NEESR-SG-0530737

Seismic Simulation and Design of Bridge Columns under Combined Actions, and Implications on System Response

University of Nevada, Reno
University of California, Los Angeles
University of Illinois, Champaign-Urbana
Missouri University of Science and Technology
Washington University, St. Louis
University of Houston
George Washington University

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COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Great Team!

University of Nevada, Reno

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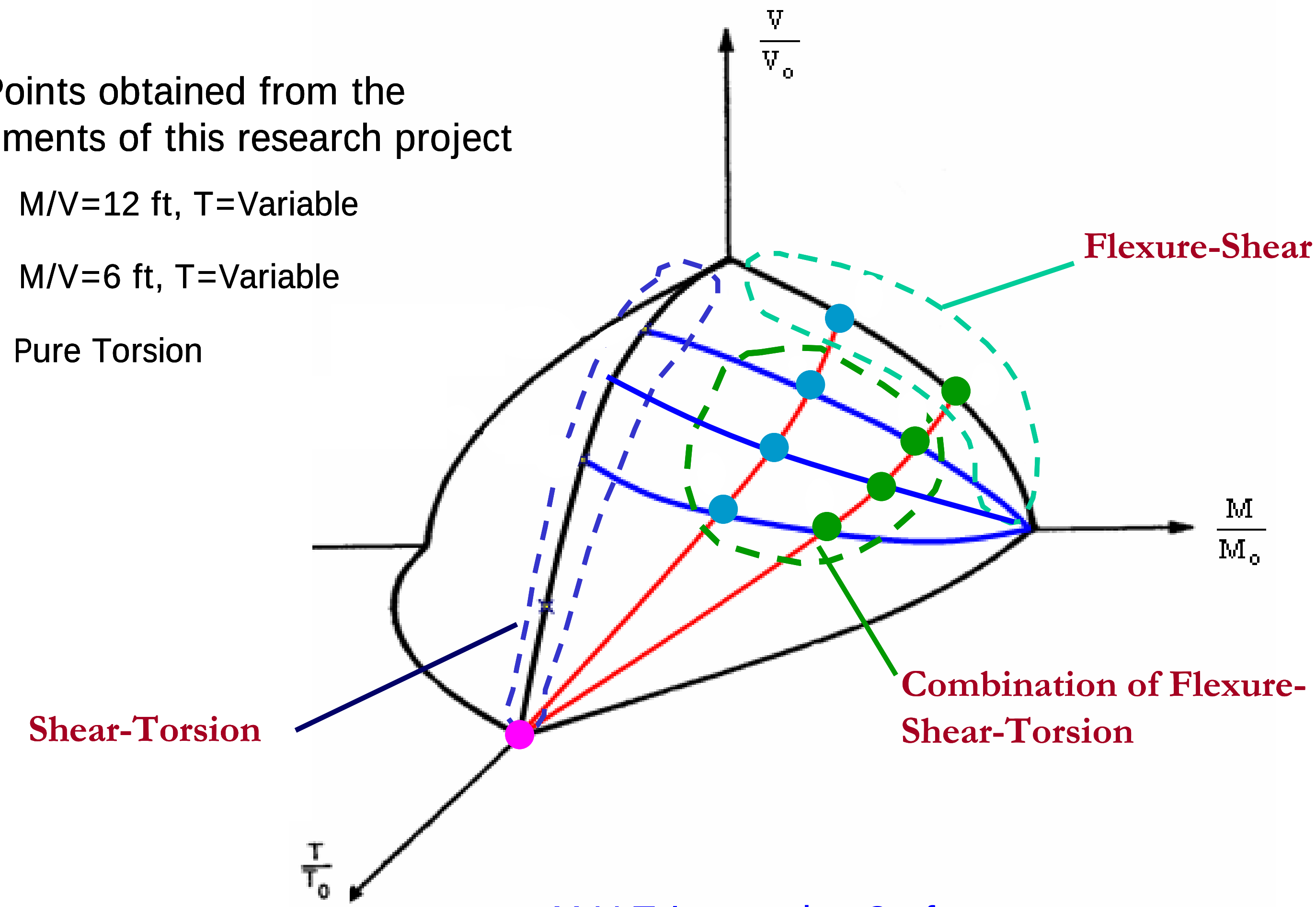
Project NEESR-SG-0530737

In order to address the complex behavior of bridge members under combined loadings and its impact on system response, a comprehensive project sponsored by the National Science Foundation was established in 2006

M-V-T Interactions

Test Points obtained from the experiments of this research project

- M/V=12 ft, T=Variable
- M/V=6 ft, T=Variable
- Pure Torsion



M-V-T Interaction Surface

Many Potential Parameters

- **Cross-section** - *Circle, Interlocking Spiral, Square*
- **Column aspect ratio** - *moment/shear ratio*
- **Torsion/shear ratio** - *high and low torsion*
- **Level of axial loads**
- **Level of detailing for high and moderate seismicity**
- **Bidirectional bending moment** - *non-circular cross-sections*
- **Type of Loading** – *Slow Cyclic, Pseudo-dynamic and shake table/dynamic*

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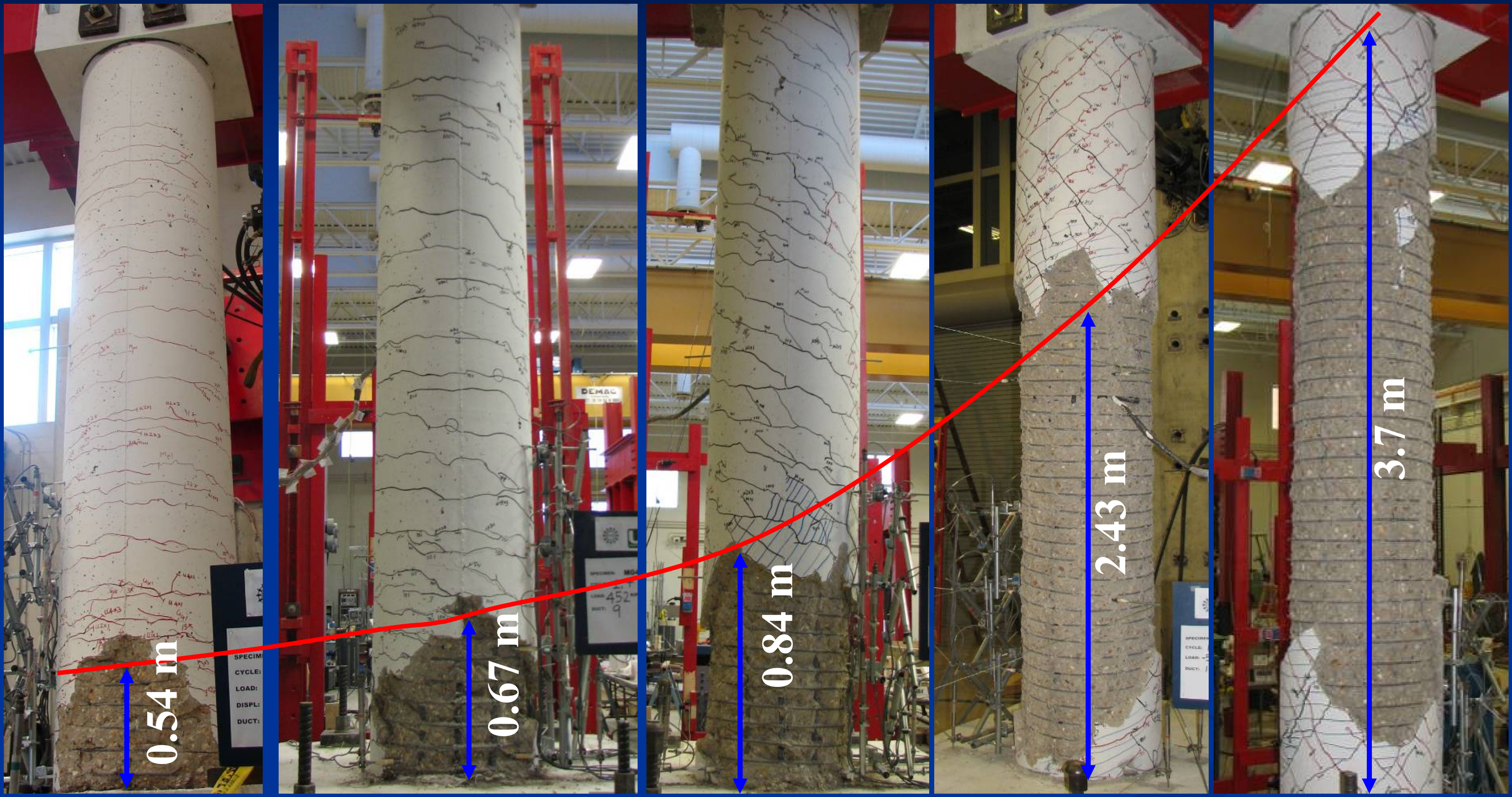
Results – Cover Spalling with Increasing T/M Ratio

Spiral Ratio of 0.73%



Increase in Torsional Moment

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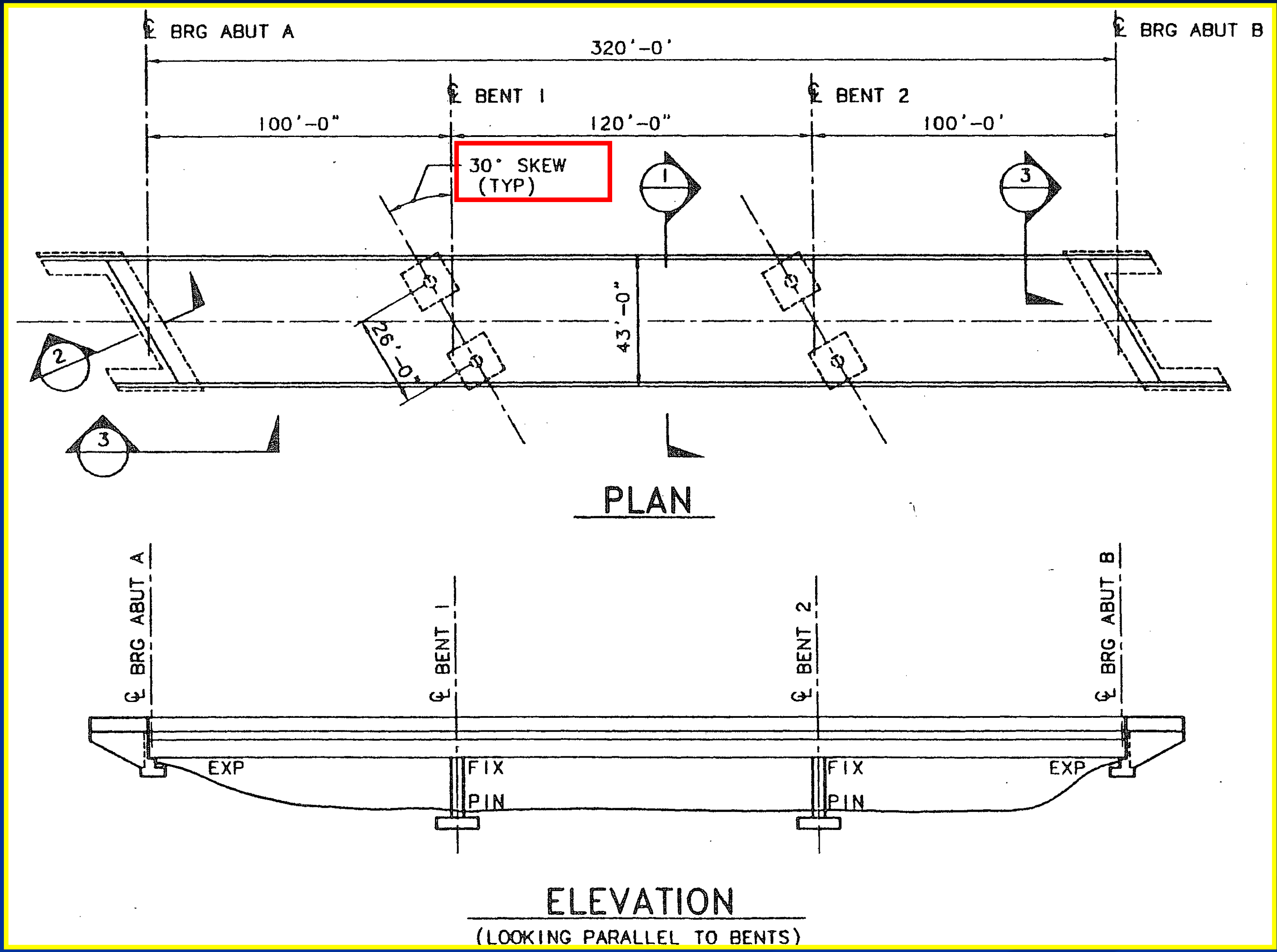
FHWA Bridge #4 – Structural Details



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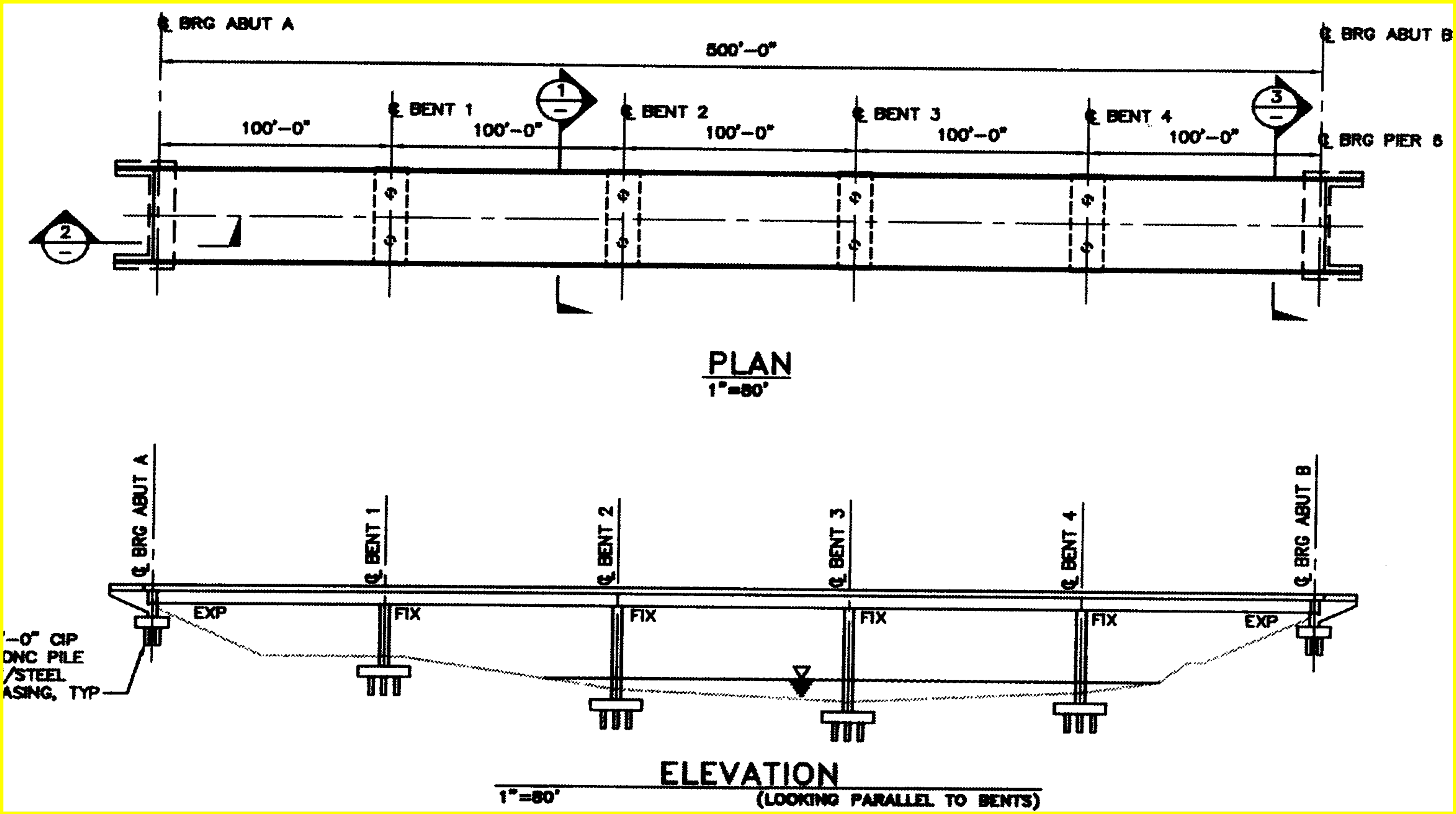
FHWA Bridge #8 – Structural Details



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Analytical Program

- Development Inelastic Models for RC Sections under Combined Loading
- Modeling of Specimens
  - Complex and Simplified Tools
- Parametric Studies
- Bridge System Analysis
- Development of Seismic Design Criteria

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Experimental Program

- Experimental investigation of columns under multi-directional loadings with varying levels of axial force and axial-flexure interaction ratios linked to analysis.
- Slow cyclic tests at MS&T.
- Pseudo-dynamic tests at UIUC
- Dynamic tests at UNR
- Integrated bridge test managed by George Washington and MS&T, tested at UIUC

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Combined Actions on Bridge Earthquake Response

Study on the Seismic Performance of Bridge Reinforced Concrete Columns under Combined Actions

@ University of Nevada, Reno

Dr. David H. Sanders, Professor
Juan G. Arias-Acosta, Graduate Student

September 2009

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UNR Previous Experiments

- 1:3 Scale
- ϕ=16'' , L=72''
- 20 # 4 (ρ=0.020)
- #2 @ 1.5'' (spiral)
- Axial load: 80 kips
- Increasing El Centro (1/3, 2/3, 1, 1.5, 2, 2.5, 3, 3.5, 4).
- CALTRANS (1990's design procedure).

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Introduction

Combined loadings (axial, shear, bending and torsion) can have significant effects on the force and deformation capacity of reinforced concrete bridge columns (RCC); that in turn can result in unexpected large deformations and extensive damage

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Work at UNR

The work at UNR focuses on the development of analysis and shaking table tests of large-scale models of bridge columns subjected to different levels of biaxial, torsion and vertical loads through real time earthquake motions

Test	Shape Diameter (in)	Scale	Ht (in)	Biaxial Bending	Torsion	Axial & PD-effect
Phase I	- 16	1:3	72	✓	Low	✗
	- 16	1:3	72	✓	High	✗
	12x17.5	1:4	72	✓	Low	✗
	12x17.5	1:4	72	✓	High	✗
Phase II	- 16	1:3	72	✓	Low	✓
	- 16	1:3	72	✓	High	✓
	12x17.5	1:4	72	✓	Low	✓
	12x17.5	1:4	72	✓	High	✓

