ATLSS & NHERI Lehigh Seminar,
December 6, 2016

Hybrid Simulation of a Seismically Isolated Nuclear Power Plant

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Outline

1. Motivation
2. Prototype Structure & Bearing Designs
3. Experimental Test Program
4. Hybrid Simulation Test Results
5. Characterization Test Results
6. Summary & Conclusions

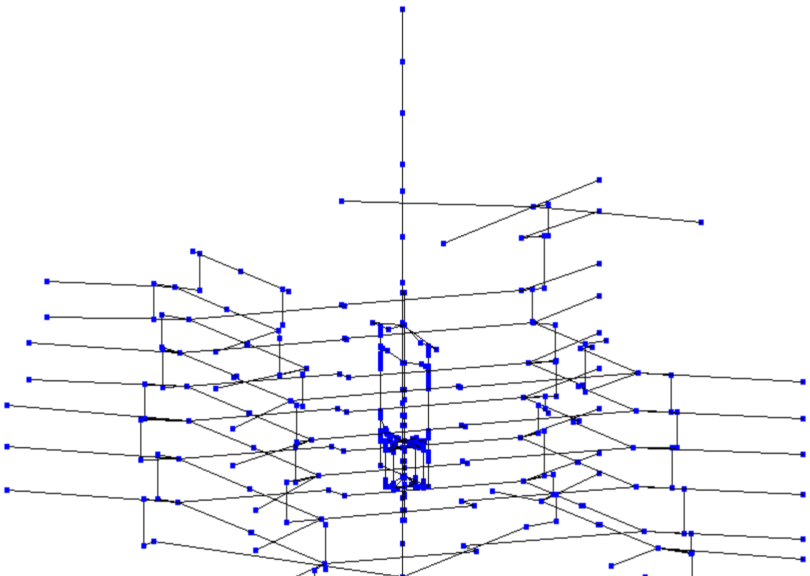
Motivation

HS of large isolated structure

- On a shaking table the testing of large structures such as NPPs is impractical due to the size, weight and strength limitations imposed by the simulator platform
- Using hybrid simulation
  - The linear-elastic plant superstructure can be modelled analytically
  - Only the nonlinear isolator behavior needs to be tested physically
  - Large axial loads due to gravity and axial load fluctuations caused by overturning and vertical input can be imposed in force control
- Need a testing facility that can be converted to perform real-time hybrid simulations on large full-scale isolators

Hybrid Simulation Concept

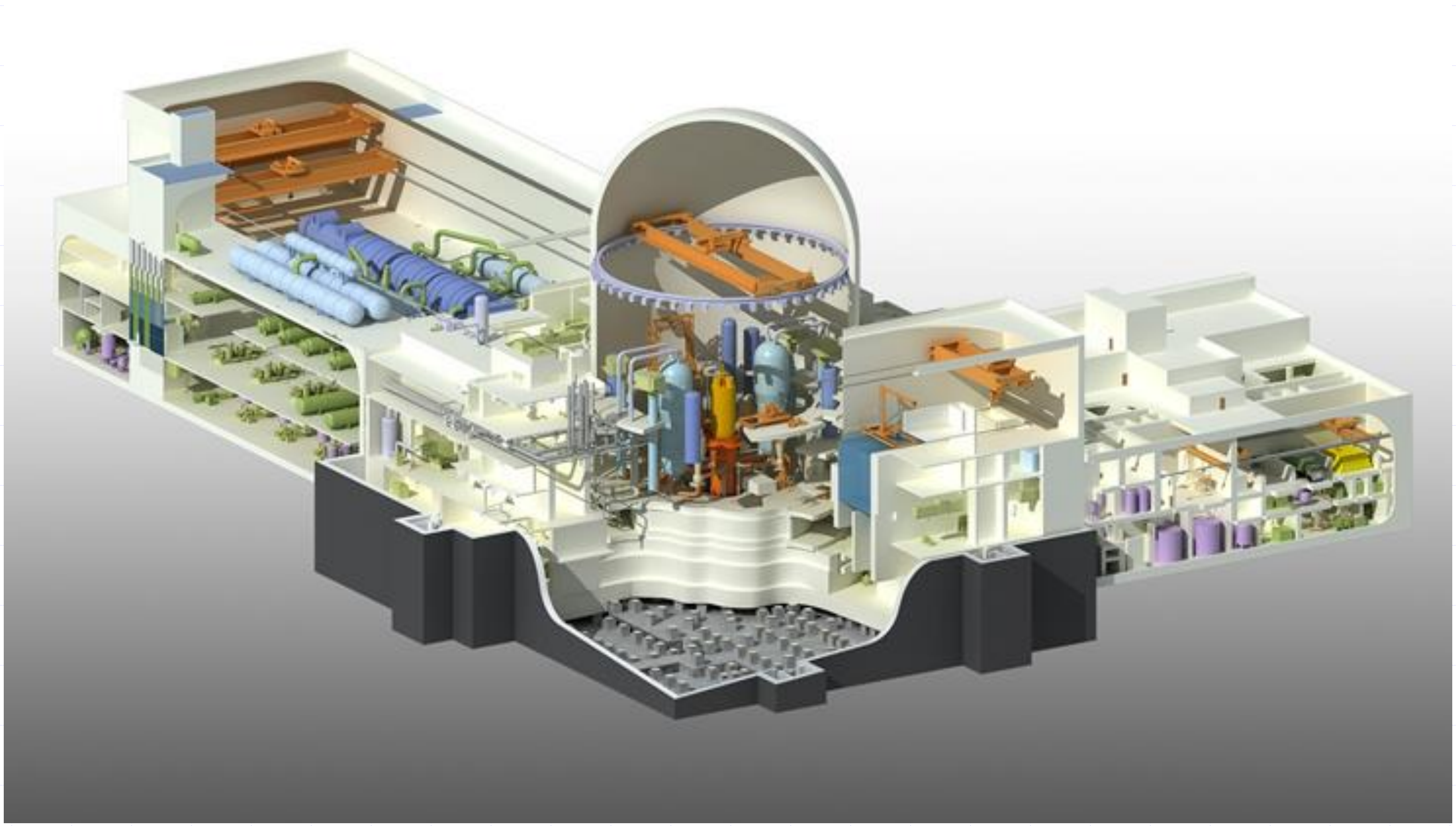
$$\mathbf{M} \cdot \ddot{\mathbf{u}} + \mathbf{C} \cdot \dot{\mathbf{u}} + \mathbf{P}_{\mathbf{r}}\left(\mathbf{u}, \dot{\mathbf{u}}, \ddot{\mathbf{u}}\right) = \mathbf{P}(t)$$



Prototype Structure & Bearing Designs

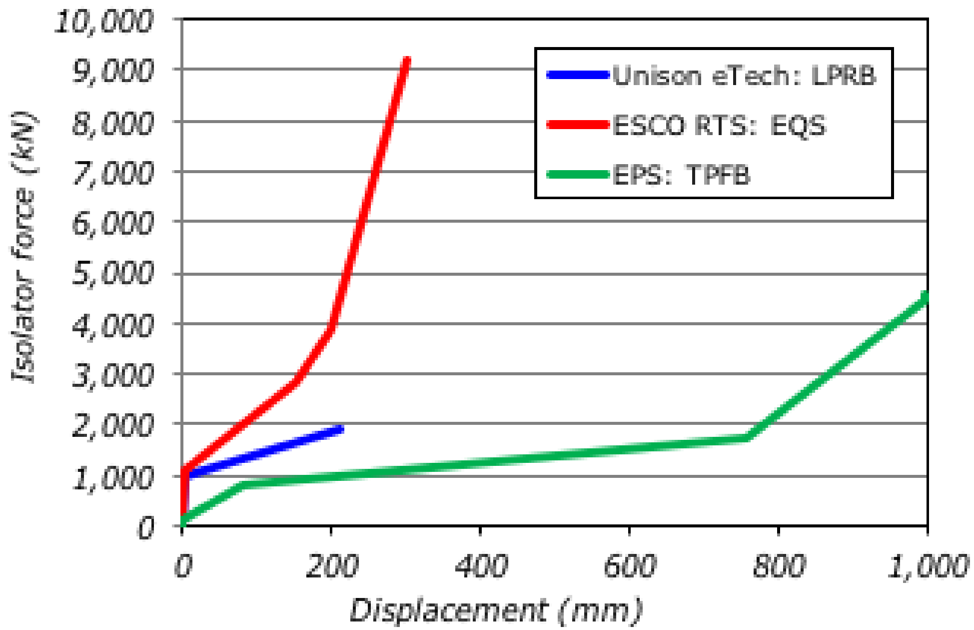
Prototype Structure

Korean Advanced Power Reactor (APR1400)

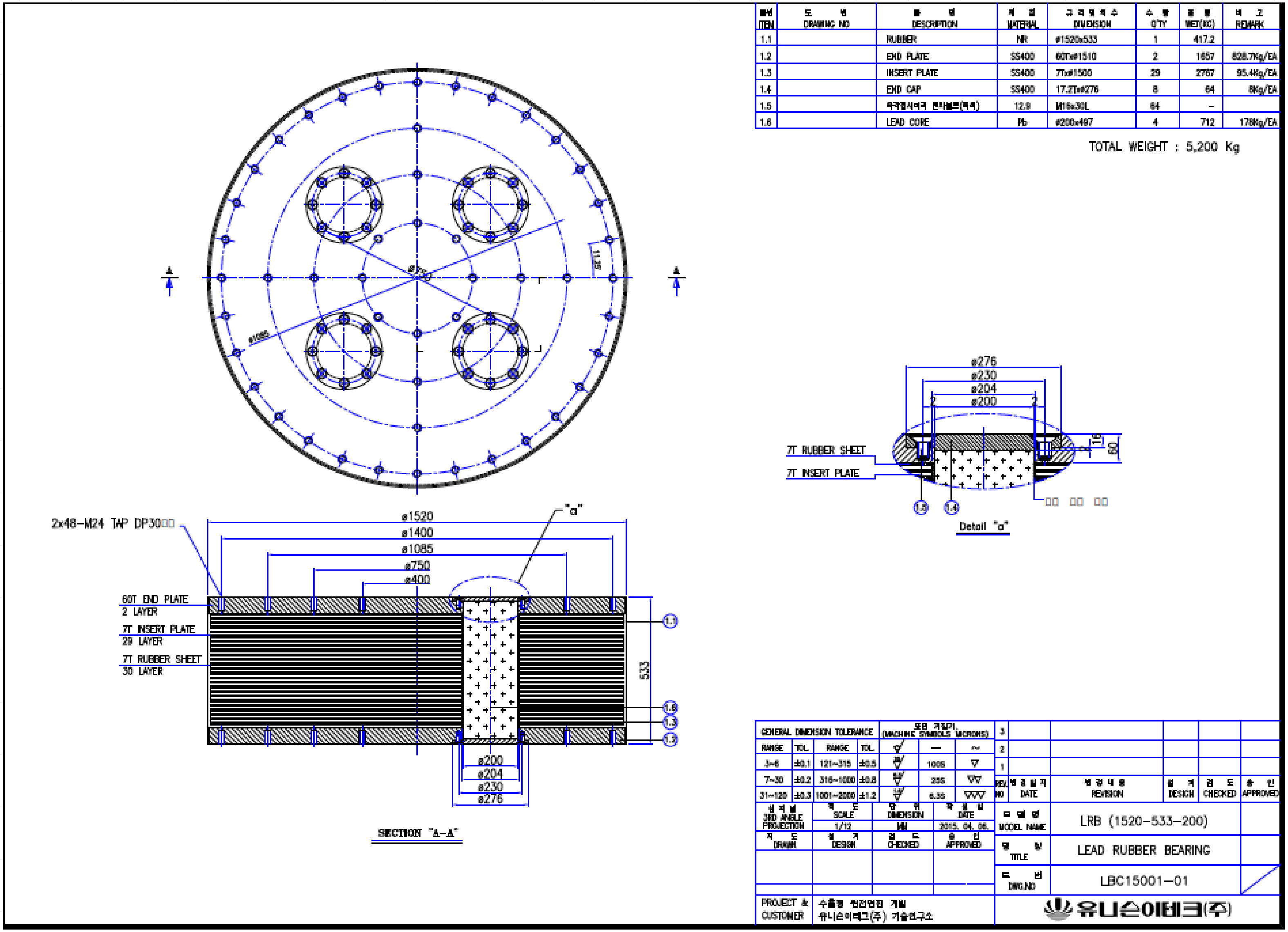


Three Bearing Designs

Isolation bearing	Design displacement, D_d (mm)	Lateral force at D_d (kN)	Q_d (kN)	Plan dimension (mm)	Height (mm)
Unison eTech (LPRB)	210	1,900	1,010	1,520	533
ESCO RTS (EQSB)	152	2,920	1,090	2,900	607
Earthquake Protection Systems (TFPB)	584	1,510	730	1,980	711



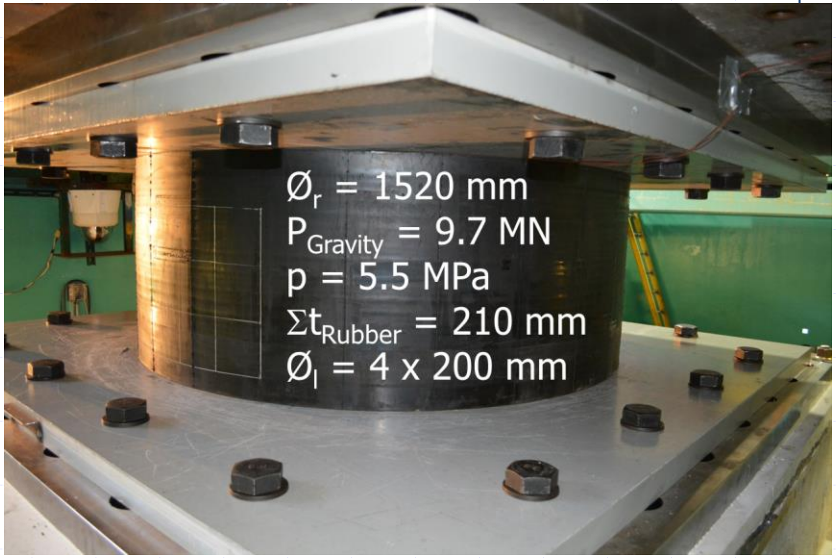
Unison eTech

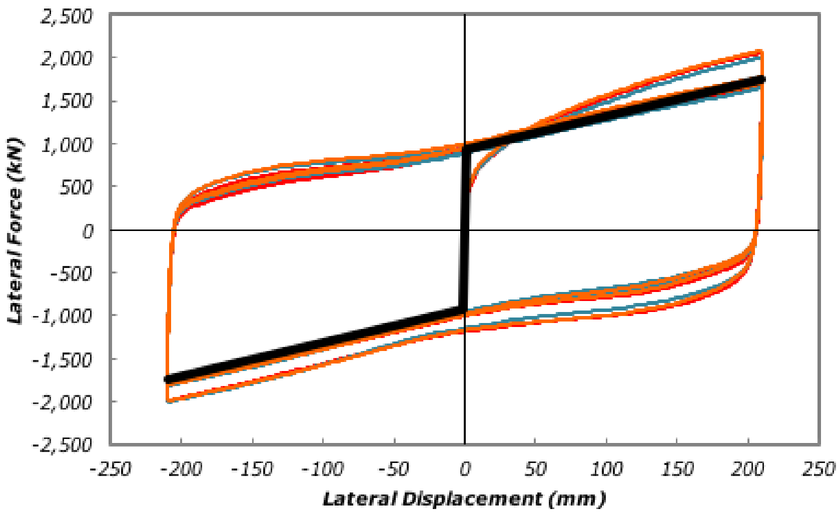


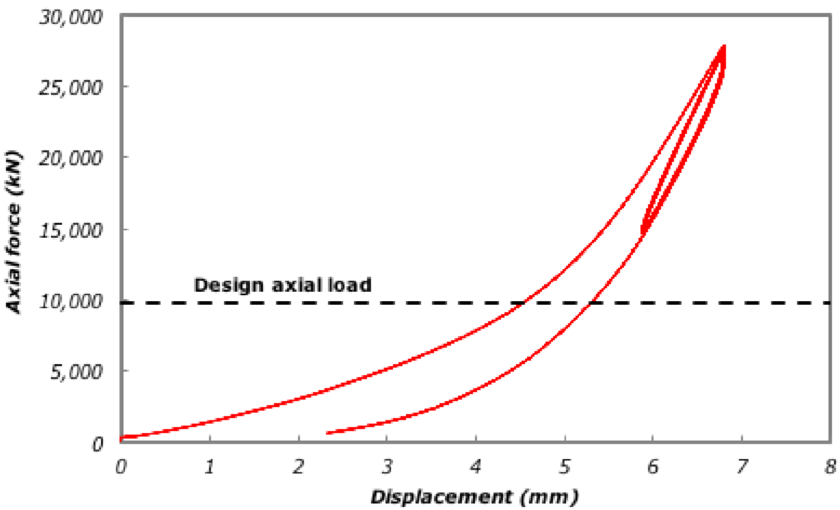
Unison eTech Bearing

Table 2.2-1 LPRB design properties.

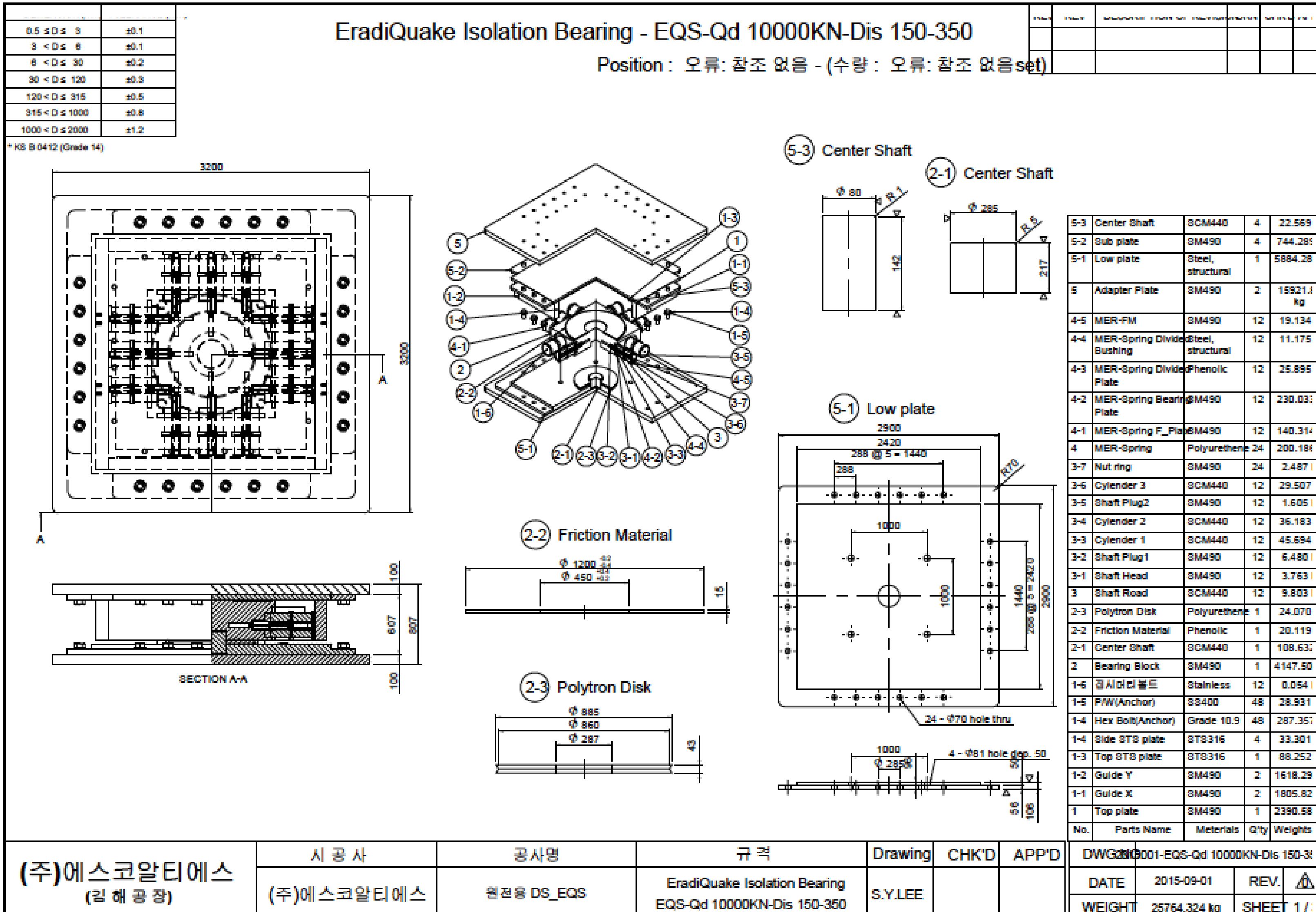
Vertical stiffness (K_v)	12,896 kN/mm
Initial stiffness (K_1)	545 kN/mm
Second slope stiffness (K_2)	4.2 kN/mm
Characteristic strength (Q_d)	1,002 kN
Equivalent stiffness (K_{eq})	9.0 kN/mm
Equivalent damping ratio (H_{eq})	0.335







