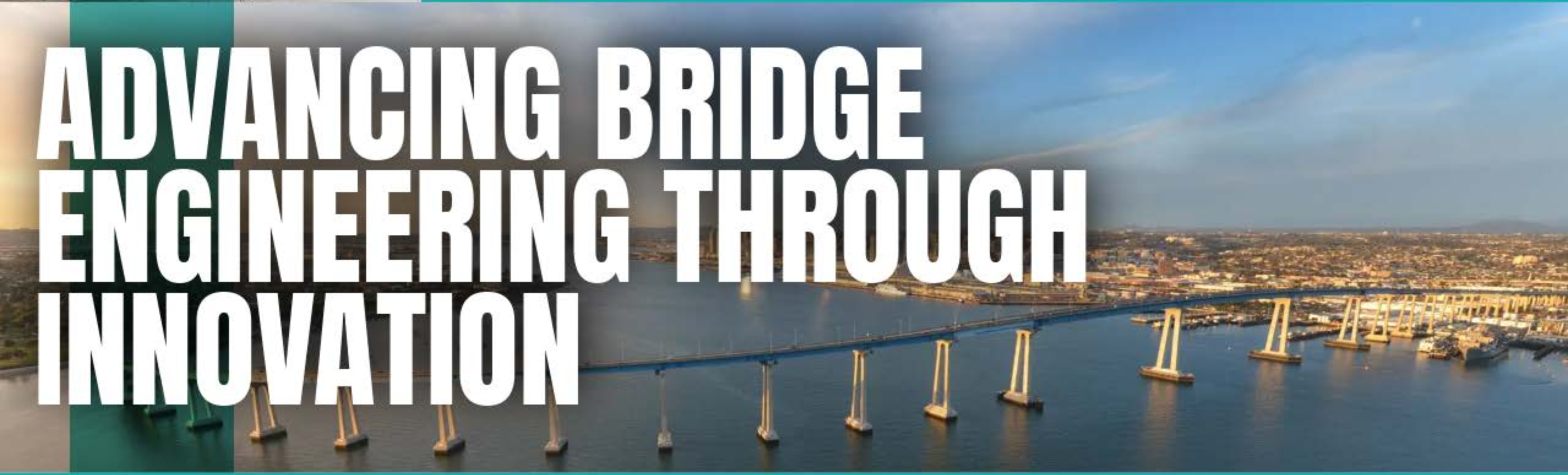
CABES

CALIFORNIA BRIDGE ENGINEERS SEMINAR



ADVANCING BRIDGE ENGINEERING THROUGH INNOVATION

Caltrans

CABES 2026

Presentation 1 - Experimental Performance of Seismically Isolated Bridge Bent Subject to Beyond Design Shaking

DES

DIVISION OF ENGINEERING SERVICES

Experimental Performance of Seismically Isolated Bridge Bent Subject to Beyond Design Shaking

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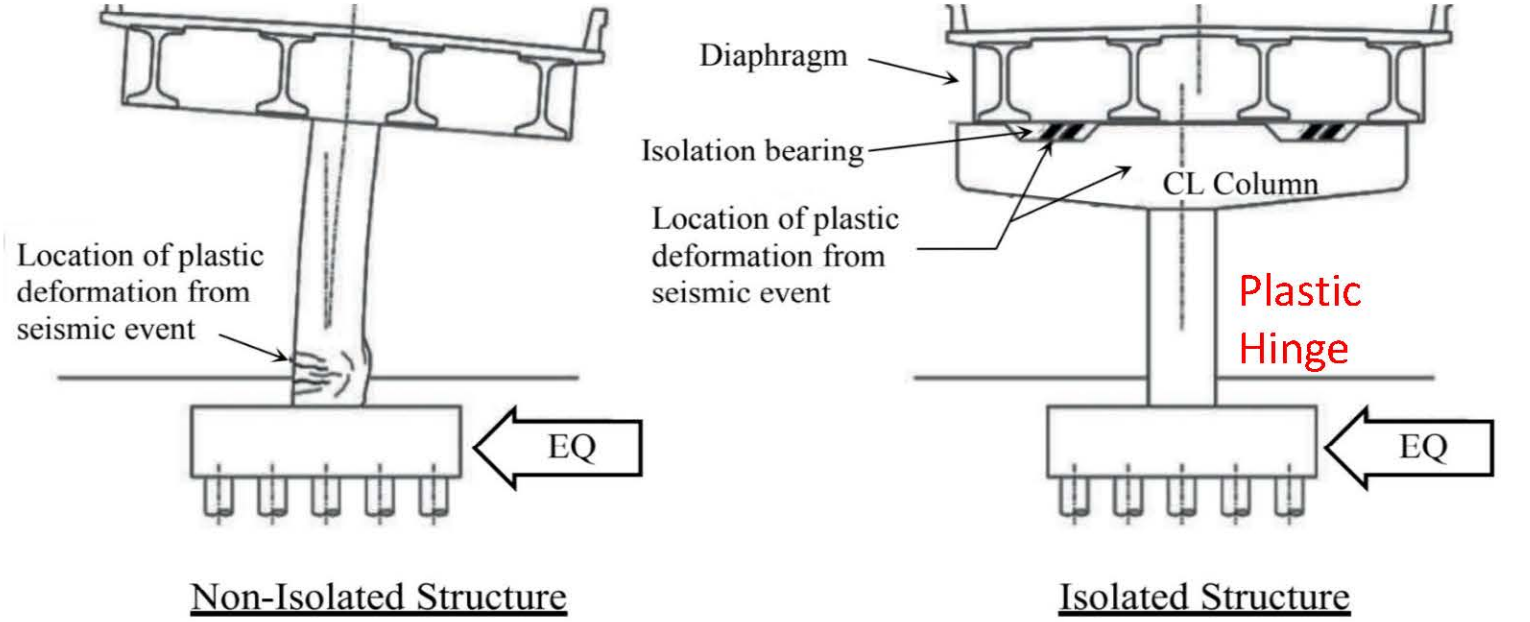
CABES

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

Caltrans

Objectives of Research

- Assess Caltrans guidelines for design of seismically isolated bridges
  - Caltrans plans to increase use of seismic isolation including ordinary bridges
  - Bridges remain in full or partial service after a design level earthquake
  - Verify proposed design strategy and expected limit states for beyond design loading
- Conduct shake table experiments to evaluate progression of damage
  - Beyond design, failure modes and progression of damage not well understood



(Caltrans BDM 20.33)

Caltrans Bridge Design Memo 20.33 - Isolation

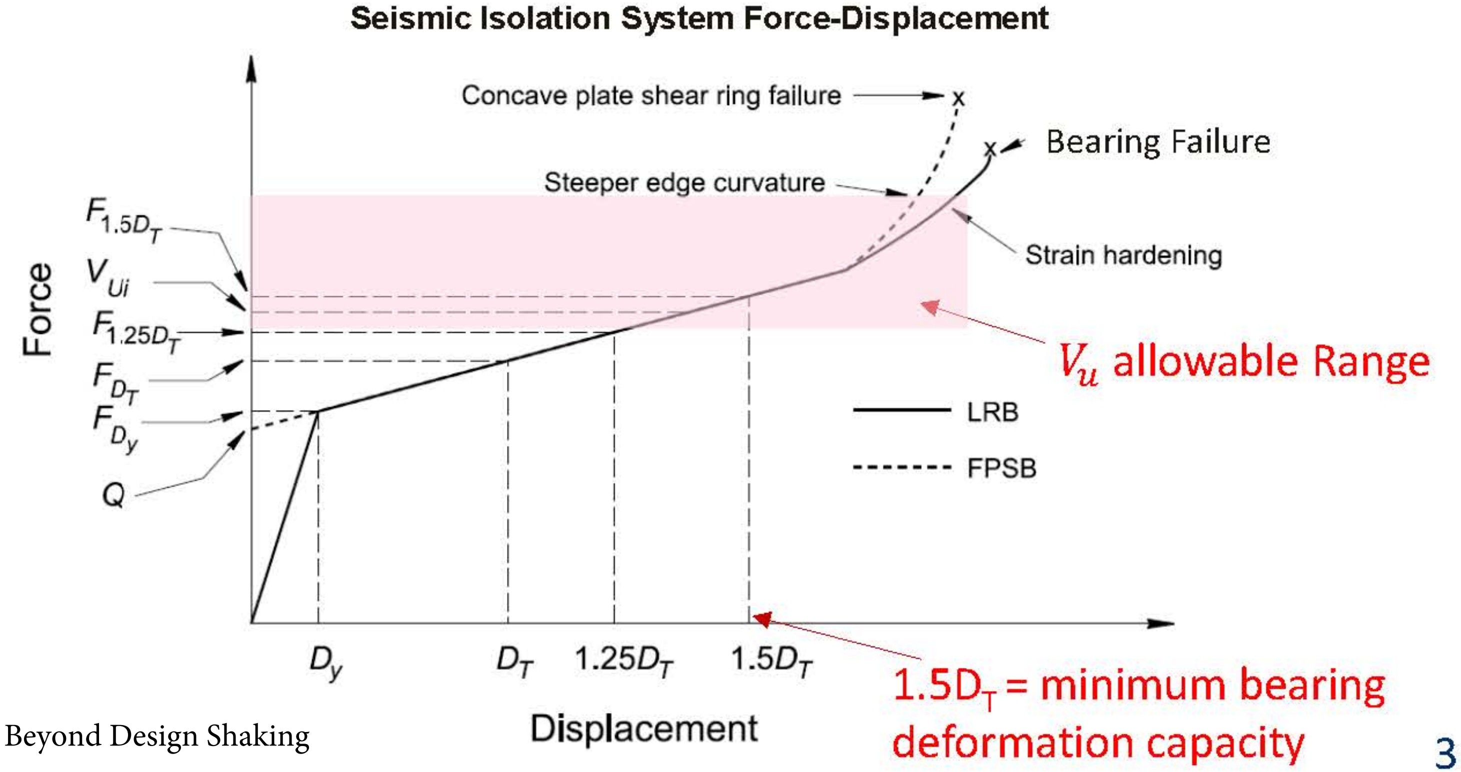
- Seismic isolation is the Primary Earthquake Resisting System (ERS) with essentially elastic structure performance for design level shaking
- Provide Secondary ERS (SERS) such as plastic hinging in columns for beyond design loading to protect isolation system from failure

  - $V_u > F_{1.25D_T}$
  - $F_u > Vu$
  - $F_u > F_{1.5D_T}$

V_u: lateral force that can cause plastic hinging in the substructure

F_u: isolation layer ultimate strength

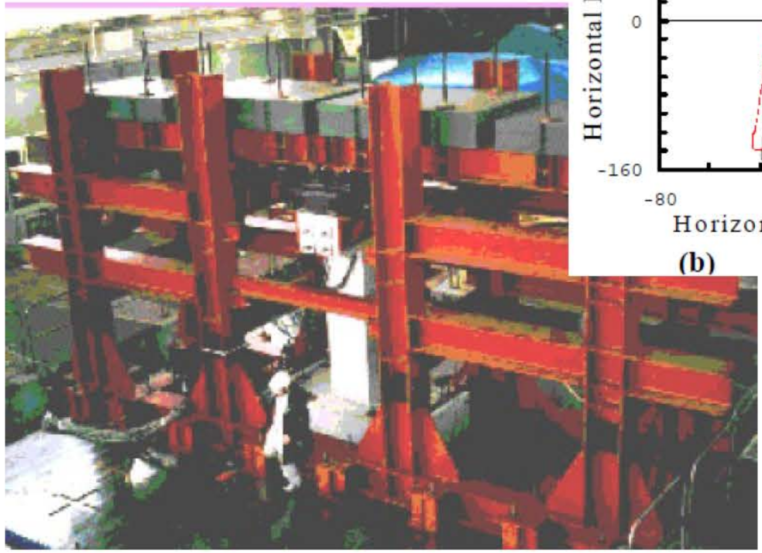
D_T: design level seismic displacement demand of the isolators

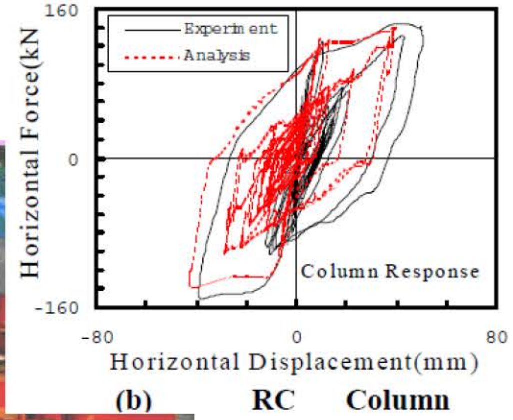


Past Studies on Bridge Limit States

- Multi-span bridge tests at UNR demonstrated effectiveness of isolation system to <u>3X design motion:</u> localized bearing instability but stable overall response
- Isolated bent tests in Japan examined plastic hinges in columns with energy dissipation shifting from bearings to substructure

