University of Nevada, Reno

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

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Objective/Scope of PEER Pendulum Bearing Study

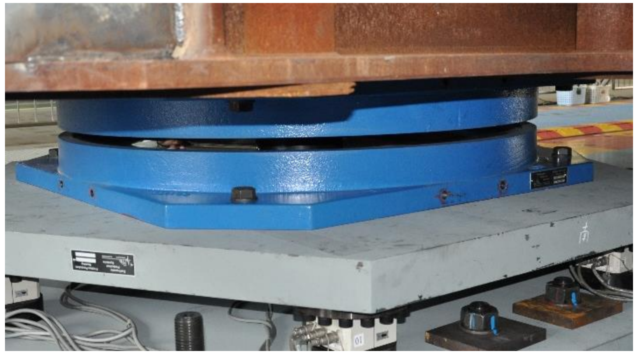
- **Objective 1**: Comprehensively evaluate influence of vertical shaking on base shear/column forces in representative isolated bridges.
- **Objective 2**: Based on study, develop guidance for accounting for the influence of vertical shaking in design (e.g. required time history analysis, amplification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

Scope of Investigation:

- Develop computational models in OpenSees for 4-5 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

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

Isolated with triple friction pendulum (TP) bearings



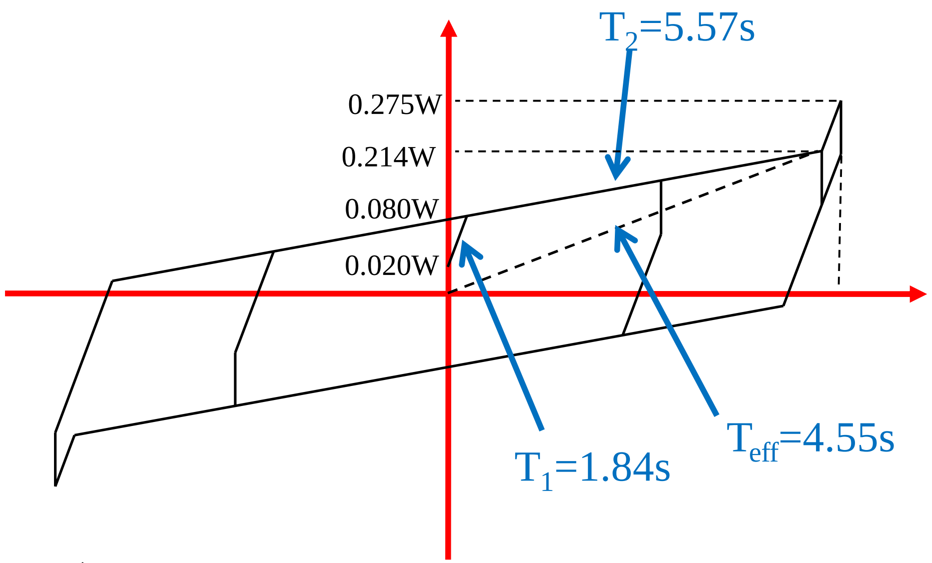
Isolated with hybrid configuration of lead-rubber and cross-linear bearings

Fixed at the base

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

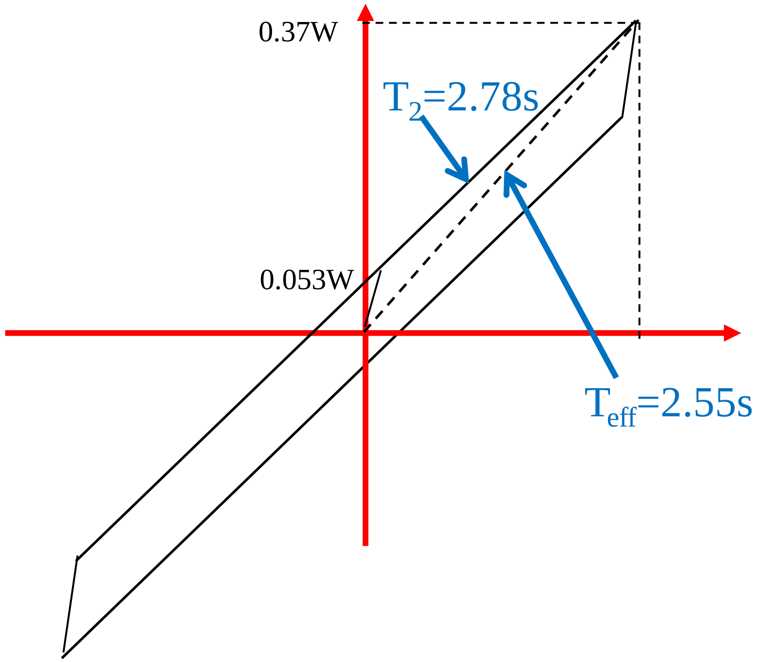
Isolation System Force-Deformation Comparison

Triple Pendulum System



- ✓ Yield Force = 0.08W
- ✓ T_2 = 5.57 sec
- ✓ Disp. Capacity = 1.14 m (45 in)
- ✓ 9 identical isolators, 1 beneath each column