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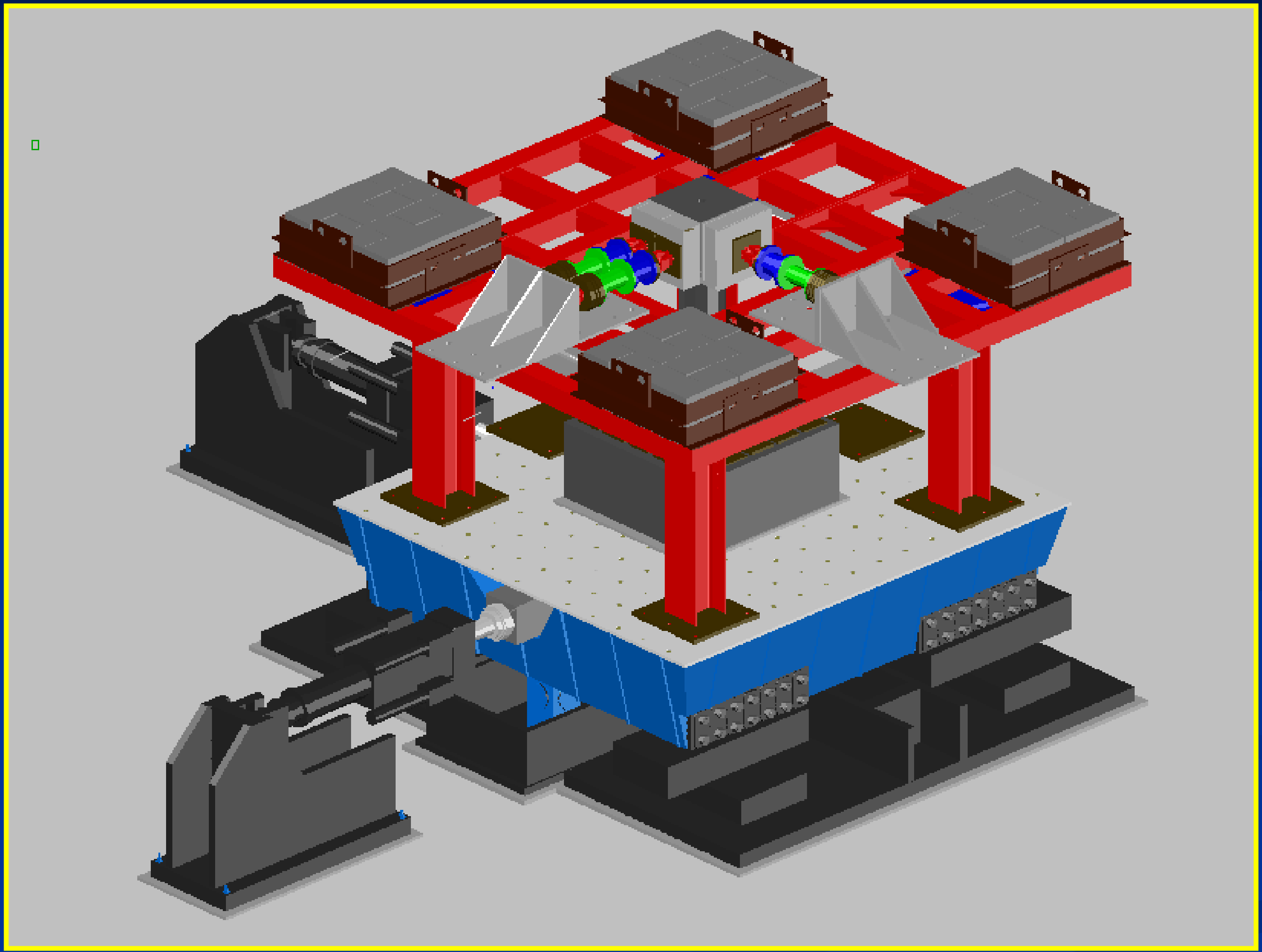
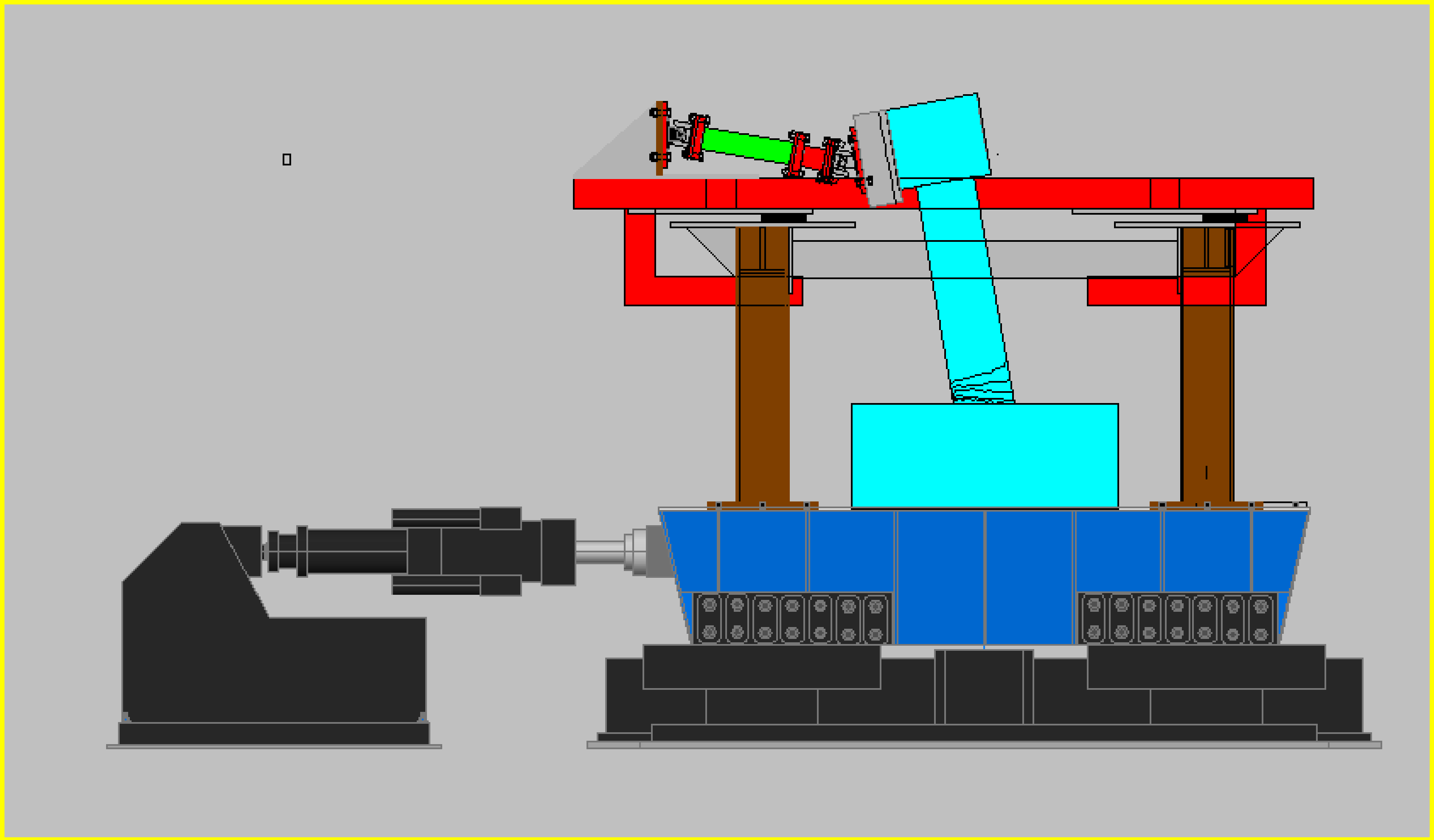
Bidirectional Mass Platform (Phase I)



Bidirectional Mass Platform (Without Axial load)



Bidirectional Mass Platform (Assembling sequence)

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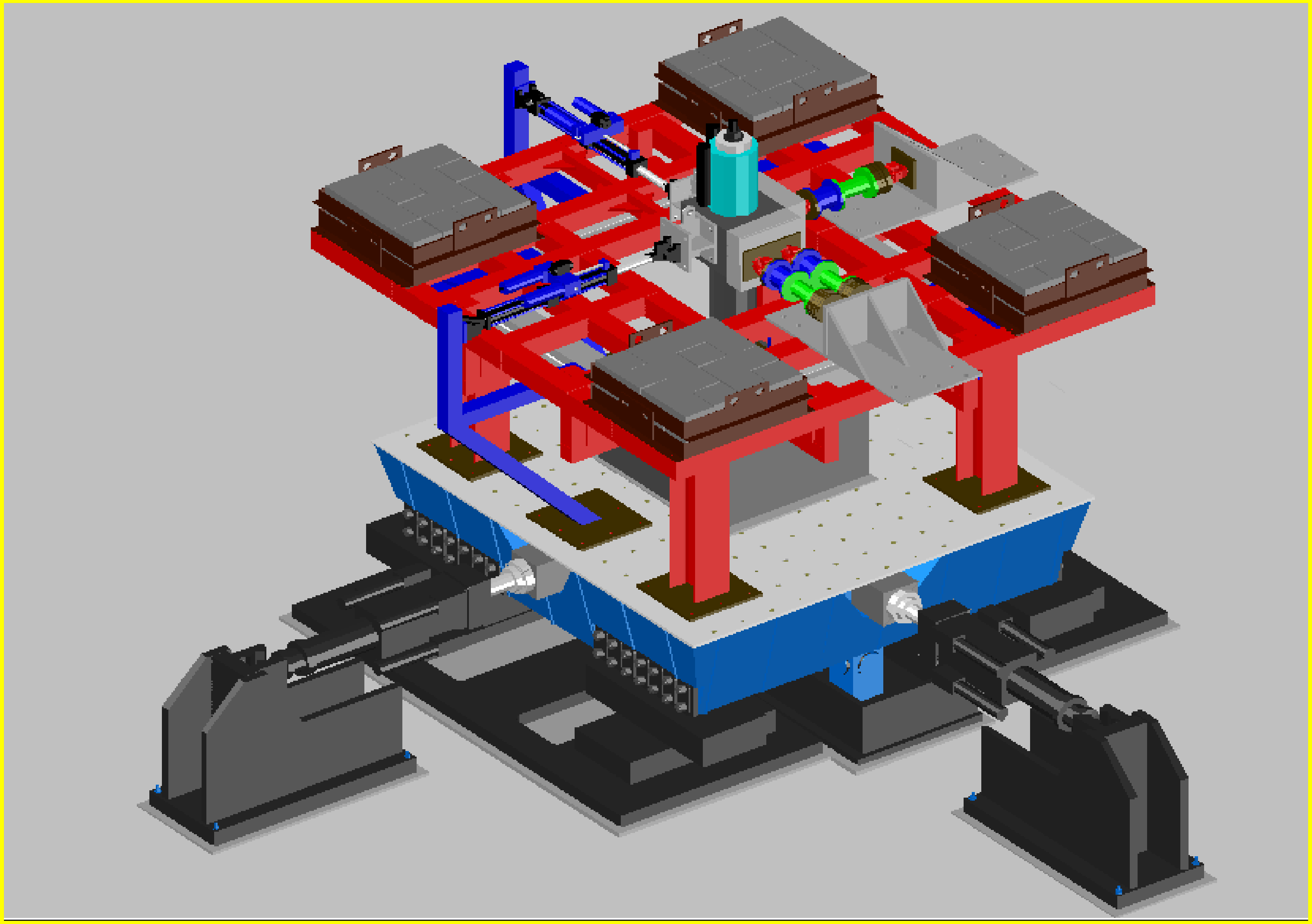
Bidirectional Mass Platform (Phase II)



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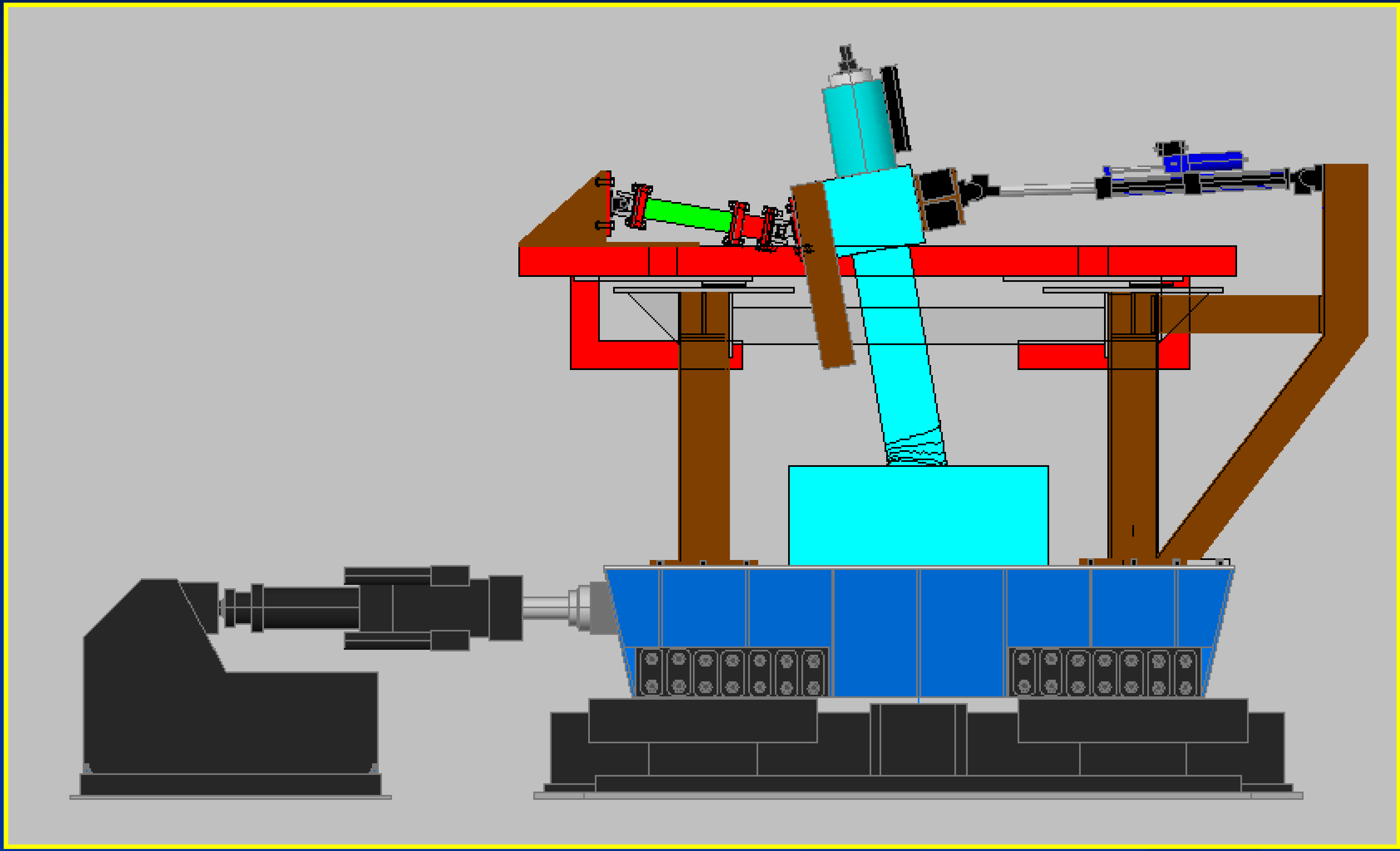
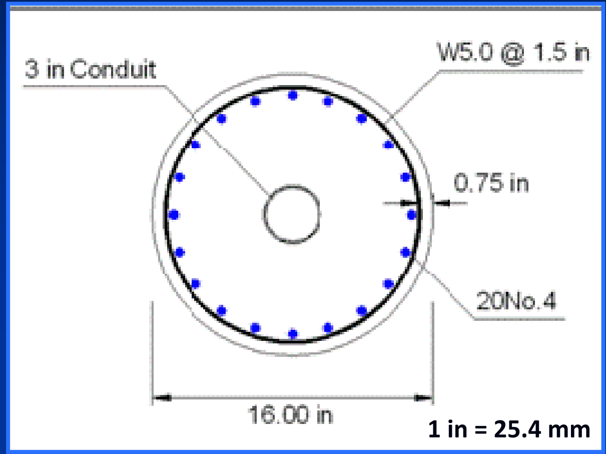
Bidirectional Mass Platform (With Axial load)

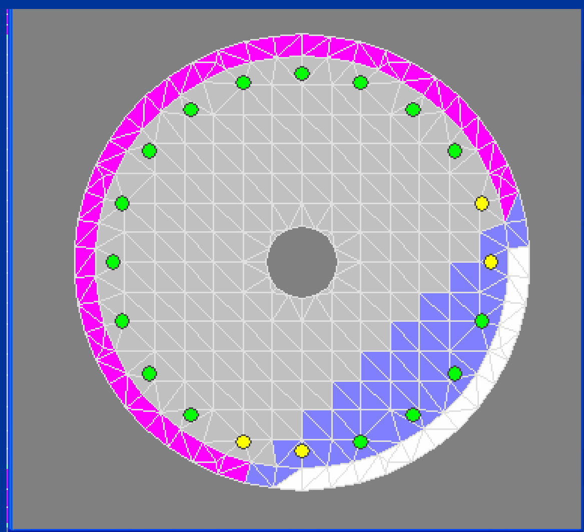


Circular Columns (Design Parameters)

Biaxial Moment – Curvature

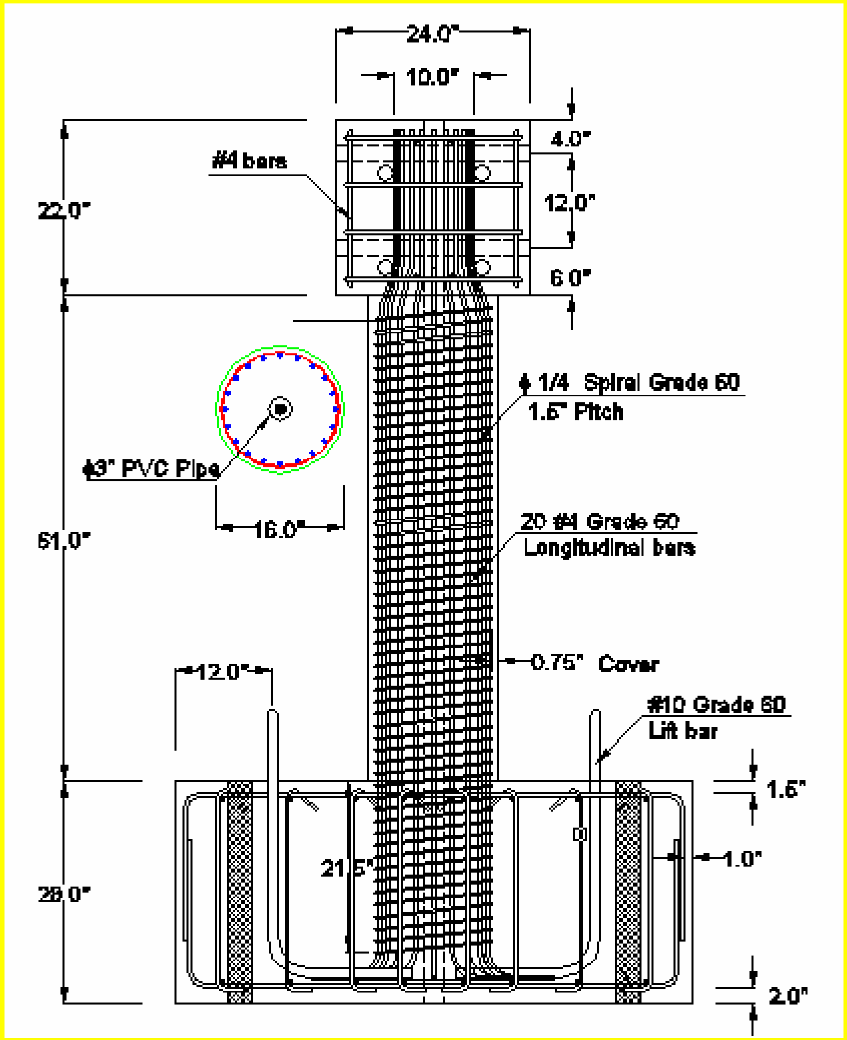
Circular Columns P=0	
Properties	Radial
ϕy	0.00034
My (k-in)	1566
ϕu	0.00584
Mu (k-in)	1973
$\mu\Delta$	8.29
Vu (kip)	27.41
Tcr (k-in)	230
Tu (k-in)	708





Circular Columns P=80 kip	
Properties	Radial
ϕy	0.00034
My (k-in)	1884
ϕu	0.00492
Mu (k-in)	2194
$\mu\Delta$	7.06
Vu (kip)	30.56
Tcr (k-in)	354
Tu (k-in)	780

Circular Columns Details



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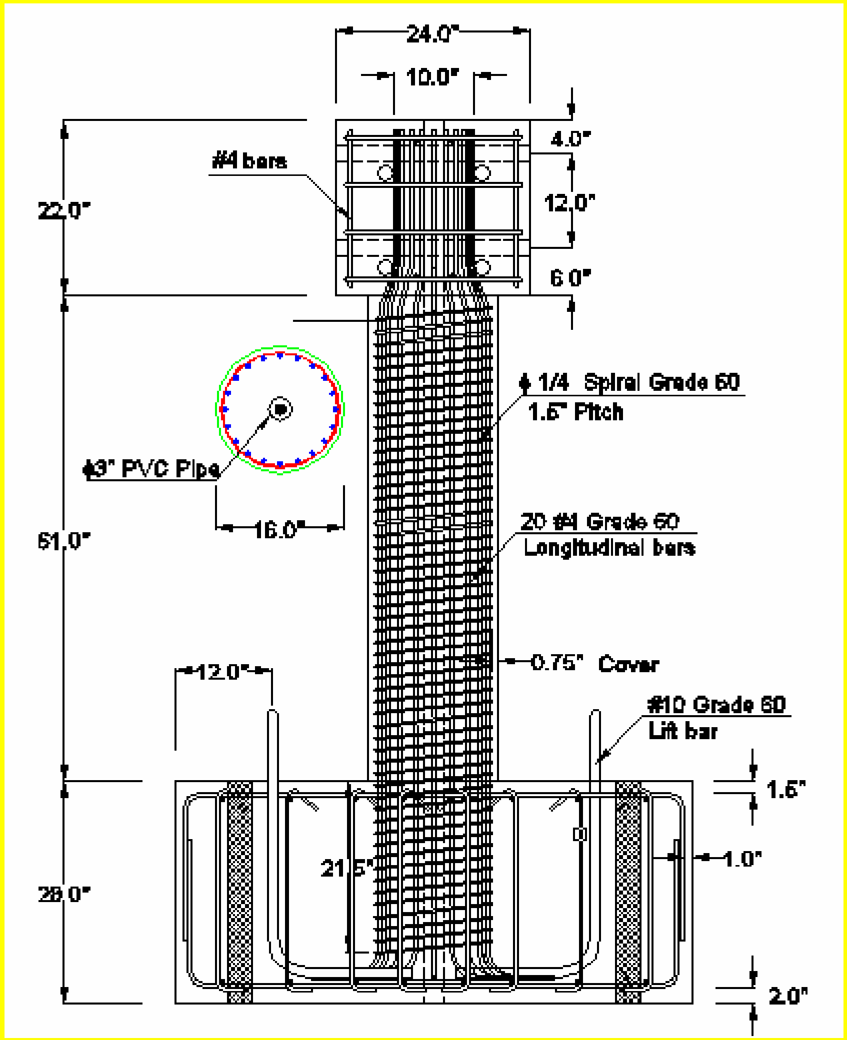
Circular Columns Details



Material Properties

Days	Concrete Compressive Strength [ksi]			
	Circular		Interlocking	
	Footing	Column	Footing	Column
28	4.79	4.1	5.22	3.92

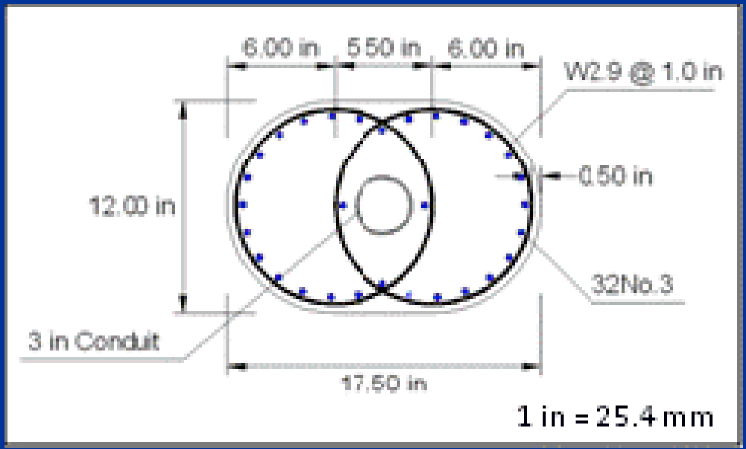
Steel Properties	No.3	No.4	W2.9	W5.0
Yield stress [ksi]	61.4	65.0	58.1	58.1
Yield strain	0.0022	0.0023	0.0024	0.0024
Strain at hardening	0.012	0.0075	N.A	N.A
Peak stress [ksi]	95.6	103.3	78.5	78.5
Strain at peak	0.124	0.115	0.115	0.126
Fracture stress [ksi]	81.4	99.7	77.9	70.2
Fracture strain	0.195	0.151	0.154	0.138

