University of Nevada, Reno

Influence of Vertical Ground Shaking on Design of Bridges Isolated with Friction Pendulum Bearings

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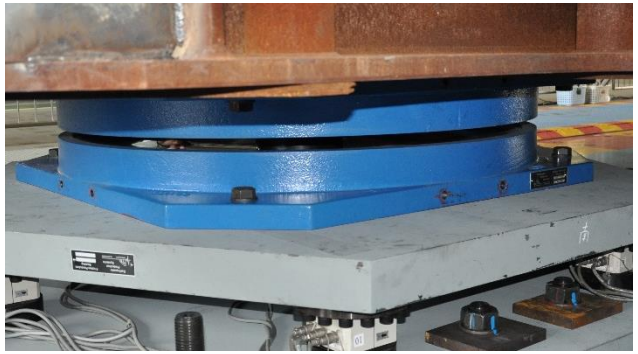
Motivation: Results of Full-Scale Building Tests at E-Defense

Isolated with triple friction pendulum bearings (TPB)



Isolated with hybrid configuration of lead-rubber and cross-linear bearings

Fixed at the base

Period T = 0.7 sec
First Yield Base Shear ~ 0.67W

Experimentally Observed Influence of Vertical Shaking in Isolated Buildings - Summary

Effect	Building Configurations Affected	Predicted Significance for Bridges
Increased Base Shear due to Friction	TPB	Bridges will experience increased base shear, similar to buildings. Expected to influence column design.
Increased Horizontal Accelerations due to H-V Coupling	Primarily TPB (small in LRB, fixed base)	Insignificant for bridges
Floor Slab Vibration as a Direct Effect of Vertical Shaking	All configurations	Bridge spans may be susceptible to large vertical accelerations mid-span.

Objective/Scope of PEER Pendulum Bearing Study

- **Objective 1**: Comprehensively evaluate influence of vertical shaking on base shear/column forces in representative isolated bridges.
- **Objective 2**: Based on study, develop guidance for accounting for the influence of vertical shaking in design (e.g. required time history analysis, amplification factor based on V/H, etc.)

Scope of Investigation:

- Develop computational models in OpenSees for archetype bridges isolated with FPB
- Include important parameter variation (e.g. number of spans, span length, pier/column flexibility, and isolation system parameters).
- Statistical evaluation of isolator/column shear and other responses of interest through time history analysis to a suite of 3D motions

Bridge Selection Strategy

- Ramanathan (2012) conducted a comprehensive investigation of the California bridge inventory to develop fragility curves for common bridge types.
- NBI provides information regarding number of spans, maximum span length, deck width, minimum vertical under clearance. Column heights were inferred from vertical clearance.
- Bridge classes in California are classified under thirteen main types, where the three most common are listed below.

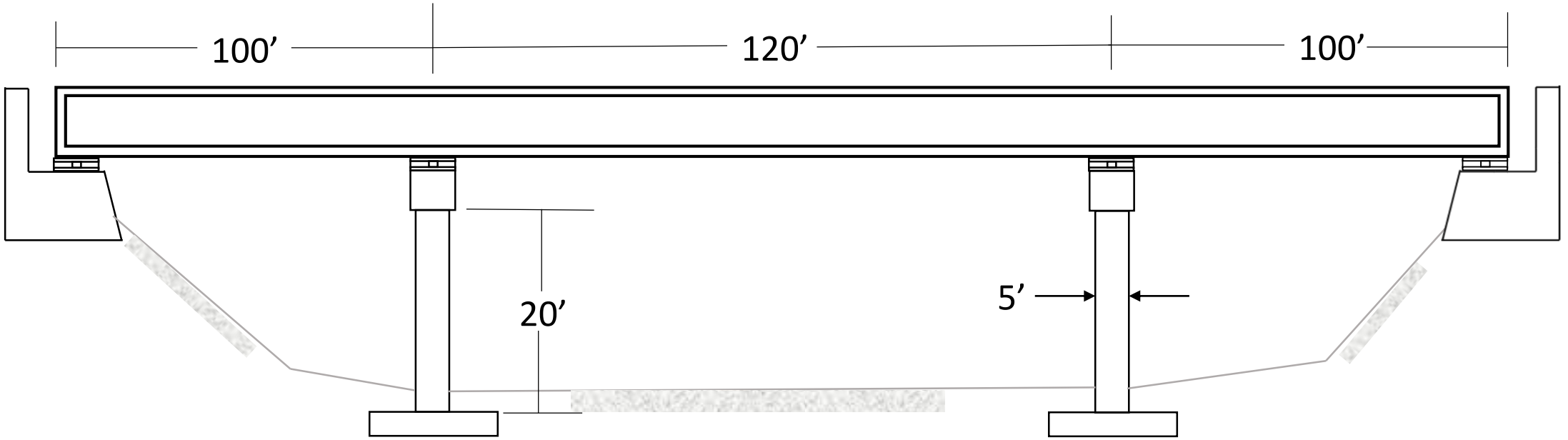
Bridge Class	Nomenclature	Bridge Count		Suitable for Isolation
		Count	Percentage	
Multi-span continuous concrete box-girder	MSCBG	5314	20.89	Yes (*Focus on this class.*)
Multi-span continuous slab	MSCSL	4004	15.74	No
Multi-span continuous concrete girder	MSCG	2164	8.51	Yes

Source: Ramanathan, K. (2012). Next Generation Seismic Fragility curves for California Bridges Incorporating the Evaluation in Seismic Design Philosophy. PhD Dissertation, Georgia Institute of Technology

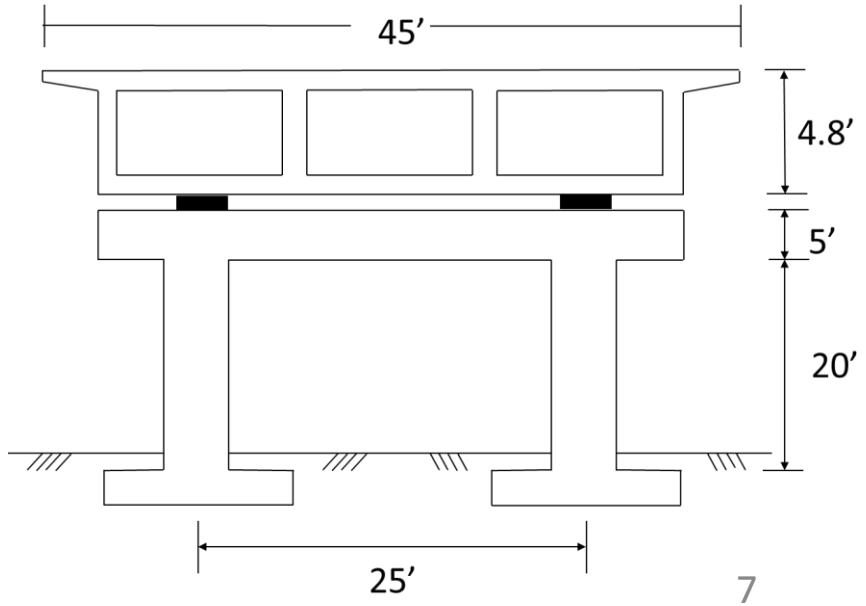
Feedback from Advisory Board Meeting – 6/6/18

- **Members: Allaoua Kartoum (Caltrans), Bijan Khalegi (WashDOT), Mason Walters (Forell-Elsesser)**
- Continuous bridge configurations are preferred, and expansion joints are generally not needed.
- Concrete box girder is the preferred bridge class in California, with span lengths from 150-200 ft.
- Steel girder is the preferred bridge class in Washington. Use low number of girders with cross frames.
- Isolation system parameters: T_2 = 2 to 5 sec, Q/W = 0.04 to 0.08.
- Include foundation springs to represent site conditions.

