Performance-Based Analysis and Design for California Ordinary Standard Bridges

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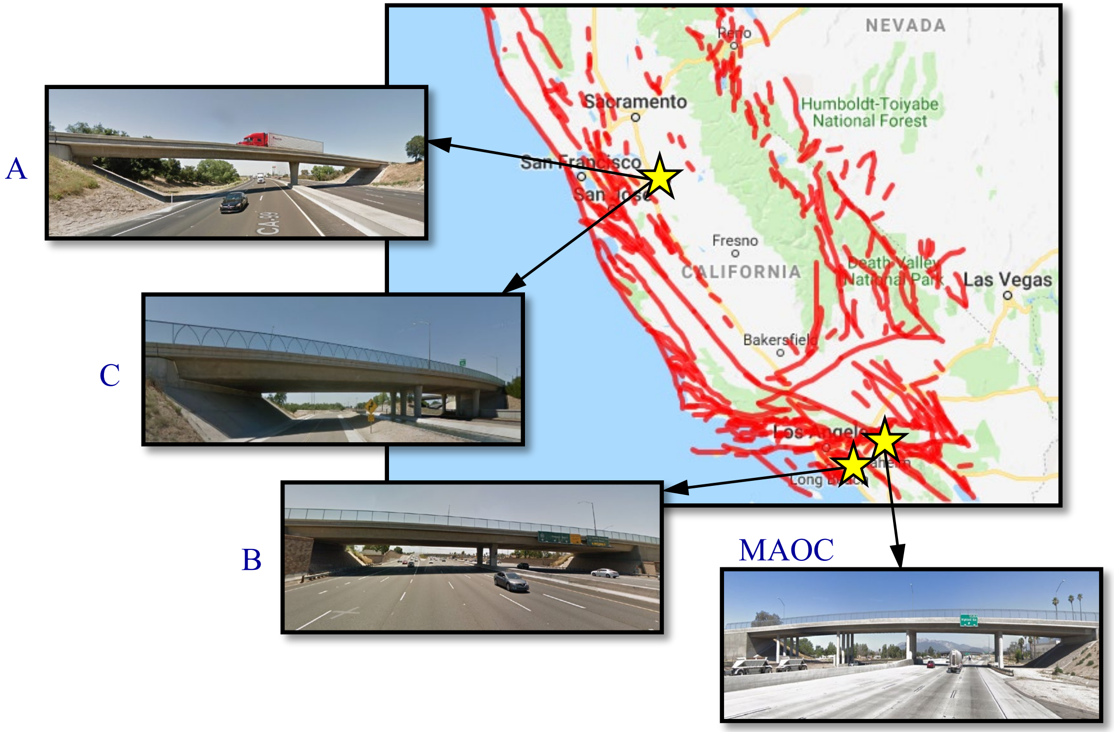
Outline

- Testbed California Ordinary Standard Bridges (OSBs) and Computational Models
- PEER PBEE Assessment Methodology
- Parametric Probabilistic Seismic Performance Assessment Framework
- Simplified Risk-Targeted Performance-Based Seismic Design (PBSD) Method
- Concluding Remarks & Recommendations for Future Work

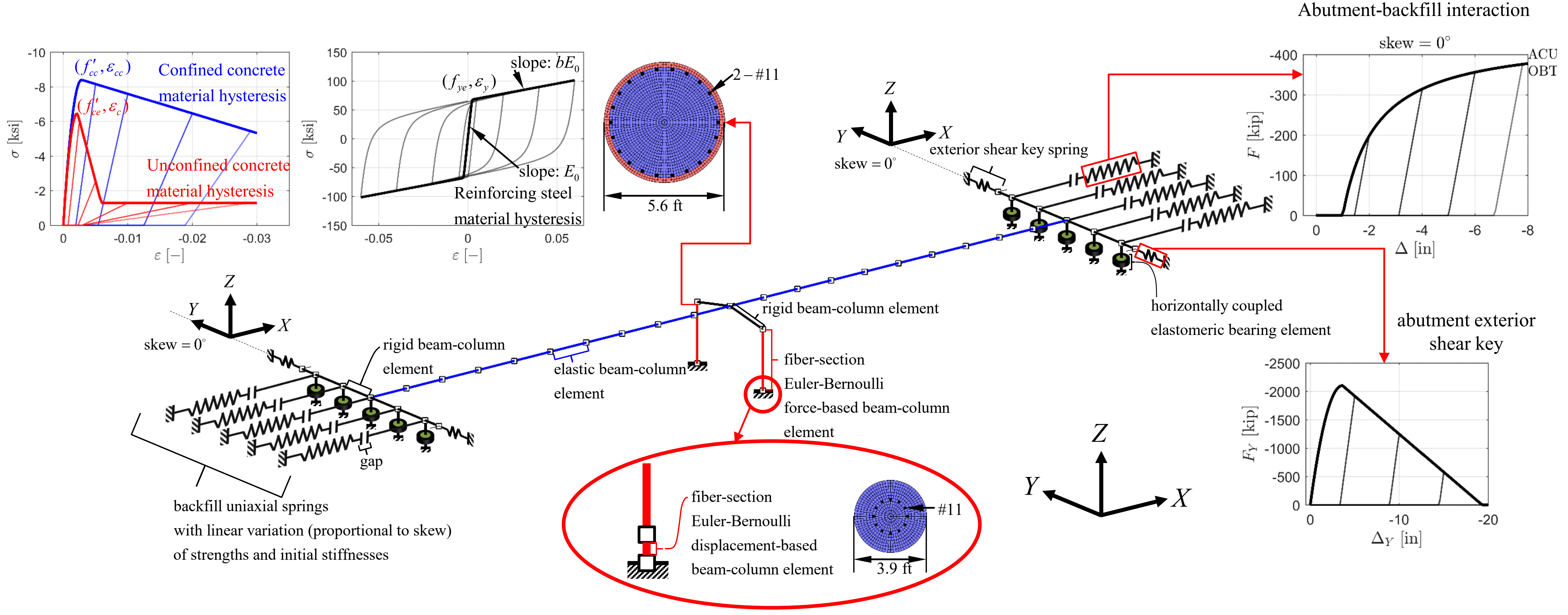
Ordinary Standard Bridge (OSB) Testbeds Considered

Bridge Designation	A	B	C	MAOC
Name	Jack Tone Road Overcrossing	La Veta Avenue Overcrossing	Jack Tone Road Overhead	Massachusetts Avenue Overcrossing
Location: City, State	Ripon, CA	Tustin, CA	Ripon, CA	San Bernardino, CA
Total Length	220.4 ft	299.8 ft	418.2 ft	413.4 ft
Number of Spans and Span Length	2 Span 1: 108.6 ft Span 2: 111.8 ft	2 Span 1: 154.8 ft Span 2: 145 ft	3 Span 1: 156.2 ft Span 2: 144 ft Span 3: 118 ft	5 Span 1: 49.2 ft Span 2: 94.5 ft Span 3: 91.9 ft Span 4: 99.7 ft Span 5: 78.1 ft
Type of Column Bent	Single Column (RC Circular) Column Diameter: 5.5 ft Column Height: 19.7 ft	Two-column (RC Circular) Column Diameter: 5.5 ft Column Height: 22.0 ft	Three-column (RC Circular) Column Diameter: 5.5 ft Column Height: 24.6 ft	Four-column (RC Circular) Column Diameter: 4.0 ft Column Heights: 29.5 ft, 31.5 ft, 30.7 ft, 27.4 ft
Skew	33 degrees	0 degrees	36 degrees	8 degrees

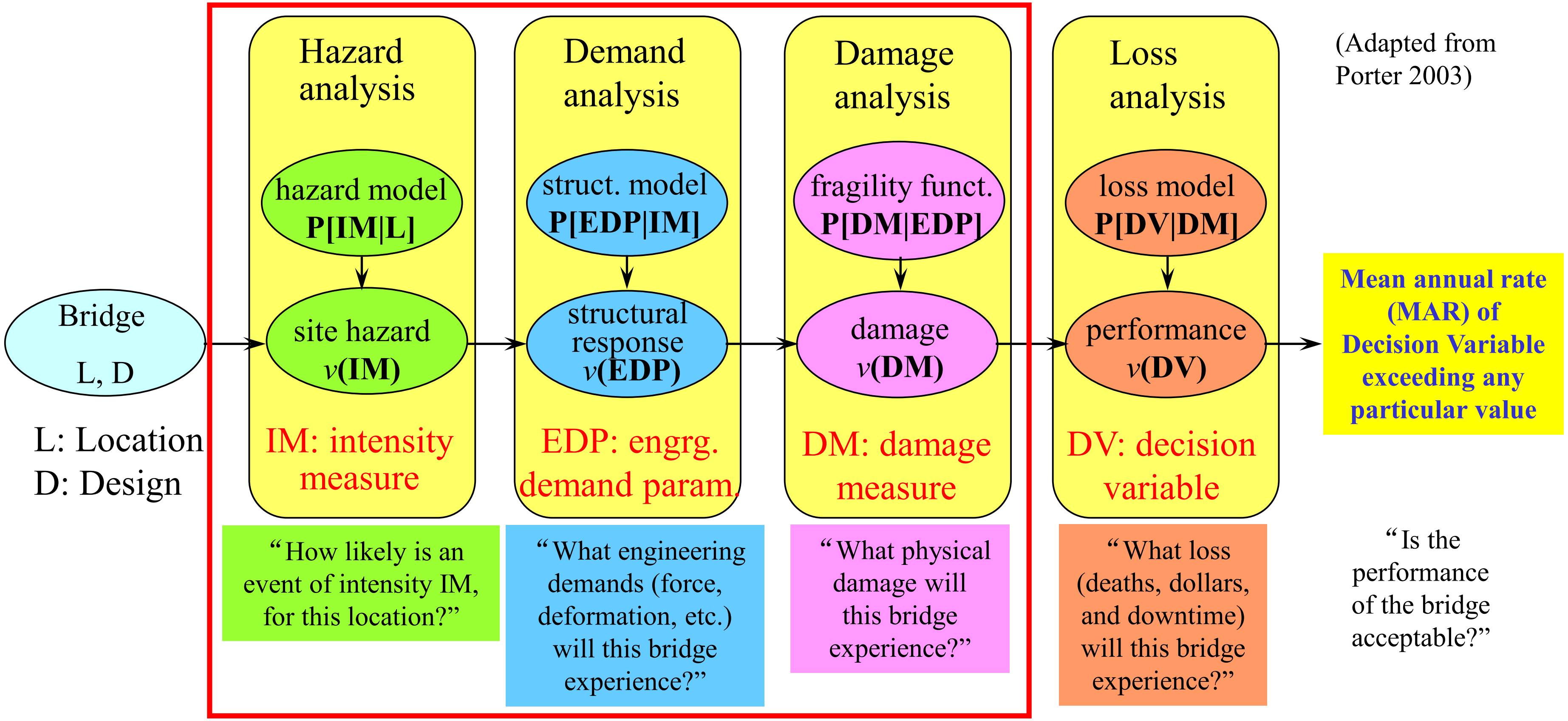


Computational Bridge Models

➢ Schematic Representation of FE Model of Bridge B in OpenSees:



PEER Performance-based Earthquake Engineering Assessment Methodology



$$\therefore \nu_{DV} = \int_{dm}\int_{edp}\int_{im} G_{DV|DM}\left(dv \mid DM = dm\right) \cdot \left| dG_{DM|EDP=edp}\left(dm \mid EDP = edp\right)\right| \cdot \left| dG_{EDP|IM=im}\left(edp \mid IM = im\right)\right| \cdot \left| d\nu_{IM}\left(im\right)\right|$$

$P(X \mid Y)$: Conditional PDF of X given Y

$\nu_X(x)$: Mean annual rate of X exceeding the threshold value x

$G(X \mid Y)$: Conditional complementary CDF of X given Y

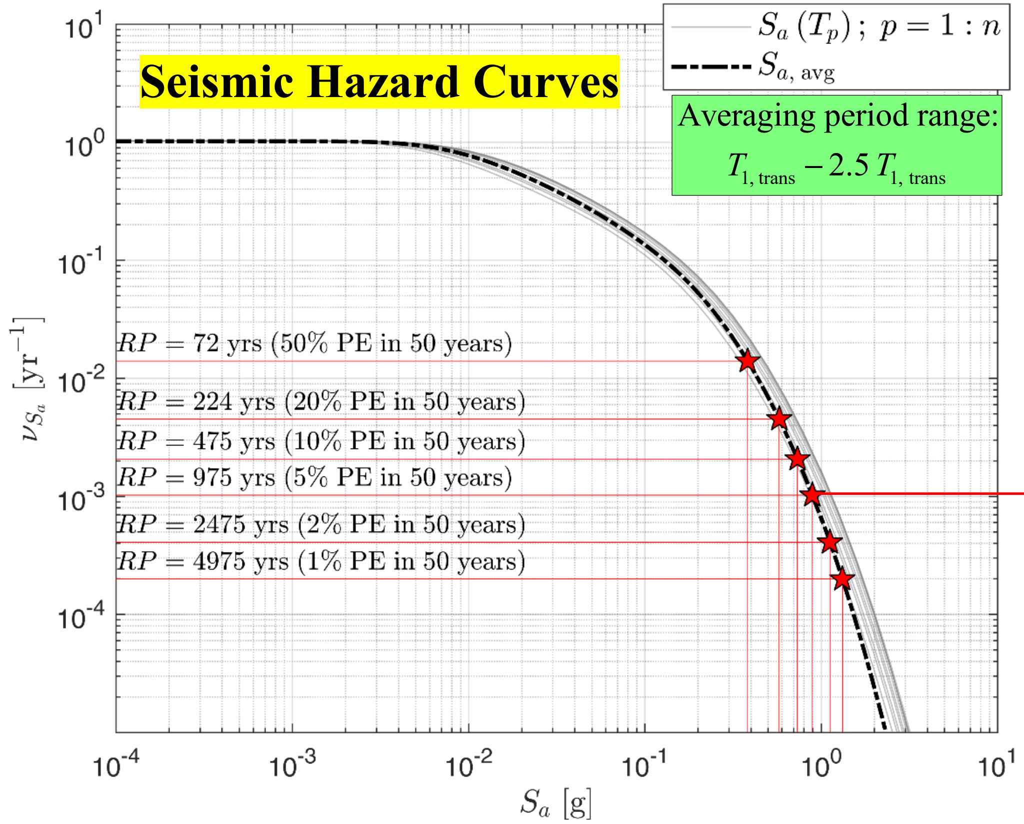
PSHA & Target Spectrum for Earthquake Ground Motion Selection

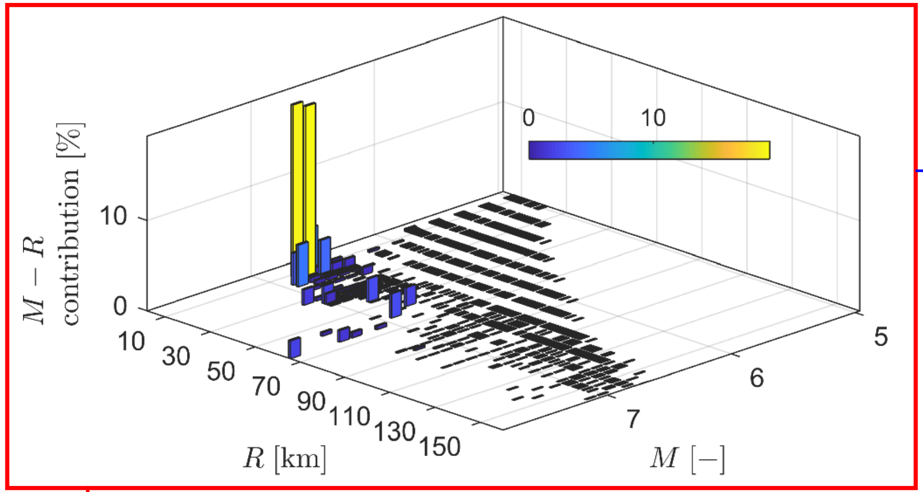
Baker and Cornell (2006)

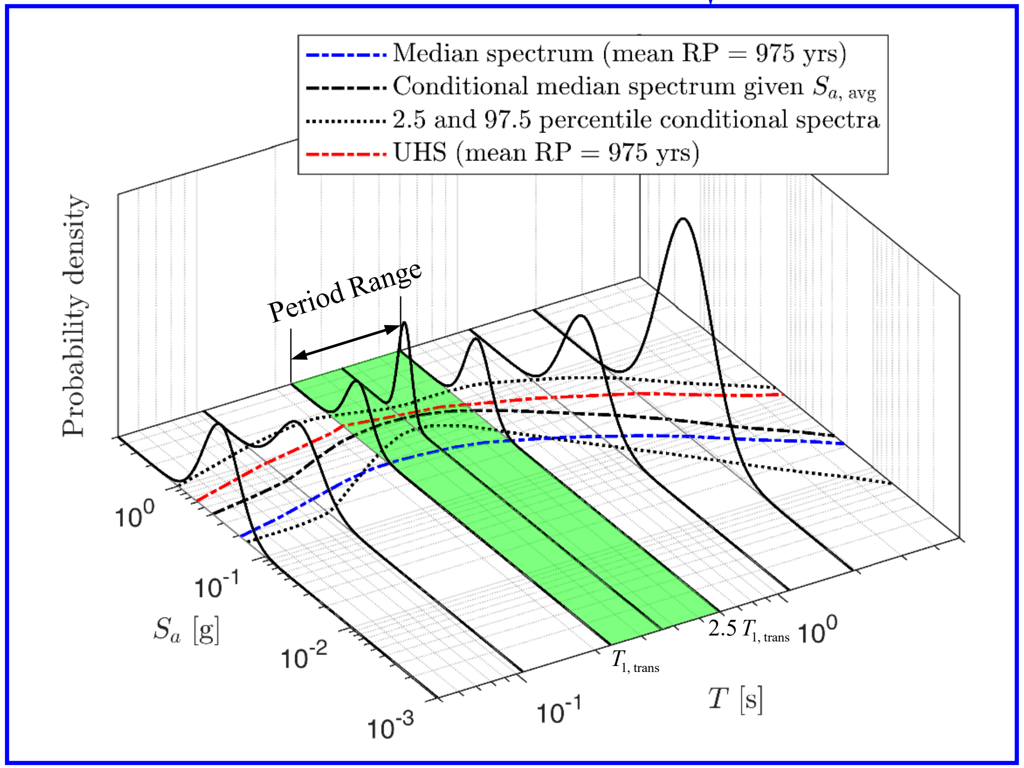
$$IM: \quad S_{a,avg}\left(T_1,\ldots,T_n\right) = \left[\prod_{k=1}^{n} S_a\left(T_k\right)\right]^{1/n}$$

