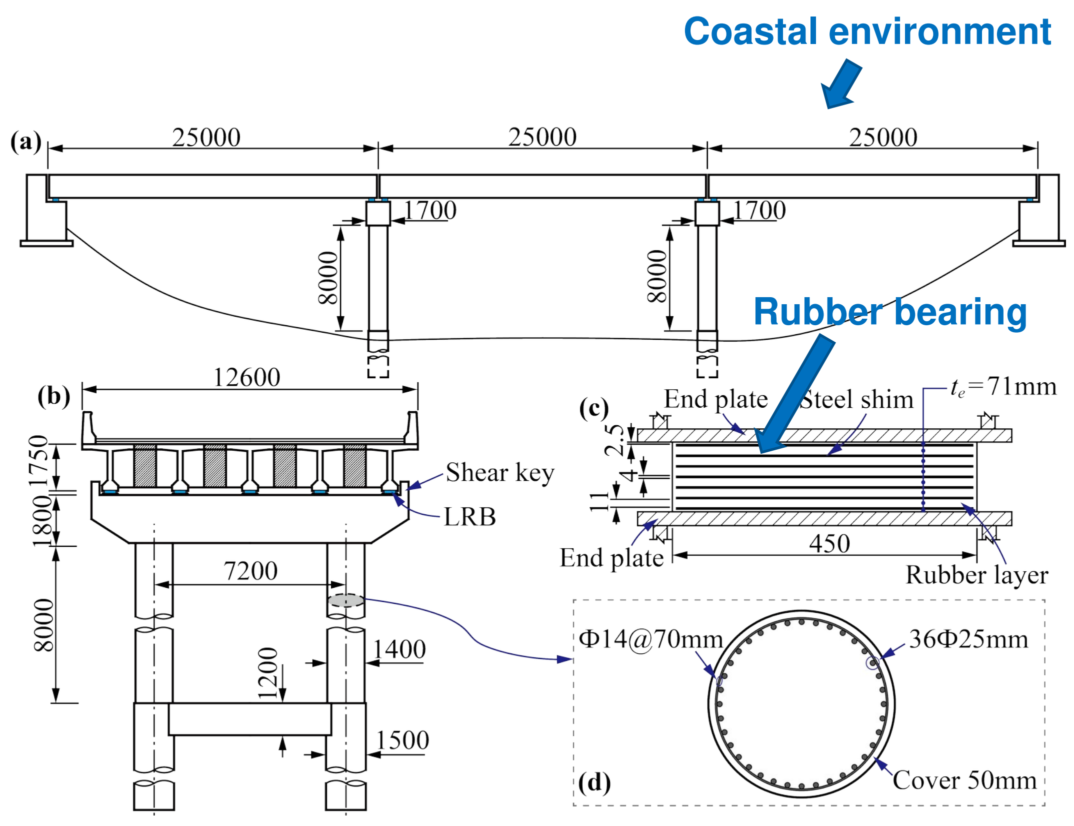
Total seismic risk over remaining service life modeled as a non-homogeneous Poisson process

[1] Ghosh J, Padgett JE. Probabilistic seismic loss assessment of aging bridges using a component-level cost estimation approach. Earthquake Engineering & Structural Dynamics. 2011;40:1743-61.

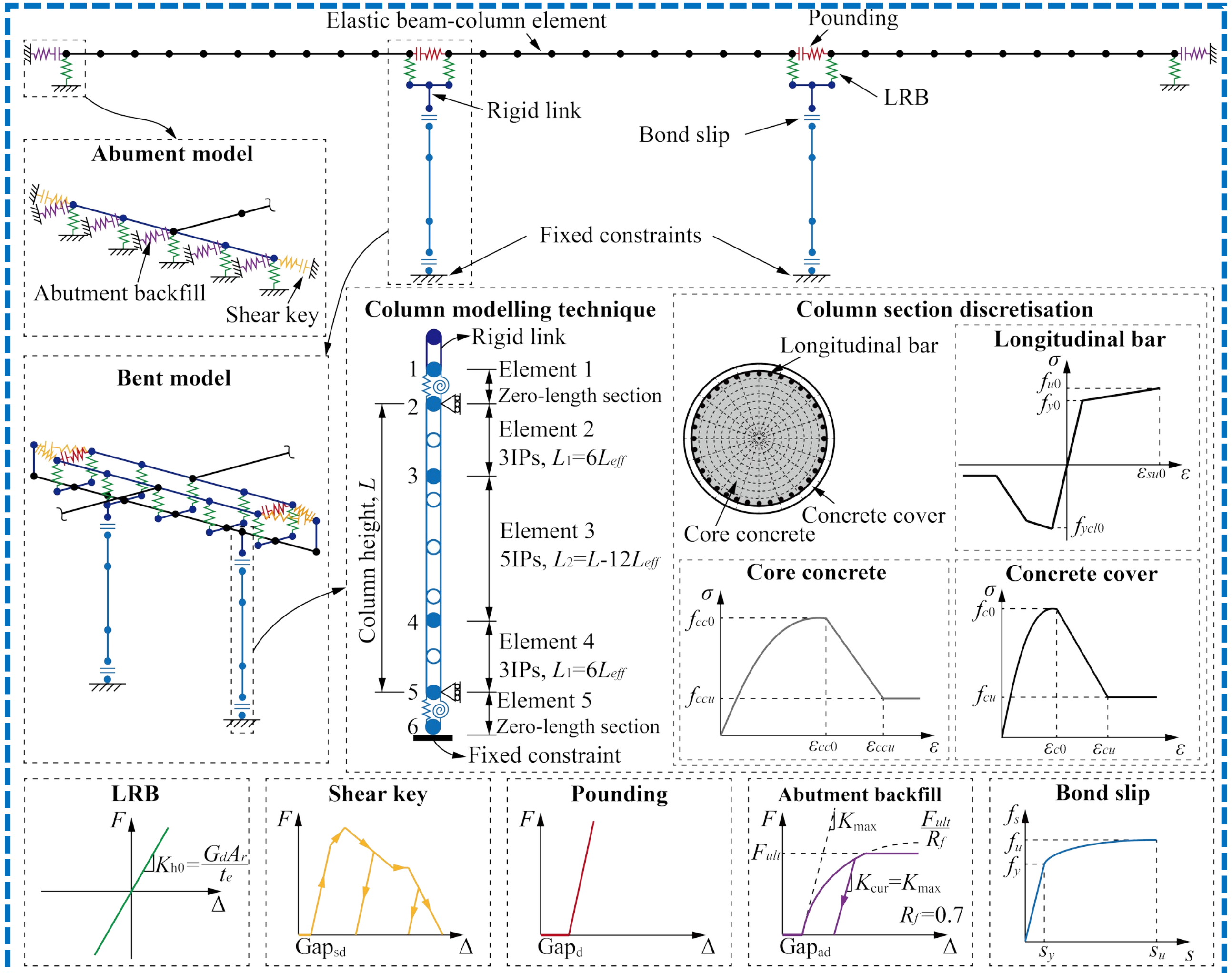
3. Uncertainty-Included Time Varying Bridge Modeling