Testing at UNR, Buckle et al. 2017

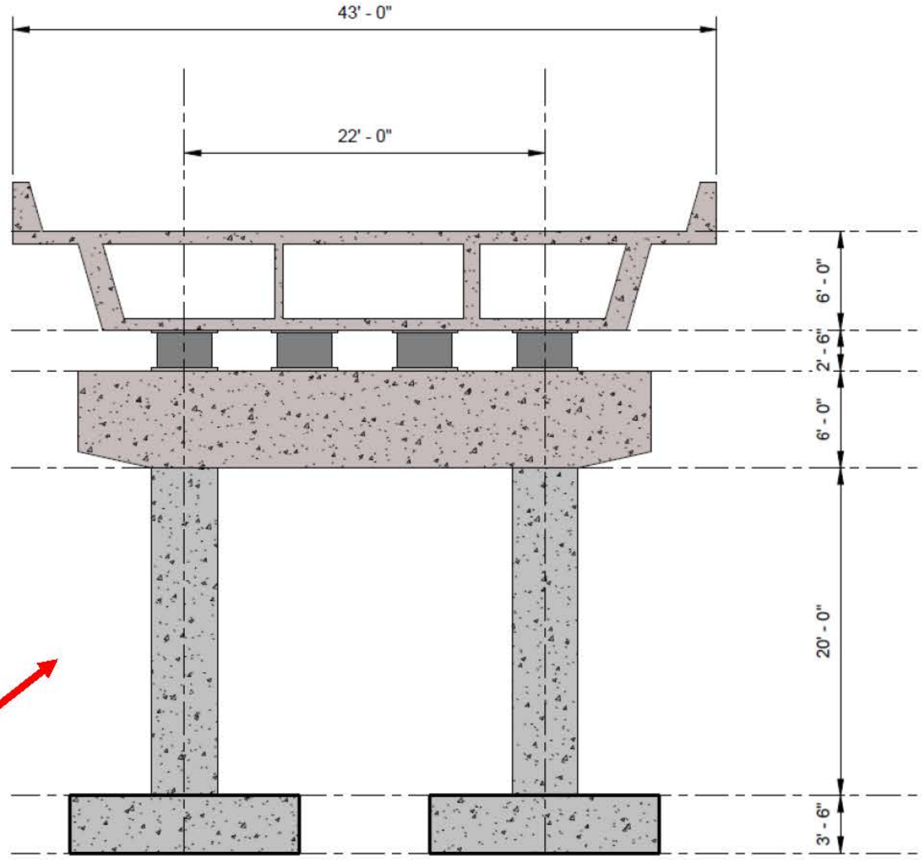


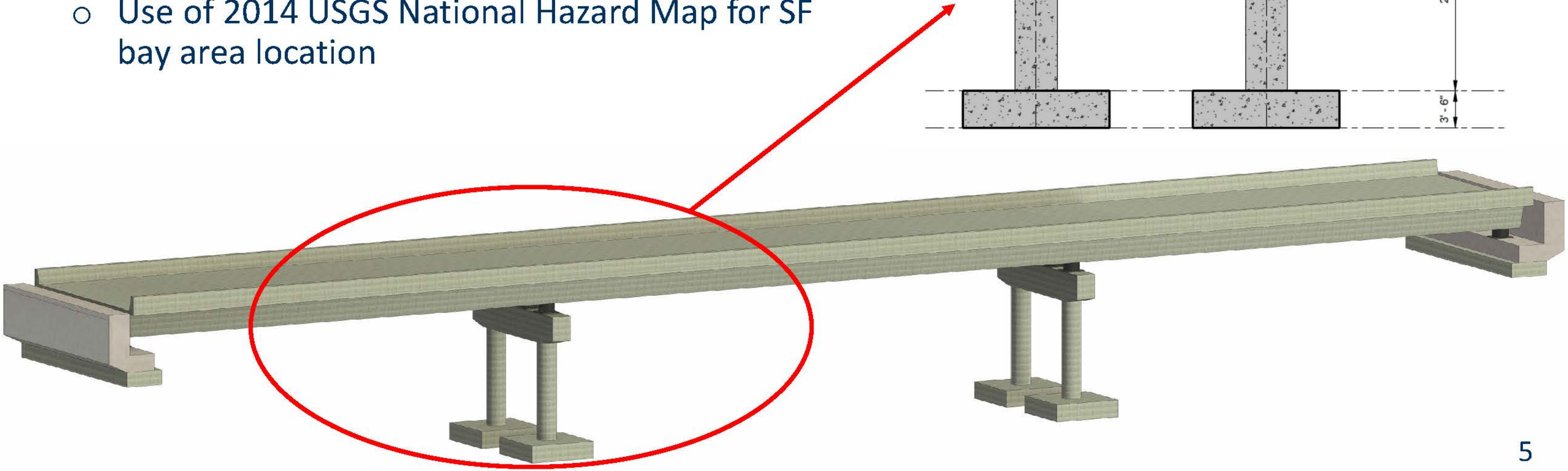


Adachi et al. 2000

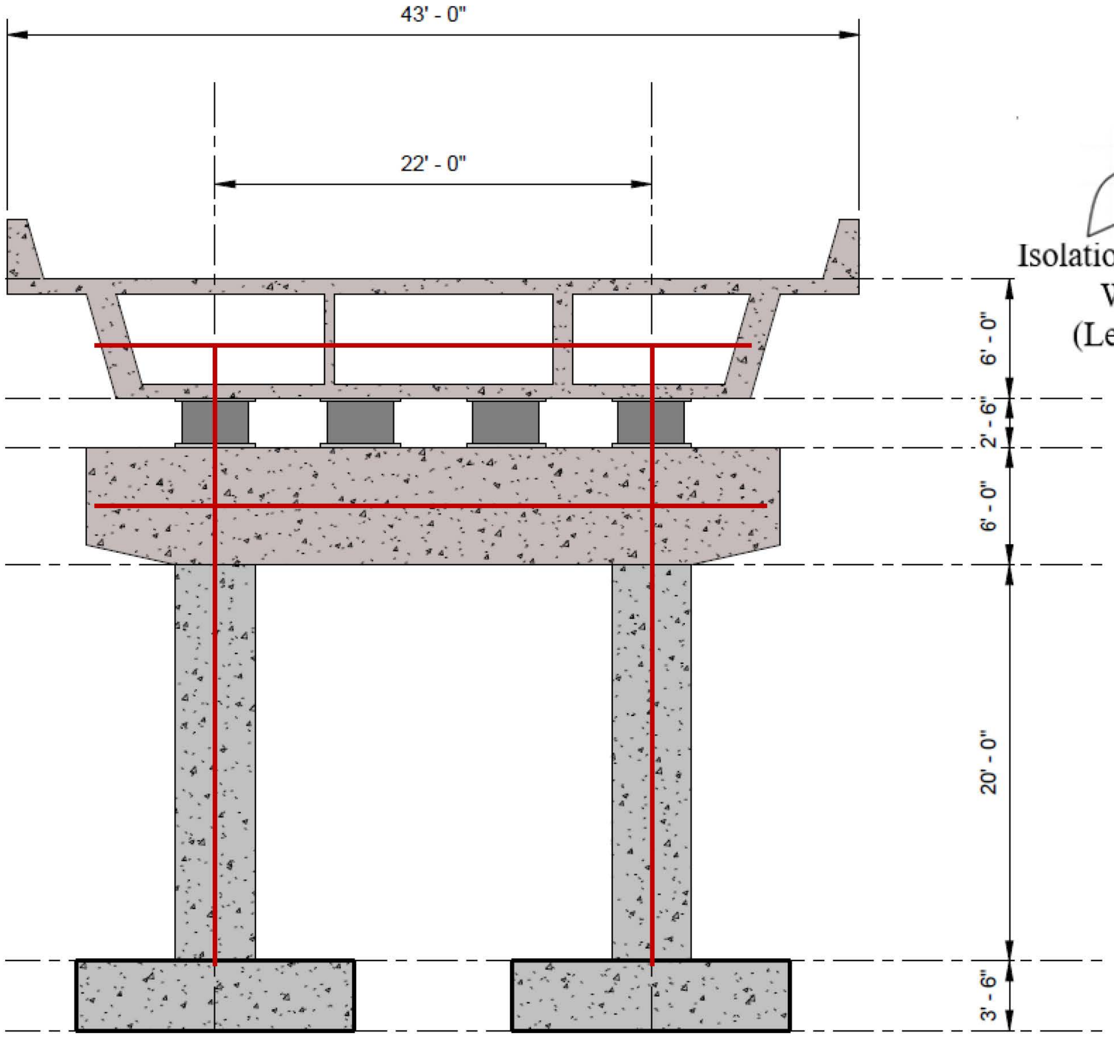
Prototype Bridge

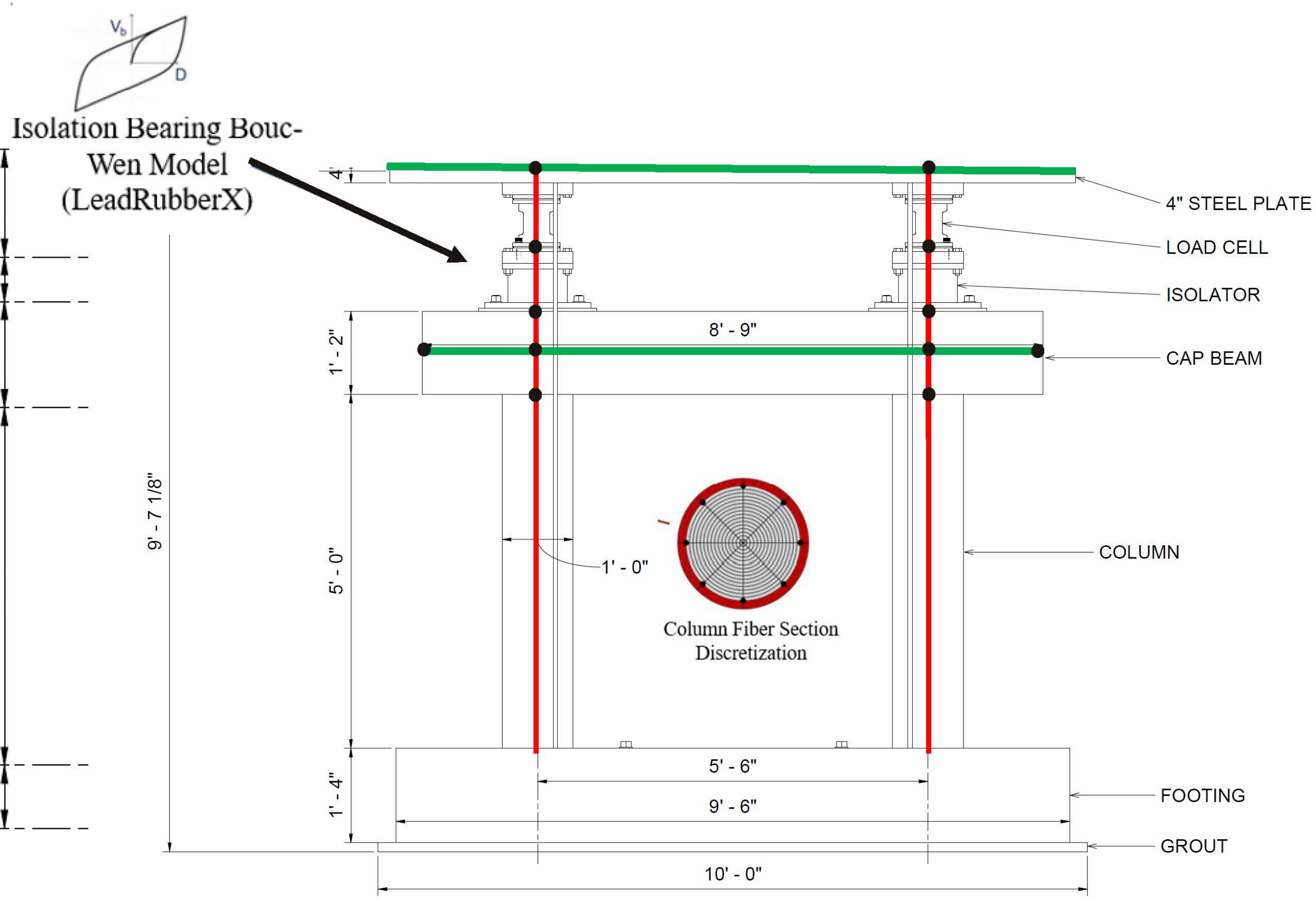
- Ordinary bridge - three span, two column bent, concrete box girder
- Design specifications:
  - Caltrans SDC 2.1 and BDM 20.33
  - AASHTO Guide Specifications for Seismic Isolation Design 2014
  - Use of 2014 USGS National Hazard Map for SF bay area location