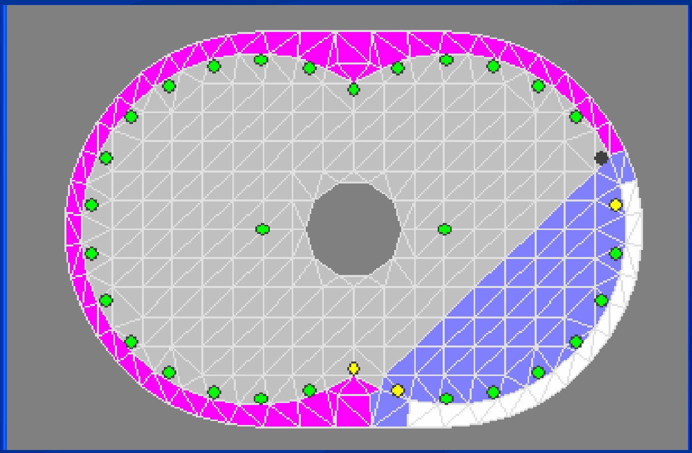
Double Interlocking Columns (Design Parameters)

Biaxial Moment – Curvature

Interlocking Columns P=0		
Properties	Short Dim.	Long Dim
ϕy	0.0004	0.0004
My (k-in)	616.3	1175
ϕu	0.004	0.004
Mu (k-in)	785	1615
$\mu\Delta$	6.13	4.45
Vu (kip)	216	444

Interlocking Columns P=80 kips		
Properties	Short Dim.	Long Dim
ϕy	0.00034	0.00034
My (k-in)	756.2	1642
ϕu	0.0039	0.0039
Mu (k-in)	837.6	1837
$\mu\Delta$	7.03	5.08
Vu (kip)	520	505





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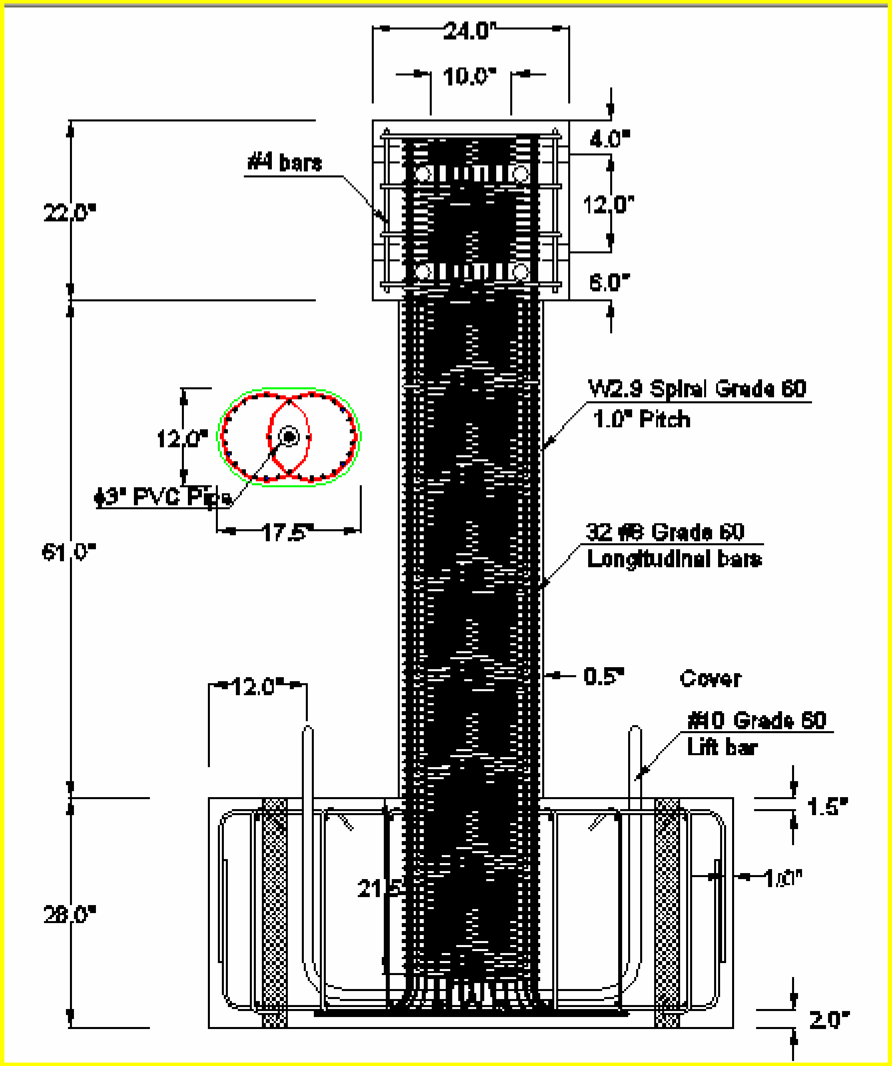
Double Interlocking Columns Details



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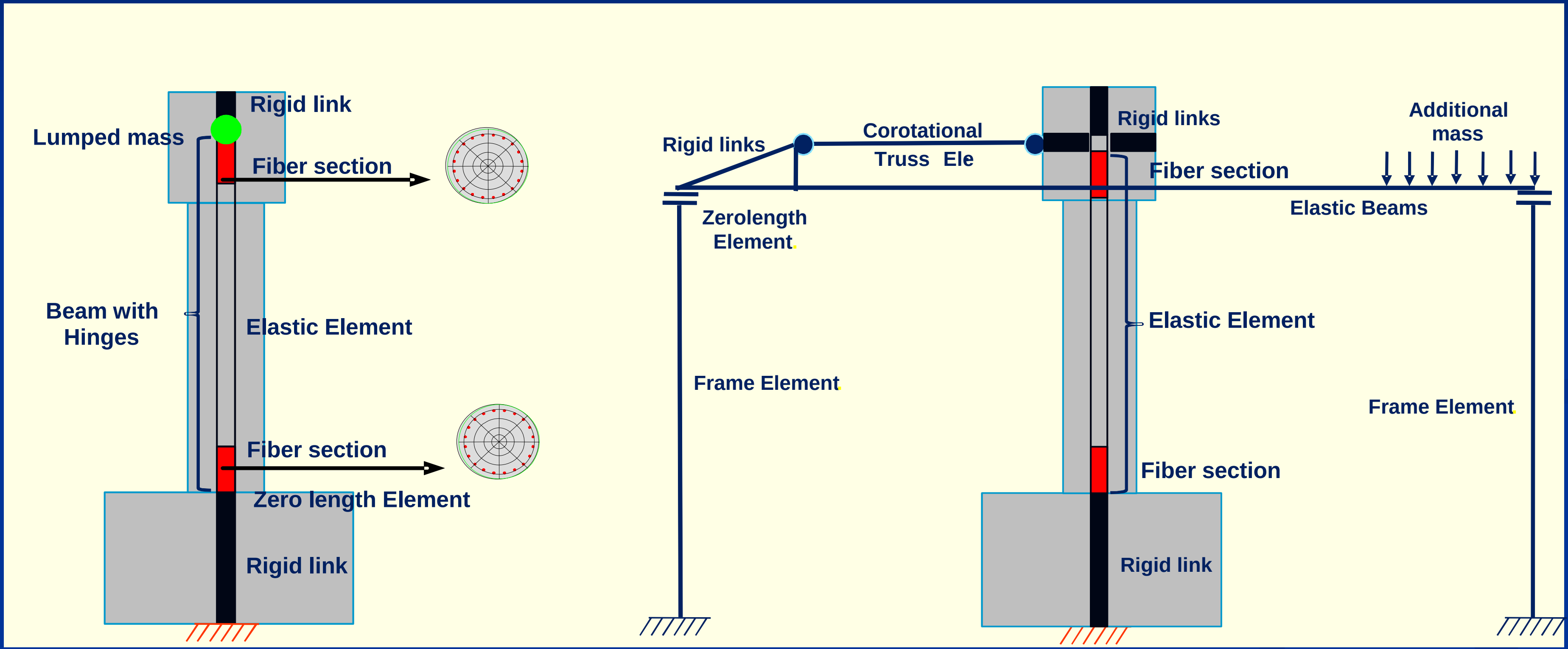
Analytical Models (OpenSees)



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Analytical model (OpenSees)

Mass=80 kips
Axial load 80 Kips
Torsional stiffness 0.2JG

Biaxial motions
El Centro: 0.33, 0.66, 1.0, 1.5, 2.0, 2.5, 3.0
Sylmar: 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6
Kobe: 0.3, 0.6, 0.9, 1.2, 1.5, 1.8

Mendocino (Petrolia): 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4
Northridge (Sepulveda): 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4

Model 1: Single Column, without axial load, without PD-effect.
Model 2: Inertial frame, with unbonded tendon, with PD-effect.

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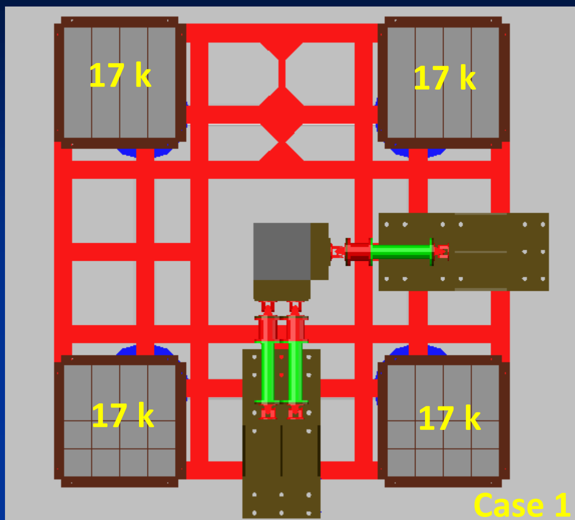
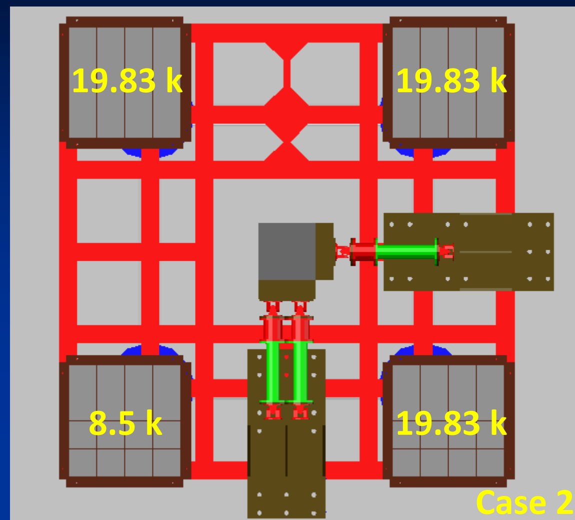
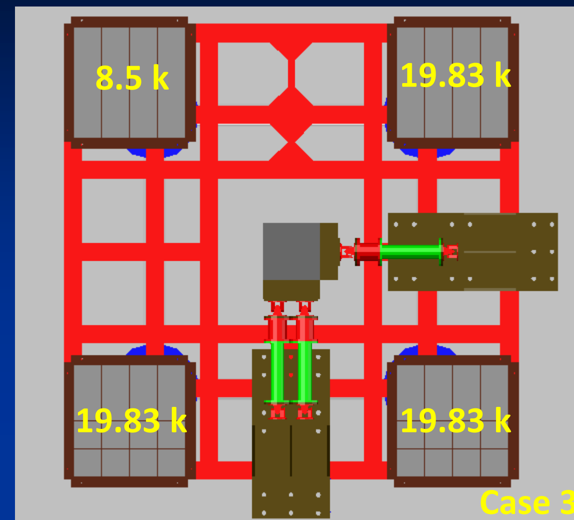
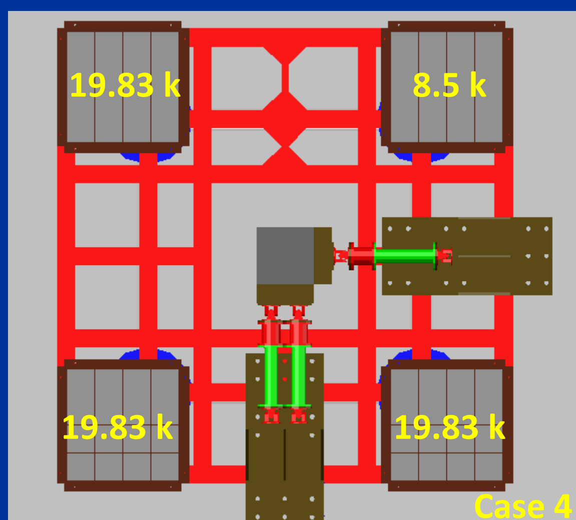
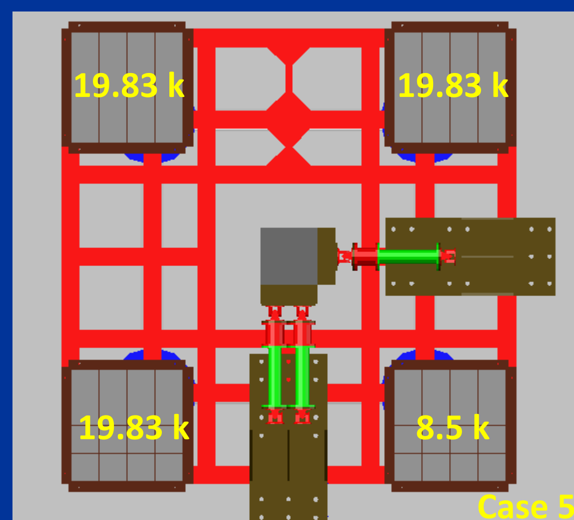
Mass Distribution (Plan view)











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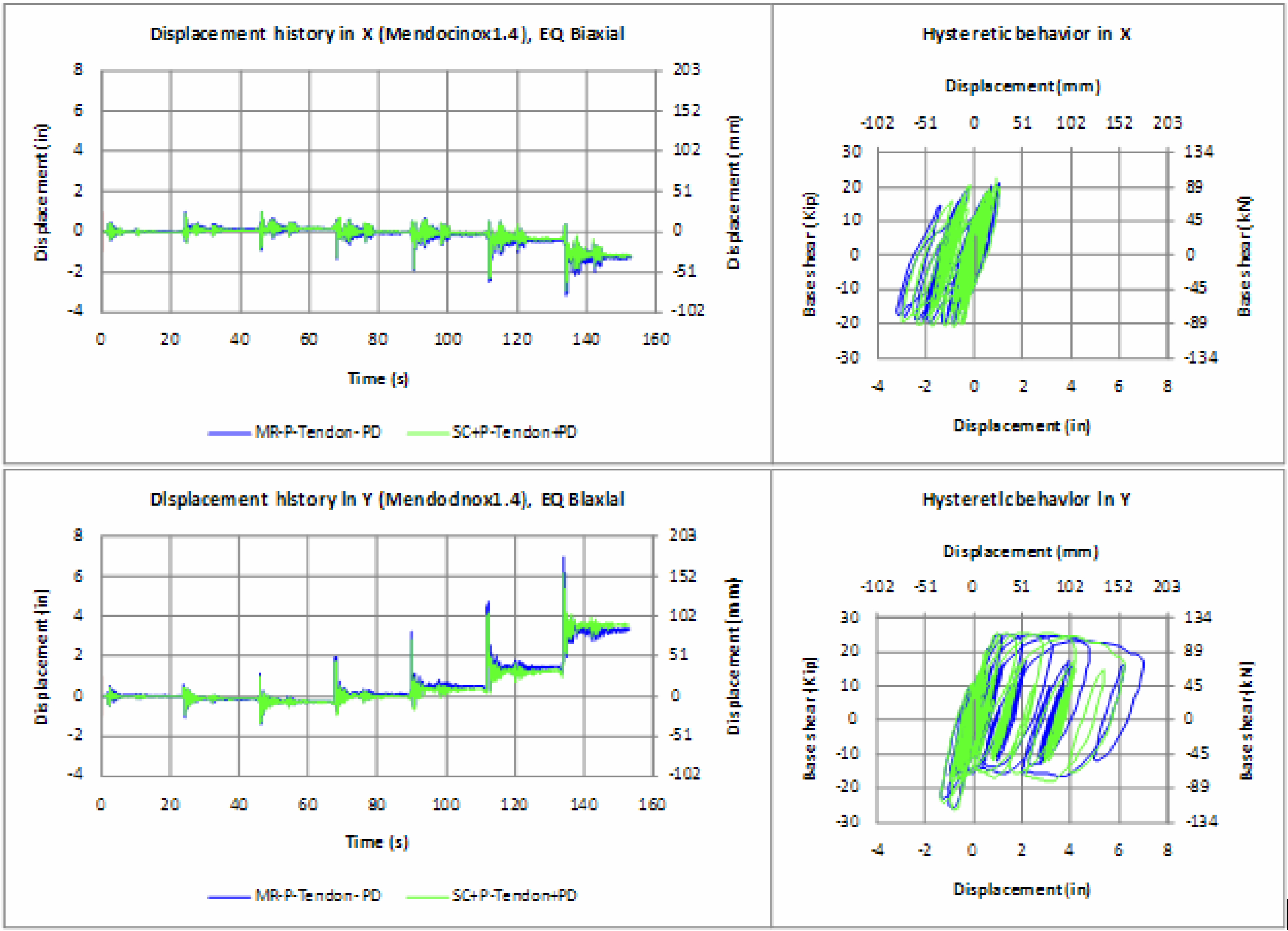
Analysis Results (Circular Column P=0)

Petrolia at Mendocino, Earthquake (1992)
Scaled to have a Hazard level 2% in 50 years

Max acceleration in X 0.8 g
Max acceleration in Y 0.98 g

Earthquake	Load	Max Top Displ. (cm)			Max Base Shear. (kN)			Max. Base Moments. (kN-m)			T/Mx	T/My
	Case	X	Y	Comp	X	Y	Comp	Mx	My	T		
Mendocino	1	3.17	8.15	8.19	19.0	28.8	32.3	2791.2	1896.6	55.4	0.02	0.03
Petrolia x1.4	2	8.05	8.05	8.09	18.9	28.0	32.4	2802.7	1888.2	596.6	0.21	0.32
	3	8.05	8.05	8.09	19.2	28.0	32.5	2796.6	1915.2	430.3	0.15	0.22
	4	3.13	8.08	8.12	18.9	28.0	32.4	2803.4	1889.9	493.4	0.18	0.26
	5	3.22	8.00	8.04	19.1	27.9	32.5	2795.4	1912.3	457.5	0.16	0.24

Analysis (Petrolia @ Mendocino-Case1)



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Column C1- Front View

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Column C1- Top View

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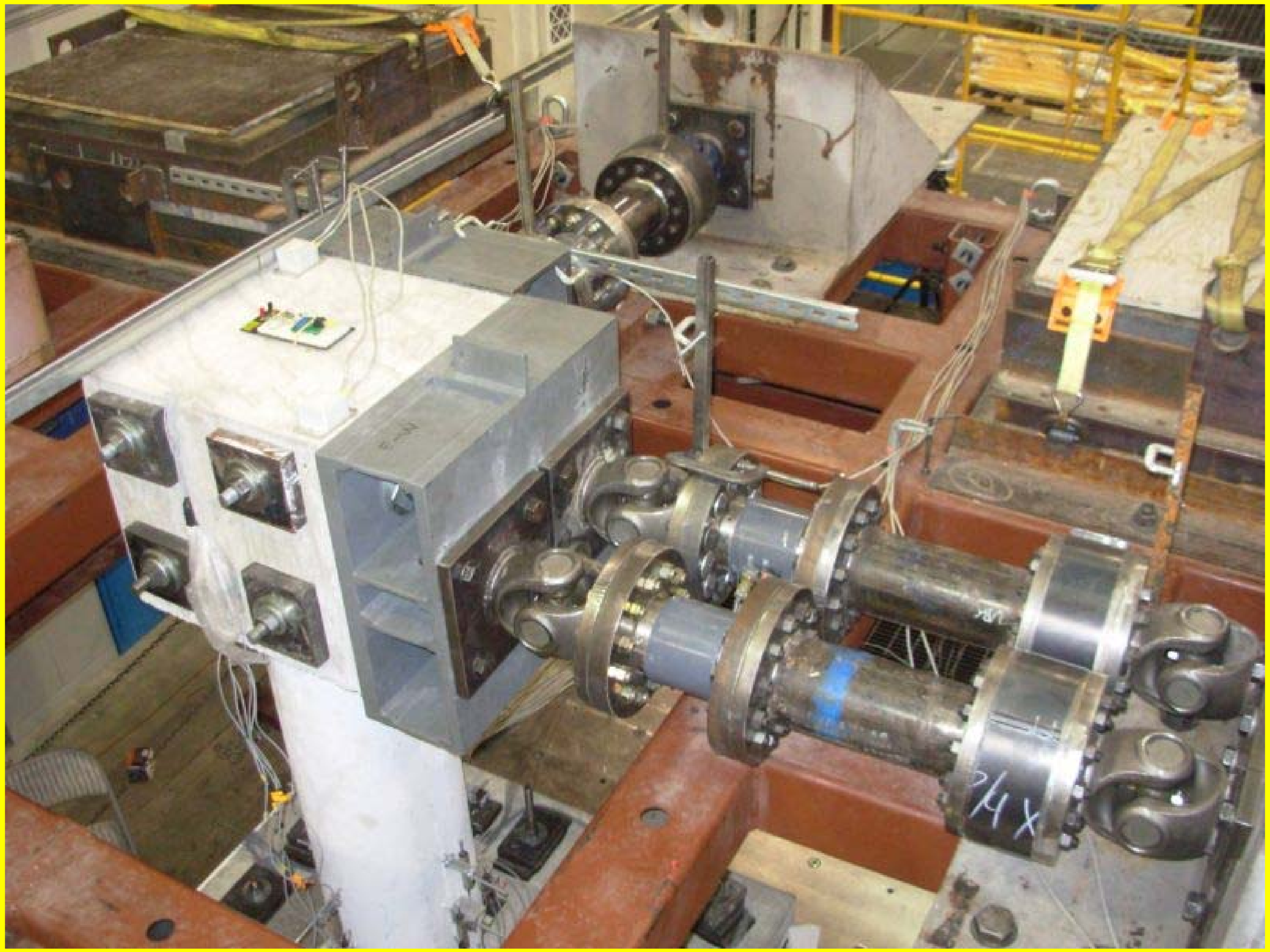
Column C1- Links