Kohrangi, Bazzurro and Vamvatsikos (2016)

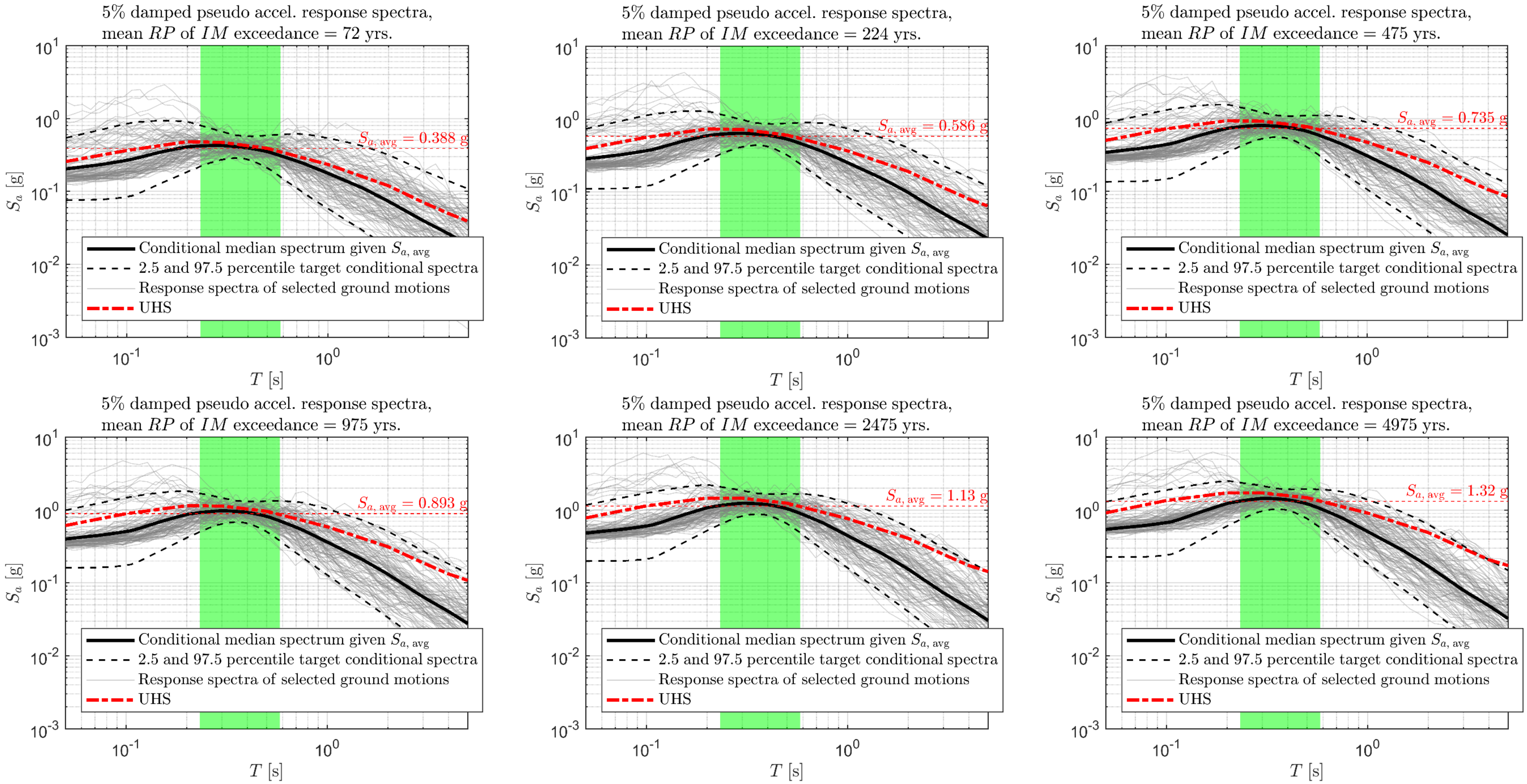
$$\nu_{S_{a,\,\mathrm{avg}}}(x) = \sum_{s=1}^{N_S} \nu_{\mathrm{scenario}_s} \cdot P\left[\underbrace{\left[\prod_{p=1}^{n} S_a\left(T_p\right)\right]^{1/n}}_{S_{a,\,\mathrm{avg}}} > x \,\middle|\, \underbrace{\mathrm{scenario}_s}_{M-R\ \mathrm{bin}}\right]$$







Selection of Ensembles of Site-specific Risk-consistent Ground Motion Records



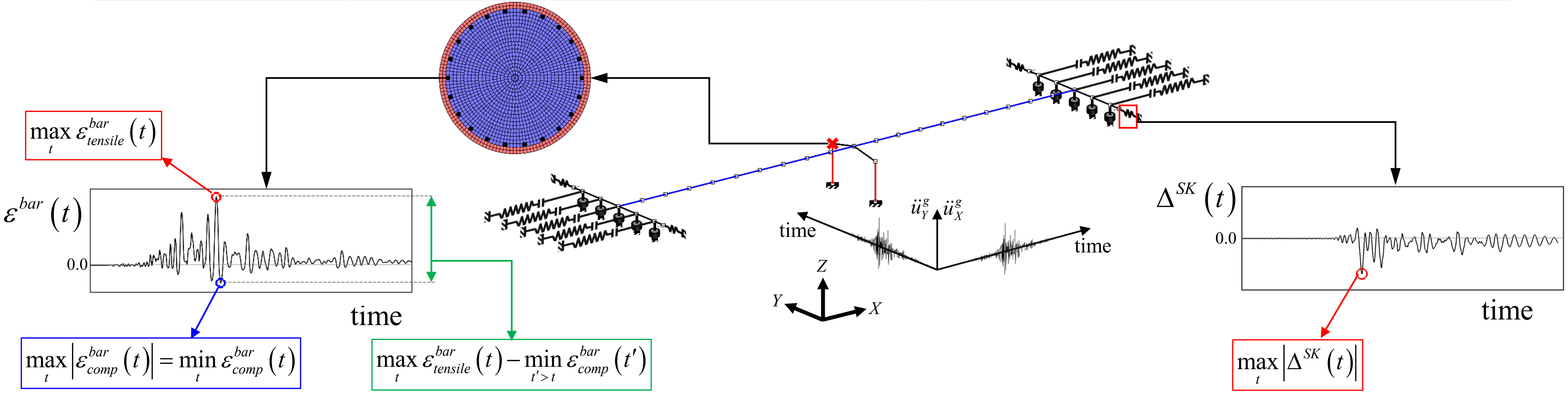
Refs.: Baker and Jayaram (2011)
Kohrangi, Bazzurro, Vamvatsikos, and Spillatura (2017)

Definition of Limit-States and Associated Engineering Demand Parameters

Limit-state (LS)	Associated Engineering Demand Parameter (EDP)	
Concrete cover crushing (LS	Maximum absolute compressive strain of any	$EDP_1 = \max\left(\max\left(\max\left|\varepsilon^{bar}\ (t)\right|\right)\right)$
Longitudinal buckling (LS		
Longitudinal fracture (LS_3)	former, of any longitudinal rebar in any column	$\varepsilon^{bar}_{comp}(t')\big)\big)$
Shear key damage (LS_4)	Maximum horizontal displacement of any shear key normalized by the displacement at peak strength.	$EDP_4 = \max\limits_{SK}\left(\max\limits_{t}\left|\Delta^{SK}(t)\right|\right)$

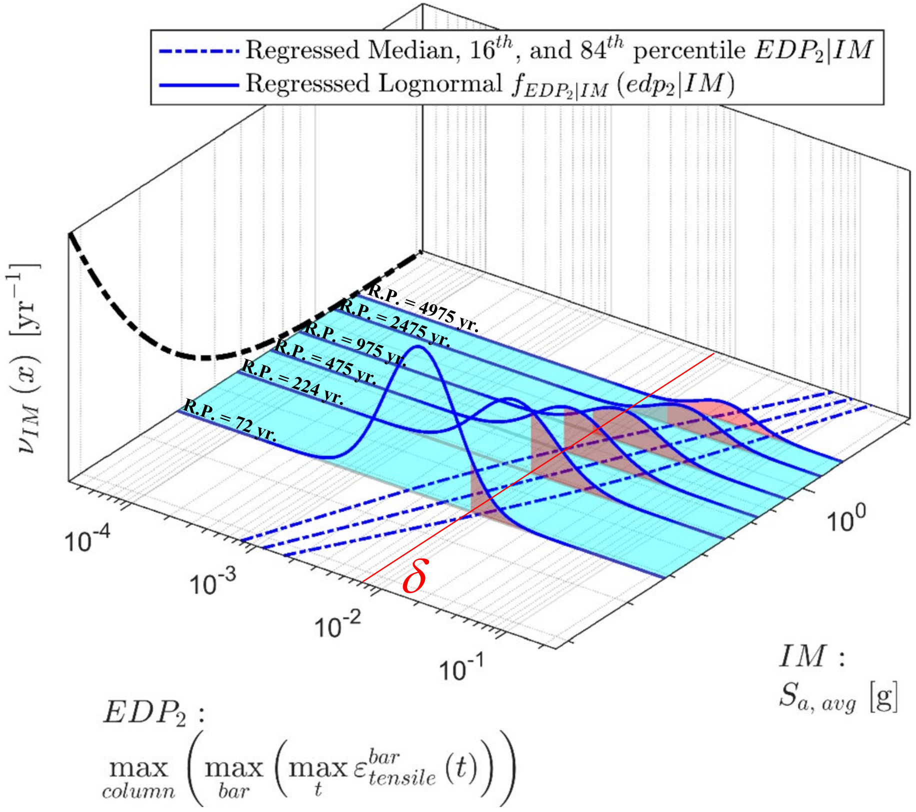
"Structural displacements, which can be directly related to damage potential through material strains (structural damage)… , are [currently] checked through coarse and unreliable methods…"

- Nigel Priestley, 2007

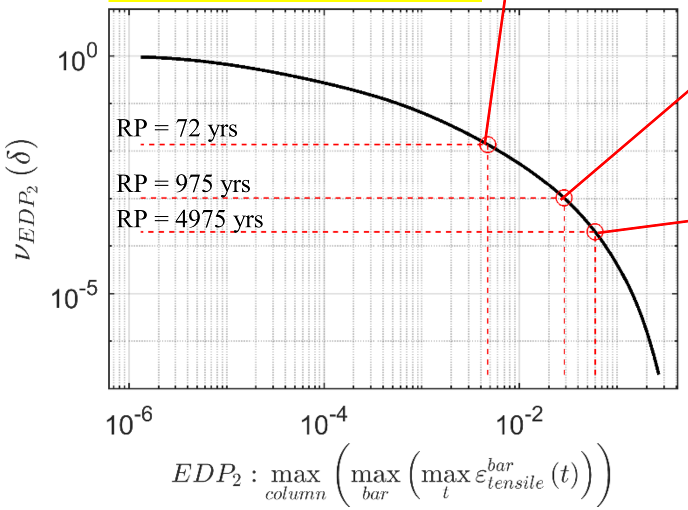


Probabilistic Seismic Demand Hazard Analysis

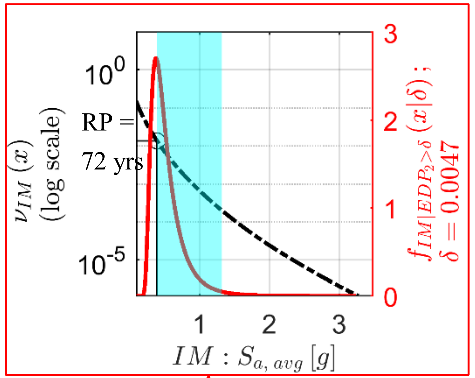
$$\nu_{EDP_k}(\delta) = \int_{IM} P\left[EDP_k > \delta \mid IM = x\right] \cdot \underbrace{\left| d\nu_{IM}(x) \right|}_{\left| \nu_{IM}(x+dx) - \nu_{IM}(x) \right|}$$

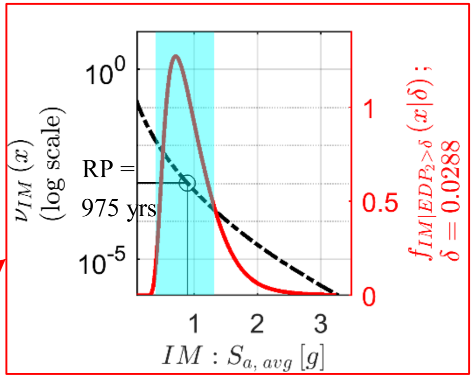


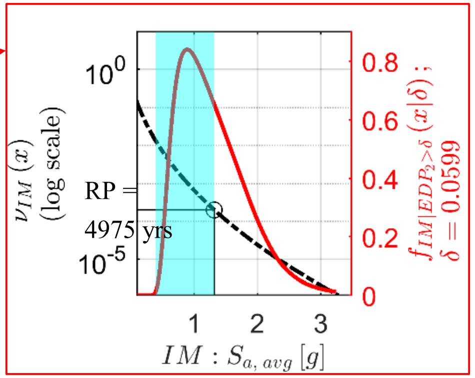
Demand Hazard Curve



***IM* Deaggregation of Demand Hazard**







Probabilistic Seismic Demand and Capacity

Probability density function of EDP_k :

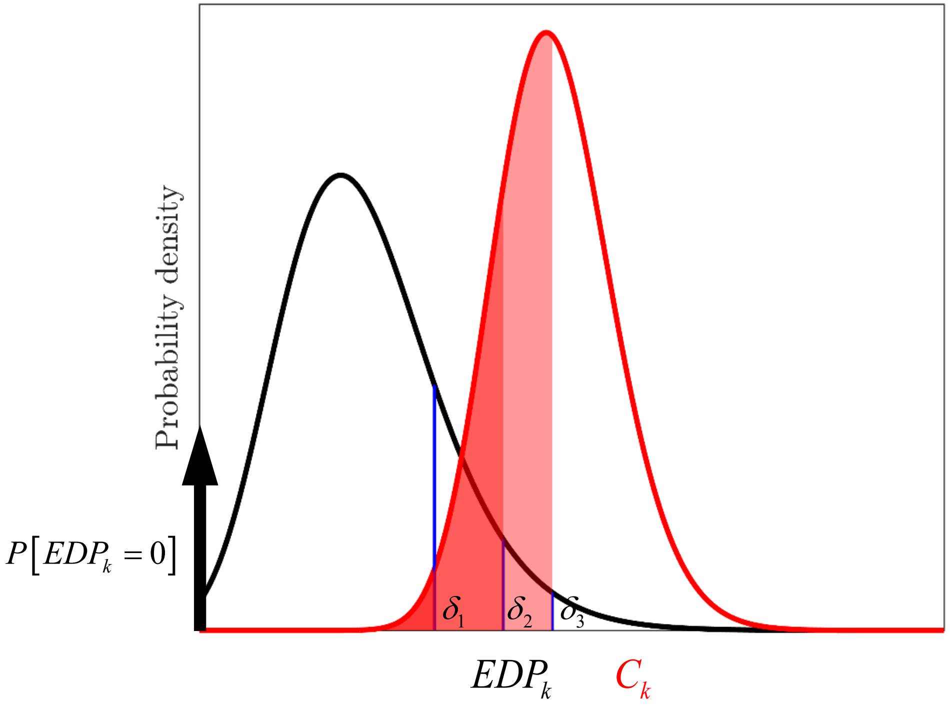
$$f_{EDP_k}(\delta) = \frac{d}{d\delta}\left(\underbrace{1 - \frac{\nu_{EDP_k}(\delta)}{\nu_{IM}(x=0)}}_{F_{EDP_k}(\delta)} \right)$$

Probability of LS exceedance :

For k^{th} limit-state,

$P[LS \text{ exceedance}] = P[C_k < EDP_k]$

$$= \int_{\delta} \underbrace{P[C_k < EDP_k \mid EDP_k = \delta]}_{\textbf{Fragility Function}} \cdot f_{EDP_k}(\delta) \cdot d\delta$$



Experimental/Numerical Data Sources for Construction of Fragility Functions

Sources	Specimen scale	Specimens	Limit-state
Schoettler, Restrepo, Guerrini and Duck (2015)	full scale	1 single column bridge bent (dynamic test)	2
Barbosa, Link, and Trejo (2014)	half scale	6 column specimens with Grade 60 and Grade 80 steel	1
Goodnight, Kowalsky and Nau (2015)	half scale	23 column specimens of varying dimensions and reinforcement	1, 2
Murcia-Delso, Shing, Stavridis, and Liu (2013)	full scale	4 column specimens embedded in enlarged shafts	1, 2
Duck, Carreño, and Restrepo (2018)	FE model	36 numerical models of column reinforcement cages with varying parameters	3
Megally, Silva, and Seible (2002)	$2/5^{th}$ scale	4 non-isolated exterior shear key specimens	4
Bozorgzadeh, Megally, Ashford, and Restrepo (2007)	$2/5^{th}$ scale	1 isolated exterior shear key specimen	4

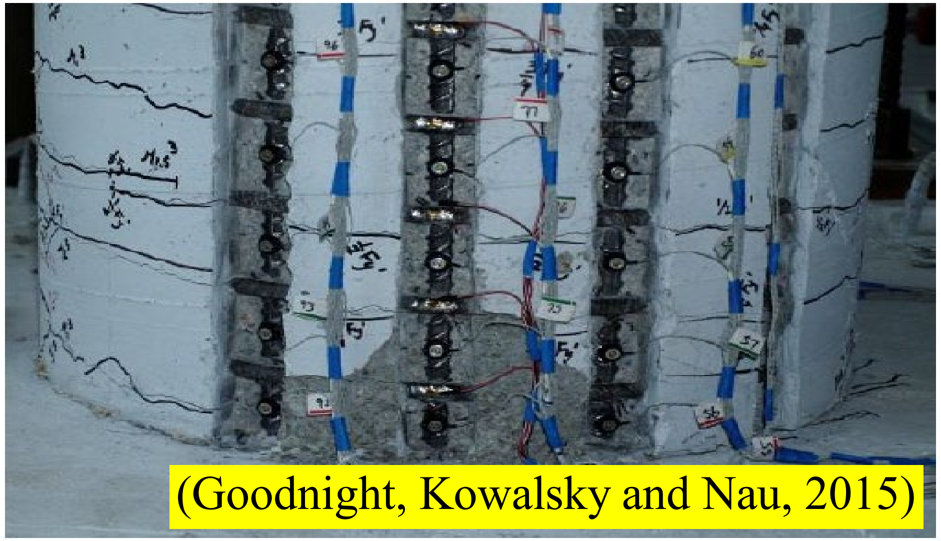
Limit-States: Limit State – 1 (Strain-based)

