OpenSees-SNOPT: A Framework for Finite Element Based Optimization

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Need for FE-Based Optimization in Structural/Geotechnical Engineering

- **FE method:** a **powerful** tool for modeling, analysis, and simulation of **structural and/or geotechnical systems.**
- **Numerical Optimization** is used in many engineering applications, e.g.,
  - **Standalone optimization** of structural/geotechnical systems
  - **Structural reliability analysis** (design point(s) search)
  - **Reliability-based optimization**
  - **Probabilistic performance-based optimum seismic design**
  - **FE model calibration/updating**
  - **System identification**

→ **Finite – Element Based Optimization**

e.g., **TOSCA-ABAQUS**; **Nastran**, **ANSYS**, **LS DYNA** include numerical optimization tools

Optimization Problems in Structural/Geotechnical Engineering

- Are **complex in** nature and stem from a **broad range of applications.**
- Involve **FE response of structural, geotechnical, or SFSI systems** to various static and/or dynamic loads.
- Require **optimization of different system properties** (e.g., modal frequencies, mode shapes, damping properties) **and/or system response behavior** (e.g., force-deformation relationships, various features of displacement/velocity/acceleration response histories).
- **Objective Functions**, e.g., weight, initial cost, life cycle cost, demand hazard curve, reliability index, loss hazard curve.
- **Constraints**, e.g., geometry, max. displ./accel./stress response, max. plastic deformation, reliability index.

Need for FE-Based Optimization Framework in Structural/Geotechnical Engineering

- **Need for a FE-based optimization framework** that is sufficiently **general** and **flexible** to accommodate the wide range of optimization problems arising in structural/ geotechnical engineering.

- This FE-based optimization framework must be **able to readily incorporate** current and future **advances in nonlinear structural/geotechnical FE analysis** and **computational optimization**.

⇒ **Coupling of OpenSees with SNOPT** (Sparse Nonlinear Optimization code):

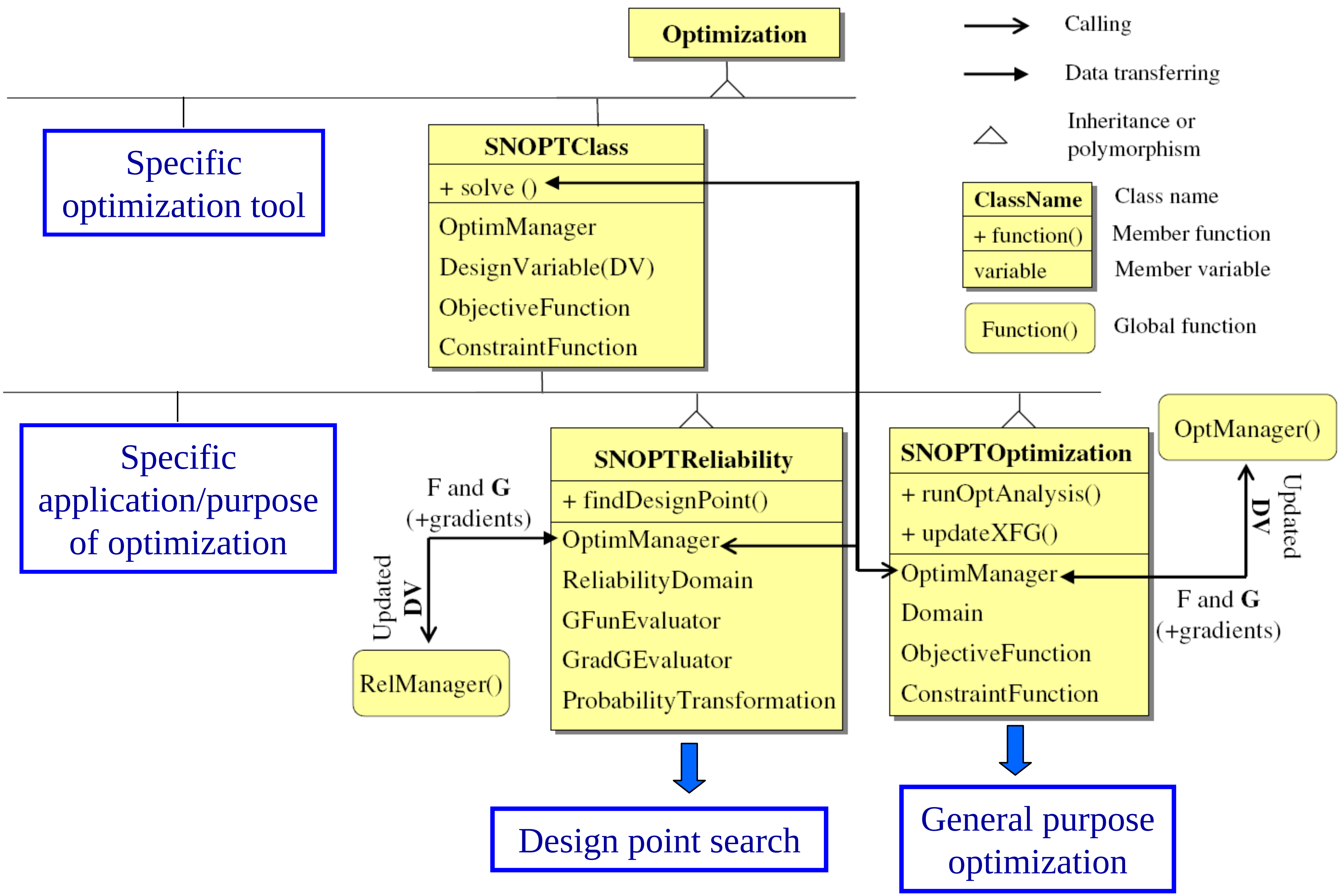
OpenSees-SNOPT Framework

SNOPT (Sparse Nonlinear OPTimization)

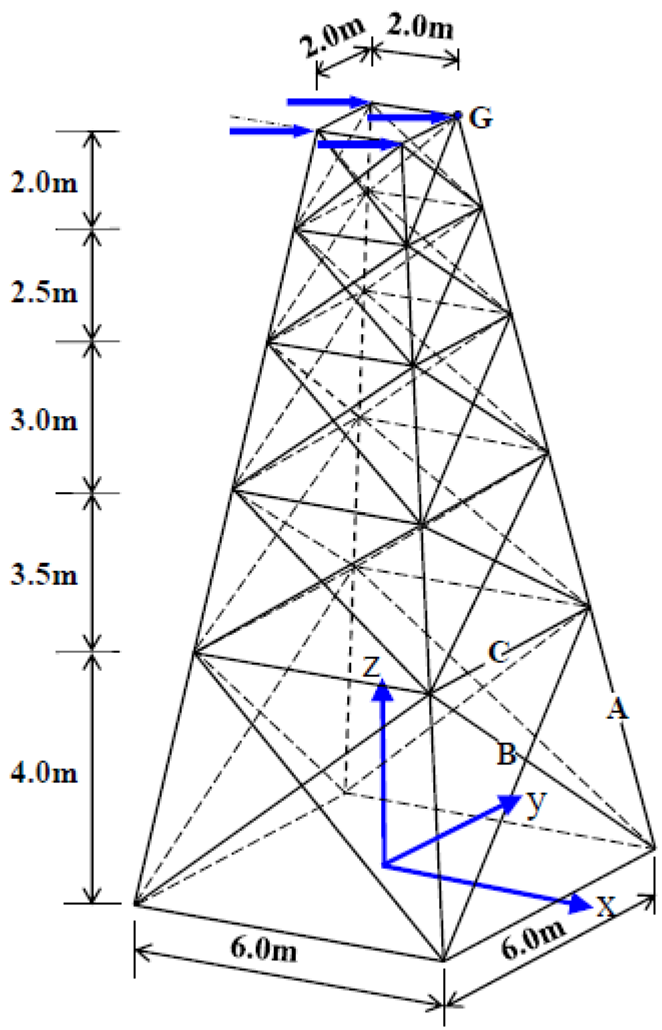
- **SNOPT** is a **general purpose nonlinear optimization code** which uses a **Sequential Quadratic Programming algorithm** **(Philip Gill, Walter Murray and Michael Saunders).**

- **Advantages of SNOPT** as optimization tool in structural/ geotechnical engineering:
  - Applies to **large scale** problems
  - **Tolerates discontinuities** in the gradients of the OF and CFs
  - **Requires relatively few evaluations** of the OF and CFs and their gradients
  - Offers a number of **options to increase performance** and customize the optimization process to specific applications