Continuous Concrete Box Girder Bridge: Base Configuration



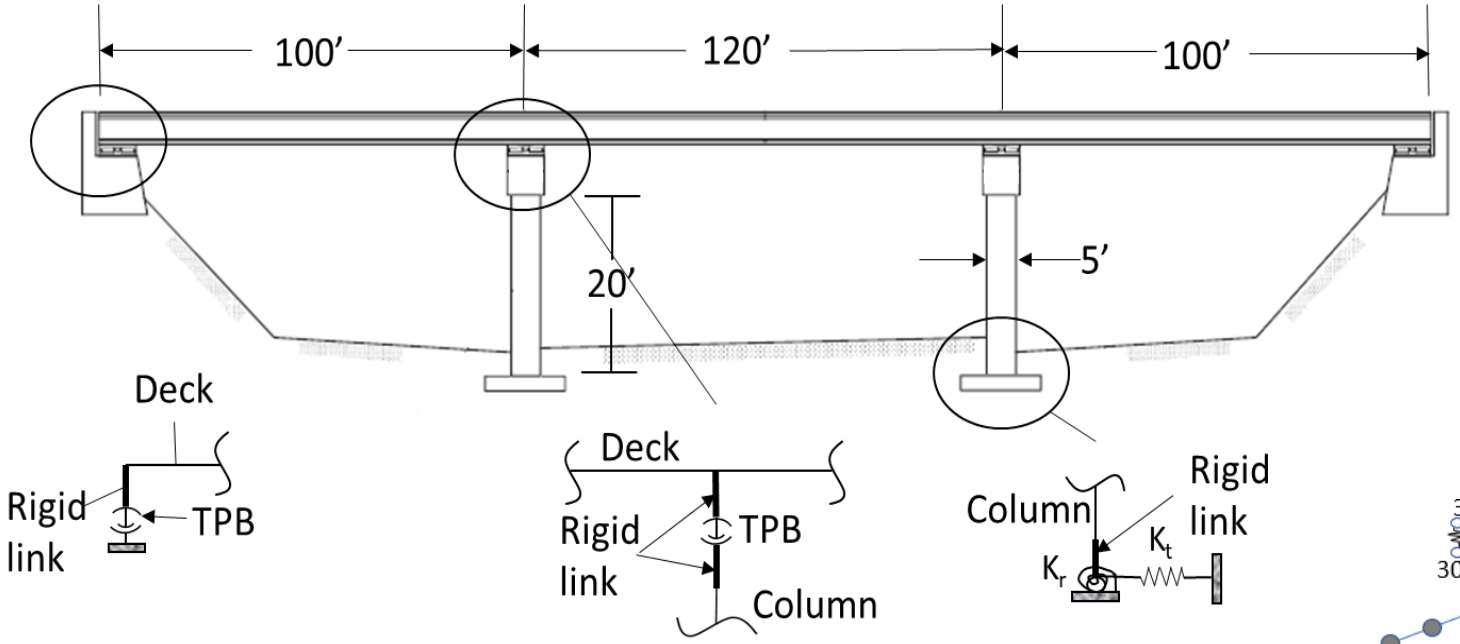
- **Three-span continuous concrete box girder bridge**
- Middle span length = 120’; end spans = 100’
- Two column bents:
  - Column height = 20’; column diameter = 5’
  - Bent depth = 5’, Distance between columns = 25’
- Superstructure = 3 cell box girder
  - Girder dimensions
- Seat type abutment with unlimited expansion gap



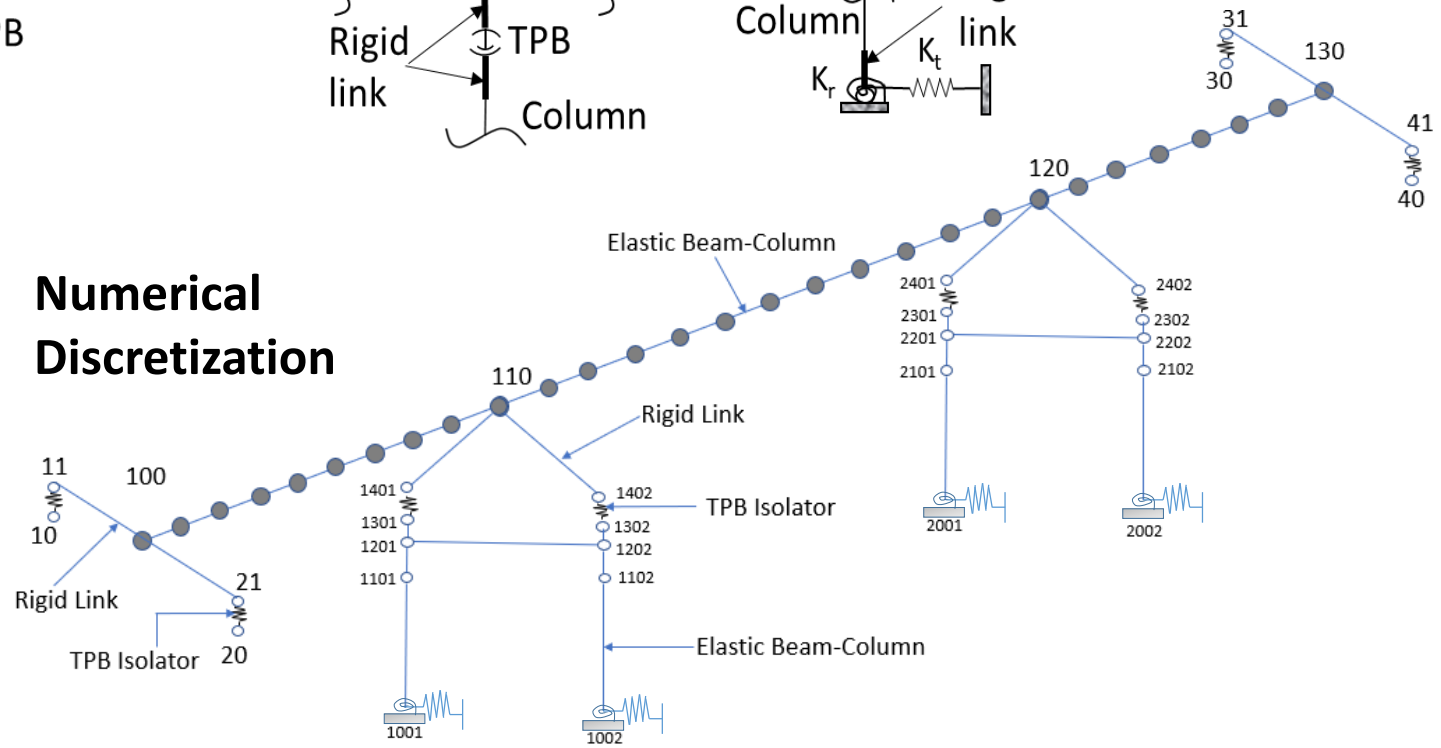
Continuous Concrete Box Girder Bridge: Modeling Assumptions

Modeling Assumptions

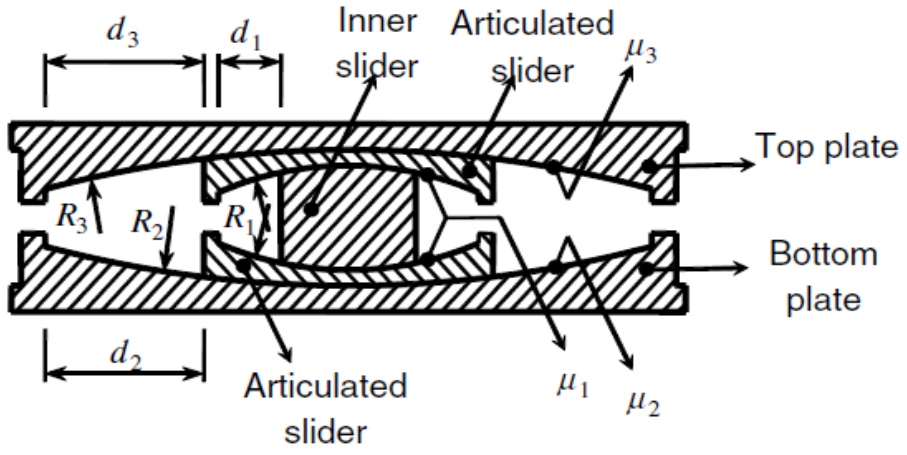
- Spine Model; Uses Elastic Frame Elements for Superstructure, Columns, Bent Cap
- Discretization of Superstructure Elements to Distribute Mass
- Unrestrained Movement at the Abutment
- Rayleigh Damping Applied to Non-Bearing Elements
- Translational/Rotational Foundations Springs Representing Stiff Soil

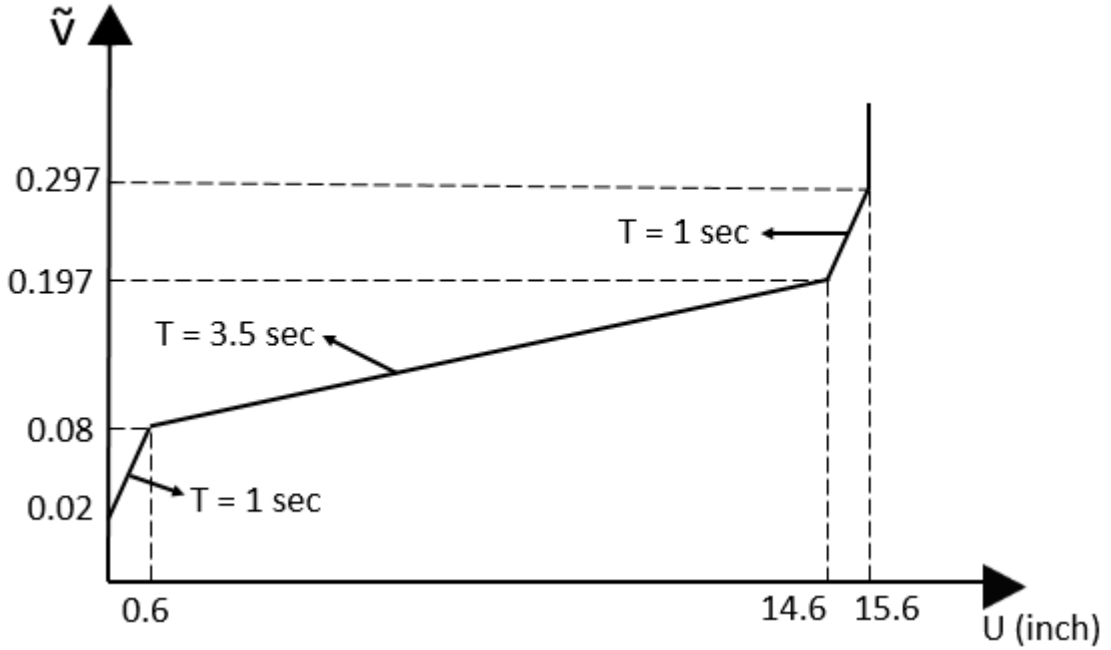


Numerical Discretization



TPB Isolator Modeling Assumptions





Isolator Model

- Used Triple Pendulum Bearing Element in OpenSees
- Bearing has sufficient capacity so that stiffening regime is not engaged.
- Bearing vertical stiffness calibrated to T_v = 0.03 sec

