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Structural Engineering
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Reliability of Dynamic and Hybrid Tests in the Presence of Control Errors

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Testing Reliability

Some examples of studies from the literature:

•**Shing, P. S. B., Mahin, S. A., 1987**. Cumulative Experimental Errors in Pseudodynamic Tests, Earthquake Engineering and Structural Dynamics, 15, 409-424

•**Thewalt, C. and Roman, M., 1994**. "Performance Parameters for Pseudodynamic Tests", ASCE Journal of Struct. Eng., 120, 9

•**Molina, F. J., Magonette, G., Pegon, P., 2002**. Assessment of systematic experimental errors in pseudo-dynamic tests, 12th European Conference on Earthquake engineering, Elsevier Science, Paper 525

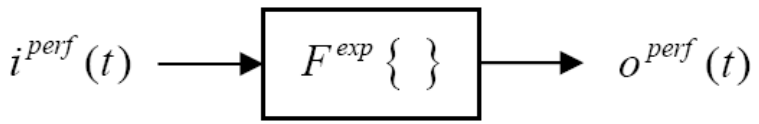
•**Mosqueda, G., Stojadinovic, B. and Mahin, S. A., 2007**. Real-Time Error Monitoring for Hybrid Simulation. Part I: Methodology and Experimental Verification, J. Struct. Engrg. 133 1100-1108.

Definition of testing reliability

PROTOTYPE SYSTEM

$$o(t) = F\{i(t)\}$$

EXPERIMENTAL SYSTEM



$$o^{perf}(t) = F^{exp}\{i^{perf}(t)\}$$

Reliability

$$o^{perf}(t) \approx o(t) \quad ?$$

$$i^{perf}(t) \approx i(t) \quad ?$$

$$F^{exp}\{\ \} \approx F\{\ \} \quad ? \Longrightarrow \omega^{exp} \approx \omega \quad ? \quad ; \quad \zeta^{exp} \approx \zeta \quad ?$$

(linear approximation)

Prototype system for a seismic problem

$$\mathbf{M}\ddot{\mathbf{d}}(t) + \mathbf{r}(\mathbf{d}(t), \dot{\mathbf{d}}(t)) = -\mathbf{M}\mathbf{J}\mathbf{a}_g(t)$$

Linear approximation:

$$\mathbf{M}s^2\mathbf{D}(s) + \mathbf{C}s\mathbf{D}(s) + \mathbf{K}\mathbf{D}(s) = -\mathbf{M}\mathbf{J}\mathbf{A}_g(s)$$

$$\mathbf{D}(s) = \mathbf{F}(s)\mathbf{A}_g(s)$$

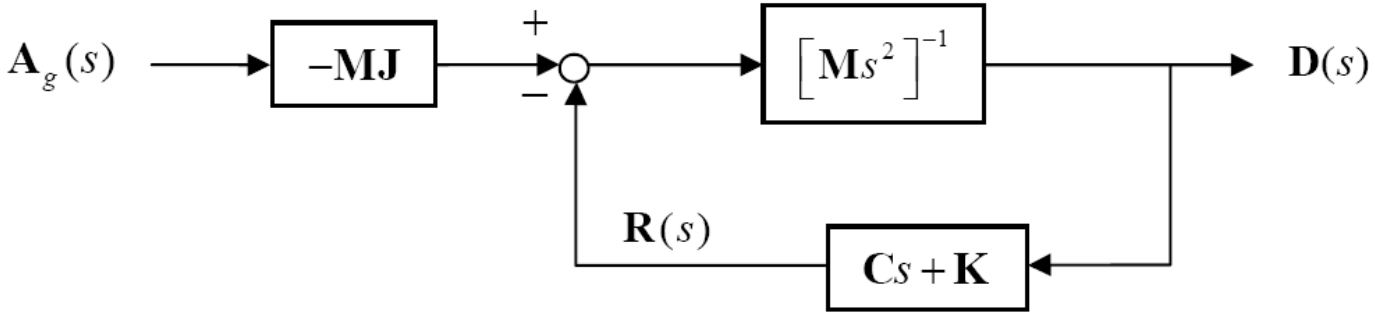
$$\mathbf{F}(s) = -\left[\mathbf{M}s^2 + \mathbf{C}s + \mathbf{K}\right]^{-1}\mathbf{M}\mathbf{J}$$

$$s\begin{bmatrix}\mathbf{C} & \mathbf{M}\\ \mathbf{M} & \mathbf{0}\end{bmatrix}\boldsymbol{\varphi} + \begin{bmatrix}\mathbf{K} & \mathbf{0}\\ \mathbf{0} & -\mathbf{M}\end{bmatrix}\boldsymbol{\varphi} = \mathbf{0}$$

$$s_i, s_i^* = \omega_i(-\xi_i \pm j\sqrt{1-\xi_i^2})$$

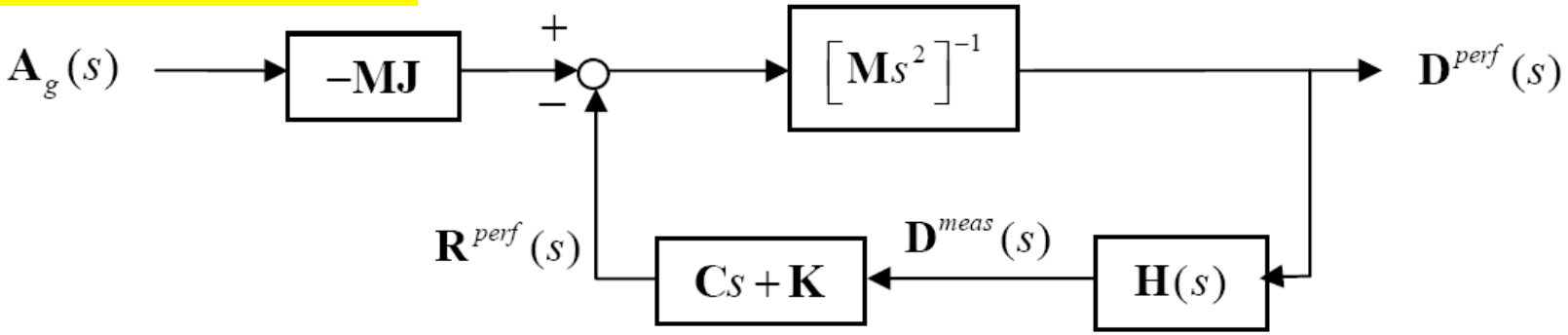
Pseudo-Dynamic Test

PROTOTYPE SYSTEM



$$\mathbf{R}(s) = [\mathbf{C}s + \mathbf{K}]\mathbf{D}(s)$$

EXPERIMENTAL SYSTEM



$$\mathbf{R}^{perf}(s) = [\mathbf{C}s + \mathbf{K}]\mathbf{D}^{meas}(s) = [\mathbf{C}s + \mathbf{K}]\mathbf{H}(s)\mathbf{D}^{perf}(s) \approx [\mathbf{C}^{perf}s + \mathbf{K}^{perf}]\mathbf{D}^{perf}(s)$$

Pseudo-Dynamic Test

$$\mathbf{R}^{perf}(s) = \left[\mathbf{C}s + \mathbf{K}\right]\mathbf{D}^{meas}(s) = \left[\mathbf{C}s + \mathbf{K}\right]\mathbf{H}(s)\mathbf{D}^{perf}(s) \approx \left[\mathbf{C}^{perf}s + \mathbf{K}^{perf}\right]\mathbf{D}^{perf}(s)$$

$$\mathbf{r}^{perf}(t) = \mathbf{C}\dot{d}^{meas}(t) + \mathbf{K}d^{meas}(t)$$

Spatial Model

$$\mathbf{r}^{perf}(t) = \mathbf{C}^{perf}\dot{d}^{perf}(t) + \mathbf{K}^{perf}d^{perf}(t)$$