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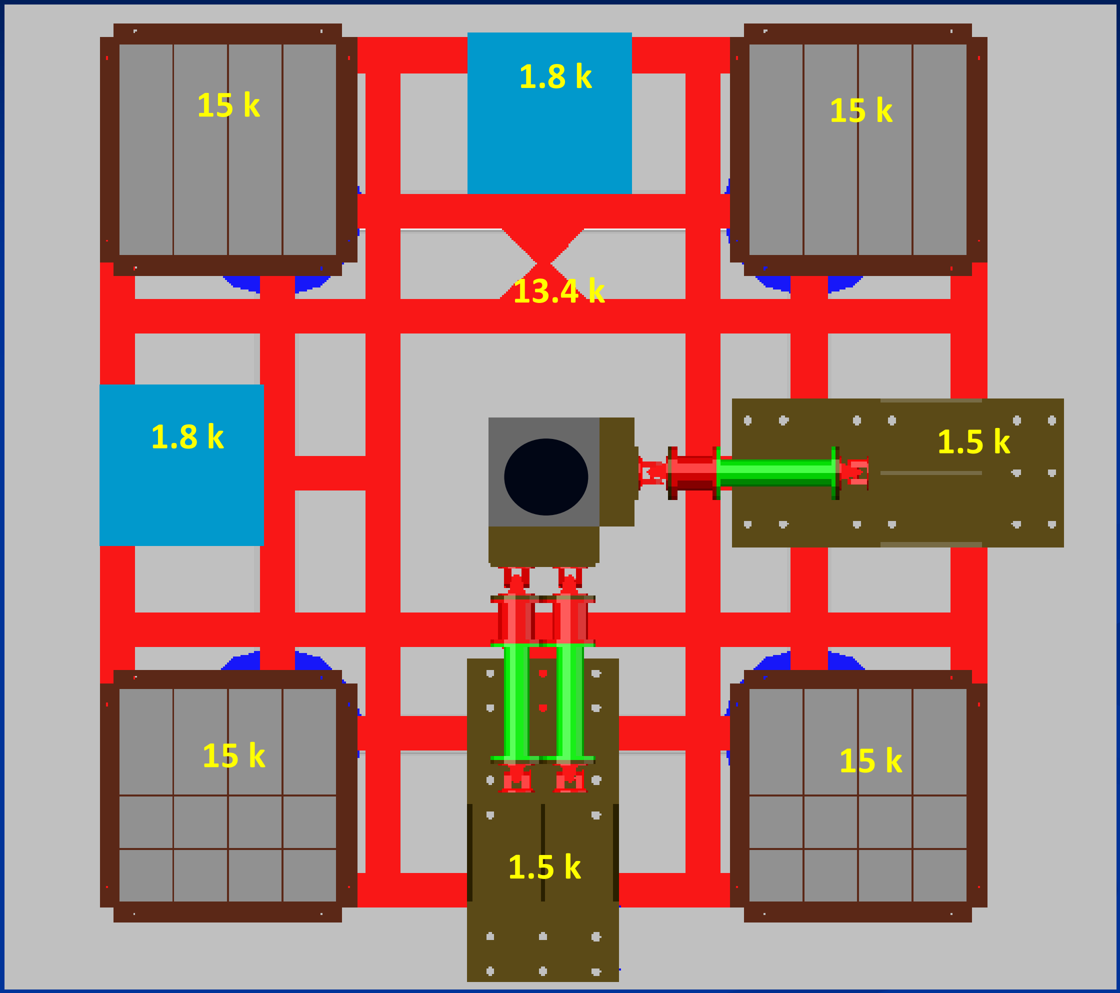
Column C1- Mass Distribution



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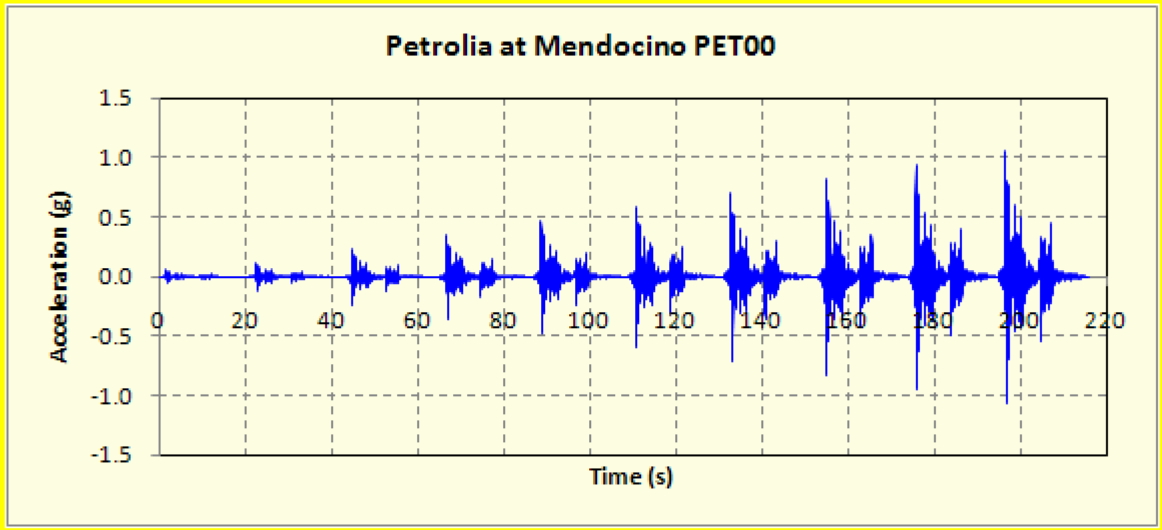
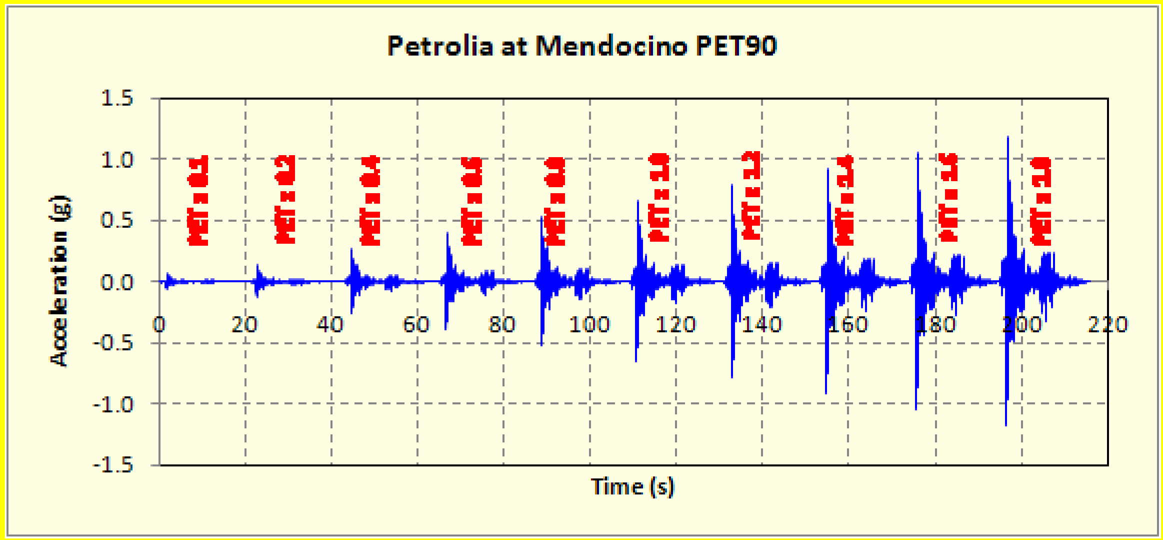
Column C1 – Test Protocol

Run	x Petrolia	Acc. in X (g)	Acc. in Y (g)
1	0.1	0.105	0.050
2	0.2	0.191	0.106
3	0.4	0.444	0.255
4	0.6	0.588	0.381
5	0.8	0.667	0.466
6	1.0	0.692	0.607
7	1.2	0.806	0.752
8	1.4	0.887	0.863
9	1.6	0.981	1.039
10	1.8	1.098	1.175

Signals of small amplitude white noise were applied between runs

Petrolia Earthquake (Column C1)





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Column C1 – Measured Dynamic Properties

Run	Period in X (s)	Period in Y (s)	Kx (kip/in)	Ky (kip/in)
WN1	0.62	0.61	2054	2122
WN2	0.63	0.64	1989	1928
WN3	0.69	0.69	1658	1658
WN4	0.80	0.77	1234	1332
WN5	0.81	0.81	1203	1203
WN6	0.86	0.88	1068	1020
WN7	0.94	0.92	894	933
WN8	0.98	0.93	822	913
WN9	1.05	1.01	716	774
WN10	1.31	1.10	460	653
WN11	1.38	1.32	415	453

$$K = M \frac{4\pi^2}{T^2}$$

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Column C1 – Last Run

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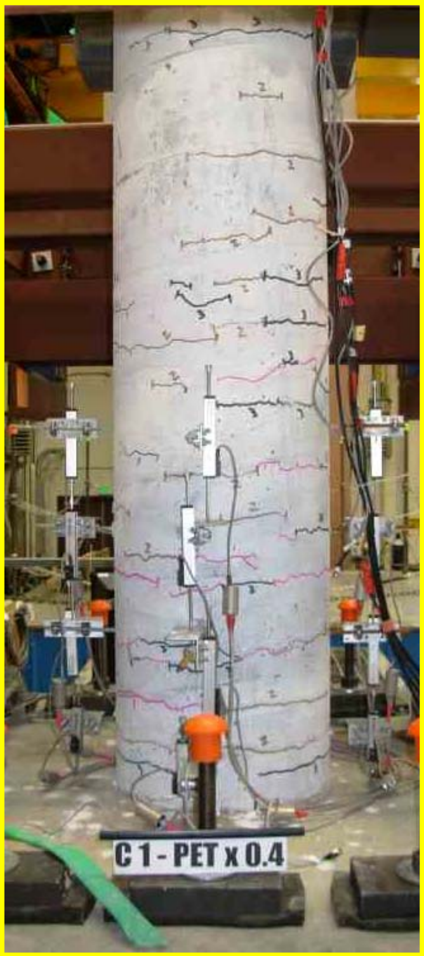
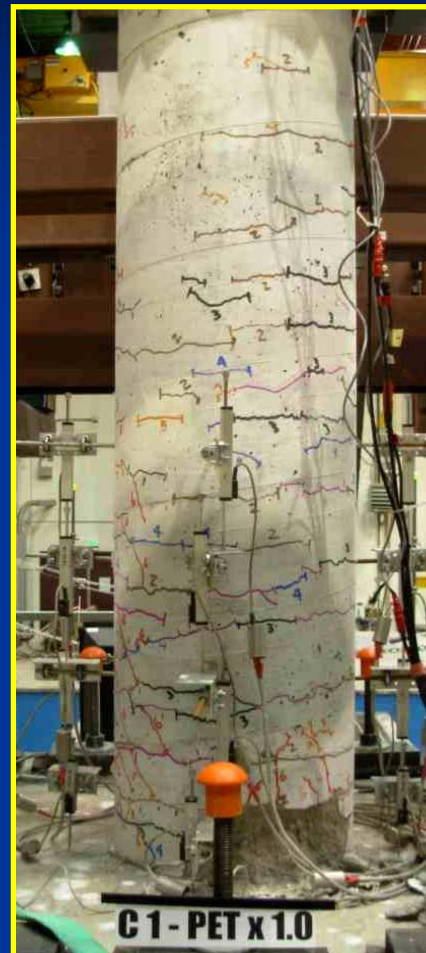
Column C1 – Damage Progression

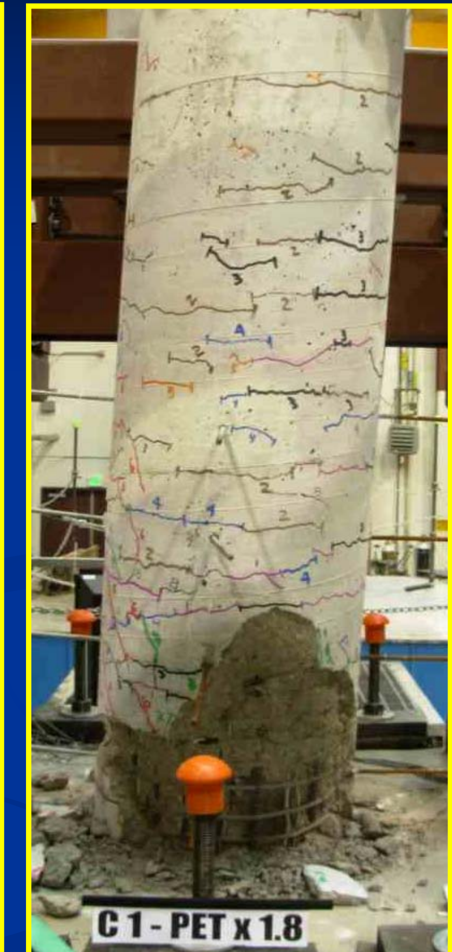


Flexural cracks

Inclined cracks



Concrete Spalling



Failure

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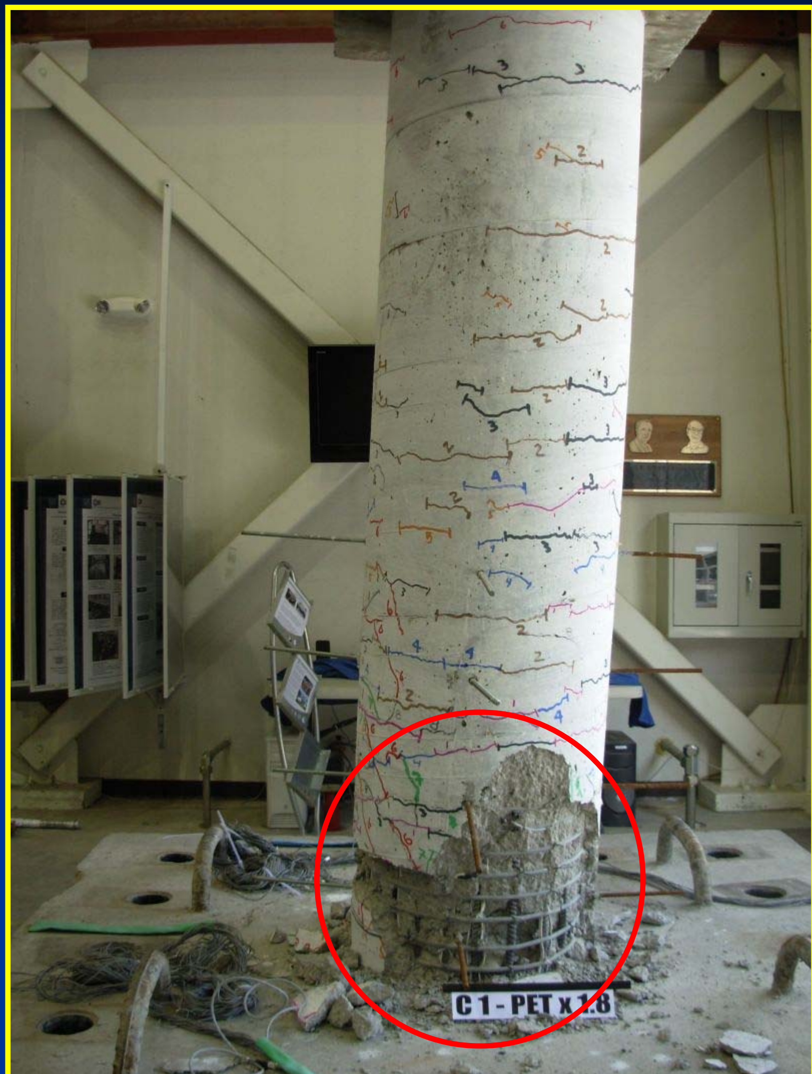
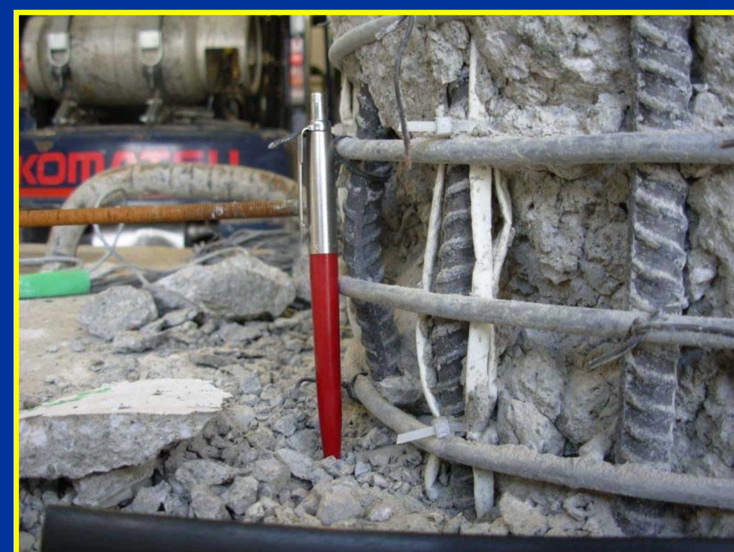
Column C1 – Failure





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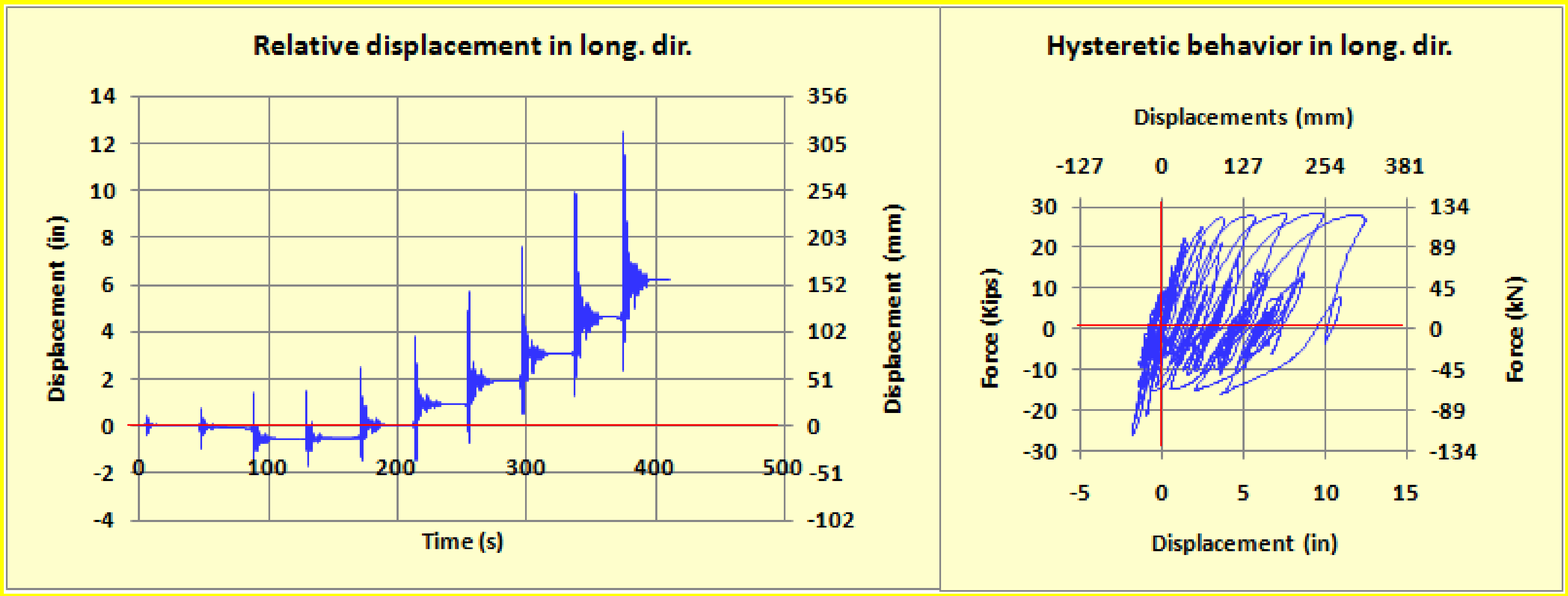
Column C1 - Performance

Run	x Petrolia	Drift in X (%)	Drift. in Y (%)	Performance
1 to 3	0.1 – 0.4	0.59 – 2.58	0.36 – 1.13	Flexural Cracks
4	0.6	2.37	1.02	First inclined Cracks
5	0.8	3.47	1.51	First Spalling
6 to 8	1.0 – 1.4	5.3 – 10.64	2.51 – 4.46	Extension of Cracks and Spalling
9	1.6	13.78	6.0	Spiral and long. Bars Visible
10	1.8	17.3	8.4	Flexural Failure (Bar Buckling)

Test Specimen C1

Earthquake		Rel. disp. in X (in)	Rel. disp. in Y (in)	Force in X (kips)	Force in Y (kips)
0.4xPET	MAX	-0.8	-0.459	22.35	12.59
	MIN	0.983	0.386	-26	-13.02
0.6xPET	MAX	-0.813	-0.504	20.98	11.31
	MIN	0.983	0.367	-23.21	-11.17
0.8xPET	MAX	1.427	0.508	25.09	11.06
	MIN	-1.159	-0.696	-18.55	-13.07
1.0xPET	MAX	1.511	1.905	27.28	10.88
	MIN	-3.82	-0.619	-14.75	-14.93
1.6xPET	MAX	3.424	1.188	28.55	10.14
	MIN	-2.578	-1.578	-15.17	-16.62
1.8xPET	MAX	-2.342	6.142	27.9	11.07
	MIN	-12.47	1.292	-16.14	-16.72

C1- Cumulative Histories in Long. dir.