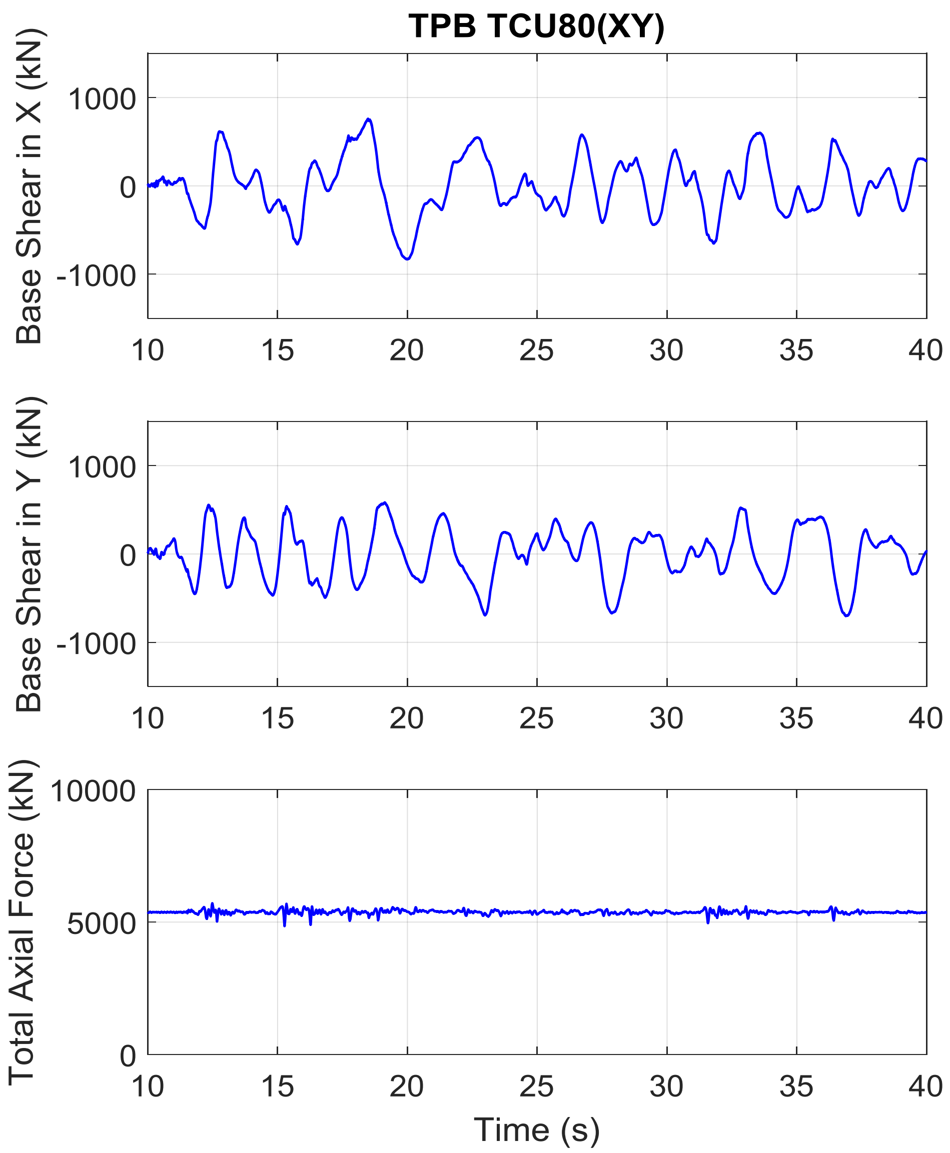
Hybrid LRB System



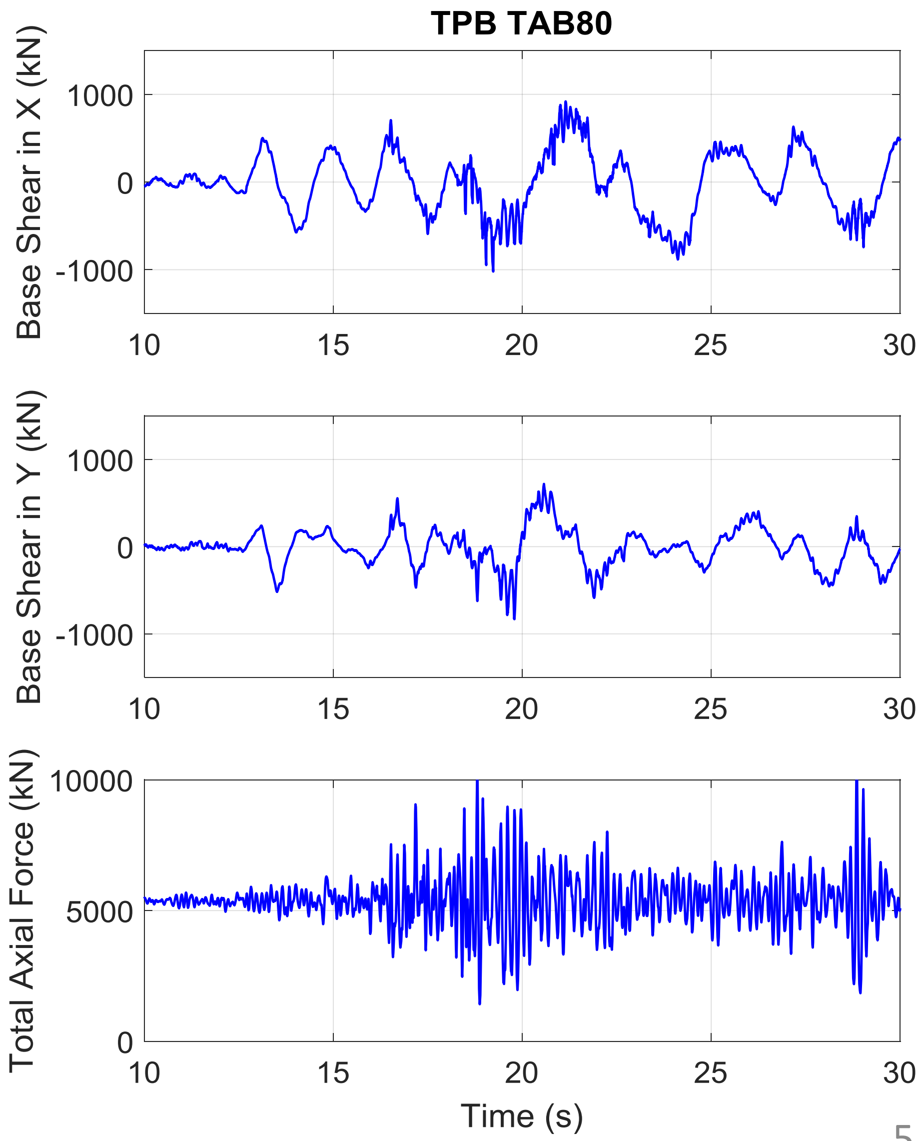
- ✓ Disp. Capacity = 0.6 m (24 in)
- ✓ Achieved by 4 LRB and 5 tension capable sliders

Influence of Vertical Shaking on the Base Shear of FPB

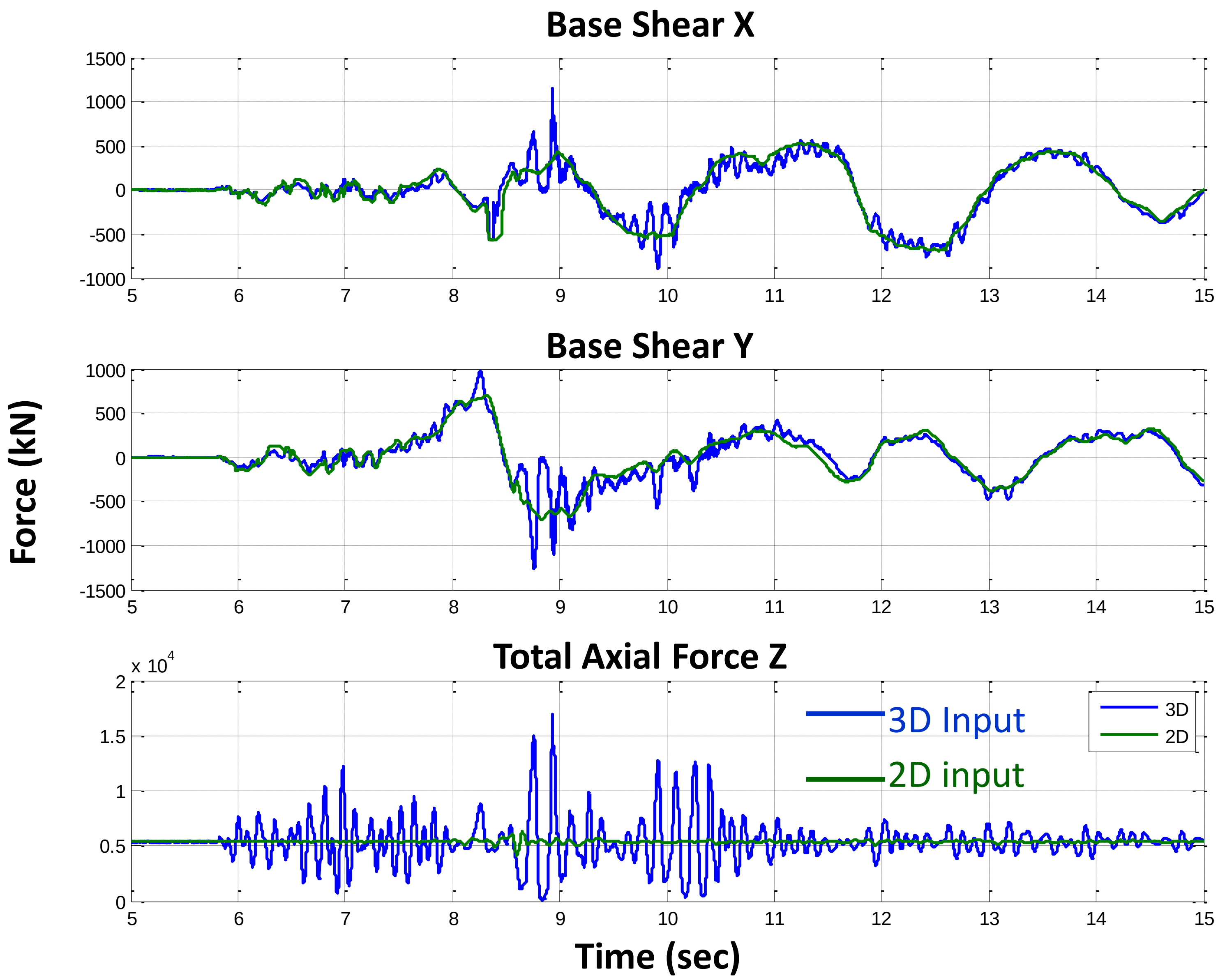
Without vertical acceleration: Peak a_z = 0.034g



With vertical acceleration: Peak a_z = 0.593g



Influence of Vertical Shaking on the Base Shear of FPB



- ✓ 1994 Northridge at Rinaldi Rec. Sta – Vertical PGA = 1.2g
- ✓ The higher frequency component of base shear is shown to be in sync with total axial force variation in a 3D motion.

Influence of Vertical Shaking - 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. Vertical vibration properties will influence the base shear effect.