Similitude Scaling: Prototype vs Scaled Analysis Model





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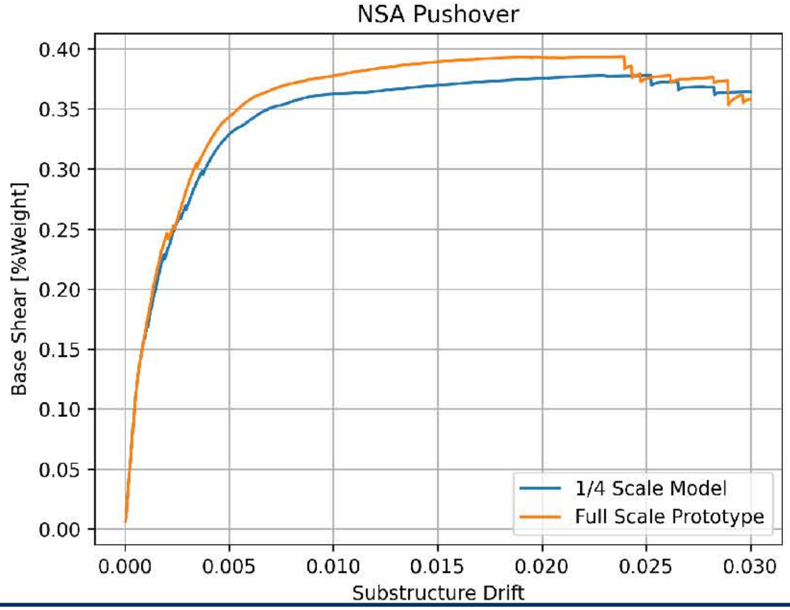
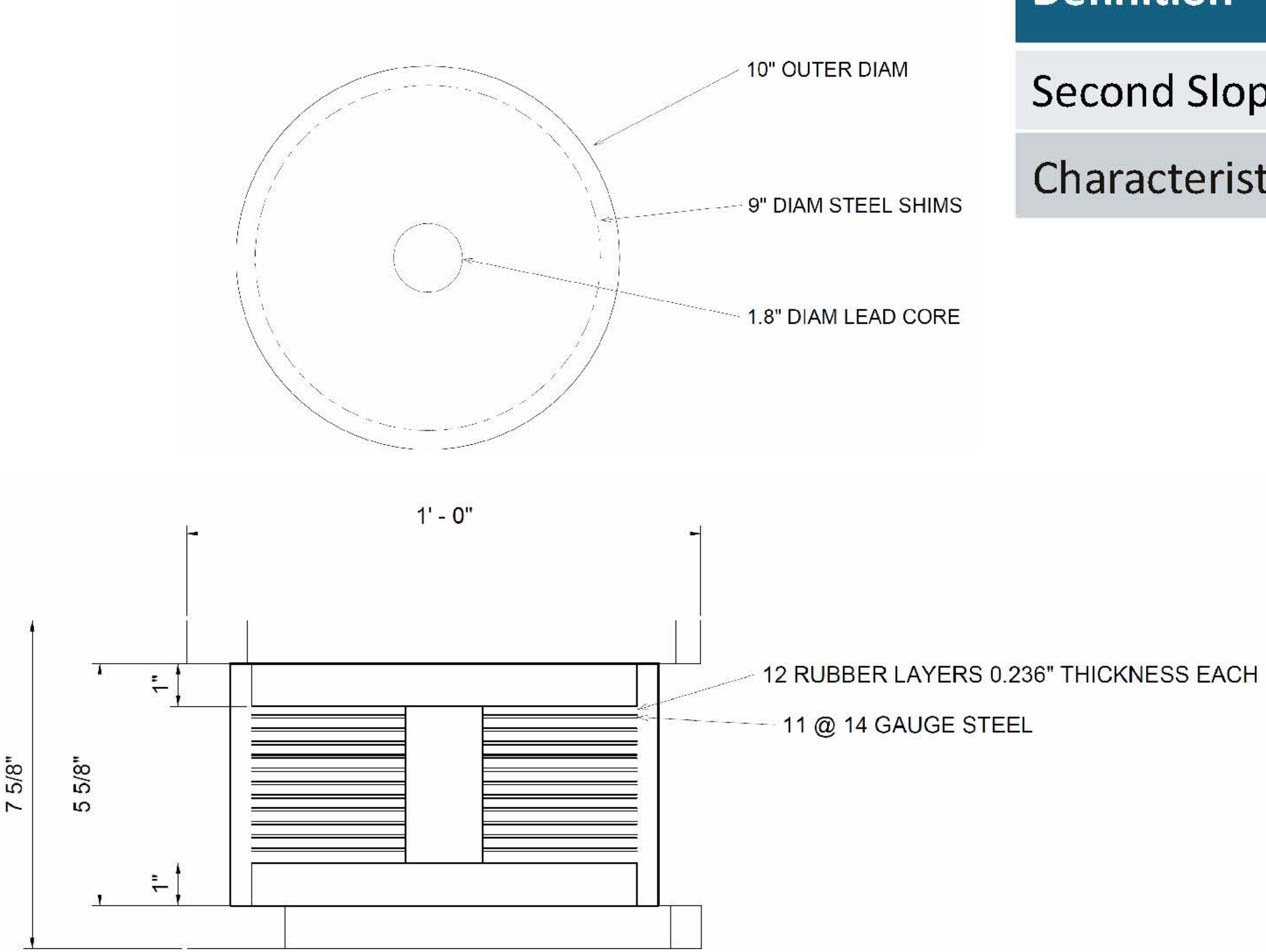


- Slightly larger normalized strength for prototype
- Similitude required additional mass on bent, axial load compensated through rams

Parameter	Definition	Prototype	Model	Description
ρ_l	$\frac{A_{st}}{A_g}$	1.40%	1.41%	long reinforcement ratio
ρ_s	$\frac{4A_b}{D' s_h}$	1.39%	1.38%	transverse reinforcement volumetric ratio
ρ_{dl}	$\frac{P_{dl}}{\min(f'c, 5ksi)\, A_g}$	13.6%	13.3%	axial load ratio w/o overturning at column base
W_{SS}	-	1680kip	105kip	superstructure weight

Seismic Isolation System: Lead Rubber Bearings

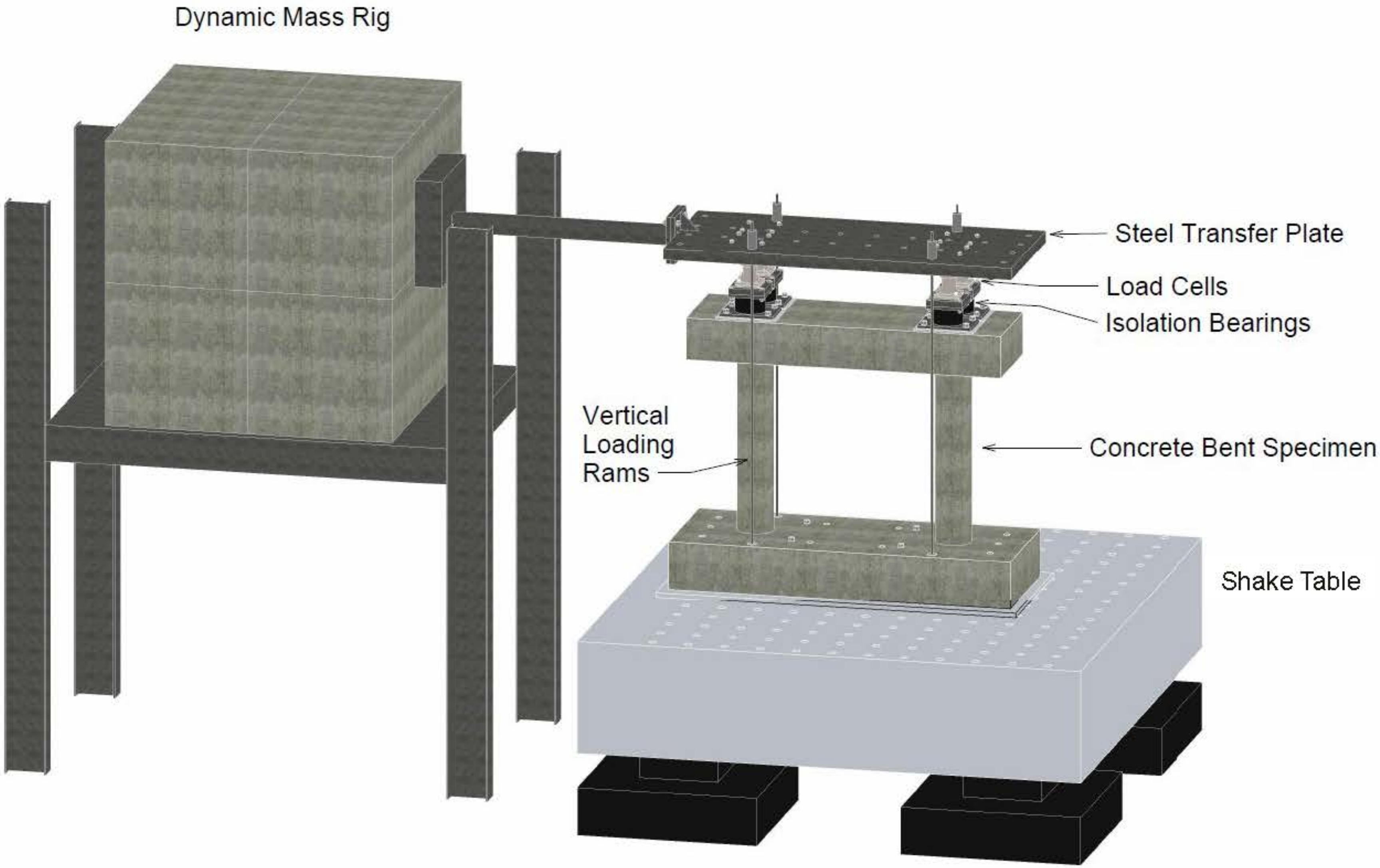


Isolation Parameters

Definition	Parameter	Scaled Model	Full Scale
Second Slope Period	T_d [s]	1.08	2.16
Characteristic Strength	Q_d [W_{SS}]	13%	13%

Experimental Program- ¼ Scale Isolated Bent

- Unique test setup for simulating bridge bent at UN Reno
- Inertial mass with safety limits and decoupled from the vertical load applied by rams
- Considered tributary area of superstructure with 1D excitation in bridge transverse direction

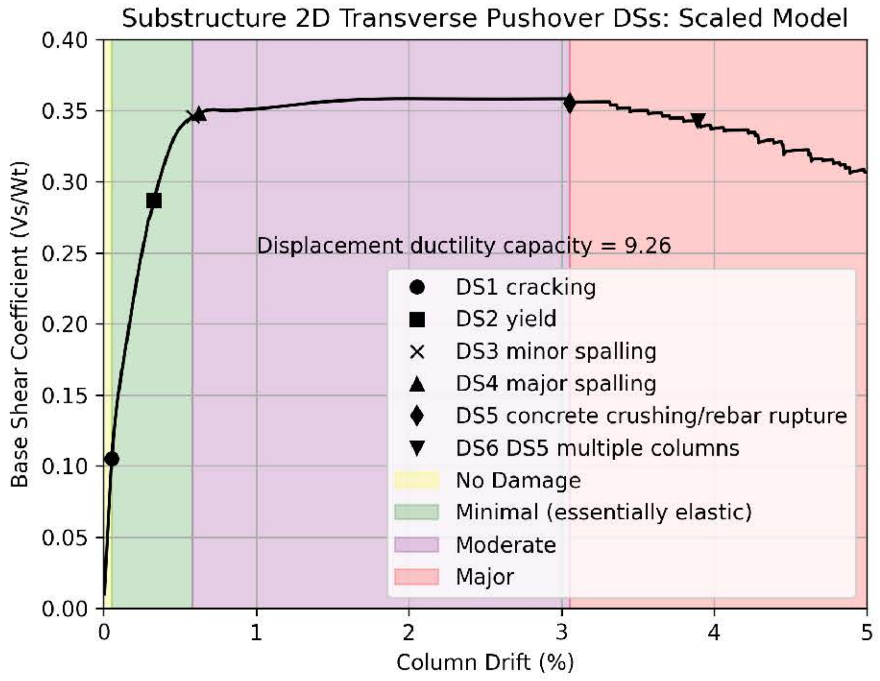


Substructure Damage State Definitions

Damage Level	Qualitative Performance	Strain Limit	Tension or Compression
I	Onset of cracking	$\epsilon_{uc} = \epsilon_{ct} = 0.00024$	Tension
II	First rebar yield	$\epsilon_s = \epsilon_{ye} = 0.0023$	Tension
III	Extensive cracks and spalling	$\epsilon_{uc} = \epsilon_{sp} = 0.005$ Outer cover	Compression
IV	Visible lateral and/or longitudinal rebar	$\epsilon_{uc} = \epsilon_{sp} = 0.005$ Inner cover	Compression
V	Onset of compressive failure of core concrete or Longitudinal rebar rupture	$\epsilon_{cc} = \epsilon_{cu} = 0.034$ or $\epsilon_s = \epsilon_{su}^R = 0.09$	Compression or tension
VI	Compressive failure or rebar rupture in both columns	DS5 in both columns	Compression or tension

SDC Definitions

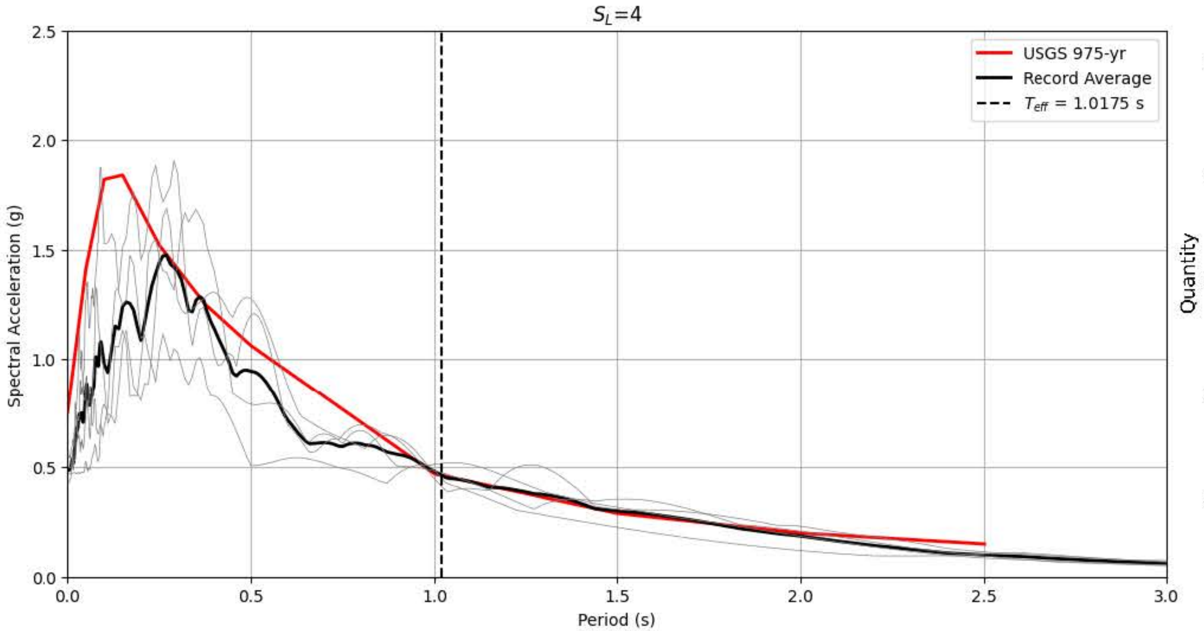
No Damage: Before DS1
Minimal Damage: DS1, DS2
Moderate Damage: DS3, DS4
Major Damage: DS5, DS6