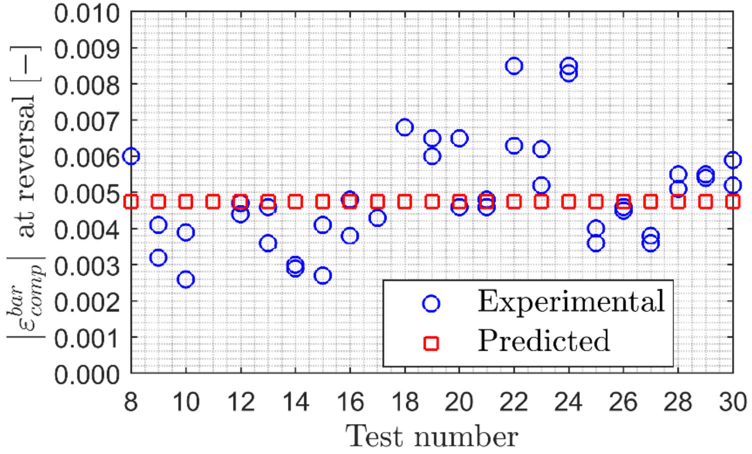
➢ Concrete cover crushing:

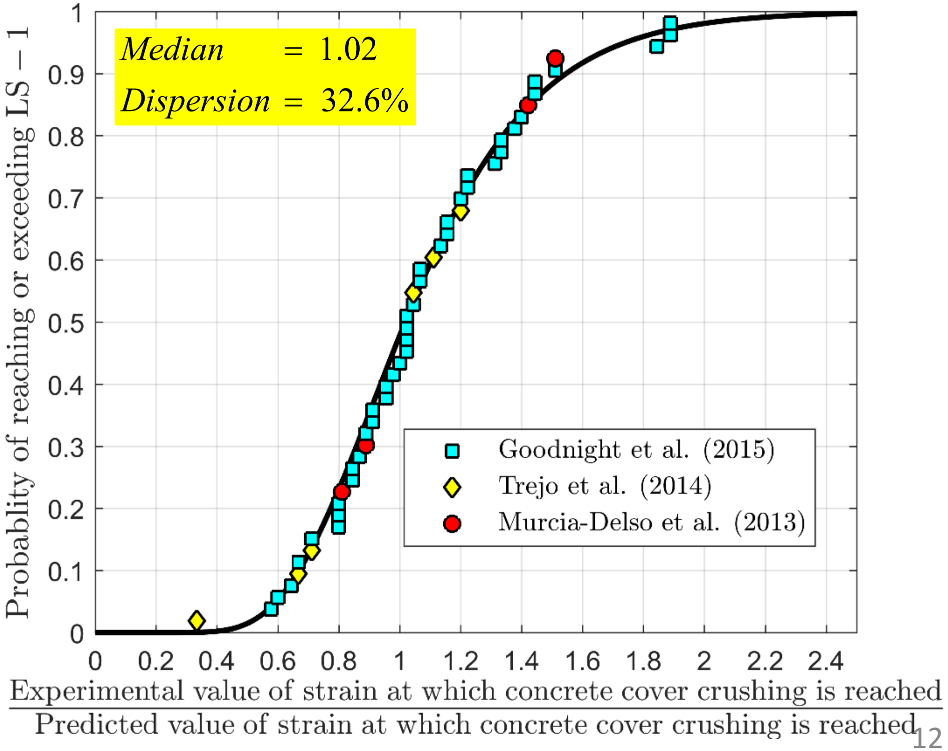
Predictive Capacity Model:

$$EDP_{C_1}^{\text{PRED}} = \varepsilon_{comp}^{bar} = 0.00475$$

(Goodnight, Kowalsky and Nau, 2015)







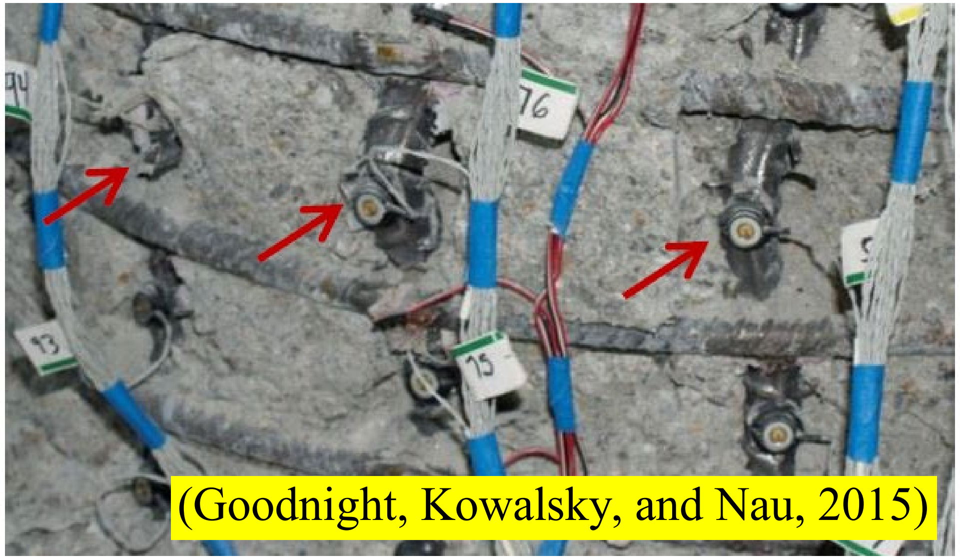
Limit-States: Limit State – 2 (Strain-based)

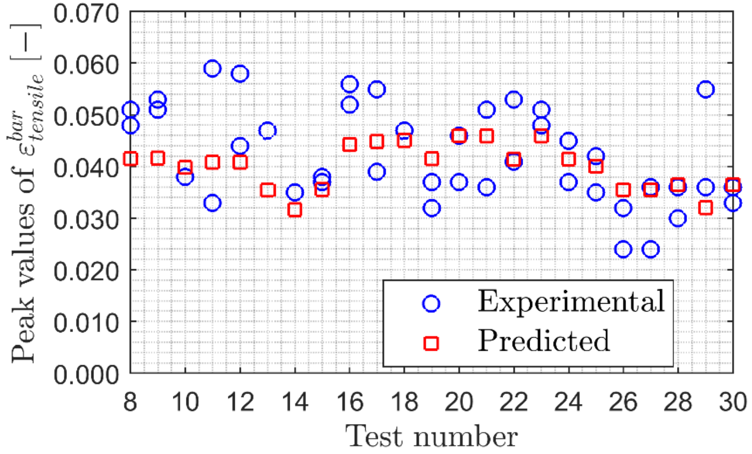
➢ Longitudinal rebar buckling (a precursor):

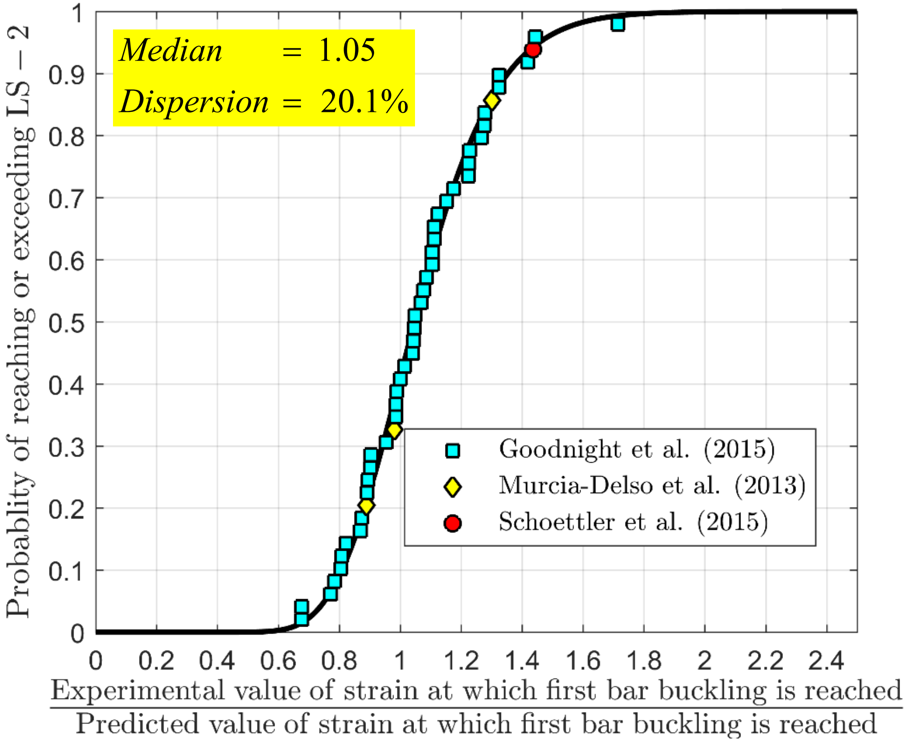
Predictive Capacity Model:

$$EDP_{C_2}^{\text{PRED}} = \varepsilon_{tensile}^{bar} = 0.03 + 700\rho_s \frac{f_{yhe}}{E_s} - 0.1\frac{P}{f'_{ce}A_g}$$

(Goodnight, Kowalsky and Nau, 2015)







Limit-States: Limit State – 3 (Strain-based)

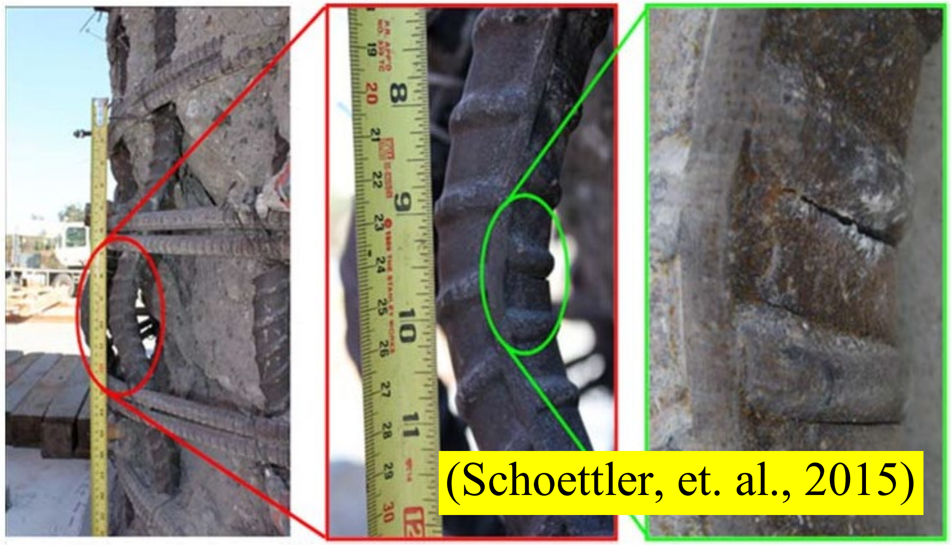
➢ Longitudinal rebar fracture (a precursor):

Predictive Capacity Model (mechanics-based):

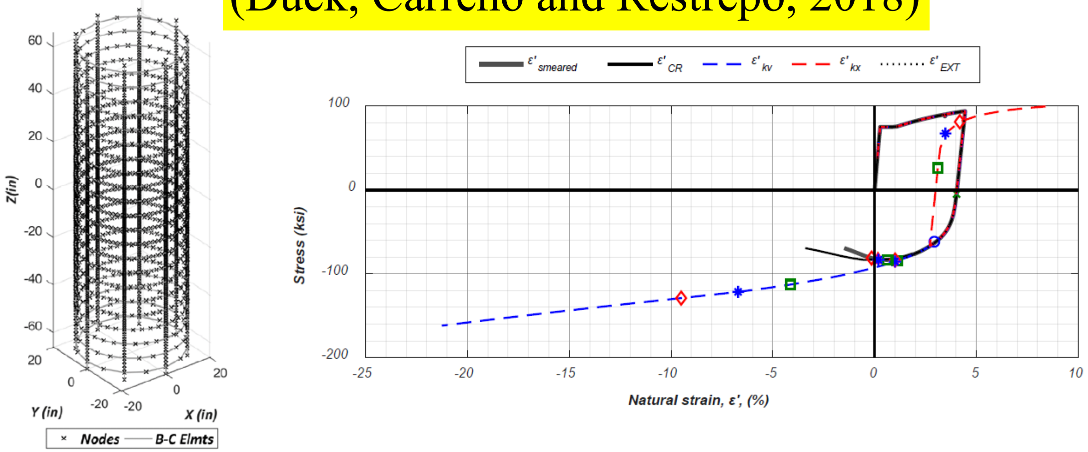
$$EDP_{C_2}^{\mathrm{PRED}} = \max_{t} \varepsilon_{tensile}^{bar}(t) - \min_{t'>t} \varepsilon_{comp}^{bar}(t') =$$

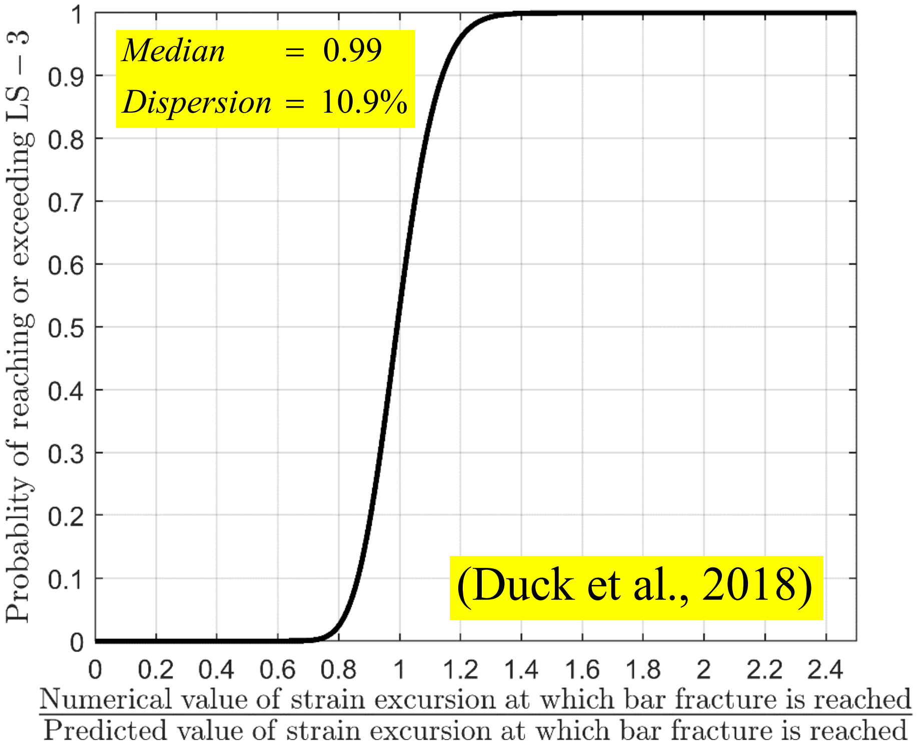
$$= \underbrace{0.11 + \min(0.054, 0.032\rho_s(\%)) - 0.0175\left|\sqrt[3]{n_{bar}} - 2.93\right| - 0.054\frac{T}{Y}}_{\Delta\varepsilon_{VK}}$$

(Duck, Carreño, and Restrepo, 2018)



(Duck, Carreño and Restrepo, 2018)





Parametric Probabilistic Seismic Performance Assessment

- Design variables & primary design parameter space
- Full-blown parametric risk-targeted seismic performance assessment and results
- Feasible design domains

Design Variables, Constraints and Primary Design Parameter Space

Primary design variables:

1. Column diameter $\left(D_{col}\right)$

2. Column longitudinal reinforcement ratio $\left(\rho_{long.}\right)$

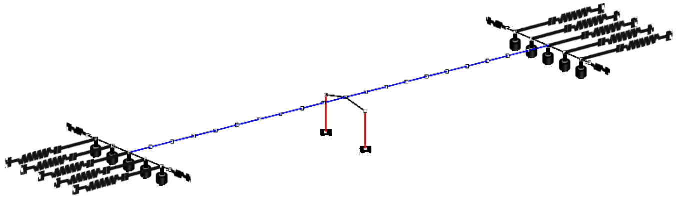
subject to: $1\% \leq \rho_{long.} \leq 3\%$

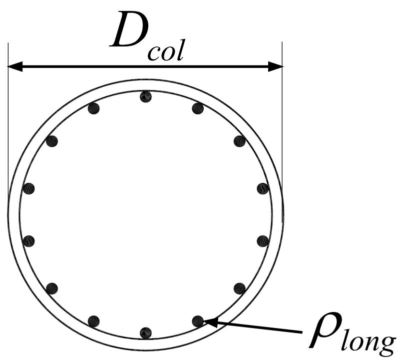
and	$D_{col} = 4 - 6$ ft	for 4 column bents
	$D_{col} = 5 - 8$ ft	for 3 column bents
	$D_{col} = 5 - 8$ ft	for 2 column bents
	$D_{col} = 5 - 8$ ft	for 1 column bent

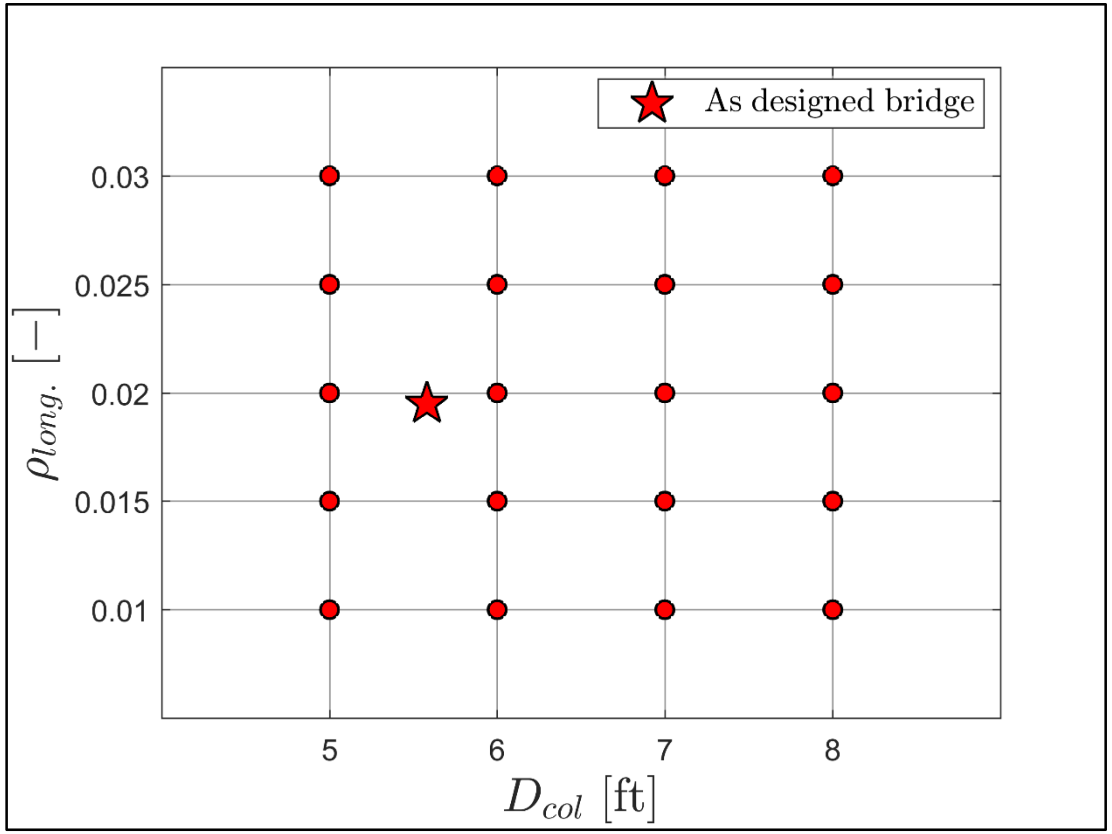
Secondary design variables / components:

1. Column transverse reinforcement ratio $\left(\rho_{trans.}\right)$
2. Bridge deck
3. Bridge abutments
4. Foundations (piles and pile caps)

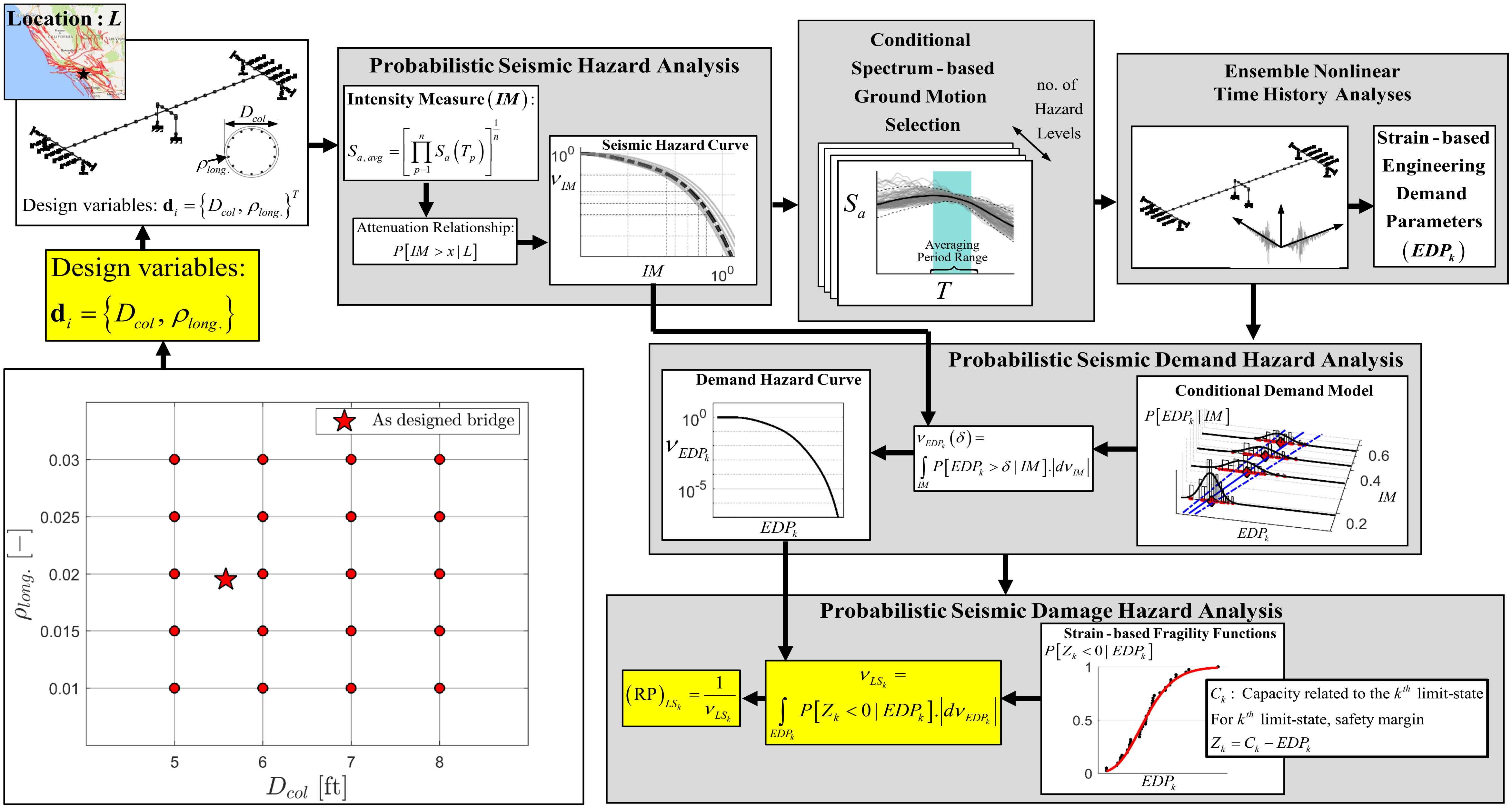
to be capacity protected against other (undesirable) failure modes



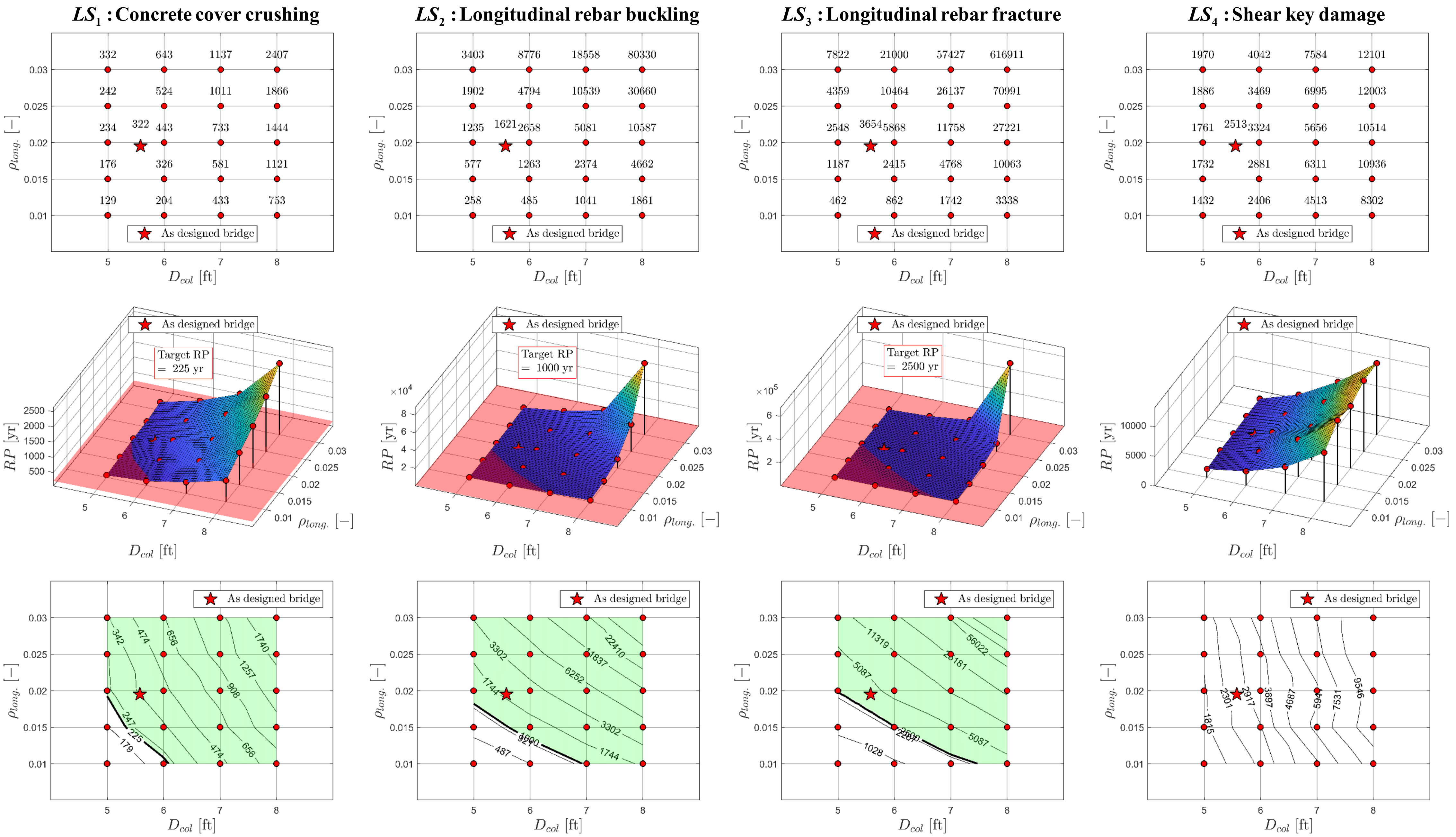




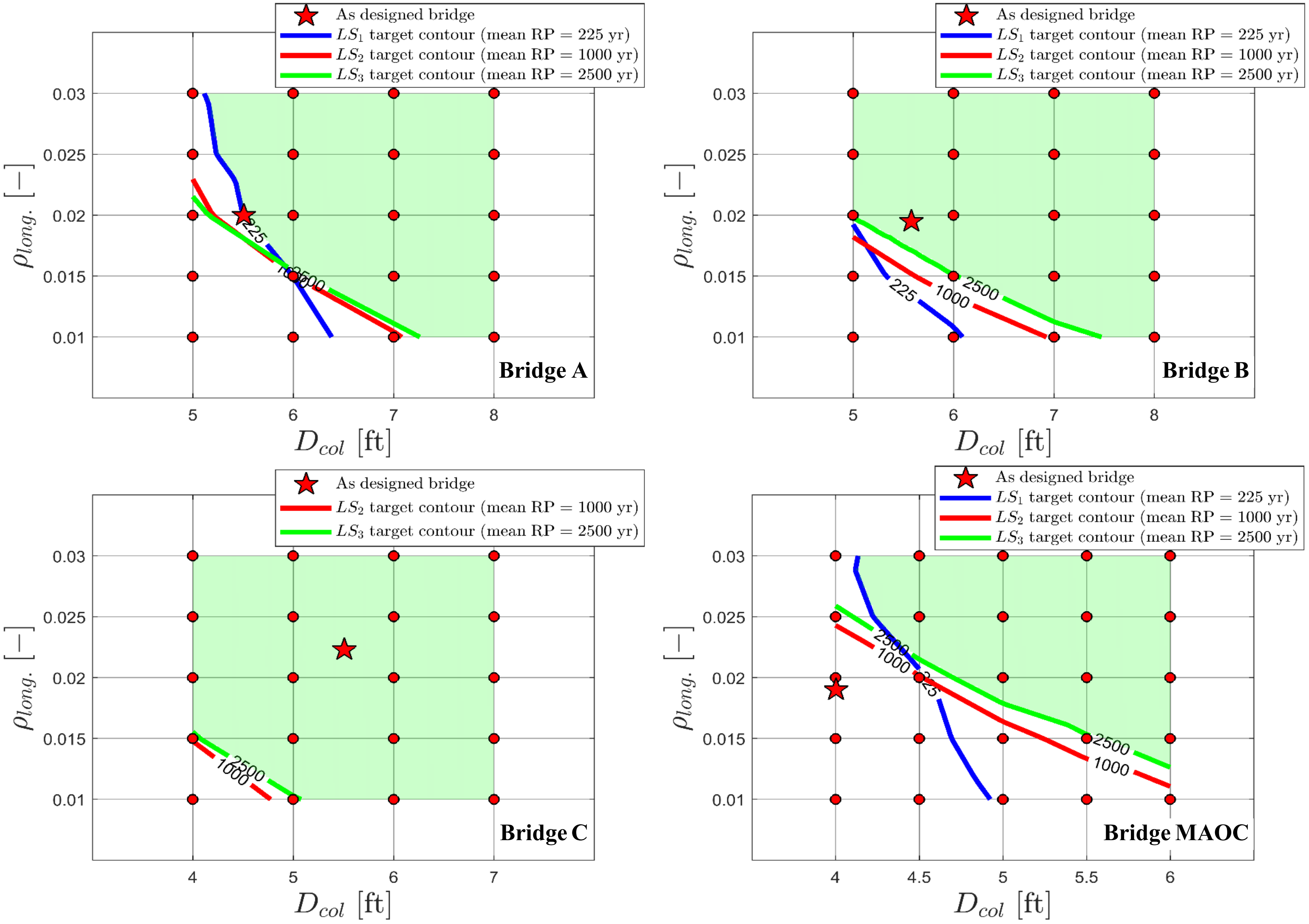
Overall Workflow for Full-blown Parametric Risk-Targeted Seismic Performance Assessment



Results of Full-blown Parametric Risk-Targeted Seismic Performance Assessment



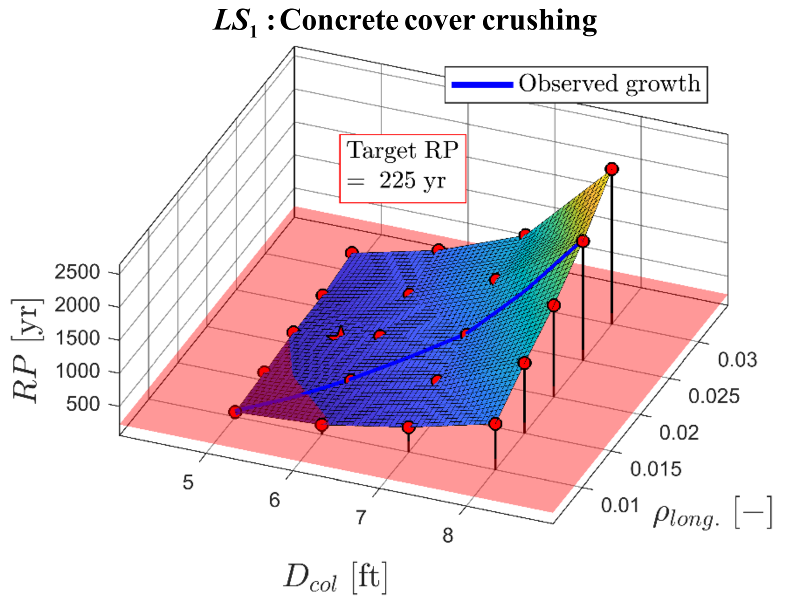
Results of Full-blown Parametric Risk-Targeted Seismic Performance Assessment: Feasible Design Domains

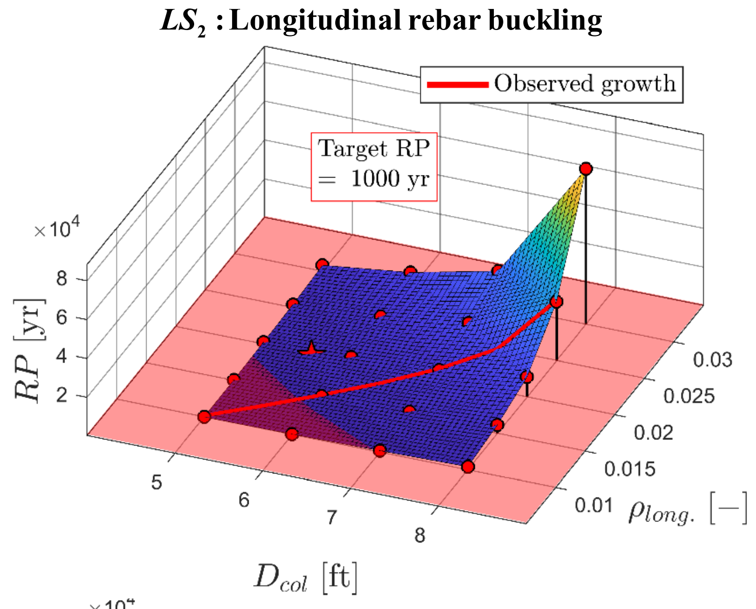


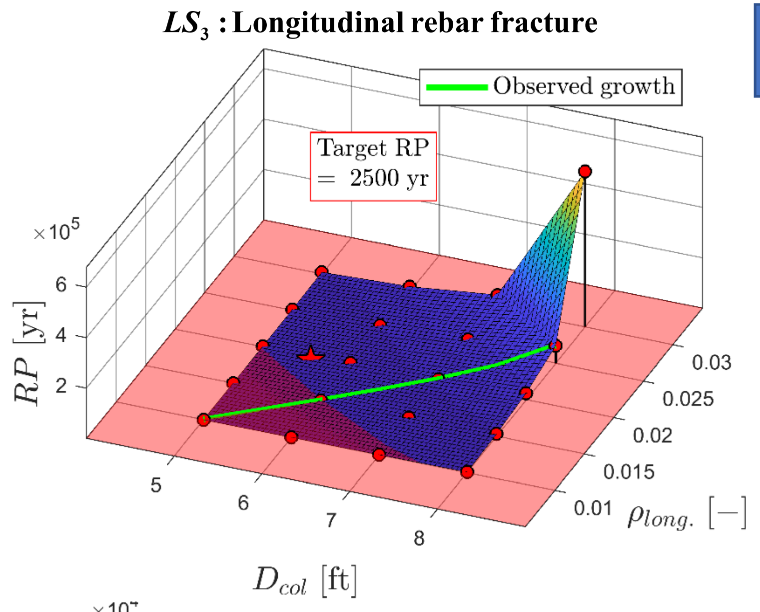
Development of Simplified Risk-targeted PBSD Method

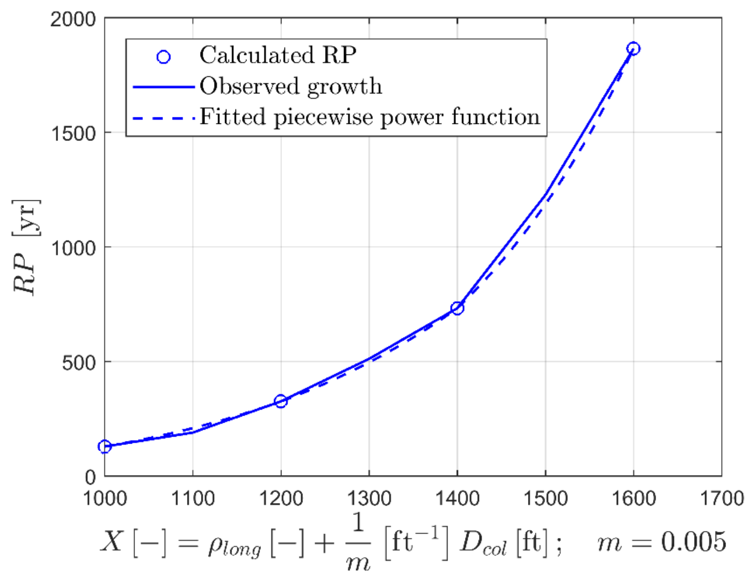
- Obtaining a design point satisfying multiple risk-based objectives
- Approximation of feasible design domain
- Reduction in computational workload