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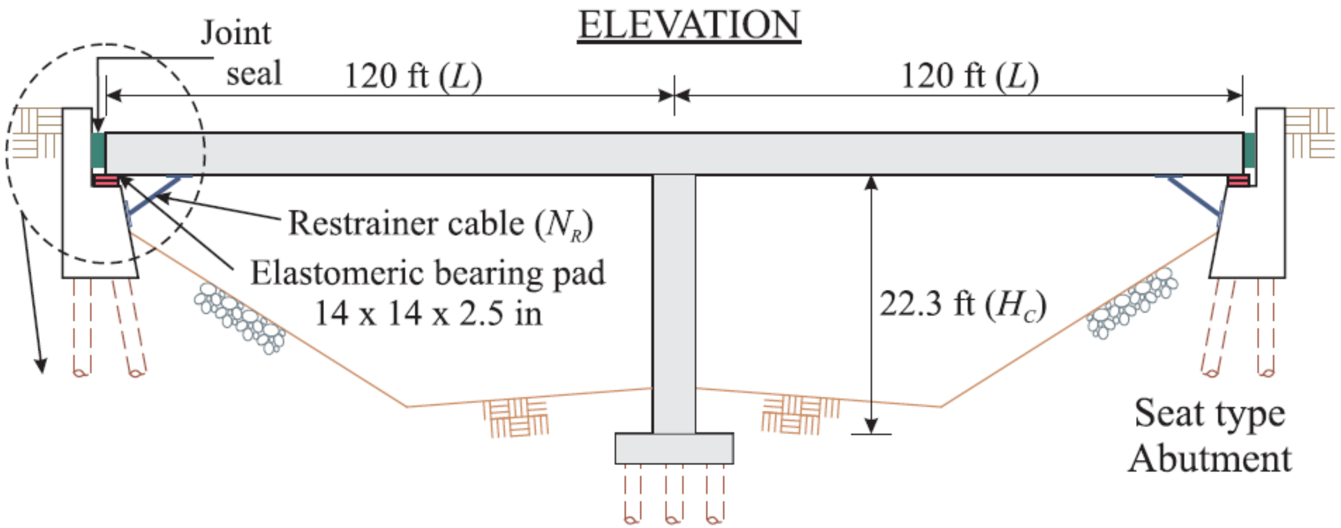
Progress to Date

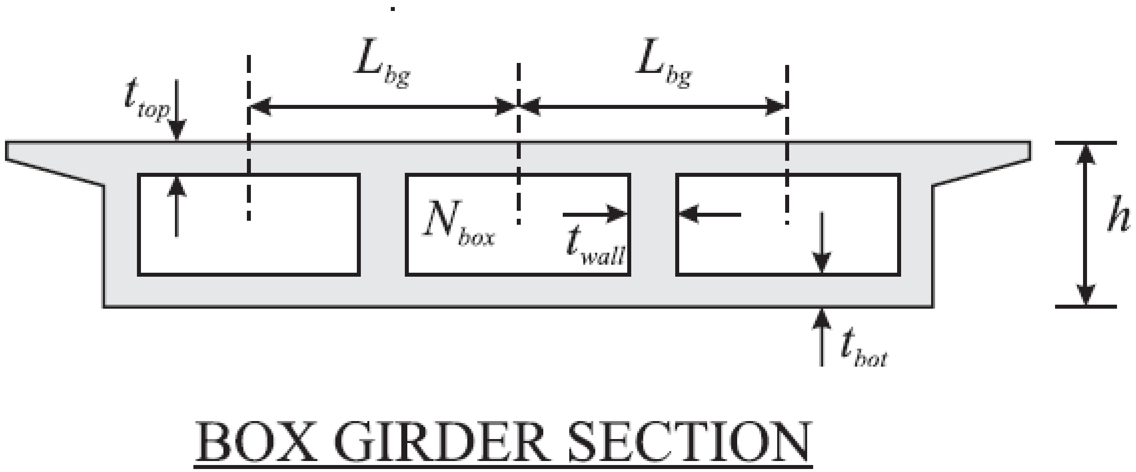
1. Literature review.
2. Learned OpenSees.
3. Selected bridge archetypes, models, and parameter variations.
4. Formed an Advisory Board and sought input on research plan.
5. Build and validate model of first archetype bridge (in progress).

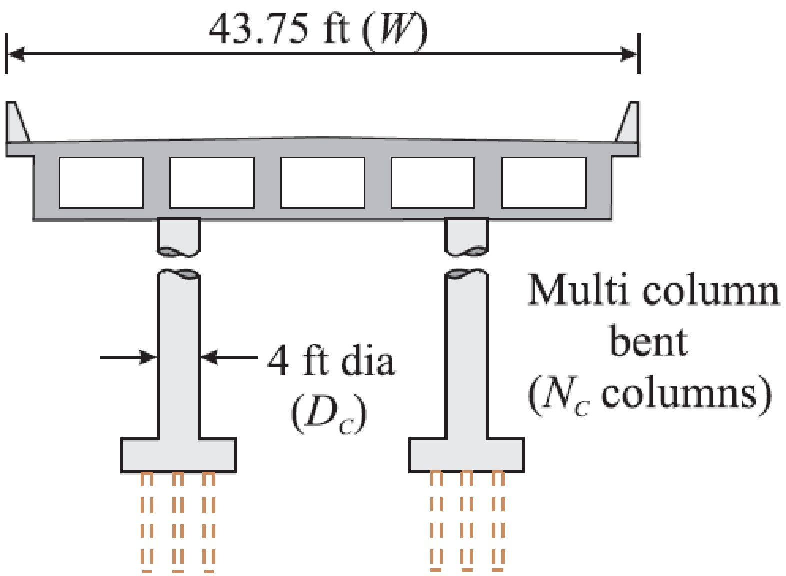
Feedback from Advisory Board Meeting – 6/6/18

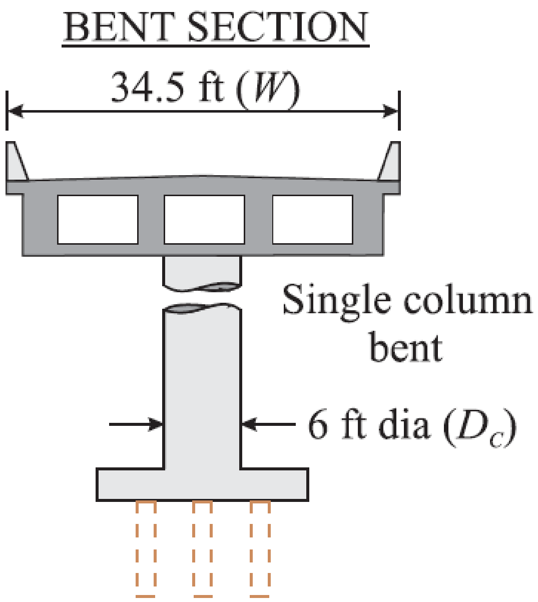
- **Members: Allaoua Kartoum (Caltrans), Bijan Khalegi (WashDOT), Mason Walters (Forell-Elsesser)**
- Continuous bridge configurations are preferred, and expansion joints are generally not needed as isolators can accommodate the thermal expansion.
- Concrete box girder is the preferred bridge type in California, with span lengths from 150-200 ft. Isolators should be placed between the bent cap and the girders.
- Steel girder is the preferred bridge type in Washington. Use low number of girders with cross frames, and isolators placed directly below girders on top of bent cap.
- Isolation system parameters: T_2 = 2 to 5 sec, Q/W = 0.04 to 0.08.
- Include foundation springs to represent stiff soil and soft soil conditions.