➢ **Uncertainties Included Rubber Bearing Supported Bridge Analysis Modeling**

Finite element modeling of bridge structure



General layout



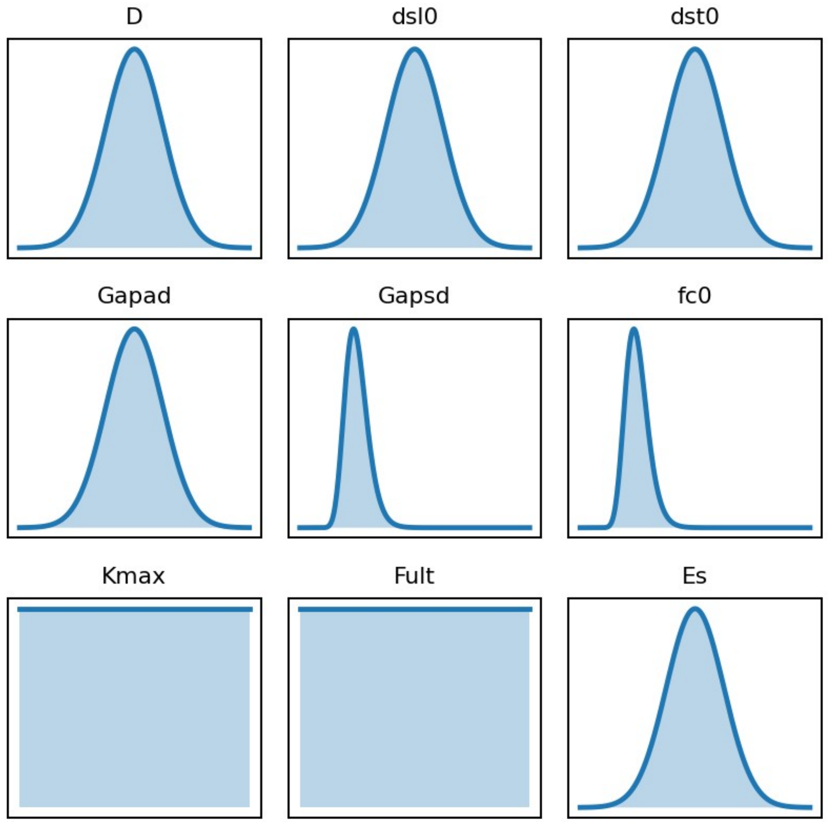
OpenSees model

3. Uncertainty-Included Time Varying Bridge Modeling

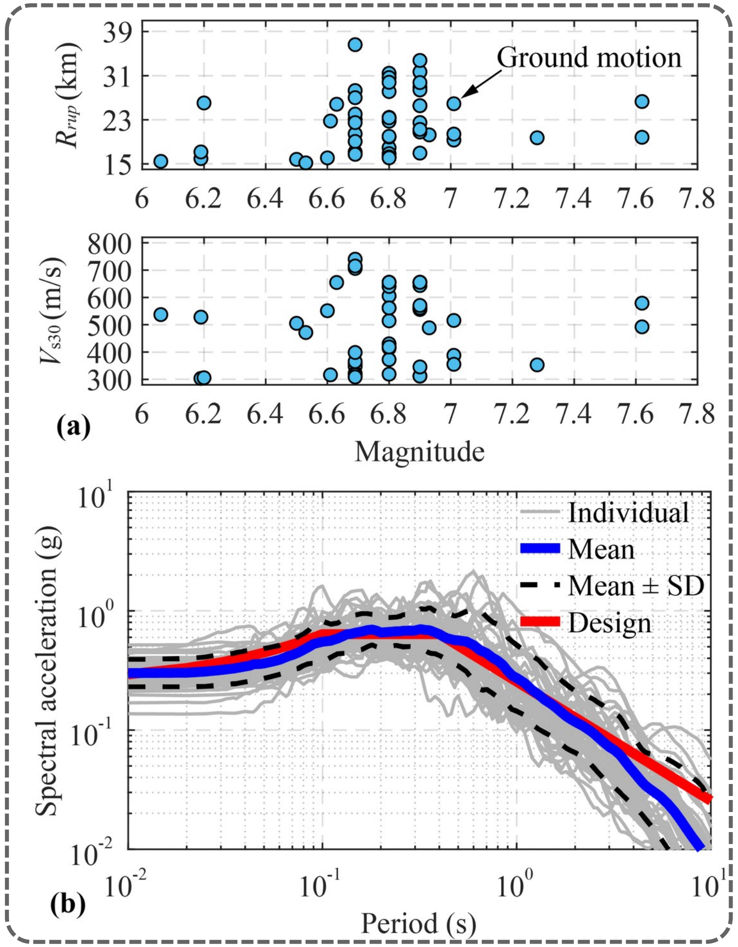
➢ Uncertainties Included Rubber Bearing Supported Bridge Analysis Modeling

Uncertainty modelling

☐ Uncertainty of structural attributes



☐ Uncertainty of ground motions



PEER strong motion database

↓ Spectrum matching

50 far-field ground motion records

↓ Amplitude Scaling

3,000 ground motions

3. Uncertainty-Included Time Varying Bridge Modelling

➢ Uncertainties Included Rubber Bearing Supported Bridge Analysis Modeling

Uncertainty modeling

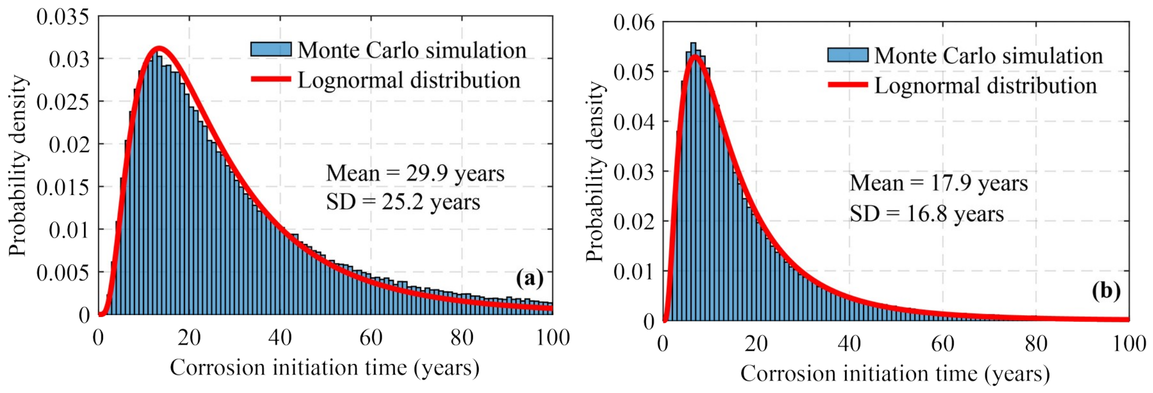
☐ Uncertainty of deterioration progress of RC bridge columns