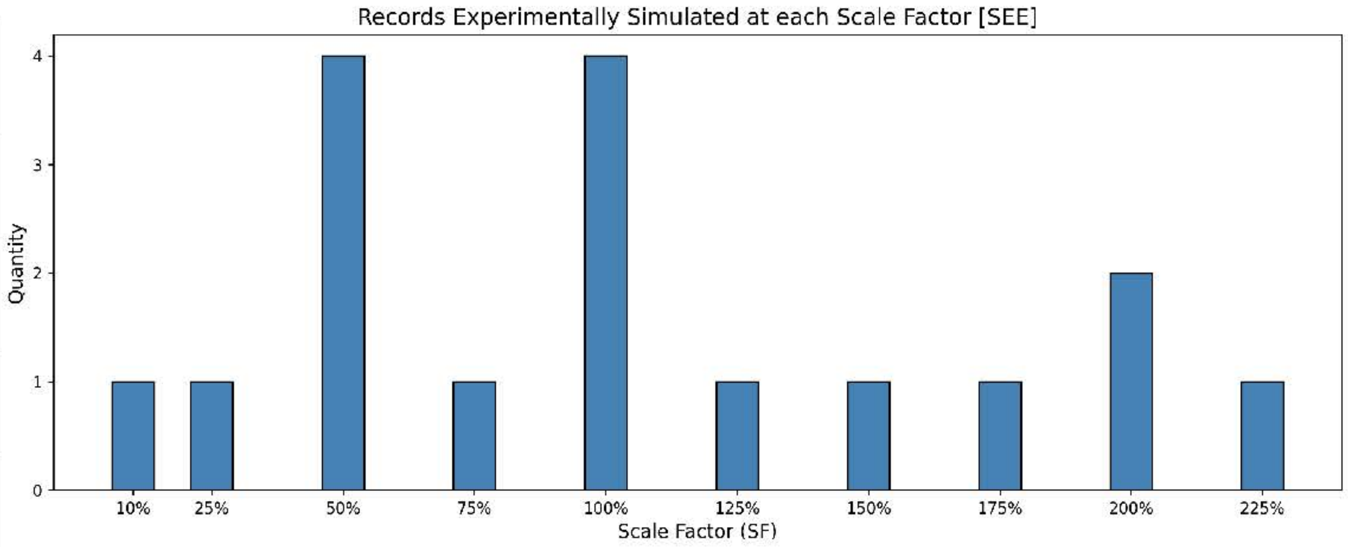


Earthquake Records – Loading Protocol

- Safety Evaluation Earthquake (SEE) - 975 yr return period
- Ground Motions scaled in time and amplitude 0.1xSEE – 2.25xSEE

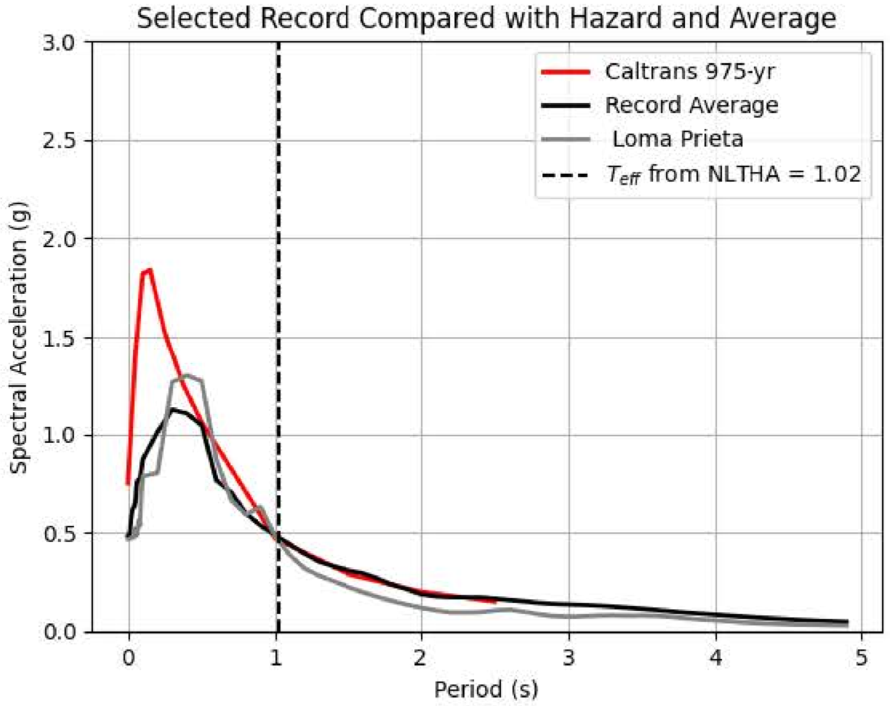
Earthquake	Station Name	SEE PGA (g)	SEE SF	5-95% Duration (s)	Rrup (km)	Vs30 (m/s)
Imperial Valley	El Centro Array #3	0.50	1.86	14.1	12.9	163
Christchurch New Zealand	Christchurch Hospital	0.55	1.58	10.6	4.85	194
Loma Prieta	Hollister - South and Pine	0.47	1.27	28.8	27.9	282
Loma Prieta	LGPC	0.43	0.75	10.2	3.88	595

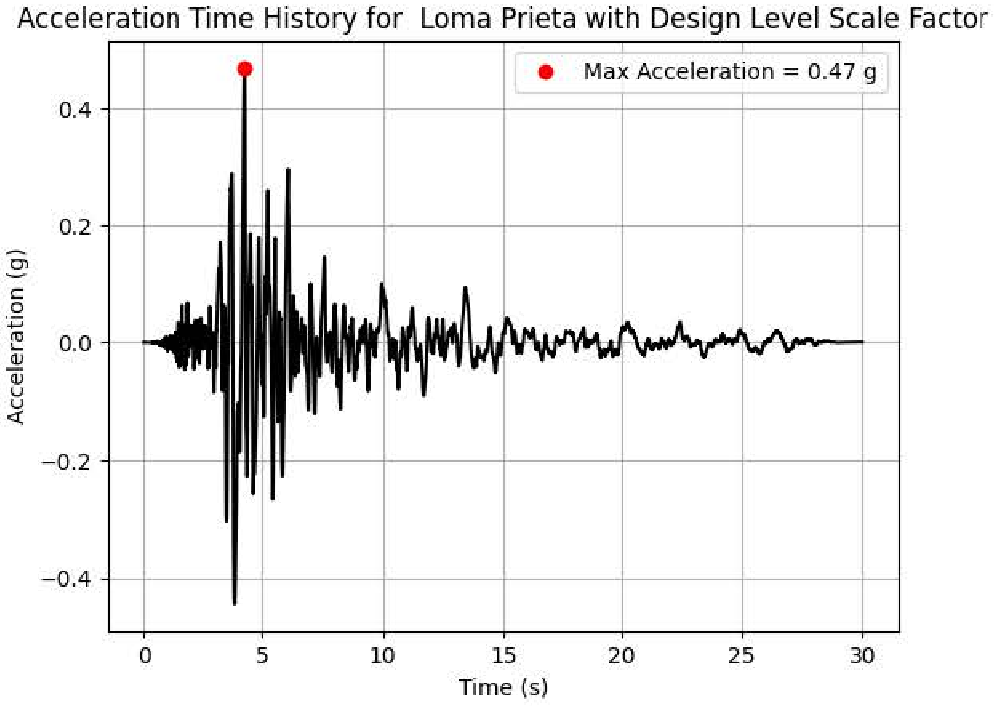




Earthquake Records - Scaling

- Primary motion: Loma Prieta-Hollister South and Pine (LP HSP) station
- Safety Evaluation Earthquake (SEE) @ 975-yr return period
- 0.5xSEE ≅ Functional Evaluation Earthquake (FEE) 225-yr return period
- 1.5xSEE produces isolator displacements ≅ $1.5D_T$