1) Continuous Concrete Box Girder Bridges



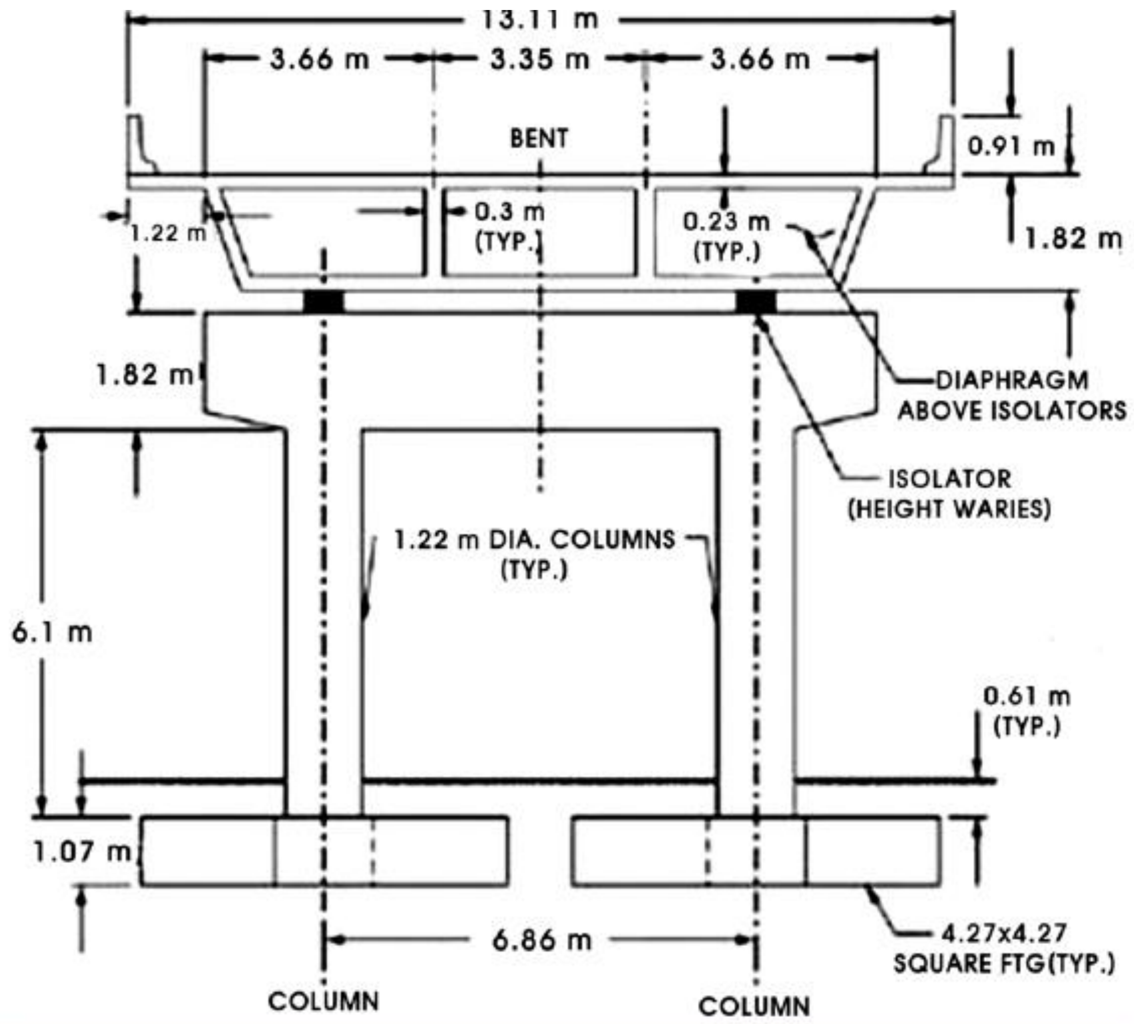






Source - Phd Thesis Karthik Ramanathan - Georgia Tech

Concrete Box Girder – Proposed Isolator Installation



Concrete Box Girder – Proposed Parameter Variation

Bridge Parameter Variations Based on NBI

- **Span Length**
  - 120 ft to 160 ft
- **Pier Type**
  - Single Col. Bent
  - Multi Col. Bent
- **Abutment Type**
  - Seat Abutment
- **No. of Spans**
  - 2 to 4
- **Deck Width & Box properties**
  - 35 ft to 127.5 ft
- **Pier Height**
  - 15 ft to 25 ft

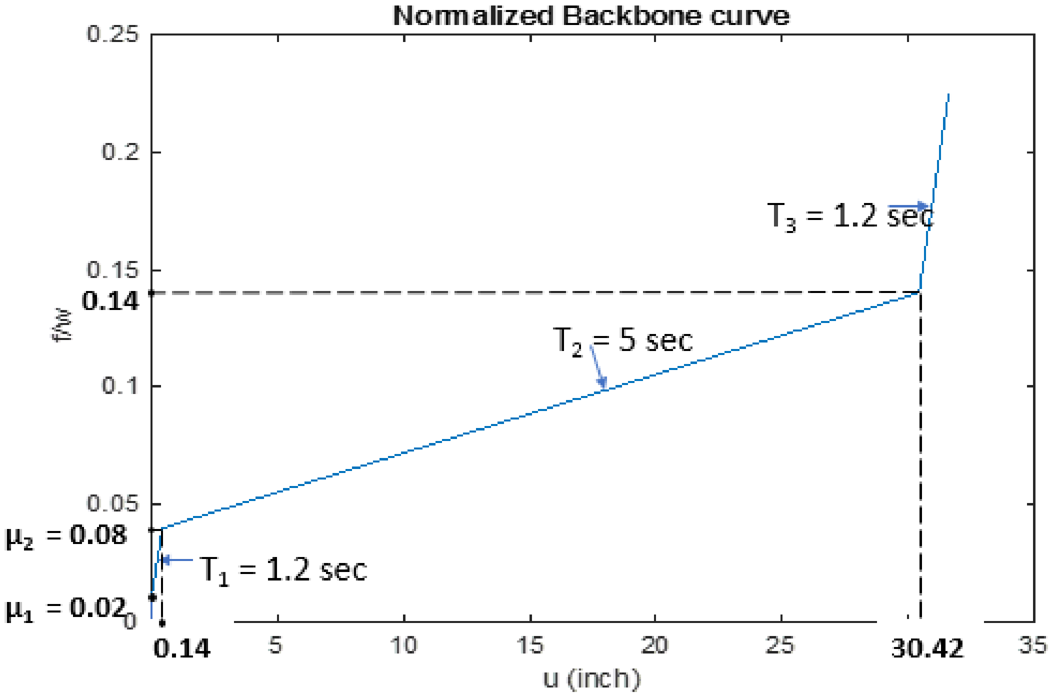
Concrete Box Girder – Proposed Parameter Variation

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**	**22.3**	**2**	**5**
2	3	45	4.8	8.875	7	12	11.75	120	**4**	22.3	2	5
3	3	45	4.8	8.875	7	12	11.75	120	**2**	22.3	2	5
4	3	45	**5.4**	8.875	7	12	11.75	**135**	3	22.3	2	5
5	3	45	**6.4**	8.875	7	12	11.75	**160**	3	22.3	2	5
6	**9**	**90**	4.8	8.375	7	12	10	120	3	22.3	**4**	5
7	3	**35**	4.8	8.875	7	12	11.75	120	3	22.3	**1**	**6**
8	3	45	4.8	8.875	7	12	11.75	120	3	**15**	2	5
9★	1	42						110	9	35	1	8

◆ Approach spans = 0.8 x span length

★→ California high speed railway prototype bridge

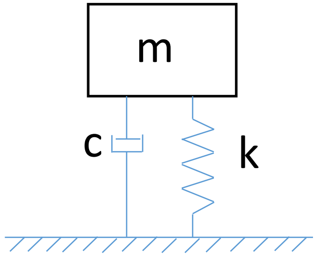
SDOF System versus 3-Span Concrete Box Girder Bridge