ESCO RTS Bearing

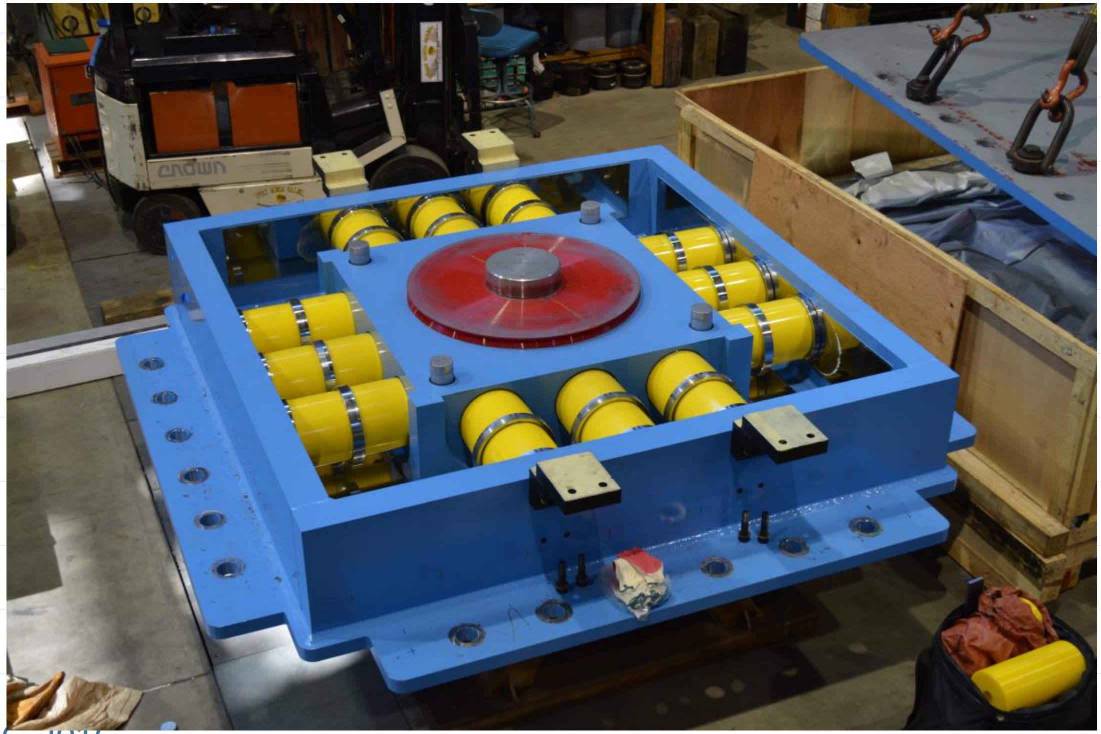


ESCO RTS Bearing

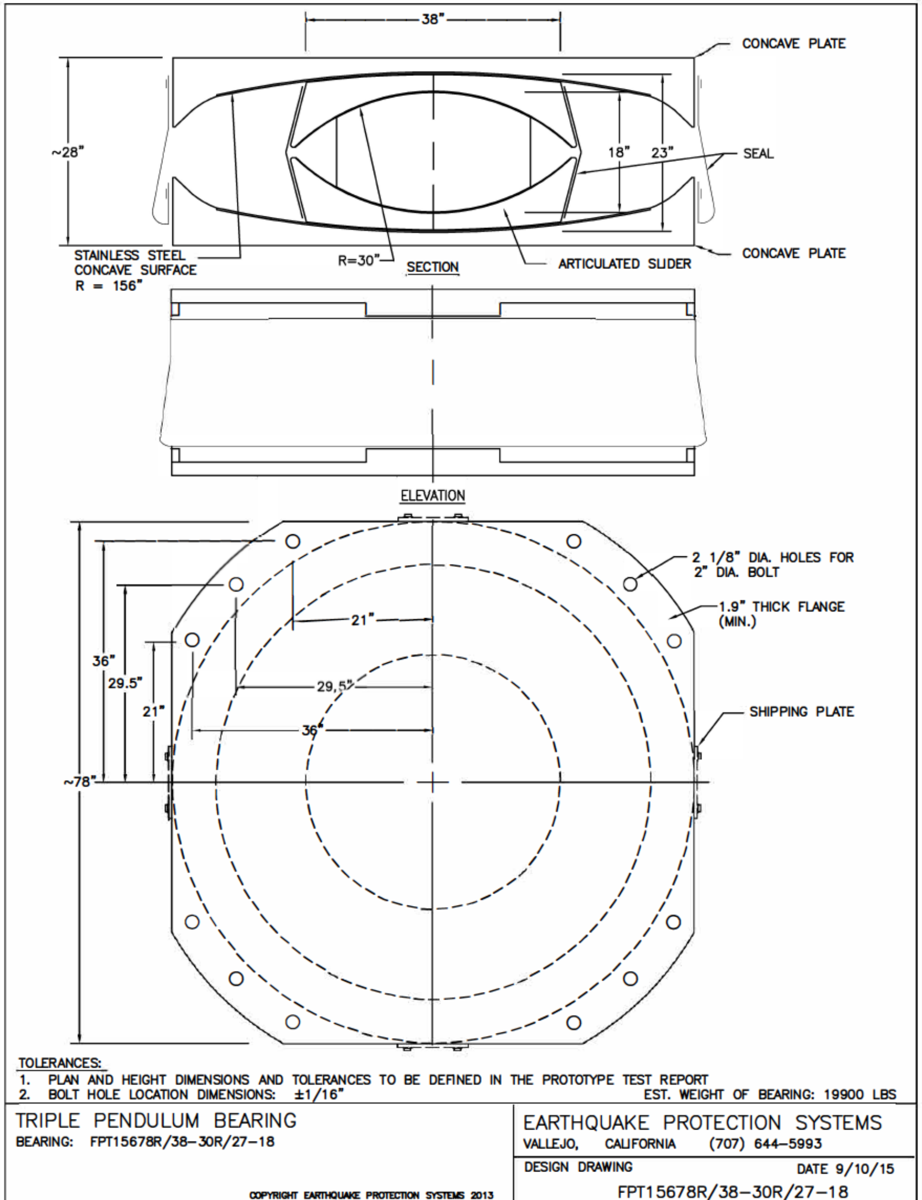
Table 2.3-1 EQSB design properties.

Coefficient of friction	0.11
Second slope stiffness (K_2)	11.6 kN/mm
Characteristic strength (Q_d)	1,092 kN
Equivalent stiffness (K_{eq})	18.8 kN/mm

WxL = 2400x2400 mm
H = 600 mm
$P_{Gravity}$ = 9.7 MN
μ = 11 %
k_2 = 11.6 kN/mm



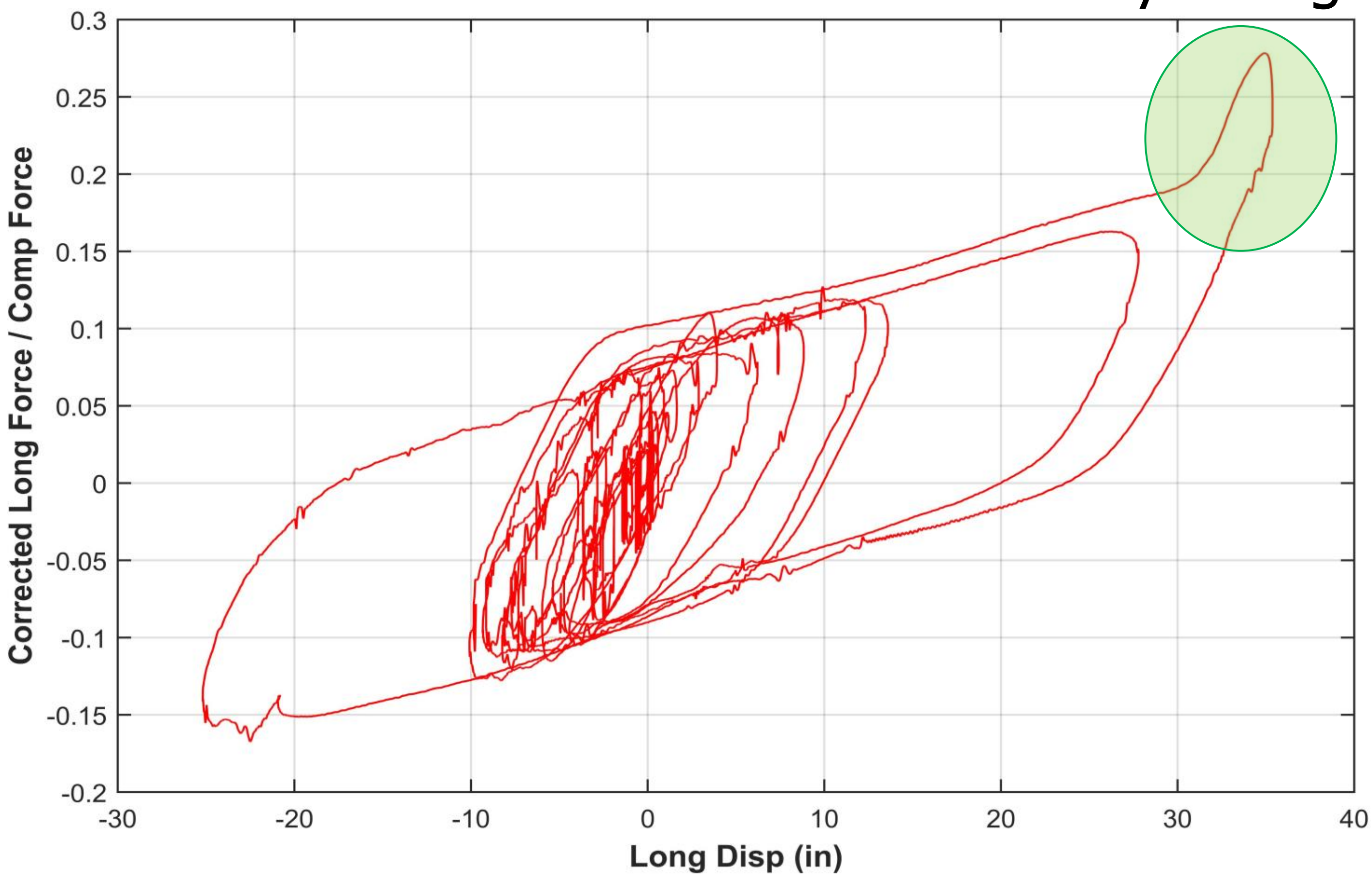
EPS Bearing


38"
CONCAVE PLATE
~28"
18"
23"
SEAL
CONCAVE PLATE
STAINLESS STEEL
CONCAVE SURFACE
R = 156"
R=30"
SECTION
ARTICULATED SLIDER
ELEVATION
2 1/8" DIA. HOLES FOR
2" DIA. BOLT
1.9" THICK FLANGE
(MIN.)
21"
29.5"
36"
36"
29.5"
21"
~78"
SHIPPING PLATE
TOLERANCES:
1. PLAN AND HEIGHT DIMENSIONS AND TOLERANCES TO BE DEFINED IN THE PROTOTYPE TEST REPORT
2. BOLT HOLE LOCATION DIMENSIONS: ±1/16"
EST. WEIGHT OF BEARING: 19900 LBS
TRIPLE PENDULUM BEARING
BEARING: FPT15678R/38-30R/27-18
COPYRIGHT EARTHQUAKE PROTECTION SYSTEMS 2013
EARTHQUAKE PROTECTION SYSTEMS
VALLEJO, CALIFORNIA (707) 644-5993
DESIGN DRAWING
DATE 9/10/15
FPT15678R/38-30R/27-18

EPS Bearing

COF = 2% - 9% - 9%

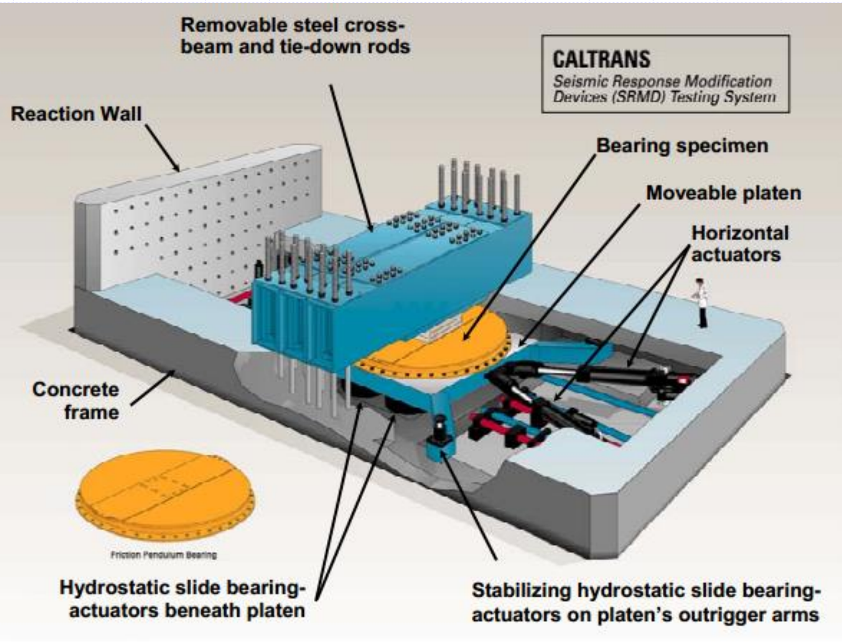
Stage 5-6
yielding



Experimental Test Program

Overview of SRMD @ UC San Diego

- Built by Caltrans, MTS and UCSD in 1999 to test Seismic Response Modification Devices at full scale
- Apply full-scale gravity loads, displacements and velocities to bearings and dampers
  - Designed for capacity rather than accuracy



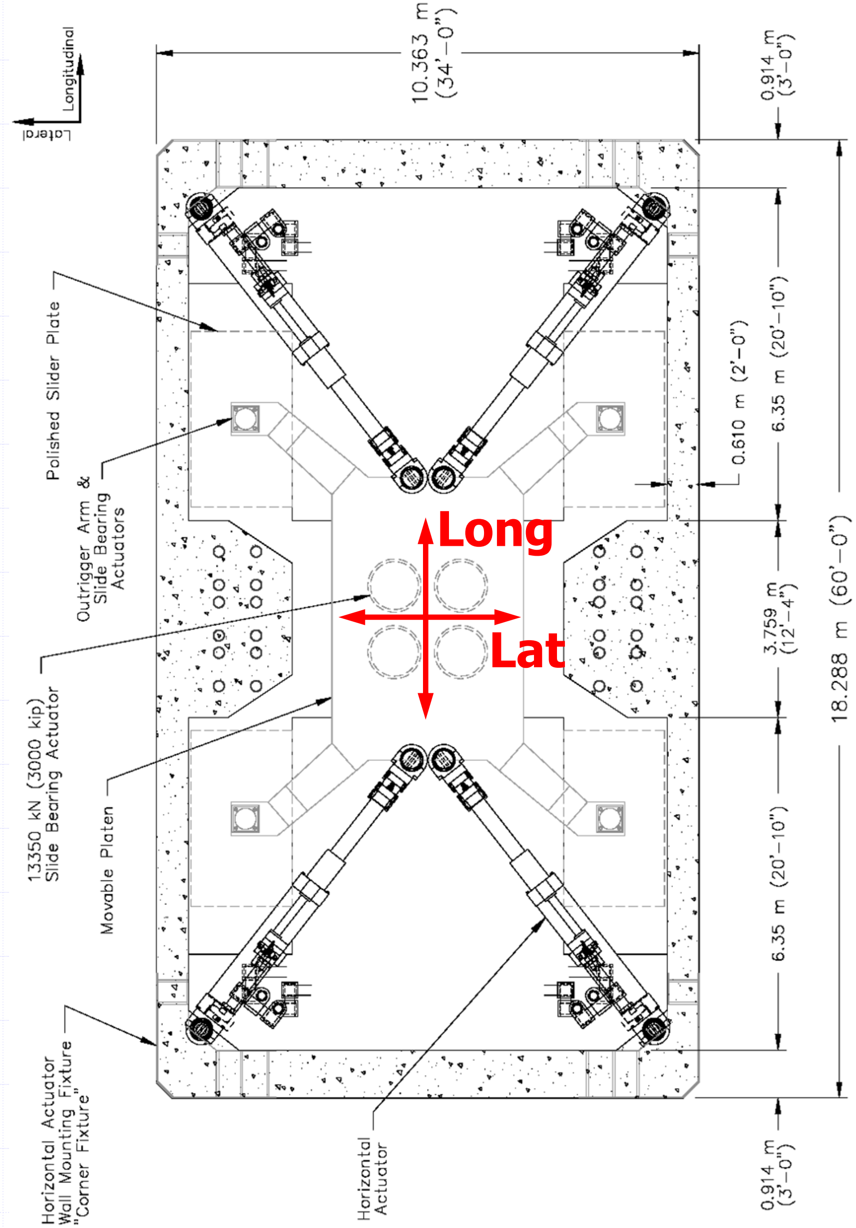
- Required significant adaptations to enable hybrid simulation while minimizing experimental errors
  - Receive and apply command displacement/forces
  - Return measured force feedback

Overview of SRMD @ UC San Diego

Specifications of SRMD testing facility

6 DOF platen

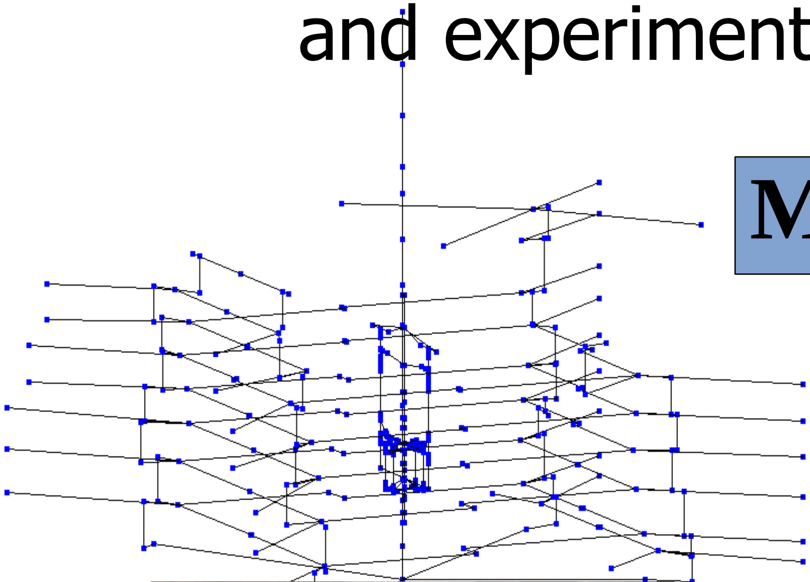
Component	Capacity	
Vertical Force	53,400 kN	12,000 kips
Longitudinal Force	8,900 kN	2,000 kips
Lateral Force	4,450 kN	1,000 kips
Vertical Displacement	± 0.127 m	± 5 in
Longitudinal Displacement	± 1.219 m	± 48 in
Lateral Displacement	± 0.610 m	± 24 in
Vertical Velocity	± 254 mm/s	± 10 in/s
Longitudinal Velocity	± 1,800 mm/s	± 70 in/s
Lateral Velocity	± 760mm/s	± 30 in/s
Relative Platen Rotation (Roll, Pitch, & Yaw)	± 2 degrees	
Maximum Specimen Height	1.524 m	60 in

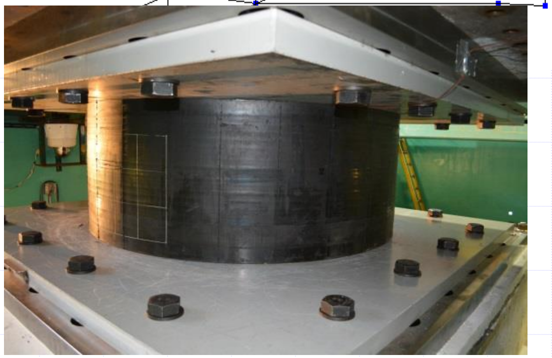


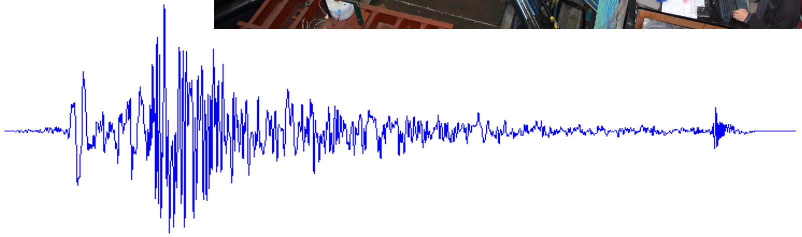
Implementation of Hybrid Simulation

- Requires **fast**, **accurate** and **reliable** communication between computer simulation and experimental setup to solve hybrid model

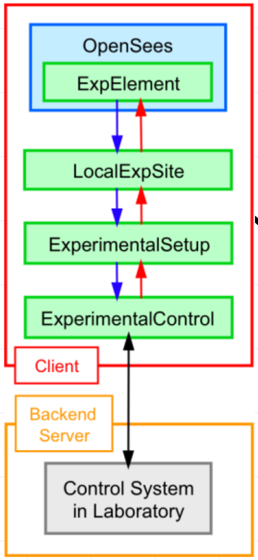
$$\mathbf{M}\cdot\ddot{\mathbf{u}} + \mathbf{C}\cdot\dot{\mathbf{u}} + \mathbf{P}_r\left(\mathbf{u},\dot{\mathbf{u}},\ddot{\mathbf{u}}\right) = \mathbf{P}(t)$$

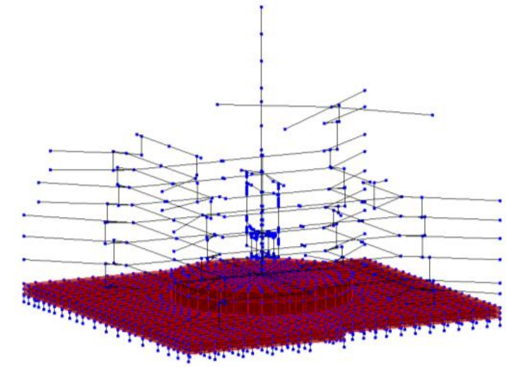






Communication Details





OpenSees Finite Element Model

OpenFresco Middleware

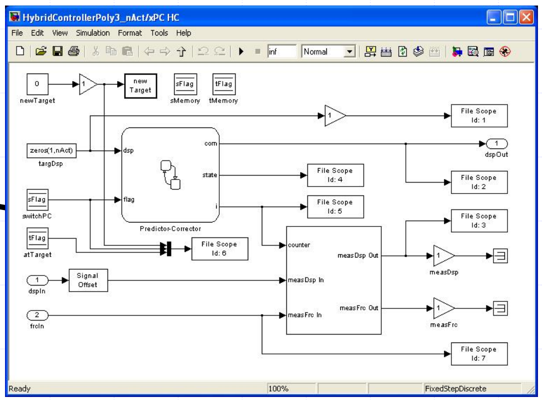
SCRAMNet+

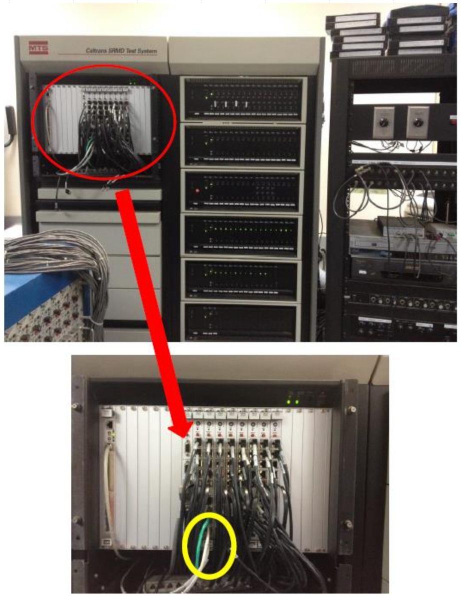
xPC-Target real-time Predictor-Corrector