- *Corrosion initiation time*

Duracrete model

$$T_{\text{init}} = X_{\text{I}}\left[\frac{d_c^2}{4k_e k_t k_c D_0 (t_0)^n}\left[\text{erf}^{-1}\left(1 - \frac{C_{cr}}{A_{cs}(w/b) + \varepsilon_{cs}}\right)\right]^{-2}\right]^{1/(1-n)}$$

Model Parameter Uncertainty



Probability distribution of corrosion initiation time

- *Deterioration modelling of RC columns*

Material	Mechanical properties
Steel rebar	Cross section area included pitting corrosion effect
	Tensile yield strength
	Tensile ultimate strength
	Ultimate tensile strain
	Compressive yield strength
Concrete cover	Compressive strength
Core concrete	Peak compressive stress
	Strain at peak compressive stress
	Ultimate compressive strain
Bond slip	Yield slip
	Ultimate slip

[1] DuraCrete. Statistical quantification of the variables in the limit state functions. The European Union-Brite EuRam III-Contract BRPR-CT95-0132-Project BE95-1347/R9. 2000.

3. Uncertainty-Included Time Varying Bridge Modeling

➢ **Uncertainties included rubber bearing supported bridge analysis modeling**

Uncertainty modeling

☐ **Uncertainty of deterioration progress of rubber bearing**

Thermal oxidative aging modelling of rubber bearings

$$\underline{K_h} = (1 + k_s \Delta f_s) K_{h0} = (1 + k_s \Delta f_s) G_d A_r / t_e$$

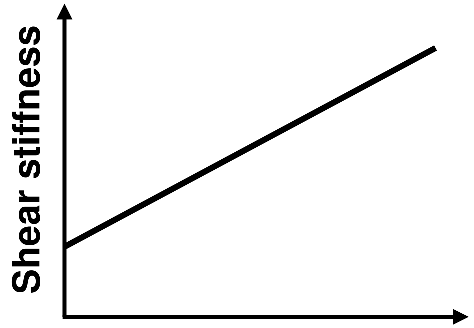
Shear stiffness

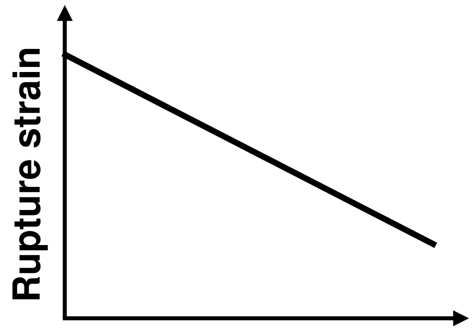
$$k_s = 2\alpha_t [\underbrace{l}_{\text{Bearing dimensions}} + \underline{m} - \alpha_t \exp(\beta_t / \underbrace{T_{ave}}_{\text{Average temperature}})] \times \exp(\beta_t / T_{ave}) / (3lm)$$

$$f_s = 0.066 \times \left[365 \underbrace{t}_{\text{Service time}} \times \exp(E_a (1/T_{ref} - 1/T_{ave}) / R) \right]^{0.515}$$

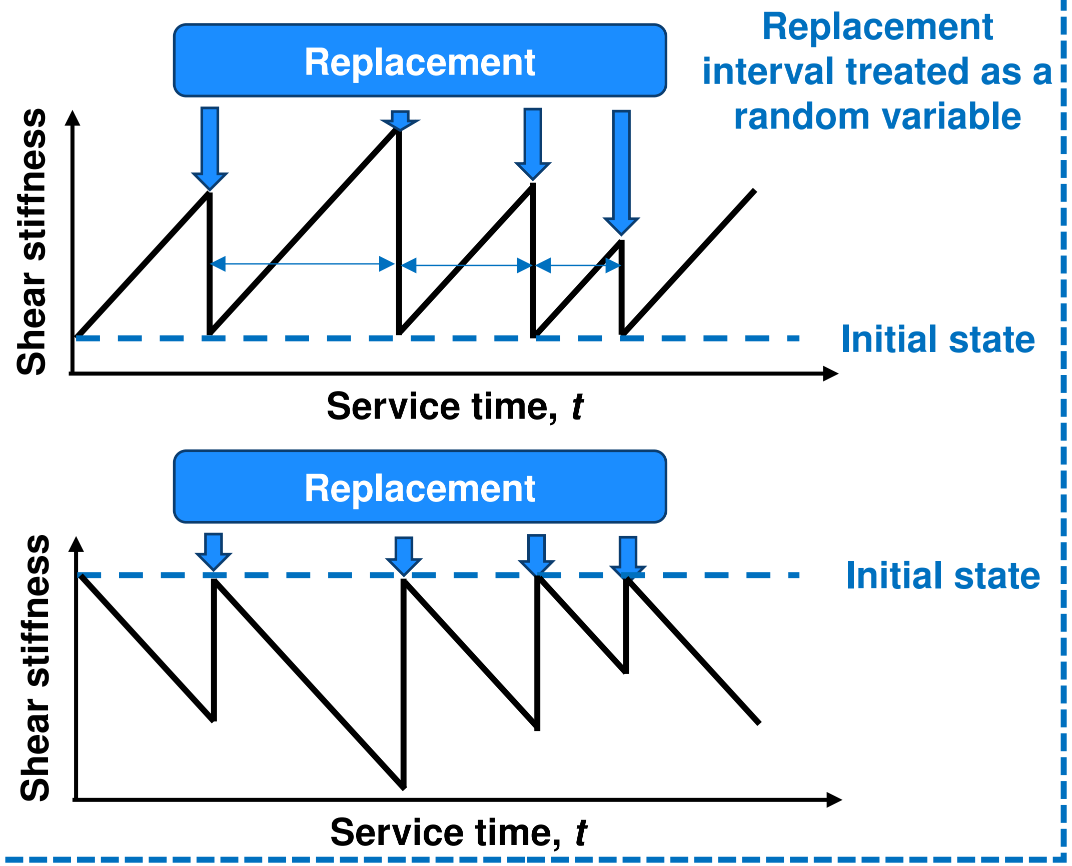
$$\underline{\gamma_h} = (1 - k_s \Delta f_s) \gamma_{h0}$$

