Bridges Crossing Faults

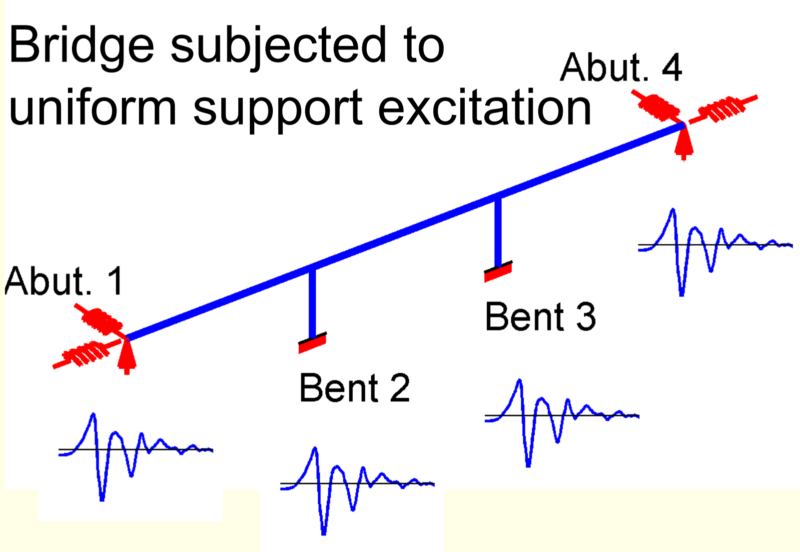
Presentation at PEER Annual Meeting
San Francisco, CA
October 16, 2009

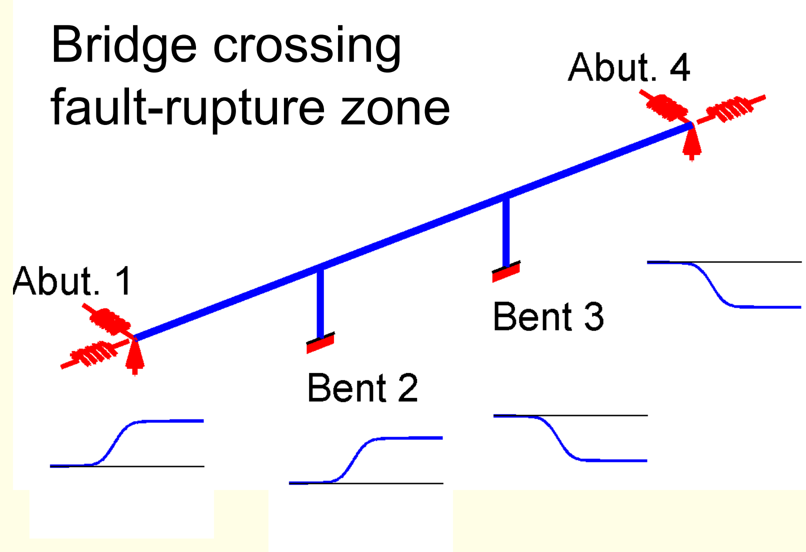
Rakesh K. Goel, PhD, PE, F.ASCE
California Polytechnic State University
San Luis Obispo, CA
rgoel@calpoly.edu

Objectives

- Develop simplified procedure to estimate seismic demands in “ordinary” bridges crossing fault-rupture zone
  - Rooted in structural dynamics theory
  - Simpler than nonlinear response history analysis
  - Utilize special feature of support motions in fault-rupture zones

Current Analytical Procedures





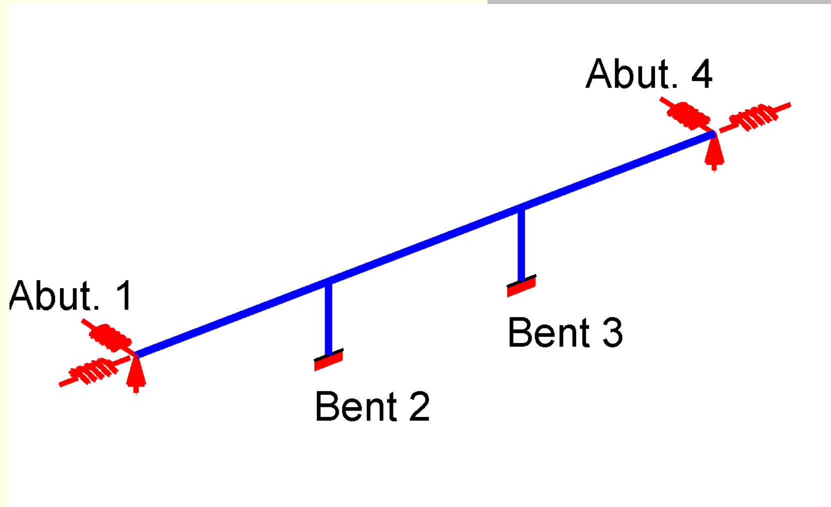
- Bridge subjected to uniform support excitation
  - Linear ELF analysis, NSP, Linear RSA, linear/nonlinear RHA
- Bridges crossing fault-rupture zones
  - Linear/nonlinear RHA for multiple support excitation