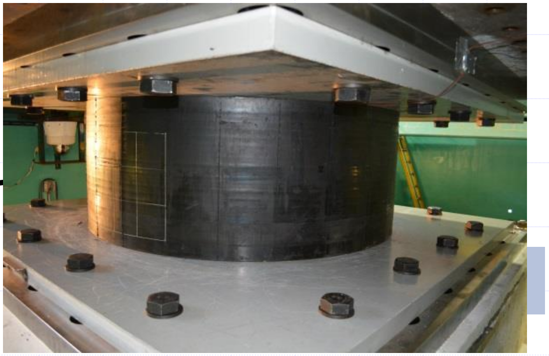
SCRAMNet+

MTS SRMD real-time Controller

Physical Specimen in Laboratory







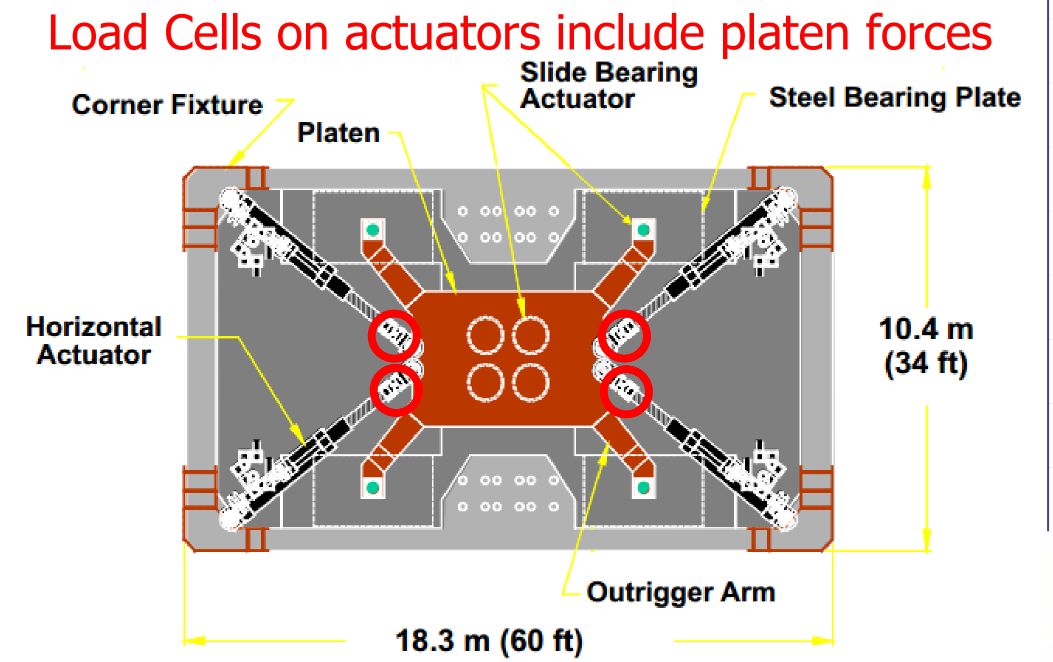
OpenSees and OpenFresco Details

- Hybrid models with several thousand DOF can be tested in real-time
  - First-time use of OpenSeesSP for HS
  - All integrators specialized for HS are now available in OpenSeesSP
  - Execution on high performance overclocked 8-core analysis machine
  - If system is linear command "algorithm Linear –factorOnce" can be used
- Added new command "partition $eleTag"
- Added new element EEBearing

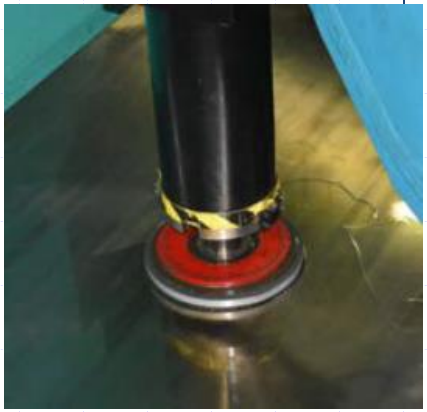
Time Delay Compensation Methods

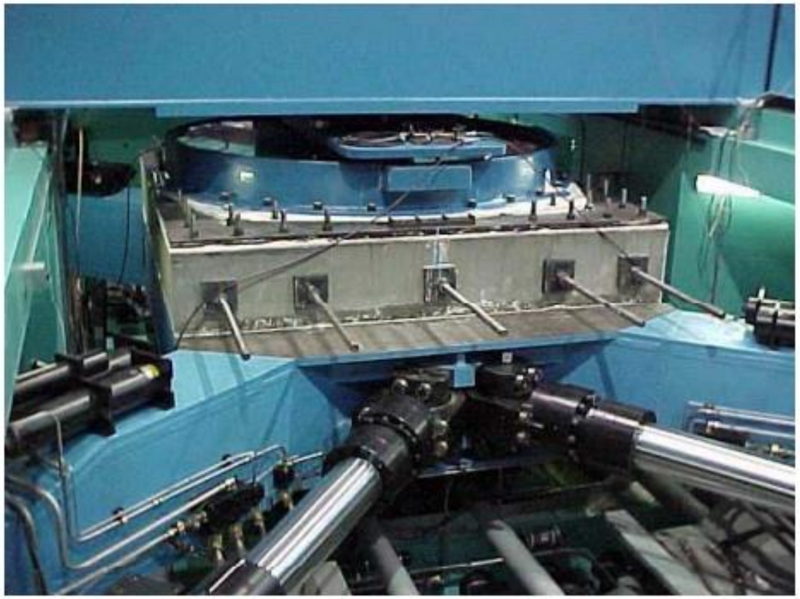
- SRMD has delay of 60 msec
- Feedforward Gain
  - used last time, limited benefit for displ. control, did not work for vertical force control
- Polynomial Extrapolation
  - used last time, works for constant delays only, limited in how much delay it can compensate for
- Inverse Models
  - does not work well, relies on accurate system ID
- Adaptive Time Series (ATS) method
  - developed at Lehigh by Y. Chae, based on least squares method, self-adapting to changes

Horizontal Force Measurements



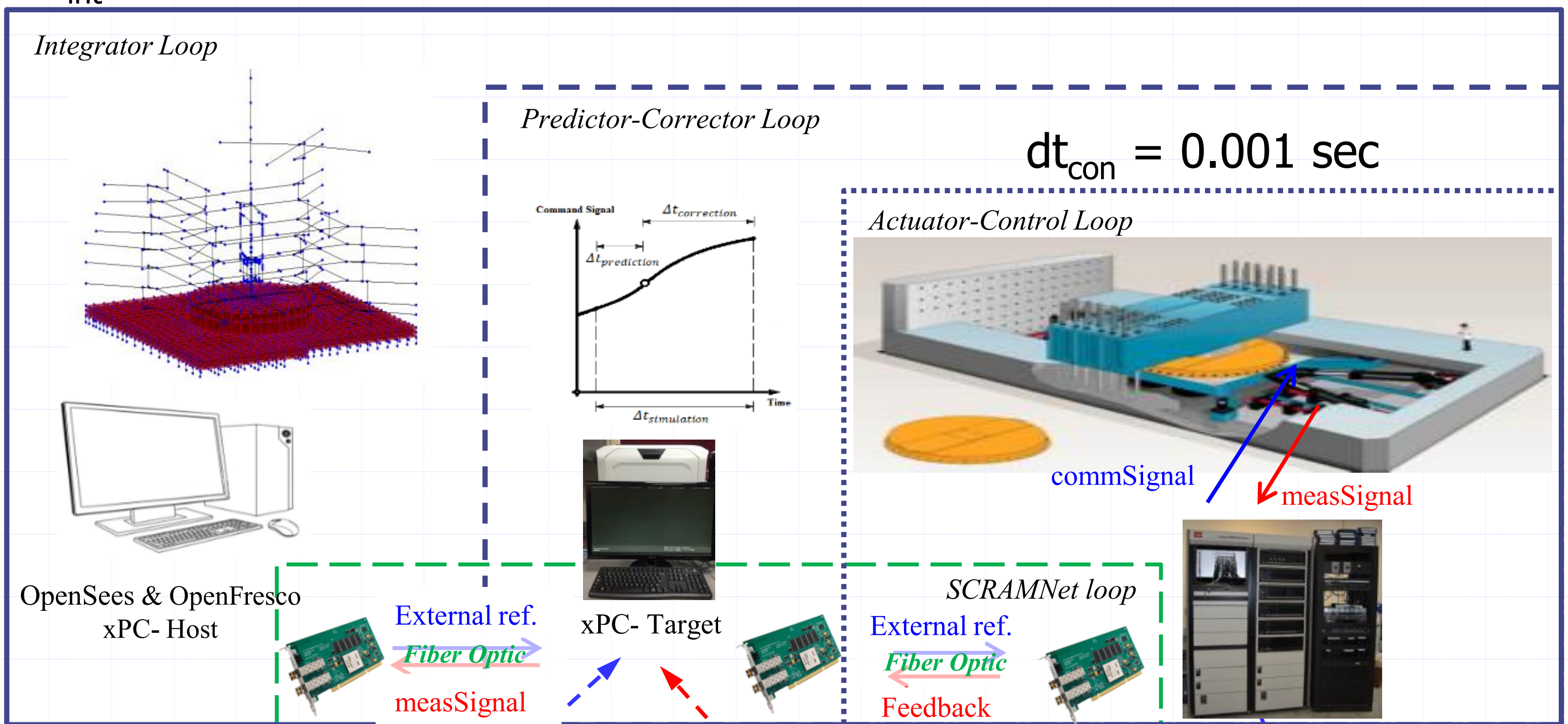
Plan View of Test System





Three-Loop Hardware Architecture

dt_{int} = 0.01 sec



ATS delay compensator

Inertia & friction compensation, filtering & noise reduction

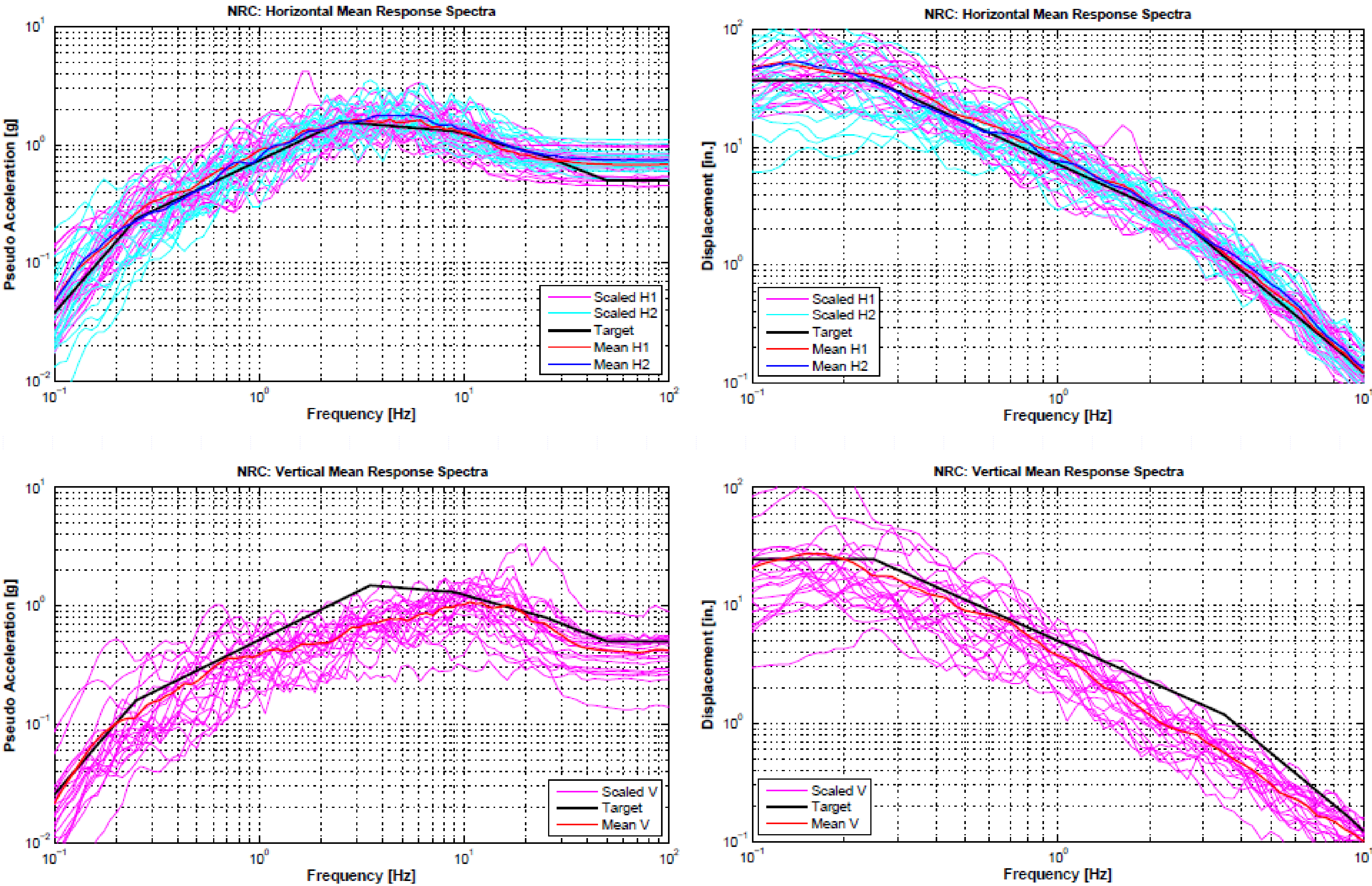
PID+F+Δp+ Notch ctrl.

Ground Motions

NRC Set: Motion Parameters

Record #	NGA #	Earthquake	Station	Mag	Dist (km)	Vs30 (m/s)	Scale Factor	NPTS	dt (s)	Duration (s)
1	68	San Fernando	LA - Hollywood Stor FF	6.6	22.8	316	3.7	2800	0.01	28
2	93	San Fernando	Whittier Narrows Dam	6.6	39.5	299	7.5	7997	0.005	39.985
3	186	Imperial Valley-06	Niland Fire Station	6.5	36.9	207	7.8	7997	0.005	39.985
4	285	Irpinia, Italy-01	Bagnoli Irpinio	6.9	8.2	1000	4.0	12712	0.0029	36.8648
5	718	Superstition Hills-01	Wildlife Liquef. Array	6.2	17.6	207	5.2	5961	0.005	29.805
6	730	Spitak, Armenia	Gukasian	6.8	36.2	275	4.4	1990	0.01	19.9
7	748	Loma Prieta	Belmont - Envirotech	6.9	44.1	628	6.9	7989	0.005	39.945
8	855	Landers	Fort Irwin	7.3	63.0	345	6.8	2000	0.02	40
9	862	Landers	Indio - Coachella Canal	7.3	54.3	345	6.5	3000	0.02	60
10	882	Landers	North Palm Springs	7.3	26.8	345	4.8	14000	0.005	70
11	1165	Kocaeli, Turkey	Izmit	7.5	7.2	811	3.3	6000	0.005	30
12	1487	Chi-Chi, Taiwan	TCU047	7.6	35.0	520	2.1	18000	0.005	90
13	1491	Chi-Chi, Taiwan	TCU051	7.6	7.7	273	3.0	18000	0.005	90
14	1602	Duzce, Turkey	Bolu	7.1	12.0	326	1.3	5590	0.01	55.9
15	1605	Duzce, Turkey	Duzce	7.1	6.6	276	1.4	5177	0.005	25.885
16	1611	Duzce, Turkey	Lamont 1058	7.1	0.2	425	7.7	3901	0.01	39.01
17	1762	Hector Mine	Amboy	7.1	43.1	271	3.5	3000	0.02	60
18	2113	Denali, Alaska	TAPS Pump Station #09	7.9	54.8	383	8.0	32895	0.005	164.475
19	2744	Chi-Chi, Taiwan-04	CHY088	6.2	48.4	273	7.4	12800	0.005	64
20	3264	Chi-Chi, Taiwan-06	CHY024	6.3	31.1	428	5.0	13204	0.005	66.02

NRC Set: Response Spectra



NRC RG1.60: Spectral Matching

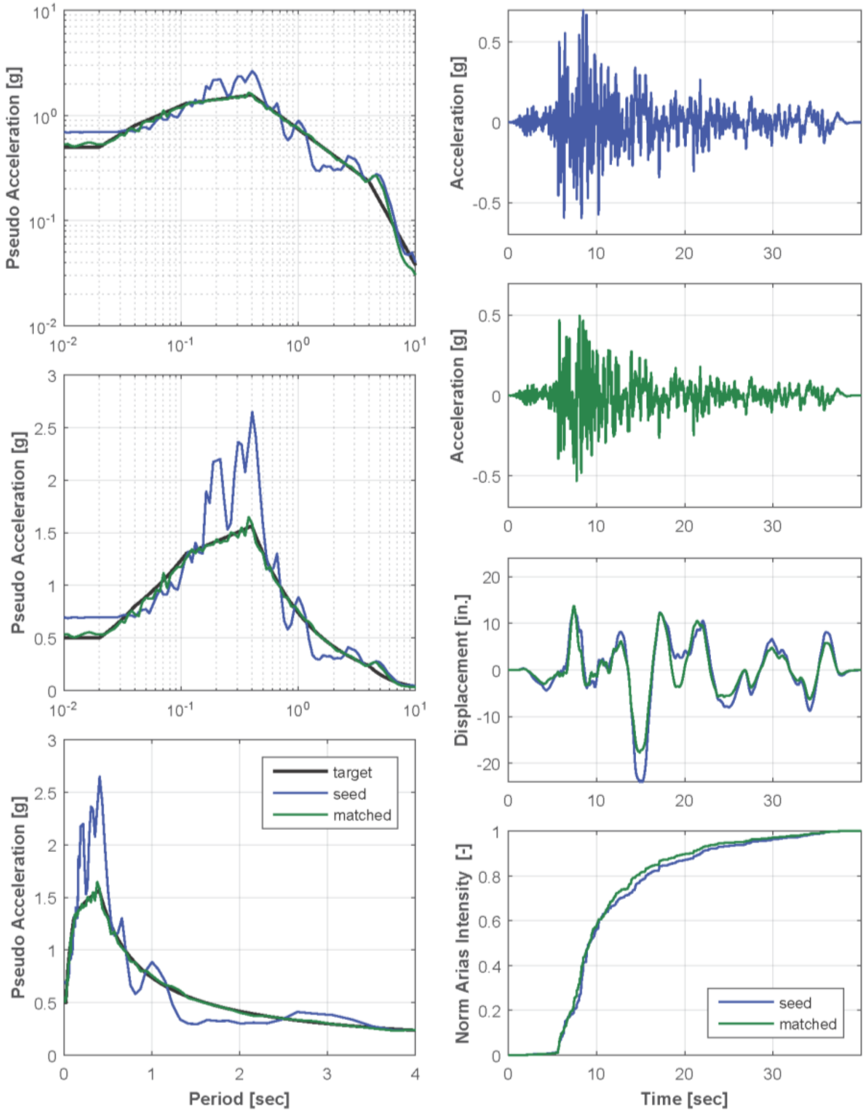


Figure NRC-REC03-A: Spectral Matching and Time Series, NRC RG1.60
Ground Motion: REC03
Component: 1