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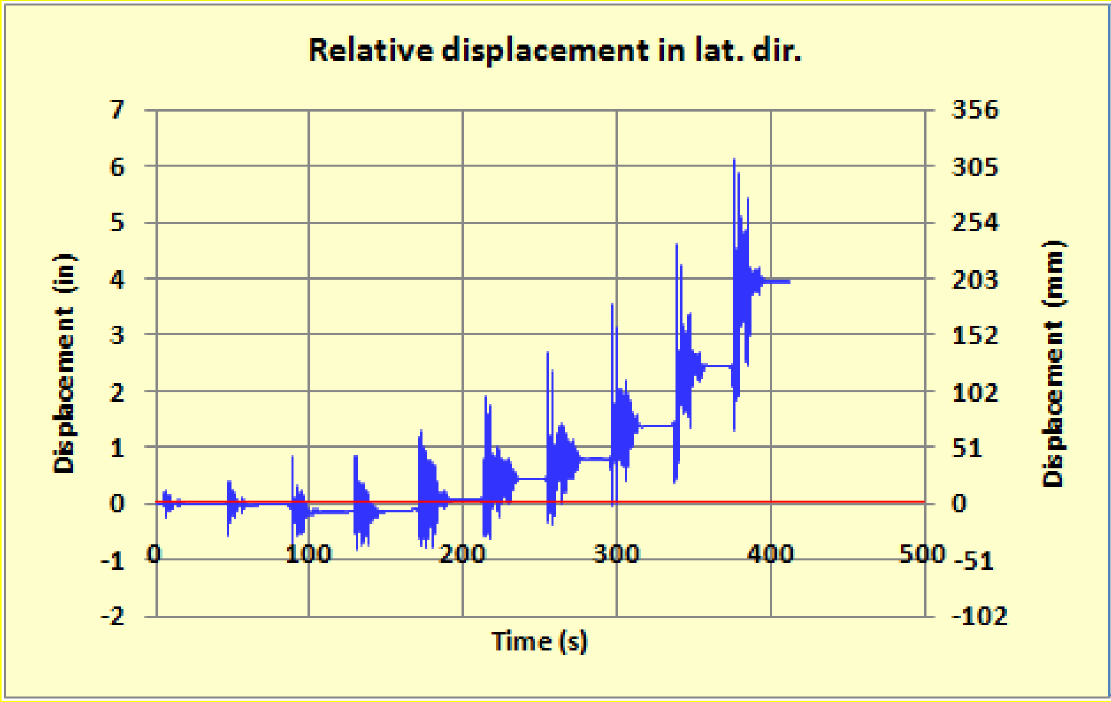
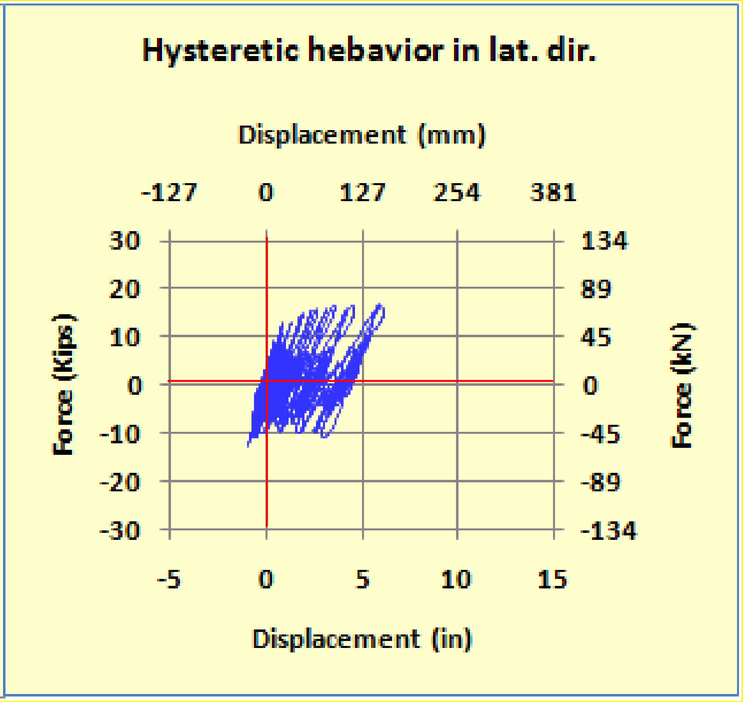
C1- Cumulative Histories in Lat. dir.





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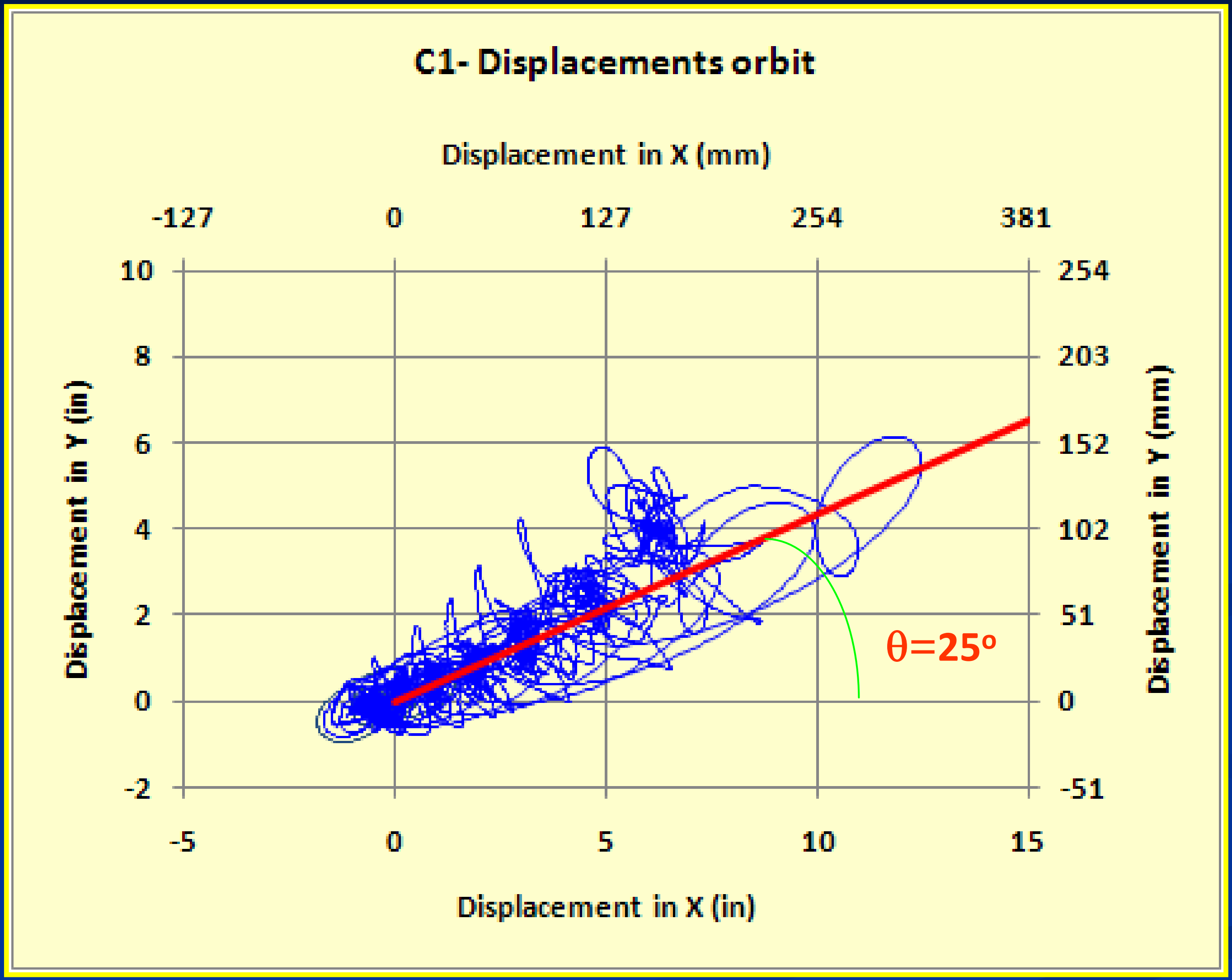
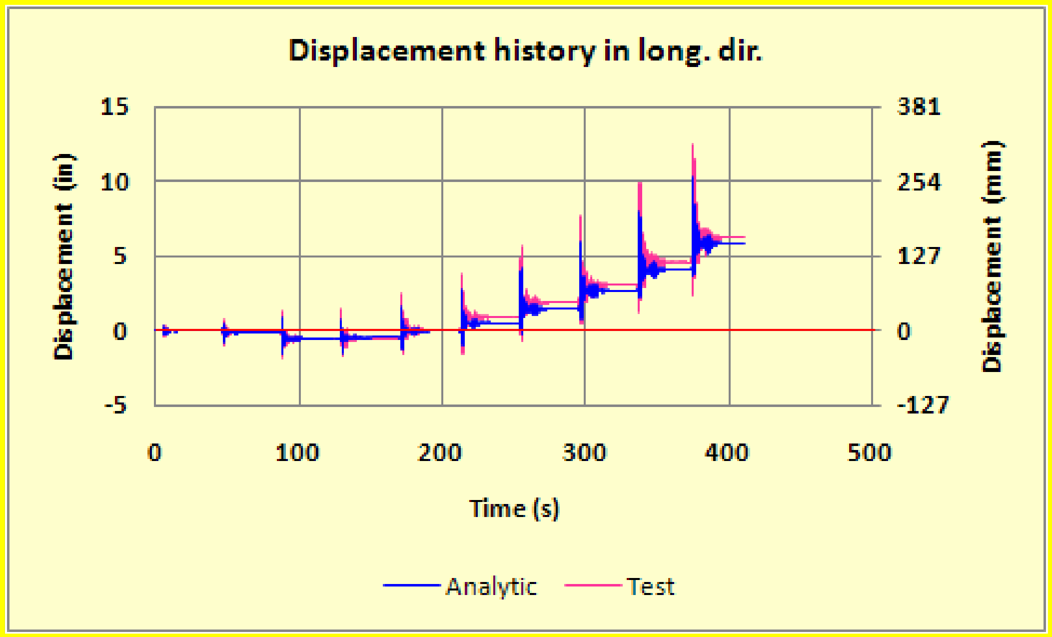
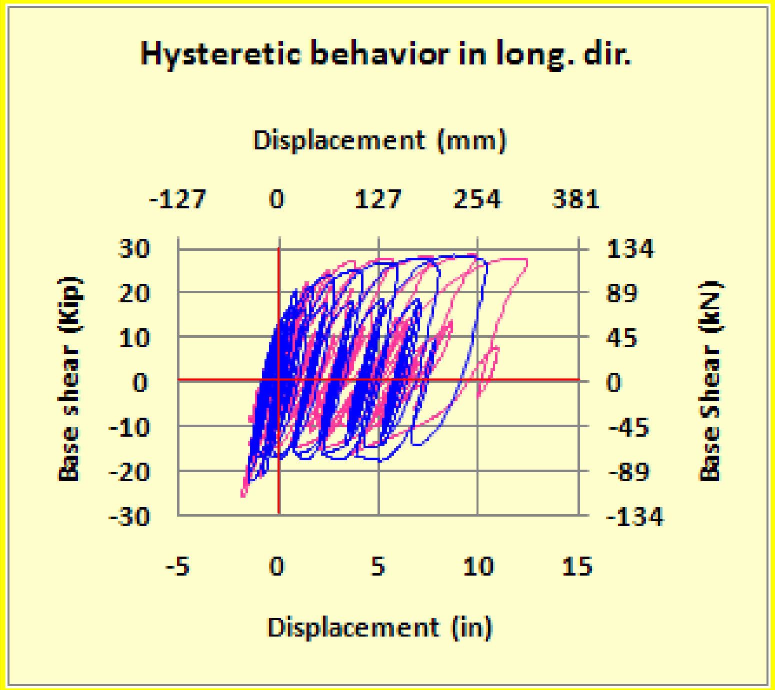
C1- Displacement Orbit



CABER
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

C1- Behavior (Analytic vs. Test)





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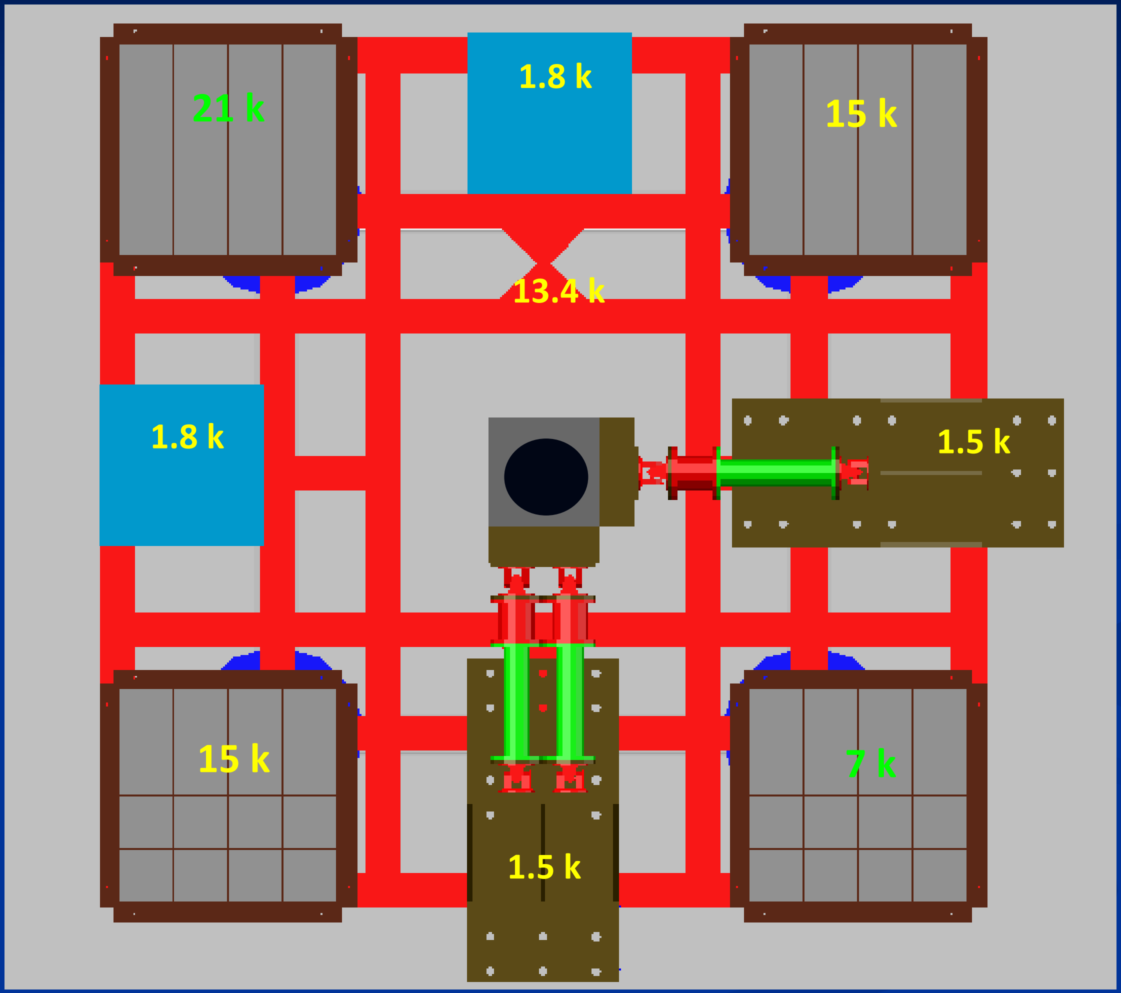
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Column C2- Mass Distribution



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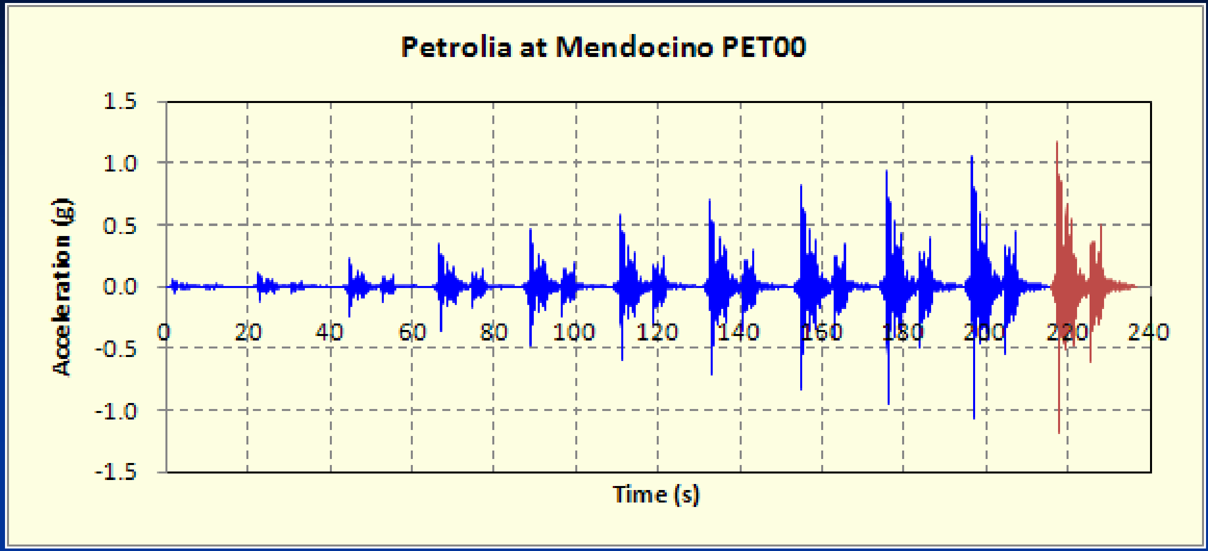
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

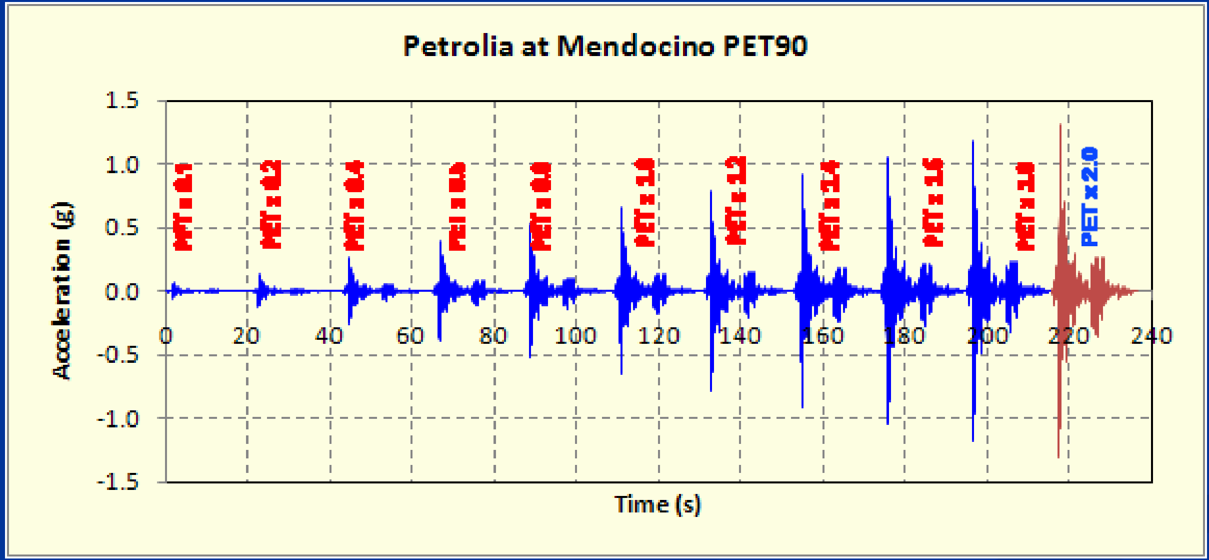
Column C2 – Test Protocol

Run	x Petrolia	Acc. in X (g)	Acc. in Y (g)
1	0.1	0.074	0.055
2	0.2	0.152	0.094
3	0.4	0.274	0.186
4	0.6	0.540	0.299
5	0.8	0.680	0.427
6	1.0	0.776	0.553
7	1.2	0.817	0.689
8	1.4	0.878	0.849
9	1.6	0.954	0.989
10	1.8	1.068	1.137
11	2.0	1.345	1.353

Signals of small amplitude white noise were applied between runs

Petrolia Earthquake (Column C2)





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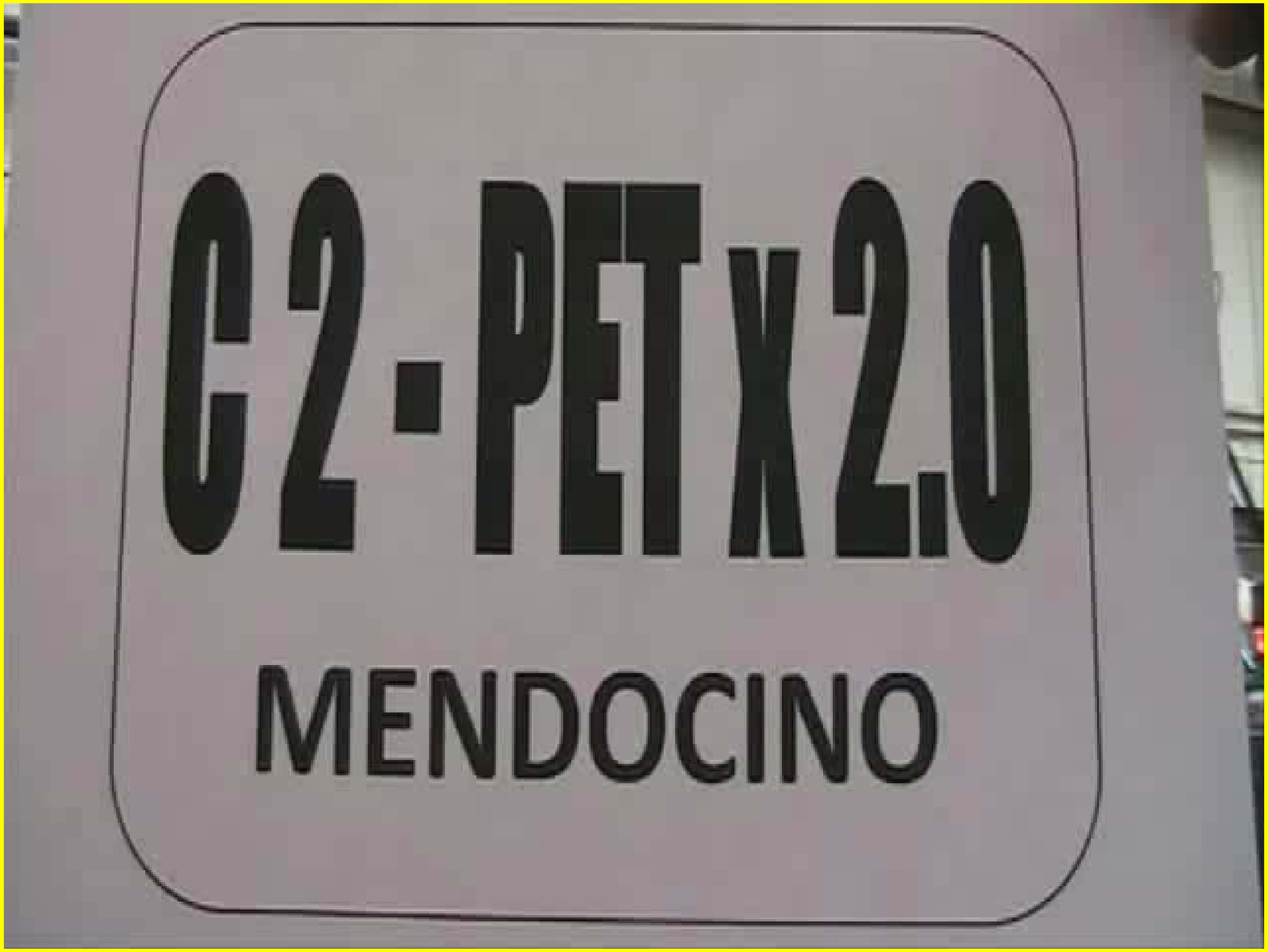
Column C2 –Last Run