Ground Motion Selection

Abbreviation	NGA #	Event	Year	Station	M_W	R_{rup} (km)	V_{s30} (m/s)
SFPU	77	San Fernando	1971	Pacoima Dam (upper left abut)	6.61	1.81	2016
IIB	285	Irpinia, Italy-01	1980	Bagnoli Irpinio	6.9	8.18	1000
IIS	292	Irpinia, Italy-01	1980	Sturno	6.9	10.84	1000
LPG	763	Loma Prieta	1989	Gilroy - Gavilan Coll.	6.93	9.96	729.7
CAM	825	Cape Mendocino	1992	Cape Mendocino	7.01	6.96	513.7
LAL	879	Landers	1992	Lucerne	7.28	2.19	1369
NPD	1050	Northridge-01	1994	Pacoima Dam (downstr)	6.69	7.01	2016.1
NPA	1051	Northridge-01	1994	Pacoima Dam (upper left)	6.69	7.01	2016.1
KCL	1148	Kocaeli, Turkey	1999	Arcelik	7.51	13.49	523
CT46	1486	Chi-Chi, Taiwan	1999	TCU046	7.62	16.74	465.6
CT78	3473	Chi-Chi, Taiwan-06	1999	TCU078	6.3	11.52	443

Source: Carlton (2014). An Improved Description of the Seismic Response of Sites with High Plasticity Soil, Organic Clays, and Deep Soft Soil Deposits. PEER Report, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Selection and Scaling

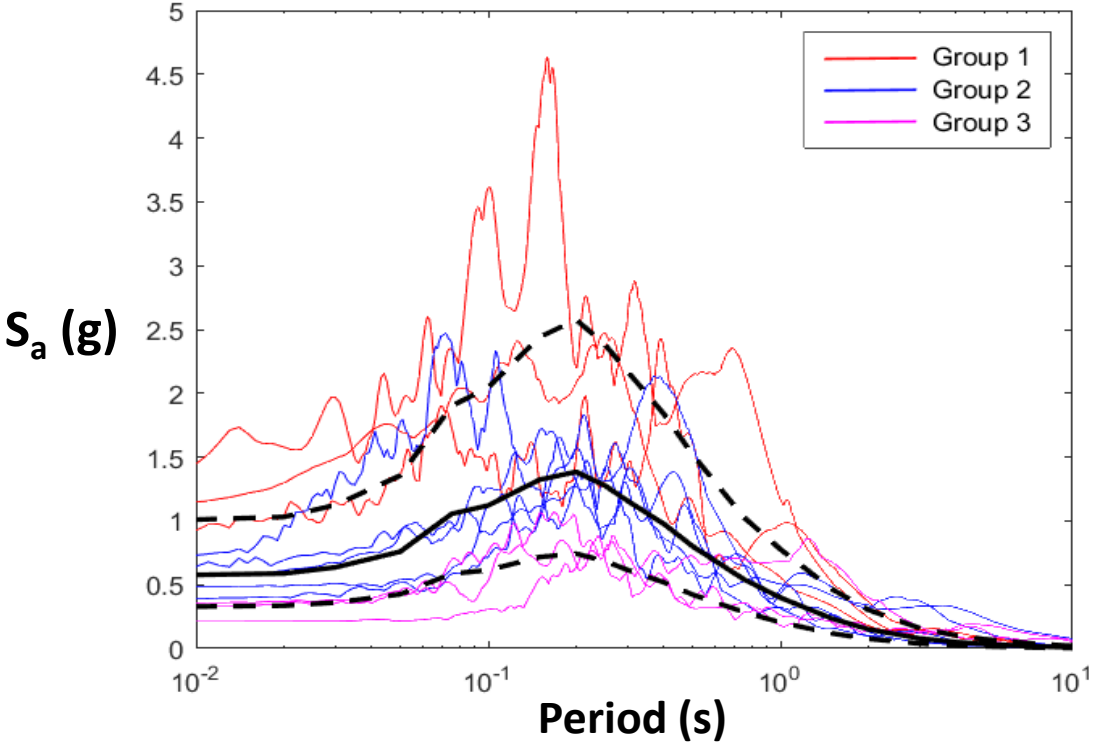
- Used suite developed by Carlton (2014) for shallow crustal earthquakes with near-fault effects.
- Motions were rotated so that spectral acceleration S_a at T = 1.0 sec was maximized, and amplitude scaled to represent the median and standard deviation (distribution) of the target spectrum.
- We developed a vertical target spectrum from the horizontal target spectrum, and scaled the vertical components accordingly.

Ground Motion Spectra

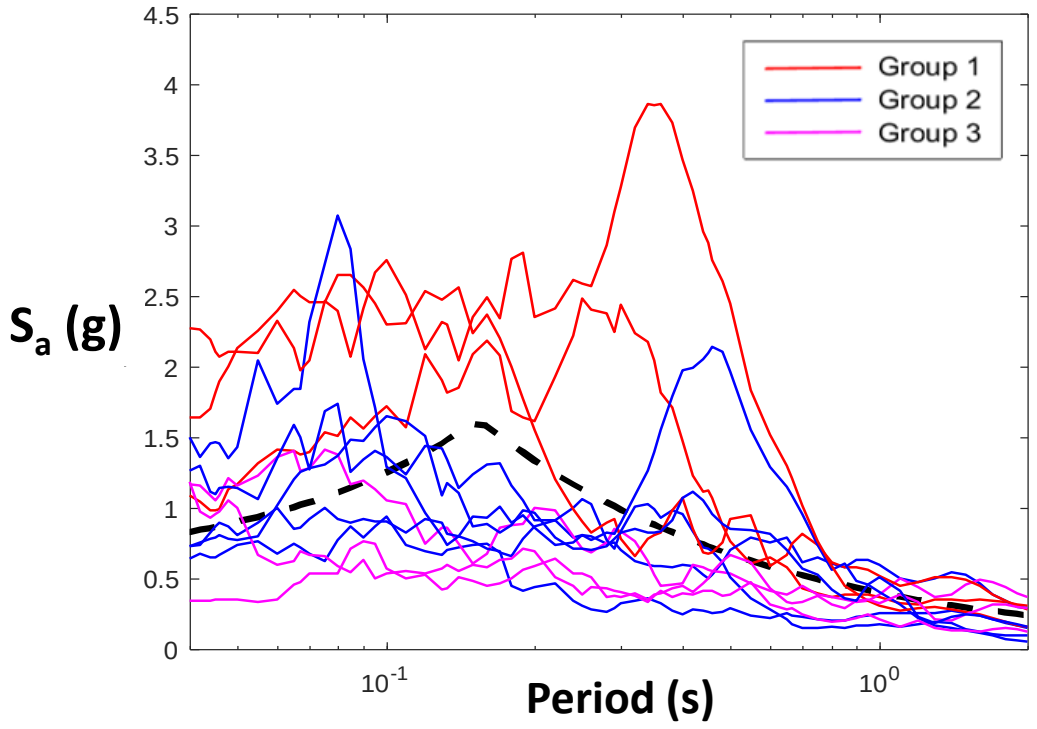
Ground motions were further sorted into bins according to vertical acceleration intensity (vPGA)

Group #	Motions Included	vPGA range (with Scaling)
Group 1 (Large vPGA)	SFPU, CAM, NPA	0.8g – 1.7g
Group 2 (Moderate vPGA)	LPG, LAL, NPD, CT78, IIS	0.5g – 0.7g
Group 3 (Small vPGA)	IIB, KCL, CT46	0.2g – 0.4g