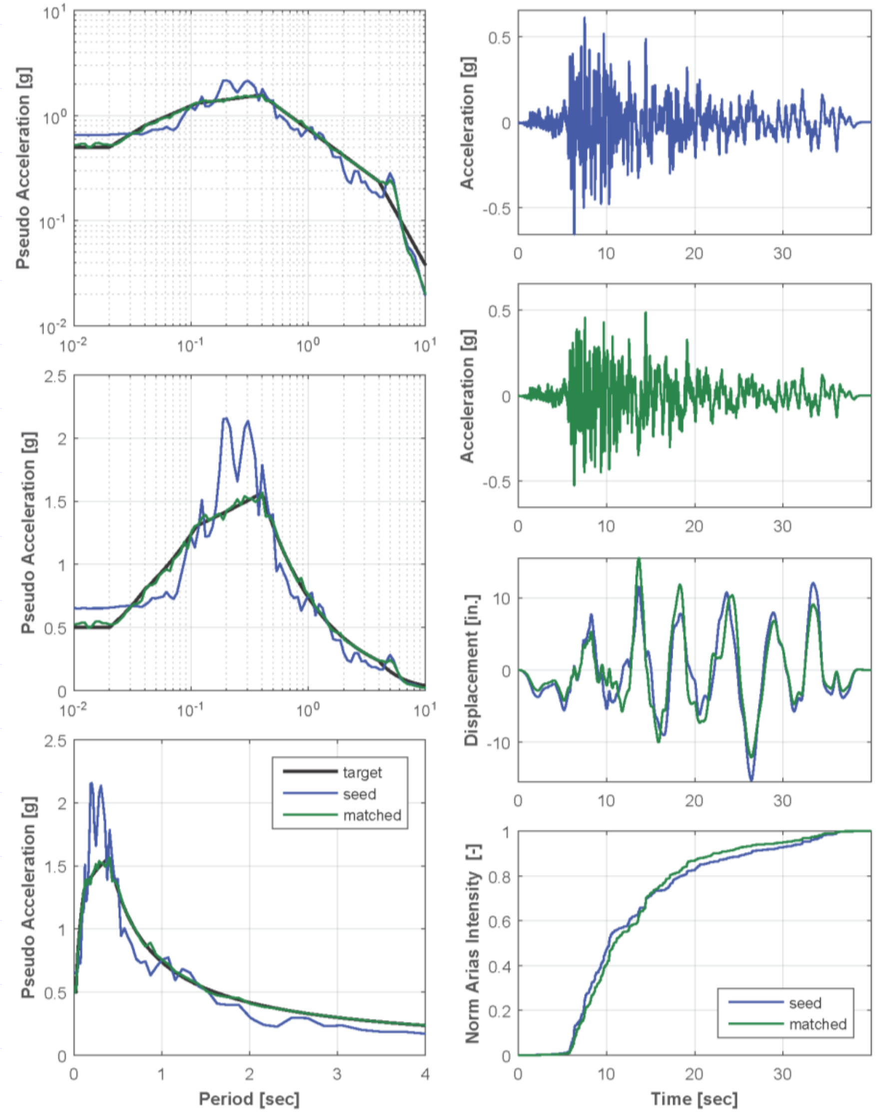
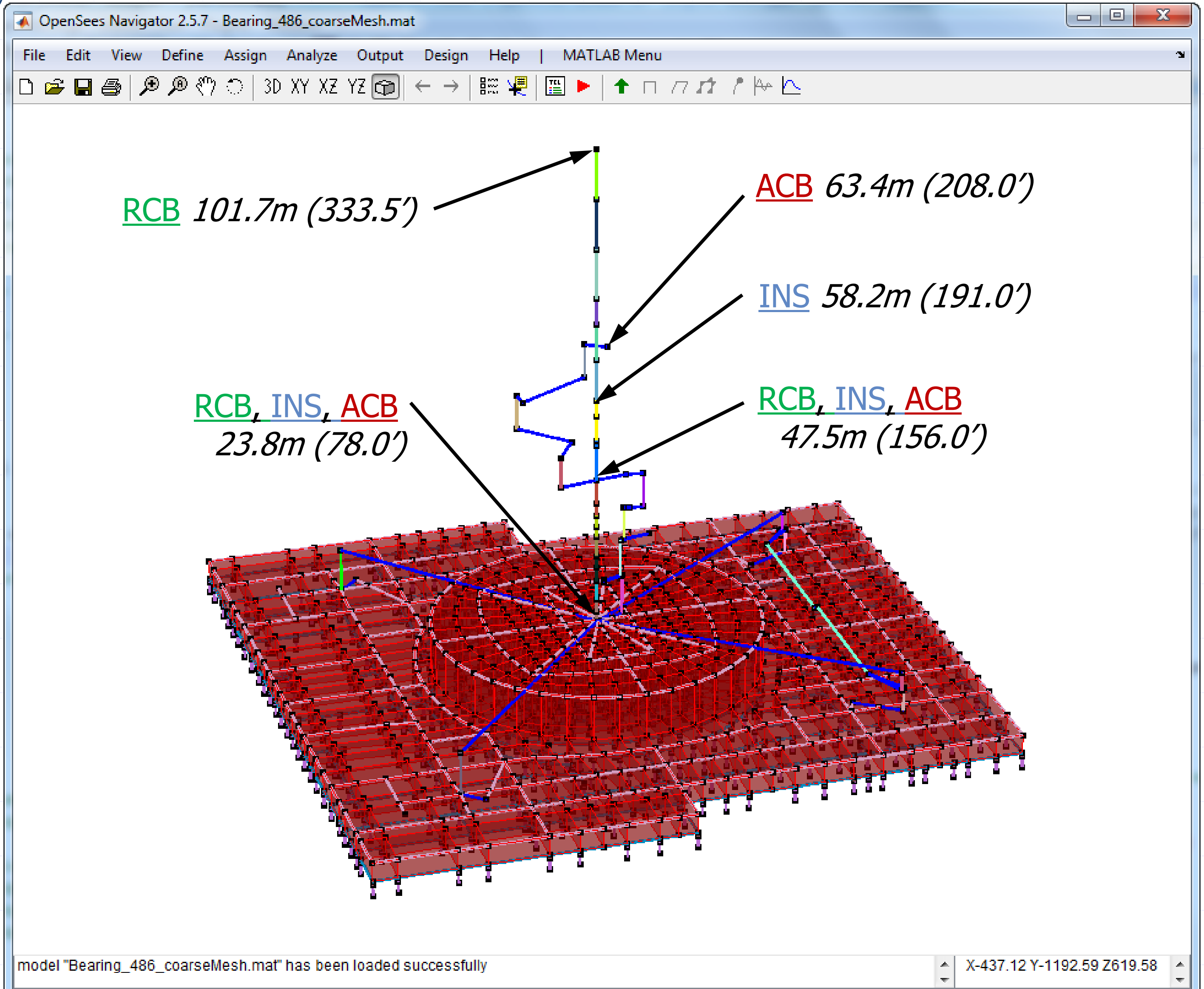


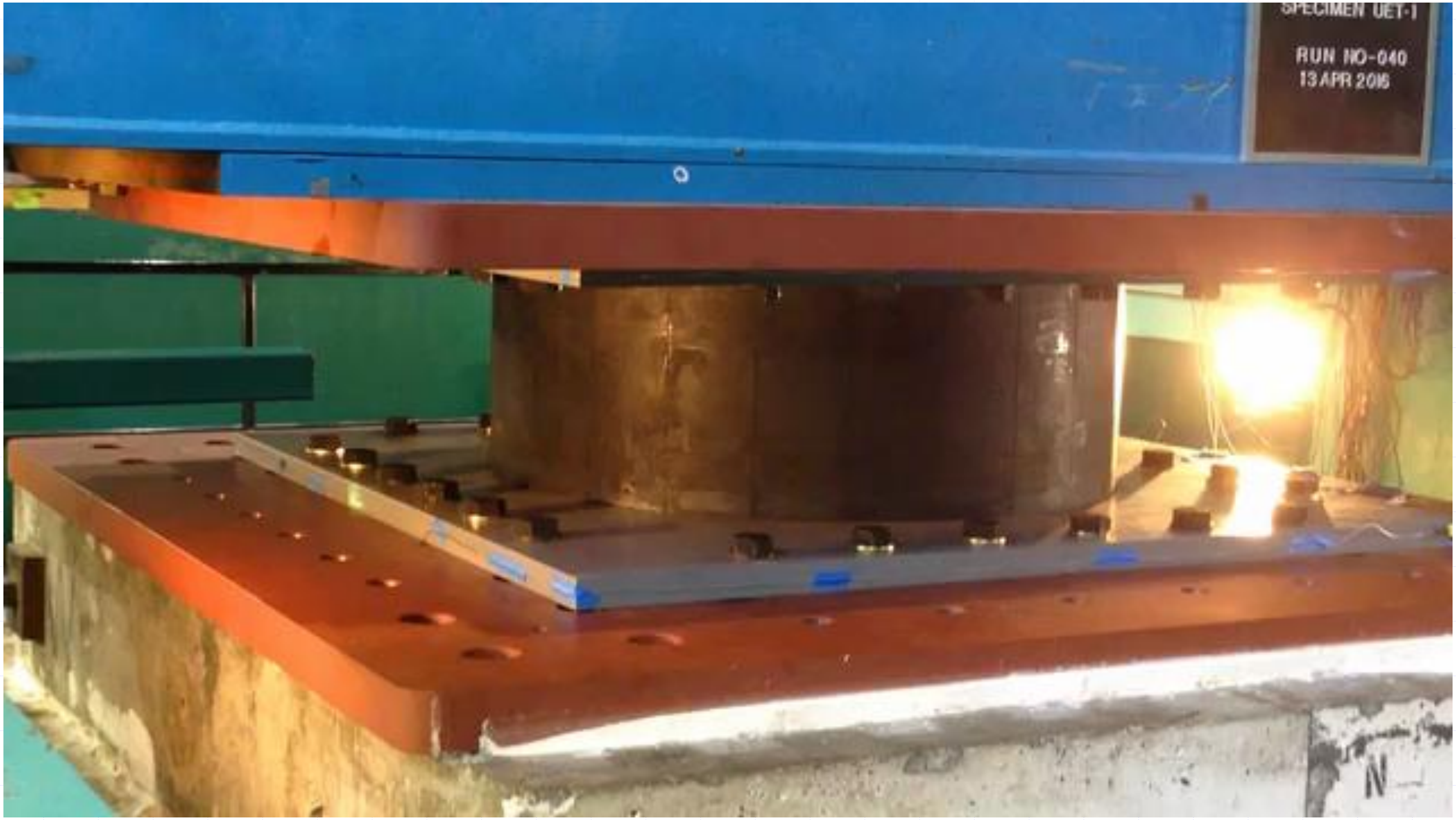
Figure NRC-REC03-B: Spectral Matching and Time Series, NRC RG1.60
Ground Motion: REC03
Component: 2

Hybrid Simulation Test Results

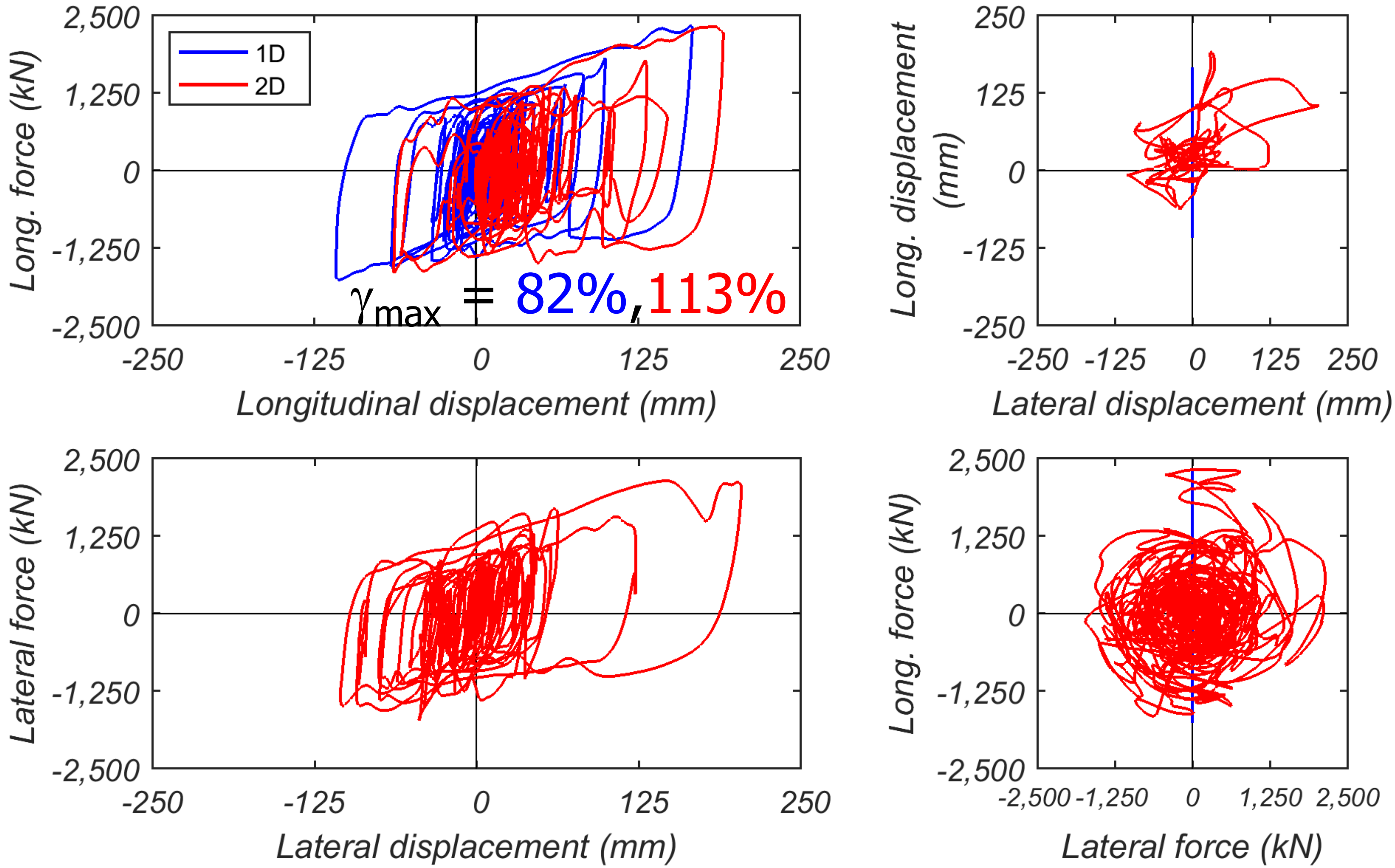
Result output locations



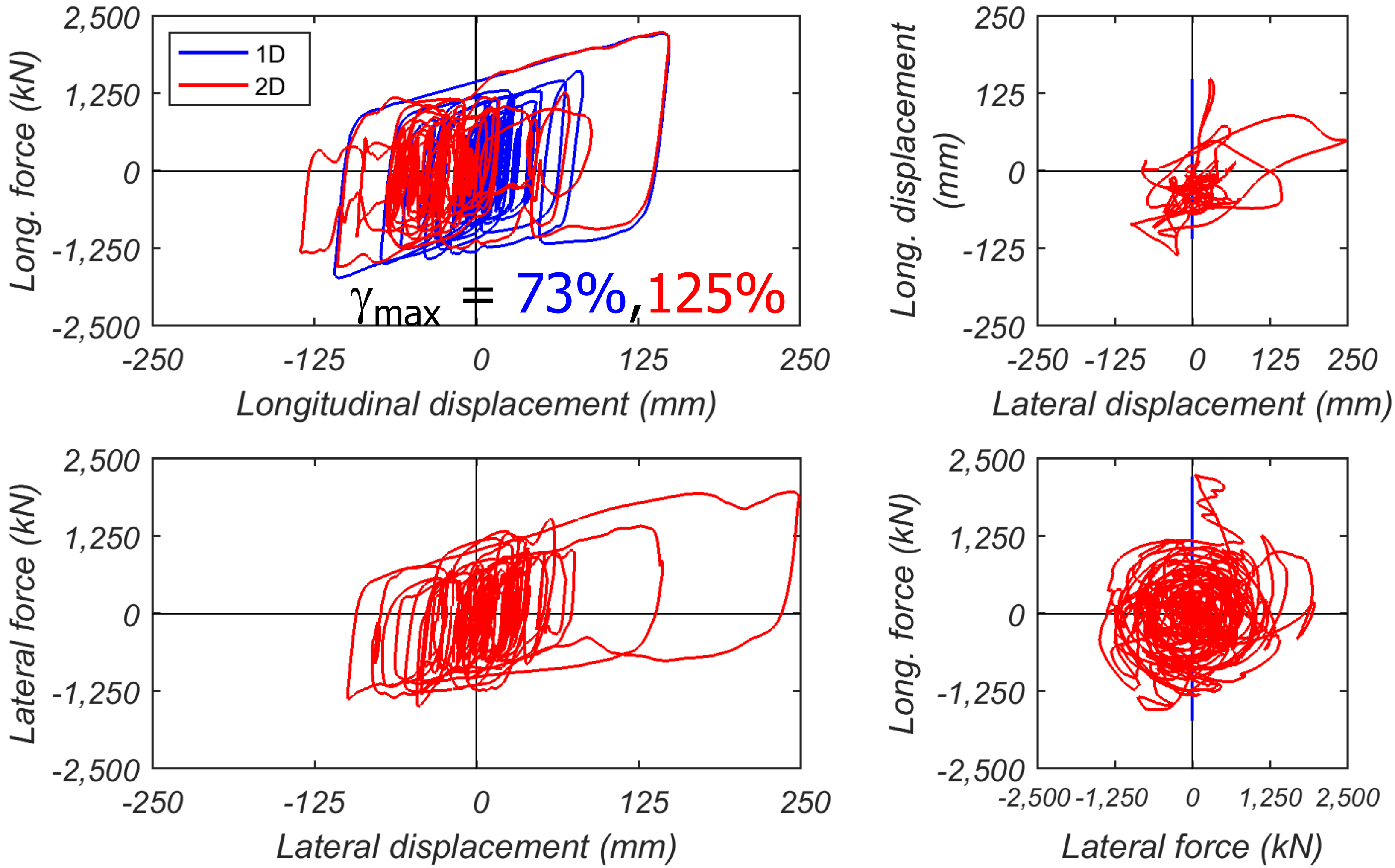
2D Hybrid Simulation (LPRB)



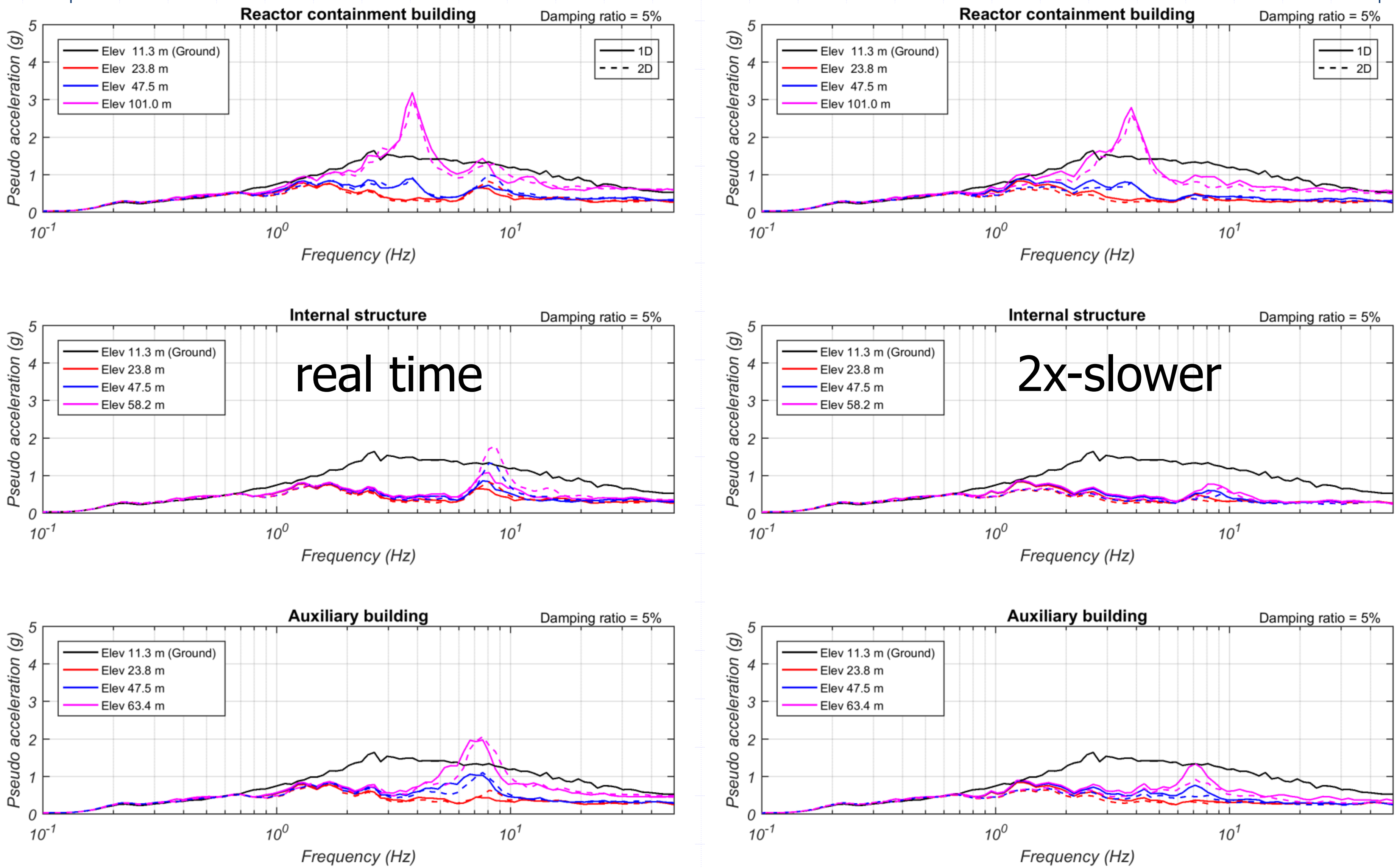
1D vs. 2D real time (LPRB)