Least-Square Estimation

$$\mathbf{C} \quad \mathbf{K}$$

$$\mathbf{C}^{perf} \quad \mathbf{K}^{perf}$$

$$s\begin{bmatrix}\mathbf{C} & \mathbf{M}\\ \mathbf{M} & \mathbf{0}\end{bmatrix}\boldsymbol{\varphi} + \begin{bmatrix}\mathbf{K} & \mathbf{0}\\ \mathbf{0} & -\mathbf{M}\end{bmatrix}\boldsymbol{\varphi} = \mathbf{0}$$

$$s\begin{bmatrix}\mathbf{C}^{perf} & \mathbf{M}\\ \mathbf{M} & \mathbf{0}\end{bmatrix}\boldsymbol{\varphi} + \begin{bmatrix}\mathbf{K}^{perf} & \mathbf{0}\\ \mathbf{0} & -\mathbf{M}\end{bmatrix}\boldsymbol{\varphi} = \mathbf{0}$$

Reliable experiment?

$$\approx$$

$$s_i, s_i^* = \omega_i(-\zeta_i \pm j\sqrt{1-\zeta_i^2})$$

$$s_i^{exp}, s_i^{exp*} = \omega_i^{exp}(-\zeta_i^{exp} \pm j\sqrt{1-\zeta_i^{exp2}})$$

ESECMaSE project: masonry model

4-DOF masonry model: free oscillation

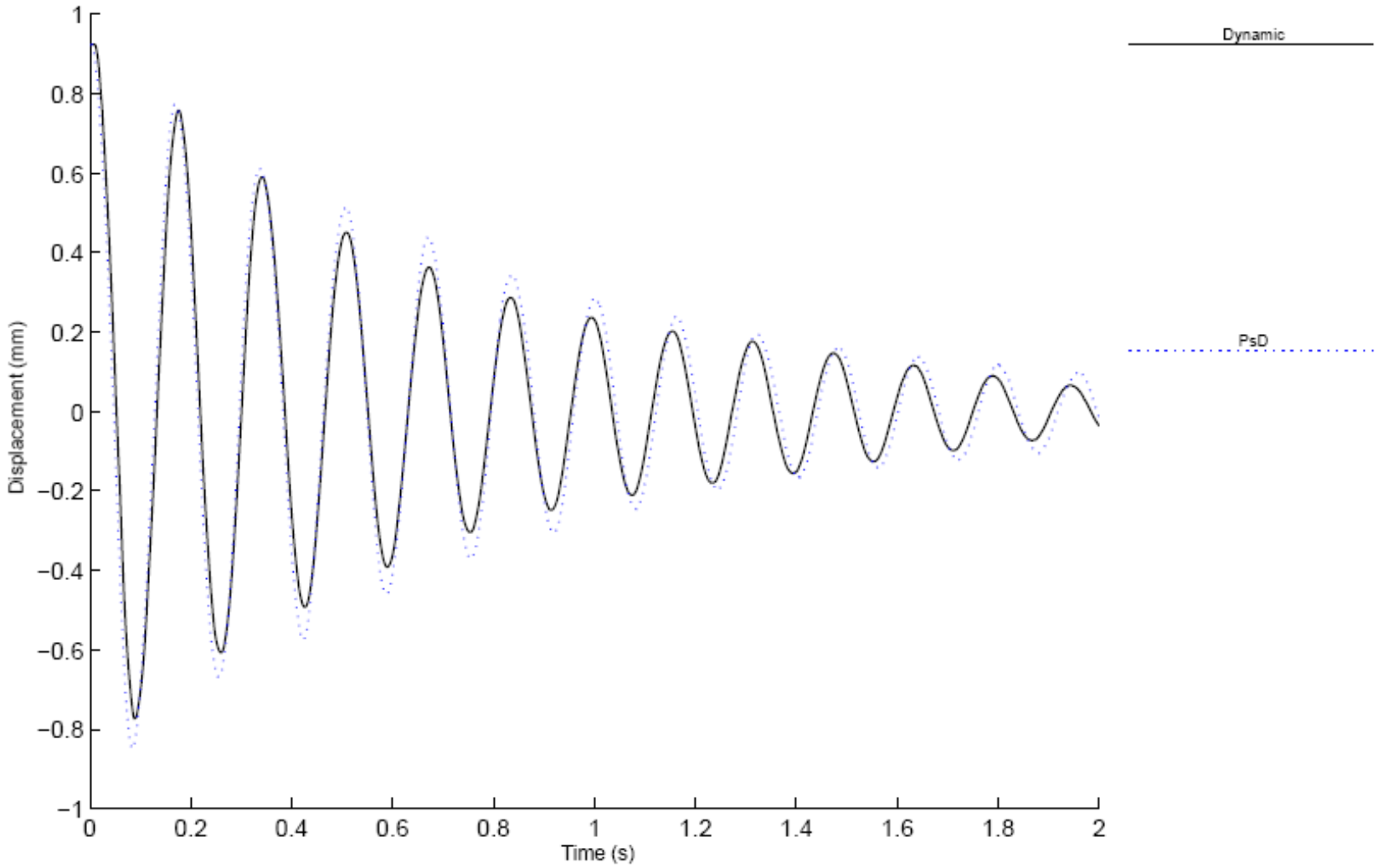


Figure 6. Snap-back tests on the two-storey clay brick house. Dynamic and PsD displacement at one of the top transducers.

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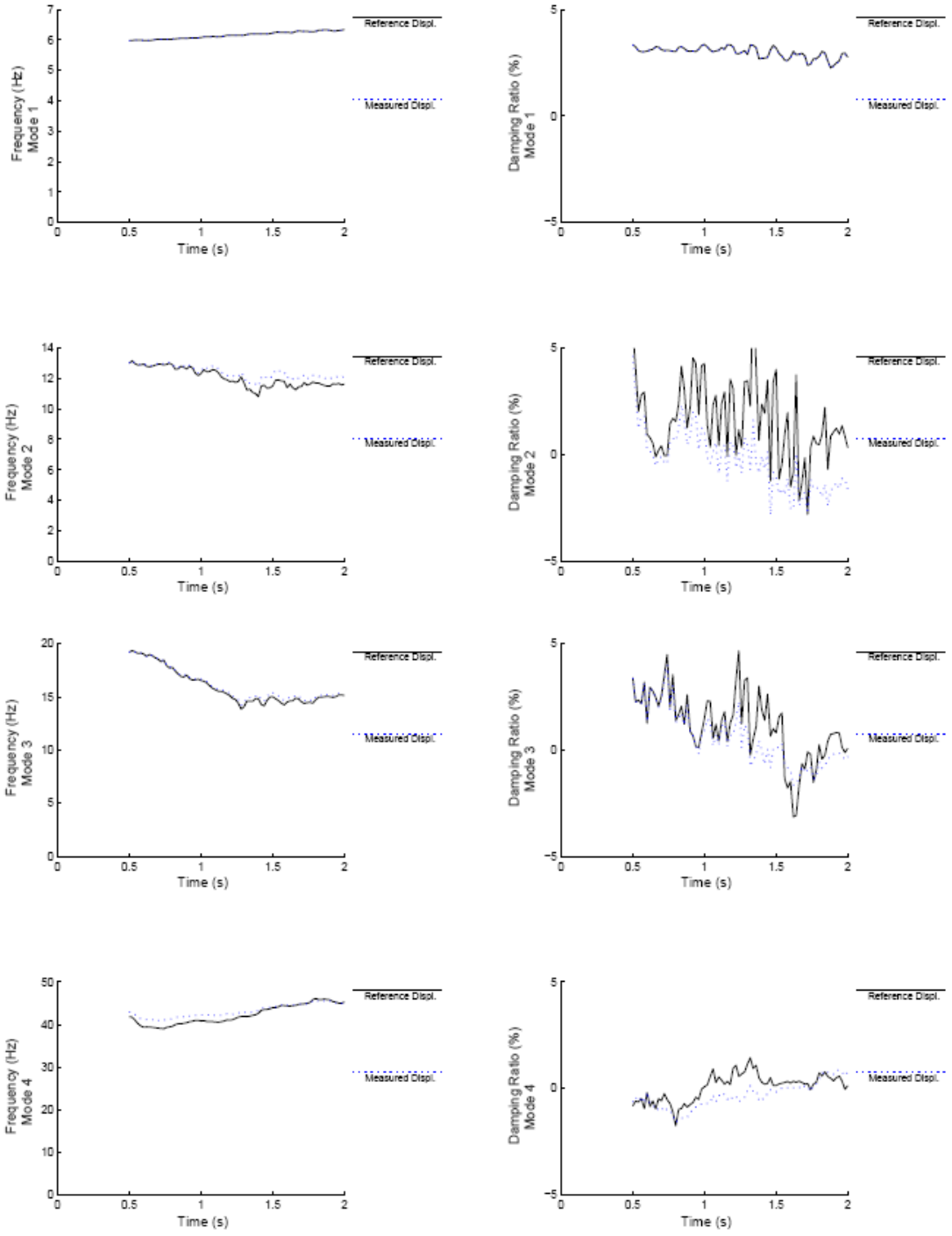
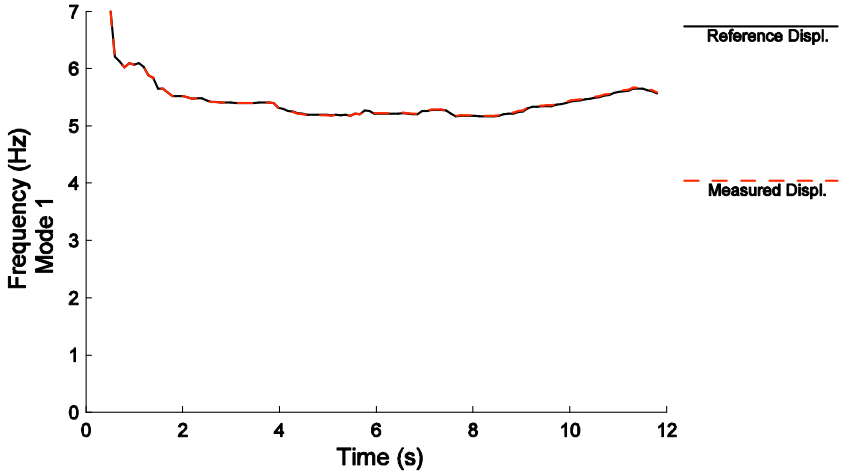
Identified eigen frequency and damping ratio from PsD results