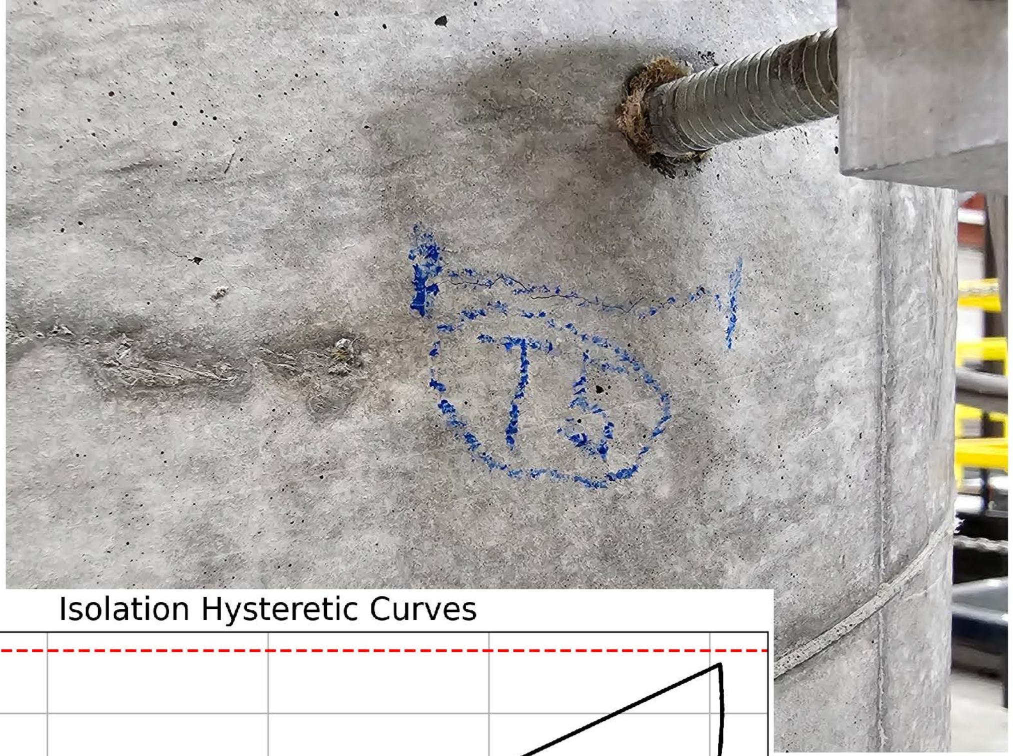


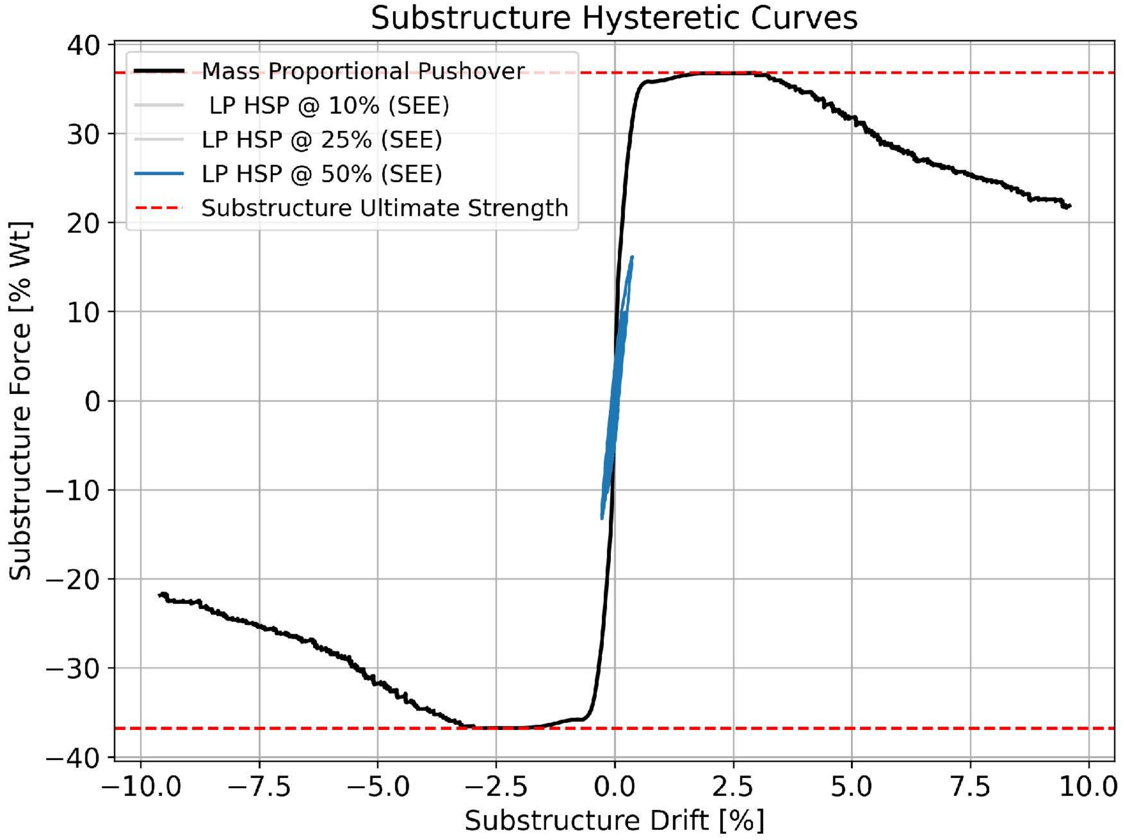


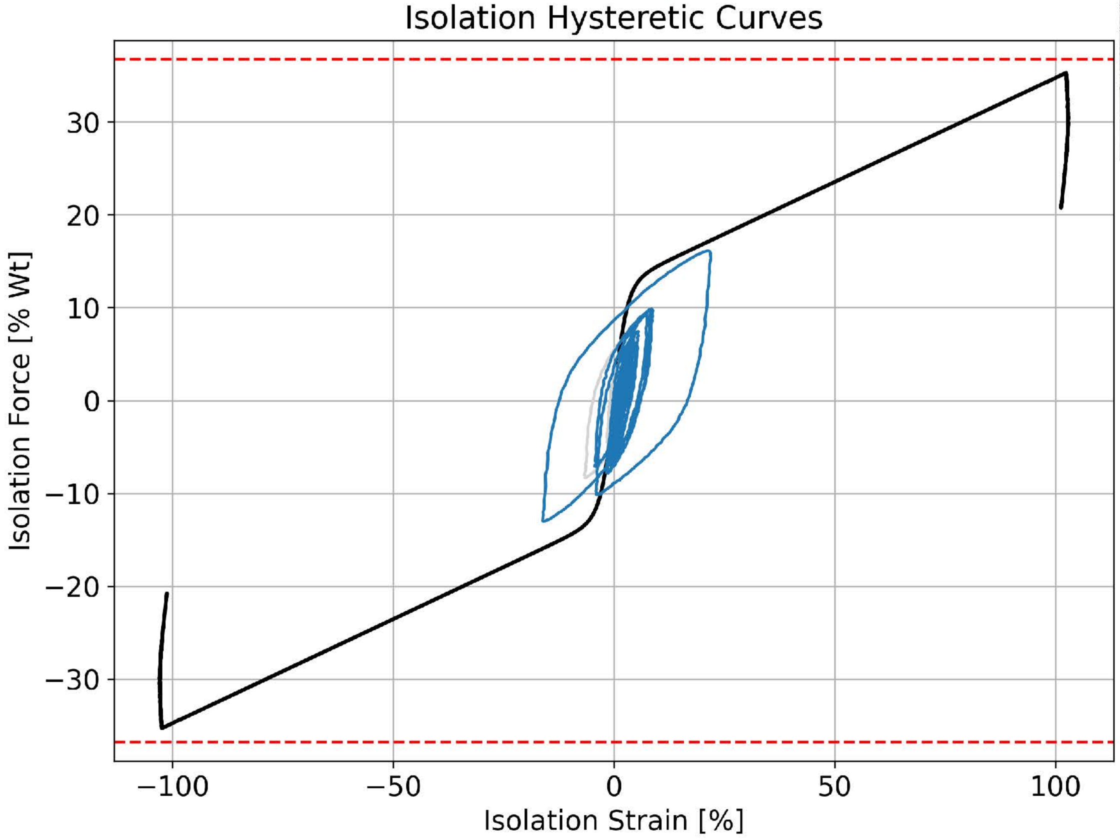

UNR UCSD Caltrans
SIBENT1_SERS
LP HSP 2.25 SEE
9/5/2025

Response for FEE Motion

- Substructure DS1 (hairline cracks)
- Elastic behavior with essentially no damage

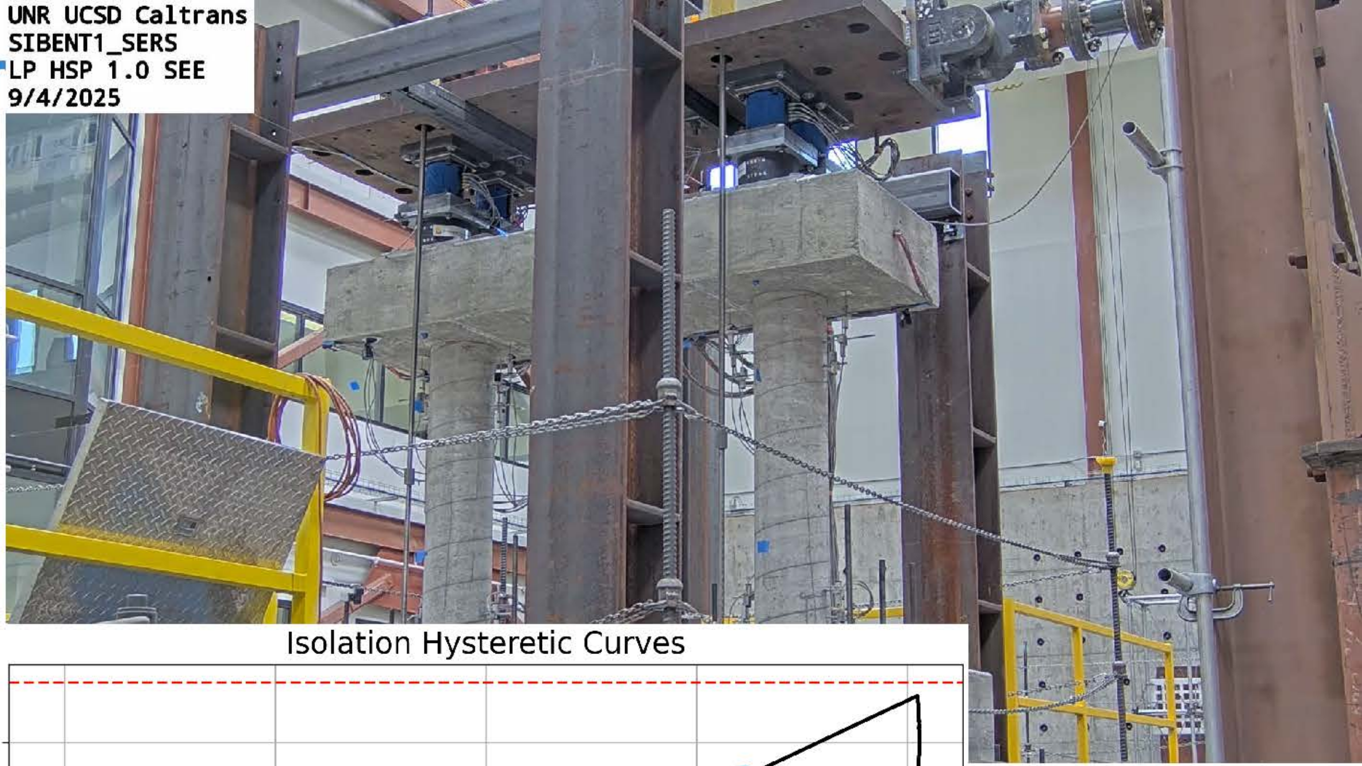


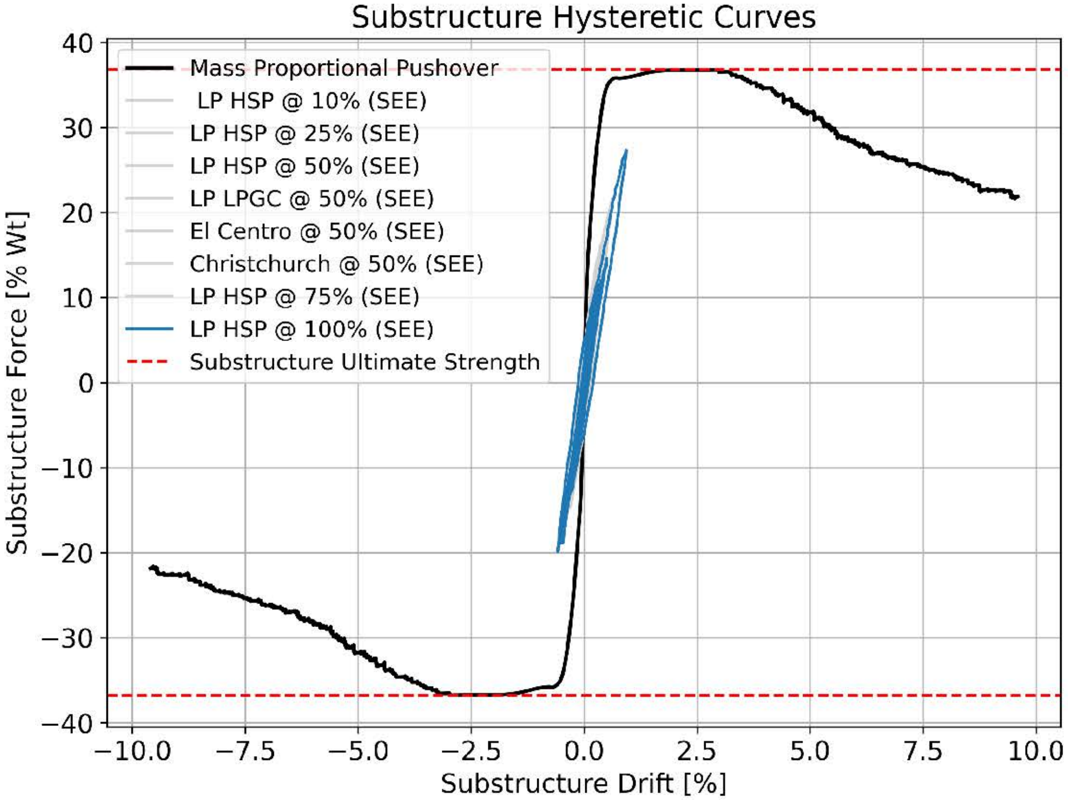


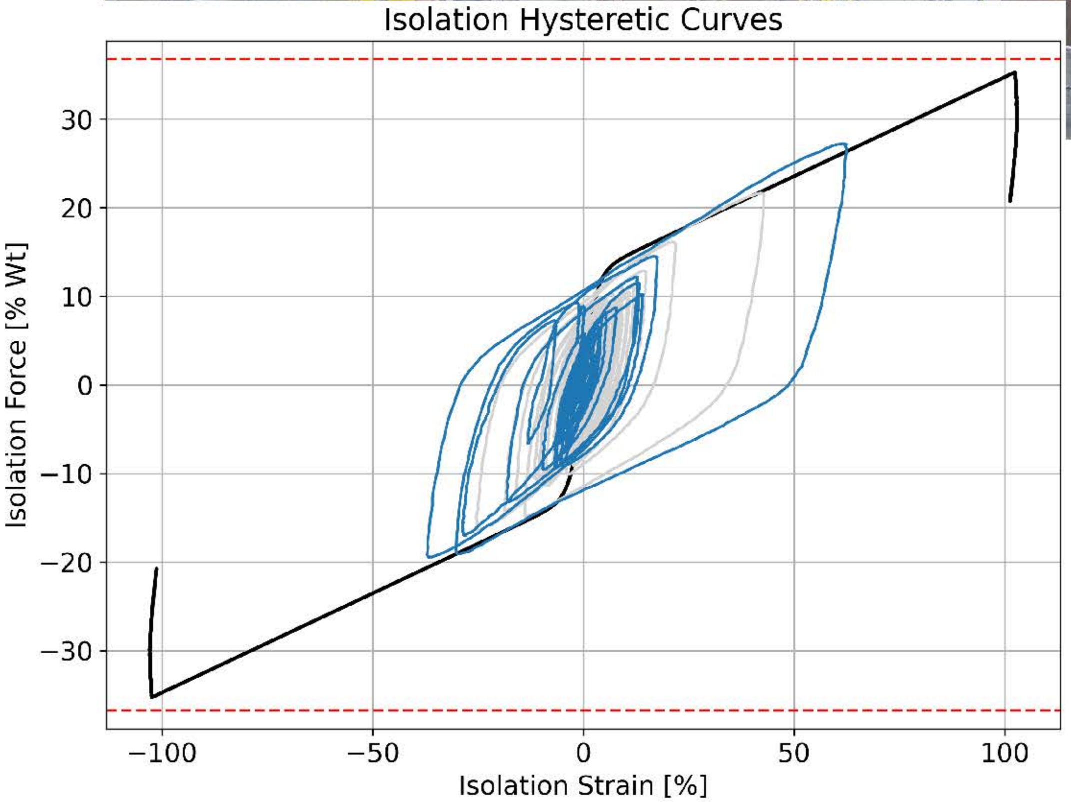


Response for SEE Motion

- Substructure DS2 (first rebar yield)
- Essentially elastic behavior with minimal damage