Horizontal Acceleration Spectra



Vertical Acceleration Spectra

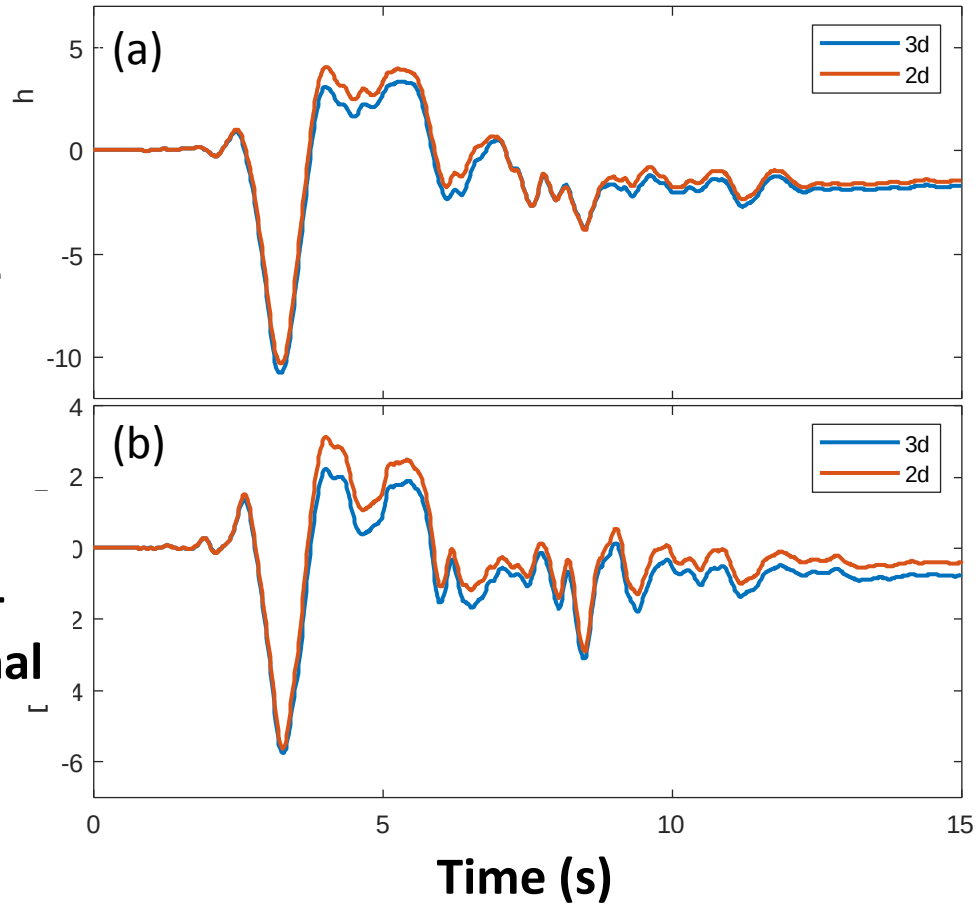


Representative History Responses: Isolator Displacement

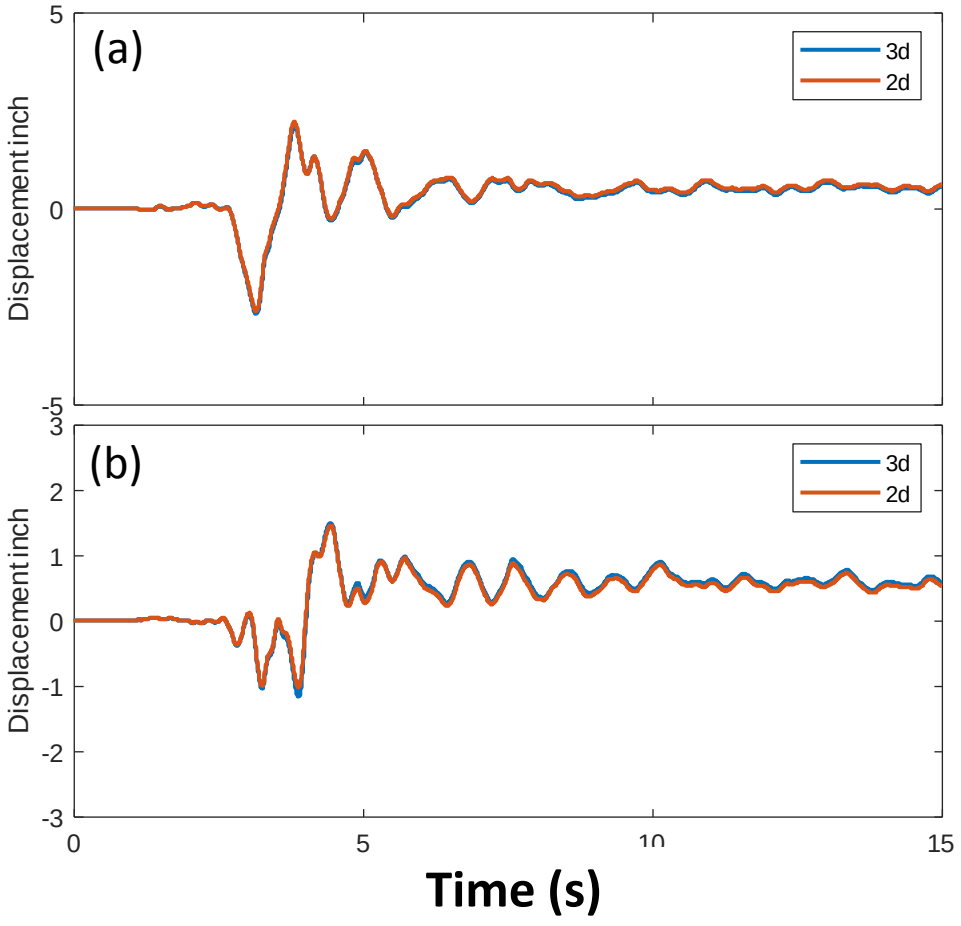
Isolator Disp. (in) - Transverse

Isolator Disp. (in) – Longitudinal

SFPU (Group 1, Large vPGA)



LPG (Group 2, Moderate vPGA)

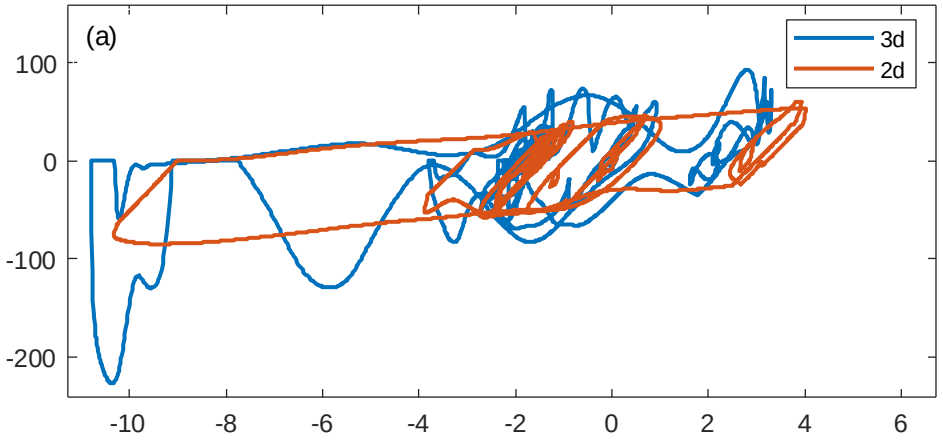


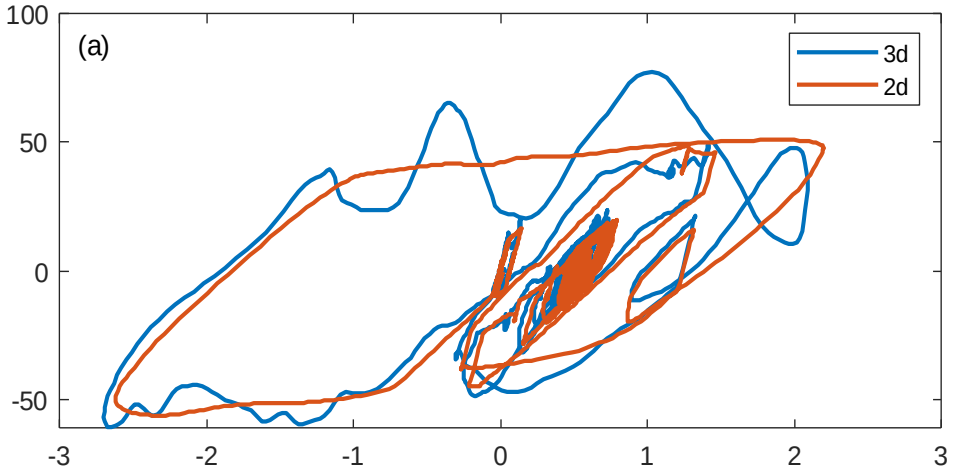
Representative Responses: Hysteresis Loop

SFPU (Group 1, Large vPGA)

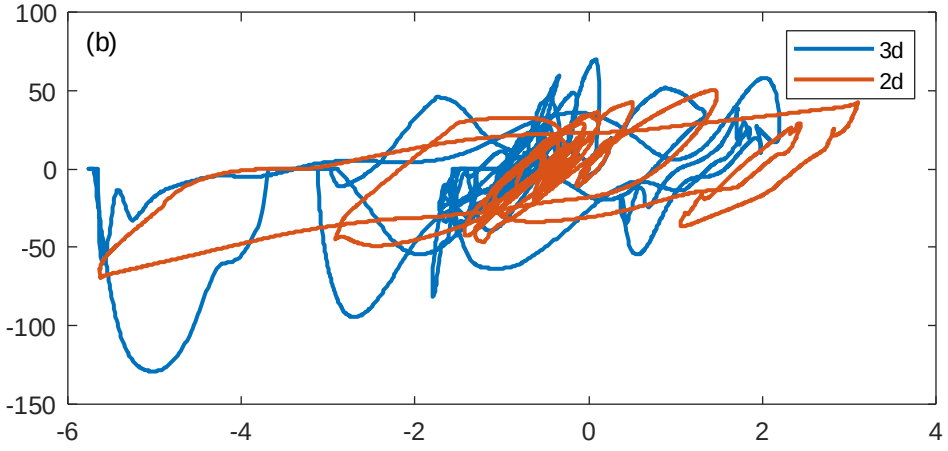
LPG (Group 2, Moderate vPGA)