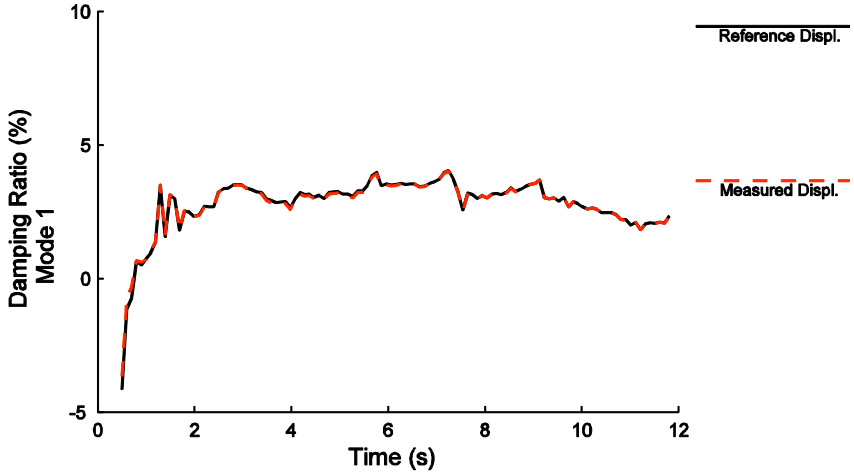
(comparison of identified values from measured displacements and from solved ones)