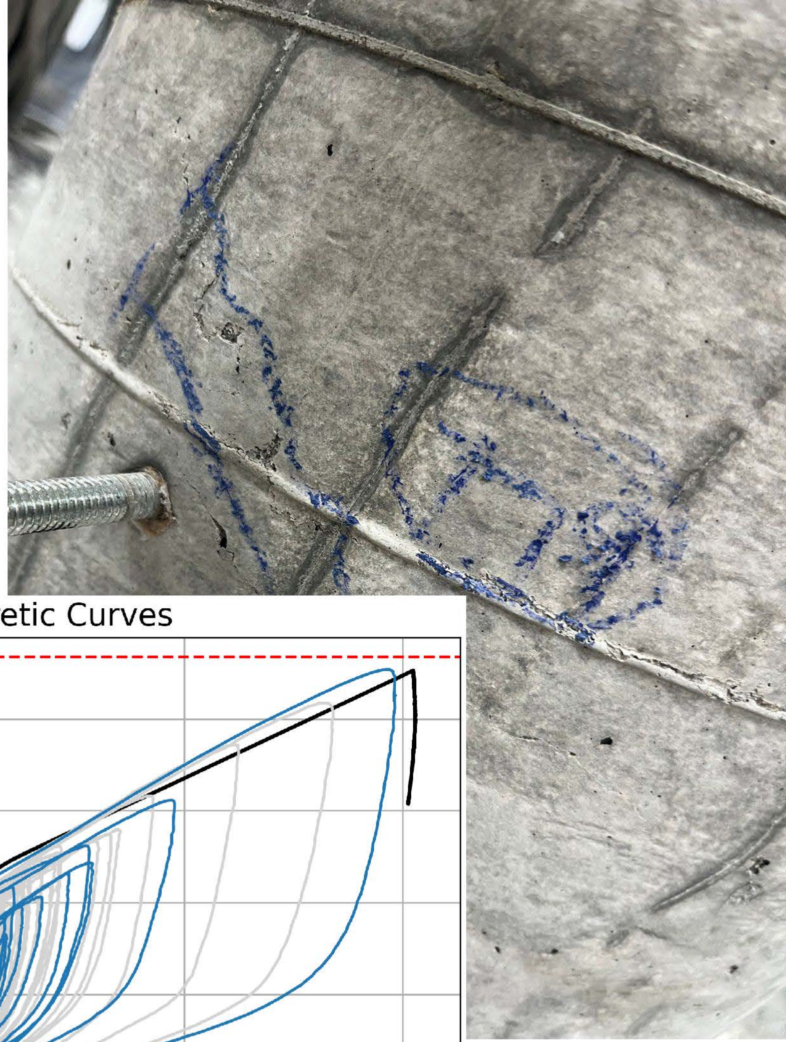


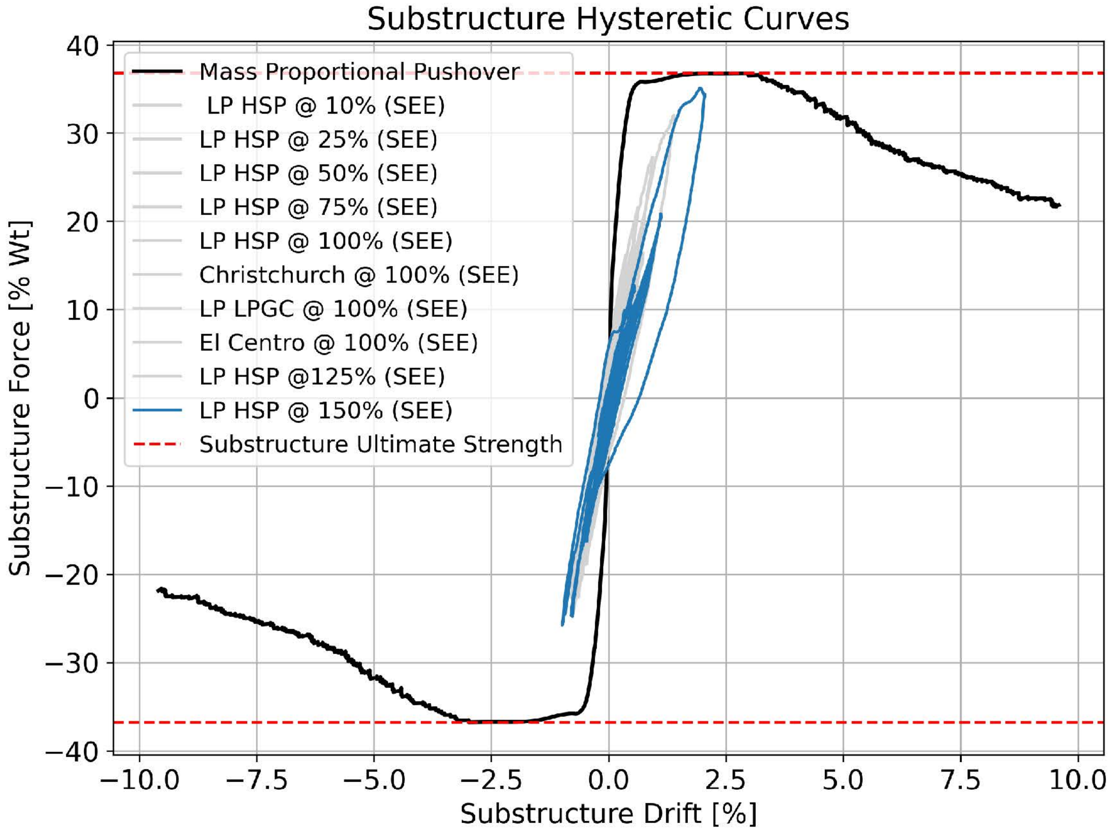


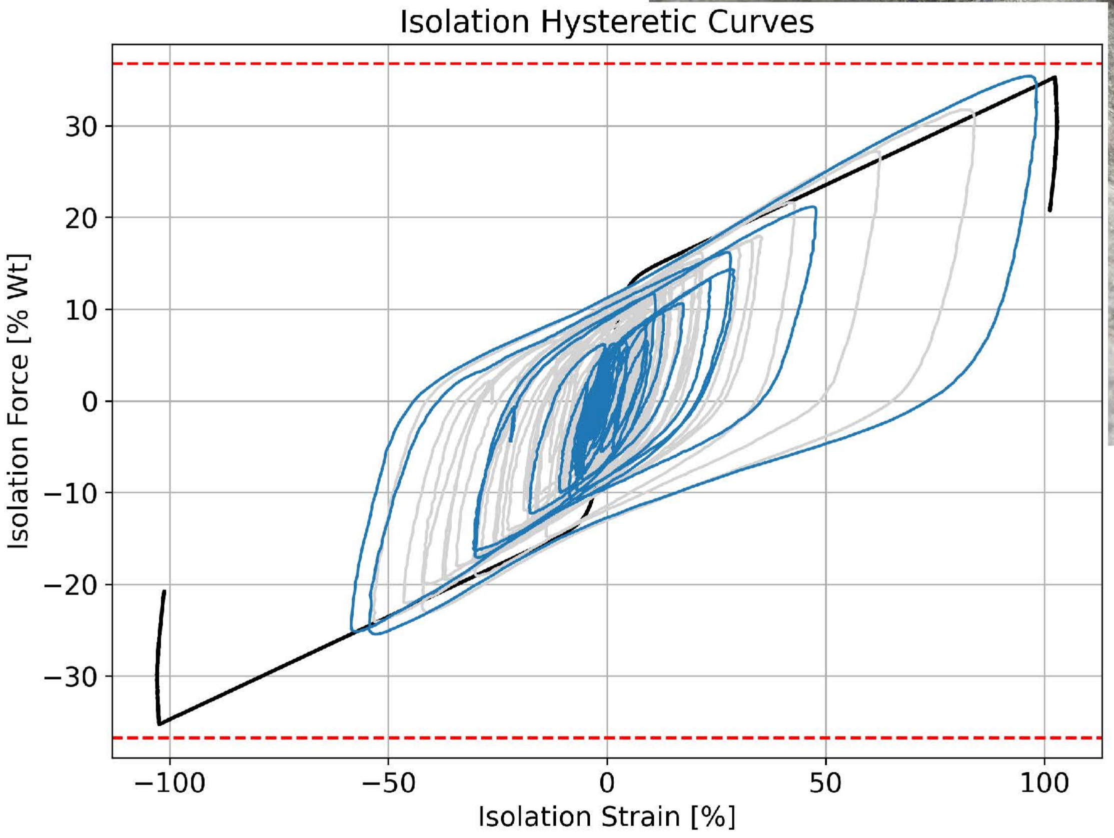


Response for 1.5xSEE

- Substructure DS3 (onset of spalling)
- Notable hysteretic behavior in column

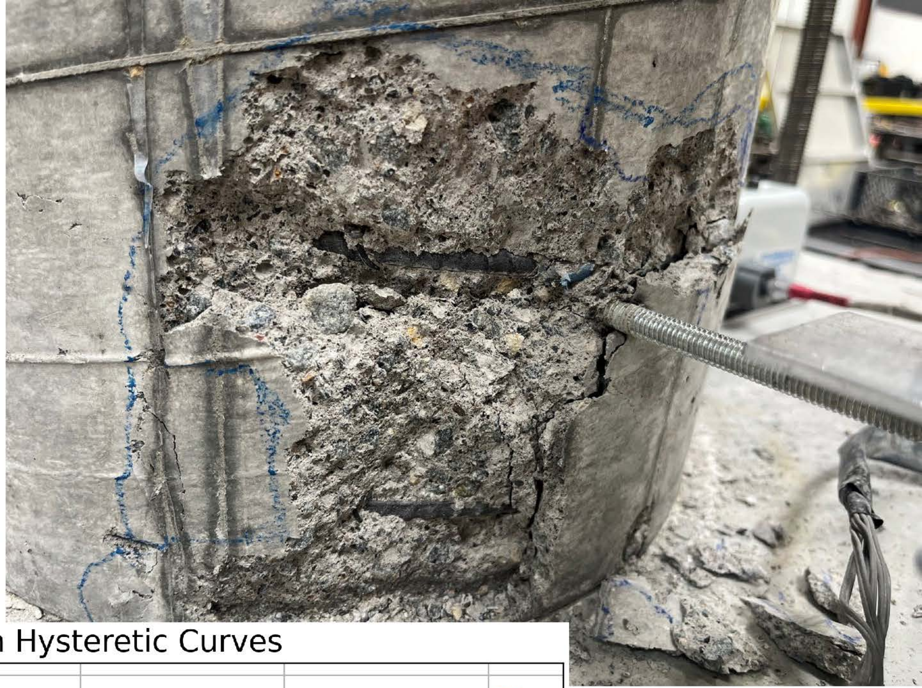


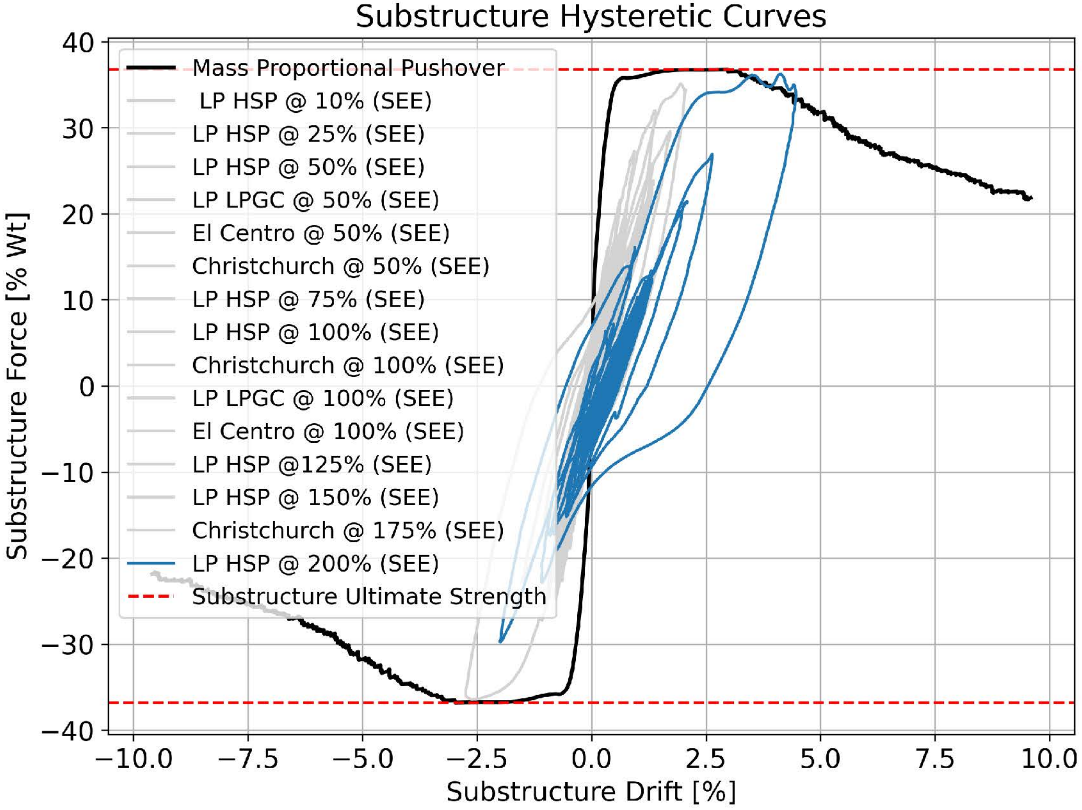


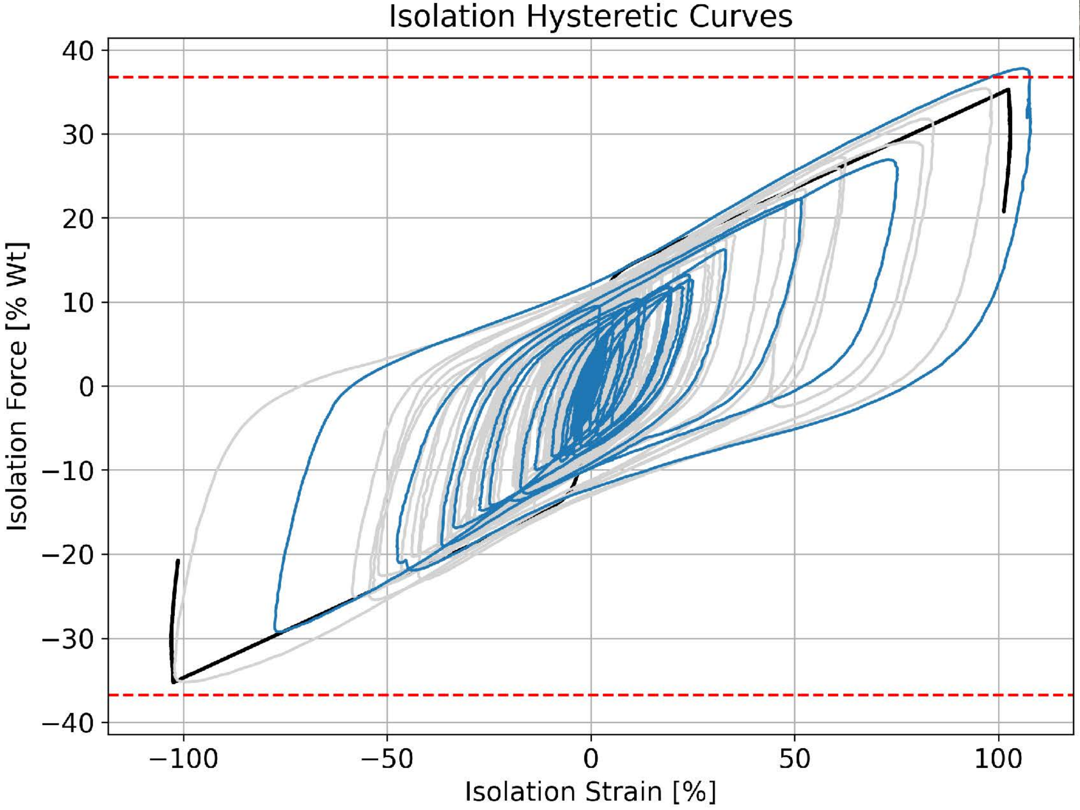


Response for 2.0xSEE

- Substructure DS4 (rebar exposed)
- Moderate damage
- Ductile substructure behavior with minimal residual drift