Rupture strain





- *Replacement of rubber bearings*



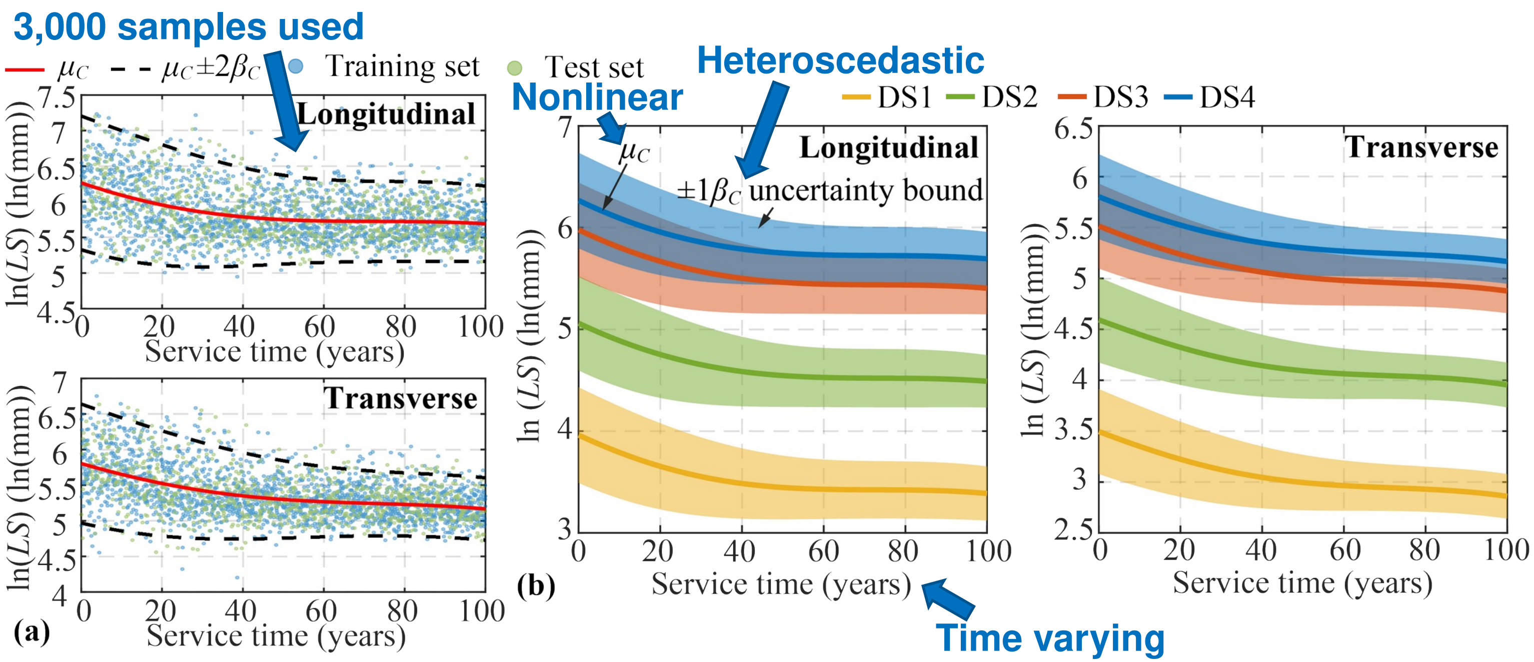
4. Results and Conclusions

➢ Seismic Fragility Analysis

GPR-driven probabilistic capacity model of RC columns

Limit state definition

Damage State	Description	Drift Limit
DS1	Slight	0.10 × DS4
DS2	Moderate	0.30 × DS4
DS3	Extensive	0.75 × DS4
DS4	Complete	First occurrence of: longi. bar fracture / core concrete crushing / longi. bar buckling



Time varying trend

Mean capacity: nonlinear time-dependent decrease
Uncertainty band: time-dependent reduction

4. Results and Conclusions

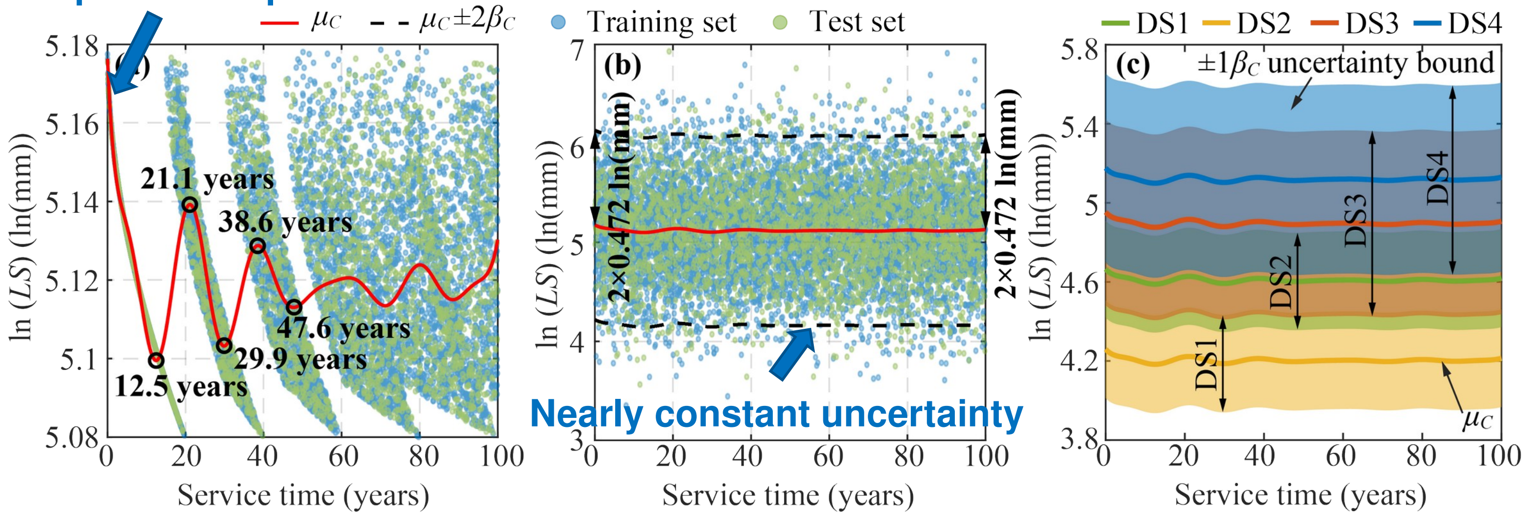
➢ Seismic Fragility Analysis

GPR-driven probabilistic capacity model of rubber bearings

Limit state definition

Damage State	Median LS (mm)	Log-dispersion (ln(mm))
DS1 – Slight	71.0	0.246
DS2 – Moderate	106.5	0.246
DS3 – Extensive	142.0	0.472
DS4 – Complete	177.5	0.472