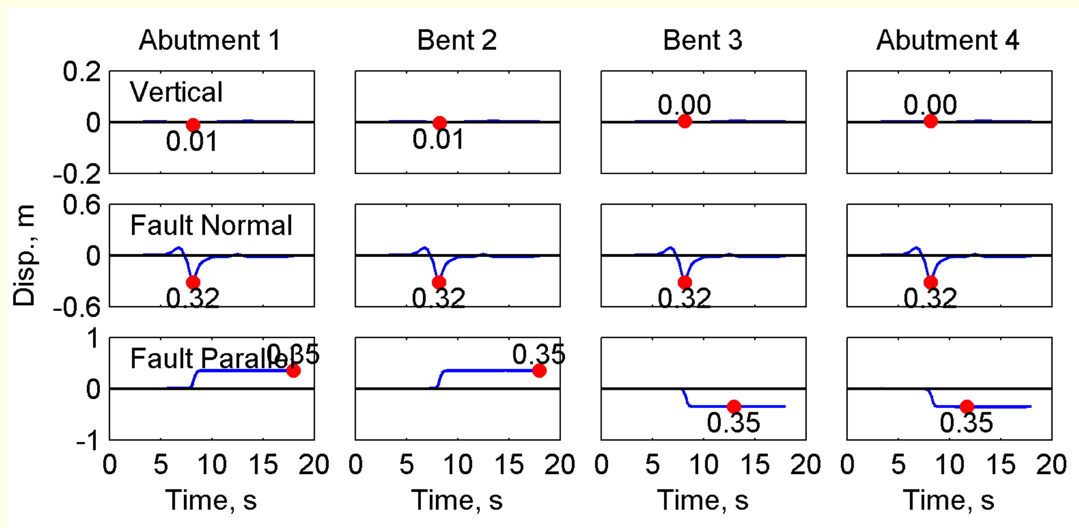
Ground Motions

- Motions at bridge supports on two sides of the fault are needed
  - Bridge supports are very close to the fault
    - Supports are within few tens of meters from the fault
  - Motions have not been recorded so close to the fault on both sides
    - Recorded motions are at few hundred meters from the fault
  - Support motions were simulated on faults with various orientations
    - Simulations by Prof. Doug Dreger at UC Berkeley

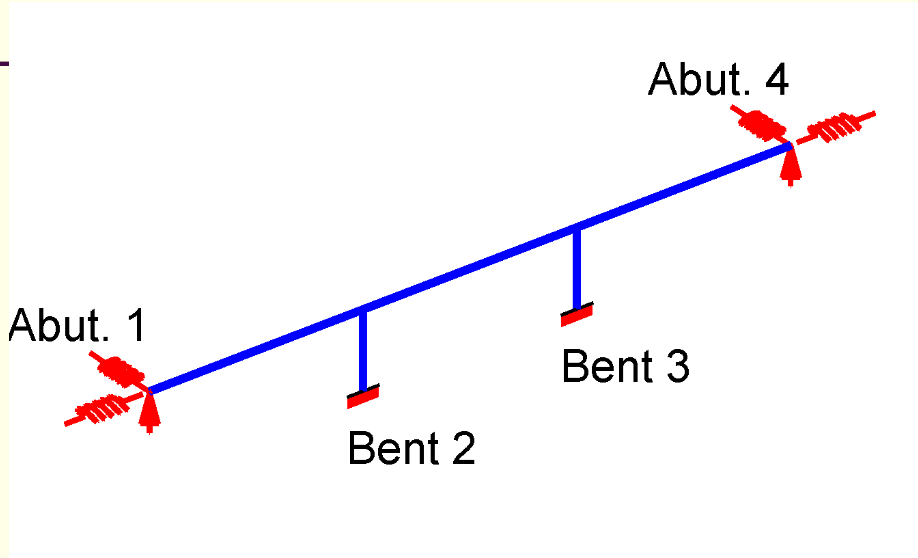
Motions Across Strike-Slip Fault

- FP motions are anti-symmetric with respect to the fault
- FN motions are symmetric with respect to the fault
- Vertical motions are anti-symmetric with respect to the fault
  - Vertical motions for strike-slip fault at selected location are very small