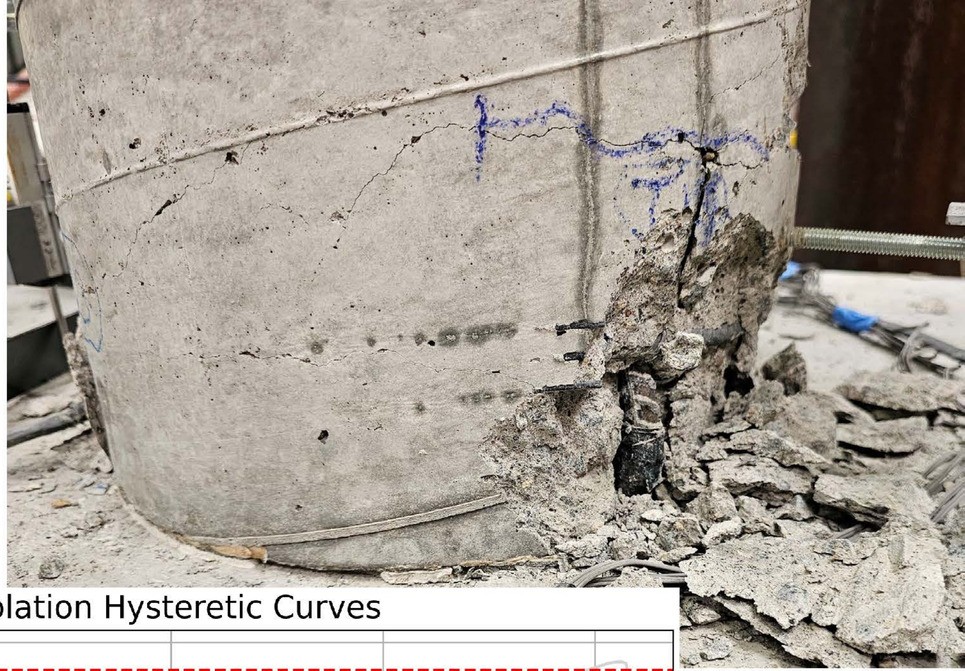


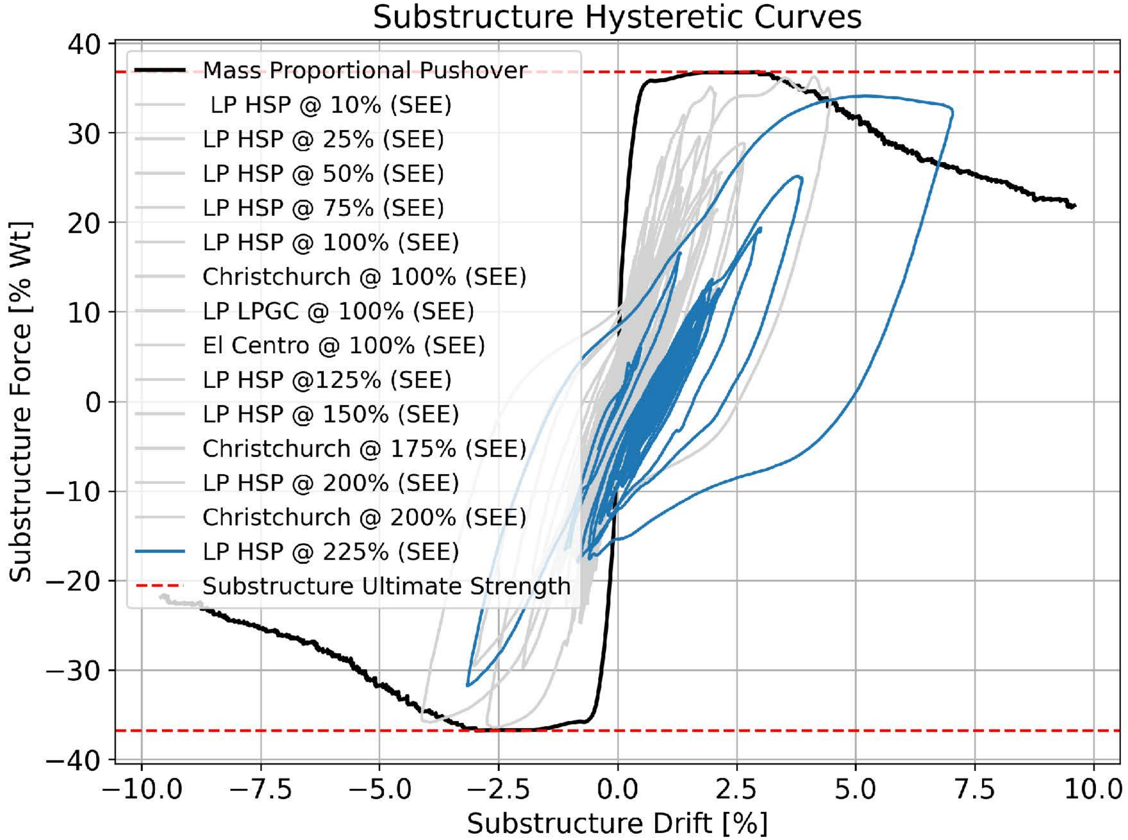


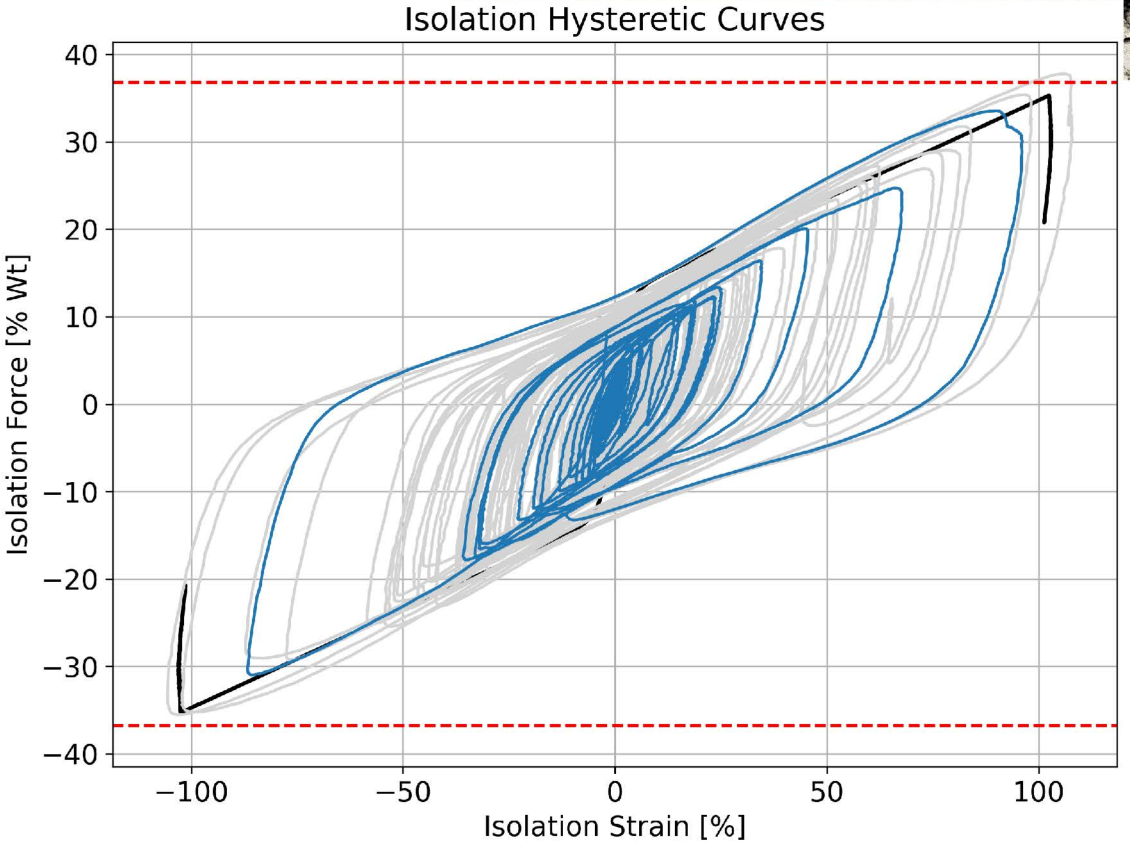


Response for 2.25xSEE

- Maximum earthquake level applied in testing
- Substructure DS4
- Loss of cover at multiple plastic hinge zones and rebar buckling



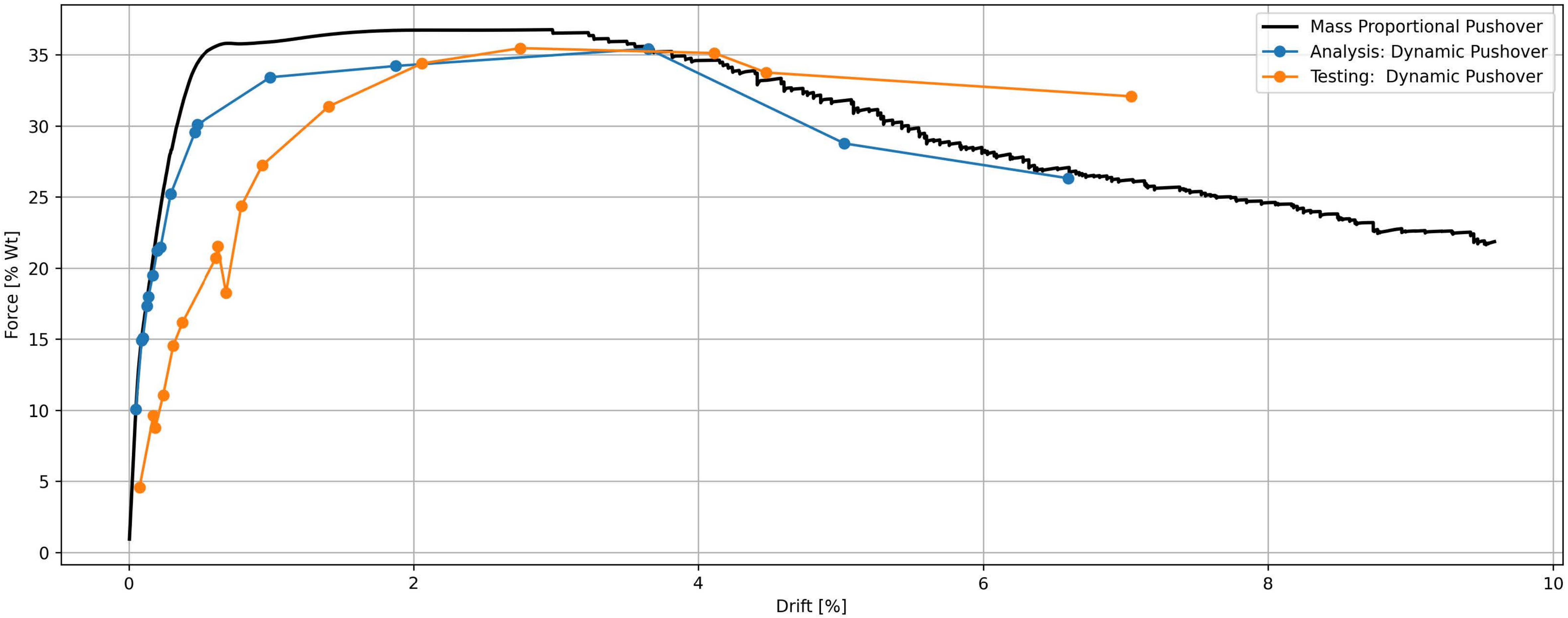




Substructure Damage State Progression

Test Number	Ground Motion	Scale [SEE]	PGA [s] Target	PGA [s] Experienced	DS Strain Based	DS Observed	DS Design	Strain [Tr] Isolation	Drift [lu] Substructure	Disp [DT] Isolation
2	LP HSP	0.10	0.05	0.05	1	0	0	2%	0.1%	0.03
3	LP HSP	0.25	0.12	0.10	1	0	1	8%	0.2%	0.13
4	LP HSP	0.50	0.24	0.21	1	0	1	22%	0.4%	0.35
5	LP LPGC	0.50	0.21	0.16	1	1	1	12%	0.2%	0.19
6	El Centro	0.50	0.25	0.16	1	1	1	9%	0.2%	0.14
7	Christchurch	0.50	0.27	0.11	1	1	1	19%	0.3%	0.30
9	LP HSP	0.75	0.35	0.33	1	1	1	43%	0.6%	0.69
11	LP HSP	1.00	0.47	0.43	2	2	2	62%	0.9%	1.00
13	Christchurch	1.00	0.55	0.33	2	2	2	53%	0.8%	0.86
14	LP LPGC	1.00	0.43	0.31	1	1	1	38%	0.7%	0.60
15	El Centro	1.00	0.50	0.32	2	2	2	42%	0.6%	0.68
17	LP HSP	1.25	0.59	0.56	2	2	2	84%	1.4%	1.35
19	LP HSP	1.50	0.71	0.69	3	3	4	98%	2.1%	1.58
21	Christchurch	1.75	0.95	0.66	4	4	4	102%	2.7%	1.64
23	LP HSP	2.00	0.94	0.87	4	4	4	108%	4.5%	1.73
24	Christchurch	2.00	1.09	0.85	5	4	6	106%	4.1%	1.69
26	LP HSP	2.25	1.06	0.98	6	4	6	96%	7.0%	1.54
28	Christchurch	1.00	0.55	0.37	6	5	6	60%	2.4%	0.96