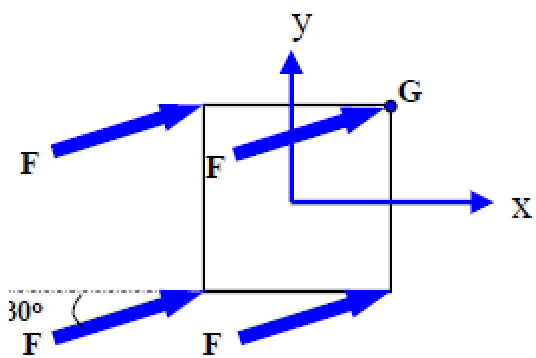
Optimization Framework in OpenSees



Example 1: Structural Optimization of an Electrical Transmission Tower



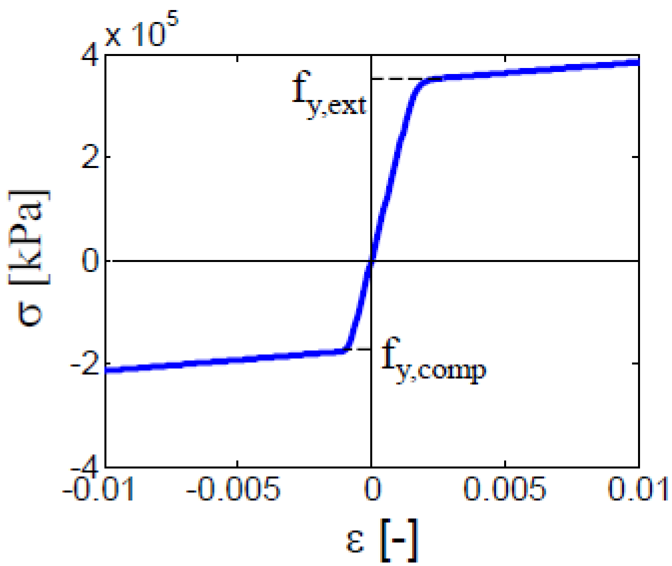
3-D truss model of electrical transmission tower



Serviceability: F = 25 kN

Ultimate: F = 100 kN

Asymetric Menegotto-Pinto constitutive model



Optimization Problem and Solution

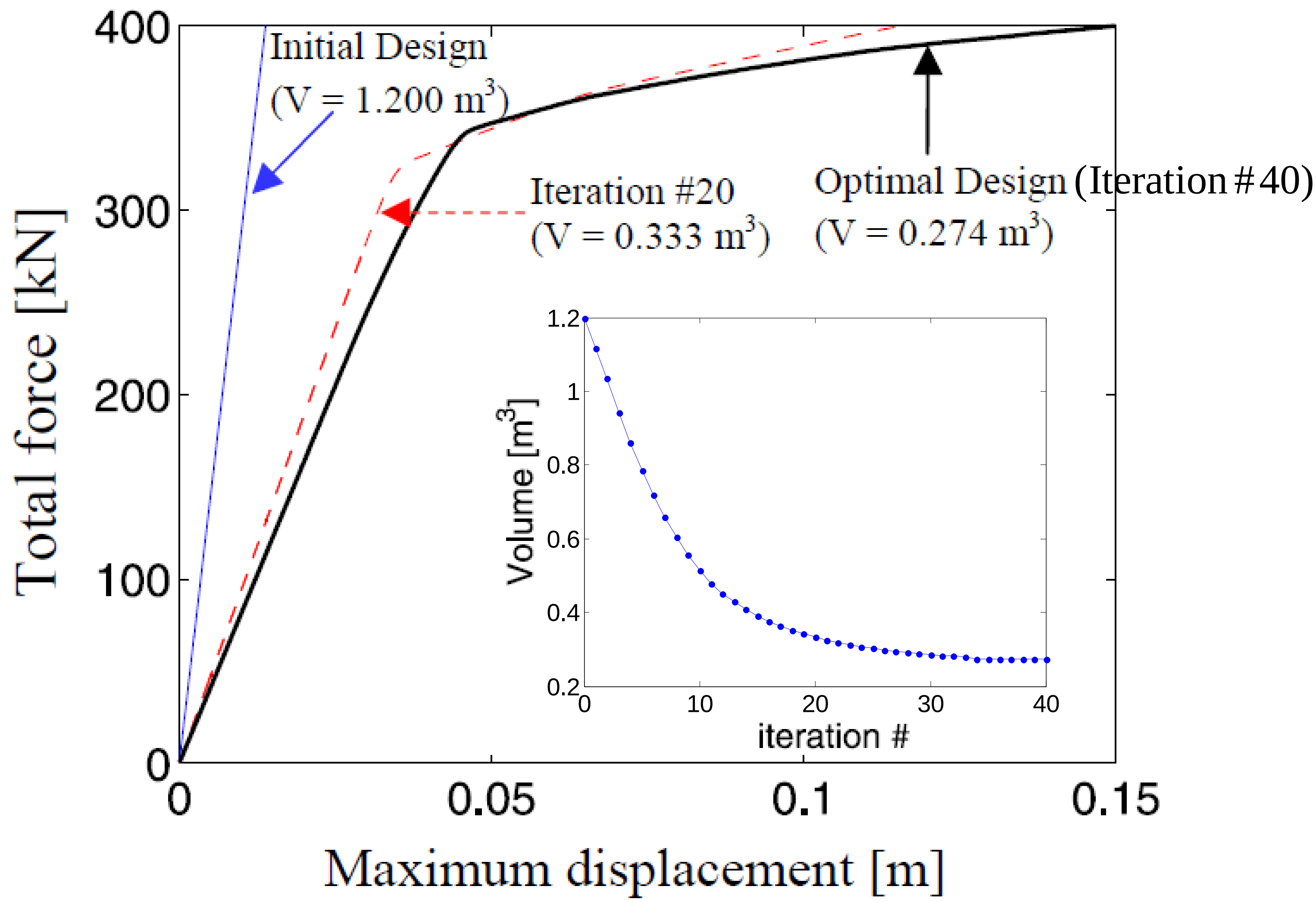
- Design variables
  (1) Cross-section Area A: in range [8.0e-4, 1.6e-2] m^2, initial 8e-3 m^2
  (2) Cross-section Area B: in range [3.0e-4, 6.0e-3] m^2, initial 3e-3 m^2
  (3) Cross-section Area C: in range [2.0e-4, 4.0e-3] m^2, initial 2e-3 m^2

- Minimize the total cost (or volume) of the tower such that
  (1) when F = 25 kN, $u_{max} < 1.50$ cm (at the top of the tower)
  (2) when F = 100 kN, $u_{max} < 15.0$ cm (at the top of the tower)

- Optimal design
  (1) A = 3.17e-3 m^2, B = 3.51e-4 m^2, C = 2.00e-4 m^2
  (2) Total volume = **0.274 m^3** (compared with initial volume of **1.20m^3**).