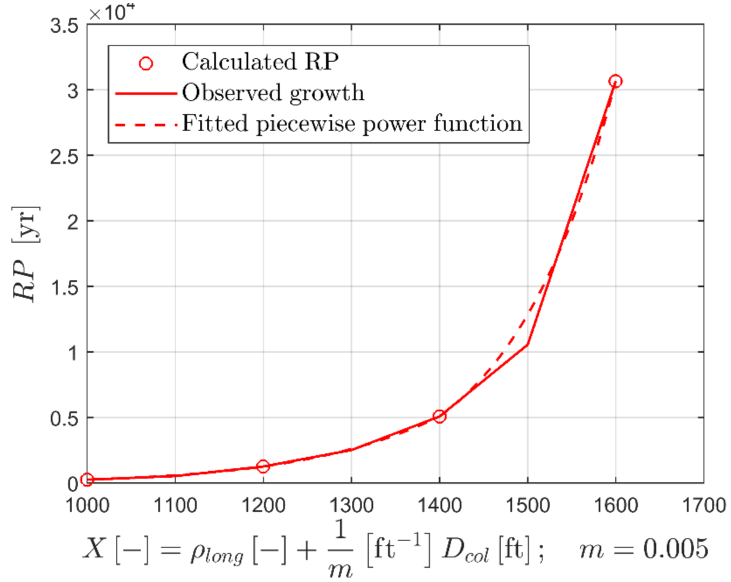
Development of Simplified Risk-Targeted PBSD Procedure: Topology of Mean RP Surfaces

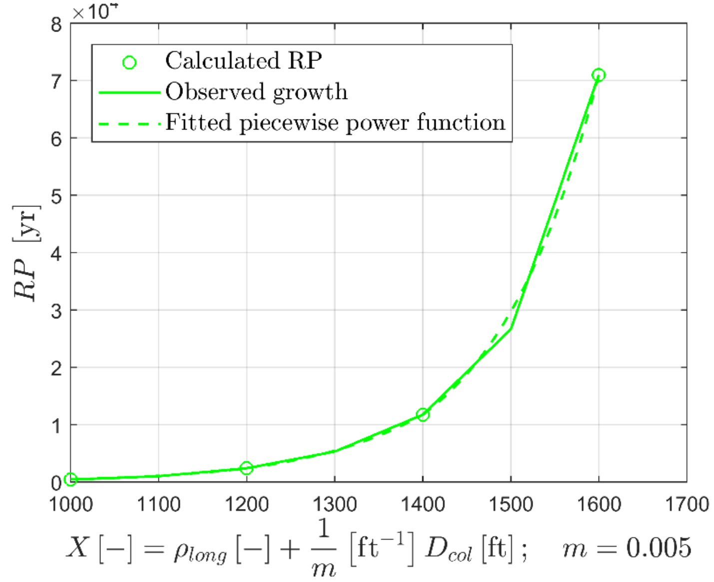








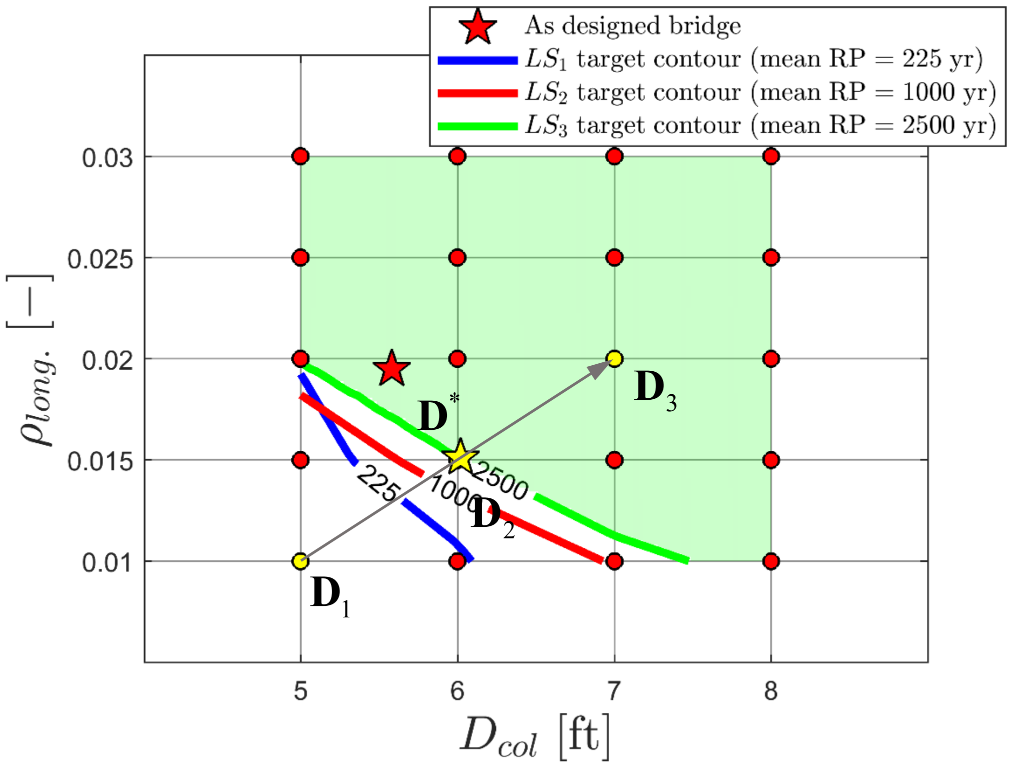




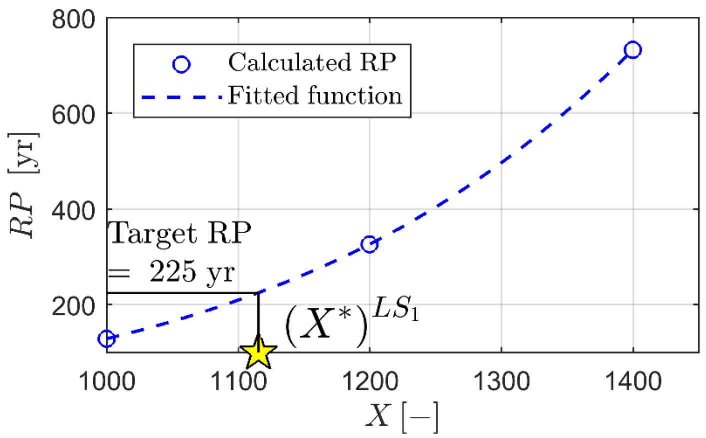
Development of Simplified Risk-Targeted PBSD Procedure: Finding a Design Point along a Positive Gradient Line

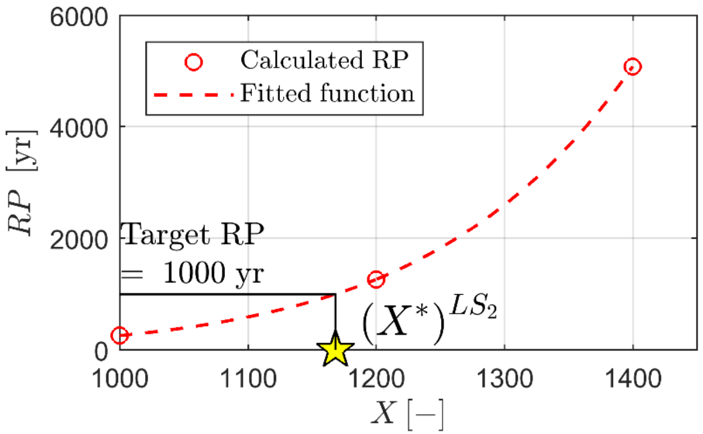
Equation of positive gradient line:

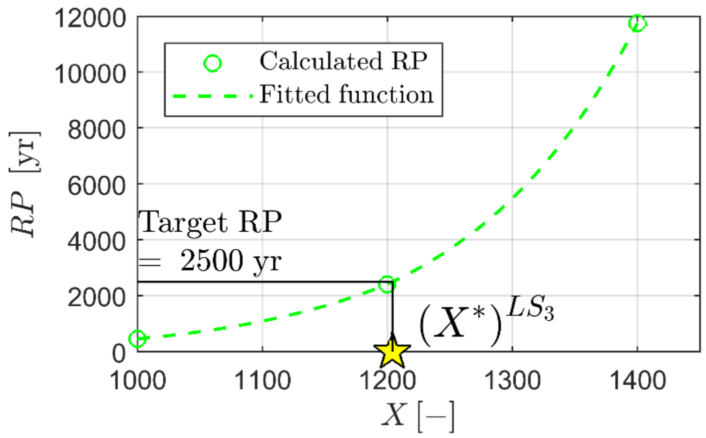
$$\rho_{long}[-] = m\left[\mathrm{ft}^{-1}\right]\cdot D_{col}[\mathrm{ft}] + \alpha[-]$$



$$\mathbf{D}^* = \begin{bmatrix} D^*_{col}[\mathrm{ft}] \\ \rho^*_{long}[-] \end{bmatrix} = \begin{bmatrix} \frac{1}{m}\left[\mathrm{ft}^{-1}\right] & 1[-] \\ -m\left[\mathrm{ft}^{-1}\right] & 1[-] \end{bmatrix}^{-1} \begin{bmatrix} X^*[-] \\ \alpha[-] \end{bmatrix}$$





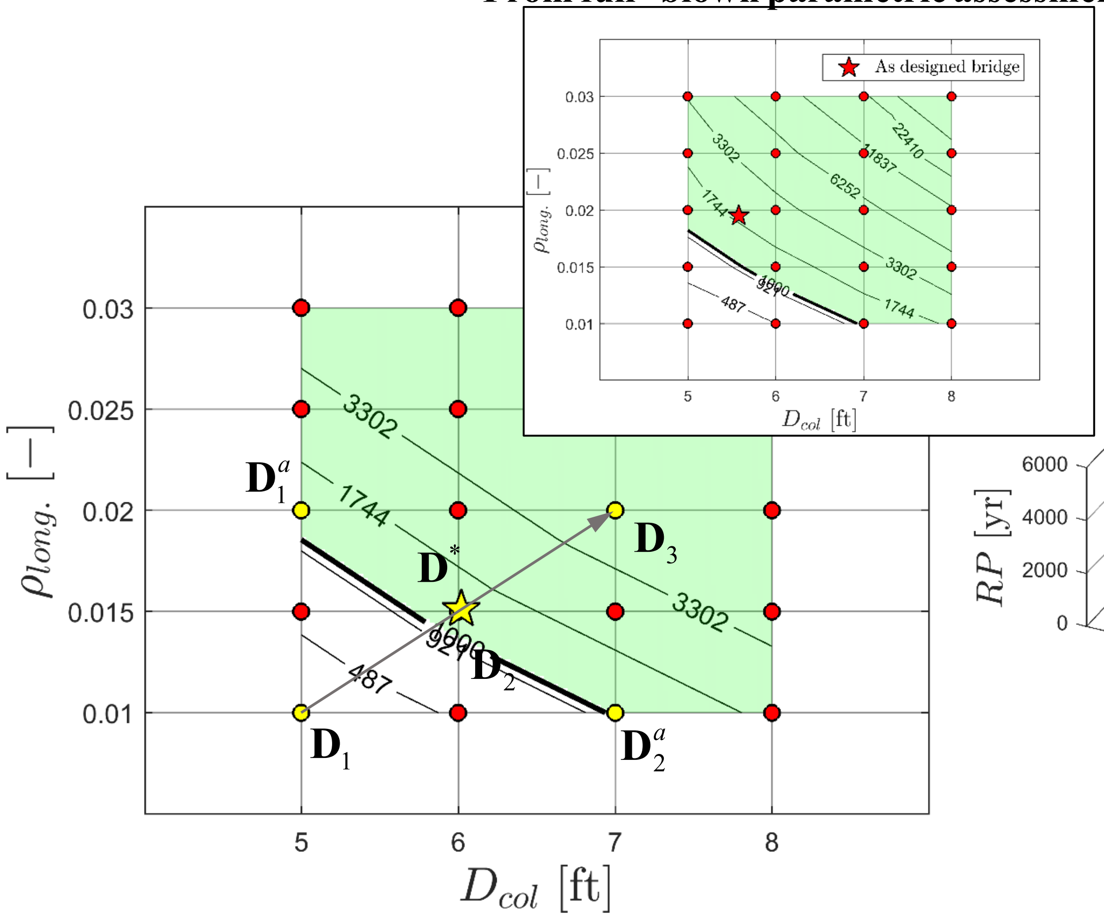


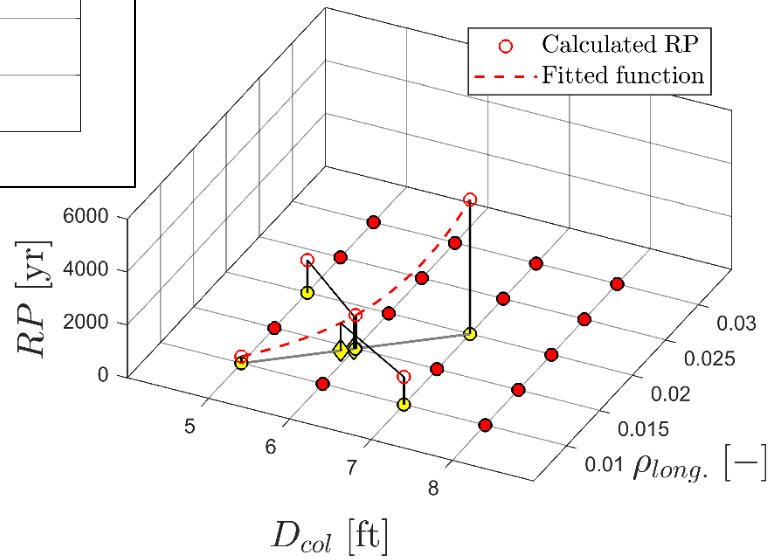
$$X = \rho_{long}[-] + \frac{1}{m}\left[\mathrm{ft}^{-1}\right] D_{col}[\mathrm{ft}]$$

$$X^* = \max\left((X^*)^{LS_1}, \cdots, (X^*)^{LS_n}\right)$$

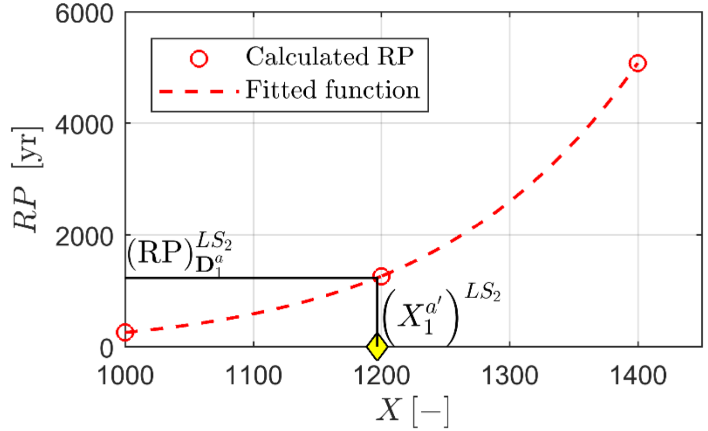
Development of Simplified Risk-Targeted PBSD Procedure: (Bi)Linear Approximation of Contour Lines