Fluctuations induced by aging and periodic replacements



Nearly constant uncertainty

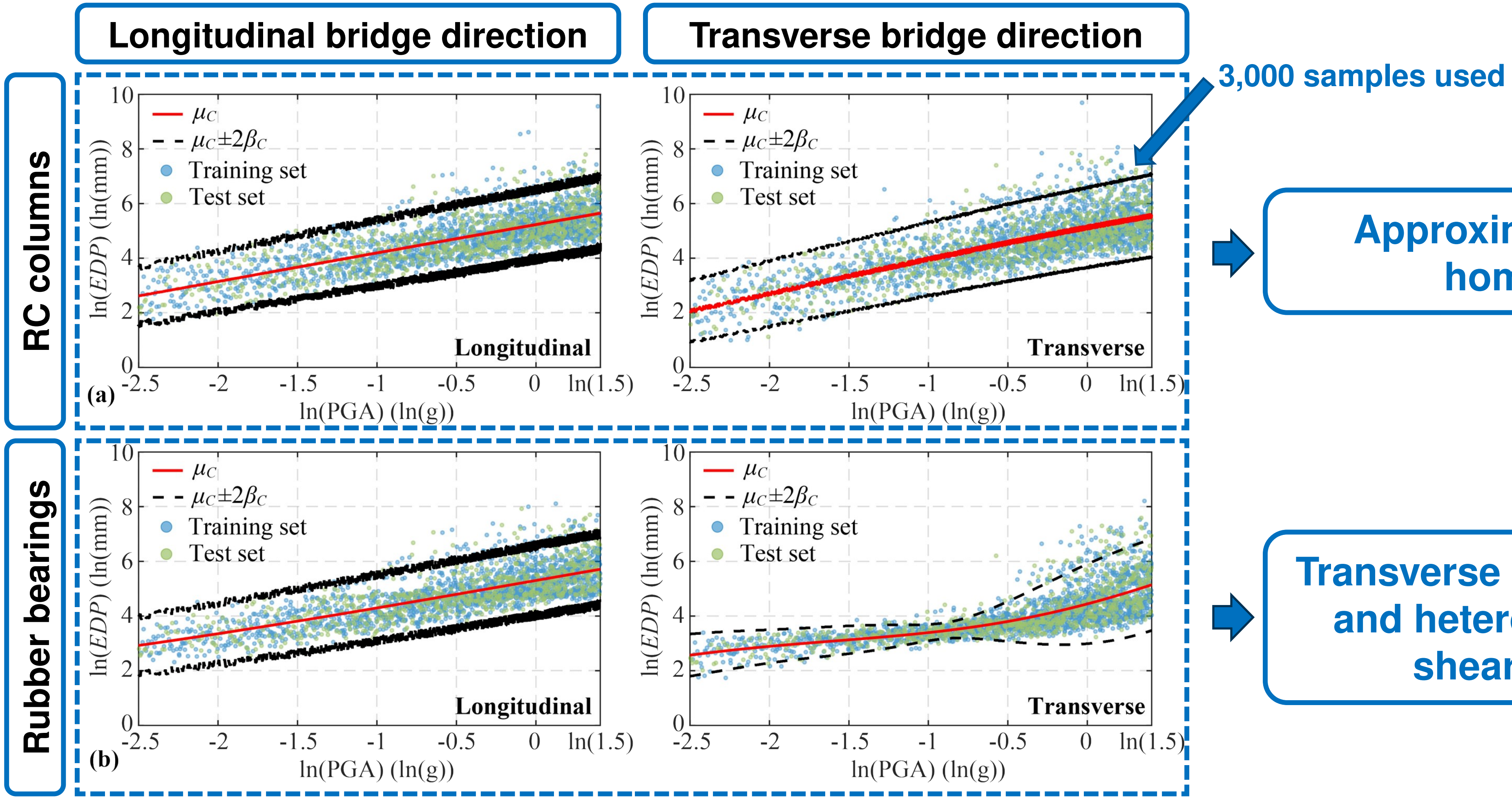
Time varying trend

Mean capacity: oscillatory time-varying trend
Uncertainty band: nearly constant over time