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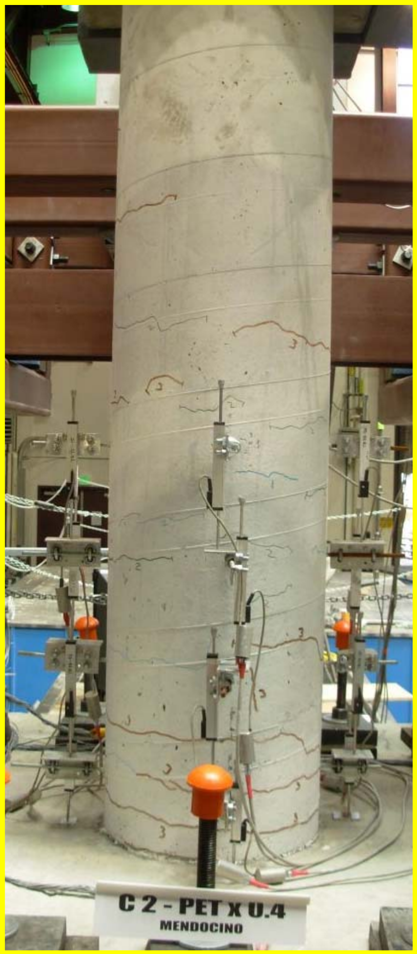
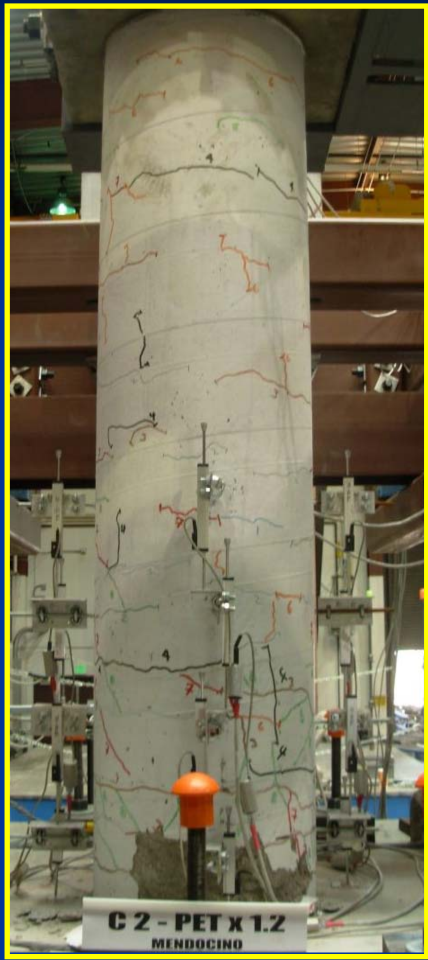
Column C2 – Damage Progression

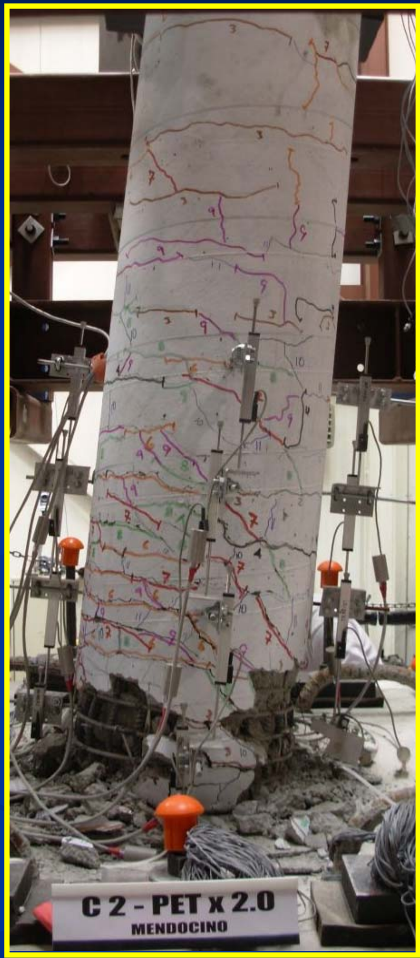


Flexural cracks

Inclined cracks



Concrete Spalling



Failure

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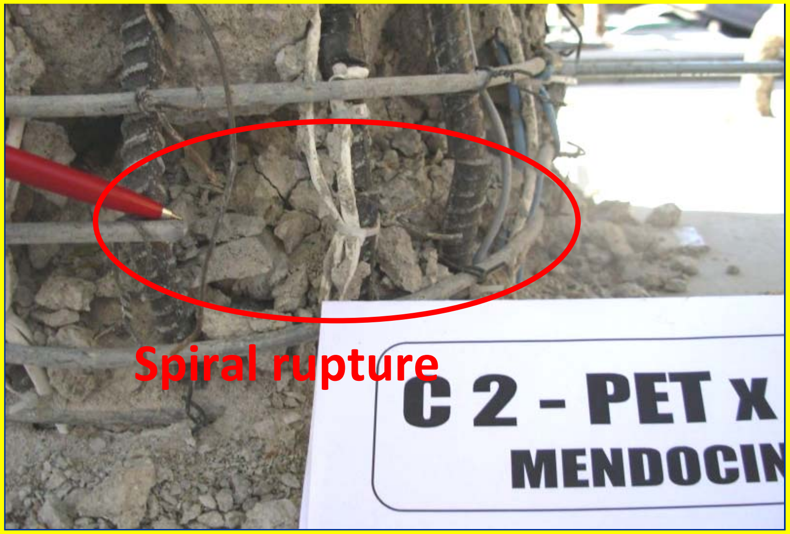
Column C2 – Failure Mode



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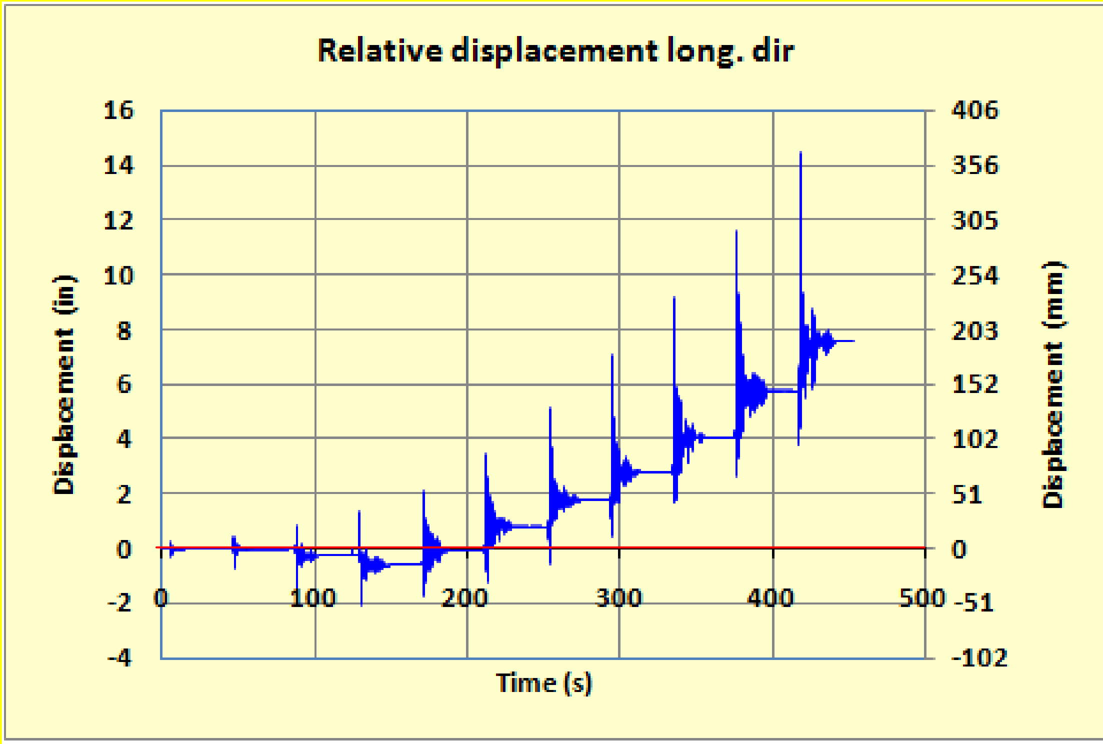
Column C2 - Performance

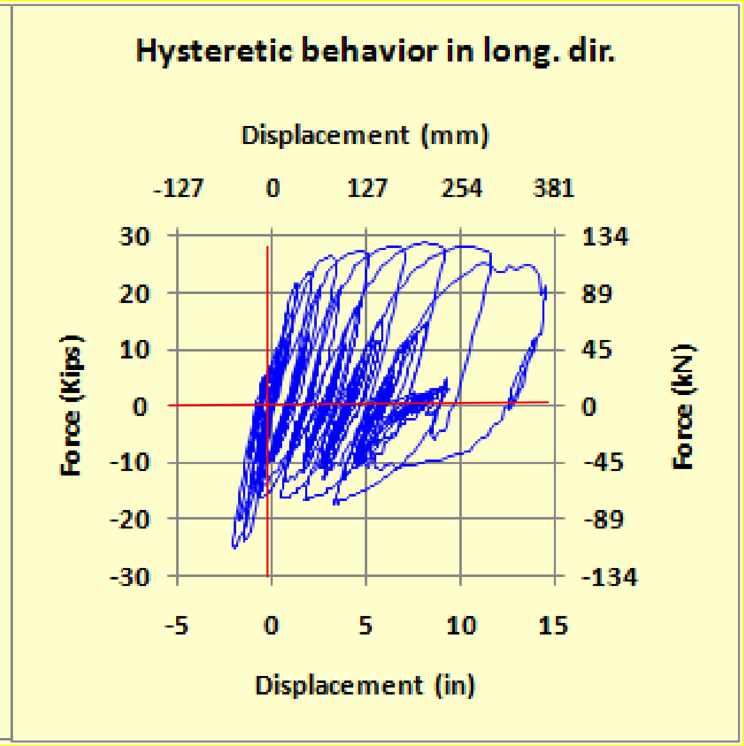
Run	x Petrolia	Drift in X (%)	Drift. in Y (%)	Performance
1 to 3	0.1 – 0.4	0.23 – 0.87	0.20 – 0.48	Flexural Cracks
4	0.6	1.31	0.70	First inclined Cracks
6	1.0	2.62	1.24	First Spalling
7	1.2	3.3	1.6	Extension of Cracks and Spalling
8 - 10	1.4 – 1.8	4.0 – 16.2	1.8 – 7.4	Spiral and long. Bars Visible
11	2.0	20.2	10.2	Flexural Failure (Bar Buckling, spiral and long. Bars rupture)

Test Specimen C2

Earthquake		Rel. disp. in X (in)	Rel. disp. in Y (in)	Force in X (kips)	Force in Y (kips)
0.4xPET	MAX	0.454	0.344	17.74	10.04
	MIN	-0.624	-0.145	-23.87	-8.54
0.6xPET	MAX	0.761	0.491	21.70	10.77
	MIN	-0.945	-0.261	-24.99	-10.12
1.0xPET	MAX	1.503	0.891	26.41	9.84
	MIN	-1.883	-0.587	-15.36	-13.46
1.2xPET	MAX	1.857	1.144	27.44	10.13
	MIN	-2.379	-0.730	-16.18	-14.66
1.8xPET	MAX	11.643	5.339	28.11	12.13
	MIN	2.572	1.064	-17.25	-16.45
2.0xPET	MAX	14.508	7.330	25.17	11.42
	MIN	3.752	1.725	-13.01	-13.22

C2- Cumulative Histories in Long. dir.





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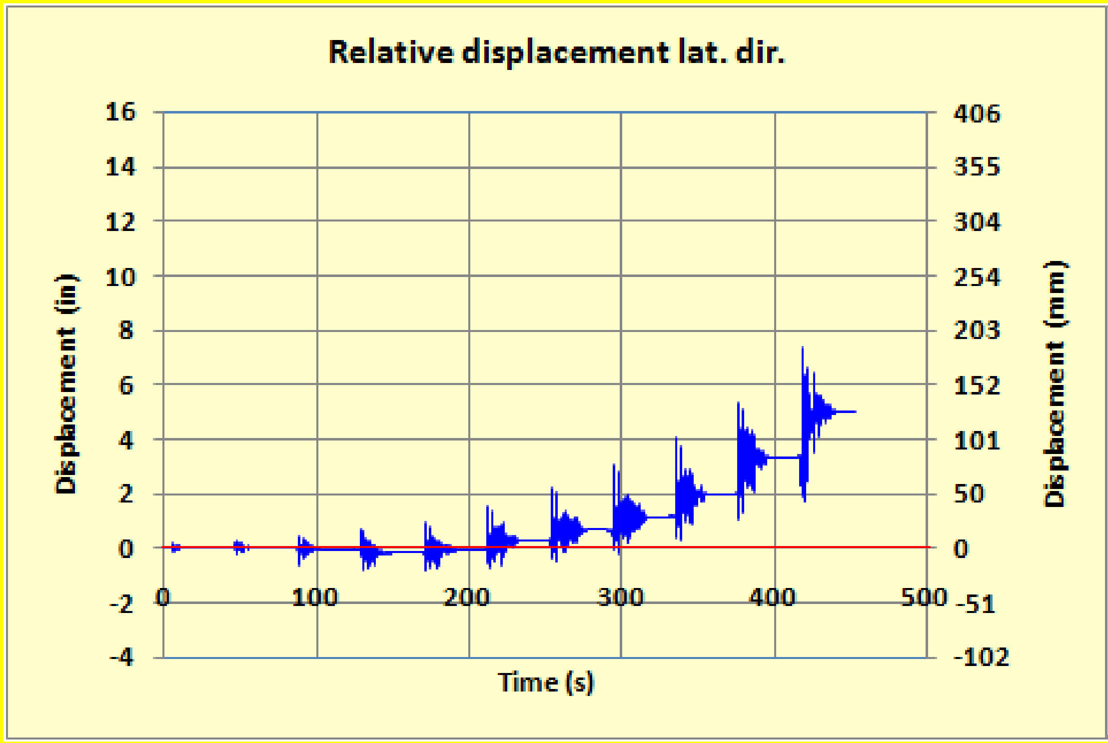
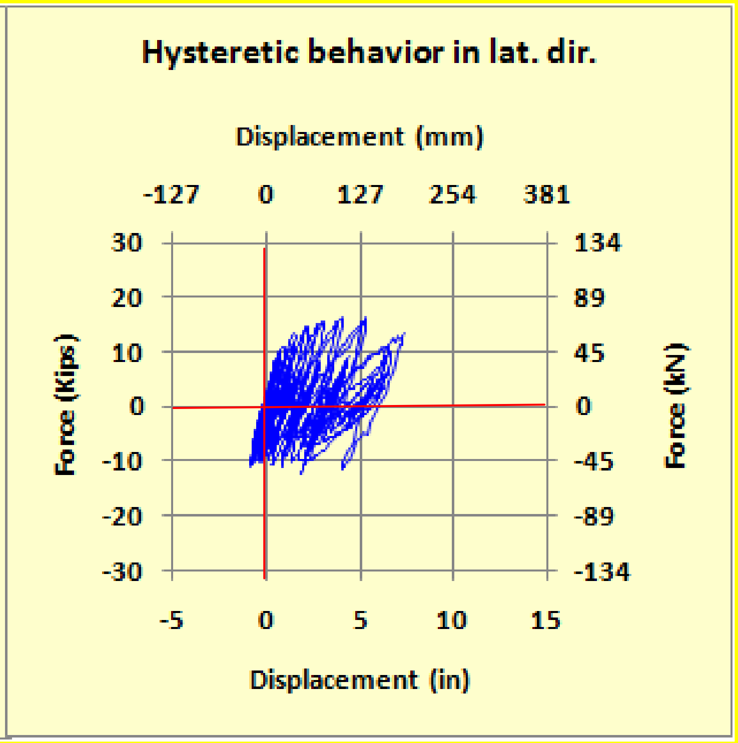
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

C2- Cumulative Histories in Lat. dir.





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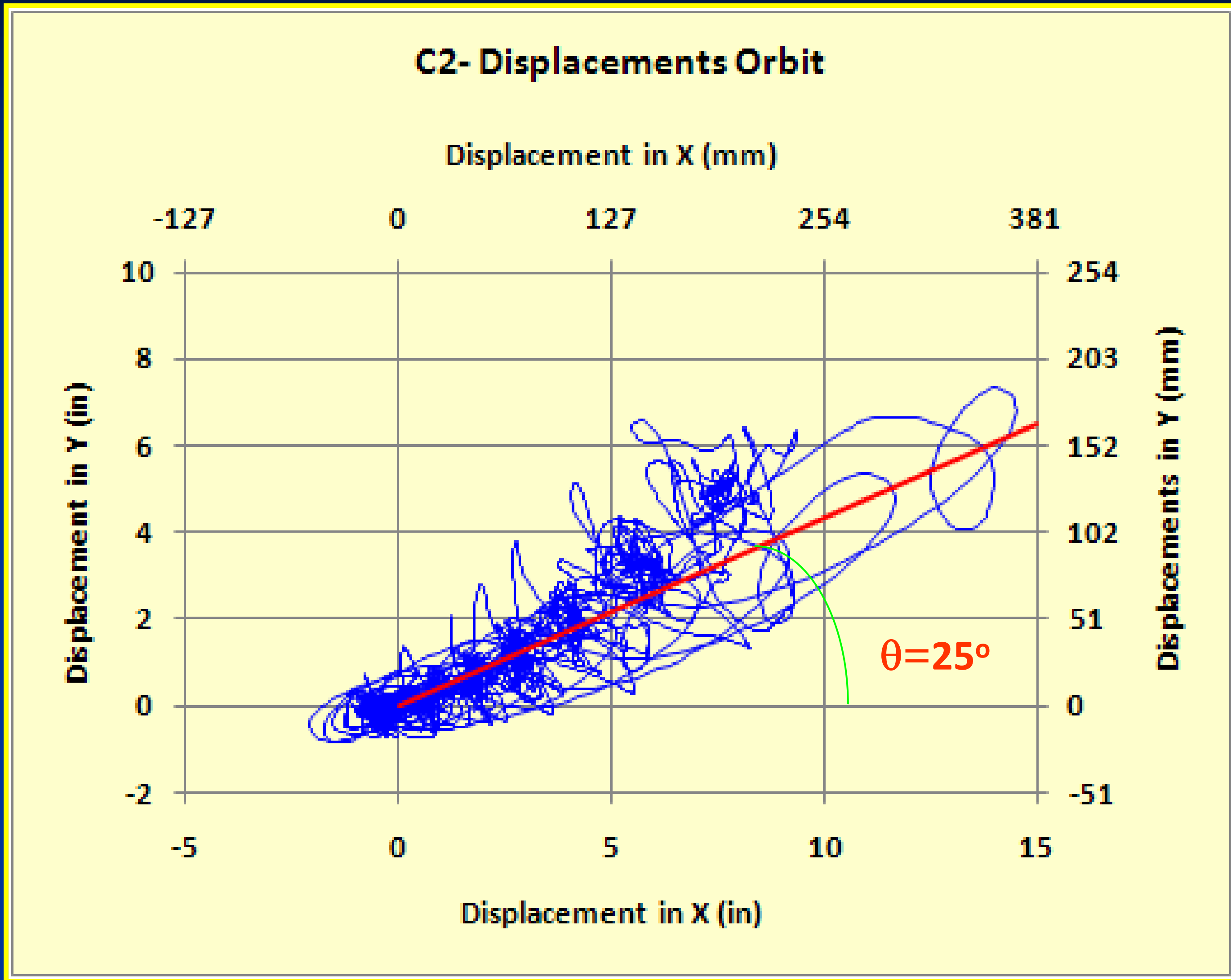
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