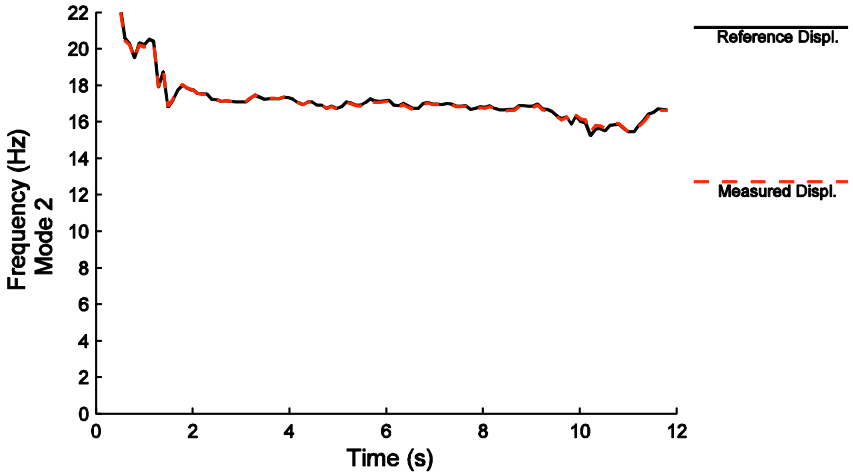
Masonry model free oscillation

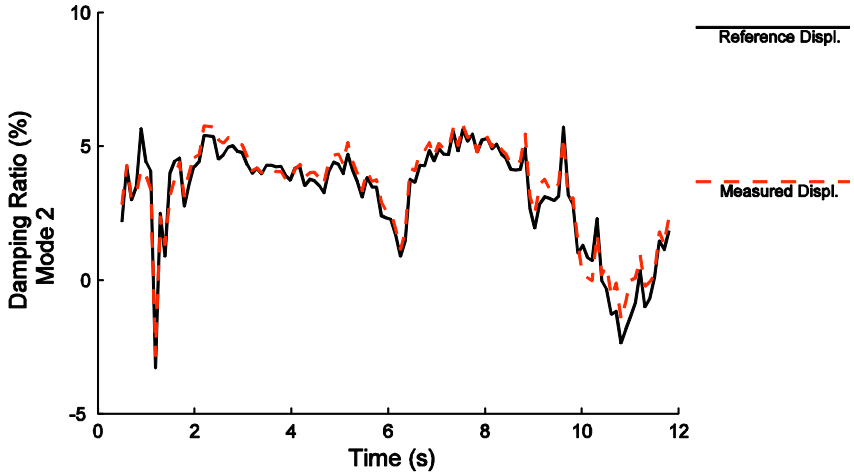


Masonry model seismic response
0.02 g PGA

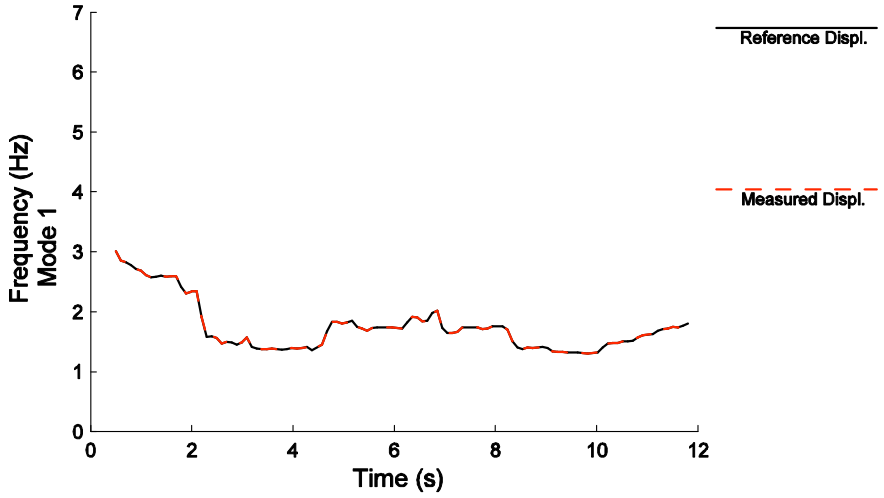


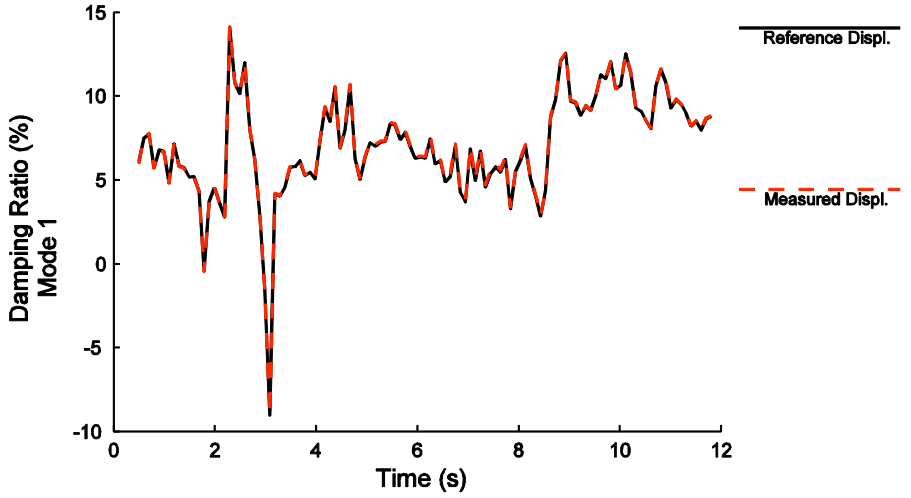


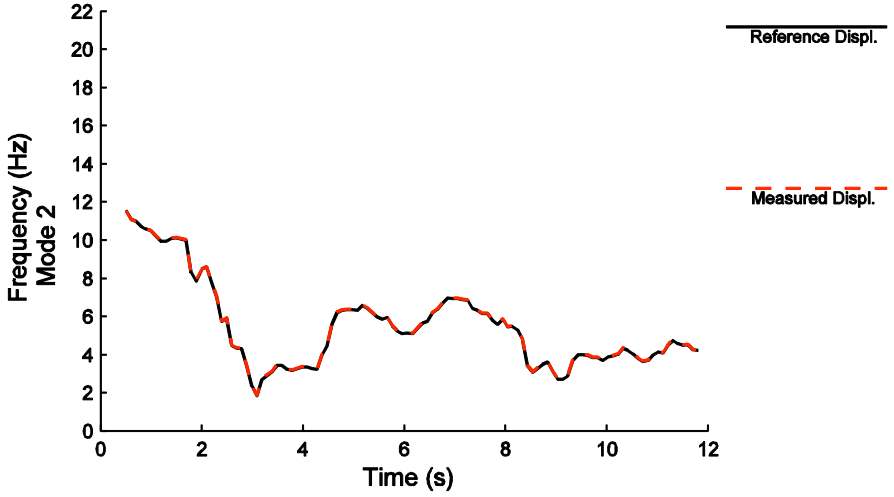


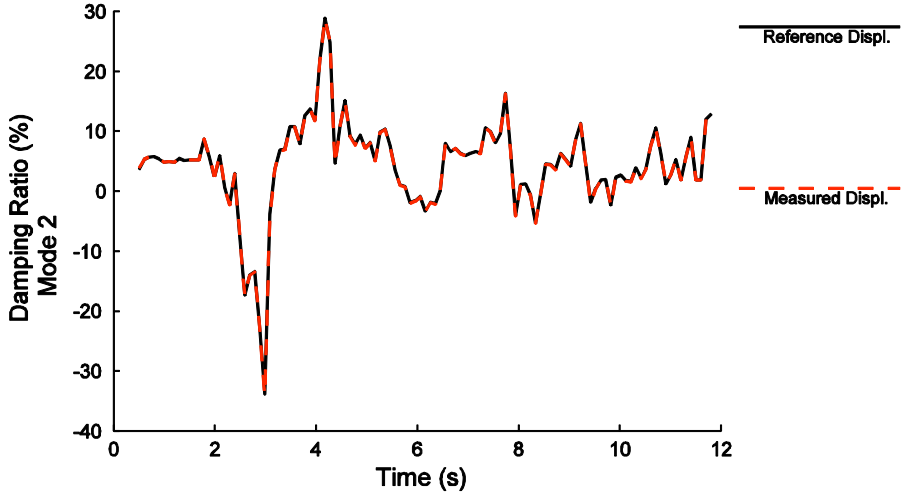


Masonry model seismic response
0.22 g PGA



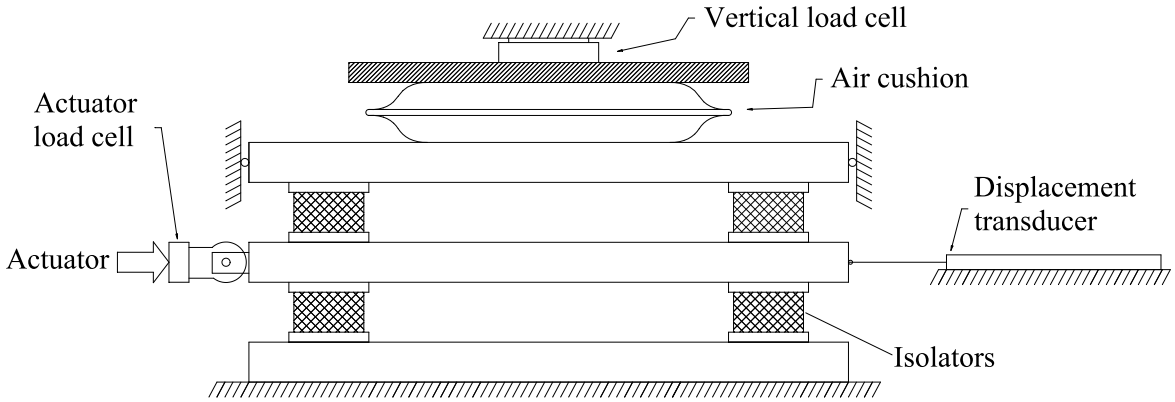






Pseudo-dynamic test of a 4-storey building with base isolation

Experimental isolation system:



Numerical superstructure:

$$\mathbf{k} = \begin{bmatrix} 52130000 & -45580000 & 12530000 & -270000 \\ -45580000 & 66410000 & -31350000 & 1700000 \\ 12530000 & -31350000 & 26670000 & -6410000 \\ -270000 & 1700000 & -6410000 & 4930000 \end{bmatrix}$$