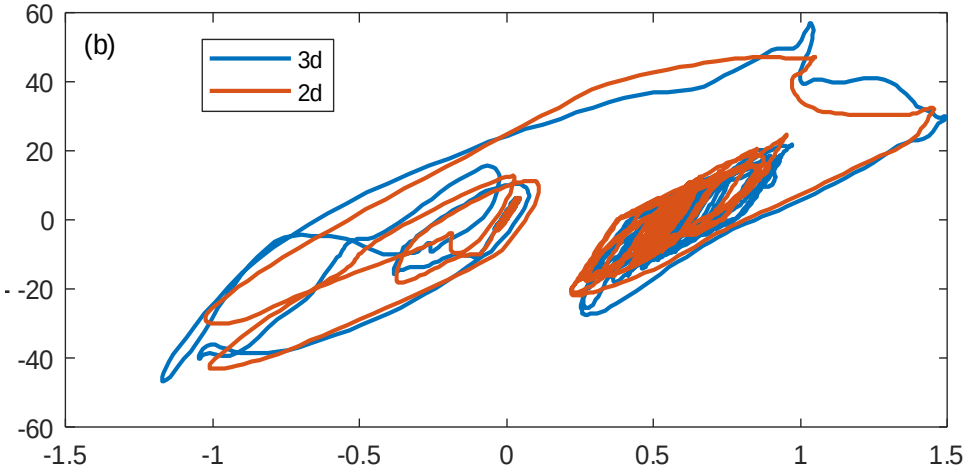
Isolator Force (k) Transverse





Isolator Force (k) Longitudinal

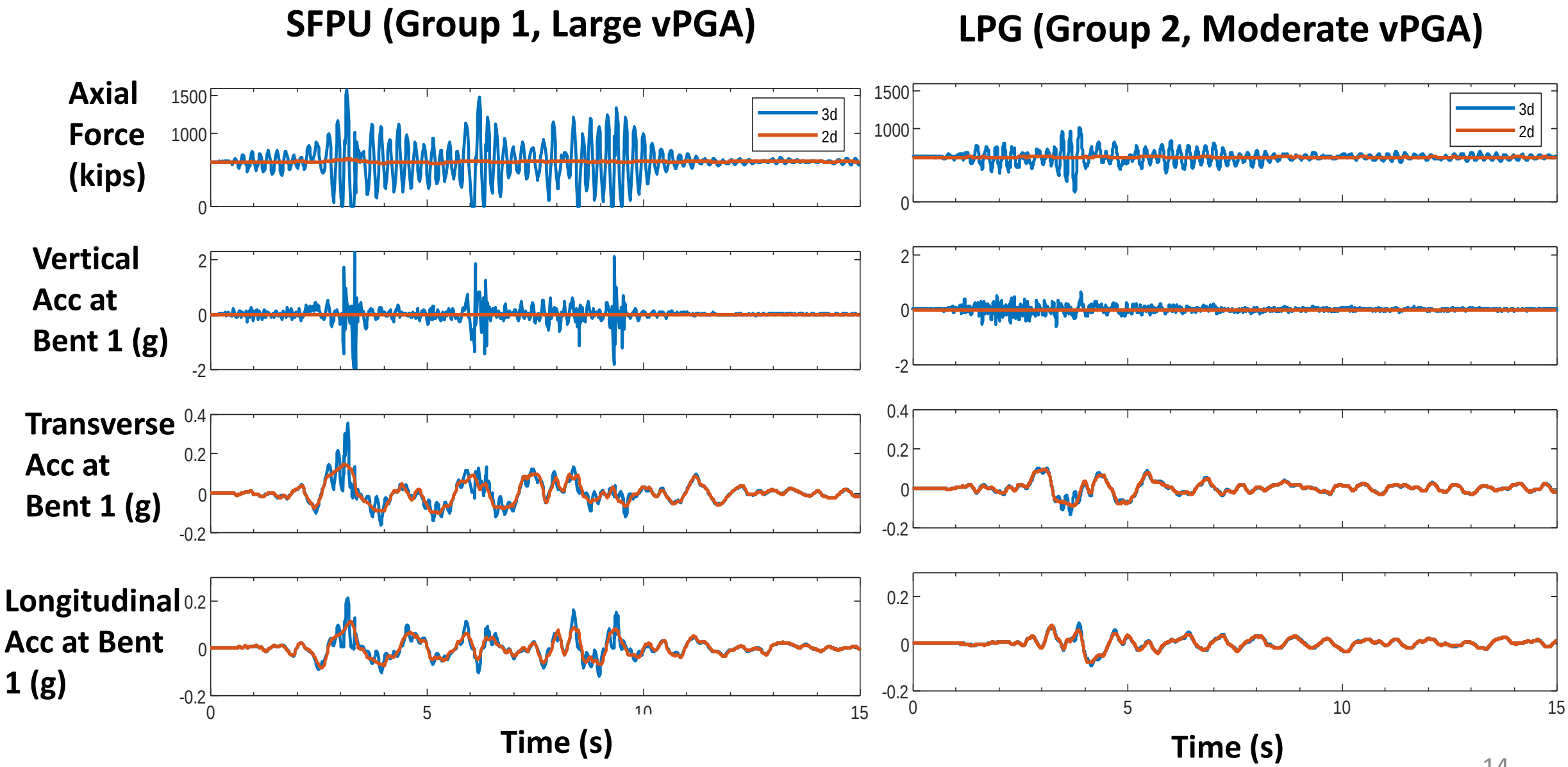




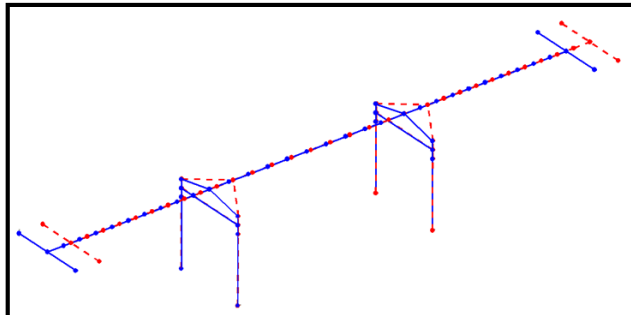
Displacement (in)

Displacement (in)

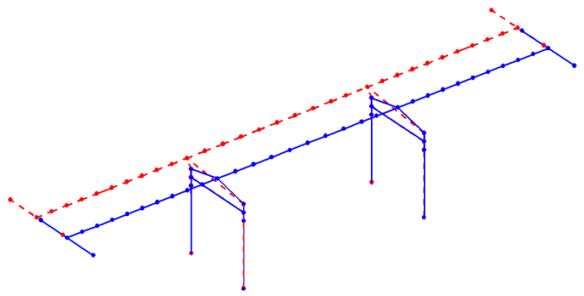
Representative History Responses



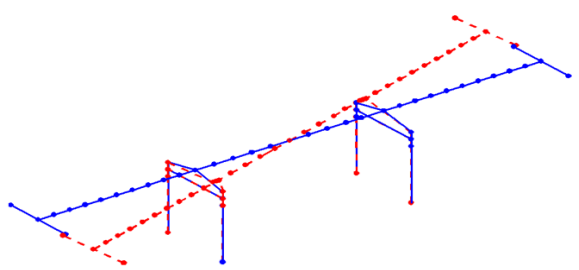
Modal Properties of the Bridge



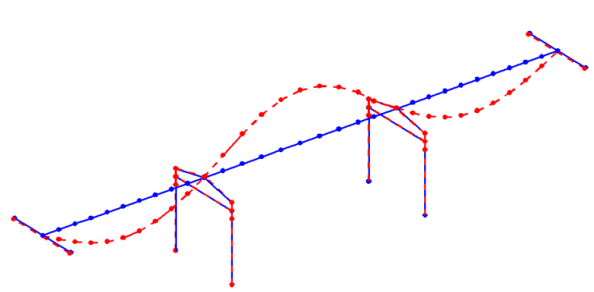
Mode 1: Longitudinal mode (2.96 sec)



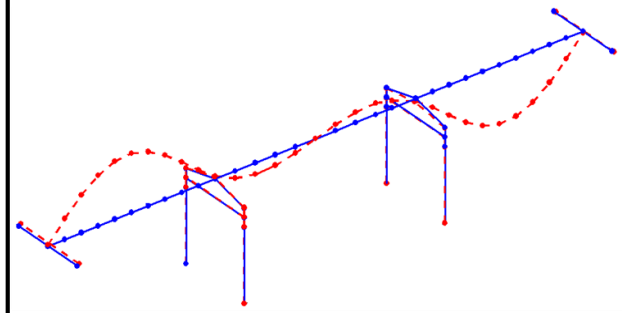
Mode 2: Transverse mode (2.94 sec)