Optimization Results

Total applied wind force versus total displacement of node G

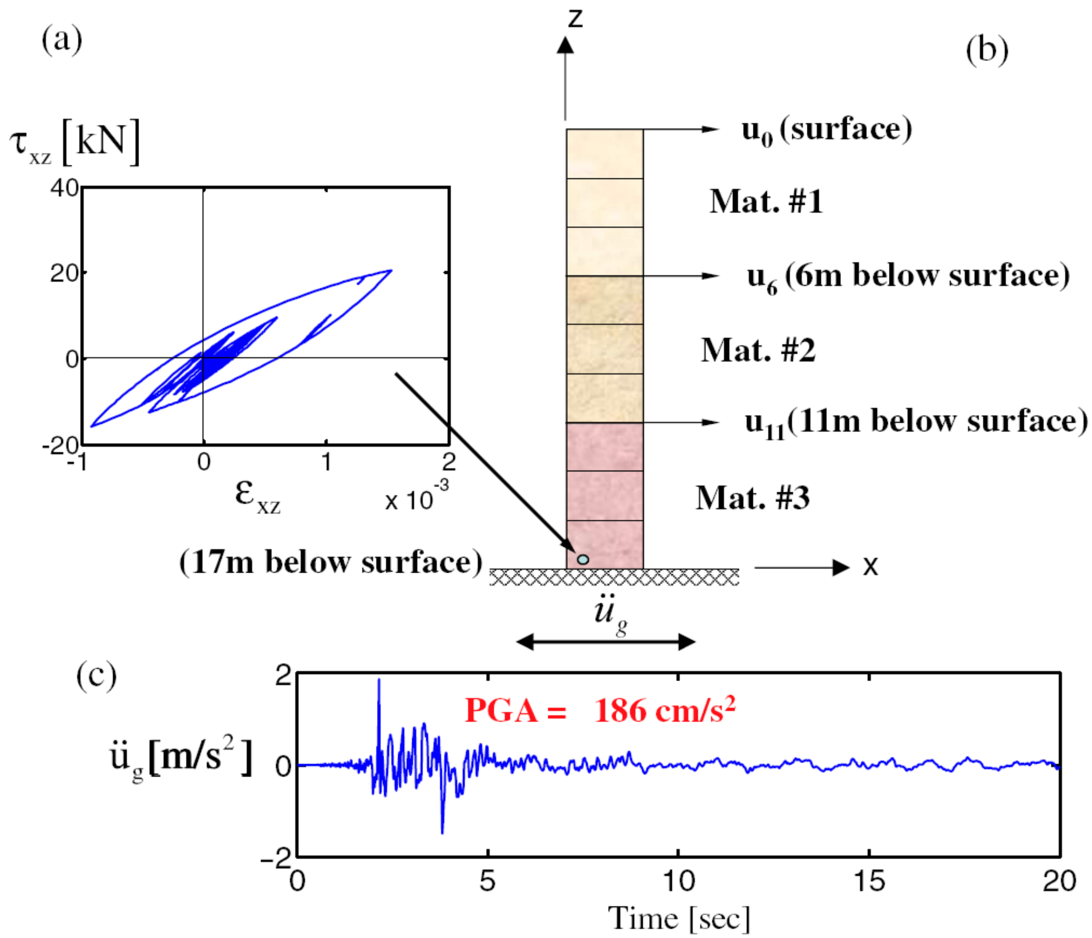


Example 2: Nonlinear FE Model Updating of Soil Column

- 2D soil column modeled by three layers of pressure-independent multi-yield surface J_2 soil plasticity models
- Kinematics: shear column
- Reference material properties

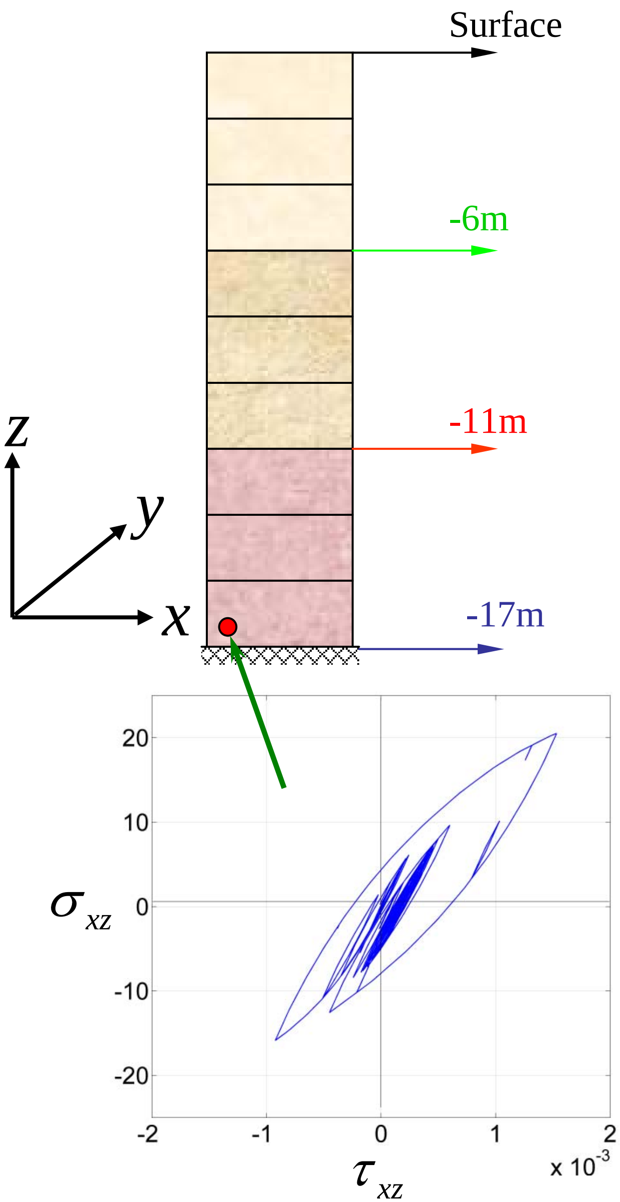
G_1(MPa)	**28.8**	**$\tau_{max,1}$ (kPa)**	**31.0**
G_2(MPa)	**39.2**	**$\tau_{max,2}$ (kPa)**	**33.0**
G_3(MPa)	**57.8**	**$\tau_{max,3}$ (kPa)**	**34.0**

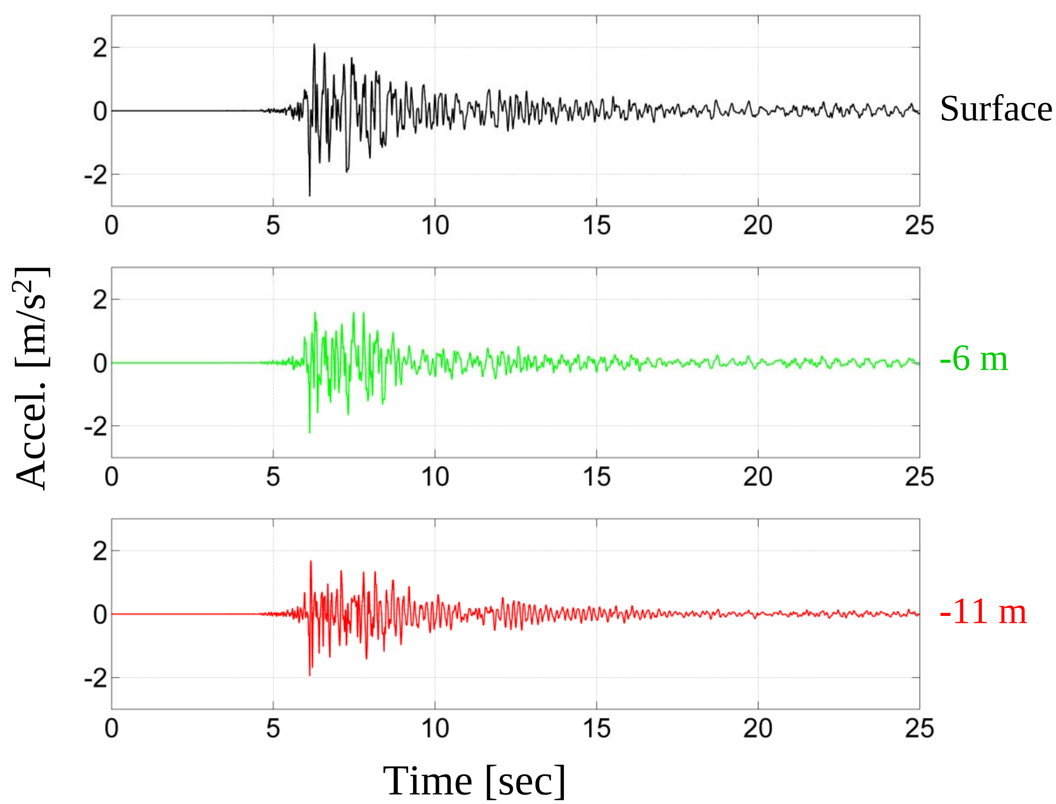
- Input motion: the downhole acceleration record (#12 N-S direction at 17 m depth) obtained during the Lotung China earthquake of 1986



Base acceleration time history

'Experimental'/Reference Earthquake Responses





Objective & Constraint Functions and Results

- **Objective Function:**

$$F = \sum_{j=1}^{\#stations} \left(\sum_{i=1}^{\#time\ steps} \frac{1}{2} \left(\ddot{u}_{j,t_i}^{FE} - \ddot{u}_{j,t_i}^{exp} \right)^2 \right)$$