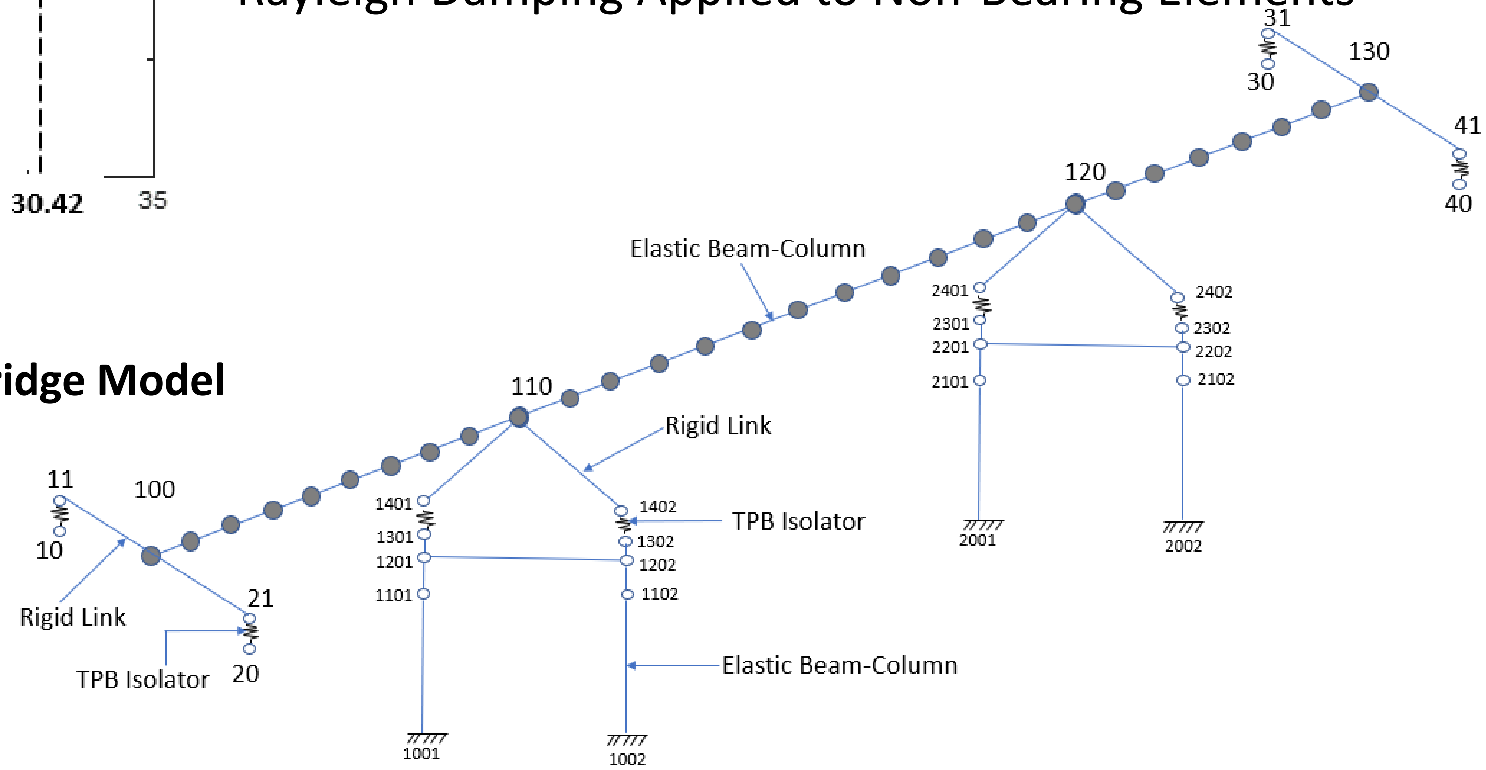
Modeling Assumptions

- Elastic Frame Elements for Superstructure, Columns, Bent Cap
- Discretization of Superstructure Elements to Distribute Mass
- Unrestrained Movement at the Abutment
- Triple Friction Pendulum Elements for Bearings
- Rayleigh Damping Applied to Non-Bearing Elements