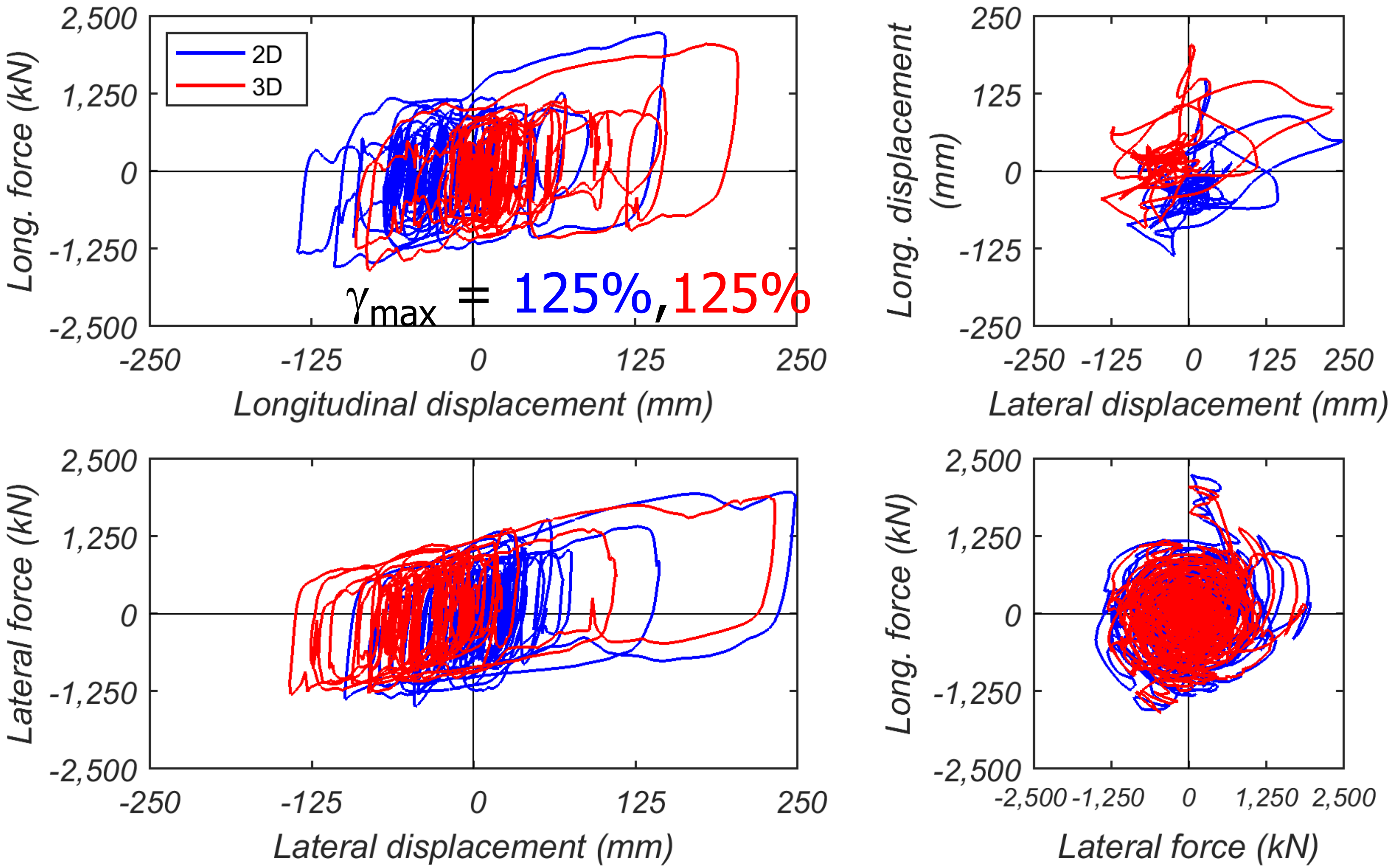
1D vs. 2D 2x-slower (LPRB)



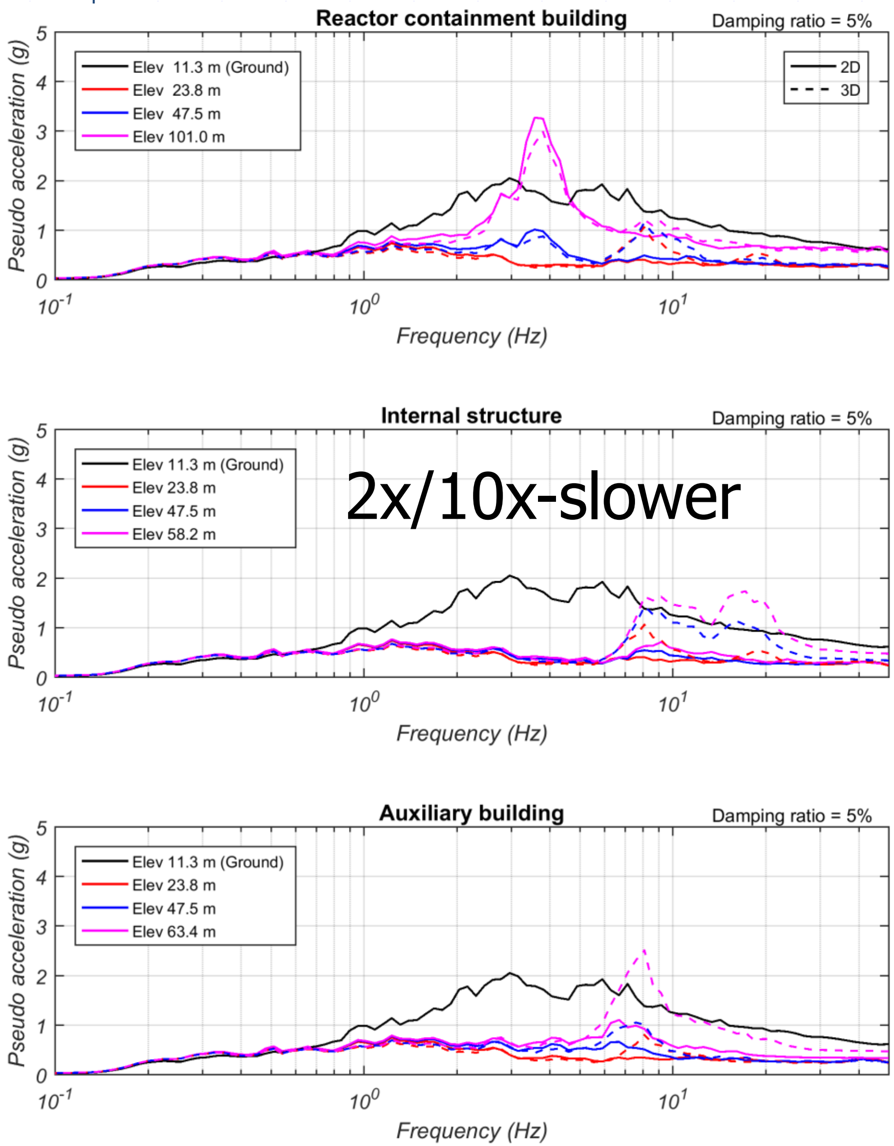
1D vs. 2D (LPRB)


Reactor containment building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 101.0 m
1D
2D
Internal structure
Elev 58.2 m
real time
2x-slower
Auxiliary building
Elev 63.4 m
Pseudo acceleration (g)
Frequency (Hz)

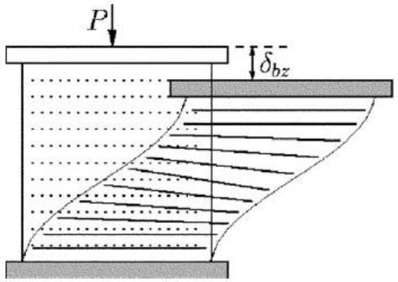
2D 2x-slower vs. 3D 10x-slower (LPRB)



2D vs. 3D (LPRB)



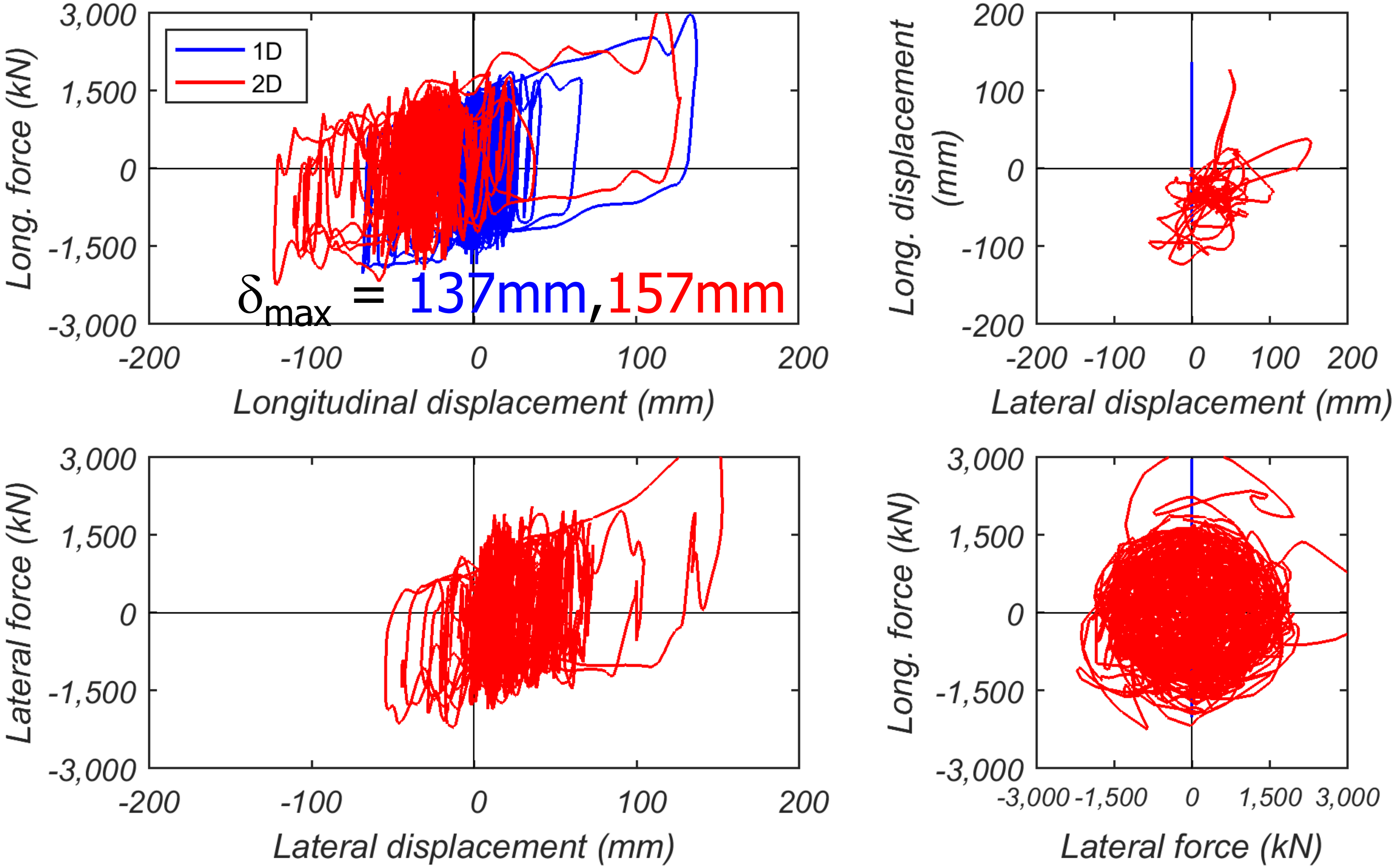
2x/10x-slower



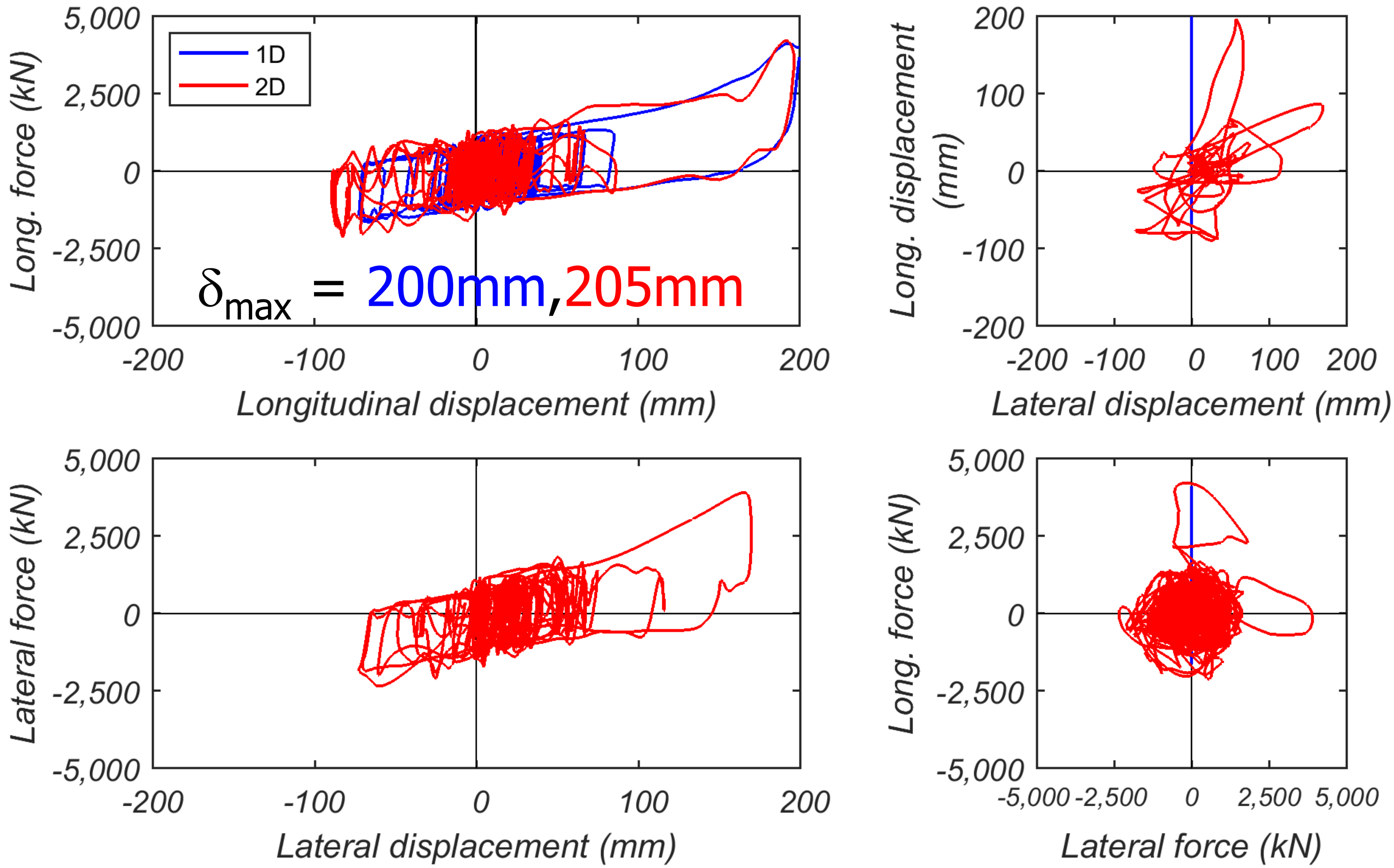
Conclusions wrt LPRB isolator

- Need analytical model that can capture v-h force interaction correctly
- Need analytical model that can capture v-h displacement coupling
- Need analytical isolator model that can account for the reduction in the lead yield strength with increasing bearing temperature

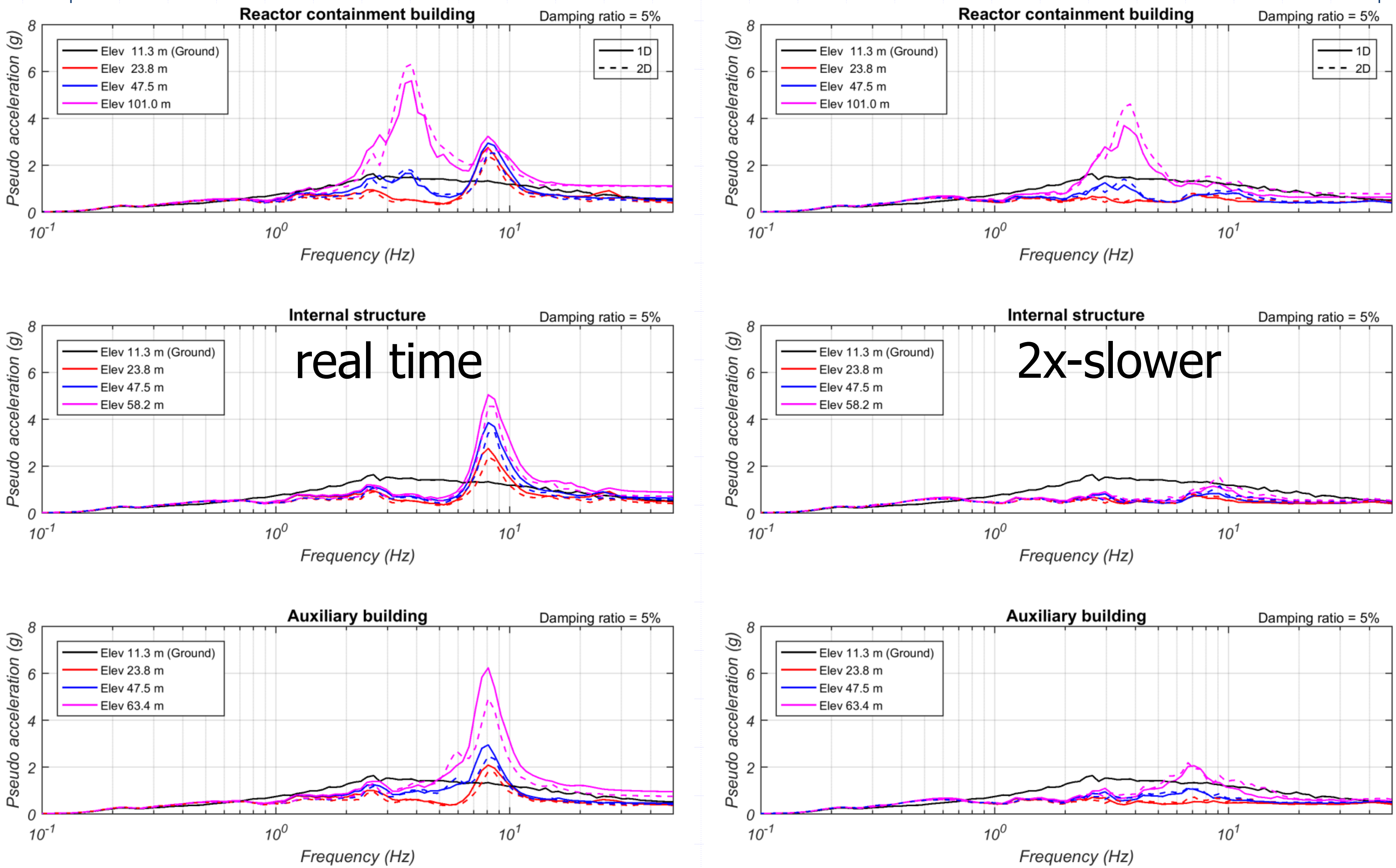
1D vs. 2D real time (EQSB)



1D vs. 2D 2x-slower (EQSB)



1D vs. 2D (EQSB)



Reactor containment building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 101.0 m
1D
2D
Pseudo acceleration (g)
Frequency (Hz)
Reactor containment building
Damping ratio = 5%
Elev 11.3 m (Ground)
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1D
2D
Internal structure
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
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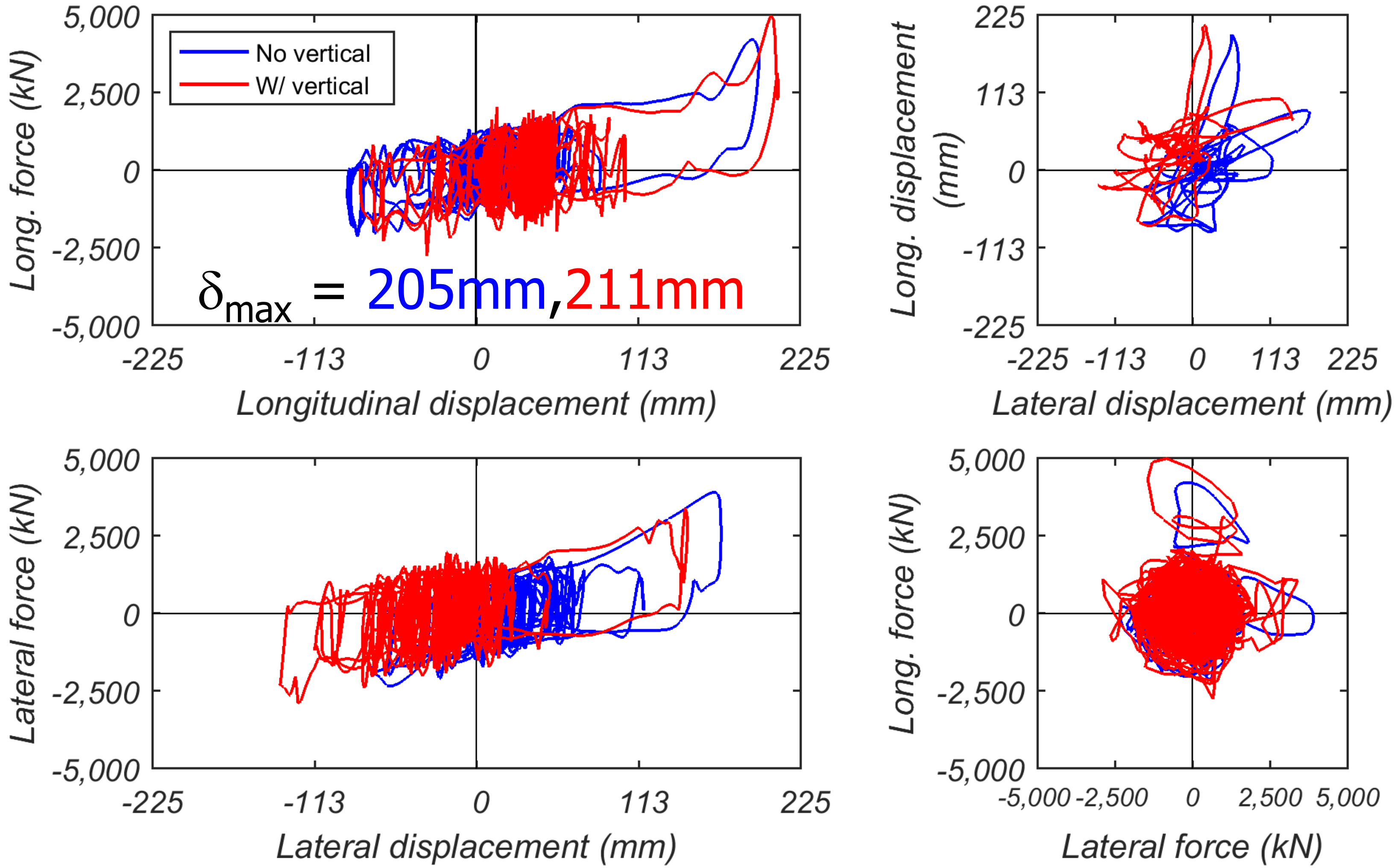
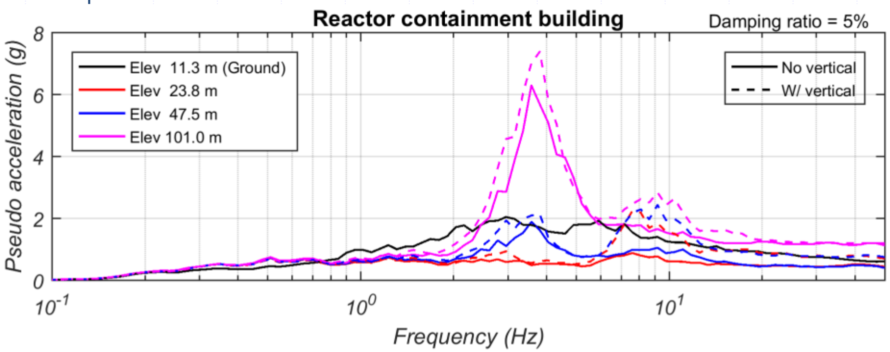
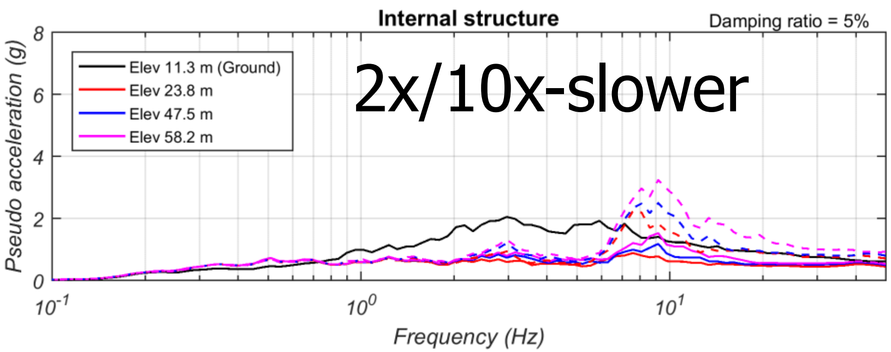
real time
Internal structure
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 58.2 m
2x-slower
Auxiliary building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 63.4 m
Auxiliary building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 63.4 m