Motions in Fault-Rupture Zones



$$u_{gl}(t) = \alpha_l \, u_g(t)$$

Motion at l^{th} Support

Motion at a Reference Location

Proportionality Constant

Proportional Multiple-Support Excitation

Proportional Excitation – Strike-Slip Fault

$$u_{gl}(t) = \alpha_l u_{g,Abut1}(t)$$

Fault-Parallel Motions

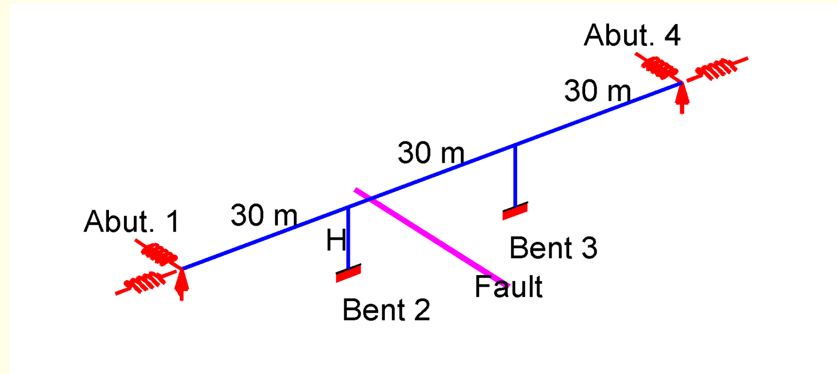
$$\alpha_{Abut1} \text{ and } \alpha_{Bent2} = 1$$

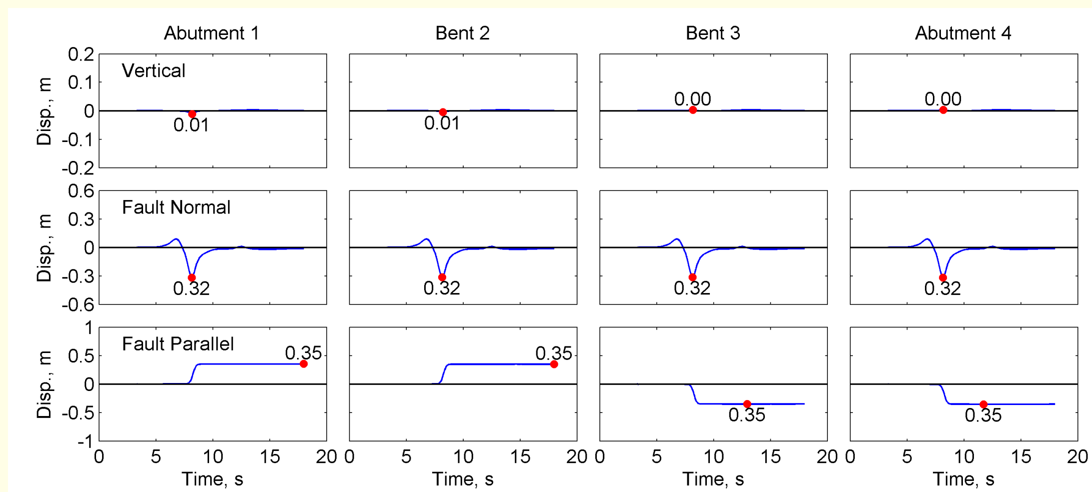
$$\alpha_{Bent3} \text{ and } \alpha_{Abut4} = -1$$