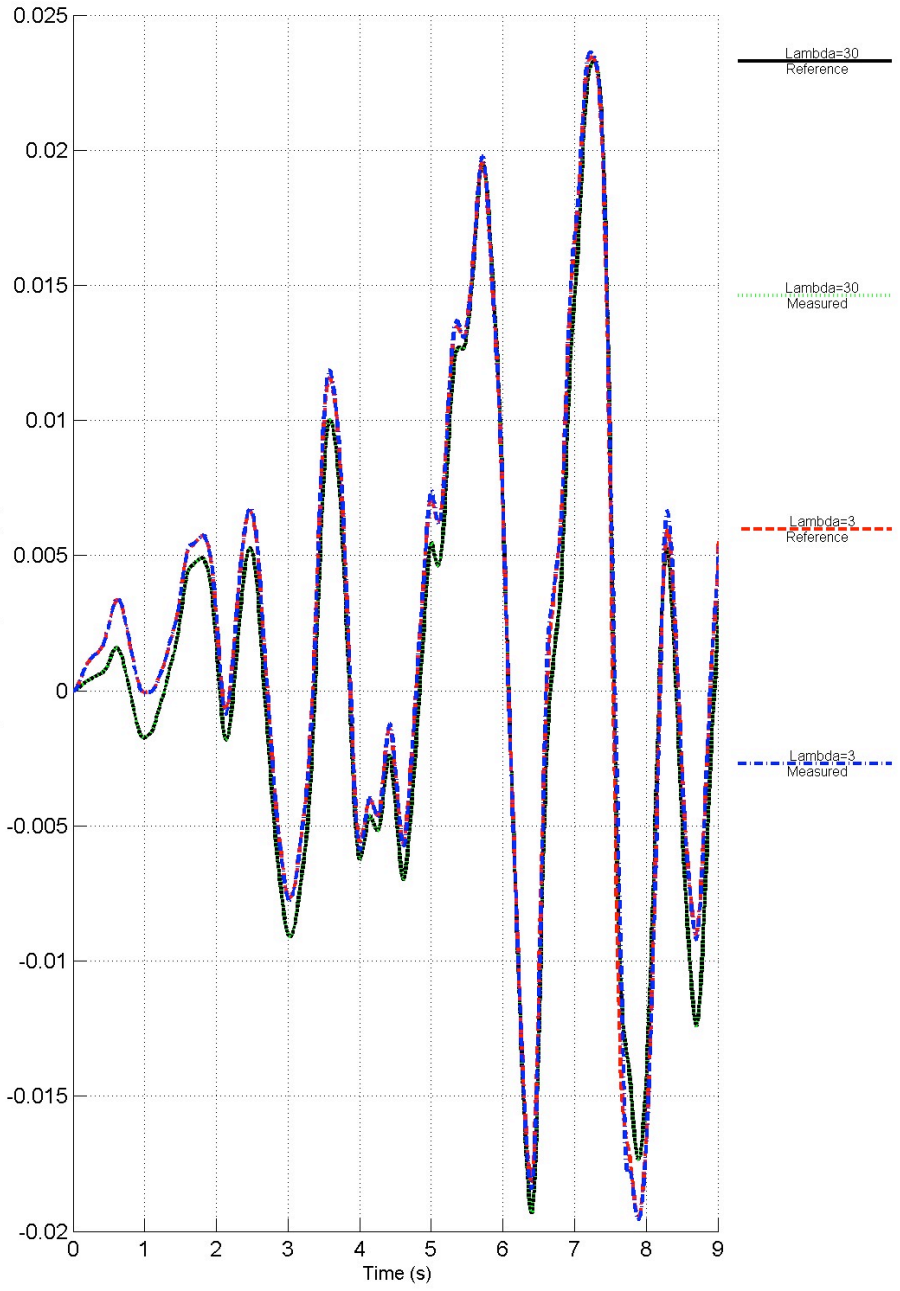
$$\mathbf{c} = \beta \mathbf{k}$$

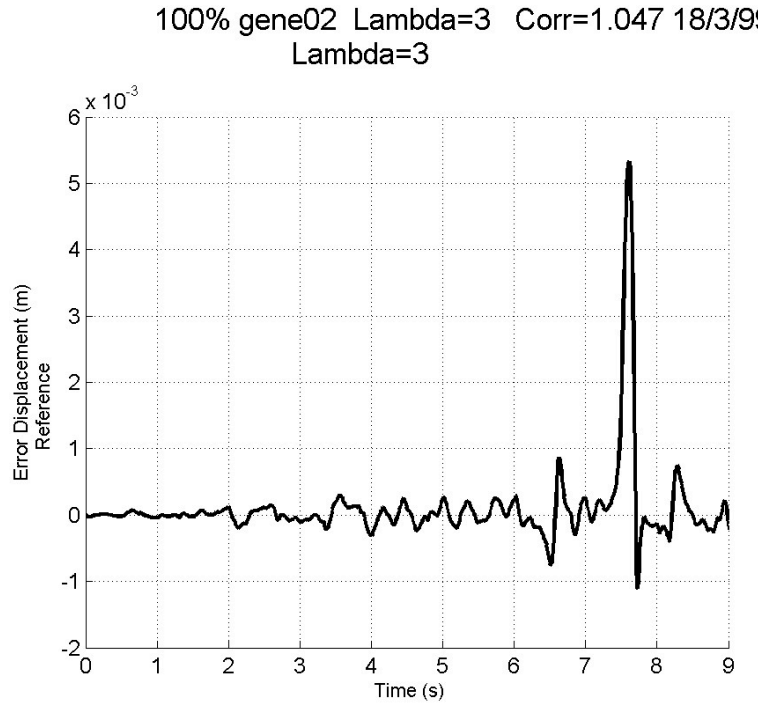
$$\beta = 2\zeta_1/\omega_1 = 0.0123 \text{ s}$$