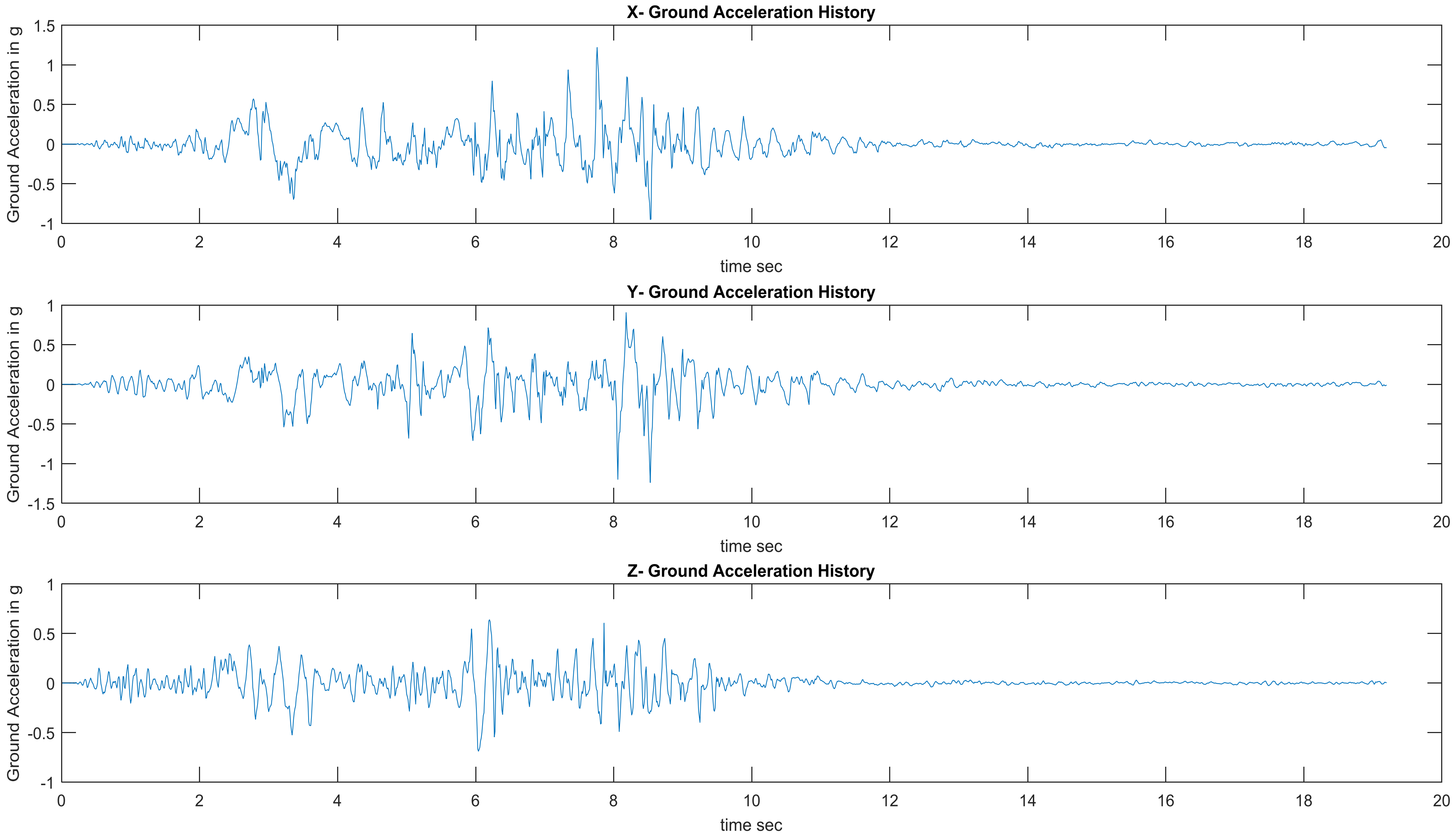
1. SDOF System



2. Bridge Model



Sample Recorded Acceleration: 1971 San Fernando Pacoima Dam

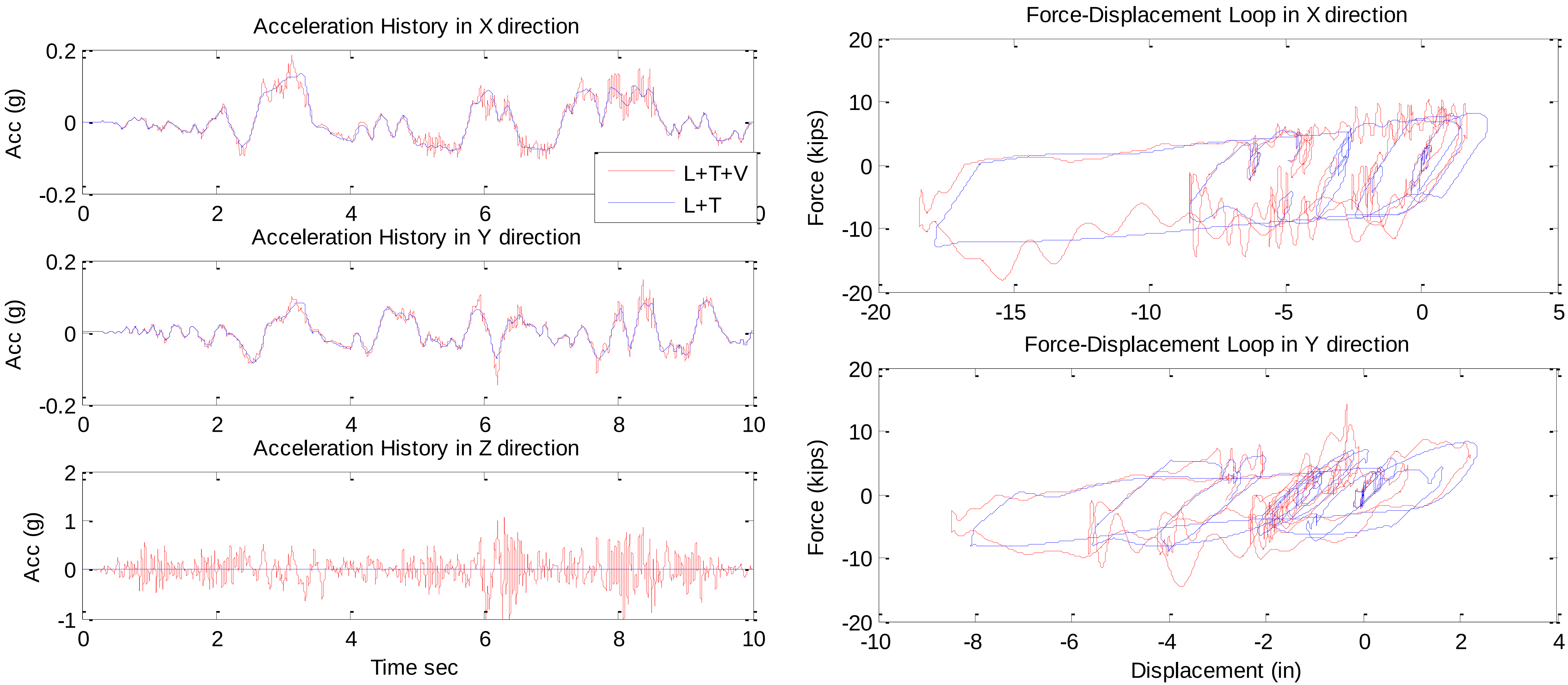


PGA(x) = 1.22g

PGA(y) = 1.24g

PGA(z) = 0.69g

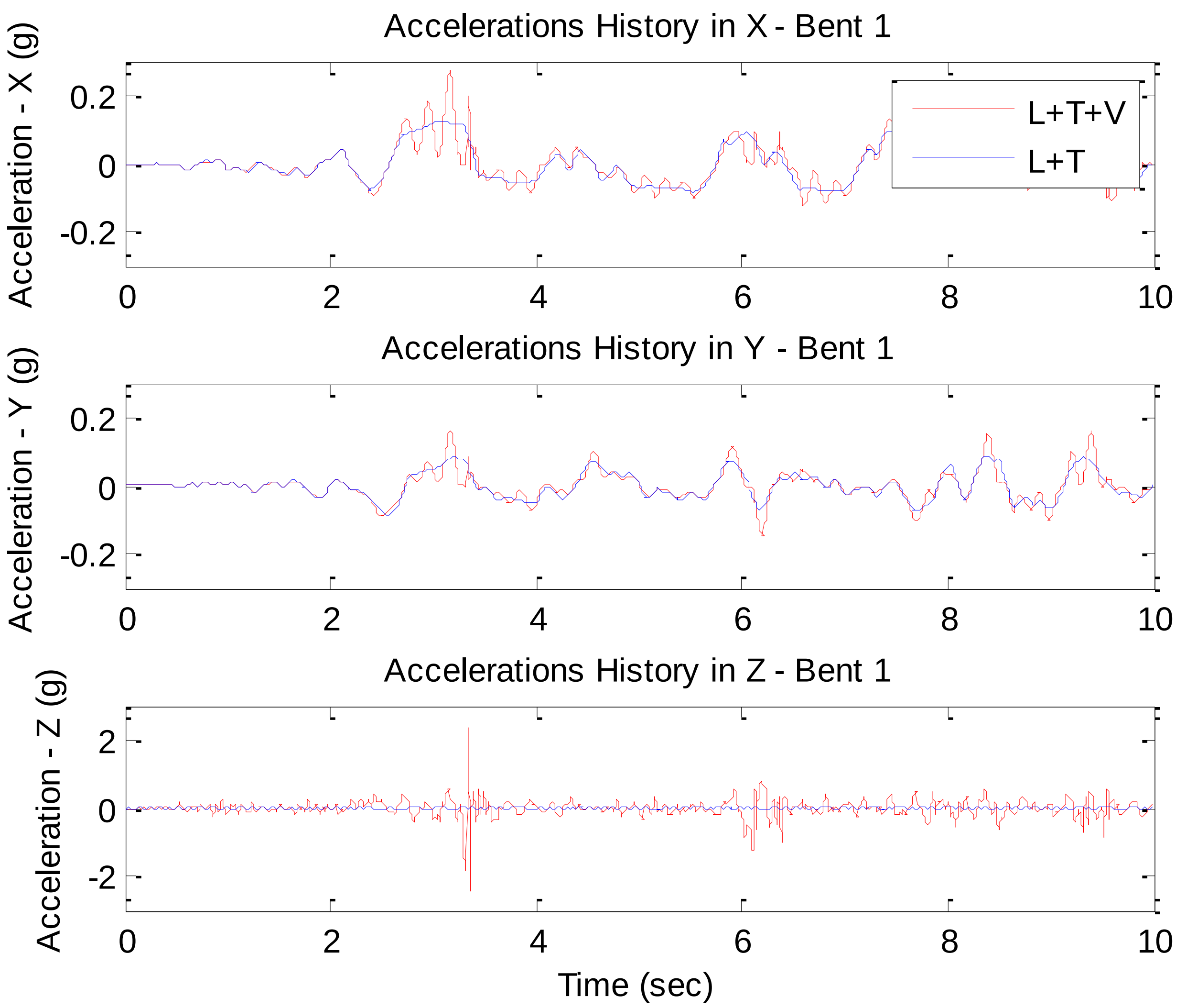
Response of SDOF System (T_v = 0.05 sec)