2D 2x-slower vs. 3D 10x-slower (EQSB)

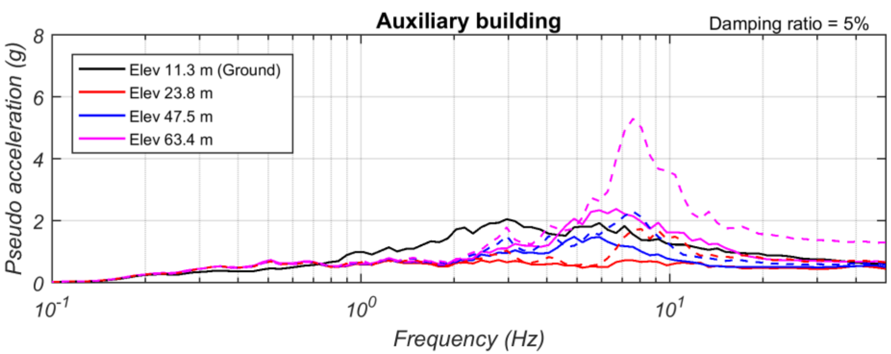


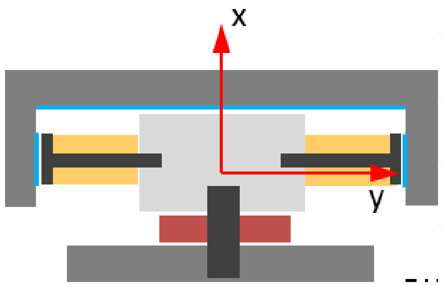
2D vs. 3D (EQSB)

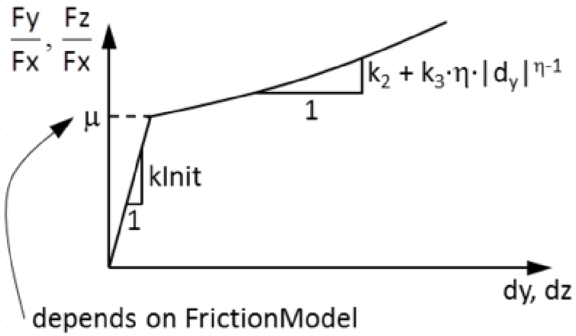




2x/10x-slower



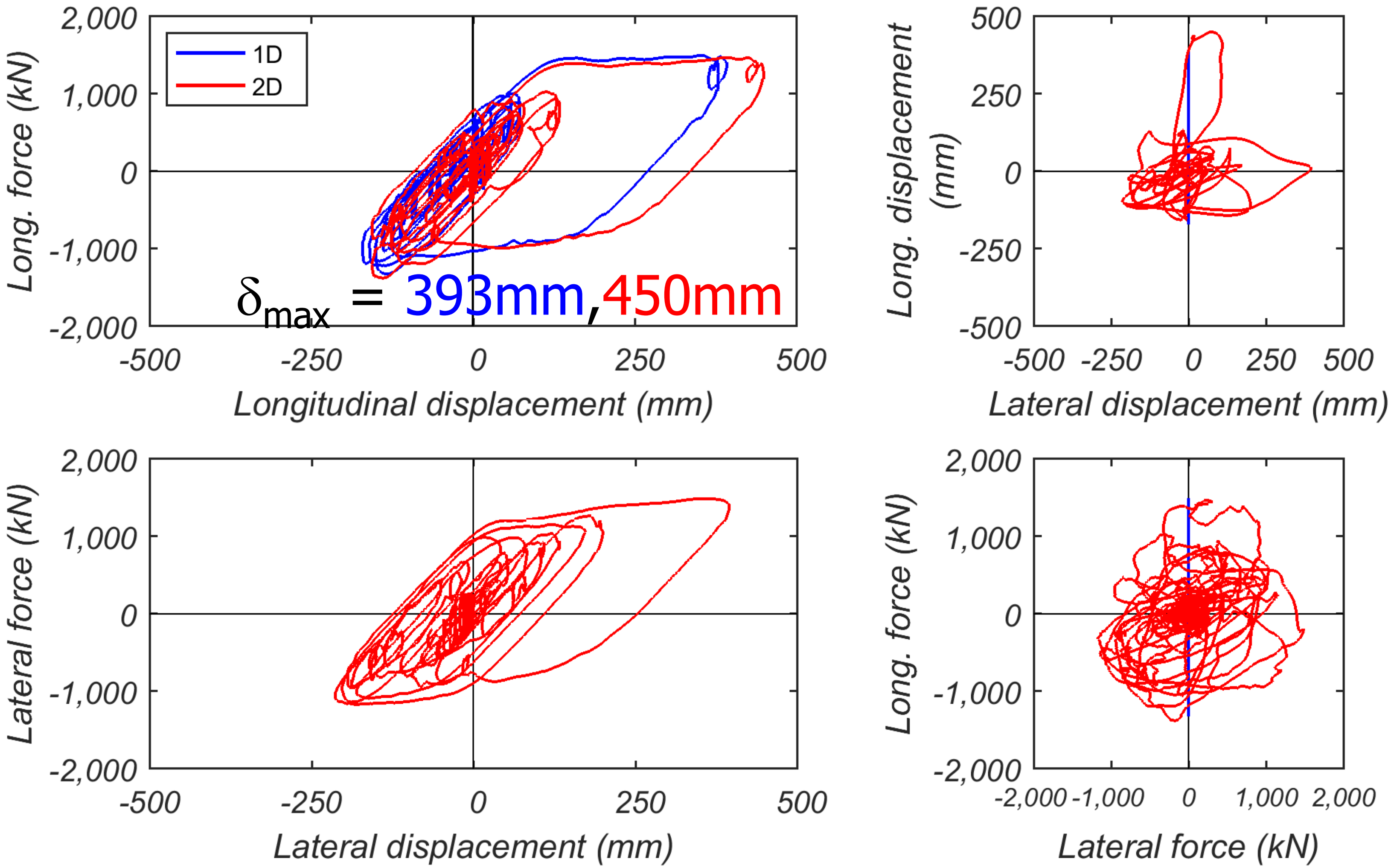




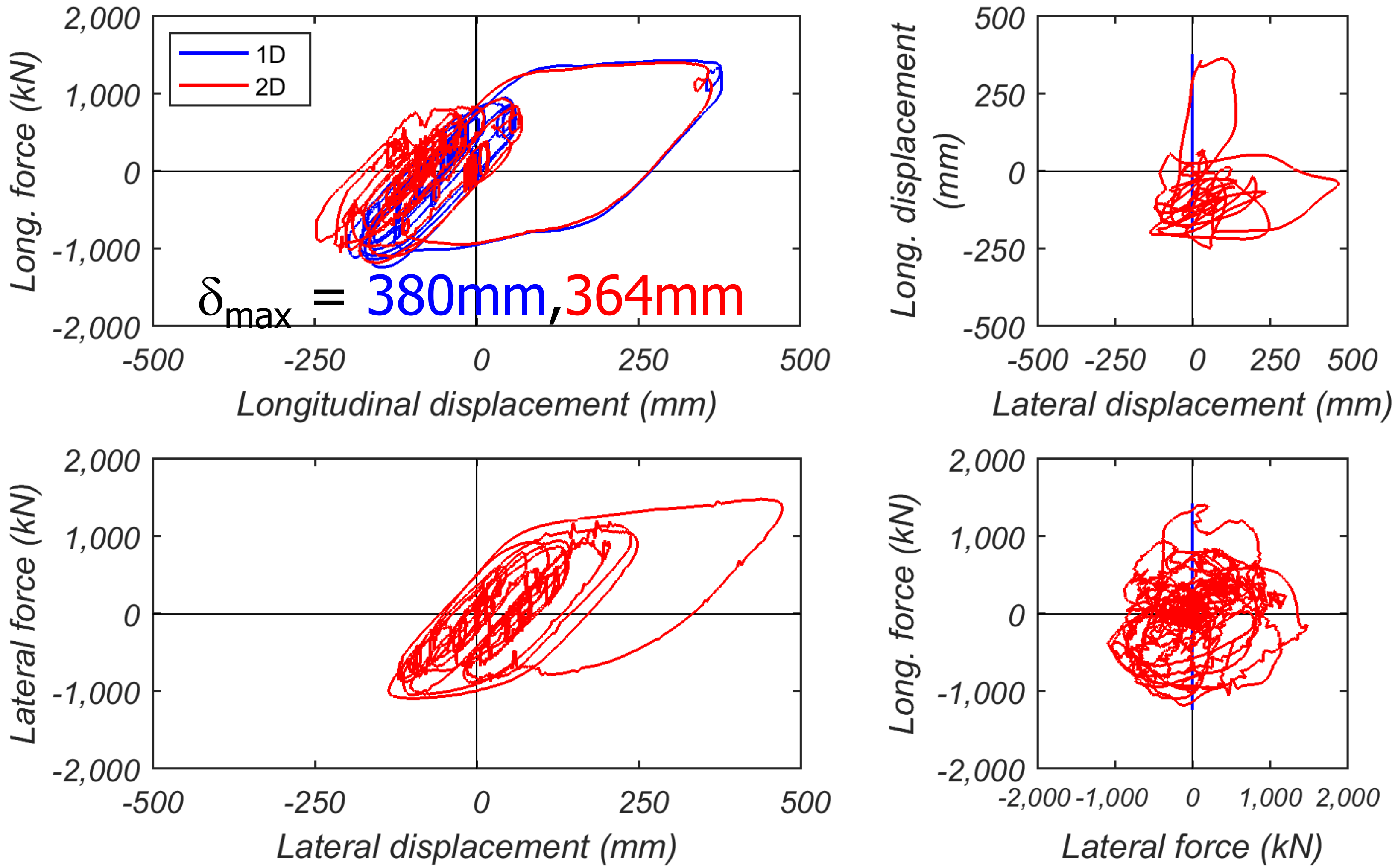
Conclusions wrt EQSB isolator

- Need analytical model that can capture v-h force interaction correctly
- Need analytical isolator model that can capture adhesion (break-away) effects on COF
- Need analytical isolator model that can capture temperature effects on COF

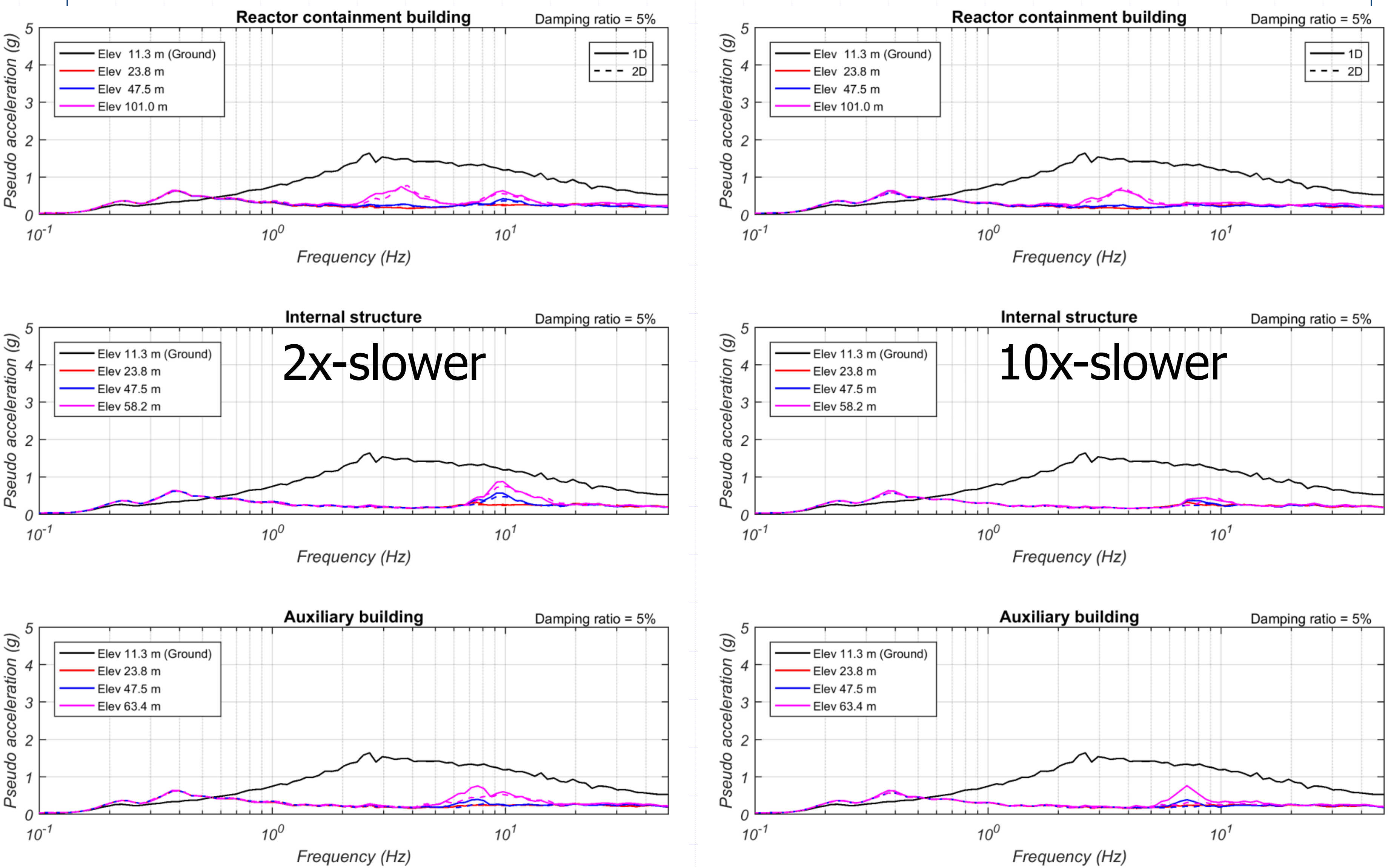
1D vs. 2D 2x-slower (TFPB)



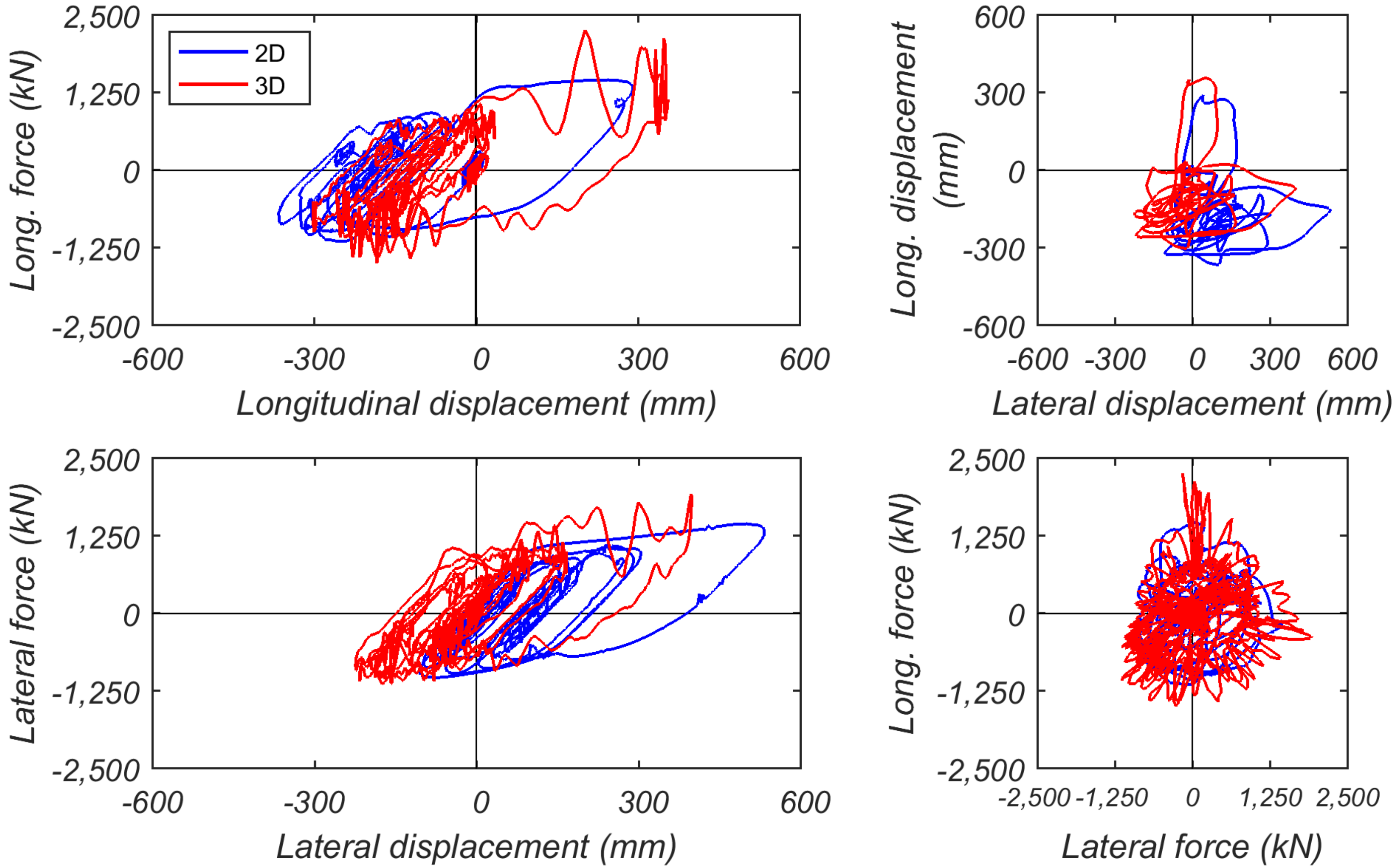
1D vs. 2D 10x-slower (TFPB)



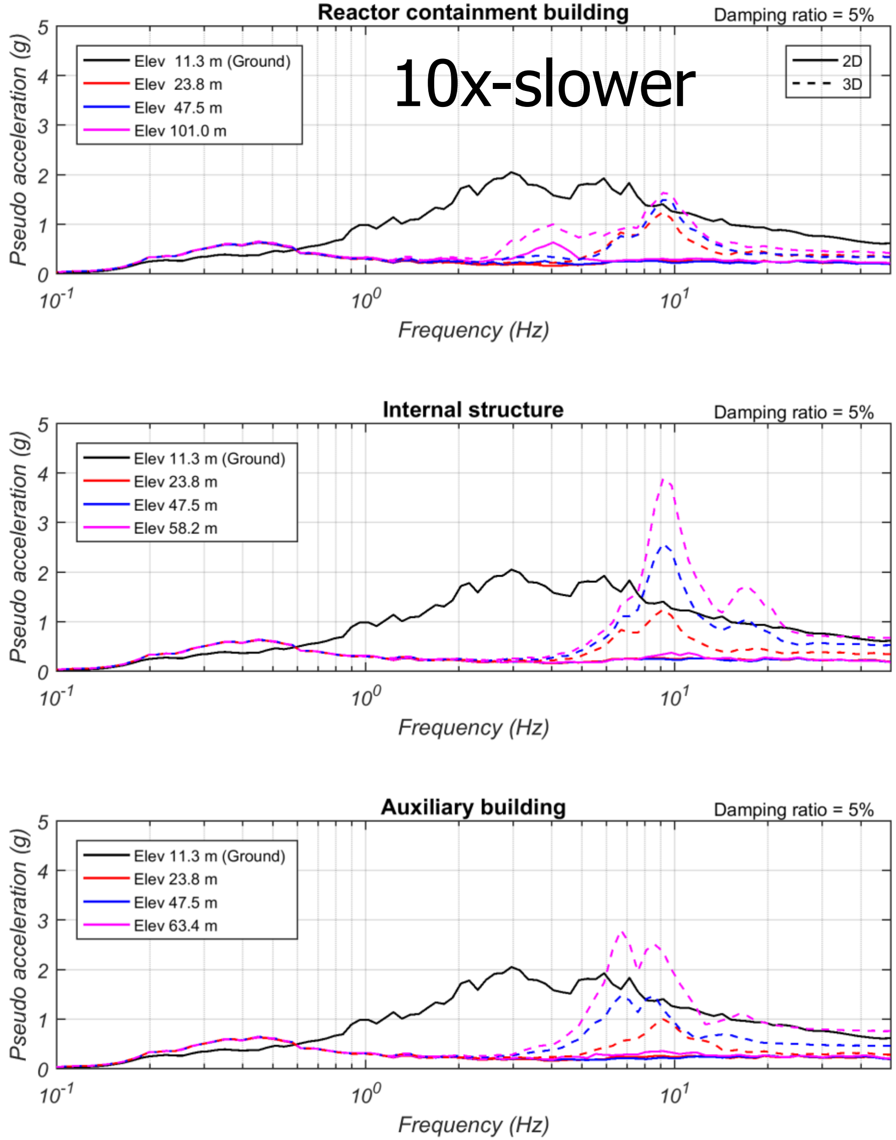
1D vs. 2D (TFPB)