C2- Displacement Orbit



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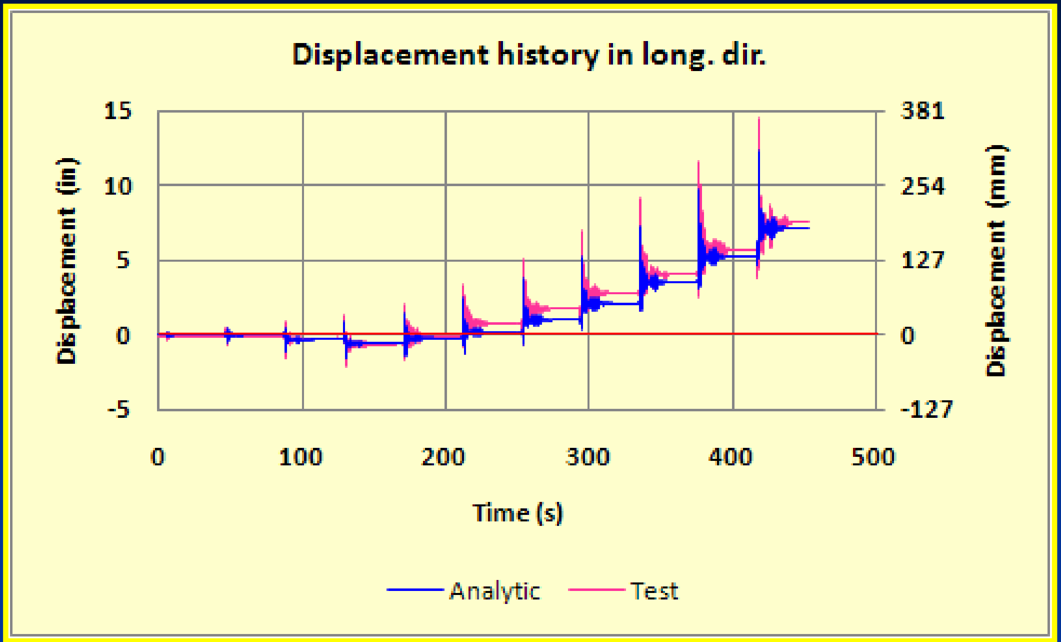
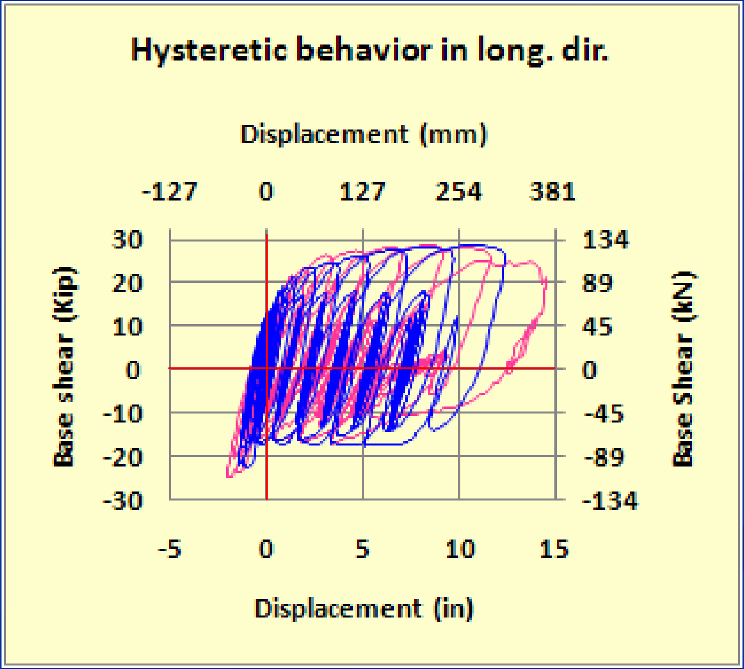
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

C2- Behavior (Analytic vs. Test)





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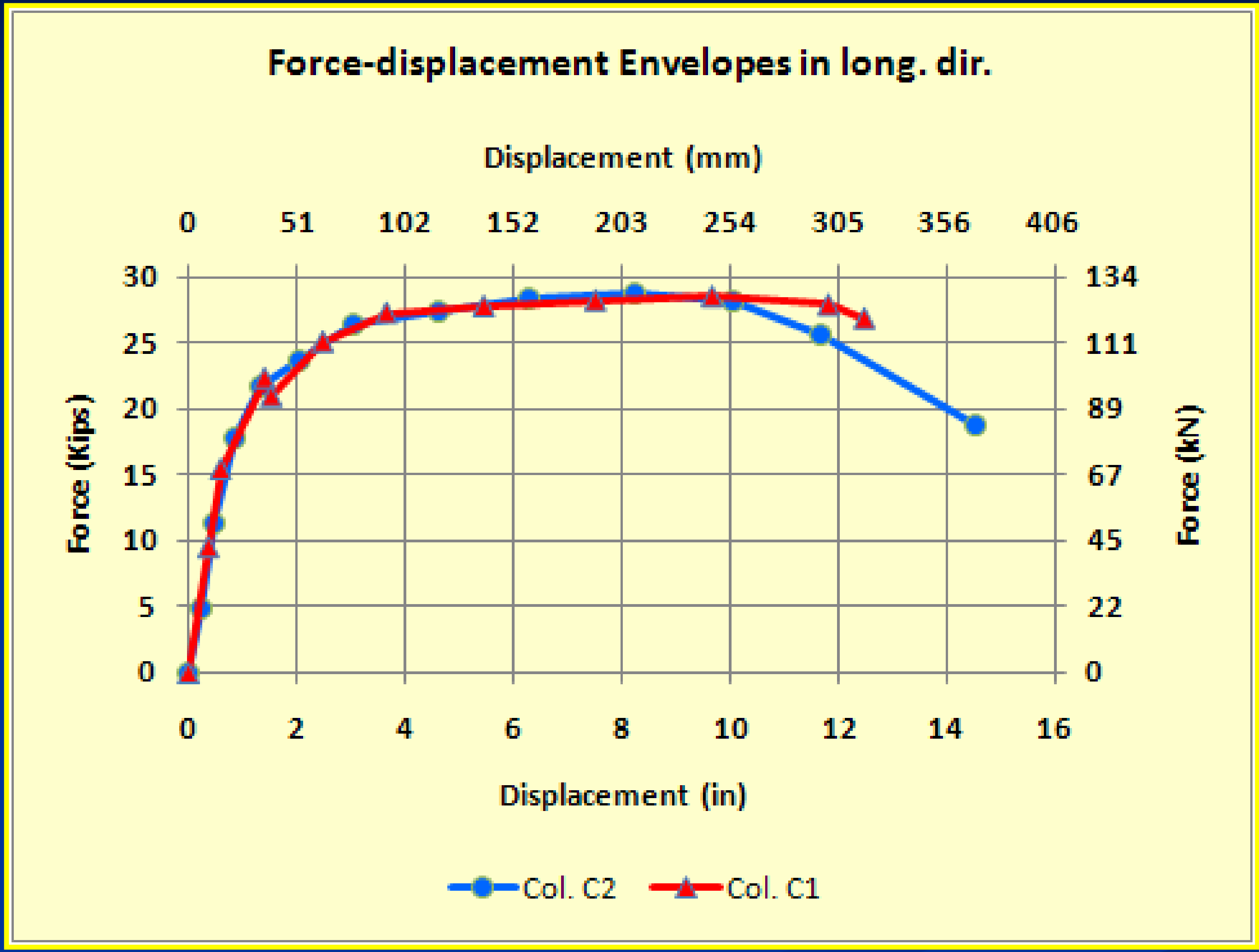
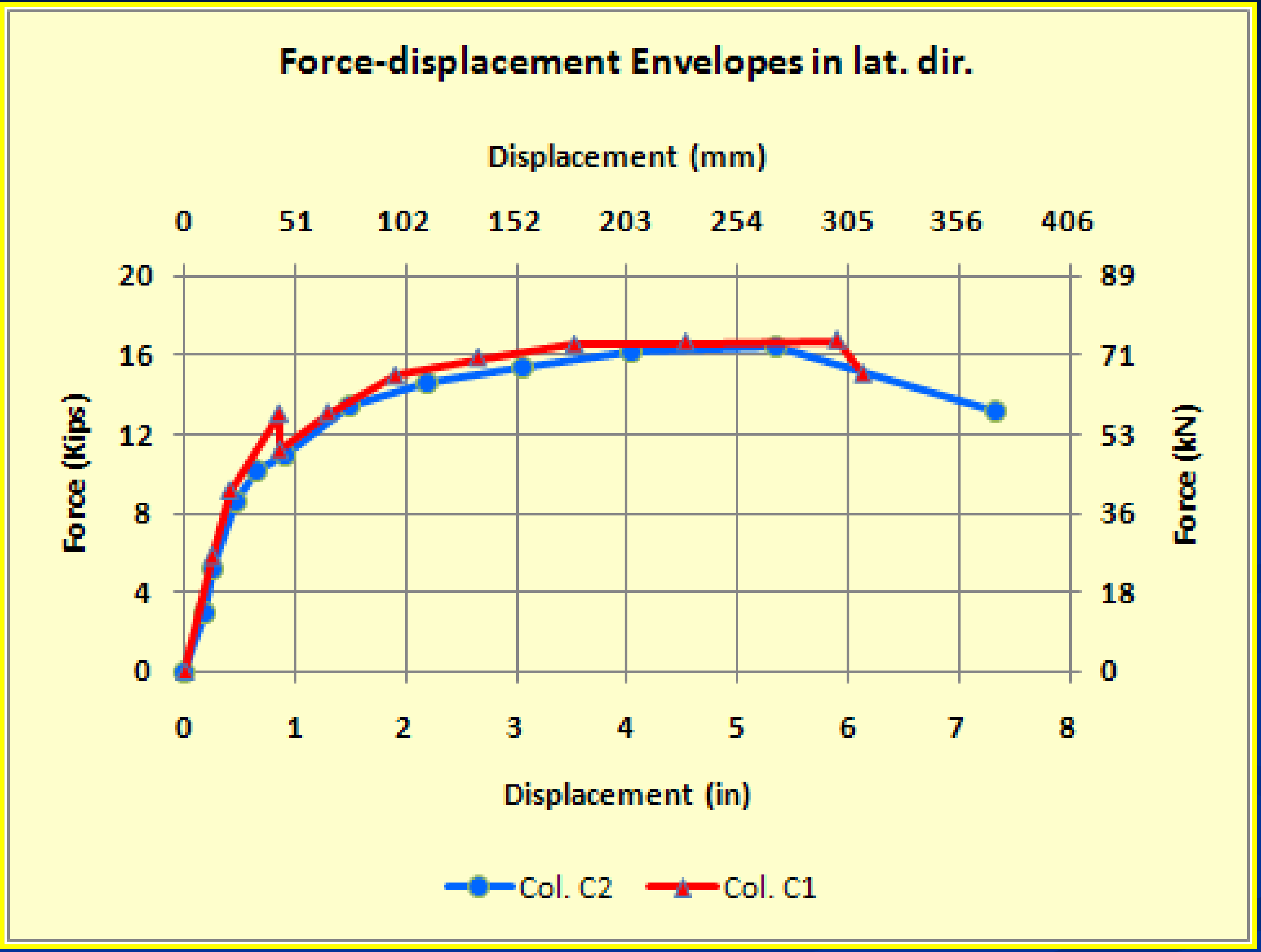
C1-C2 Force-Displacement Envelopes



C1-C2 Force-Displacement Envelopes



Concluding Remarks

- The new inertial mass system to be used on bidirectional shake table tests at UNR represent a significant advance in the simulation of single RCC under simultaneous loads induced by real time earthquake motions.

- Preliminary analytical and experimental results found at UNR and by researchers from other institutions involved in the project have shown that the interaction between loads have a significant effect in the capacity of reinforced concrete bridge columns under combined seismic loads.

CABER
Combined Actions on Bridge Earthquake Response

University of Houston Contribution

- Development of a new fiber beam-column element with combined Shear/Bending/Axial Interaction
- Model based on rotating crack concept with biaxial strength envelope for concrete
  - Model accounts for Cyclic & Dynamic/Seismic effects
- Model was calibrated and used for simulation of RC specimens under static and dynamic loads

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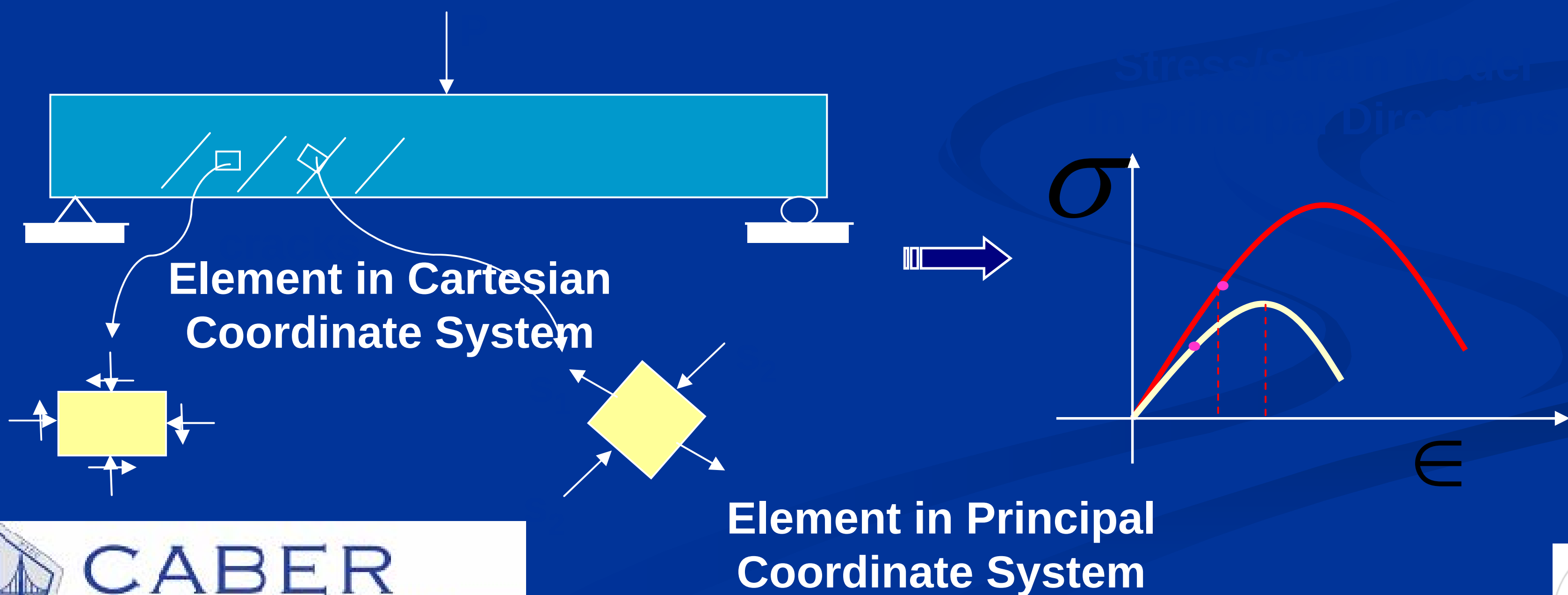
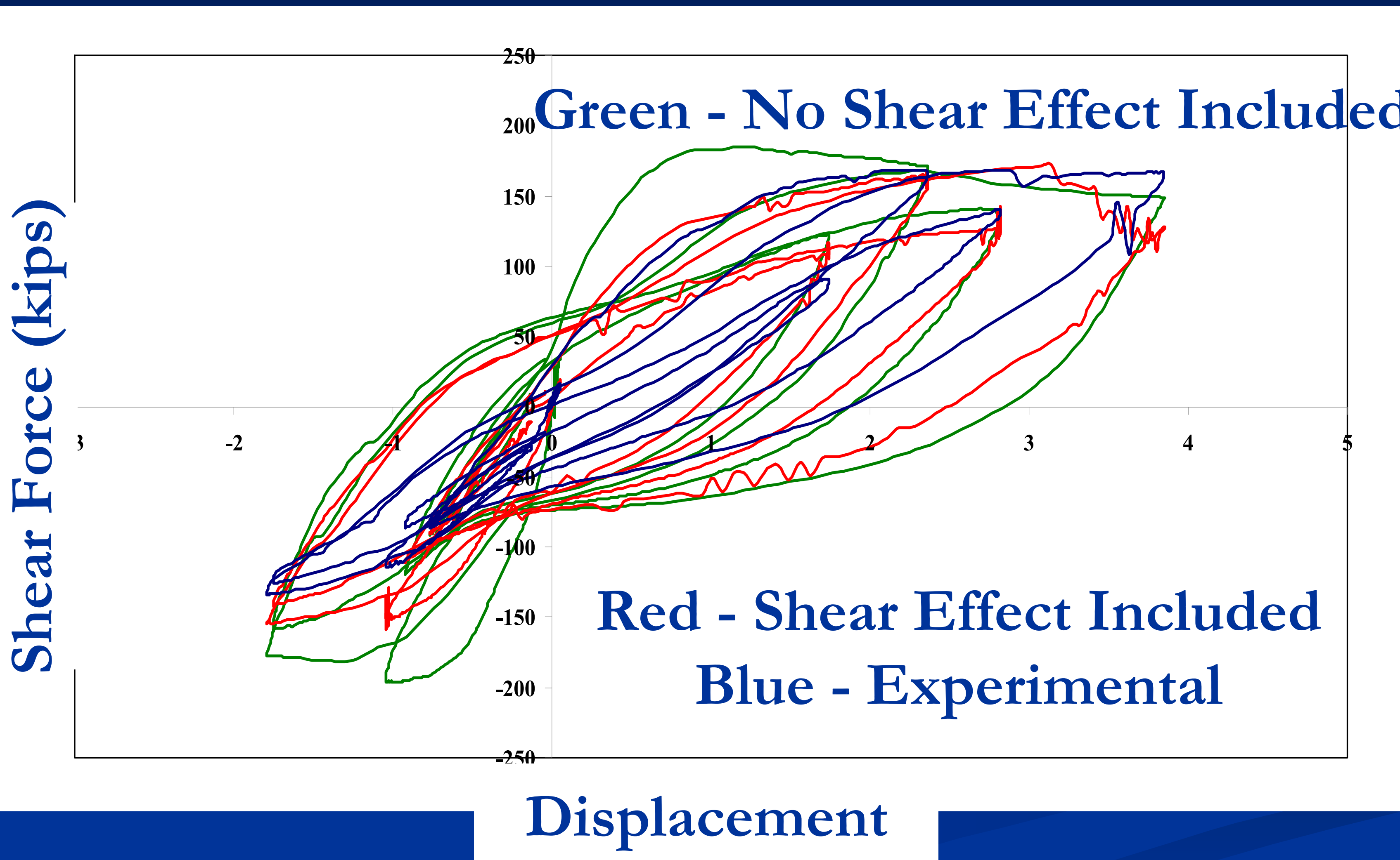
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Extension of RC Fiber Beams to Account for Shear Effects

- Adopt a Timoshenko Beam Formulation with Shear Deformations
  - Impose Equilibrium in Transverse Direction to Determine Concrete Lateral Strain
  - Rotate Stresses to Principal (Crack) Directions
    - Use Concrete Biaxial Constitutive Models



UIUC Reinforced Concrete Short Column



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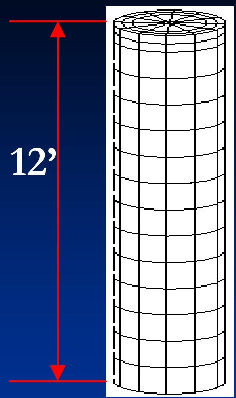
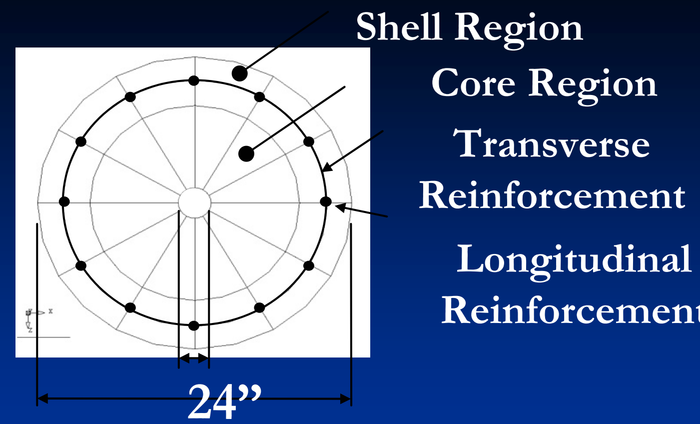
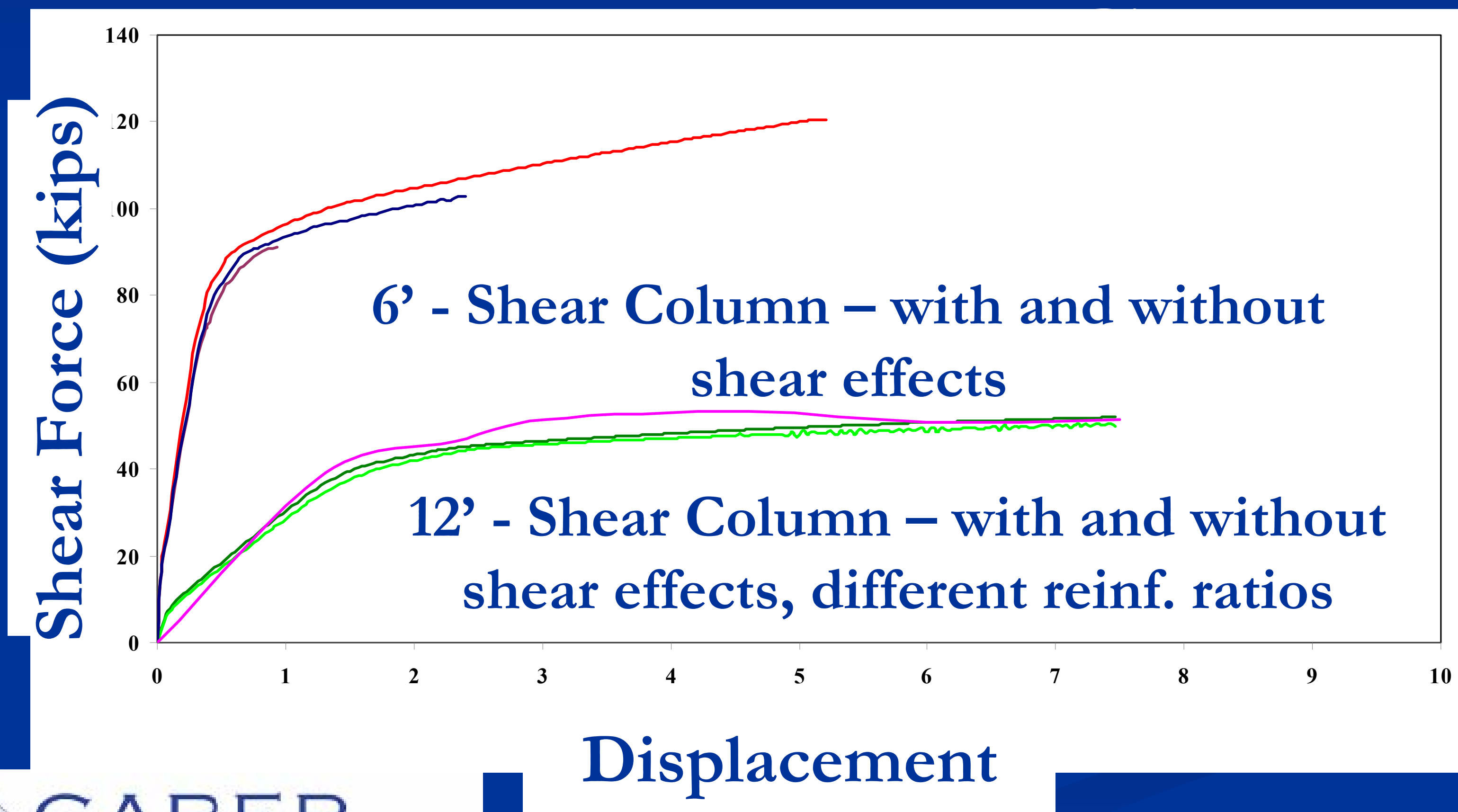
MS&T Circular Columns