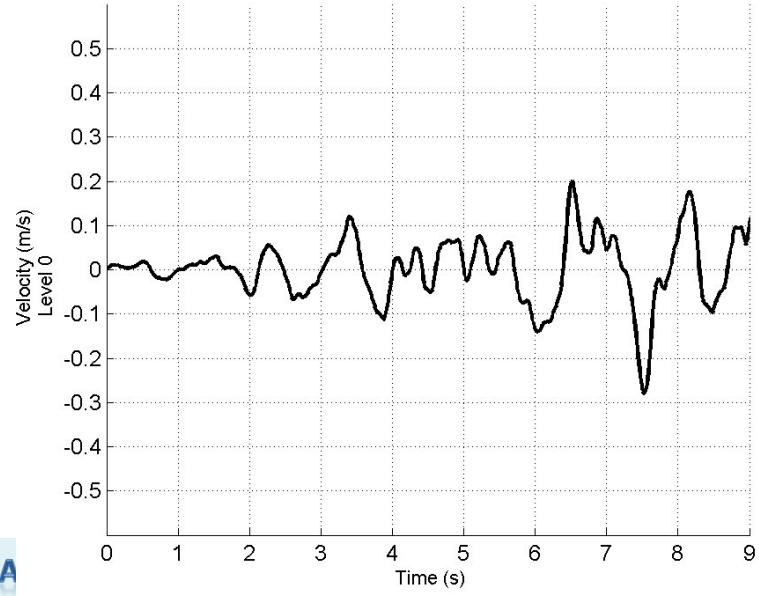
$$\zeta_1 = 5\%$$

$$\mathbf{m} = \text{diag}(20500, 20500, 18800, 2250)$$

Pseudo-dynamic test of a 4-storey building with base isolation







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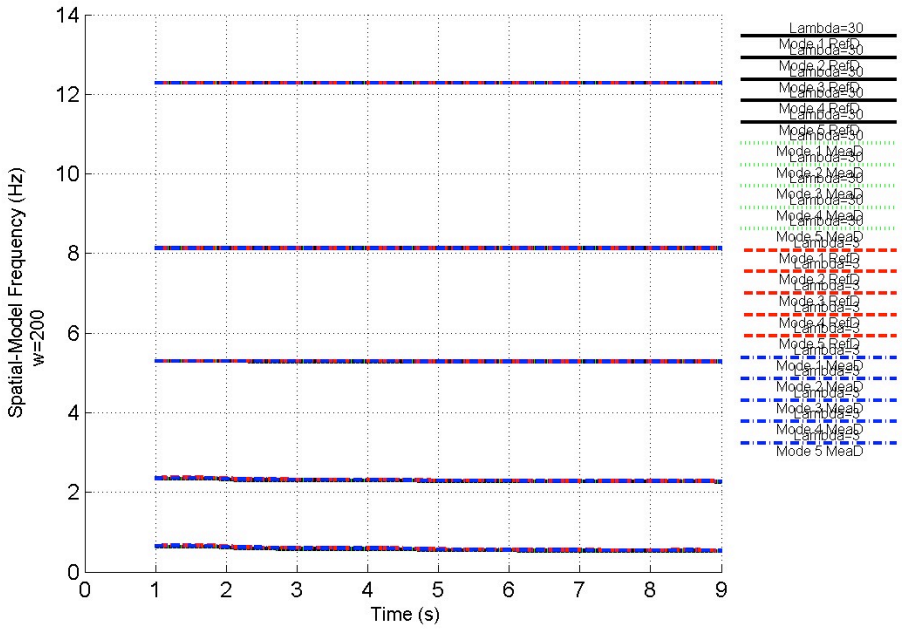
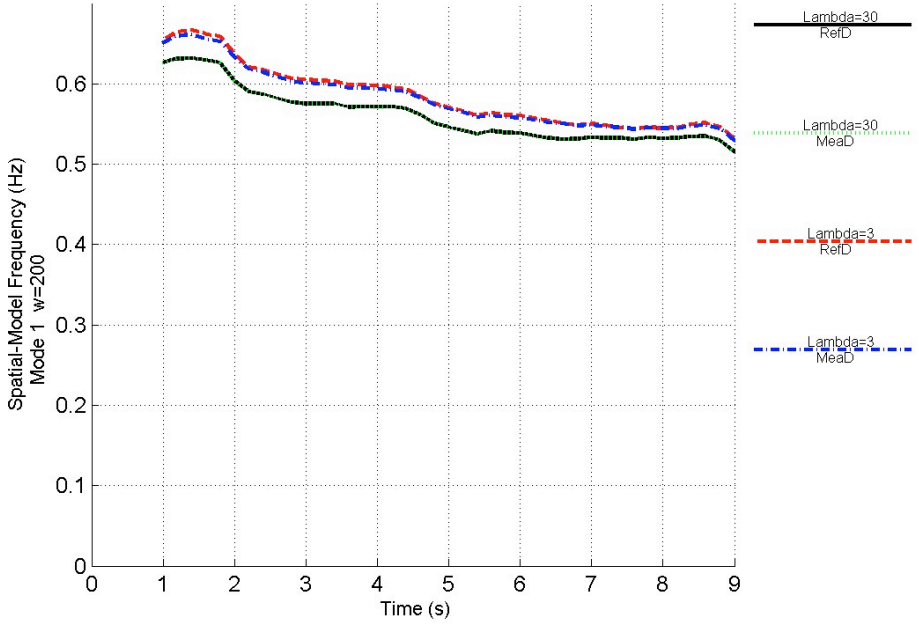
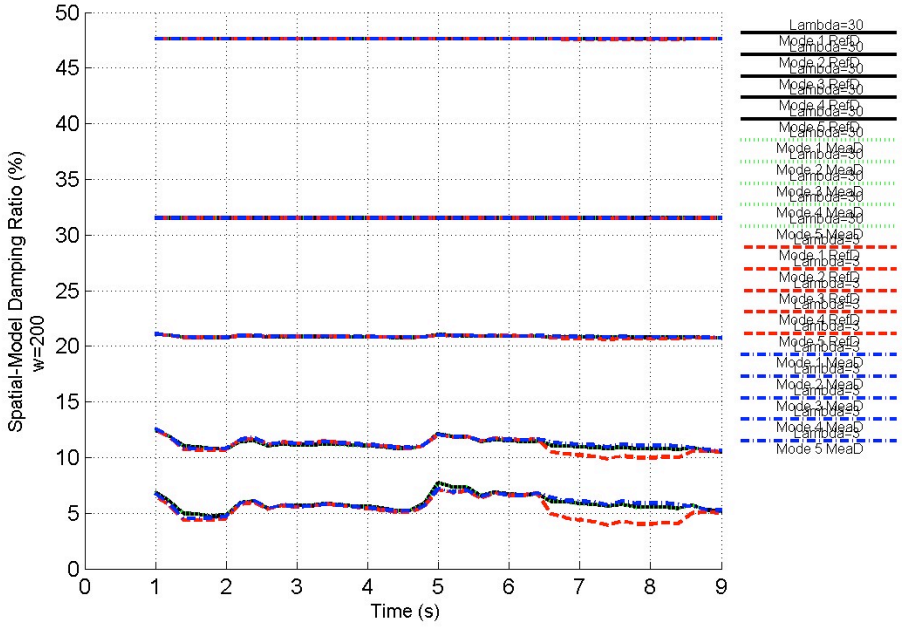
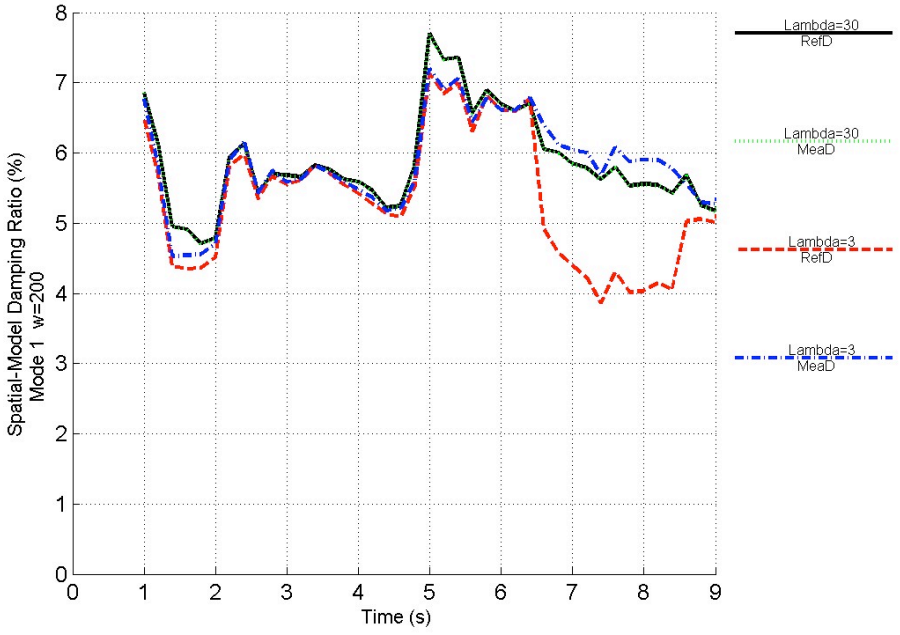
Pseudo-dynamic test of a 4-storey building with base isolation