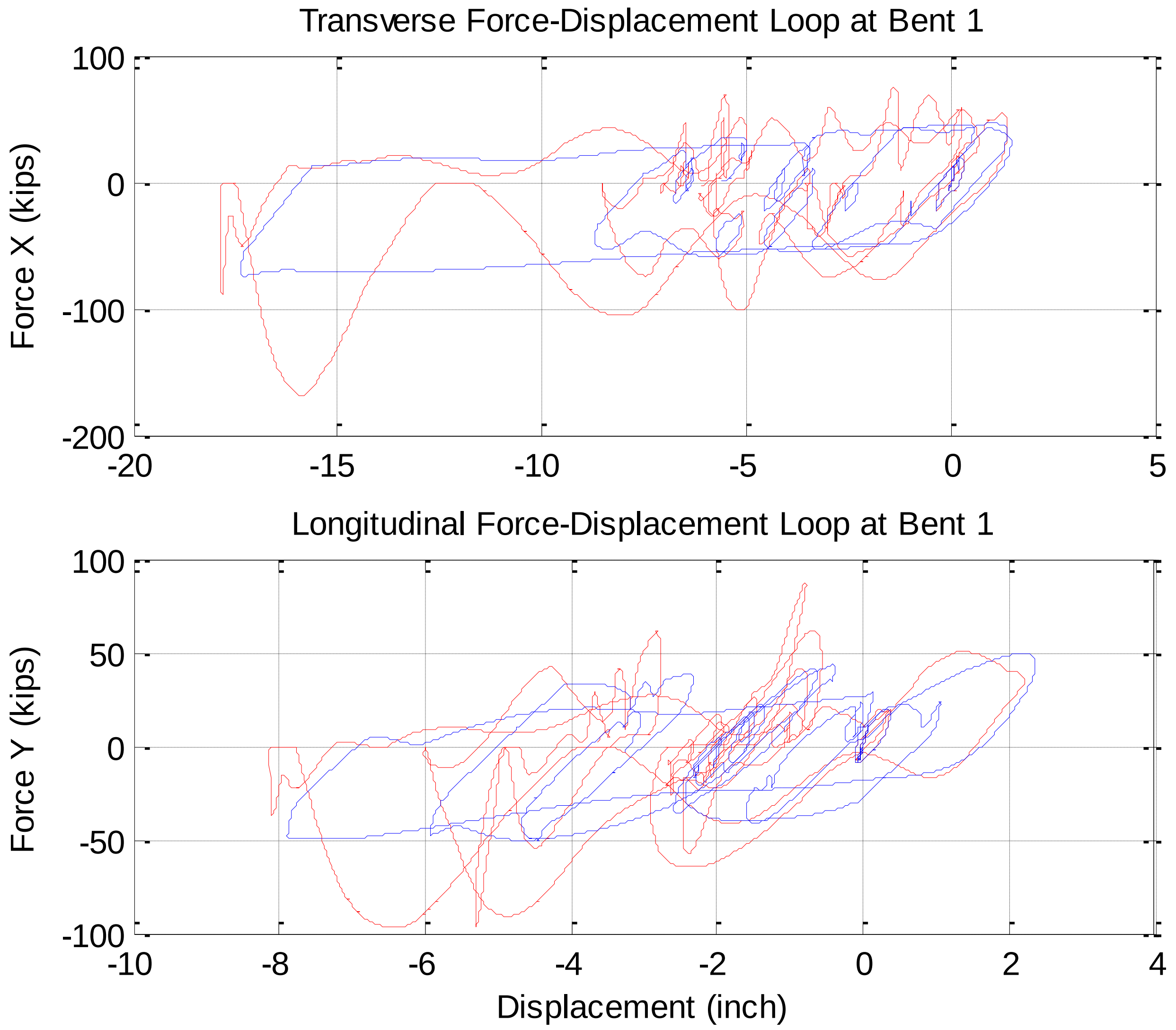


A_{xo} = 0.13g (no z), 0.185g (w/z)   Amp Factor = 1.61

A_{yo} = 0.092g (no z), 0.148g (w/z) A_{zo} = 1.07g

Response of Bridge – Representative Bearing at Bent 1

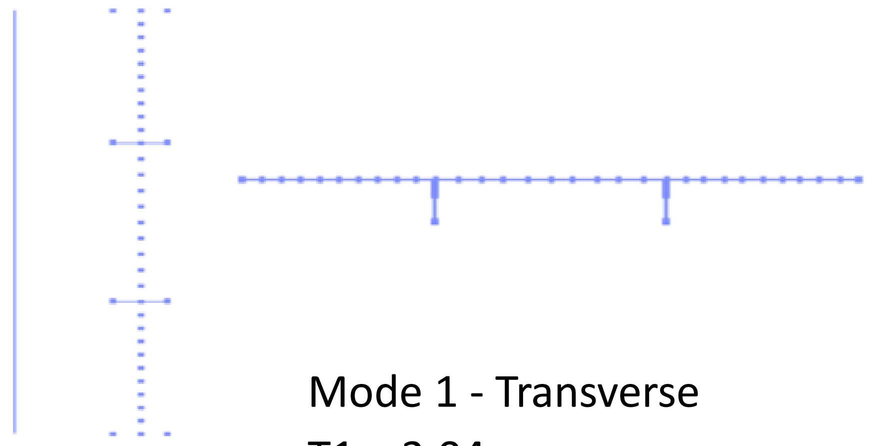




A_{xo} = 0.14g (no z), 0.29g (w/z)
A_{yo} = 0.09g (no z), 0.17g (w/z)

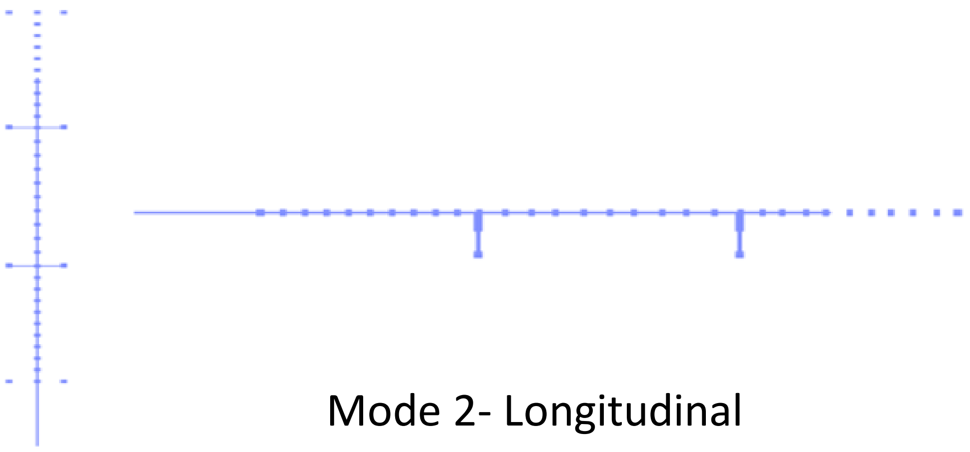
Amp Factor (Horiz) = 2.14
A_{zo} = 2.45g