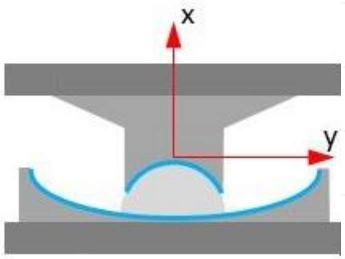

Reactor containment building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 101.0 m
1D
2D
Internal structure
Elev 58.2 m
2x-slower
10x-slower
Auxiliary building
Elev 63.4 m
Pseudo acceleration (g)
Frequency (Hz)

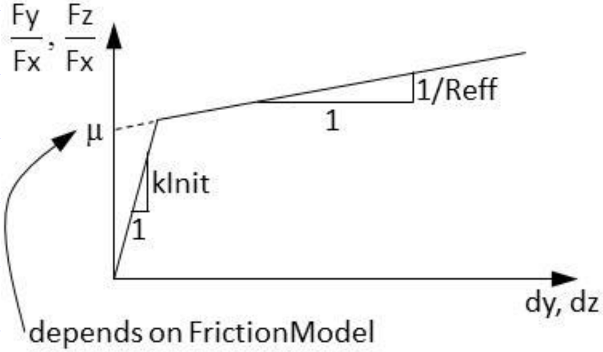
2D vs. 3D 10x-slower (TFPB)



2D vs. 3D (TFPB)


Reactor containment building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 101.0 m
10x-slower
2D
3D
Pseudo acceleration (g)
Frequency (Hz)
Internal structure
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 58.2 m
Pseudo acceleration (g)
Frequency (Hz)
Auxiliary building
Damping ratio = 5%
Elev 11.3 m (Ground)
Elev 23.8 m
Elev 47.5 m
Elev 63.4 m
Pseudo acceleration (g)
Frequency (Hz)


x
y


Fy/Fx, Fz/Fx
μ
1/Reff
1
kInit
1
dy, dz
depends on FrictionModel

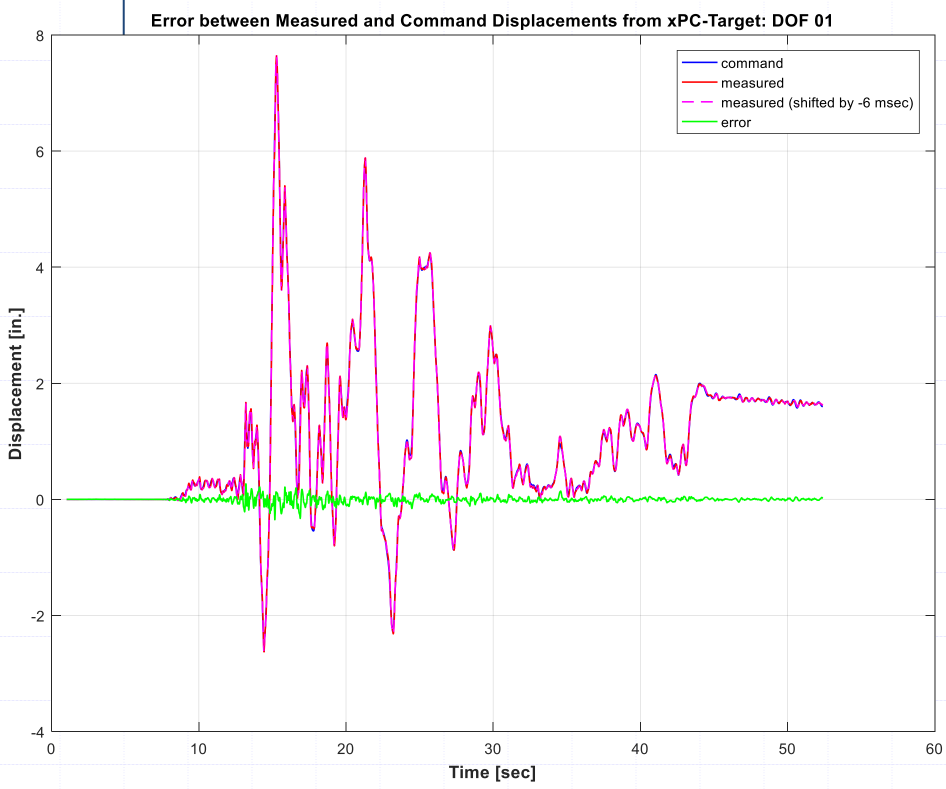
Conclusions wrt TFPB isolator

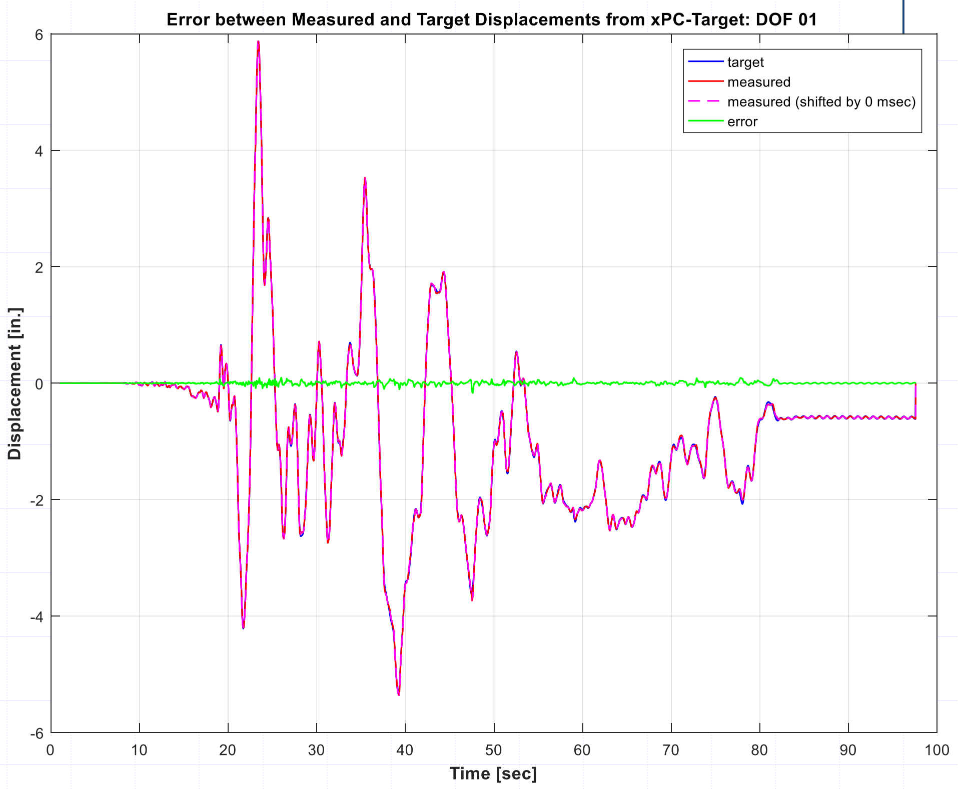
- Need analytical model that can capture v-h force interaction correctly
- Need analytical model that can capture v-h displacement coupling
- Need analytical isolator model that can capture adhesion (break-away) effects on COF
- Need analytical isolator model that can capture temperature effects on COF

Average Delay Assessment (Long)

real time -> 6 msec

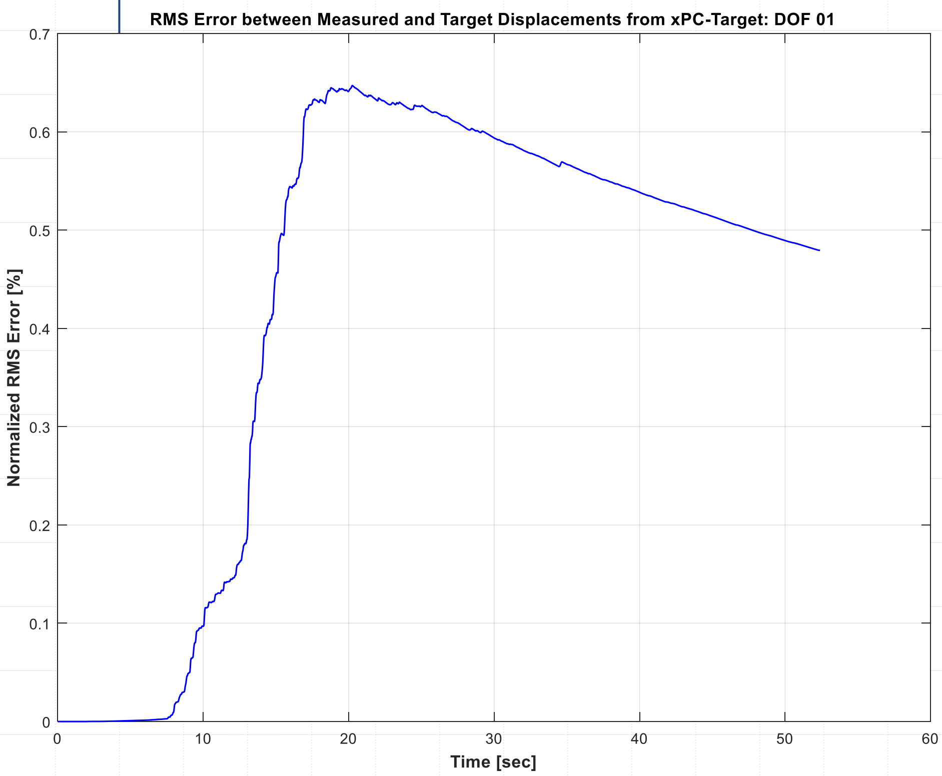
2x slower -> 0 msec



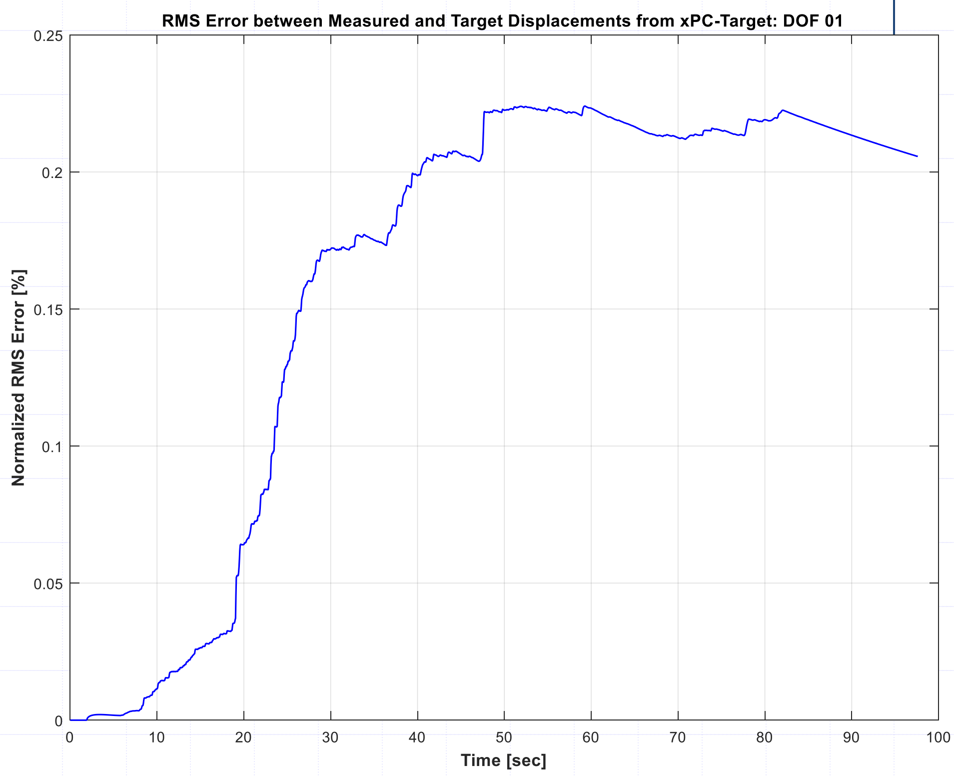


Normalized RMS Error (Long)

real time



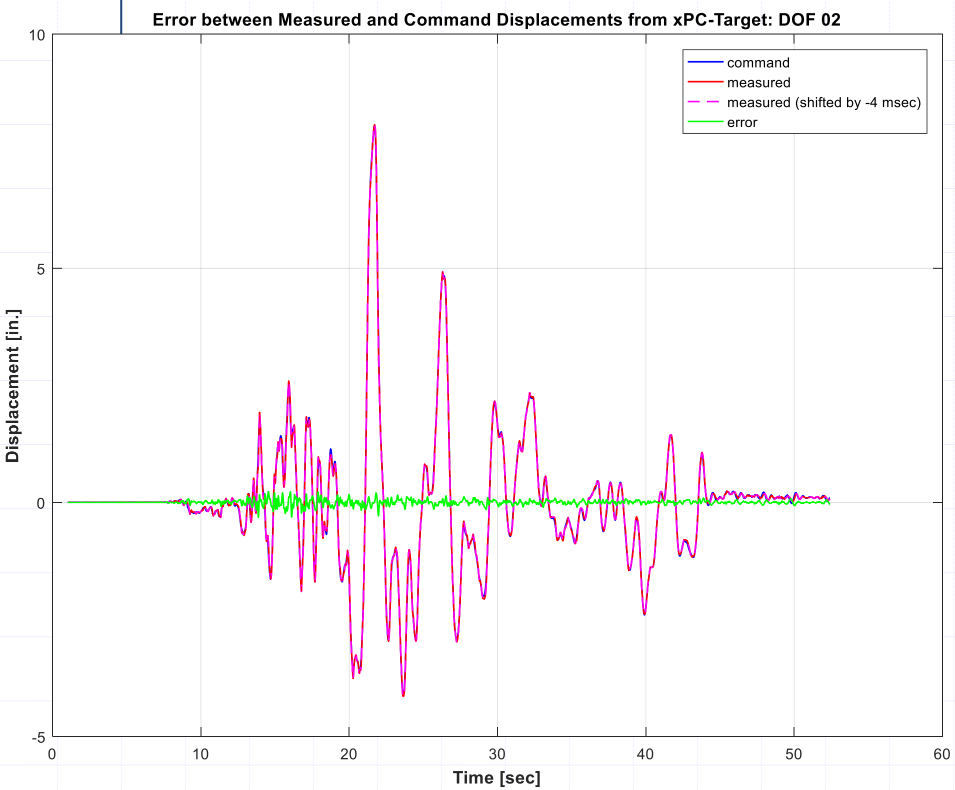
2x slower

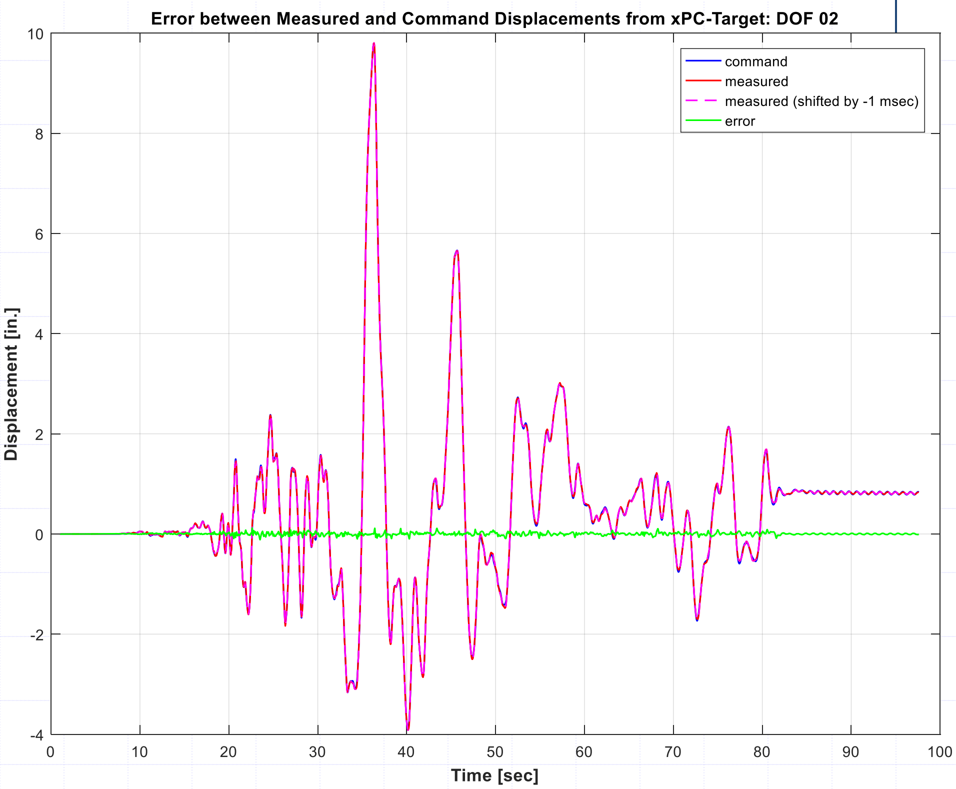


Average Delay Assessment (Lat)

real time -> 4 msec

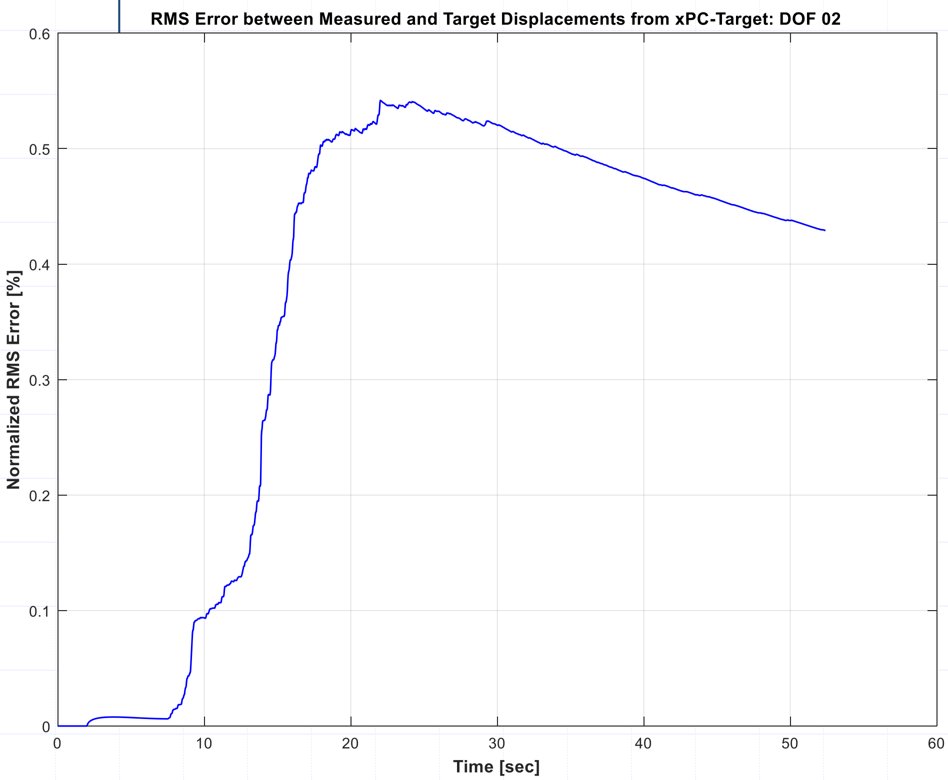
2x slower -> 1 msec



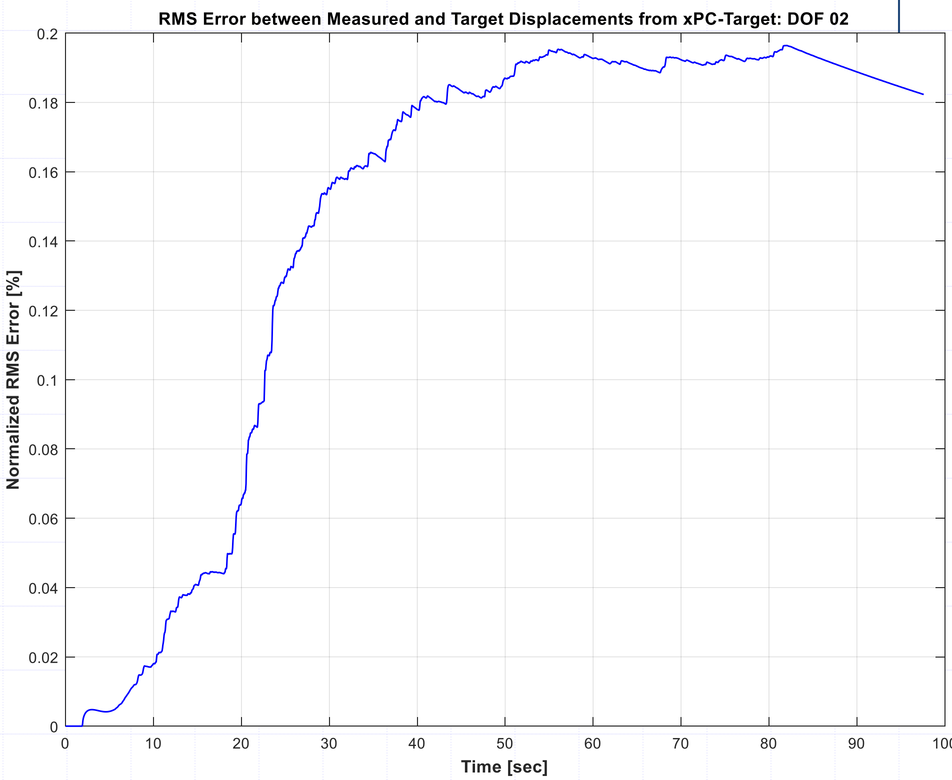


Normalized RMS Error (Lat)