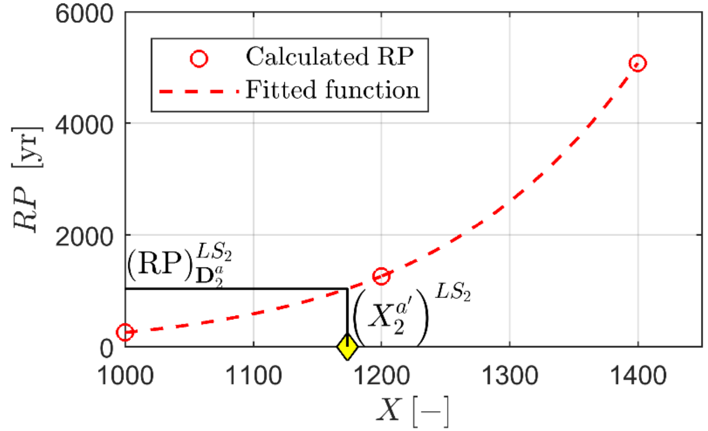
From full - blown parametric assessment



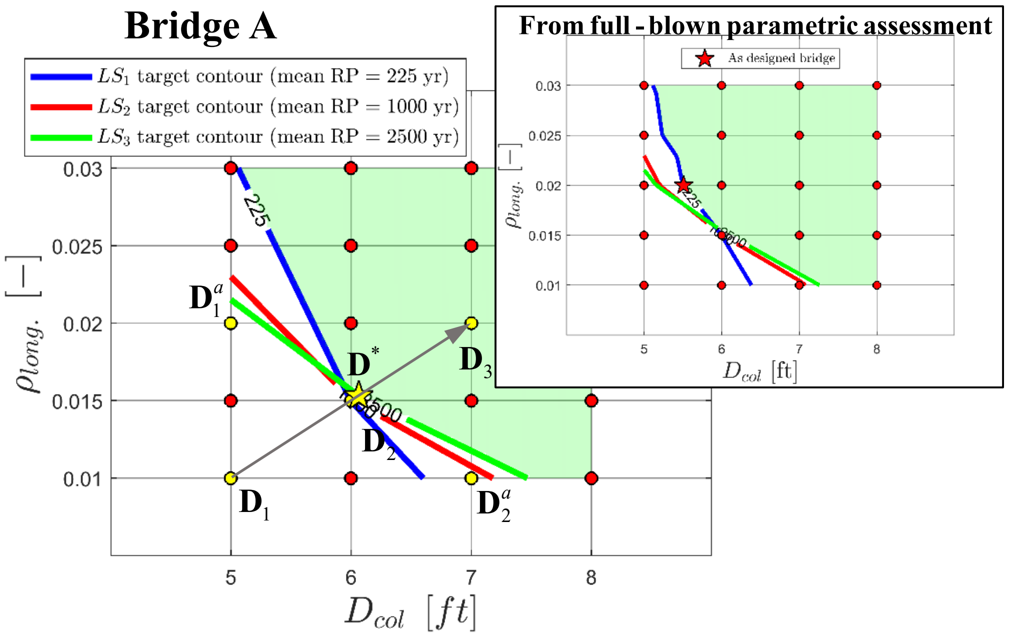


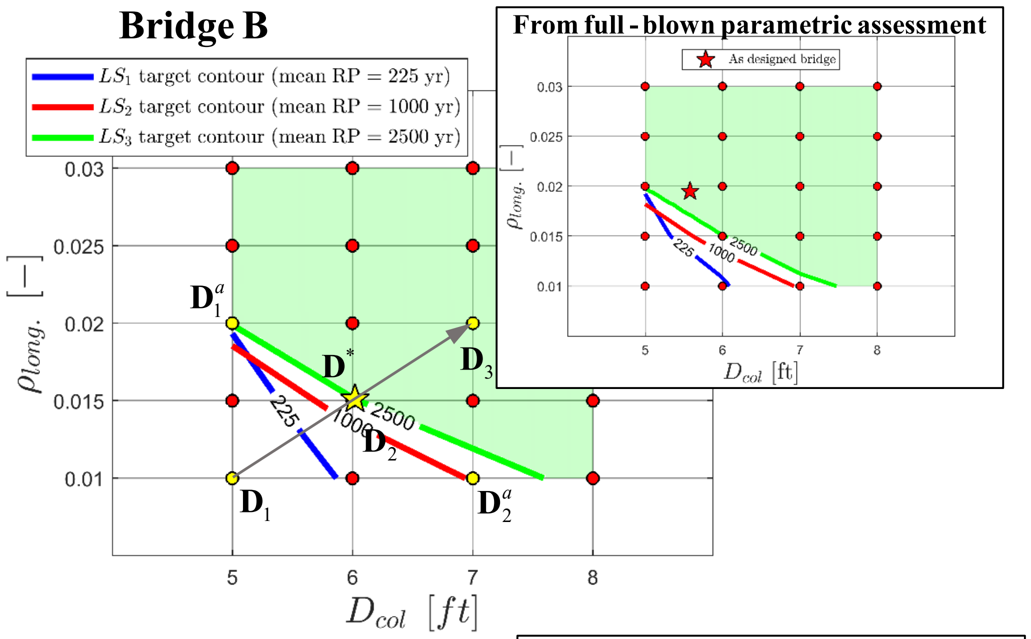
Consider LS_2

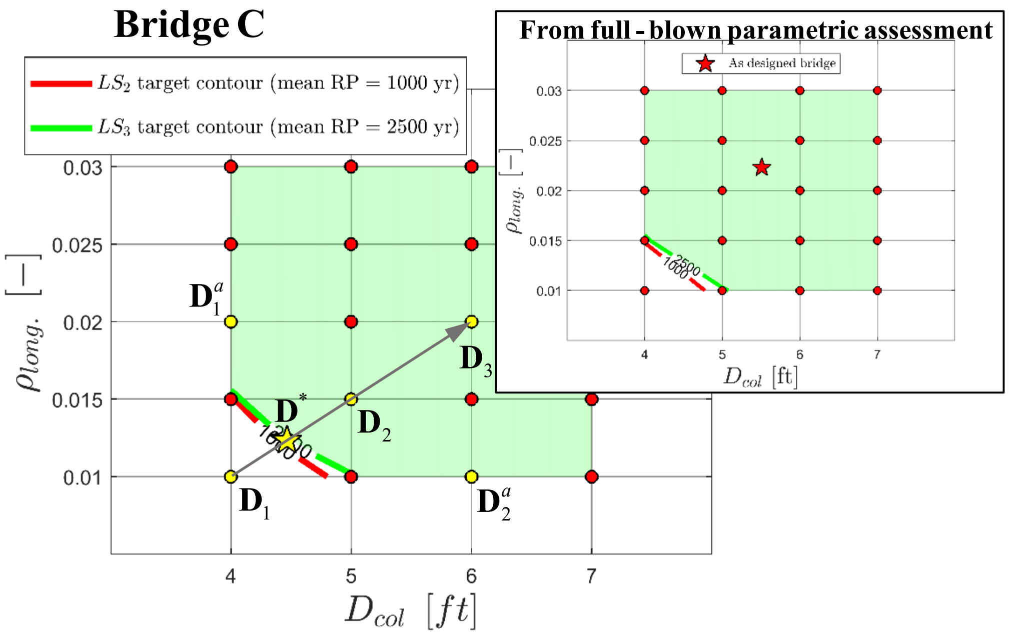


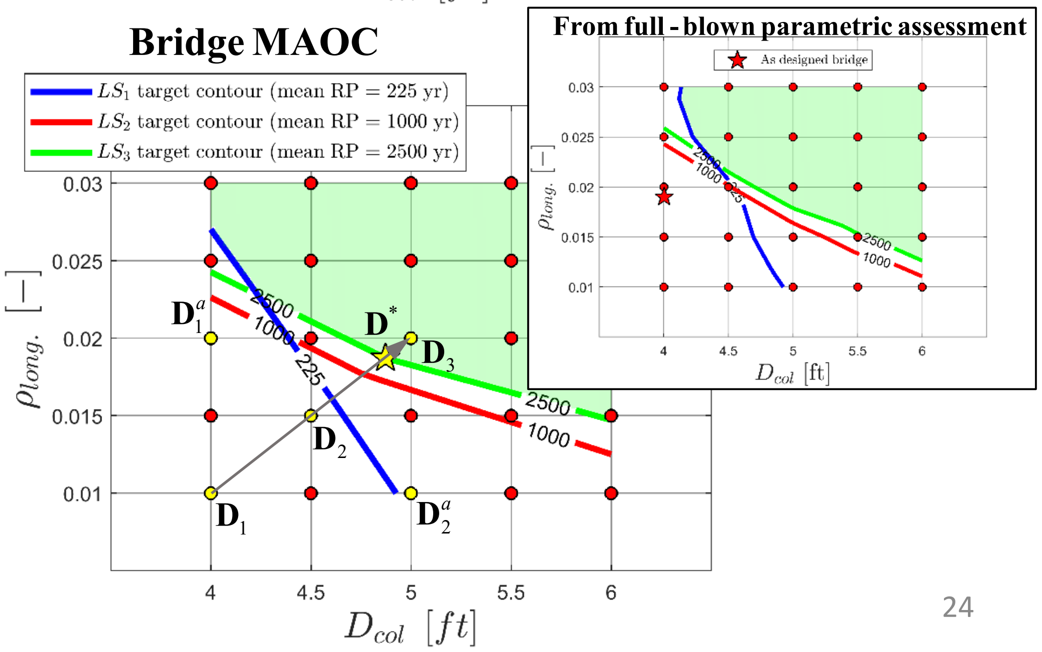


Development of Simplified Risk-Targeted PBSD Procedure: Approximate Feasible Design Domains

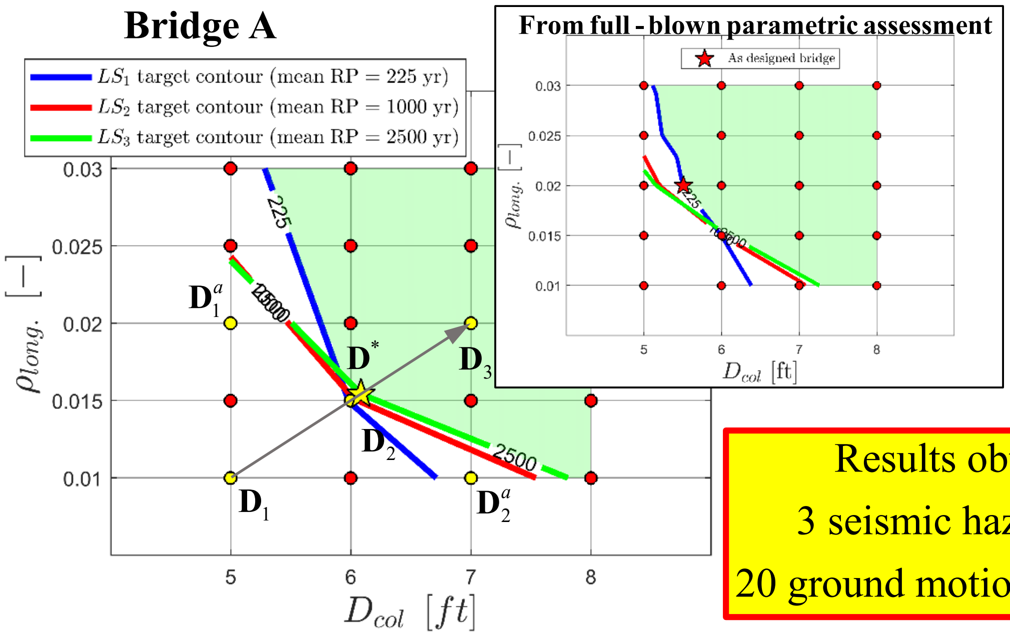


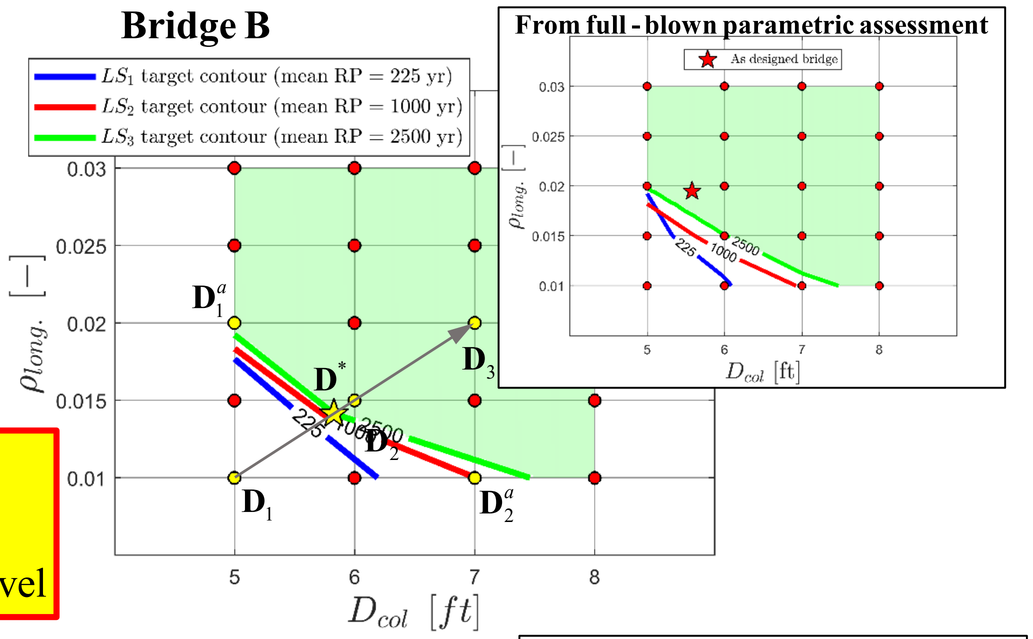




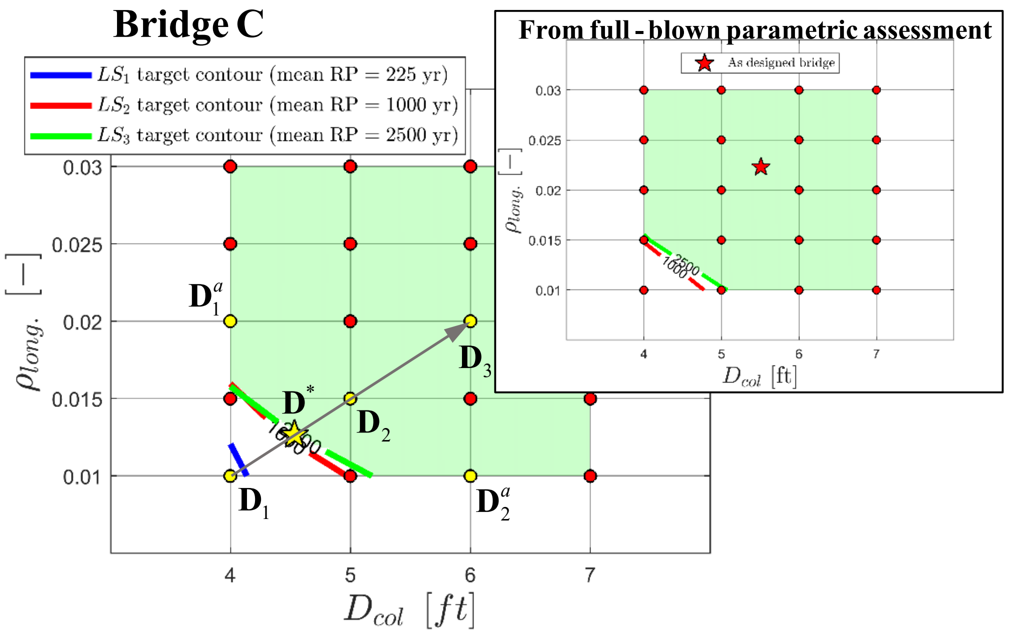


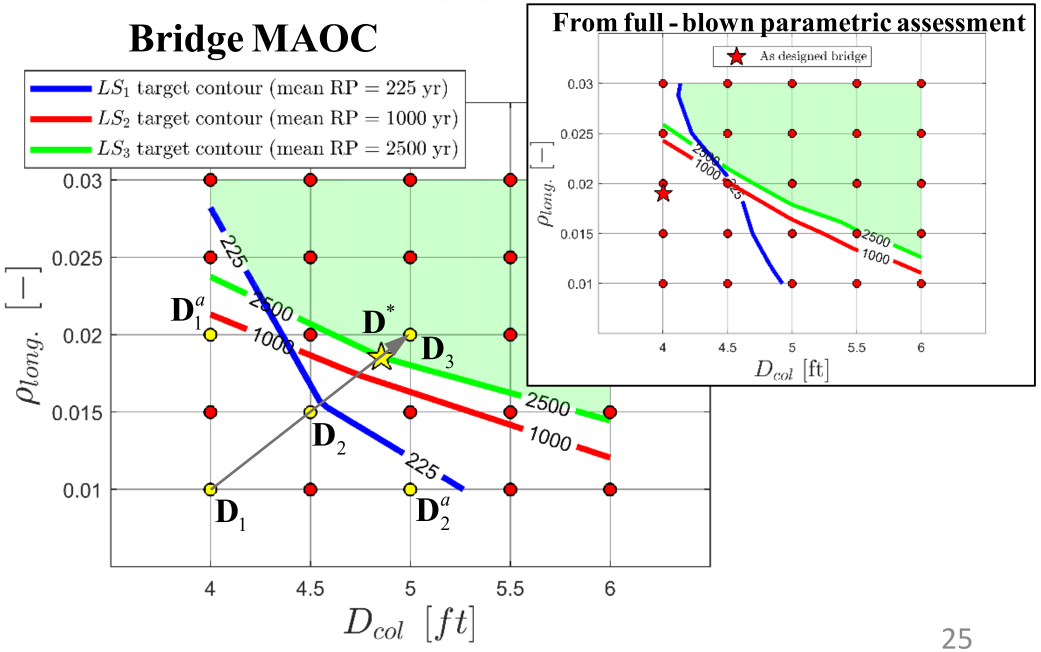
Development of Simplified Risk-Targeted PBSD Procedure: Reduction in Computational Workload





Results obtained using
3 seismic hazard levels and
20 ground motions per hazard level





Conclusions & Future Research Needs

Concluding Remarks

- **Full-fledged probabilistic performance assessment of four Ordinary Standard Bridge (OSB) Testbeds in California using improved version of the PEER PBEE framework.**
  - ✓ **Improved IM.**
  - ✓ **Seismic hazard curve for improved IM.**
  - ✓ **Conditional mean spectrum-based, site-specific, hazard/risk-consistent ground motion selection.**
  - ✓ **Limit-states considered** for RC bridge columns: (1) **concrete cover crushing**, (2) precursor to **longitudinal rebar buckling**, (3) a precursor to **longitudinal rebar fracture**.
  - ✓ **Material strain-based EDPs.**
  - ✓ **Normalized strain-based fragility functions.**

- **Parametric full-fledged probabilistic performance assessment of four considered OSBs using a fully automated workflow.**
  - ✓ Investigate the **effects of key structural design parameters on the mean RPs of limit-state exceedances.**
  - ✓ **Topologies and contours of mean return period** surfaces in the primary design parameter space.
  - ✓ **Target mean return periods of limit-state exceedances** and **feasible design domains**.
  - ✓ Full-fledged **risk-targeted design** framework.

- **As-designed OSB testbed bridges** considered exhibit **significant variability in seismic performance** as measured by the mean RPs of exceeding the selected set of limit-states.

Concluding Remarks & Future Research Needs

- Distilled out **computationally more economical**, **simplified**, **non-traditional, risk-targeted PBSD method**, building on the comprehensive probabilistic PEER PBEE framework, for Ordinary Standard Bridges (OSBs) in California.
  - ✓ **Find a design point** in the primary design parameter space.
  - ✓ **Delineate approximate, sufficiently accurate, feasible design domain.**

- **Future Research Needs:**
  - ✓ Incorporation of **(1) model parameter uncertainty**, **(2) parameter estimation uncertainty**, and **(3) modeling uncertainty**.
  - ✓ **Explicit probabilistic treatment of near fault effects.**
  - ✓ **Risk-targeted PBSD in terms of loss variables (e.g., life-cycle repair costs, downtime)**
  - ✓ **Probabilistic explicit determination of secondary design variables** to prevent undesirable failure modes with some specified level of confidence.
  - ✓ Extend proposed simplified PBSD method to accommodate **more than two primary design variables**, especially for **non-ordinary, more complex bridges**.

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  Charles Sikorsky (Caltrans)

Thank you!