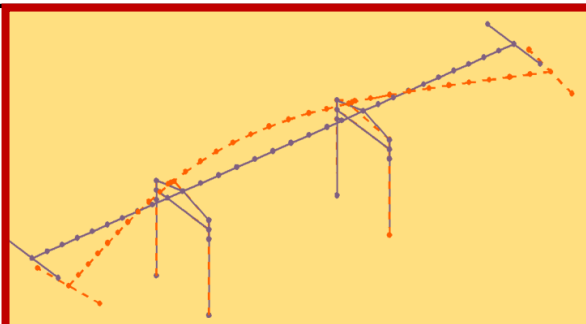
Mode 3: Torsional mode (2.61 sec)



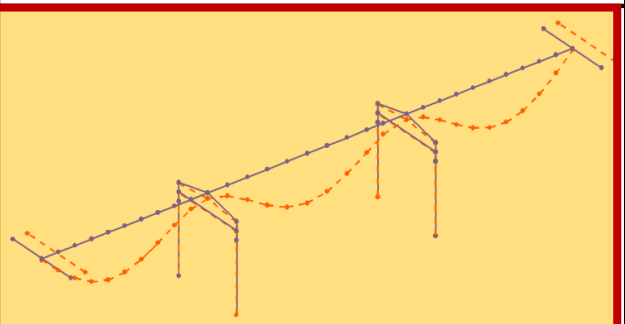
Mode 4: First Vertical mode (0.35 sec)



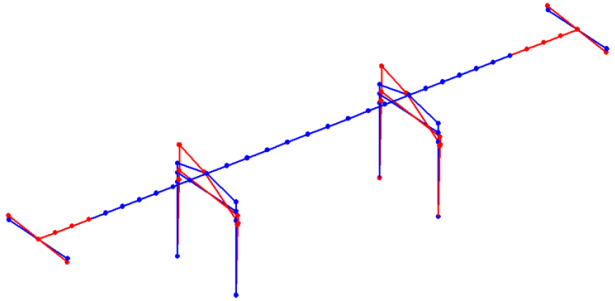
Mode 5: Second Vertical Mode (0.247 sec)



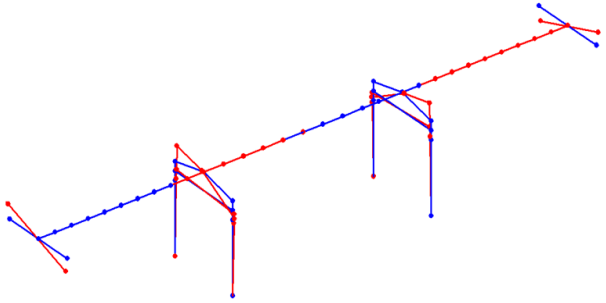
Mode 6: Transverse structural mode (0.21 sec)



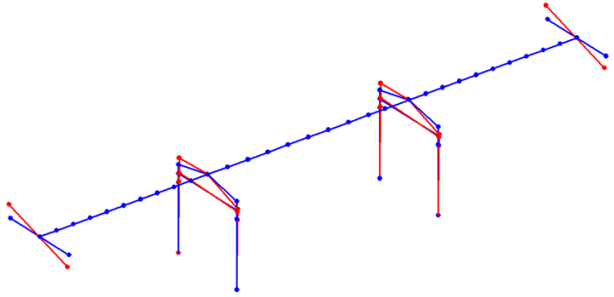
Mode 7: Third Vertical Mode (0.204 sec)



Mode 8: Rotational mode (0.143 sec)

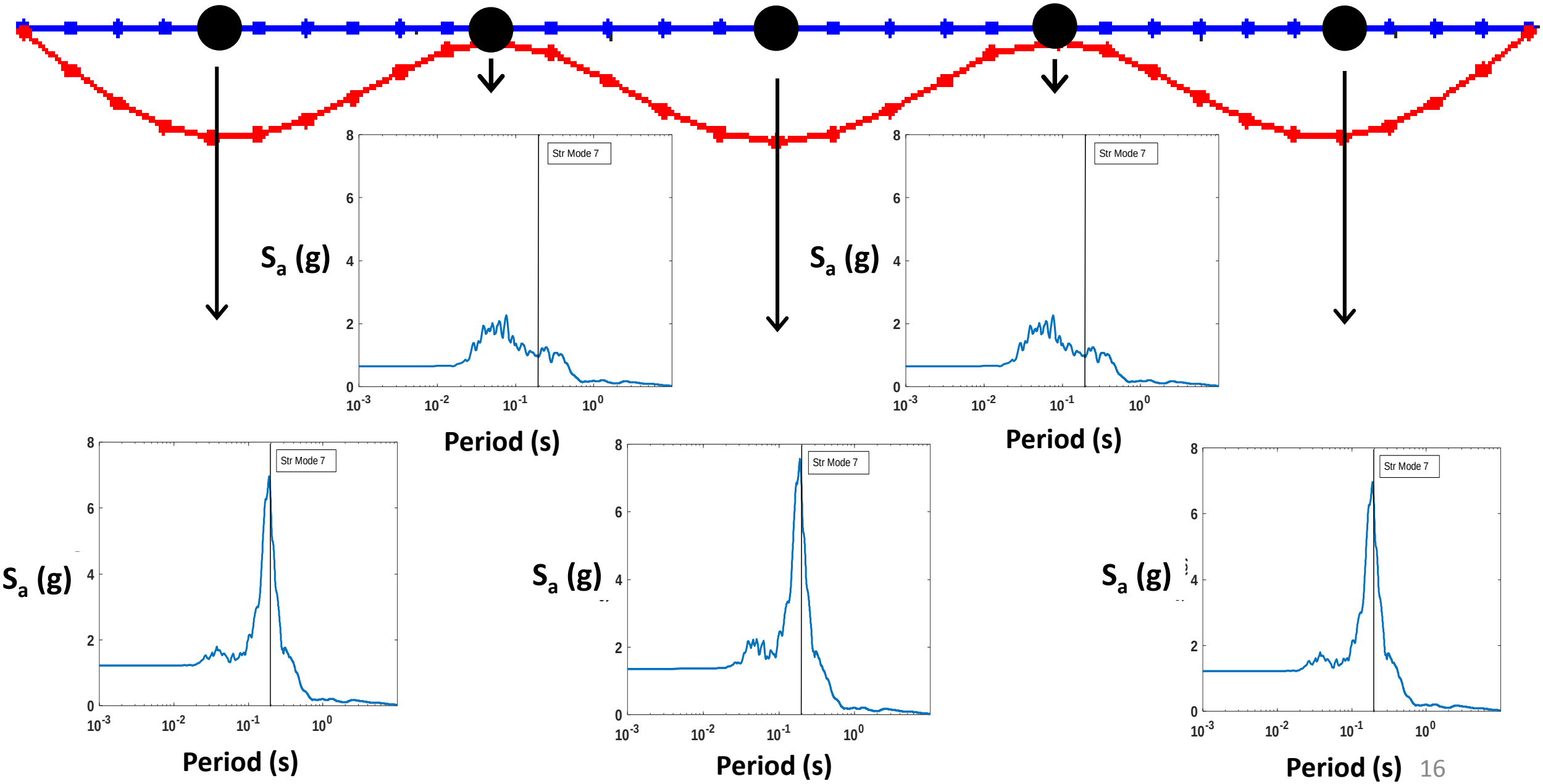


Mode 9: Deck torsional mode (0.118 sec)

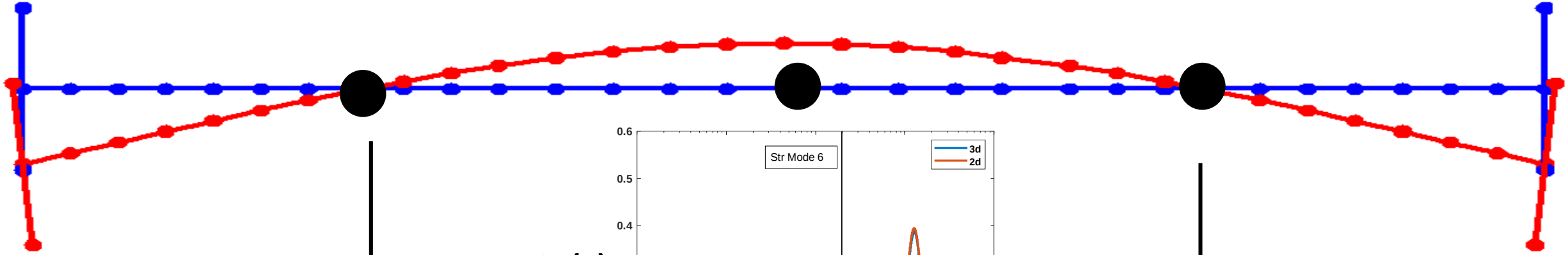


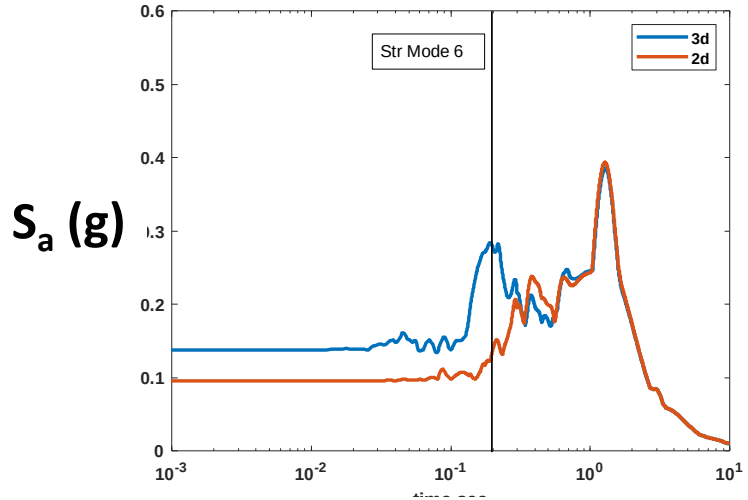
Mode 10: torsional mode (0.113 sec)