- **Method 1: Gradient by FFD**

$$\frac{\partial F}{\partial \theta} \approx \frac{\Delta F}{\Delta \theta}$$

- **Constraint Functions:**

$$20,000 < G_i < \infty \qquad 20 < \tau_i < \infty$$

- **Method 2: Gradient by DDM**

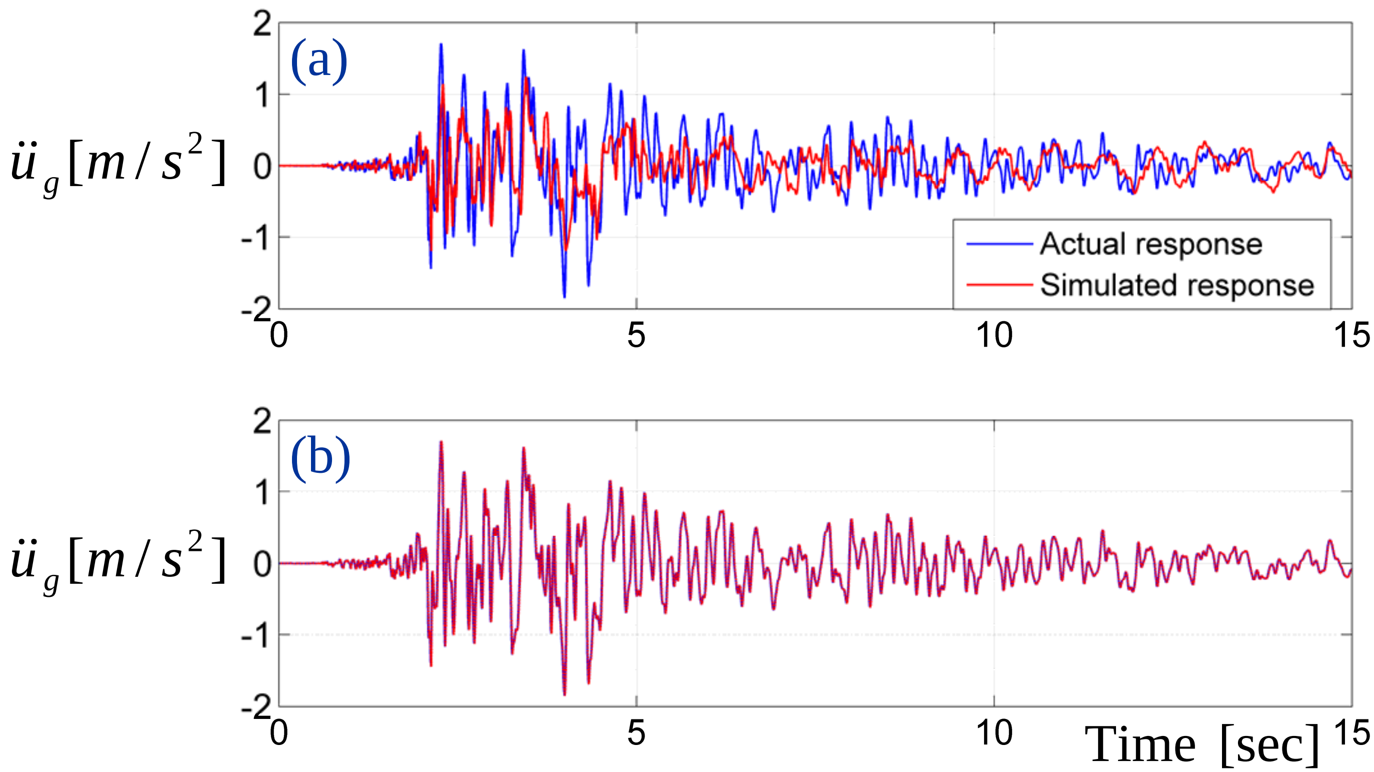
$$\frac{\partial F}{\partial \theta} = \sum_{j=1}^{\#stations} \left(\sum_{i=1}^{\#time\ steps} \left(\ddot{u}_{j,t_i} - \ddot{u}_{j,t_i}^{exp} \right) \frac{\partial \ddot{u}_{j,t_i}}{\partial \theta} \right)$$

- **Results obtained by OpenSees-SNOPT:**

Param.	G_1 (kPa)	G_2 (kPa)	G_3 (kPa)	$\tau_{max,1}$ (kPa)	$\tau_{max,2}$ (kPa)	$\tau_{max,3}$ (kPa)
True/Ref Value	28,800	39,200	57,800	31	33	34
Initial value	30,000	30,000	30,000	30	30	30
SNOPT (FFD)	28,797.40	38,941.76	57,977.04	31.145	33.660	34.156
SNOPT (DDM)	28,800.03	39,199.89	57,800.08	31.0	33.0	34.0

Comparison of Ground Acceleration after FE model Updating (DDM)

- Comparison between ‘experimental’ (reference) and FE predicted ground surface accelerations: (a) before FE model updating, (b) after FE model updating