4. Results and Conclusions

➢ Seismic Fragility Analysis

GPR-driven probabilistic seismic demand model



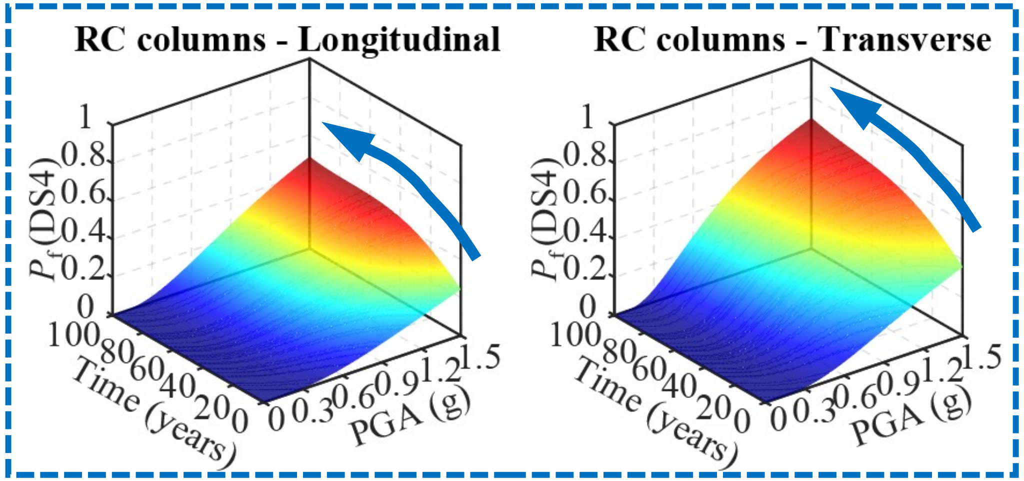
Approximately linear and homoscedastic

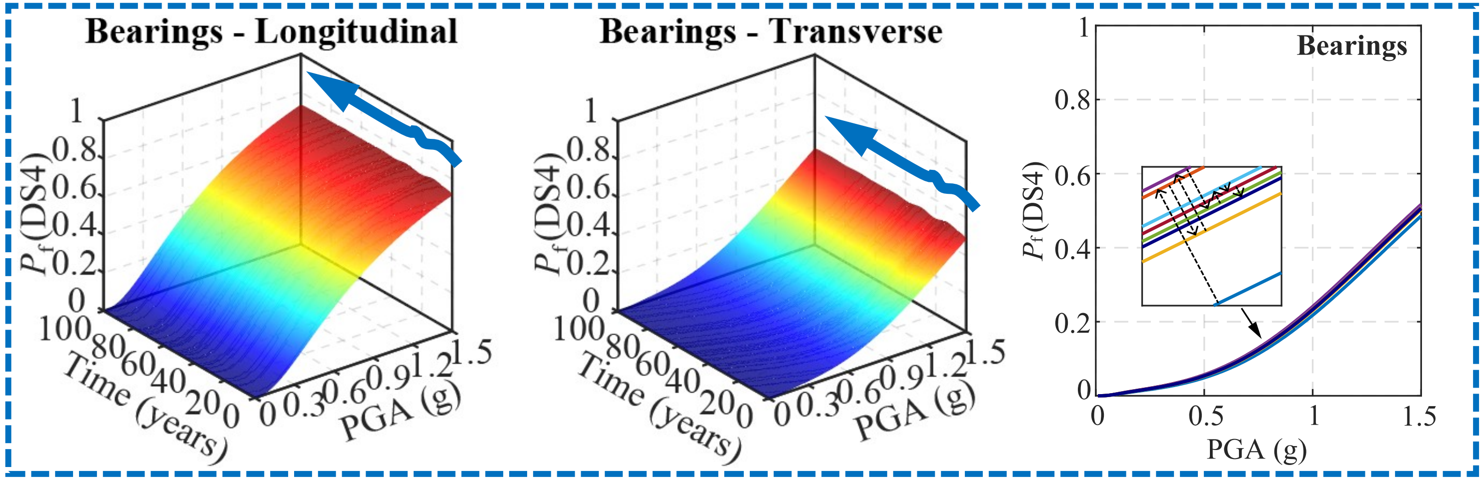
Transverse direction: nonlinear and heteroscedastic due to shear key restraint