Fault-Normal Motions

$$\alpha_{Abut1} \text{ and } \alpha_{Bent2} = 1$$

$$\alpha_{Bent3} \text{ and } \alpha_{Abut4} = 1$$





Equations of Motion: Linear Systems

General Multiple -Support Excitation

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -\mathbf{m}\sum_{l=1}^{N_g} \iota_l \ddot{u}_{gl}(t)$$

$$\mathbf{u}^t(t) = \boxed{\sum_{l=1}^{N_g} \iota_l u_{gl}(t)}$$

$$+\boxed{\sum_{l=1}^{N_g}\left[\sum_{n=1}^{N} \Gamma_{nl}\phi_n D_{nl}(t)\right]}$$

Quasi-Static

Dynamic

Proportional Multiple -Support Excitation

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -\mathbf{m}\iota_{\text{eff}} \ddot{u}_g(t)$$

$$\mathbf{u}^t(t) = \boxed{\iota_{\text{eff}} u_g(t)}$$

$$+\boxed{\sum_{n=1}^{N} \Gamma_n \phi_n D_n(t)}$$

Peak Response

$$\mathbf{u}_o^t \simeq \mathbf{u}_o^s + \mathbf{u}_o$$

Peak response from dynamic analysis:
Combine peak values from significant modes using appropriate combination rule: SRSS or CQC

Peak response from quasi-static analysis:
Apply peak support displacements statically

$$\mathbf{u}_o^s = \iota_{\text{eff}}\, u_{go}$$

Dynamic Response

$$\mathbf{u}_o \simeq \left[\sum_{n=1}^{J \le N} \left(\mathbf{u}_{no} \right)^2 \right]^{1/2}$$

$$\mathbf{u}_{no} = \Gamma_n \phi_n D_{no}$$

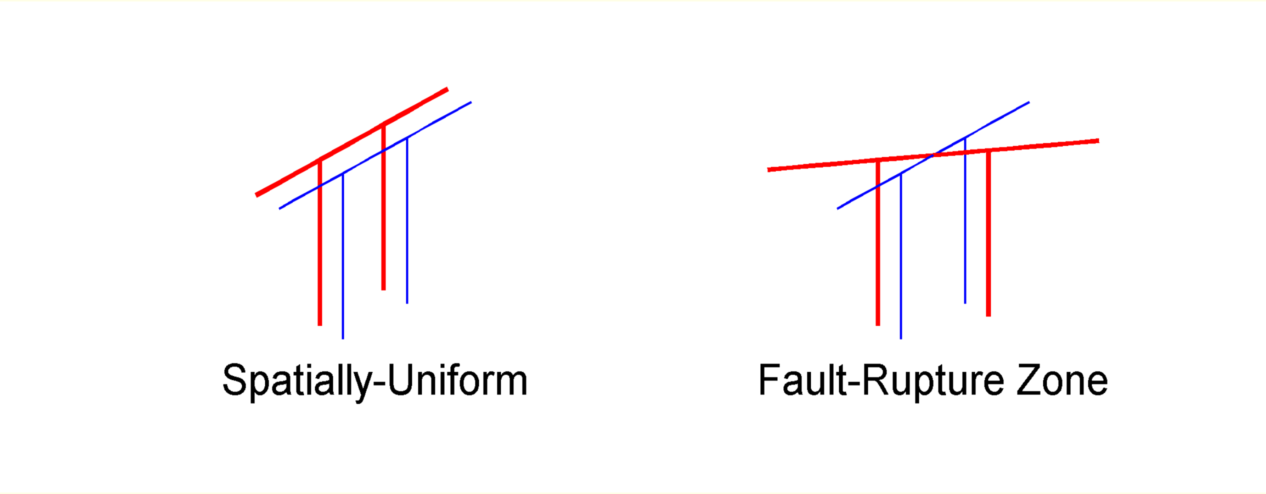
Peak Displacement of SDF System with T_n and ζ_n From Response or Design Spectrum