Response Spectra and Higher Mode Coupling Effects



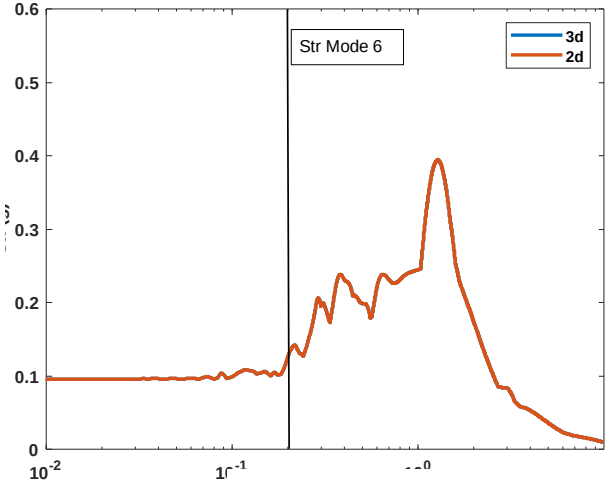
Response Spectra and Higher Mode Coupling Effects





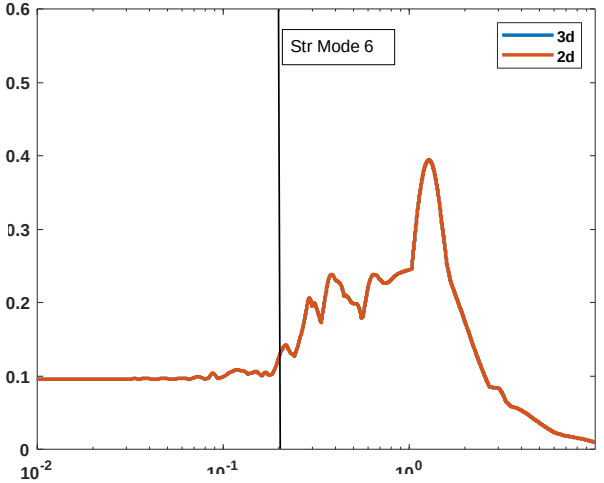
S_a (g)

Period (s)



S_a (g)

Period (s)



S_a (g)

Period (s)

Proposed Theoretical Formulation

Hypothesis: Amplified base shear can be estimated from PGA_z

1. **In an SDOF system, the base shear coefficient ≈ peak horizontal acceleration**

$$m\ddot{u} + V_b(u) = -m\ddot{u}_g \quad \Rightarrow \quad \frac{V_b}{W} = -\ddot{u}^t$$

2. **Estimating the effect of vertical acceleration**

$$V_b \propto \mu N \quad \text{where} \quad N = m(g + \ddot{u}_z^t)$$

$$\frac{V_{b(vert)}}{W} = \mu \cdot \ddot{u}_z^t$$

$\ddot{u}_z^t$ is the average peak vertical acceleration felt by the isolators

Proposed Theoretical Formulation

Hypothesis: Amplified base shear can be estimated from PGA_z

3. $\ddot{u}_z^t$ can be estimated from the vertical ground acceleration

$$\ddot{u}_z^t = AF \cdot PGA_z$$

- AF = amplification factor. It is the amplification of the vertical acceleration from the ground to the structure.

$$\frac{V_{b(vert)}}{W} = \mu \cdot \ddot{u}_z^t \quad \rightarrow \quad \mu \cdot AF \cdot PGA_z$$

Proposed Theoretical Formulation

An Example: SFPU (Group 1)

V_b/W = 0.133 (observed value for 2D)

μ = 0.08

PGA_z = 0.817g

$$\frac{V_{b(vert)}}{W} = \mu \cdot AF \cdot PGA_z$$

$$\frac{V_{b,3D}}{W} = \frac{V_{b,2D}}{W} + \frac{V_{b(vert)}}{W}$$

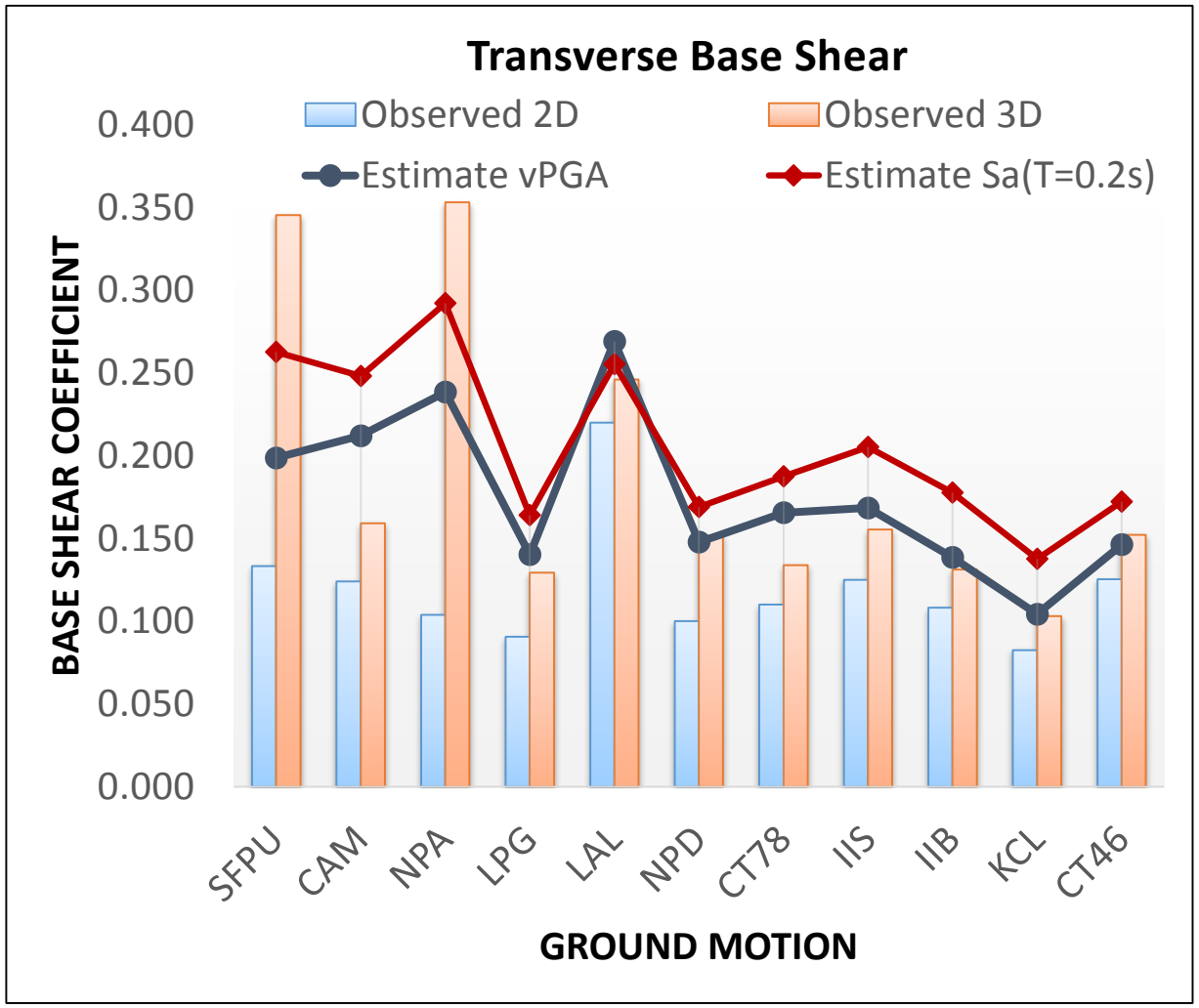
Case 1: $= (0.08) \cdot (1) \cdot (0.817) = 0.065$ $= 0.133 + 0.065 = 0.199$