4. Results and Conclusions

Seismic Fragility Analysis

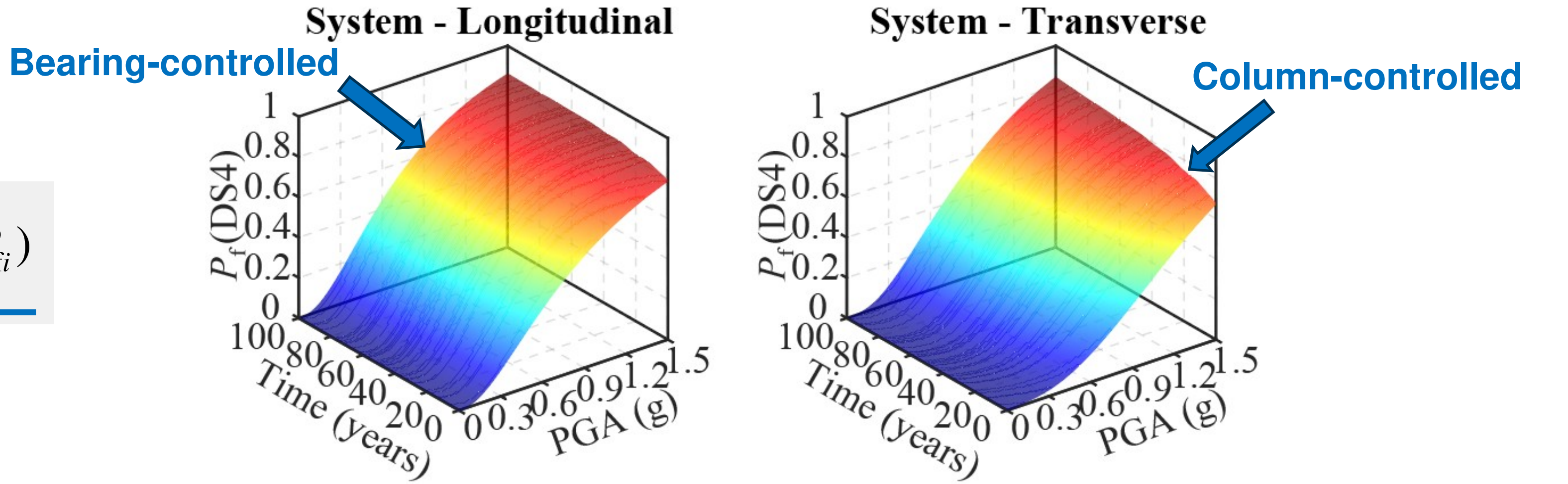
Time varying seismic fragility surface





System fragility function

$$\max_{i=1}^{n}(P_{fi}) \le P_{f,sys} \le 1 - \prod_{i=1}^{n}(1 - P_{fi})$$

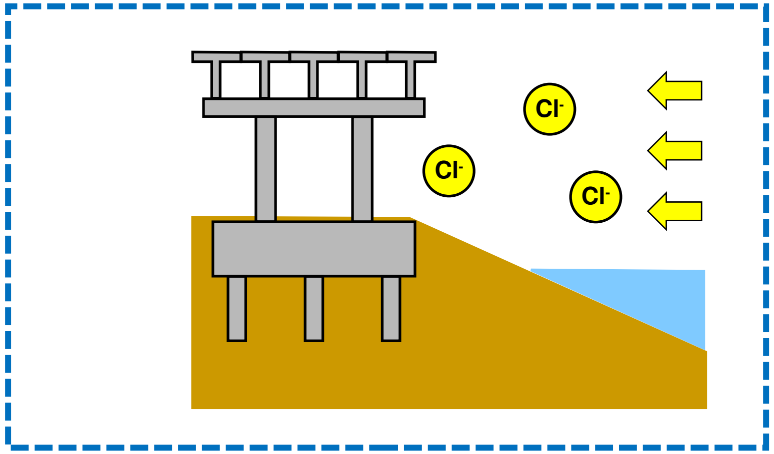


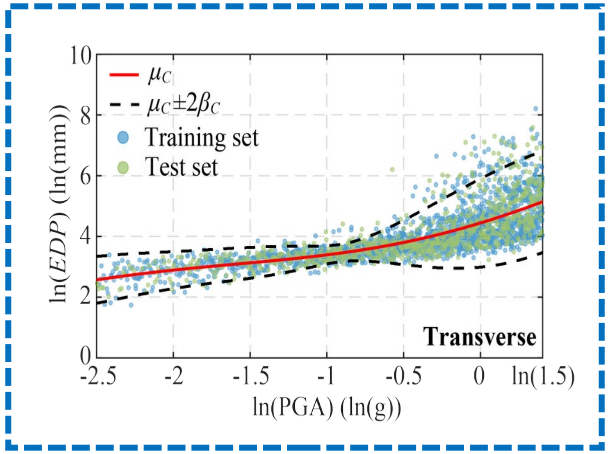
4. Results and Conclusions

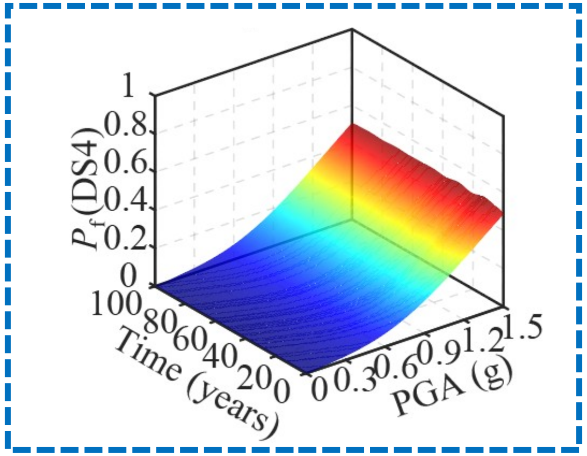
➢ Seismic Fragility Analysis

Efficiency analysis

- **Analysis conducted:** 3,000 NLTHA + 3,000 pushover + 20 GPR → time-dependent seismic fragility surface.
- **Traditional approach:** 50 ground motions × 6 scaling factors × 100 years → 30,000 NLTHA + 30,000 pushover + 200 regression analyses.
- **Efficiency gain:** GPR requires only ~10% of the computations of traditional time-discrete methods, significantly reducing computational cost.