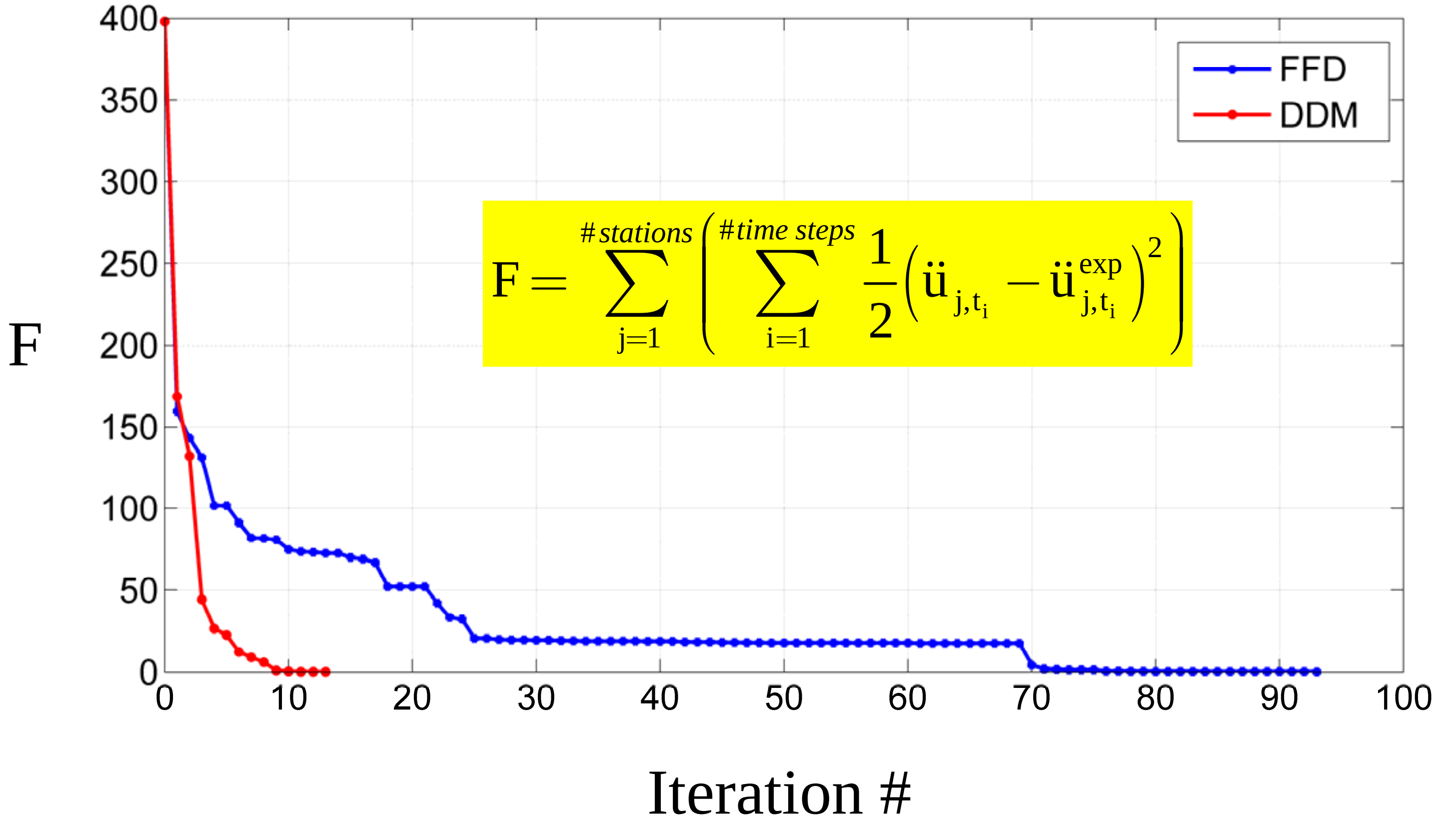
F = 398.10

Initial value of objective function

F = 2.8E-4

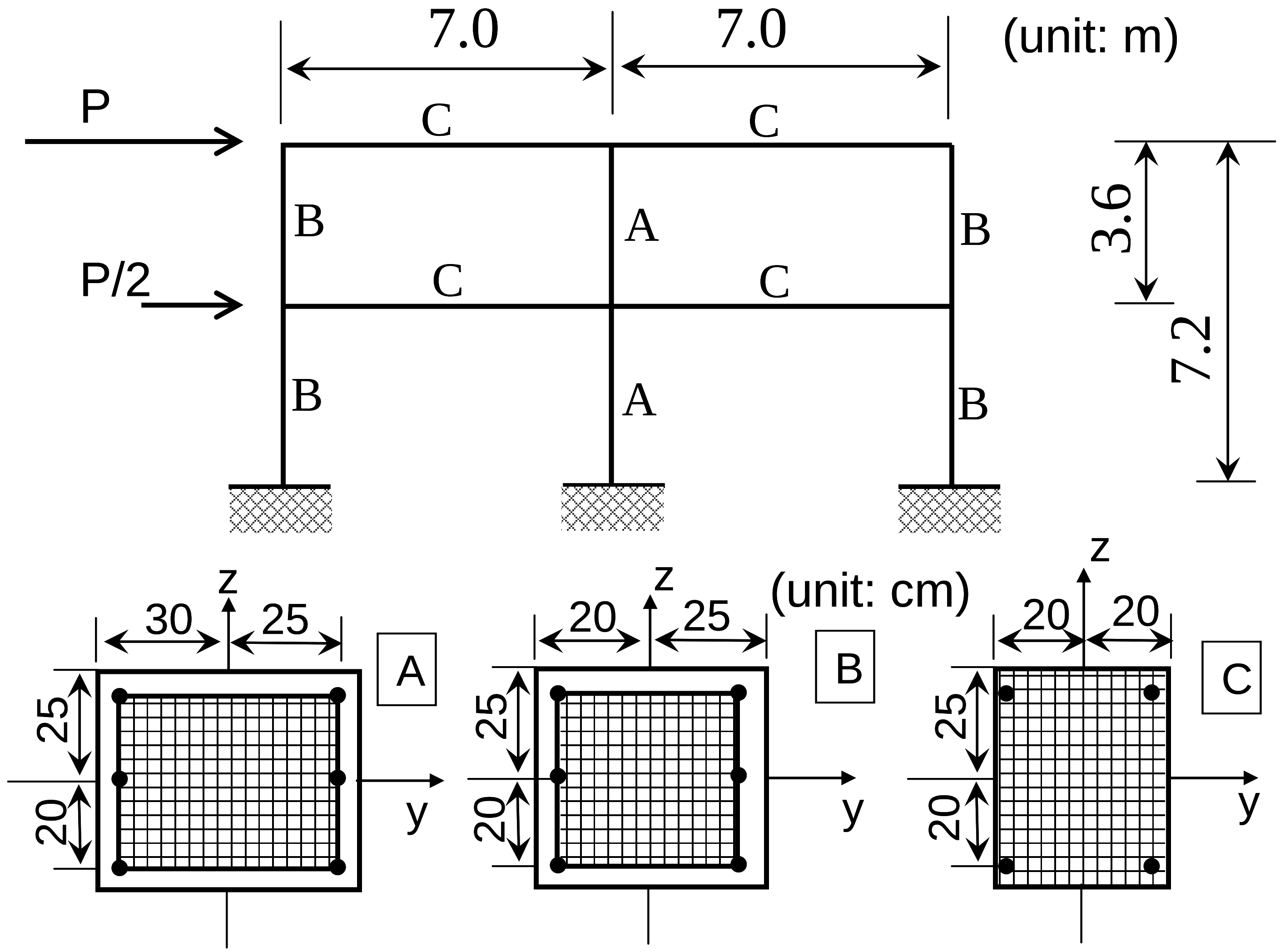
Final value of objective function

Convergence Process (DDM versus FFD)



Note: FE model updating converges MUCH FASTER using DDM versus FFD.

Example 3: FE Reliability Analysis of R/C Frame Structure



Two-story two-bay R/C frame model

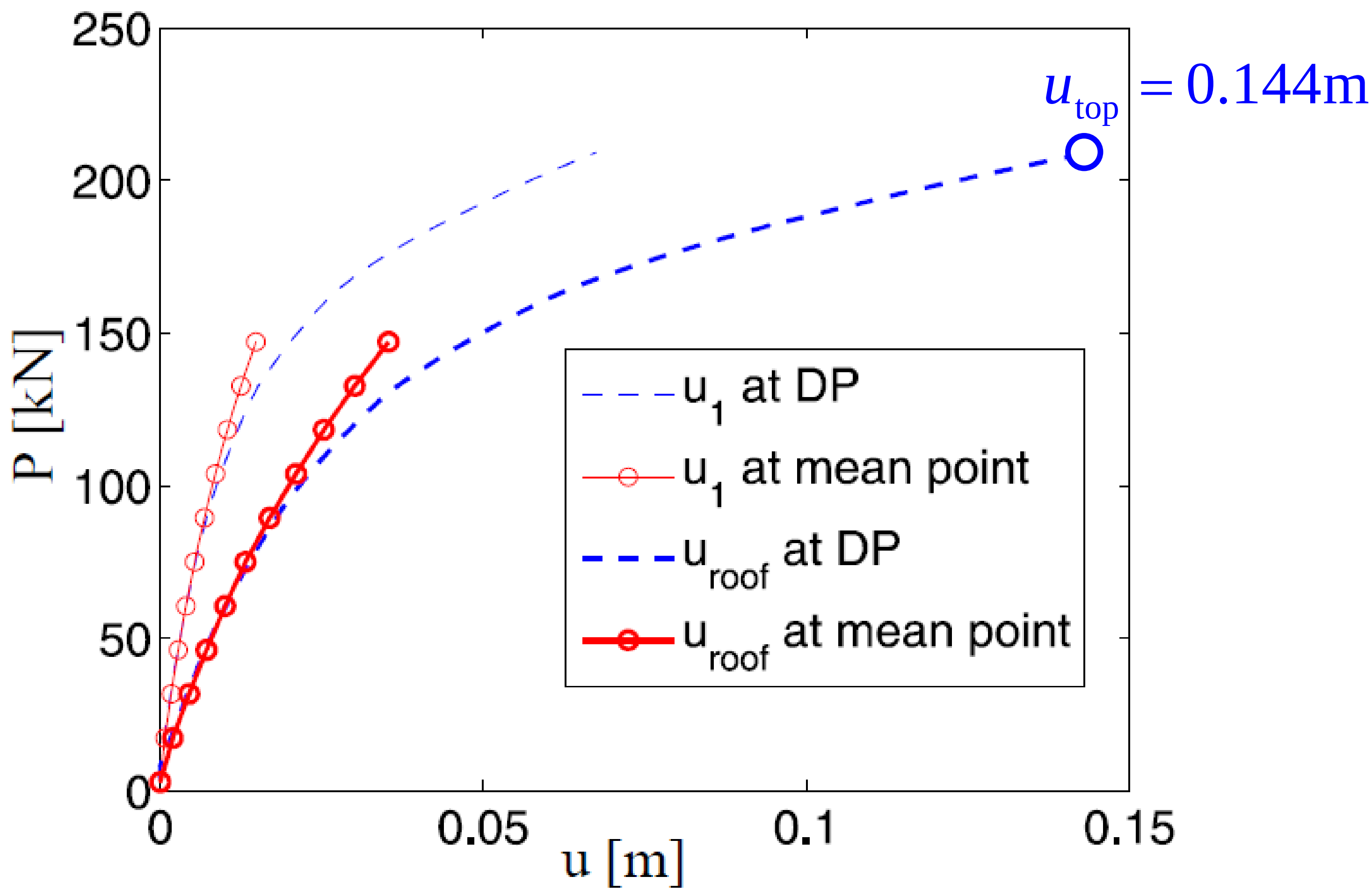
Optimization Problem and Solution

- Objective function: $F = 1/2\, \mathbf{y}^T \mathbf{y}$
- Constraint function: $G = 0.144\text{m} - u_{\text{top}} > 0$
- Material model parameters modeled as correlated lognormal RVs:

RV (unit)	Mean	COV	DP
$f_{c,\text{cover}}$ (MPa)	27.59	0.20	25.69
$\epsilon_{c,\text{cover}}$ (−)	2.000×10^{-3}	0.20	1.959×10^{-3}
$\epsilon_{cu,\text{cover}}$ (−)	8.000×10^{-3}	0.20	7.791×10^{-3}
$f_{c,\text{core}}$ (MPa)	34.49	0.20	32.55
$f_{cu,\text{core}}$ (MPa)	20.69	0.20	19.74
$\epsilon_{c,\text{cover}}$ (−)	2.000×10^{-3}	0.20	3.924×10^{-3}
$\epsilon_{cu,\text{cover}}$ (−)	1.400×10^{-2}	0.20	1.367×10^{-2}
f_y (MPa)	248.2	0.20	222.9
E (GPa)	210.0	0.20	209.2
b (−)	2.000×10^{-2}	0.20	1.790×10^{-2}
P (kN)	150.0	0.20	209.2

- Reliability: $P_{f,\text{FORM}} = 0.018;$ $\beta_{\text{FORM}} = 2.09$

- Pushover force - horizontal floor displacement with RVs set at their mean values and their design point (DP) values.



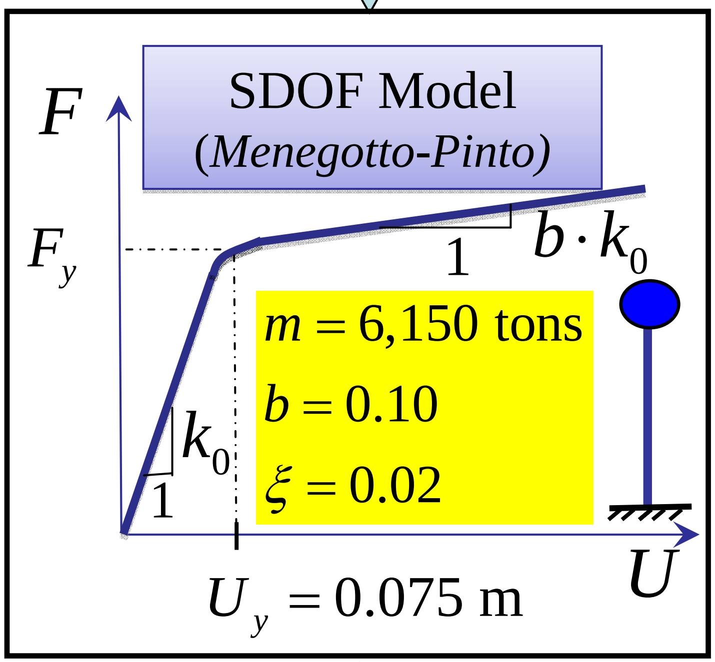
Example 4: Probabilistic Performance-based Optimum Seismic Design

$k_0 = 100{,}000$ kN/m

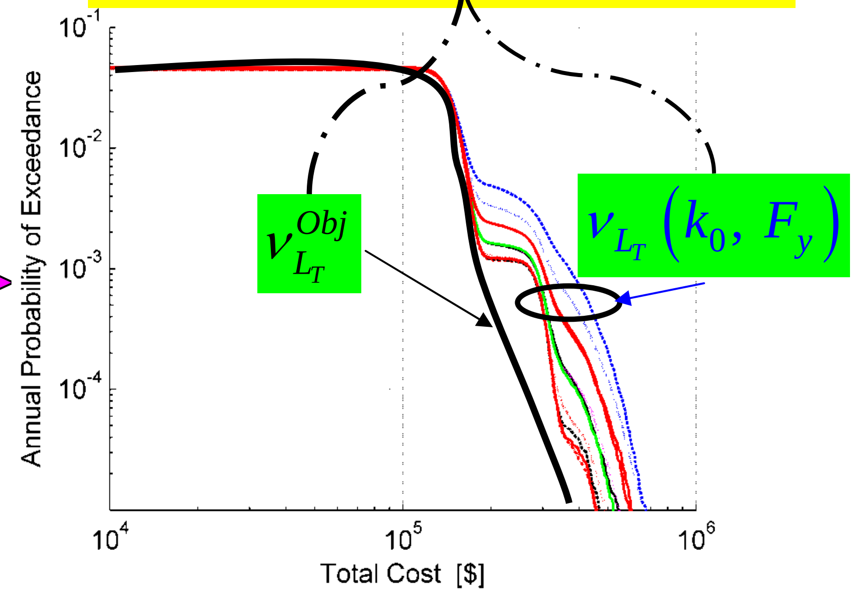
$F_y = 14{,}000$ kN

Starting Point

Objective function : $f(k_0, F_y) = \sum_i | v_{L_T}(k_0, F_y) - v_{L_T}^{Obj} |^2$



PBEE Analysis



A priori selected optimum design parameters

$k_0^* = 137{,}200$ kN/m

$F_y^* = 10{,}290$ kN

Expected Optimizer

OpenSees-SNOPT

Problem Formulation and Objective Function

- **Optimization Problem:**

$$\underset{\{k_0, F_y\}}{Minimize} \;\; f\left(k_0, F_y\right)$$

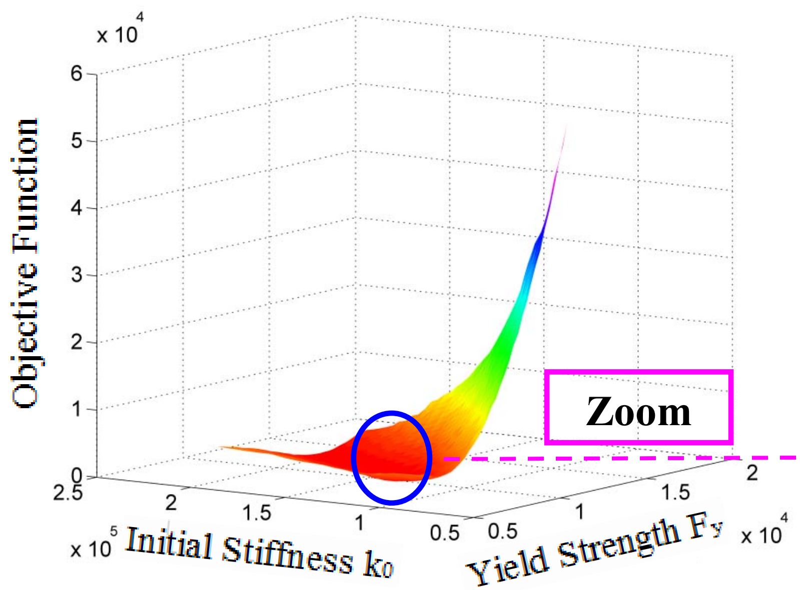
$$subject\ to:$$

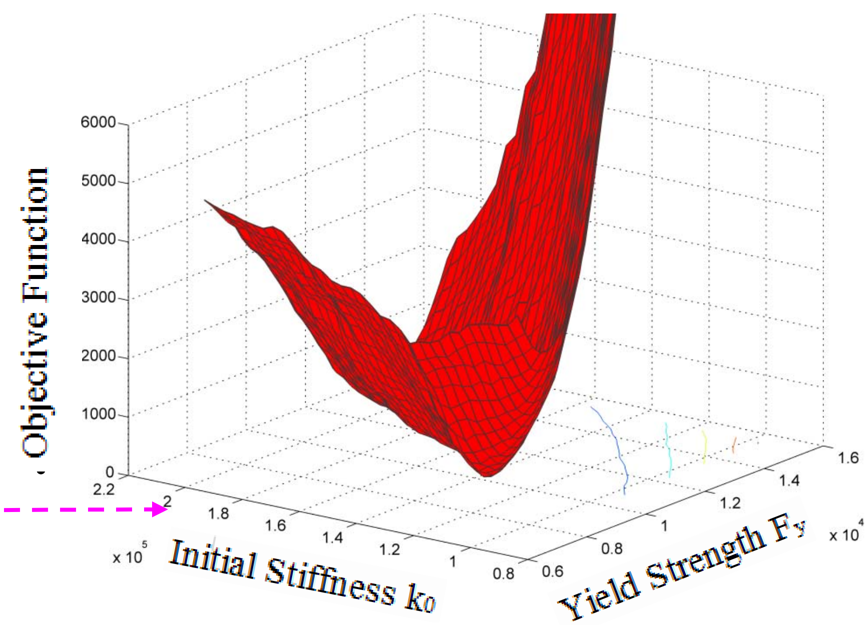
$$80{,}000 \le k_0 \le 187{,}200 \;\; \text{(kN/m)}$$