Improved Seismic Intensity Measure

- Geometric mean of spectral accelerations at different periods (T_1, …, T_n):

$$IM: \quad S_{a,avg}\left(T_1,\ldots,T_n\right) = \left[\prod_{k=1}^{n} S_a\left(T_k\right)\right]^{\frac{1}{n}}$$

Ref.: Kohrangi, Bazzurro and Vamvatsikos (2016)

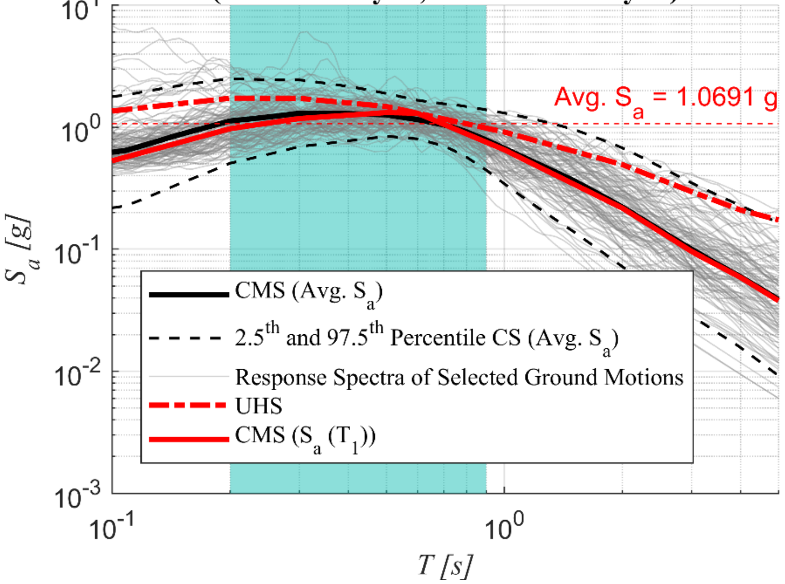
$$\nu_{S_{a,avg}}\left(s_a\right) = \sum_{i=1}^{N_{faults}} \nu_i \int_{R_i}\int_{M_i} P\left[\left[\prod_{k=1}^{n} S_a\left(T_k\right)\right]^{\frac{1}{n}} > s_a \mid M_i = m, R_i = r\right]\cdot f_{M_i}\left(m\right)\cdot f_{R_i}\left(r\right)\cdot dm\cdot dr$$

$$= \sum_{s=1}^{N_{scenarios}} P\left[\left[\prod_{k=1}^{n} S_a\left(T_k\right)\right]^{\frac{1}{n}} > s_a \mid Scenario_s\right]\cdot Rate\left(Scenario_s\right)$$

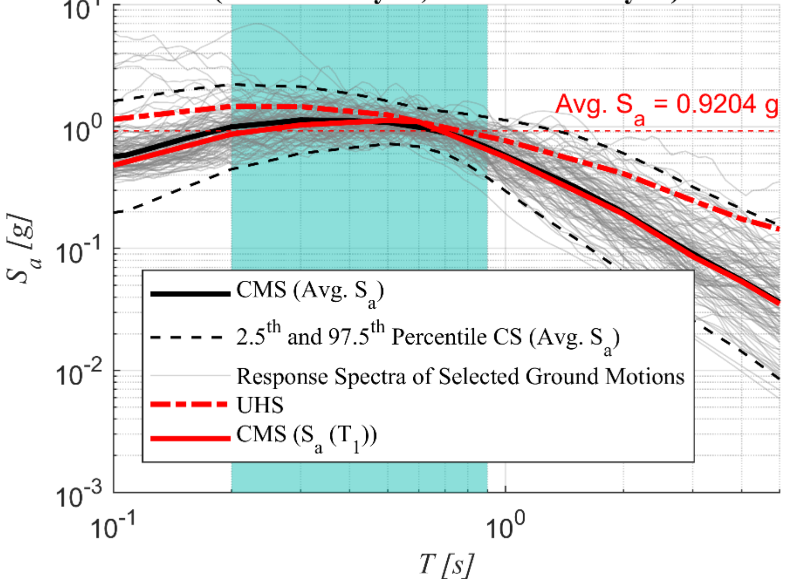
Risk - Consistent Ground Motion Ensembles

Refs.: Baker and Jayaram (2011)
Kohrangi, Bazzurro, Vamvatsikos, and Spillatura (2017)

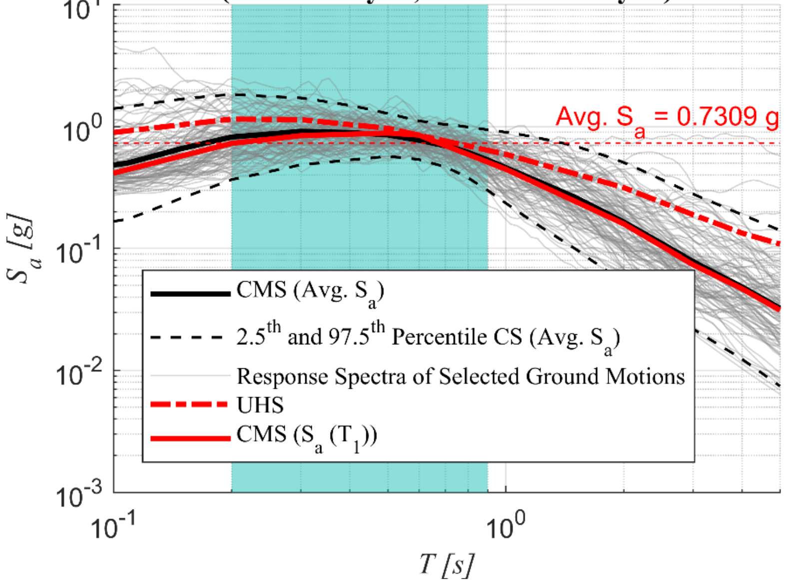
Pseudo Acceleration Response Spectrum (Bridge B)
(R.P. = 4975 yrs., PE = 1% in 50 yrs.)



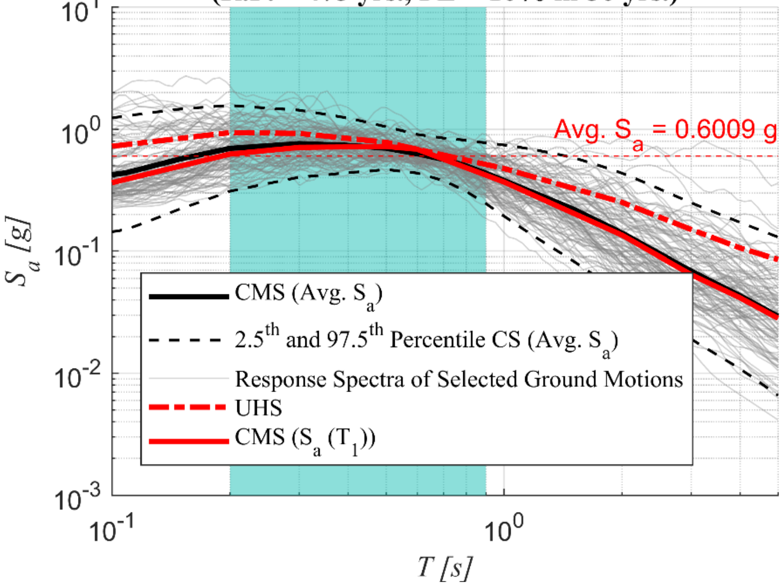
Pseudo Acceleration Response Spectrum (Bridge B)
(R.P. = 2475 yrs., PE = 2% in 50 yrs.)



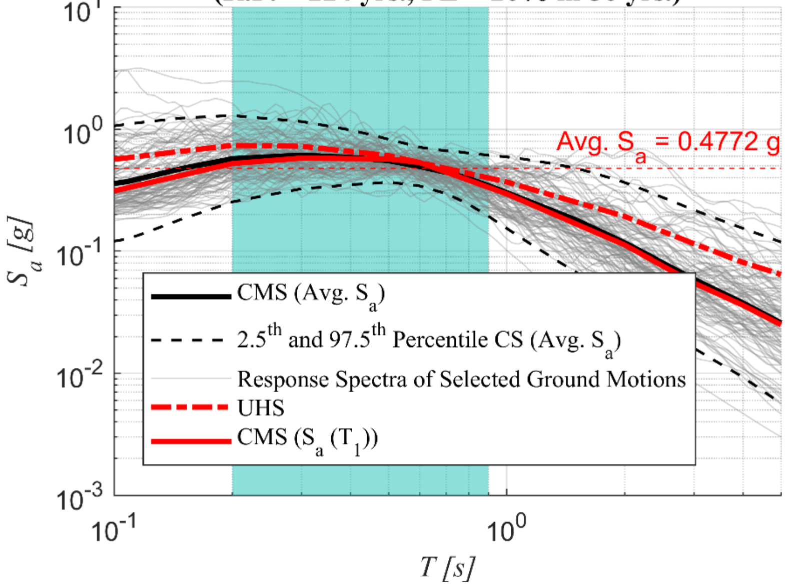
Pseudo Acceleration Response Spectrum (Bridge B)
(R.P. = 975 yrs., PE = 5% in 50 yrs.)



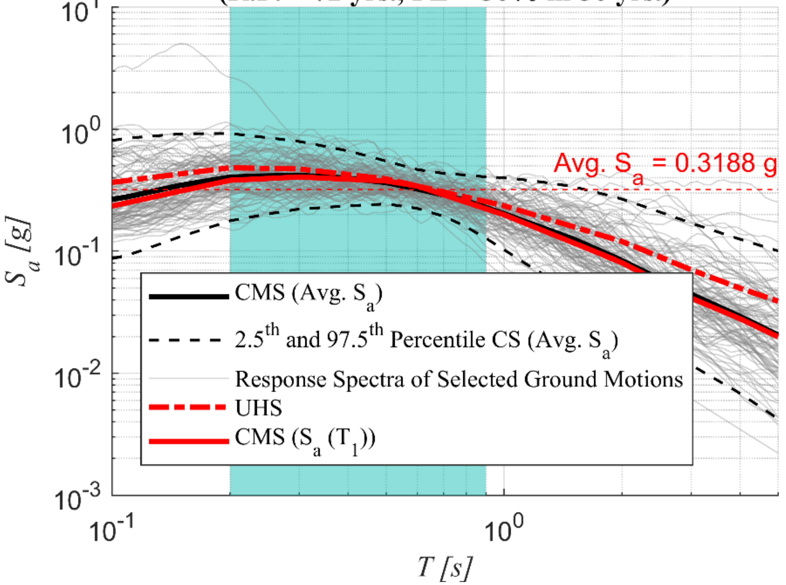
Pseudo Acceleration Response Spectrum (Bridge B)
(R.P. = 475 yrs., PE = 10% in 50 yrs.)



Pseudo Acceleration Response Spectrum (Bridge B)
(R.P. = 224 yrs., PE = 20% in 50 yrs.)



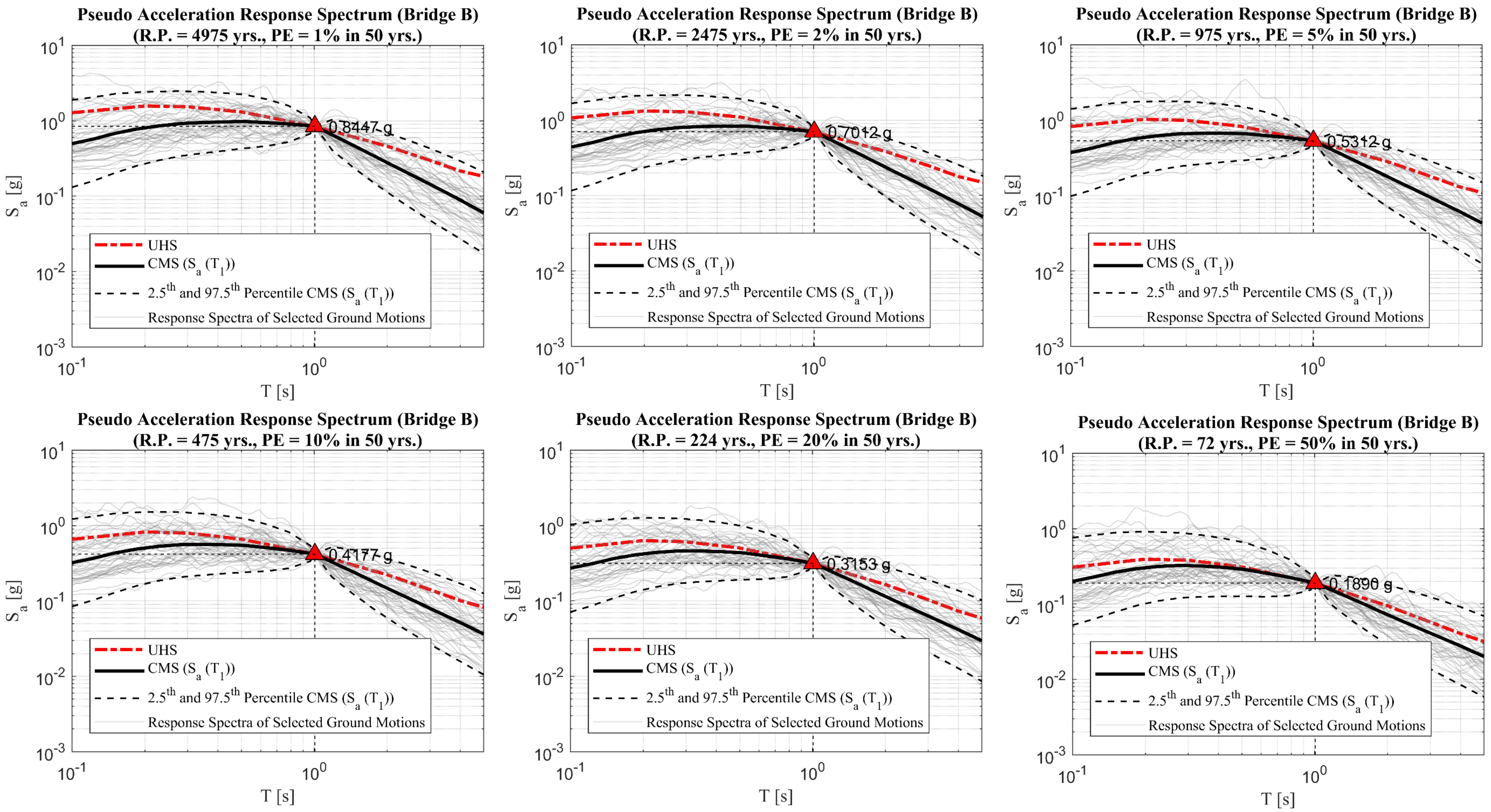
Pseudo Acceleration Response Spectrum (Bridge B)
(R.P. = 72 yrs., PE = 50% in 50 yrs.)



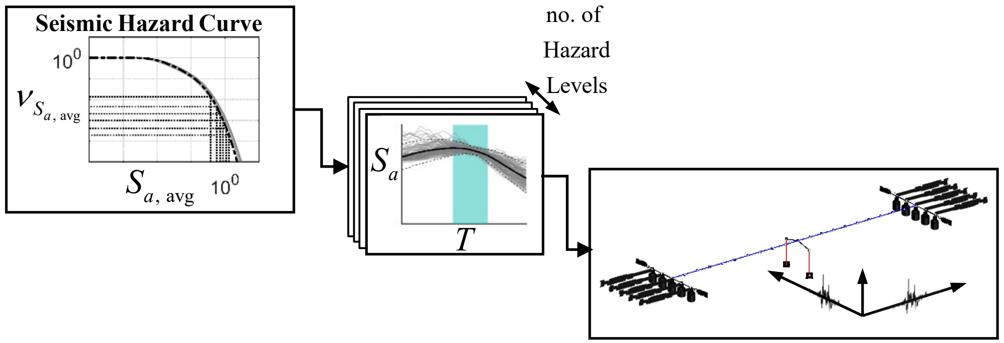
Note : Previously, ensembles of 40 ground motions were selected based on CMS $\left(IM = S_a(T_1 = 1.0s)\right)$; T_1 changed following a model update.

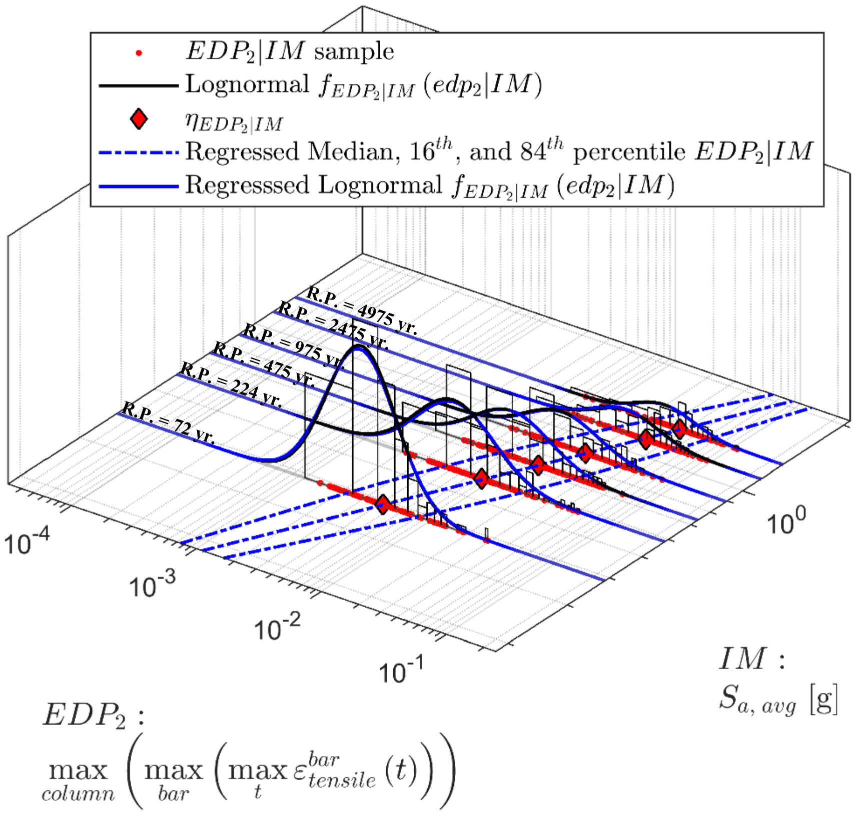
Previously Selected IM and Ground Motion Ensembles

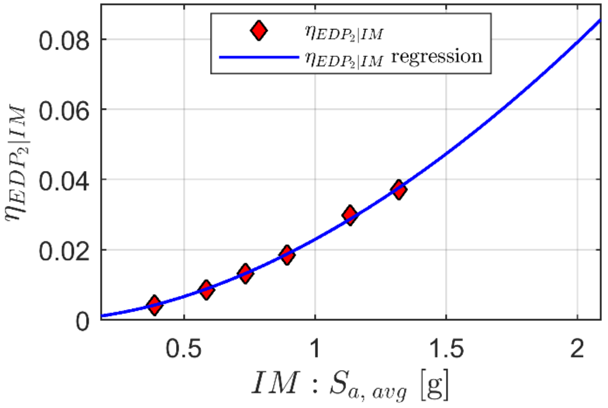
Ref.: Baker and Jayaram (2011)