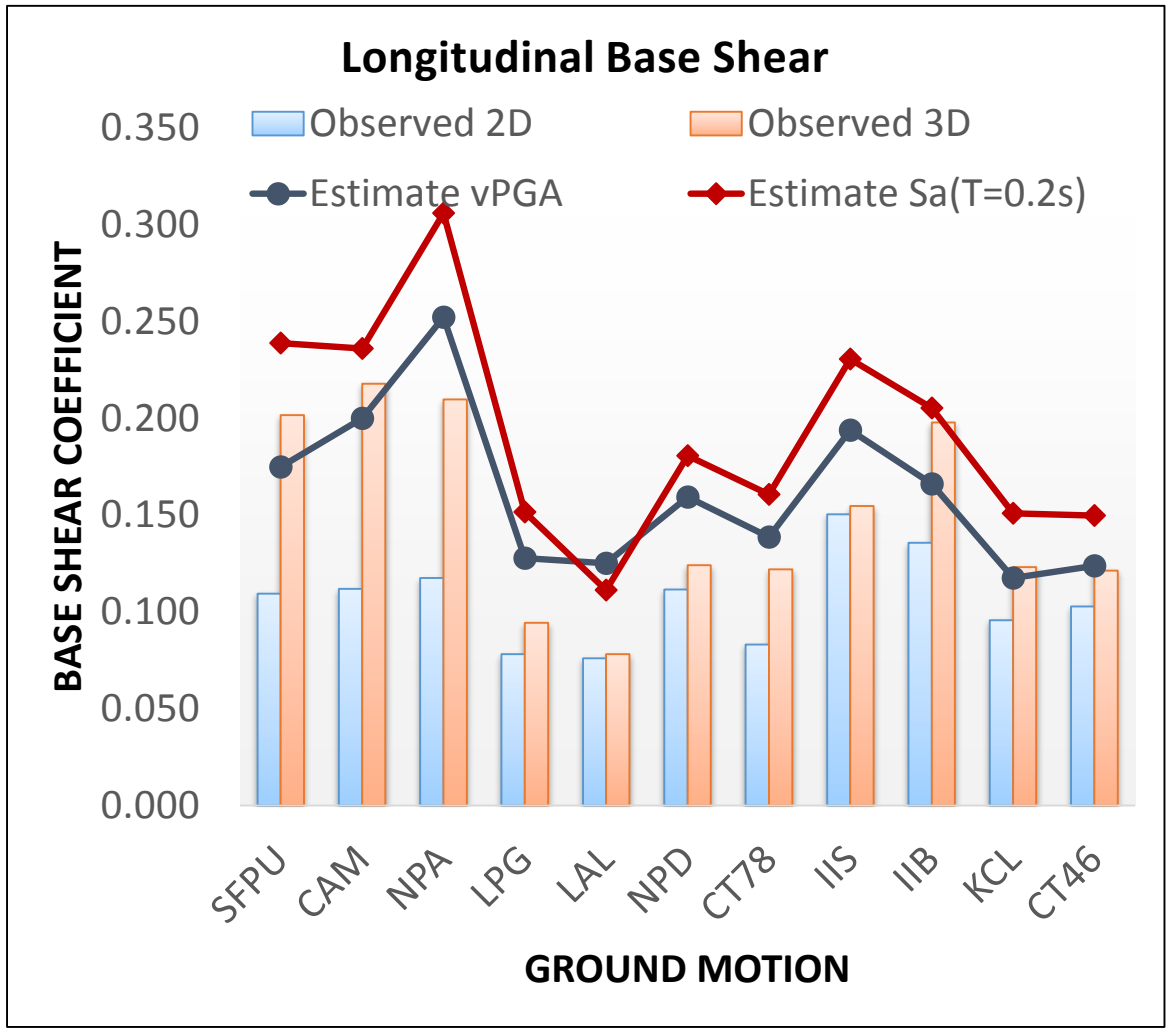
***AF* = 1**

Case 2: $= (0.08) \cdot (1.98) \cdot (0.817) = 0.129$ $= 0.133 + 0.129 = 0.262$

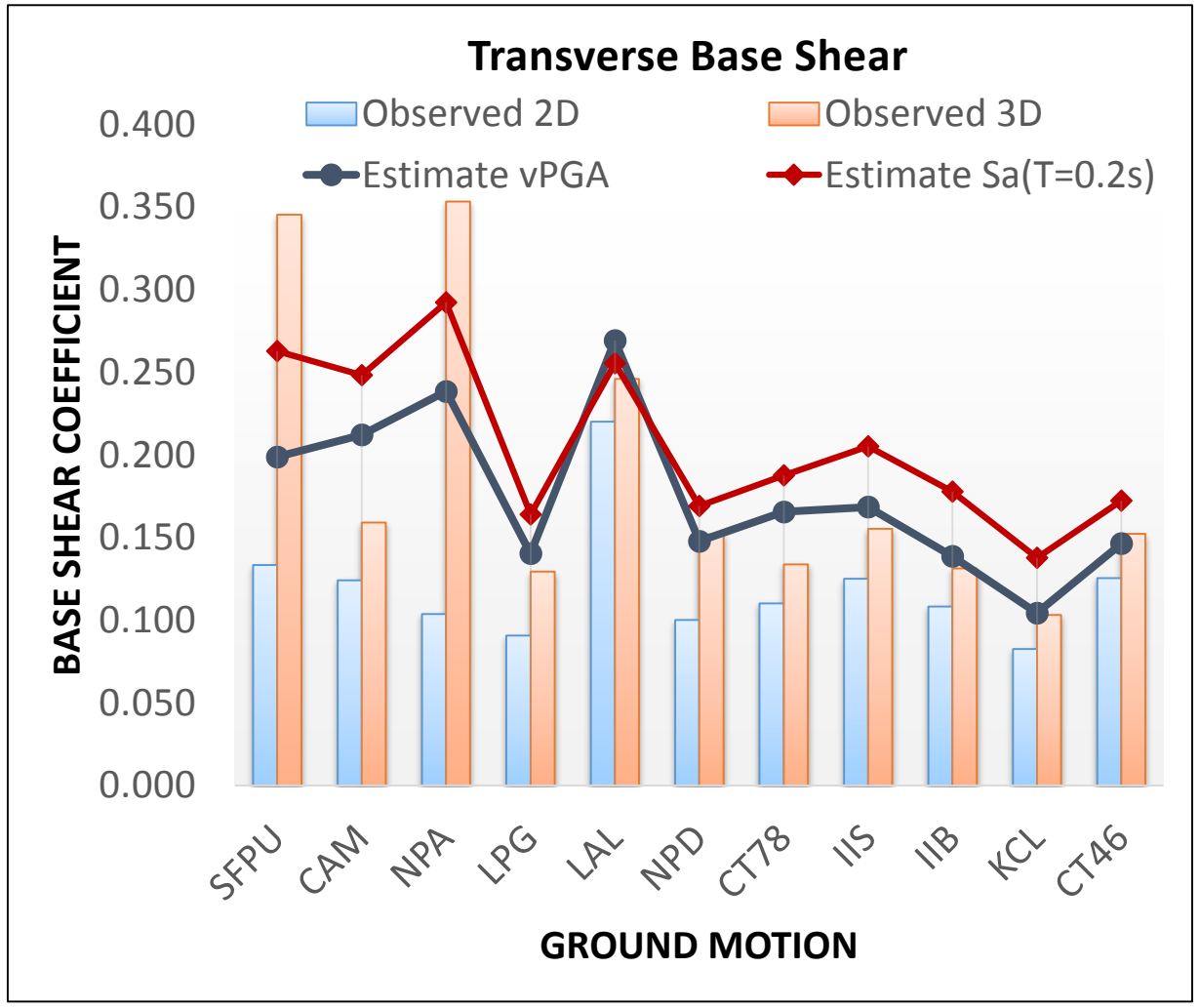
$$AF = \frac{S_a(0.2s)}{PGA_z}$$

Evaluation of Base Shear Estimates





Preliminary Conclusions



$$\frac{V_{b(vert)}}{W} = \mu \cdot AF \cdot PGA_z$$

Preliminary Conclusions

- "Estimate vPGA" (AF = 1 with no spectral amplification) usually gives a conservative estimate of the base shear.
- The approach may be unconservative when vPGA >1 (high frequency spikes due to uplift, pounding)
- The higher mode effects due to modal coupling are not strongly apparent in the base shear.

Future Work: Parameter Variation for Concrete Box Girder

Sr No.	No. of Cell	Deck Width (ft)	Depth (ft)	Deck Thickness (in)	Soffit Thickness (in)	Wall Thickness (in)	Wall C-C spacing	Span Length (ft)	No. of Span	Column Height (ft)	No. of column /bent	Column Dia. (ft)
1	**3**	**45**	**4.8**	**8.875**	**7**	**12**	**11.75**	**120** ◆	**3**	**20**	**2**	**5**
2	3	45	4.8	8.875	7	12	11.75	120	**4**	20	2	5
3	3	45	4.8	8.875	7	12	11.75	120	**2**	20	2	5
4	3	45	**5.4**	8.875	7	12	11.75	**135**	3	20	2	5
5	3	45	**6.4**	8.875	7	12	11.75	**160**	3	20	2	5
6	**9**	**90**	4.8	8.375	7	12	10	120	3	20	**4**	5
7	3	**35**	4.8	8.875	7	12	11.75	120	3	20	**1**	**6**
8	3	45	4.8	8.875	7	12	11.75	120	3	**15**	2	5
9	3	42						110	9	35	1	8

◆ Approach spans = 0.8 x span length

Isolation parameters to be widely varied.

Research Question: Does base shear amplification depend on bridge and isolator parameters?

Questions?

Acknowledgement:

We are grateful to funding from PEER Transportation Research Program to support this project.

We appreciate funding from Advisory Board Members Allaoua Kartoum, Bijan Khalegi, and Mason Walters