$$6{,}290 \le F_y \le 15{,}290 \;\; (kN)$$

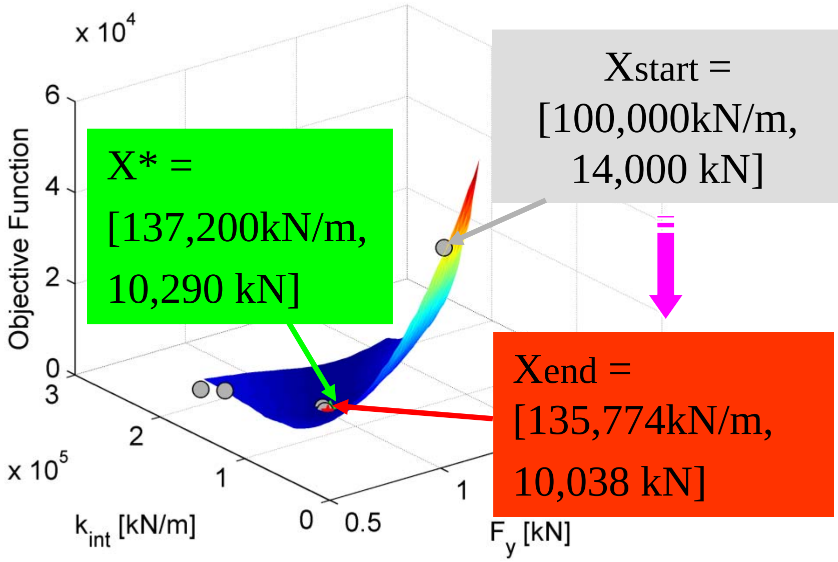
- **Starting Point:**

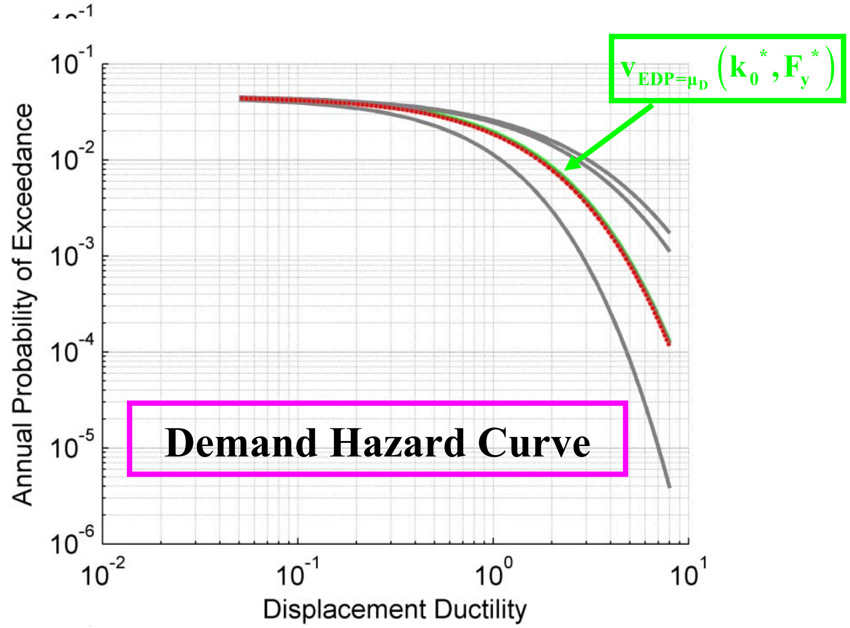
$$k_0^{(0)} = 100{,}000 \text{ kN/m}, \; F_y^{(0)} = 14{,}000\text{kN}$$