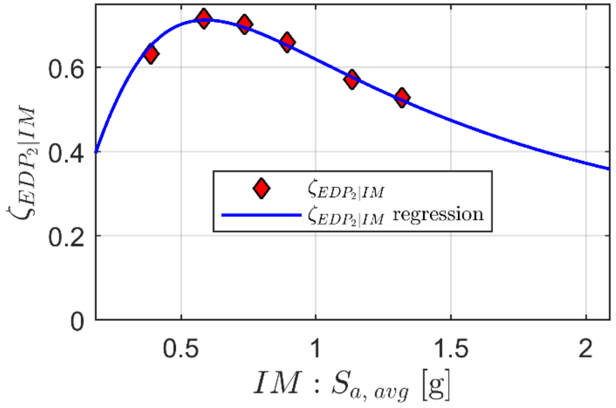


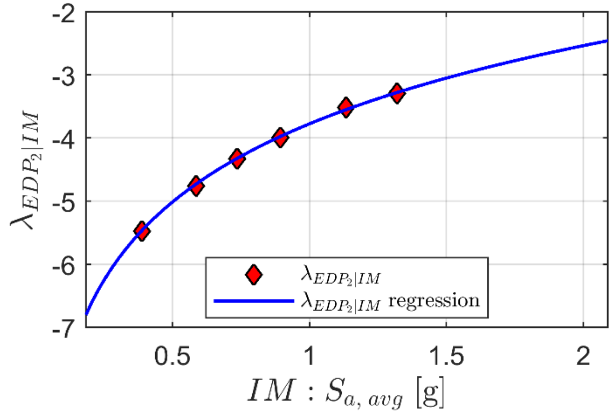
Probabilistic Seismic Demand Hazard Analysis

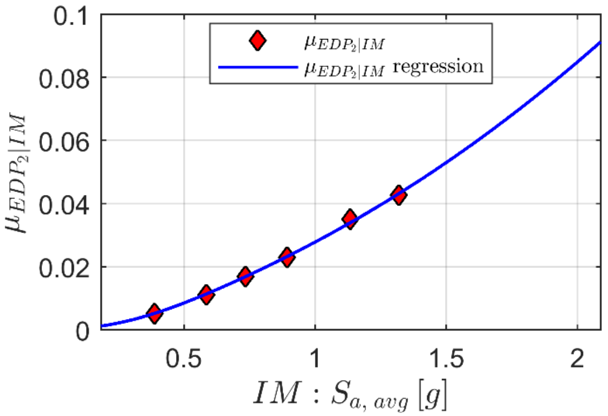


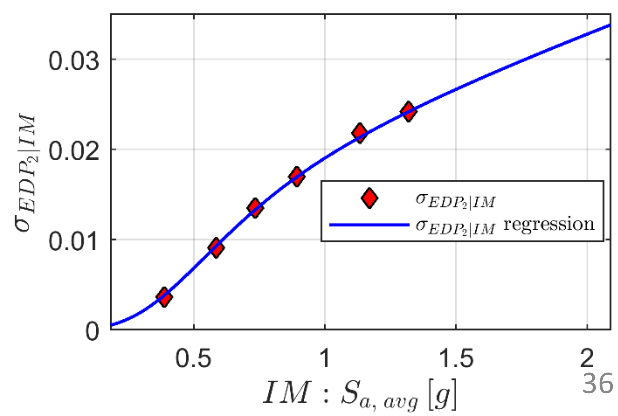






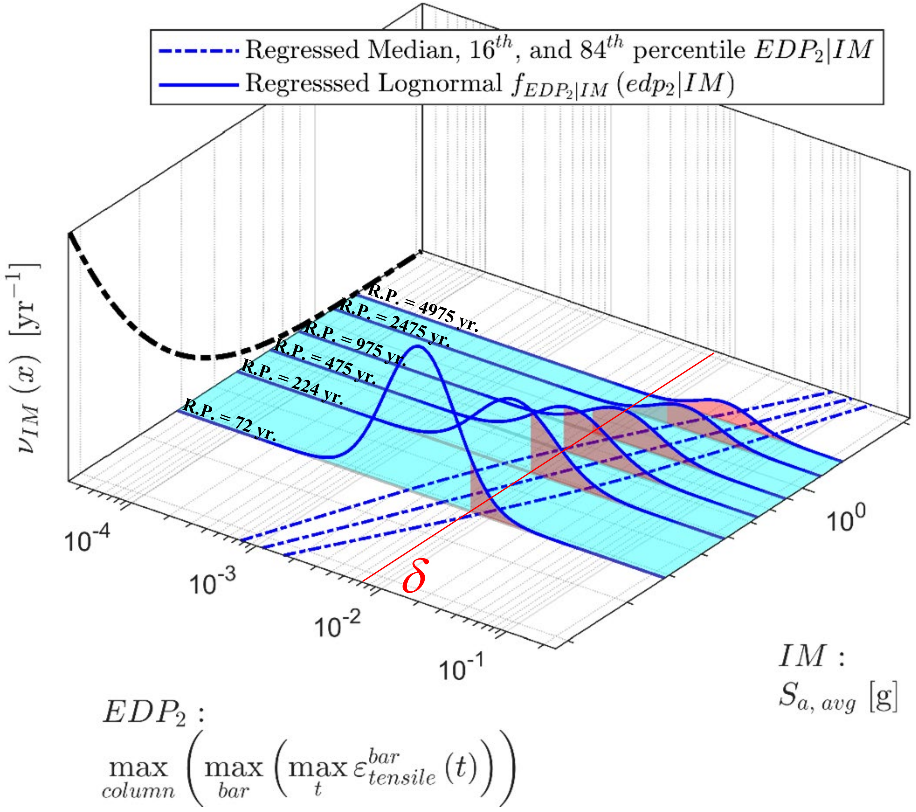




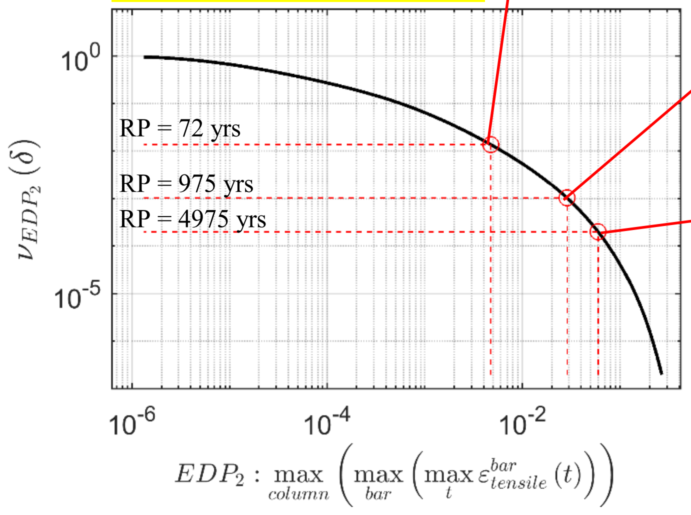


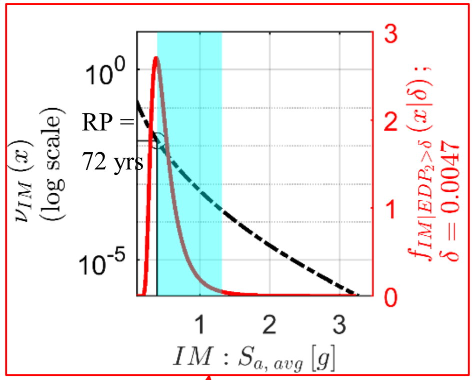
Probabilistic Seismic Demand Hazard Analysis

$$\nu_{EDP_k}(\delta) = \int_{IM} P\left[EDP_k > \delta \mid IM = x\right] \cdot \underbrace{\left|d\nu_{IM}(x)\right|}_{\left|\nu_{IM}(x+dx)-\nu_{IM}(x)\right|}$$

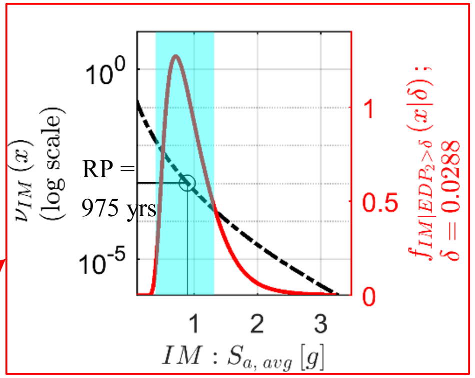


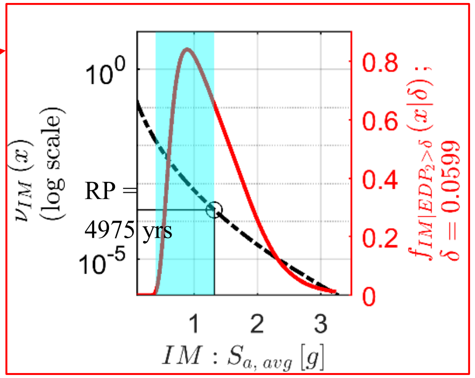
Demand Hazard Curve





IM Deaggregation of Demand Hazard





Probabilistic Seismic Demand and Capacity

Probability density function of EDP_k :

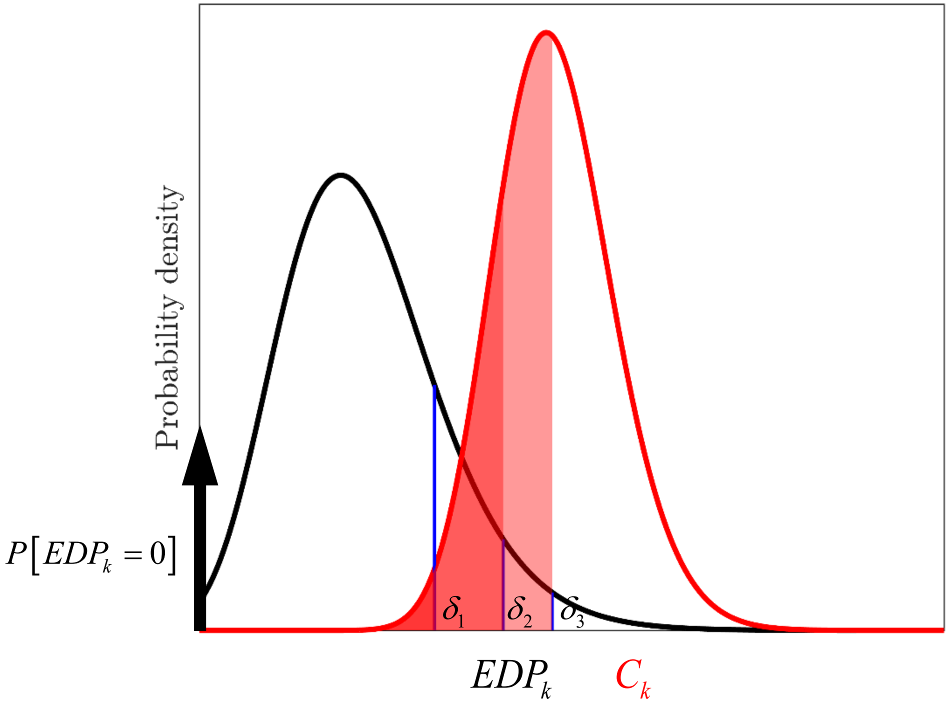
$$f_{EDP_k}(\delta) = \frac{d}{d\delta}\left(\underbrace{1 - \frac{\nu_{EDP_k}(\delta)}{\nu_{IM}(x=0)}}_{F_{EDP_k}(\delta)} \right)$$

Probability of LS exceedance :

For k^{th} limit-state,

$P[LS \text{ exceedance}] = P[C_k < EDP_k]$

$$= \int_\delta \underbrace{P[C_k < EDP_k \mid EDP_k = \delta]}_{\textbf{Fragility Function}} \cdot f_{EDP_k}(\delta) \cdot d\delta$$



Limit-States: Limit State – 4 (Displacement-based)

- **Exterior shear key reaching its shear strength capacity**

Predictive Capacity Model:

$$EDP_{C_4}^{\text{PRED}} = \Delta_C^{SK} = \sqrt{2}\varepsilon_y\left(L_d + b\right)\frac{h+d_1}{s}$$

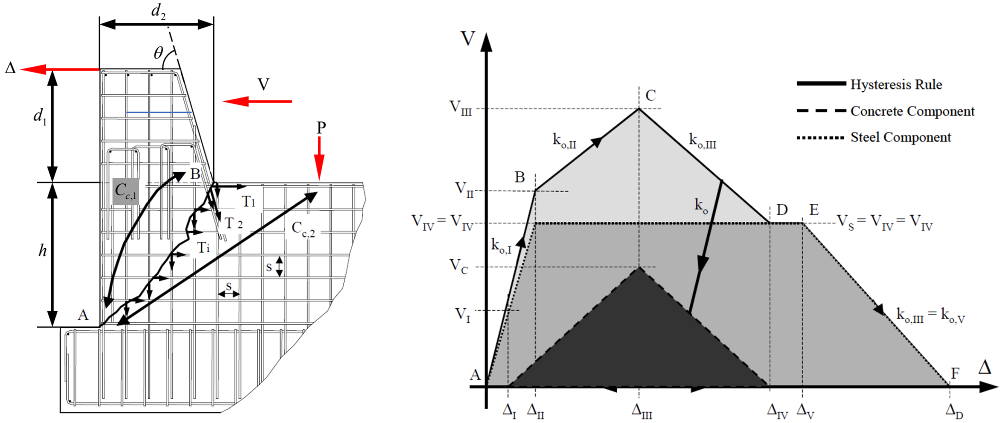
(Megally, et al., 2002)

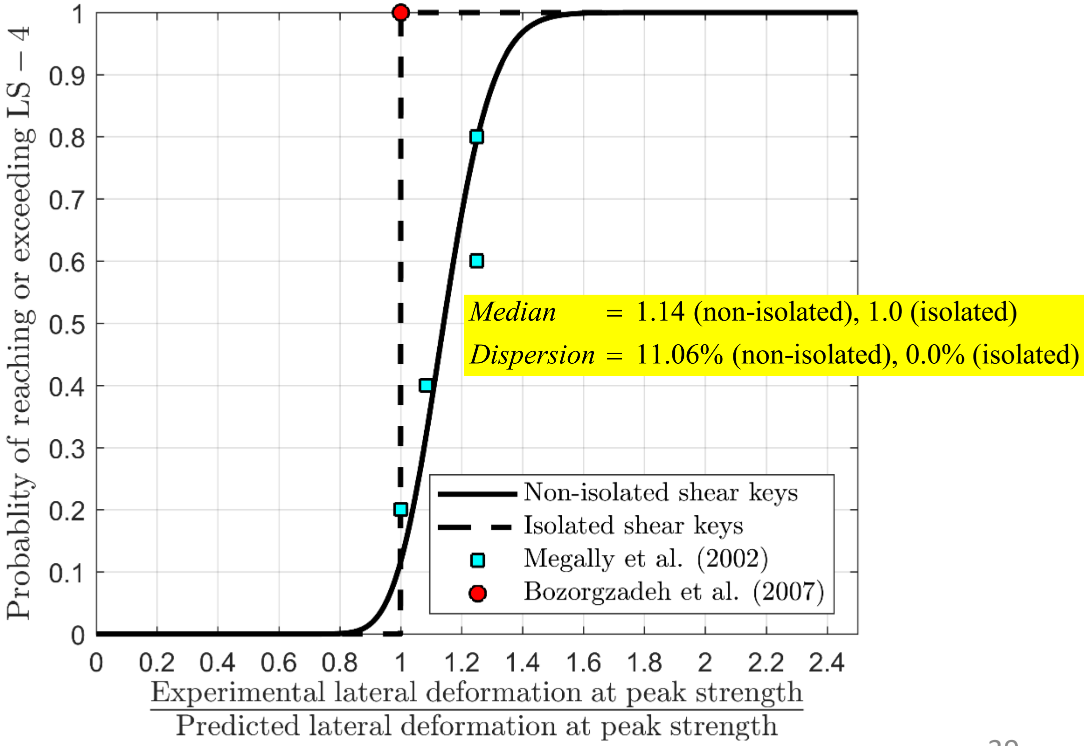
Non-isolated shear key | Isolated shear key

(Megally et al., 2002)


(Bozorgzadeh et al., 2007)

(Megally et al., 2002)





Concluding Remarks

- **Assessment of four Ordinary Standard Bridge (OSB) Testbeds in California using improved version of the PEER PBEE framework.**
  - ✓ Use of an **improved IM** consisting of the average spectral acceleration over a specified period range.
  - ✓ Derivation of **seismic hazard curve for improved IM** in terms of the results of standard PSHA for spectral accelerations at single periods.
  - ✓ **Conditional mean spectrum-based, site-specific, hazard/risk-consistent ground motion selection.**
  - ✓ **Limit-states considered** for RC bridge columns: (1) concrete cover crushing, (2) a precursor to longitudinal rebar buckling, (3) a precursor to longitudinal rebar fracture.
  - ✓ **Material strain-based EDPs** associated with limit-states considered.
  - ✓ **Normalized strain-based fragility functions** based on reliable experimental data or high-fidelity numerical data.
- **Parametric full-fledged probabilistic performance assessment of four considered OSBs using a fully automated workflow in parallel computing environment.**
  - ✓ Investigate the **effects of key structural design parameters parameters on the mean RPs of limit-state exceedances.**
  - ✓ **Topologies and contours of mean return period** surfaces in the primary design parameter space.
  - ✓ **Target mean return periods of limit-state exceedances** and **feasible design domains**.

Concluding Remarks

- **Probabilistic PBSD for California Ordinary Bridges with performance objectives explicitly stated in terms of the risk associated with the exceedance of critical damage/limit states**
  - ✓ Provides an
- Distilled out a **computationally more economical**, **simplified**, **non-traditional, risk-targeted PBSD method**, building on the comprehensive probabilistic PEER PBEE framework, for Ordinary Standard Bridges (OSBs) in California.
  - ✓ Find a design point in the primary design parameter space.
  - ✓ Delineate approximate, sufficiently accurate, feasible design domain.
- **Seismic performance of the as-designed OSB testbed bridges considered shows significant variability of seismic performance** as measured by the mean RPs of exceeding the selected set of limit-states.
  - ✓ Limit-state 1: mean RP = 150 – 1,500 years
  - ✓ Limit-state 2: mean RP = 500 – 10,000 years
  - ✓ Limit-state 3: mean RP = 1,000 – 30,000 years
  - ✓ Limit-state 4 (abutment exterior shear key reaching its shear strength capacity): 80 – 2,500 years

Concluding Remarks

- **Future research needs:**
  - ✓ Incorporation of **(1) model parameter uncertainty**, **(2) parameter estimation uncertainty**, and **(3) modeling uncertainty**.
  - ✓ **Explicit probabilistic treatment of near fault effects.**
  - ✓ **Risk-targeted PBSD in terms of loss variables (life-cycle repair costs, downtime)**
  - ✓ **Develop probabilistically explicit determination of secondary design variables** to prevent undesirable failure modes with some specified level of confidence.
  - ✓ Extend proposed simplified PBSD method to accommodate **more than two primary design variables**, especially for **non-ordinary bridges**.