Substructure Damage State Progression



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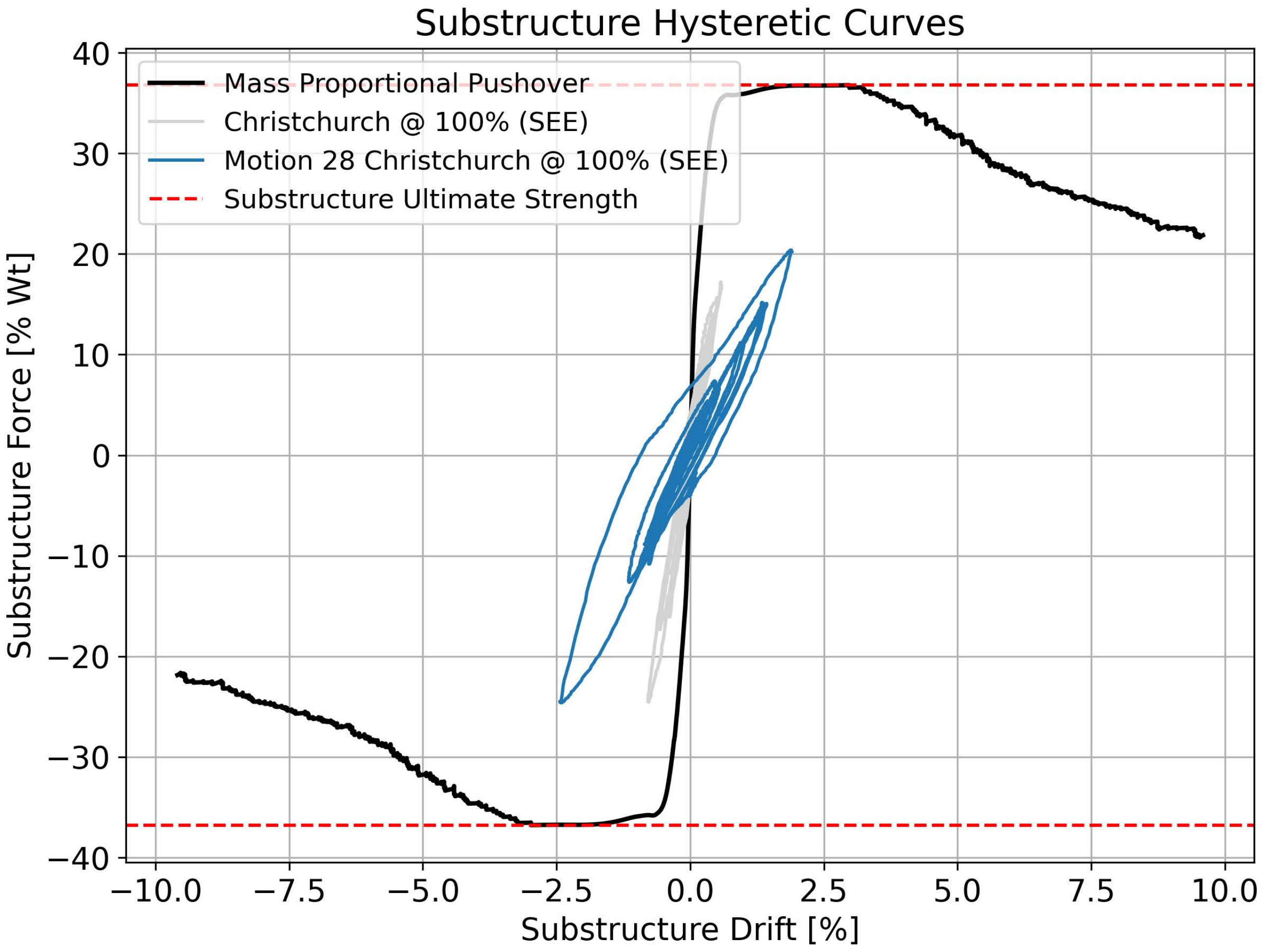
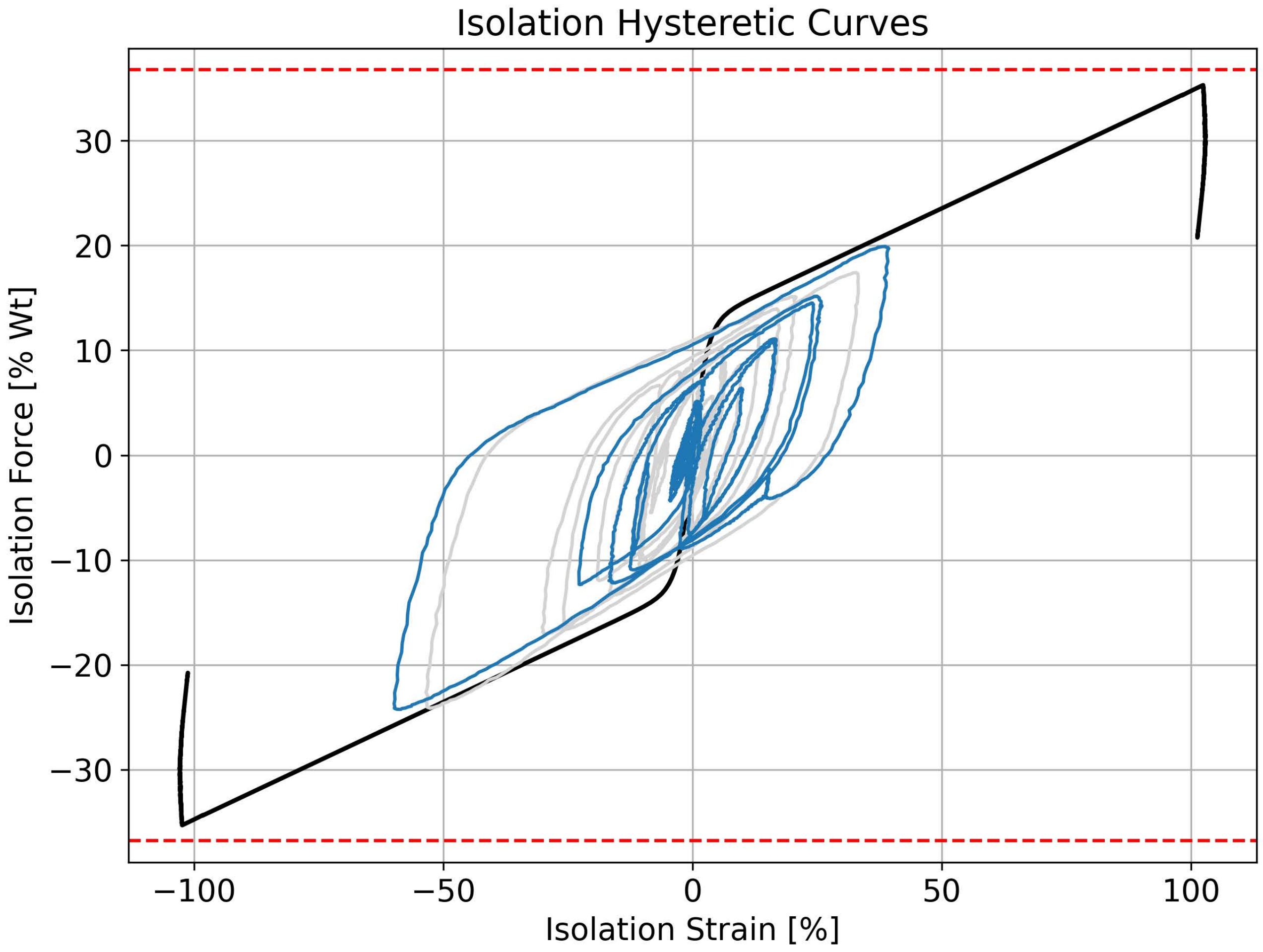
Comparison of Undamaged and Damaged Structure

- Motion 28 representative of damaged structure in aftershock



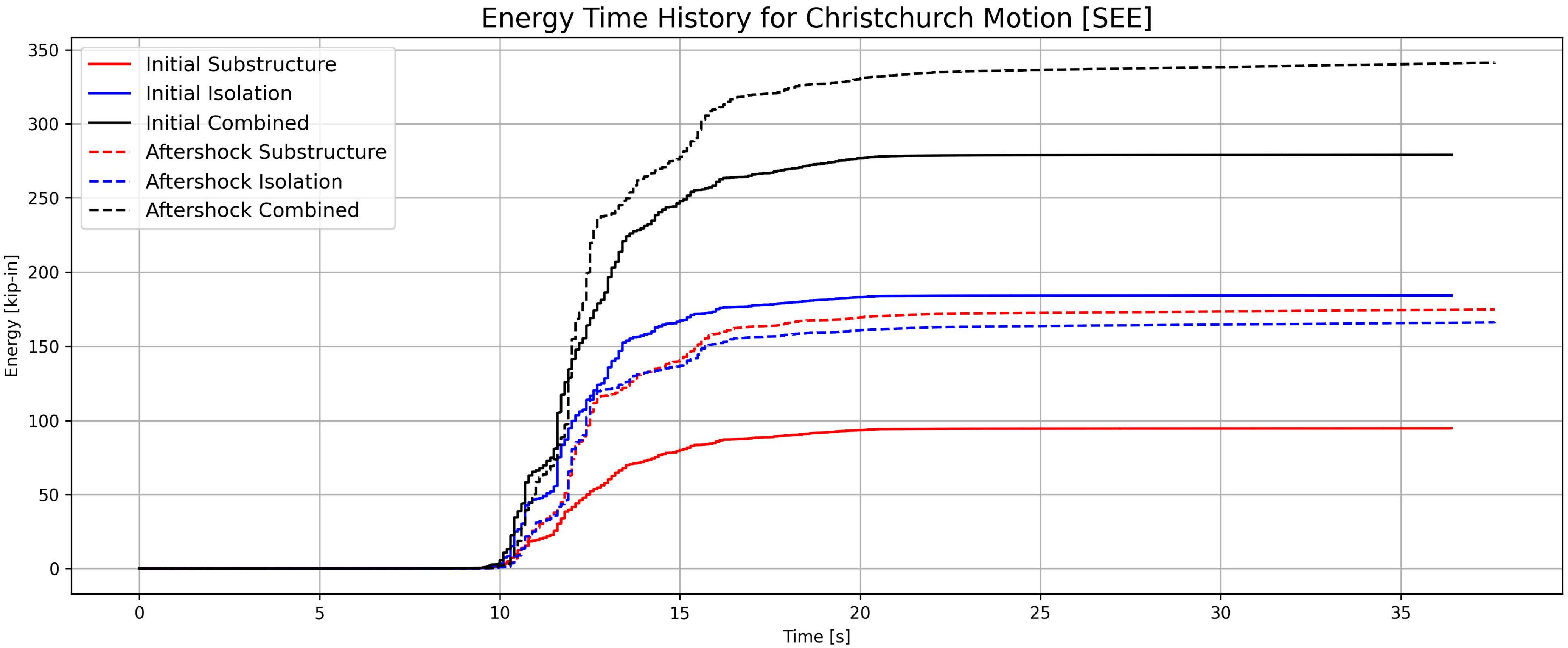


Energy Dissipation: Undamaged and Damaged

Hysteretic energy dissipation (E):

$$\Delta E_i = \frac{1}{2}(F_{i-1} + F_i)(u_i - u_{i-1})$$

$$E(T_i) = \sum_{j=1}^{i} \Delta E_j$$



Preliminary Conclusions

- Seismically isolated bridge designed per Caltrans BDM 20.33 performed as expected demonstrating reserve capacity beyond design
  - Essentially elastic behavior up to 1.5x design level motion
  - SERS showed stable progression of damage with no collapse- ductile columns response with increased shaking
  - Substructure strength can be selected to desired earthquake level and isolation displacement limit
- SERS with plastic hinging in substructure effectively limits isolator displacements – capacity protected
- Effectiveness of SERS can be considered for more cost-effective implementation of seismic isolation in ordinary bridges
- Second specimen is currently under construction to further verify conclusions – isolation system with lower strength to engage larger shear strain and potentially hardening in bearings

Acknowledgements

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- Lead rubber bearings donated by DIS
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  - Caltrans engineers - Project Manager Foued Zayati
  - Technical staff of the Structural Engineering Laboratories at the University of Nevada, Reno

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DYNAMIC ISOLATION SYSTEMS