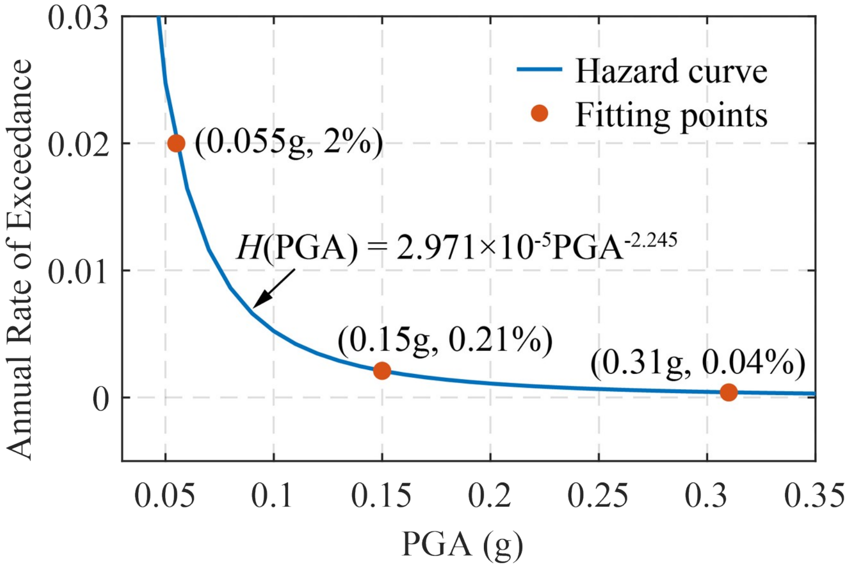
4. Results and Conclusions

➢ Life-Cycle Based Seismic Risk Analysis

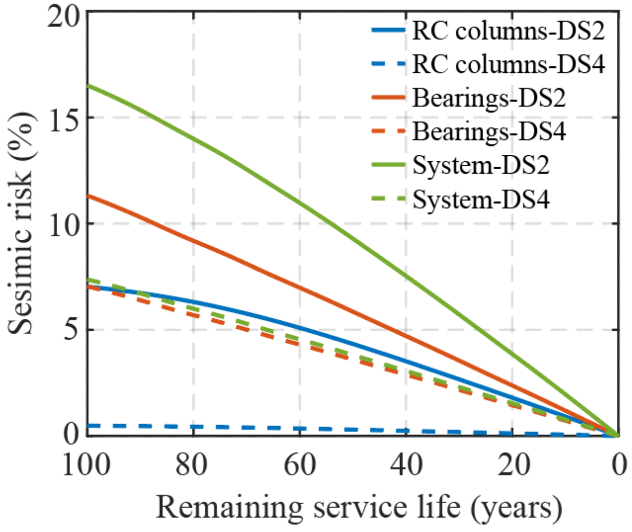
Seismic hazard analysis

Log-linear fitted seismic hazard curve

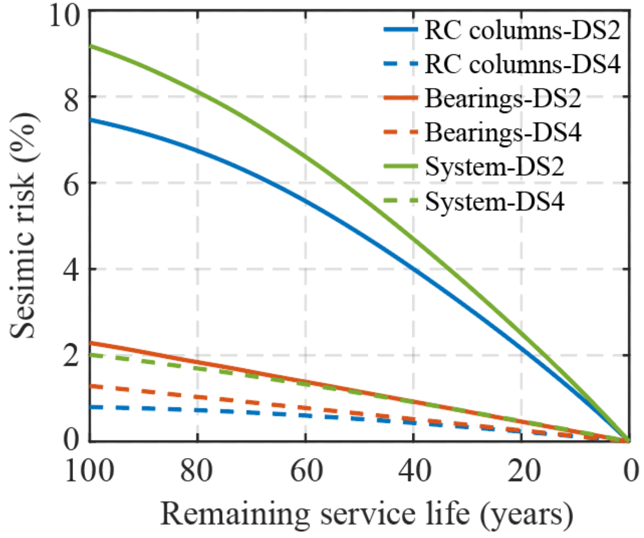
$$H(IM) = k_0 IM^{-k_1}$$



Life-cycle based total seismic risk curve



Longitudinal bridge direction



Transverse bridge direction

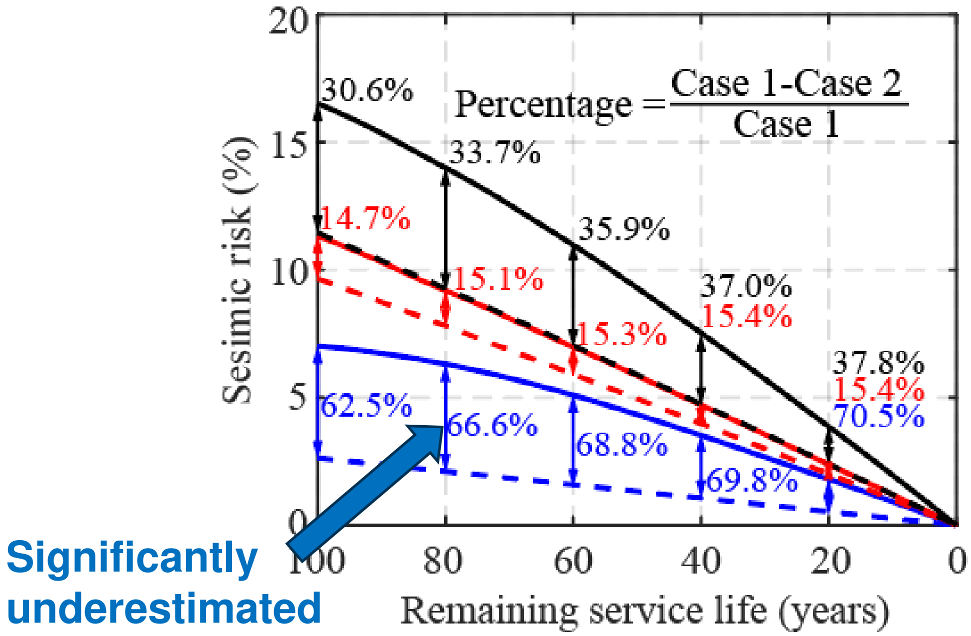
Life-cycle based total seismic risk decreases with decreasing remaining service life because hazard reduction outweighs fragility increase

[1] Cornell CA, Jalayer F, Hamburger RO, Foutch DA. Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines. Journal of structural engineering. 2002;128:526-33.

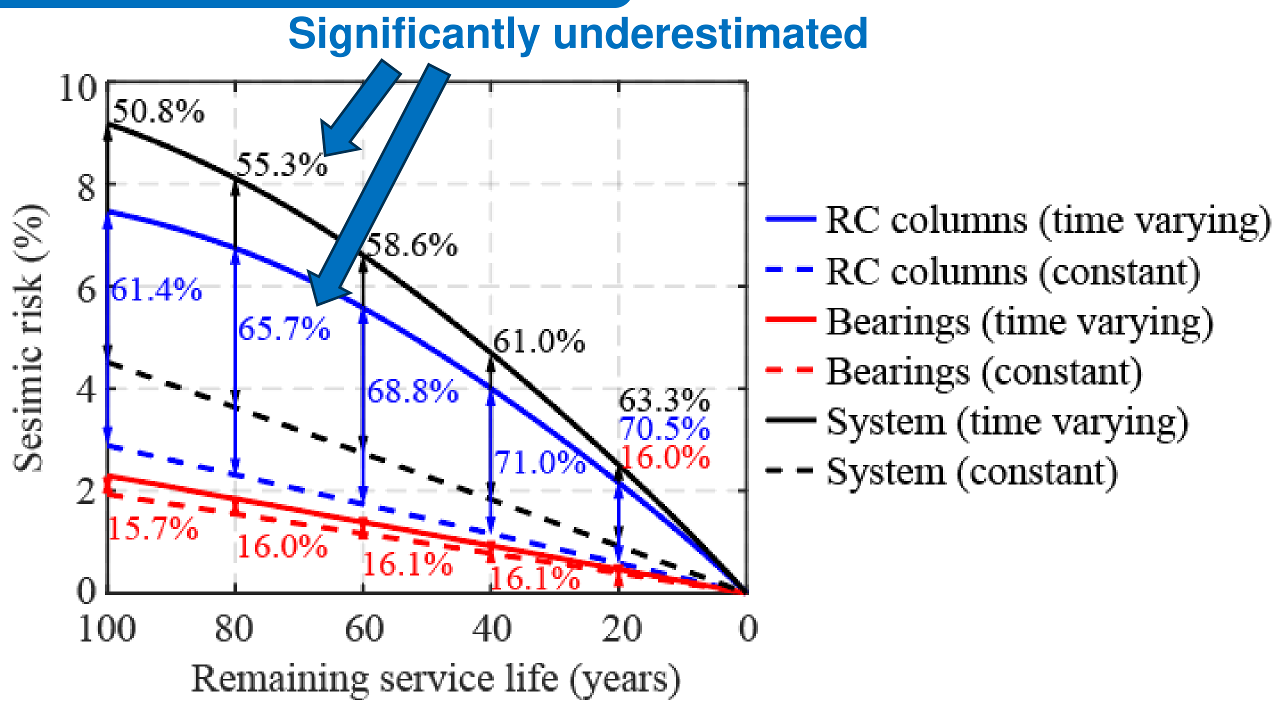
4. Results and Conclusions

➢ **Life-Cycle Based Seismic Risk Analysis**

Life-cycle based total seismic risk: time-varying vs constant



Longitudinal bridge direction



Transverse bridge direction

Ignoring deterioration leads to significant underestimation of total seismic risk, particularly for RC columns and system.

4. Results and Conclusions

➢ Conclusions

1

GPR enables efficient time-dependent seismic fragility analysis, capturing nonlinear and heteroscedastic behavior of probabilistic demand and capacity models, and is estimated to reduce computational cost by ~90% compared to traditional methods.

2

Component-level fragility evolves differently: RC columns steadily deteriorate due to corrosion; rubber bearings fluctuate due to aging and replacement; system-level control may shift between components, highlighting the need to consider multi-component deterioration.

3

Total seismic risk decreases with remaining service life, but neglecting deterioration—especially RC column corrosion—can significantly underestimate risk (up to >60%), emphasizing the importance of including deterioration, replacement, and time-dependent hazard in life-cycle analysis.

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Kangshuai Yin , Yan Xu

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Engineering Structures

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Life-cycle based time-dependent seismic design of reinforced concrete bridge piers empowered by data-driven fragility analysis

Kangshuai Yin [a], Xinzhi Duan [b], Xun Zhou [a], Yan Xu [a], Yin Gu [c]

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