Modal Properties of the Bridge



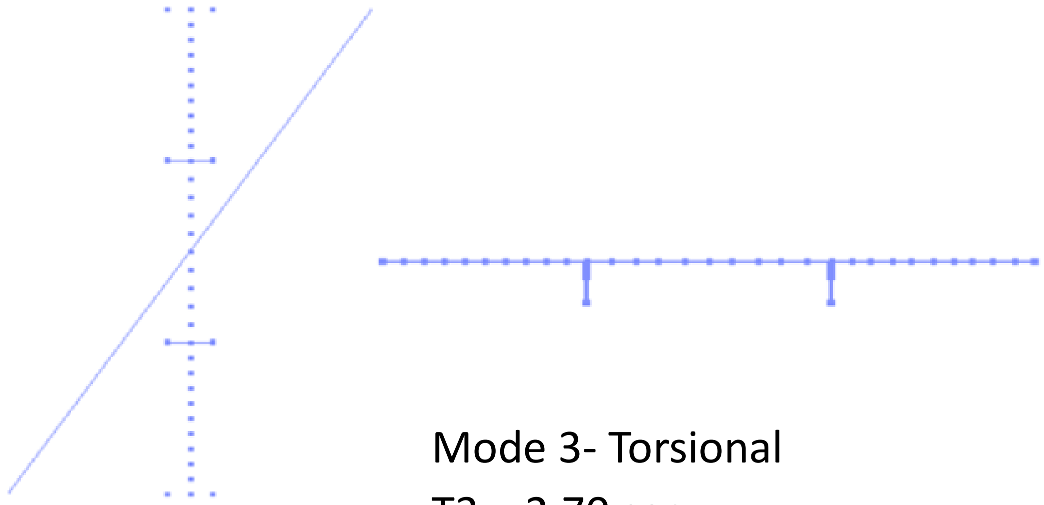
Mode 1 - Transverse

T1 = 3.04 sec



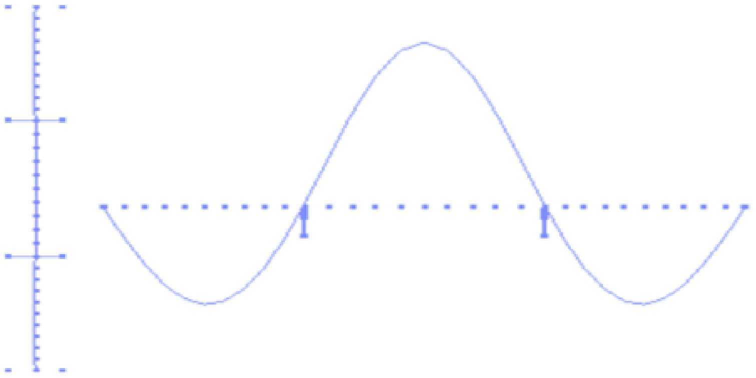
Mode 2- Longitudinal

T2 = 3.039 sec



Mode 3- Torsional

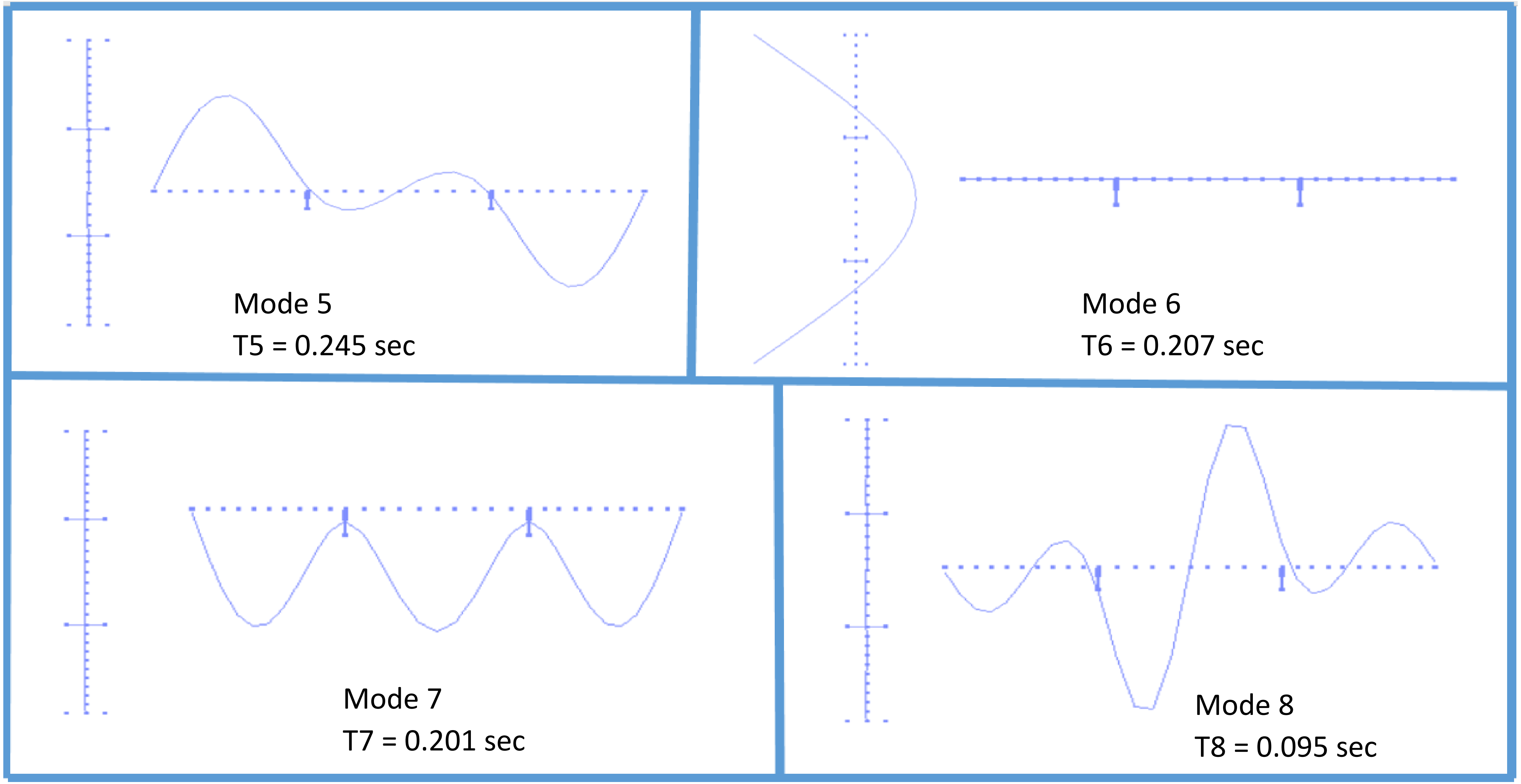
T3 = 2.70 sec



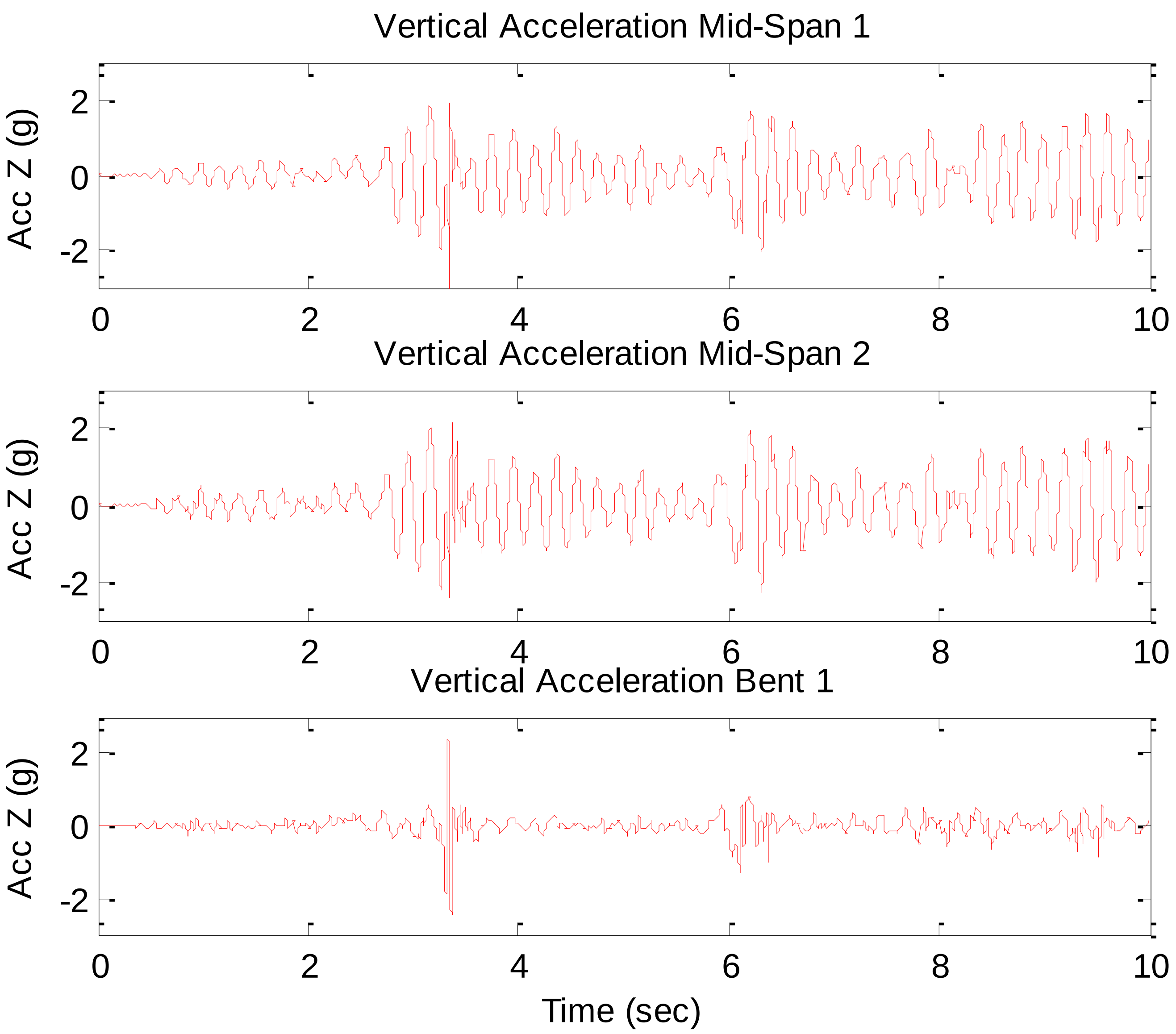
Mode 4 - Vertical

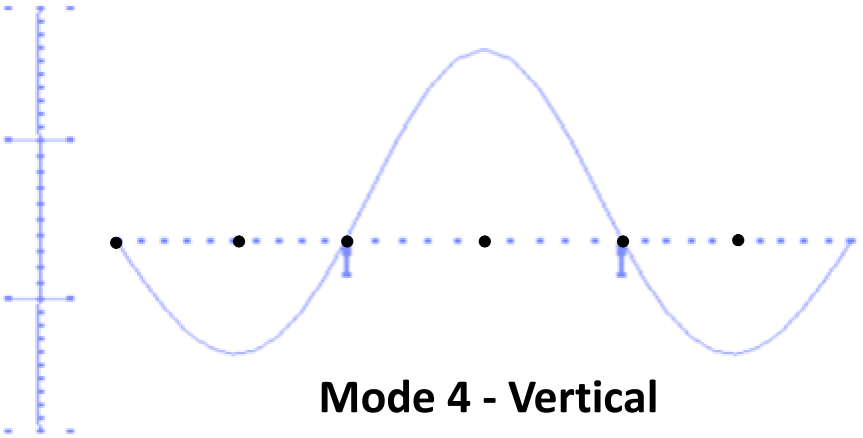
T4 = 0.35 sec

Modal Properties of the Bridge



Response of Bridge – Representative Bearing at Bent 1





Mode 4 - Vertical

T4 = 0.35 sec

Mid-Span: Vibration dominated by single mode response; 4th mode (vertical) w/ T = 0.35 sec.

A_{zo} = 2.45g
PGA_z = 0.69g
Amp Factor (Vert) = 3.55

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**

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

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

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

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

$\ddot{u}_z^t$ is the peak vertical acceleration observed at the location of the isolator

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.
- AF depends on attributes of the bridge.
- $AF \cdot PGA_z$ may be the spectral acceleration at frequency of the primary vertical mode.
- Assumes peak horizontal and vertical acceleration are perfectly phased.

4. Putting it all together

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

Proposed Theoretical Formulation

Hypothesis: Amplified base shear can be estimated from PGA$_z$

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

For the presented example:

Neglecting vertical acceleration	**Observed**	**Vb/W = 0.14**
With vertical acceleration	**Estimated** **(AF = 3 is observed)**	**Vb/W = 0.14 + μ·AF·PGAz** **= 0.14 + (0.08)(3.55)(0.69g)** **= 0.34**
With vertical acceleration	**Observed**	**Vb/W = 0.29**

The proposed estimate is reasonably accurate.
Vertical acceleration more than doubles the base shear!

Unresolved Issue

How to select and scale ground motions representative of long period range of target spectrum, that also prioritizes high intensity vertical???

Ideal: We use a suite of motions selected for another project (any high seismicity site in California) that satisfies these criteria.