$$\Gamma_n = \frac{\phi_n^T \mathbf{m} \iota_{\text{eff}}}{\phi_n^T m \phi_n}$$

Utilizes "Effective" Influence Vector
Not same as standard RSA

Effective Influence Vector

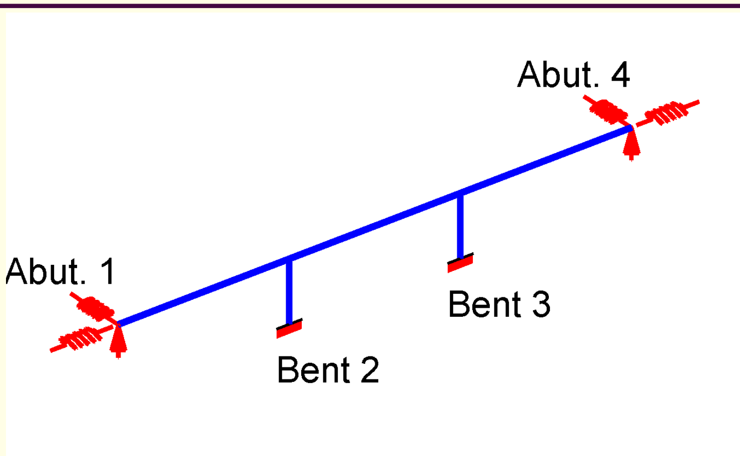
- Essentially translation in bridges subjected to spatially uniform support excitation
- Significant torsional motions about a vertical axis in bridges crossing fault-rupture zones

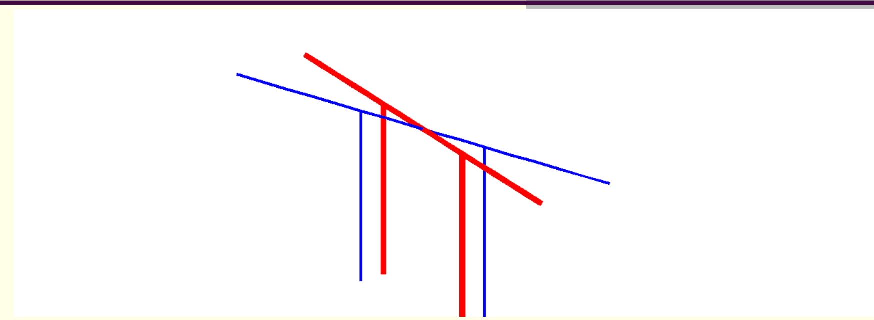


Analysis: Linear Systems

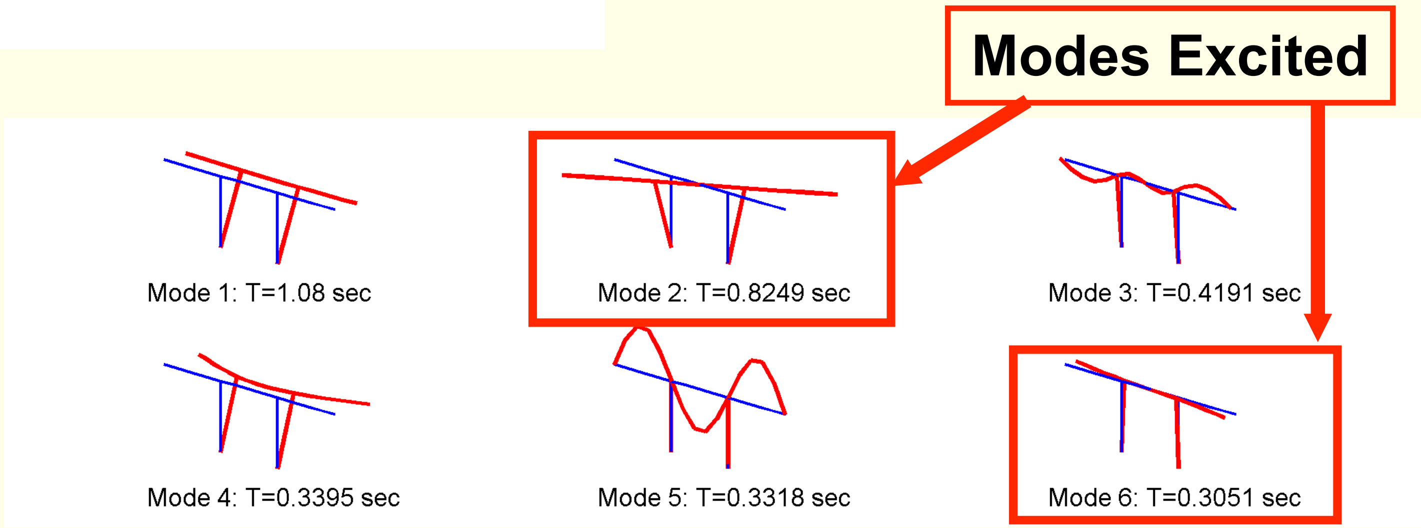
- RHA: Response history analysis to multiple-support excitation
- RSA: Response spectrum analysis
  - Use ground motions spectrum that is appropriate for motions in fault-rupture zones
  - Carefully select modes that are excited by motions in fault rupture zones
- RSA:1-Mode: Response spectrum analysis considering only the most dominant mode
- LSA: Linear static analysis due to forces equal to $2.5\boldsymbol{m}\iota_{eff}\ddot{u}_{go}$