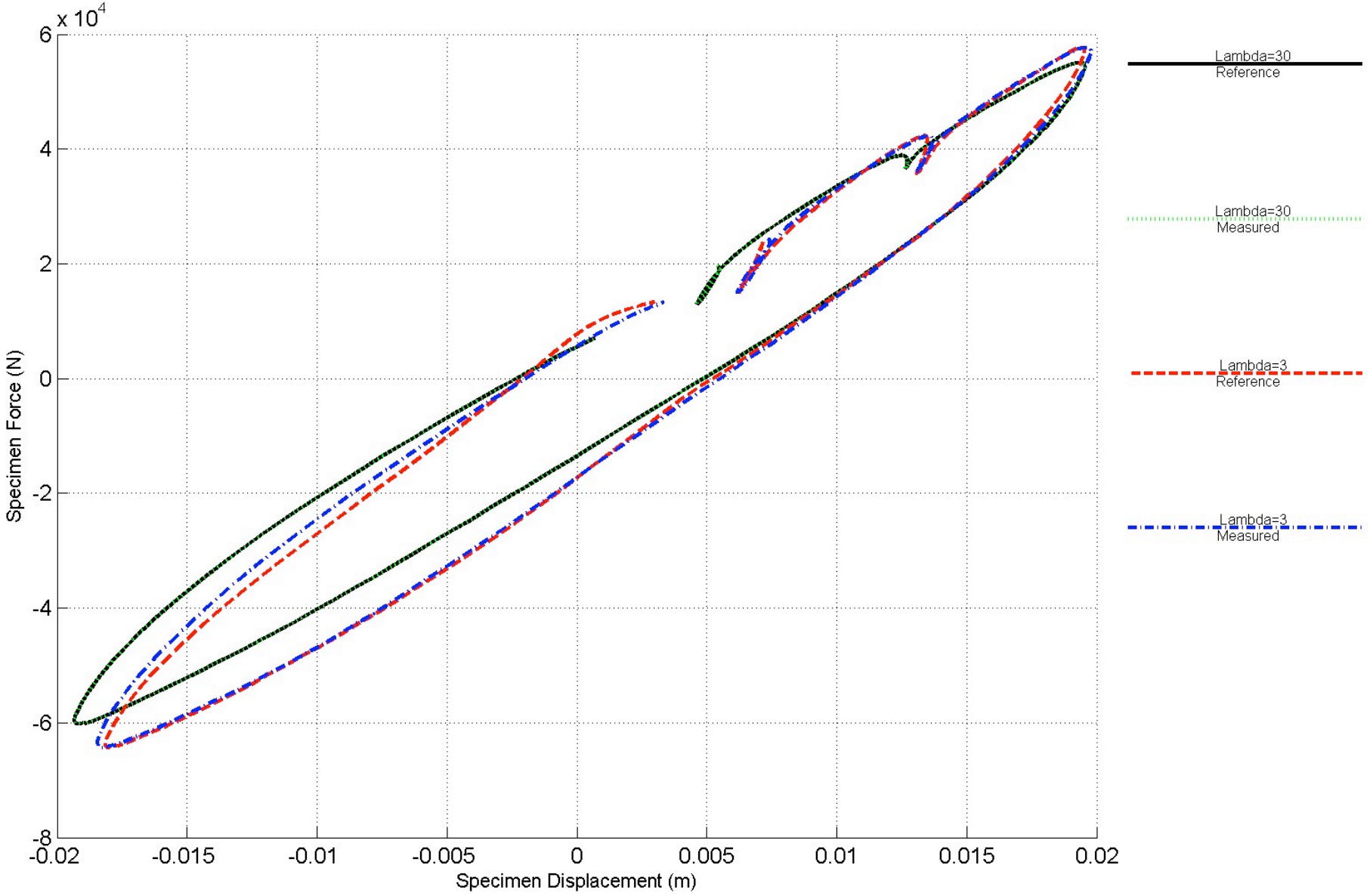




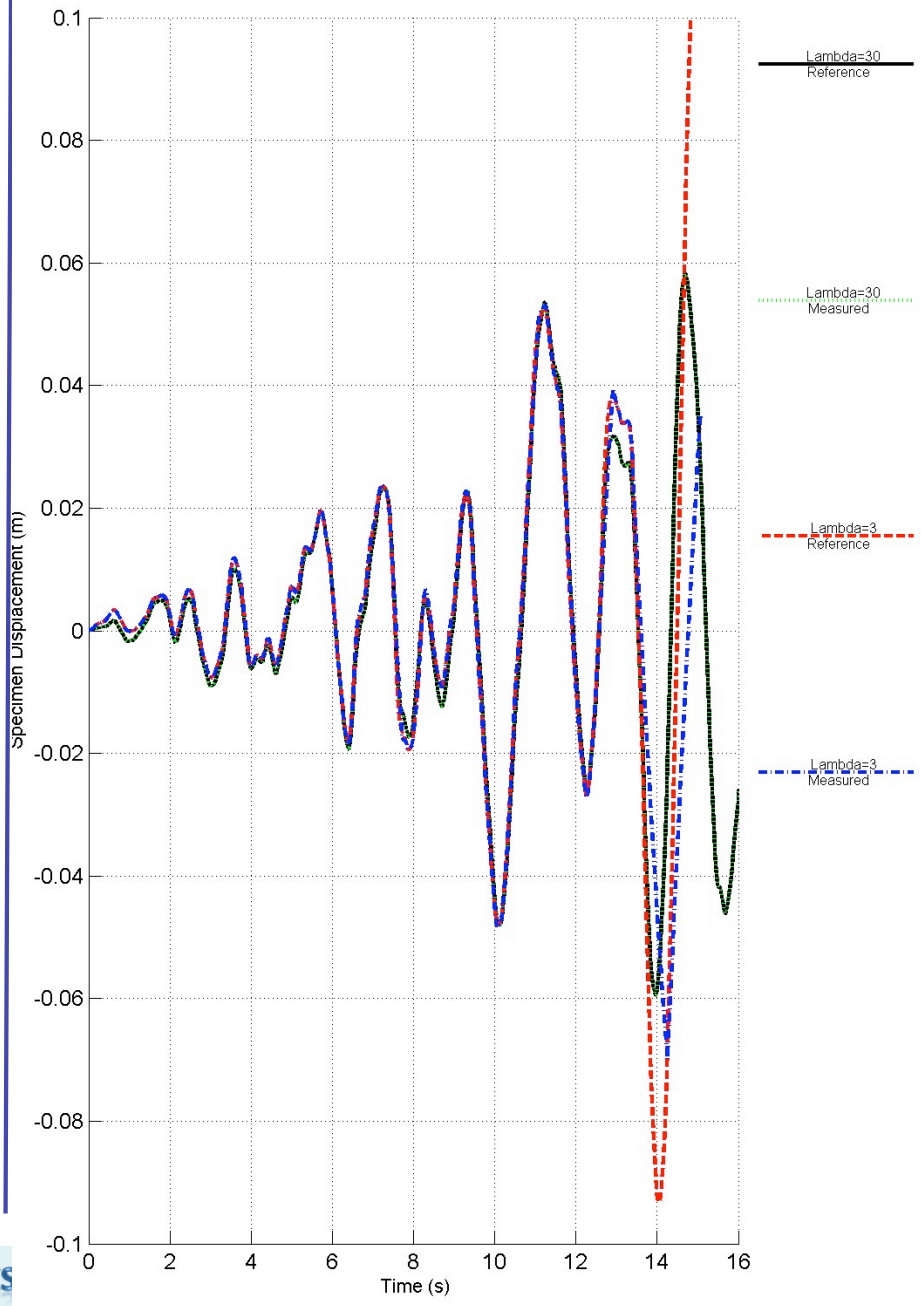


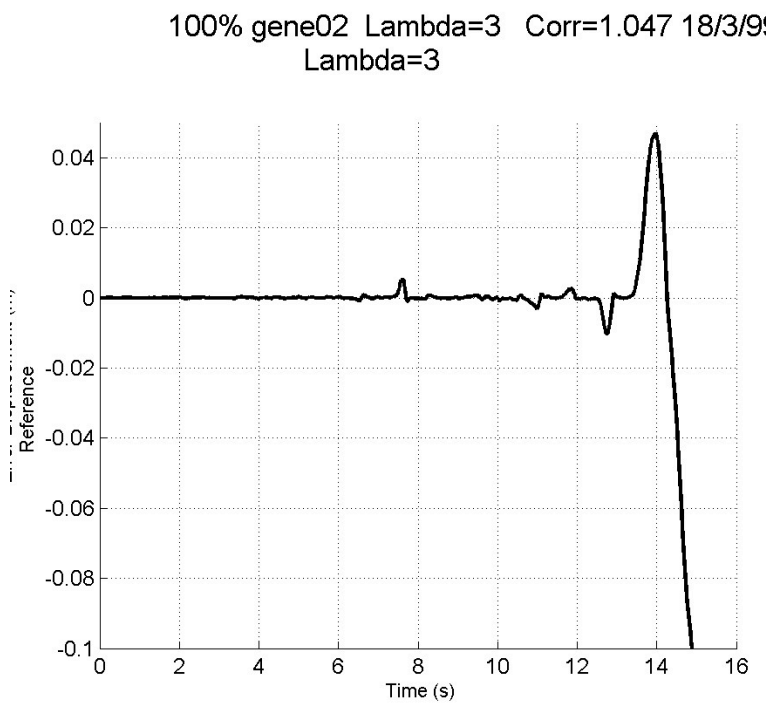


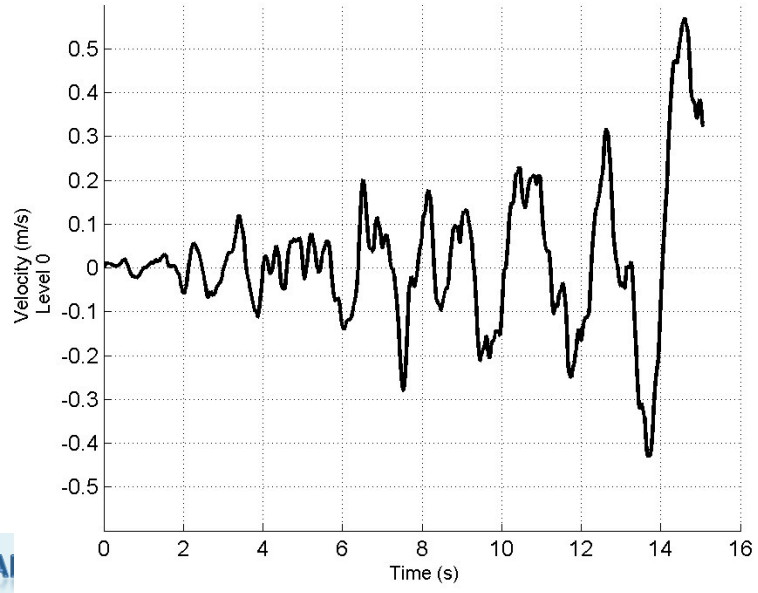
Pseudo-dynamic test of a 4-storey building with base isolation