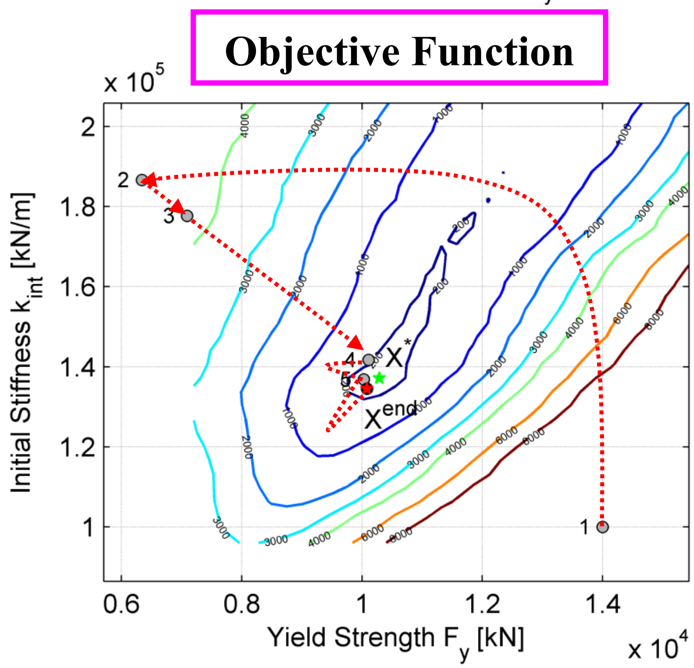


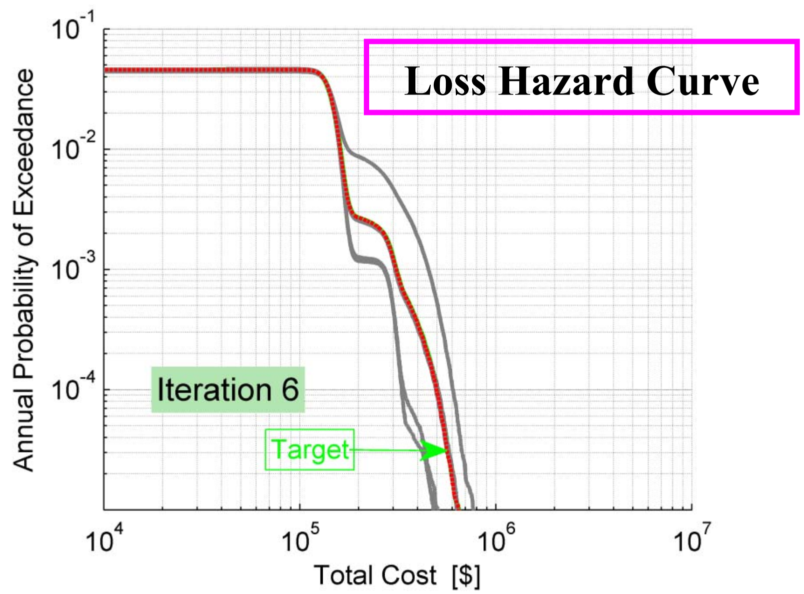


Optimization Results





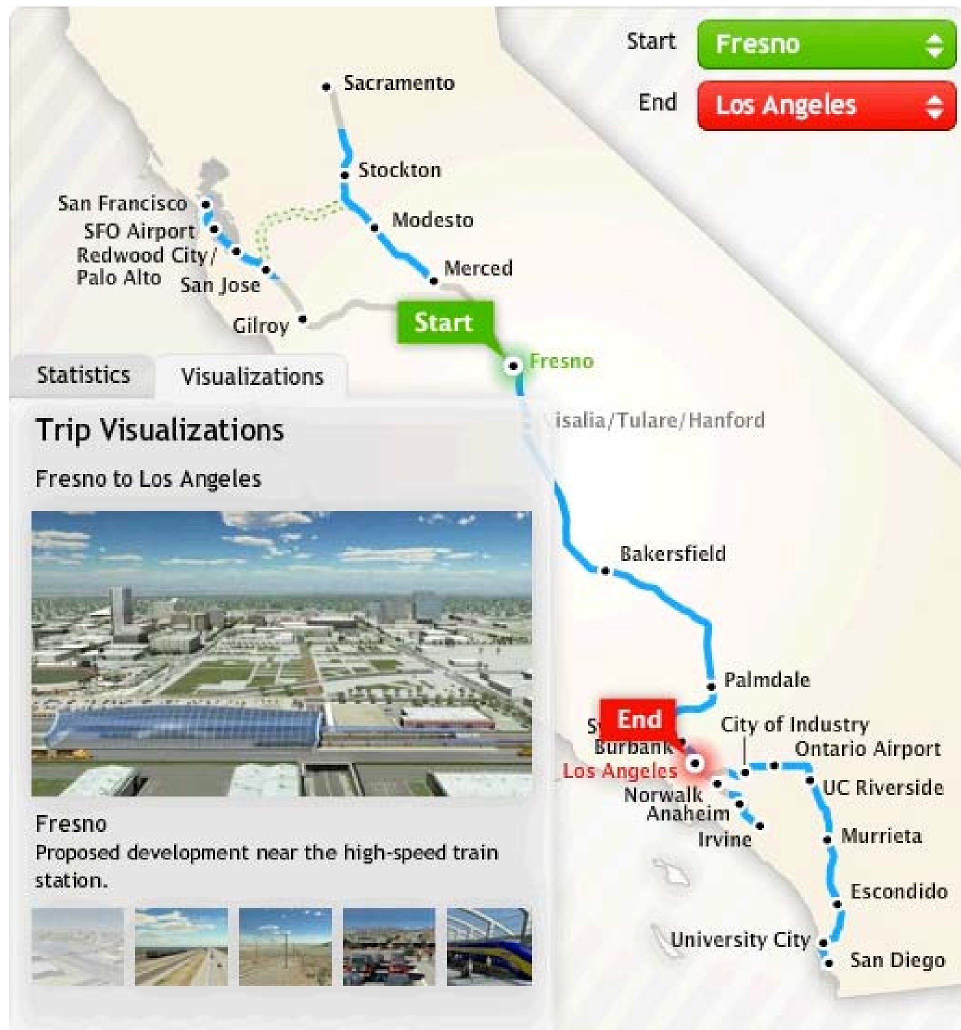




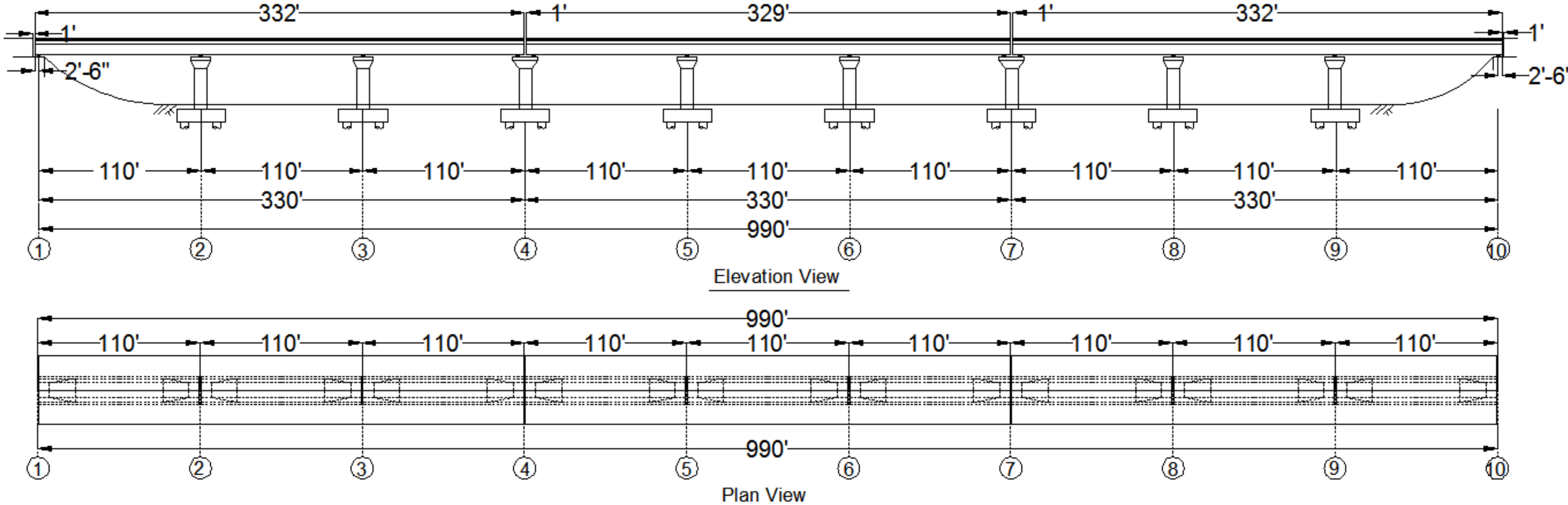
Current research based on application of OpenSees-SNOPT

Investigation of Seismic Isolation for CHSR Prototype Bridge

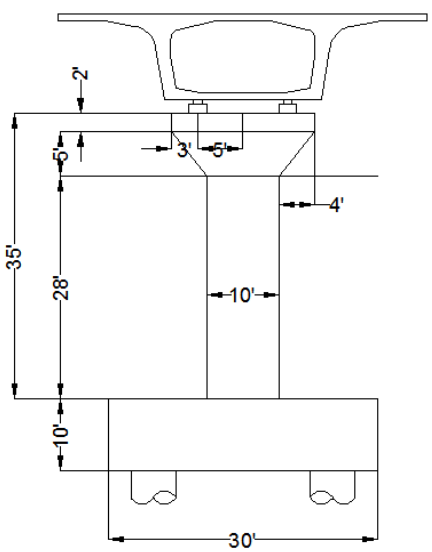
- California High-Speed Train Project (CHST)
- Arial/Bridge Structure Supporting System
- Seismic Isolation System (SIS)
- PEER Performance-based Earthquake Engineering (PBEE) Methodology
- Probabilistic Performance-based Optimization of SIS



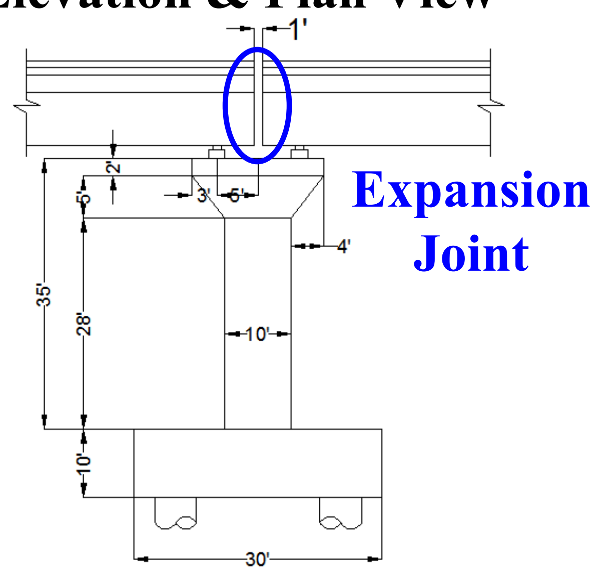
Schematic View of 110ft-Span Prototype Bridge



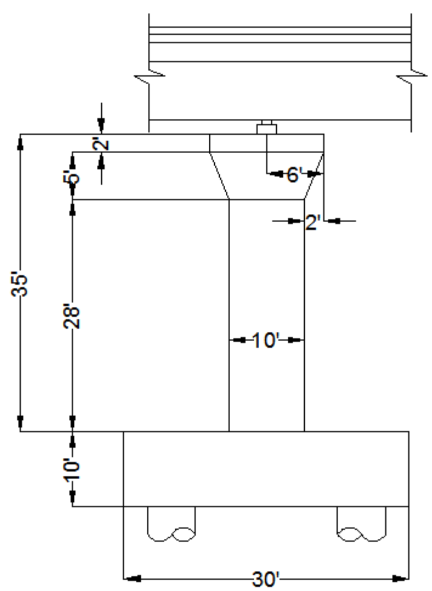
Elevation & Plan View



Transversal Section



Around Expansion Joint



Continuous Joint

Gu, Q., Barbato, M., Conte, J. P., Gill, P. E., and McKenna, F., "OpenSees-SNOPT Framework for Finite-Element-Based Optimization of Structural and Geotechnical Systems," *Journal of Structural Engineering*, ASCE, 138(6), 822-834, 2012.

Thank you !