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COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

UIUC Focus

Shear-flexural-axial interaction particularly under the presence of high vertical acceleration

- **Large scale testing - completed**
  - Pseudo dynamic tests without and with vertical ground motion: 2 specimens
  - Cyclic load tests under different axial load levels: 2 specimens
- **Small scale testing**
  - Numerous small scale piers to be used to further explore moment-axial-shear interaction and load path effects: ongoing

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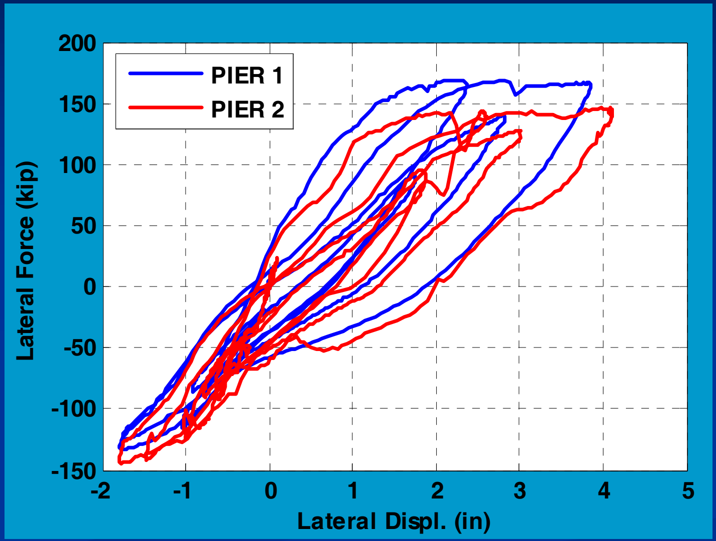
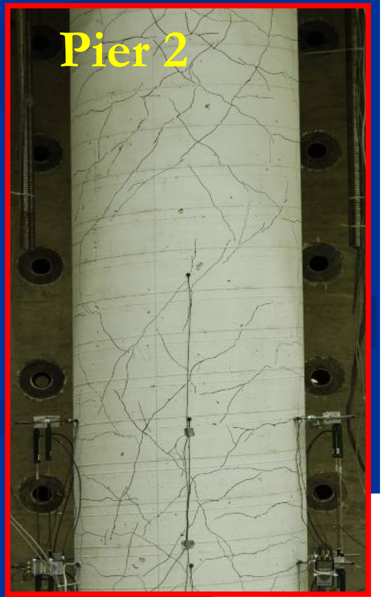
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Pseudo Dynamic Tests

- **Configuration and control**
  - Prototype: FHWA design example 4 (1996)
  - Single ½ scale experimental pier
  - Analytical model of remaining 3 piers and bridge deck
- **Input**
  - Pier 1: Horizontal ground motion
  - Pier 2: Combined horizontal and vertical ground motion
- **Test Results**
  - Vertical ground motion significantly increased the variation of axial load
    - Axial load ranged from -3.5% to 20%
  - Significant increases in shear strains (spiral) and diagonal cracking were observed when including the vertical component
  - Strong coupling of shear force demand and axial load was observed





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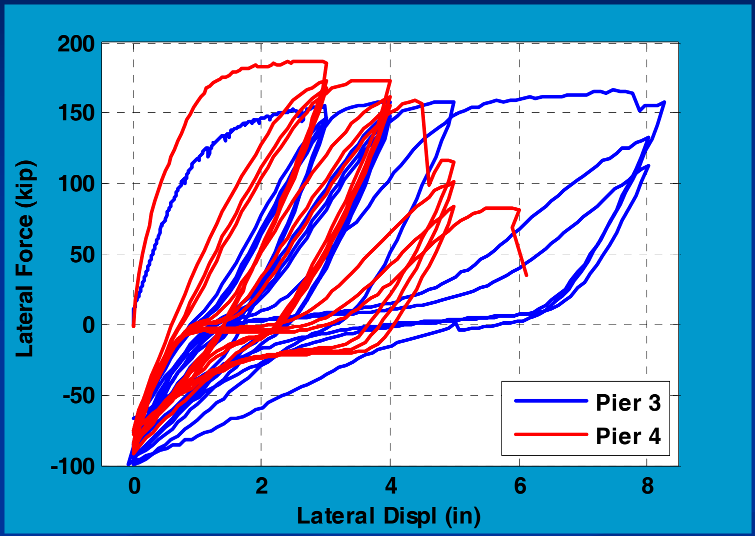
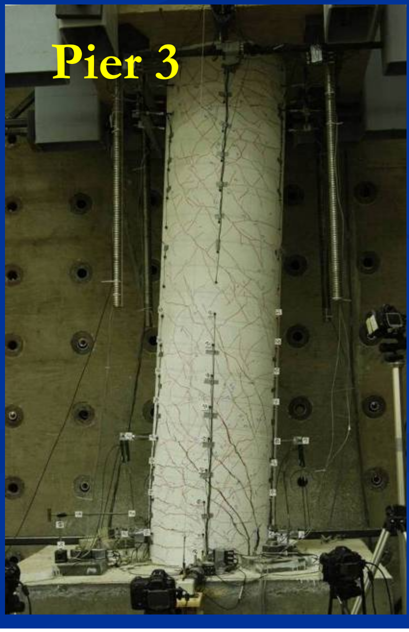
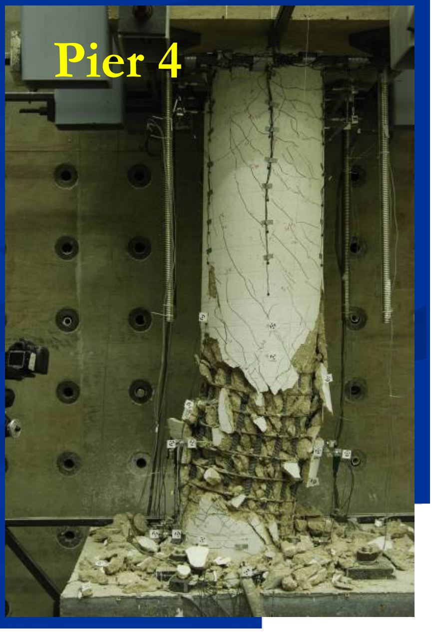
Cyclic Testing

- **Configuration and control**
  - Diameter: 24 in, Height: 102 in
  - Mixed mode control
    - Displacement control: lateral displacement and rotation
    - Force control: axial force
- **Input**
  - Cyclic lateral displacement and zero rotation (double bending)
  - Constant axial force
    - Pier 3: tension force of 50 kips
    - Pier 4: Compression force of 250kips
- **Test Results**
  - Strong coupling between shear force demand and axial load
  - Pier with moderate tension developed ductile shear failure
  - Degradation of shear capacity dominated response of pier with compression







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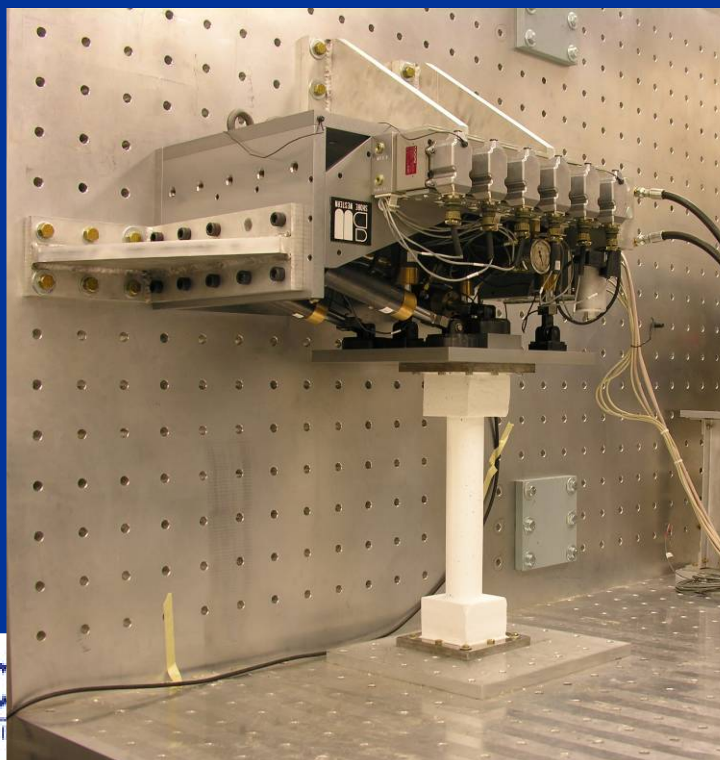
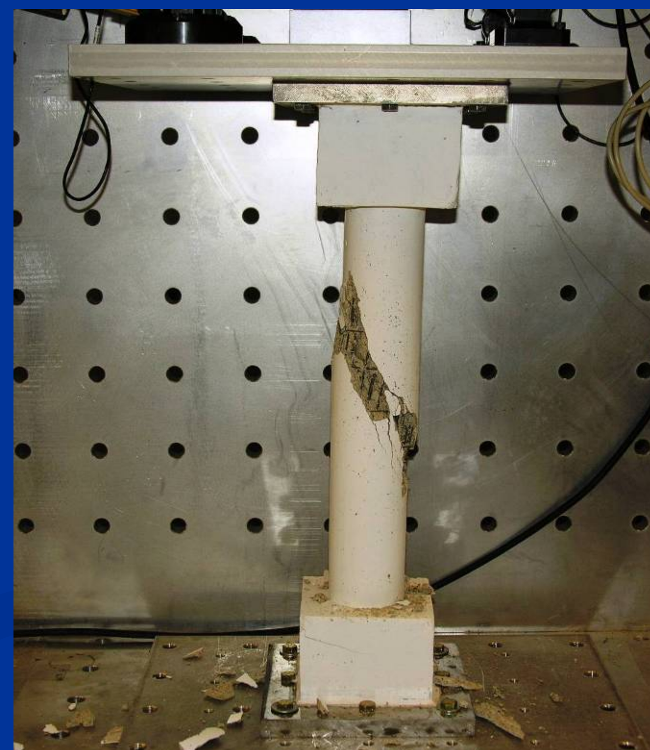
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Work in Progress

- Numerous small scale piers will be used to further investigate shear-flexure-axial interaction
- Coupling of load path (lateral and vertical) with shear capacity and demand will be investigated
- Tests will be performed using NEES@UIUC 1/5 scale testing facility





UCLA

- Conducting Global Modeling of Structures

- Development of a robust ABAQUS user element capturing the major effects observed in the realistic RC column responses, including the damage prediction and shear-flexural interaction (under constant axial force)

- Validation of the user element with 13 static cyclic pushover and 2 dynamic shake table tests has been completed.

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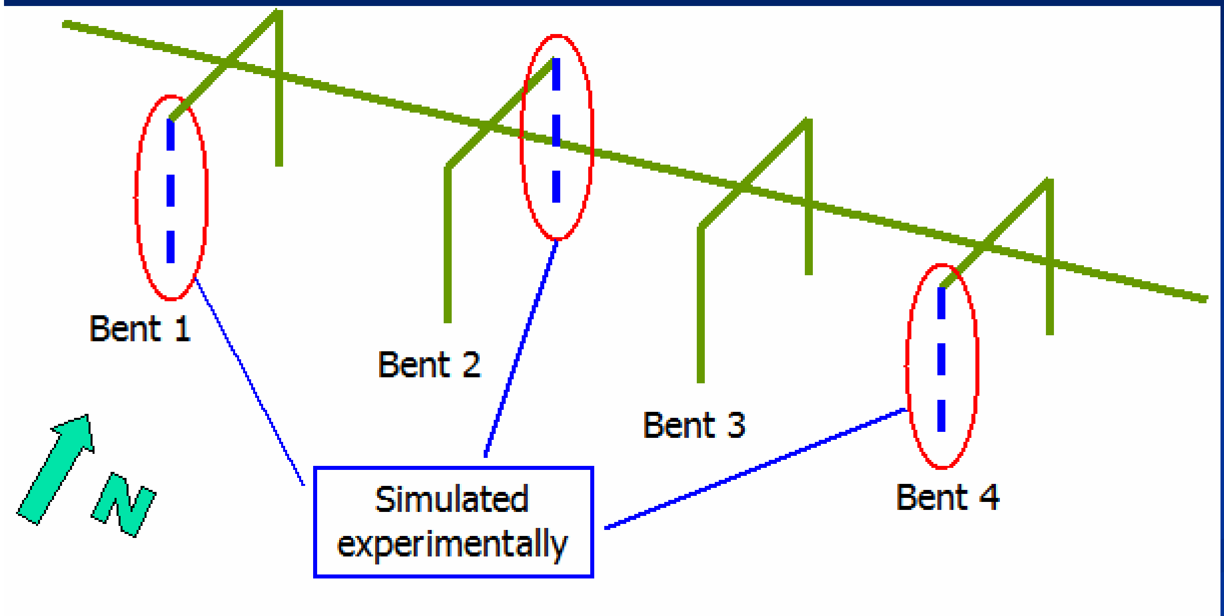
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Hybrid Simulation
George Washington – M S&T



- Hybrid simulation: Integration of analysis and experiment
  - *Simulated experimentally:* Three out of eight columns using LBCBs with OpenSees

The proposed prototype bridge is the eighth in a series of seismic design examples developed for FHWA with the earthquake site in Washington State .

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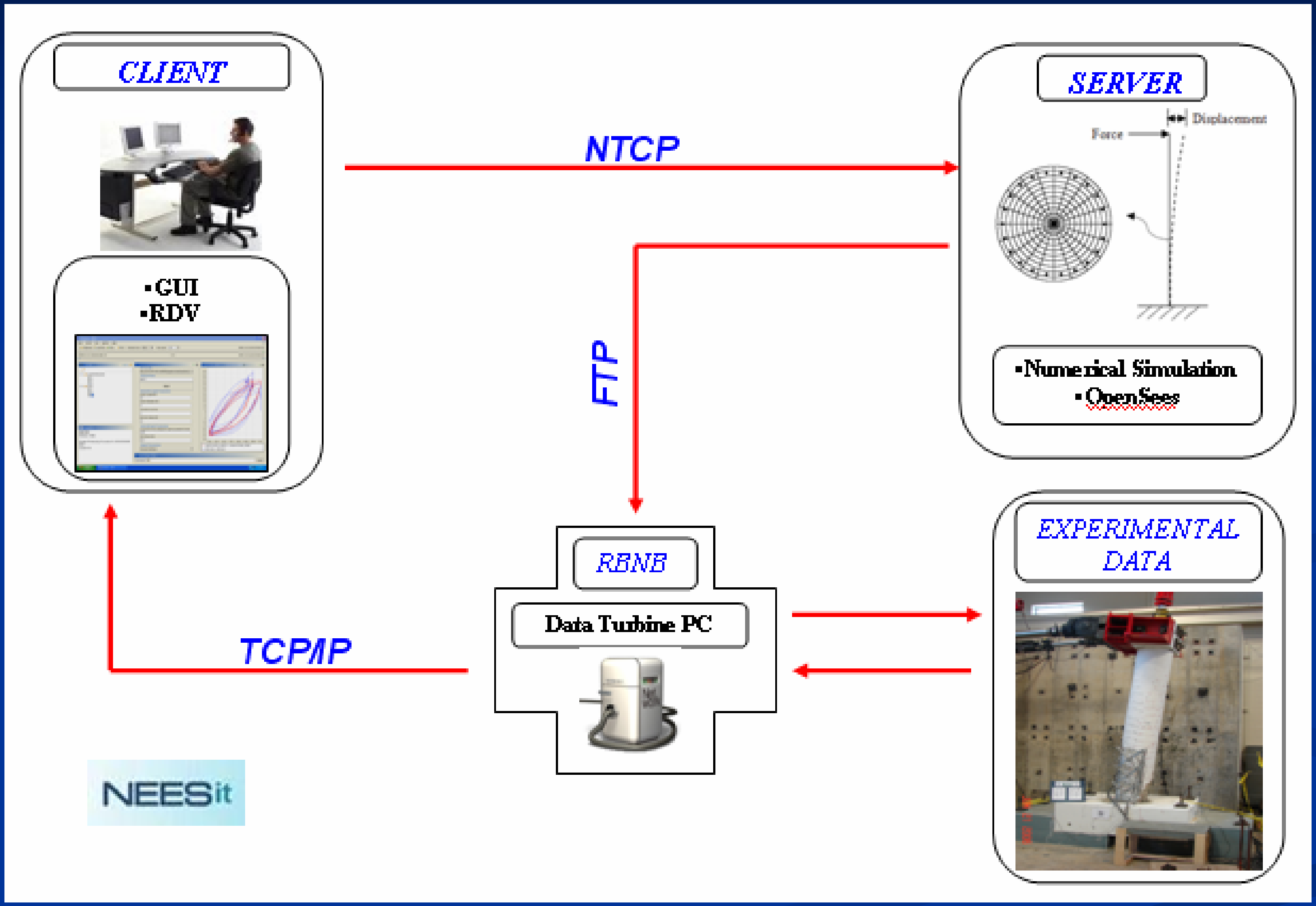
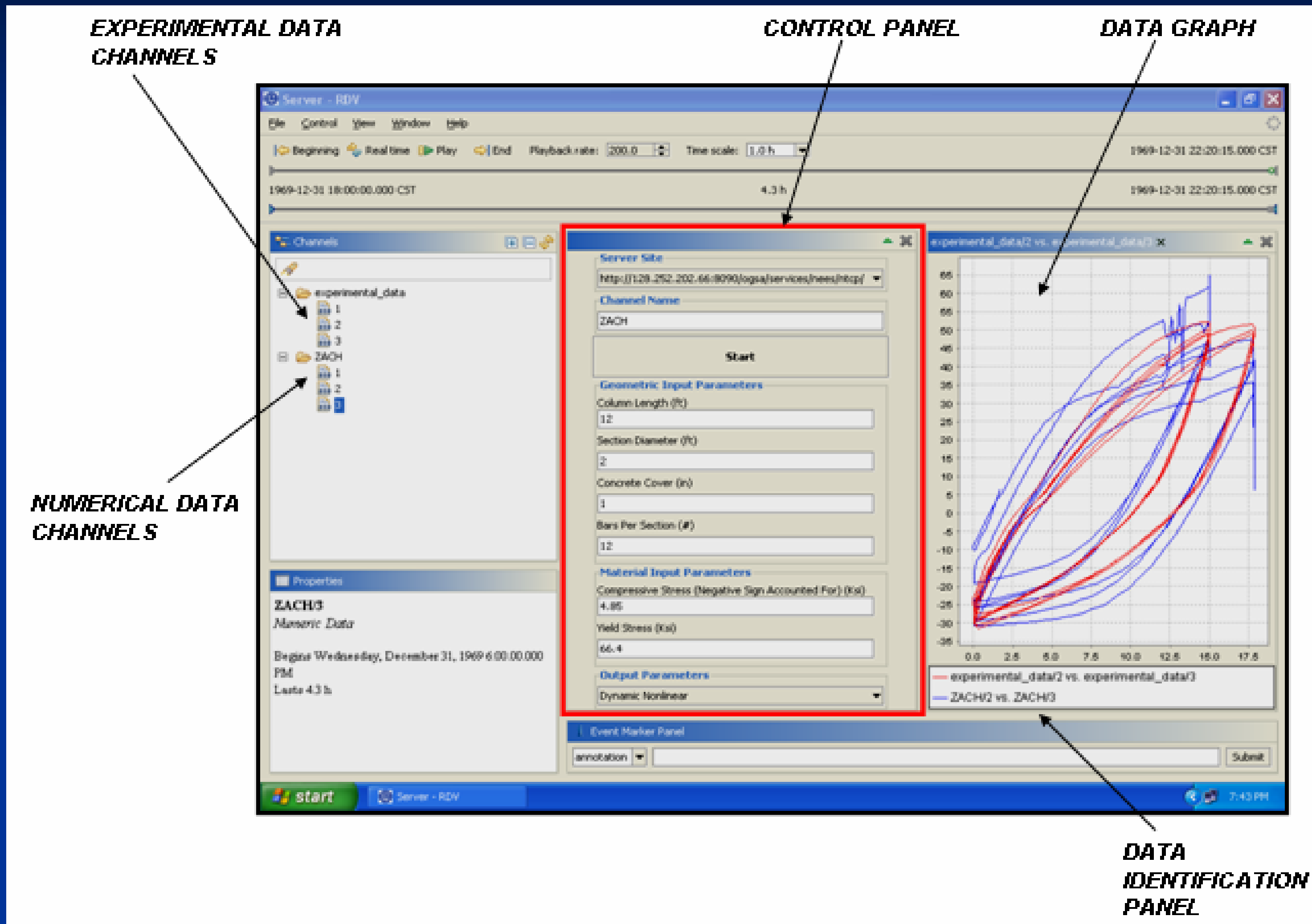
COMBINED ACTIONS ON BRIDGE EARTHQUAKE RESPONSE

Virtual Experiments…



Virtual Experiments…



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