real time

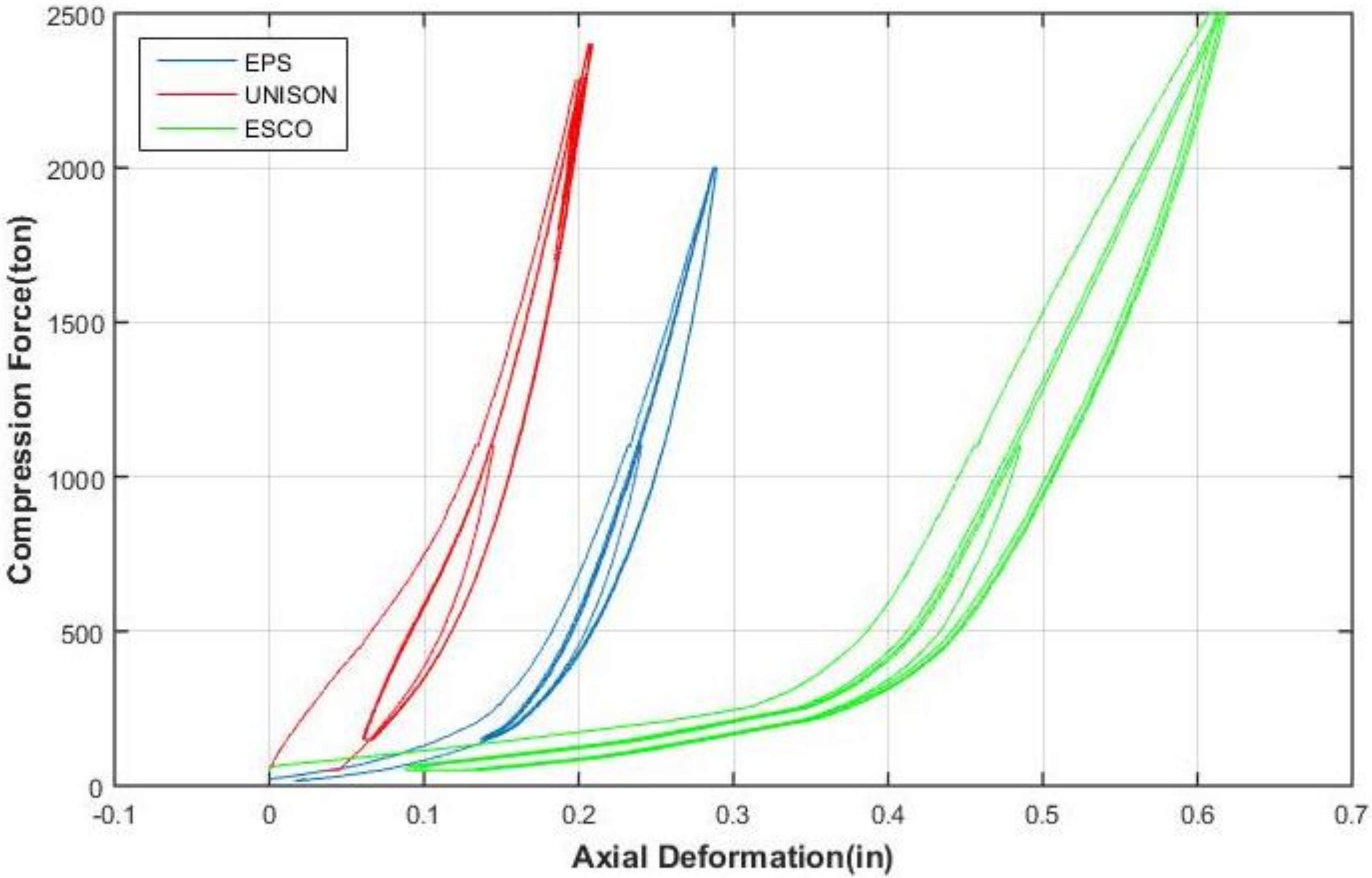


2x slower



Characterization Tests

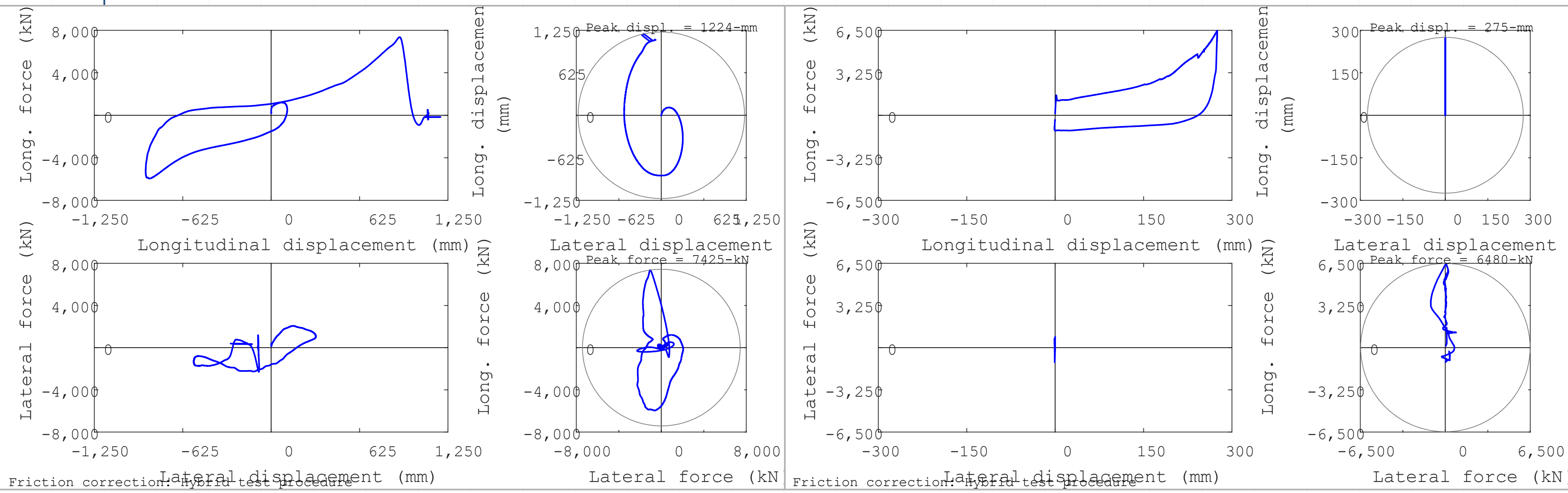
Axial Response under Compression



Failure Tests (LPRB and EQSB)

LPRB by Unison eTech

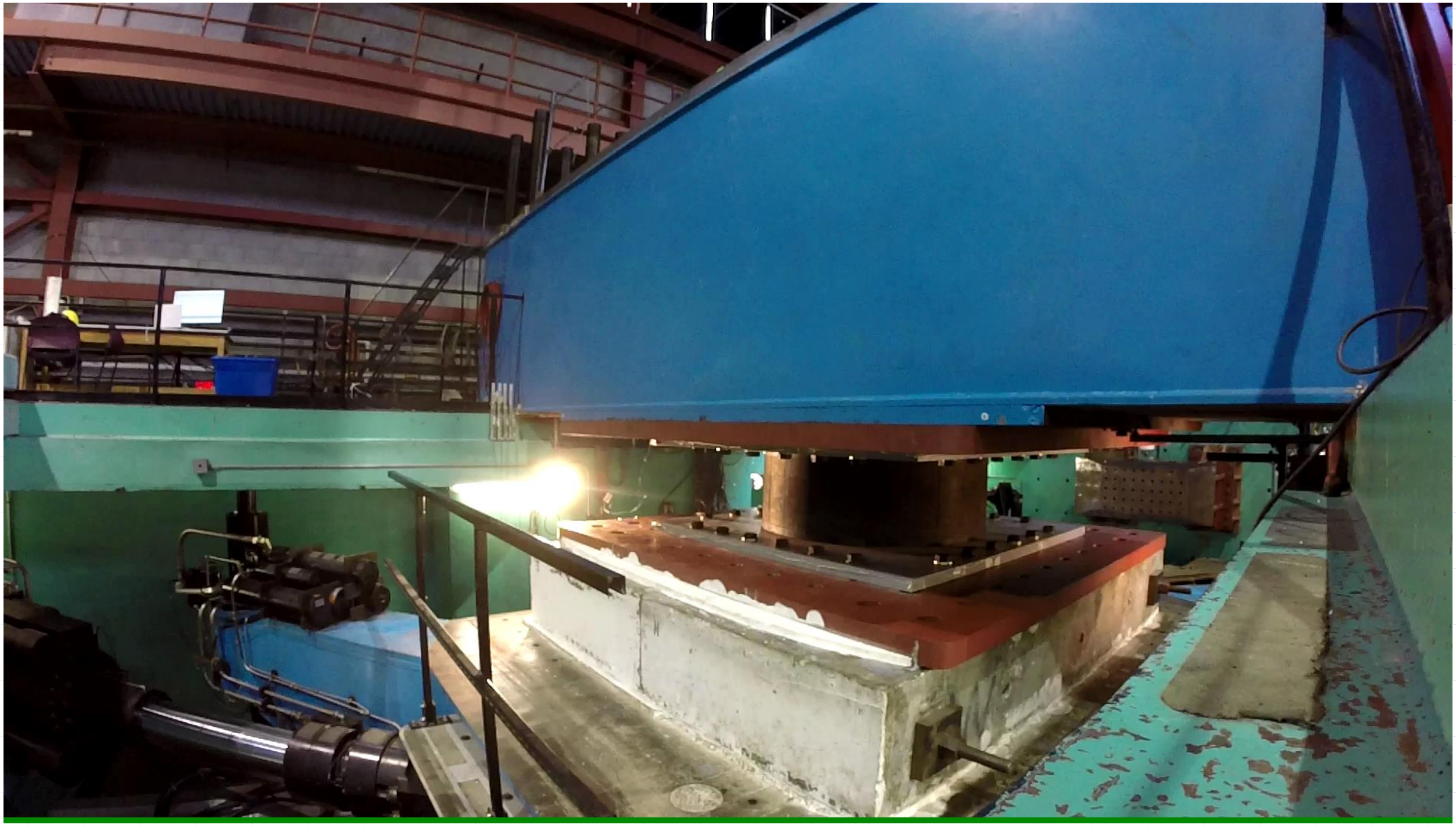
EQSB by ESCO RTS



Rupture due to delamination

Bolt slip at peak load

Failure Test (LPRB)

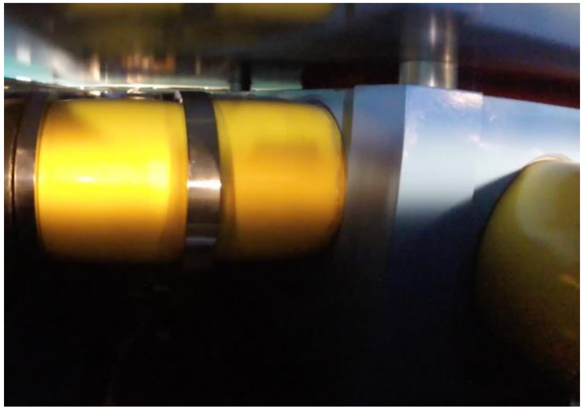


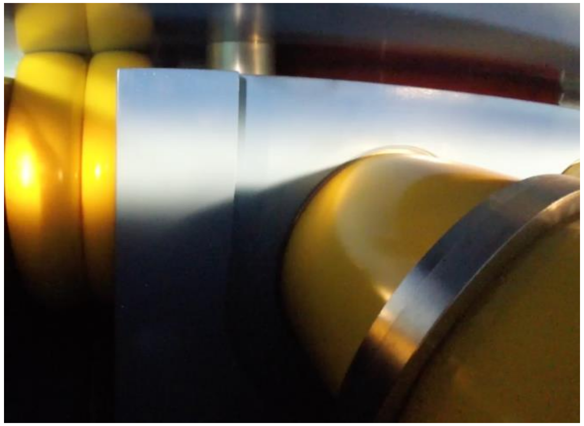
Failure Tests (LPRB and EQSB)

LPRB by Unison eTech

Rupture due to delamination

EQSB by ESCO RTS

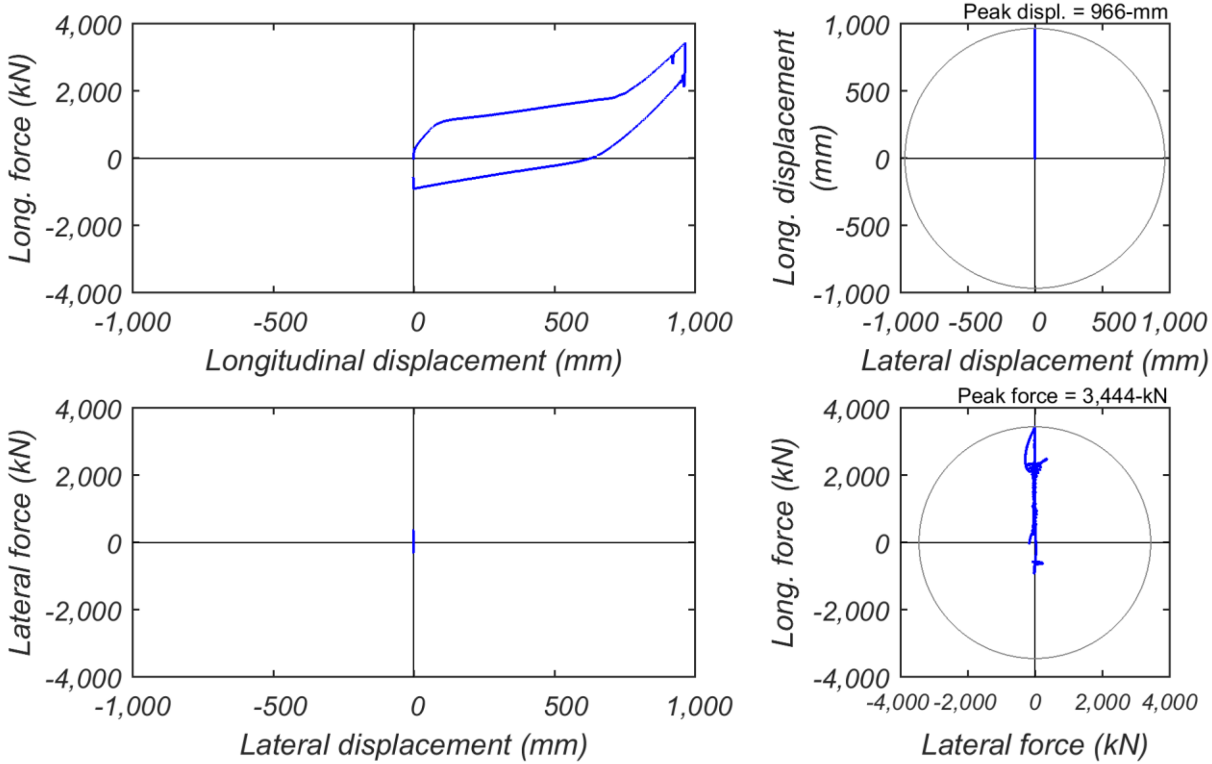




Bolt slip at peak load

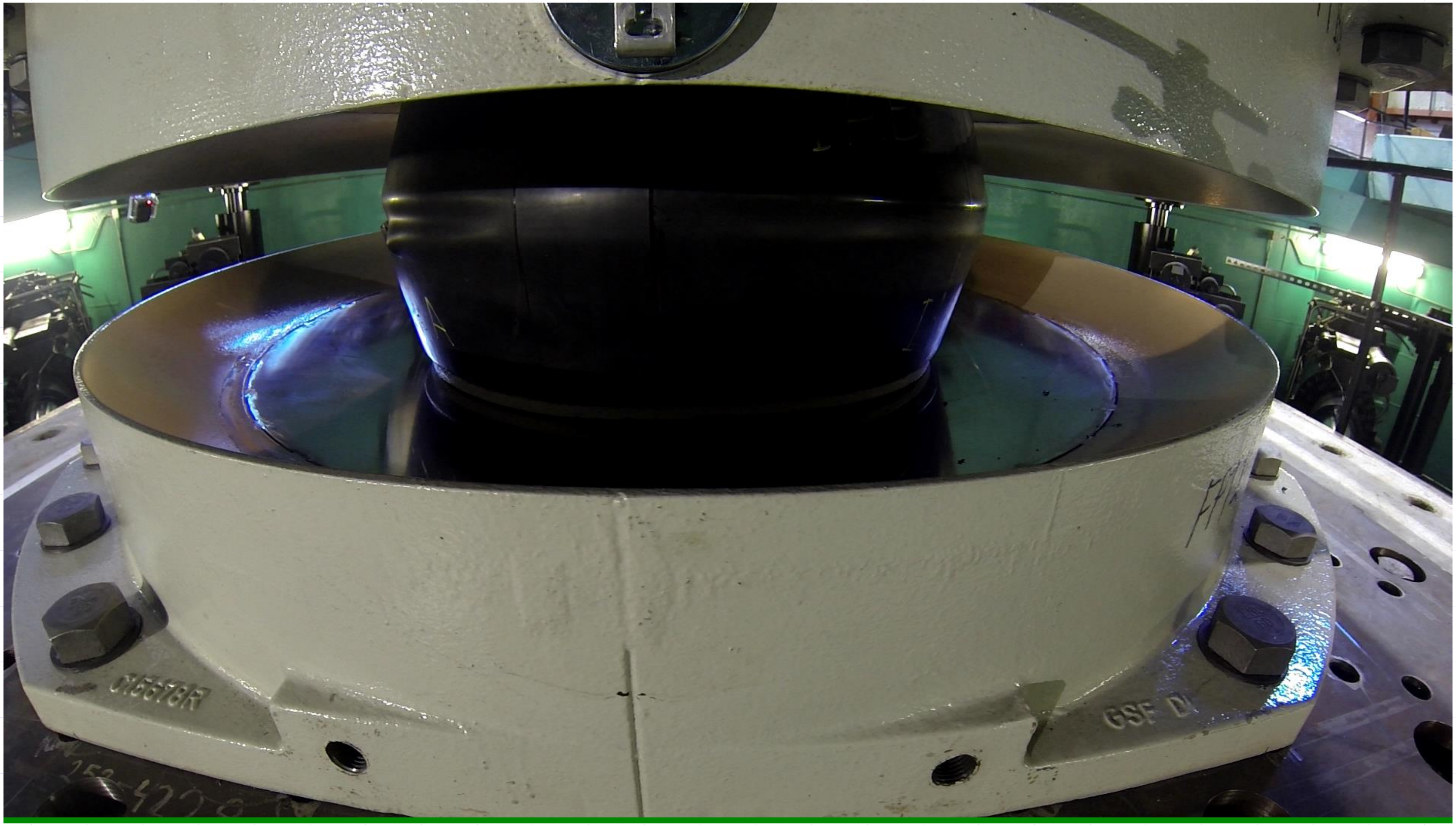
Failure Tests (TFPB)

TFPB by EPS



Stage 5-6 yielding of slider lip

Failure Tests (TFPB)



Failure Tests (TFPB)

TFPB by EPS

Stage 5-6 yielding of slider lip

Summary & Conclusions

Conclusions RTHS

- Real-time hybrid simulation is possible in 2D and is a viable testing method to experimentally assess the behavior of large isolators at full-scale.
- The SRMD bearing test machine was successfully converted to perform rapid and real-time hybrid simulation tests for large hybrid models.
- Despite the lack of a load cell to directly measure the experimental bearing forces, reliable results were obtained using a real-time correction model.
- To achieve acceptable performance and accuracy in the force controlled vertical DOF a hybrid simulation should be performed at a minimum 10x-slower than real time.
- It was demonstrated that it is possible to use a high-performance computing platform with parallel processing capabilities (OpenSees*SP*) to perform real-time hybrid simulations of large structures with many DOFs, such as nuclear power plants.

Conclusions Bearing Behavior

- Overall, the seismically isolated plant facilities behaved as expected. Base shears and floor accelerations were generally reduced substantially compared to what might be expected for a fixed-base structure. However, the tests were able to identify specific differences associated with different bearings, loading conditions, and earthquake excitations.
- Heat generation in the LPRB was larger during 2D testing than during 1D testing, causing the yield strength of the lead cores to decrease faster, and leading to larger displacement demands in the hybrid tests.
- The real-time execution of the hybrid simulations had a moderate effect on the hysteresis loops of the LPRB.
- The LPRB showed substantial vertical–horizontal coupling behavior.
- In terms of overturning effects, net tension was not recorded in any of the bearings.

Conclusions Bearing Behavior

- For the hybrid simulations on the EQSB, breakaway, static and dynamic friction values influence the response of the system.
- The EQSB isolator showed substantial vertical–horizontal coupling behavior.
- For the TFPB shear forces are significantly lower than the ones that were seen in the LPRB and EQSB. Lower isolator shear forces mean that less force is transmitted into the power plant superstructure; hence, the superstructure is better protected during seismic shaking.
- The TFPB isolator showed substantial vertical–horizontal coupling behavior.
- For the hybrid simulations on the TFPB, adhesion and static friction influence the response of the system. For modeling purposes a simple velocity dependent friction model is not sufficient. A friction model that can include adhesion, static, and dynamic friction needs to be developed and implemented.

Questions?
Discussion