Modes Excited

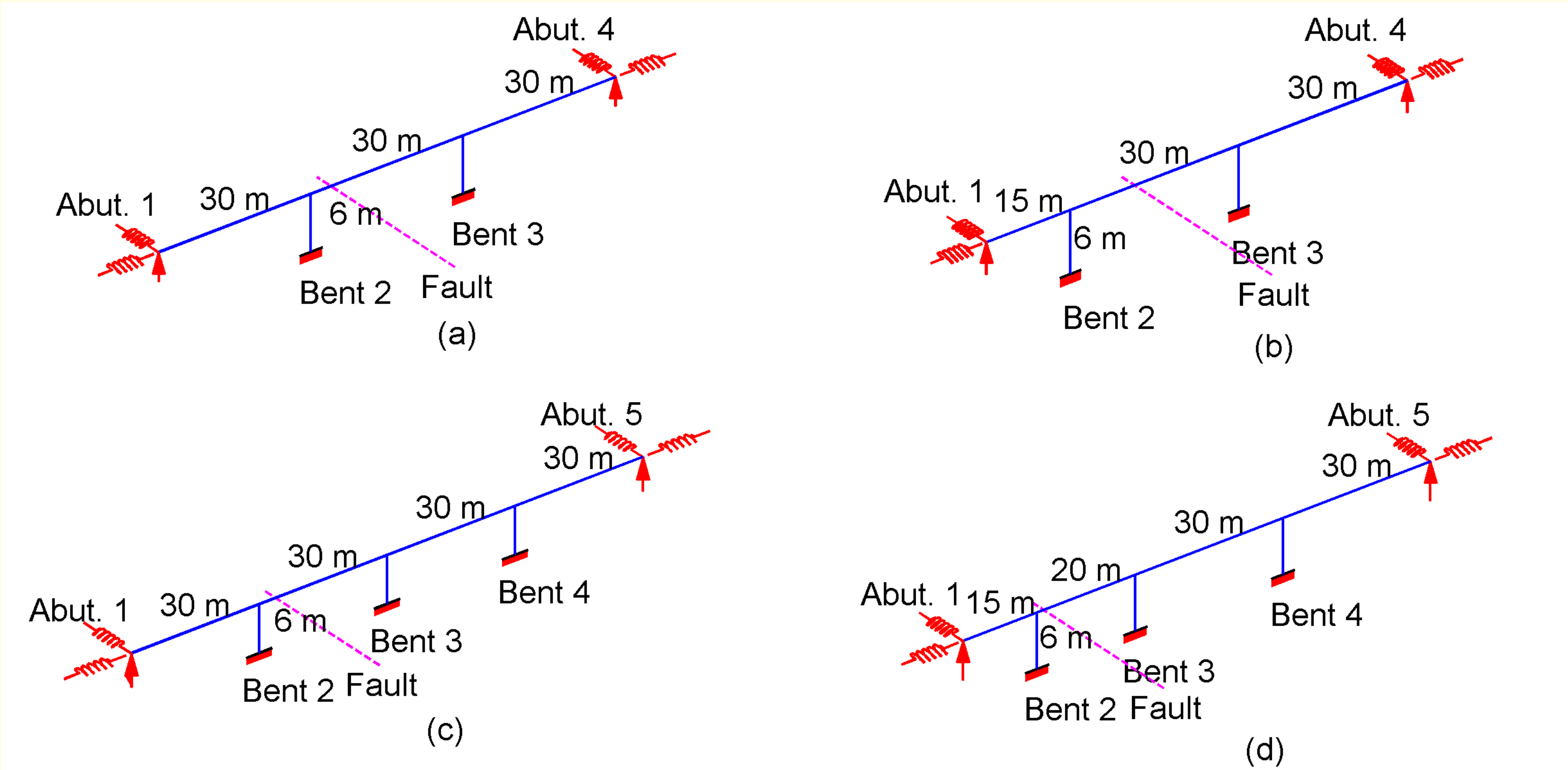




“Effective” Influence Vector

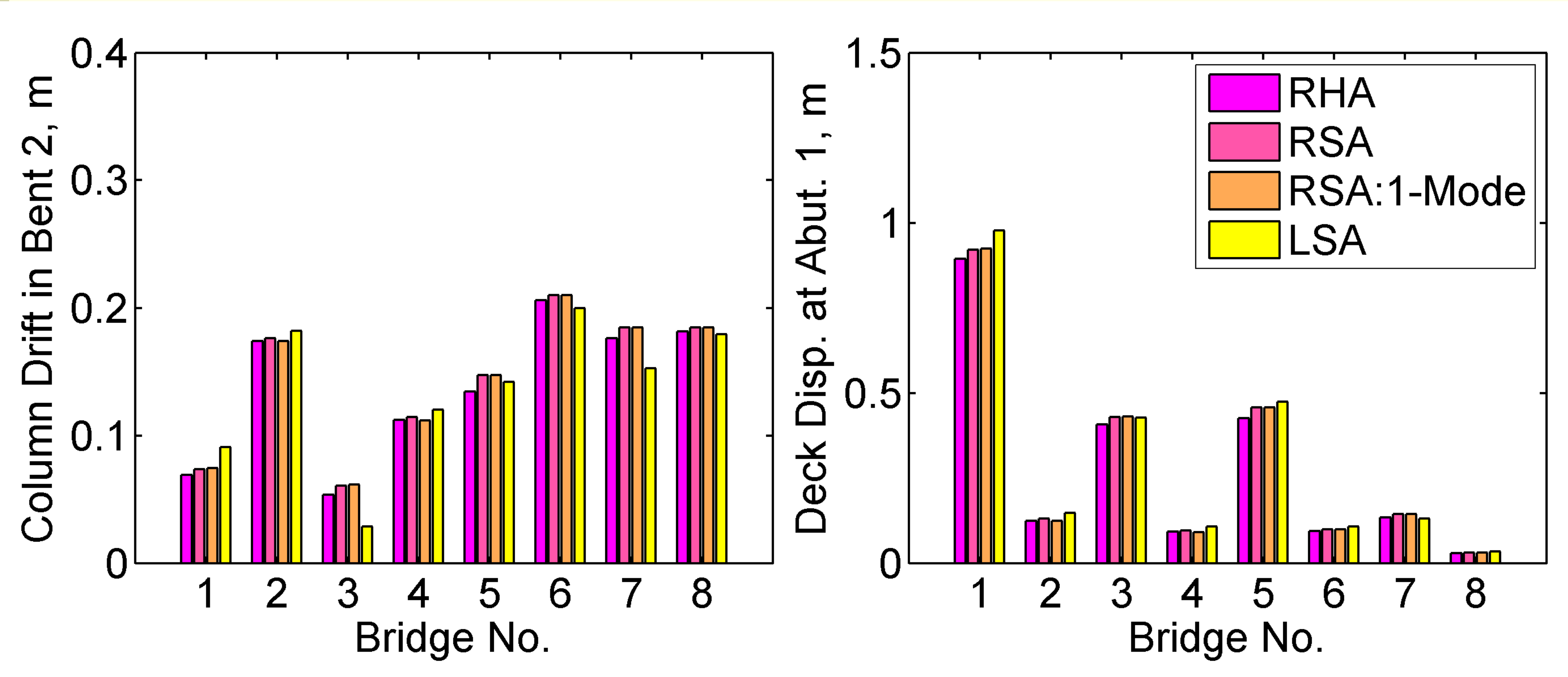


Bridges Selected



Shear Key Cases: Elastic shear keys and no shear keys

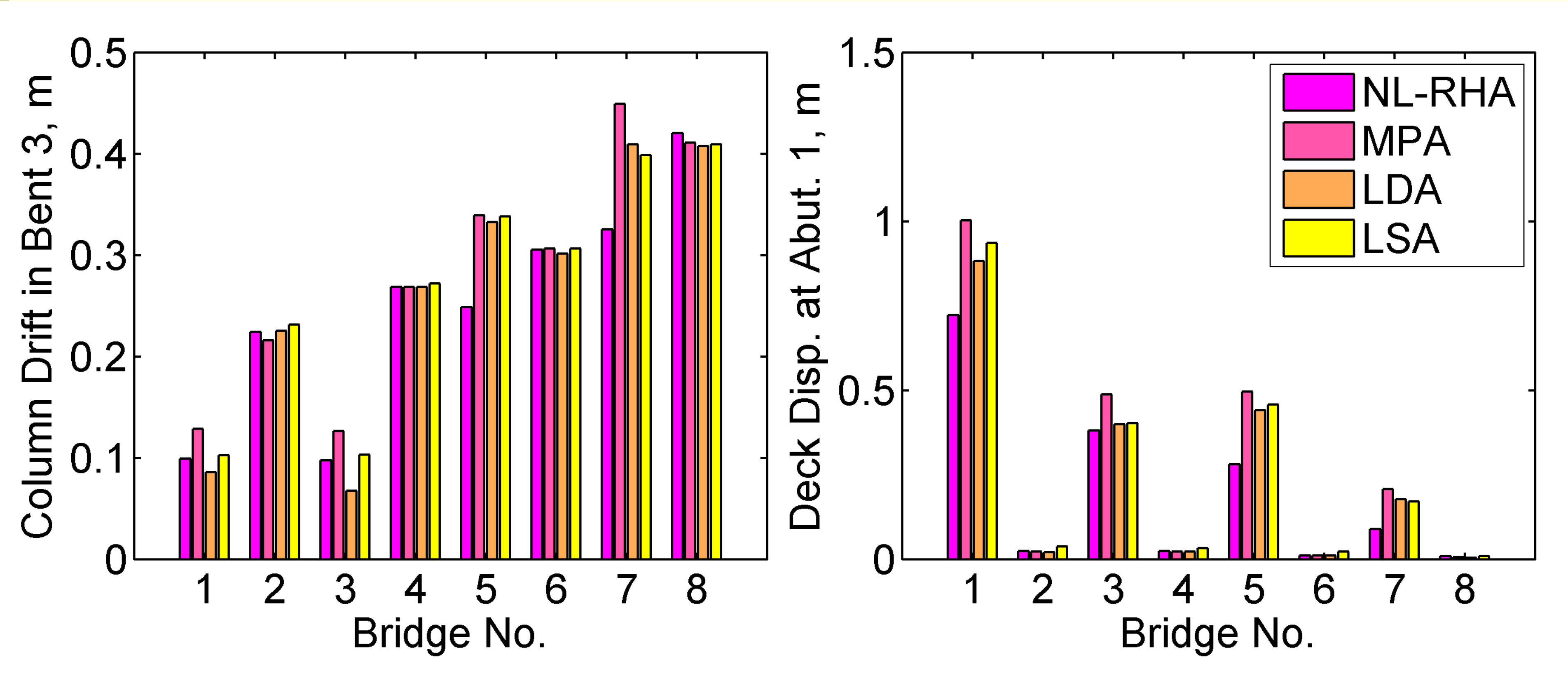
Response of Linear Bridges



Extension to Nonlinear Bridges

- Superposition assumed to be applicable
- Quasi-static response from **nonlinear static analysis** due to peak ground displacements applied simultaneously at all supports
- Dynamic response from
  - MPA: Modal pushover analysis (nonlinear static pushover)
  - LDA: Linear dynamic analysis (RSA or RSA: 1-Mode)
  - LSA: Linear static analysis due to forces equal to $2.5\boldsymbol{m}\iota_{eff}\ddot{u}_{go}$

Response of Nonlinear Bridges



Recommended Procedure

- Linear Static Analysis Procedure
  - Compute the peak value of the quasi-static response including effects of gravity loads by nonlinear static analysis of the bridge due to peak ground displacement applied at all supports simultaneously
  - Compute peak value of the dynamic response by linear static analysis of the bridge due to lateral forces equal to $2.5\boldsymbol{m}\iota_{eff}\ddot{u}_{go}$
    - Carefully compute the effective influence vector, which differs for bridges in fault-rupture zones
  - Compute the total response as superposition of the quasi-static and dynamic responses

Recommended Procedure

- Linear static analysis procedure is recommended because
  - It is simple to implement
  - It does not require mode shapes and frequencies
  - Provides results that are “accurate” for most practical applications
  - MPA and LDA are more complicated and offer only slight improvement

Acknowledgment

- Support provided by Caltrans
  - Contract No. 59A0435 with Mahmoud Khojasteh as project manager
- Prof. Anil Chopra, University of California at Berkeley
  - Principal Investigator
- Prof. Doug Dreger and Gabriel Hurtado
  - Simulated ground motions across fault rupture zones