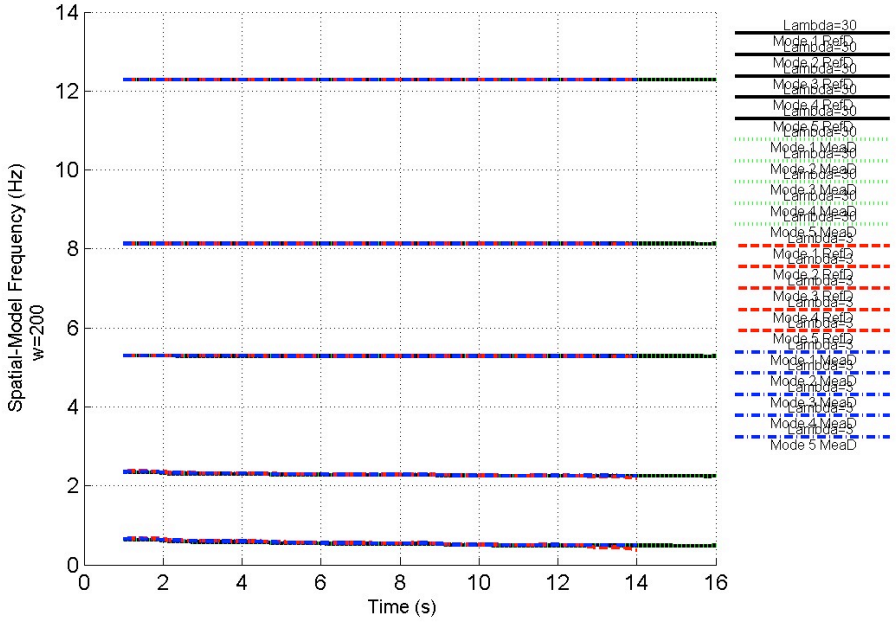
Pseudo-dynamic test of a 4-storey building with base isolation

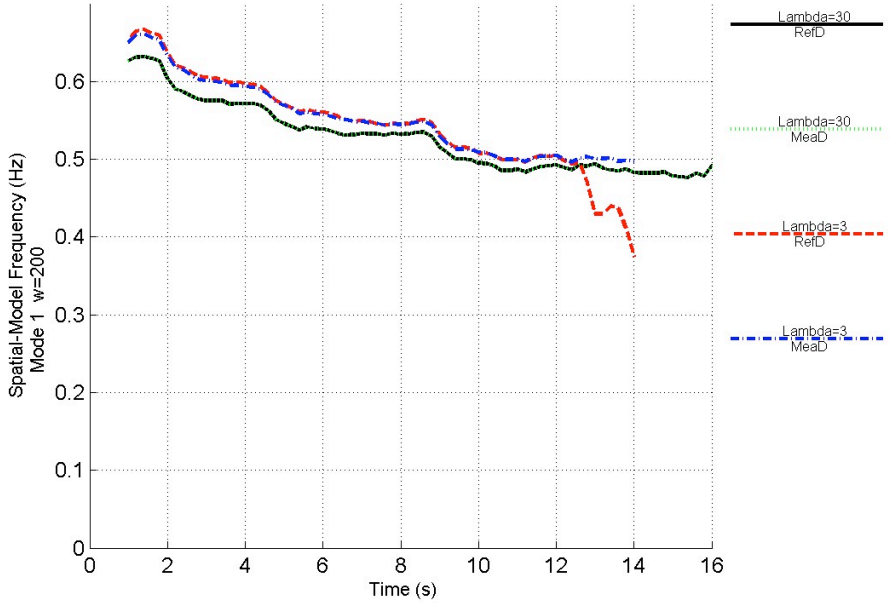


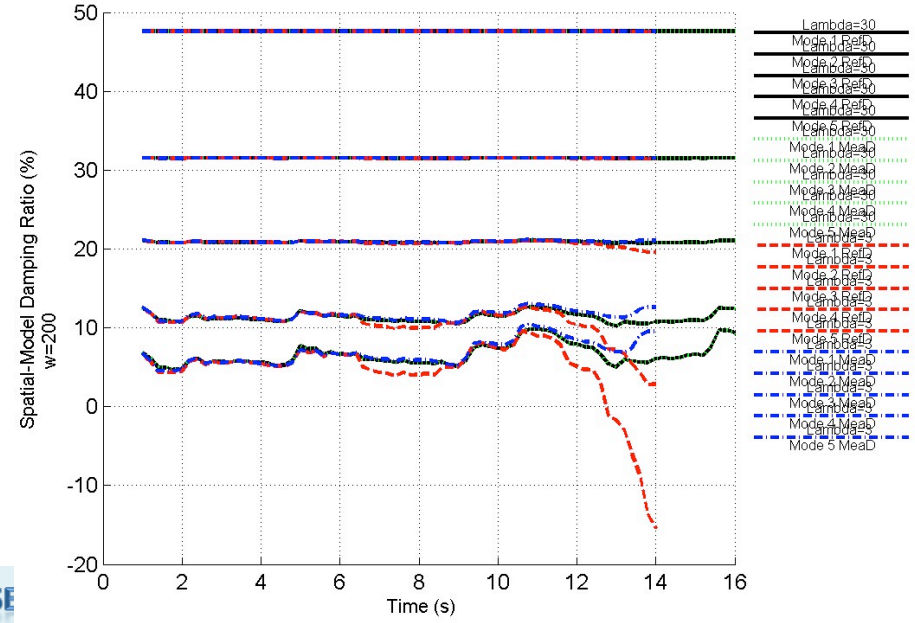


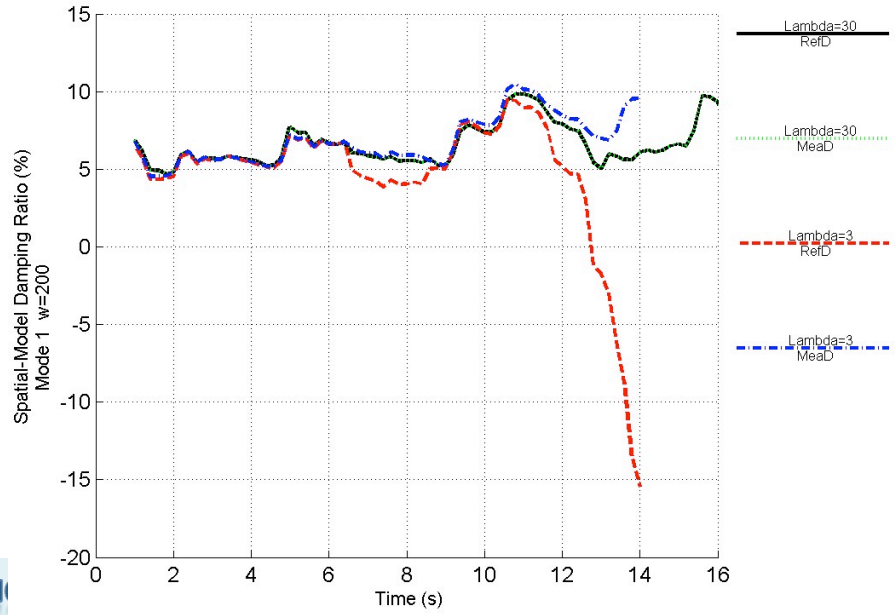


Pseudo-dynamic test of a 4-storey building with base isolation

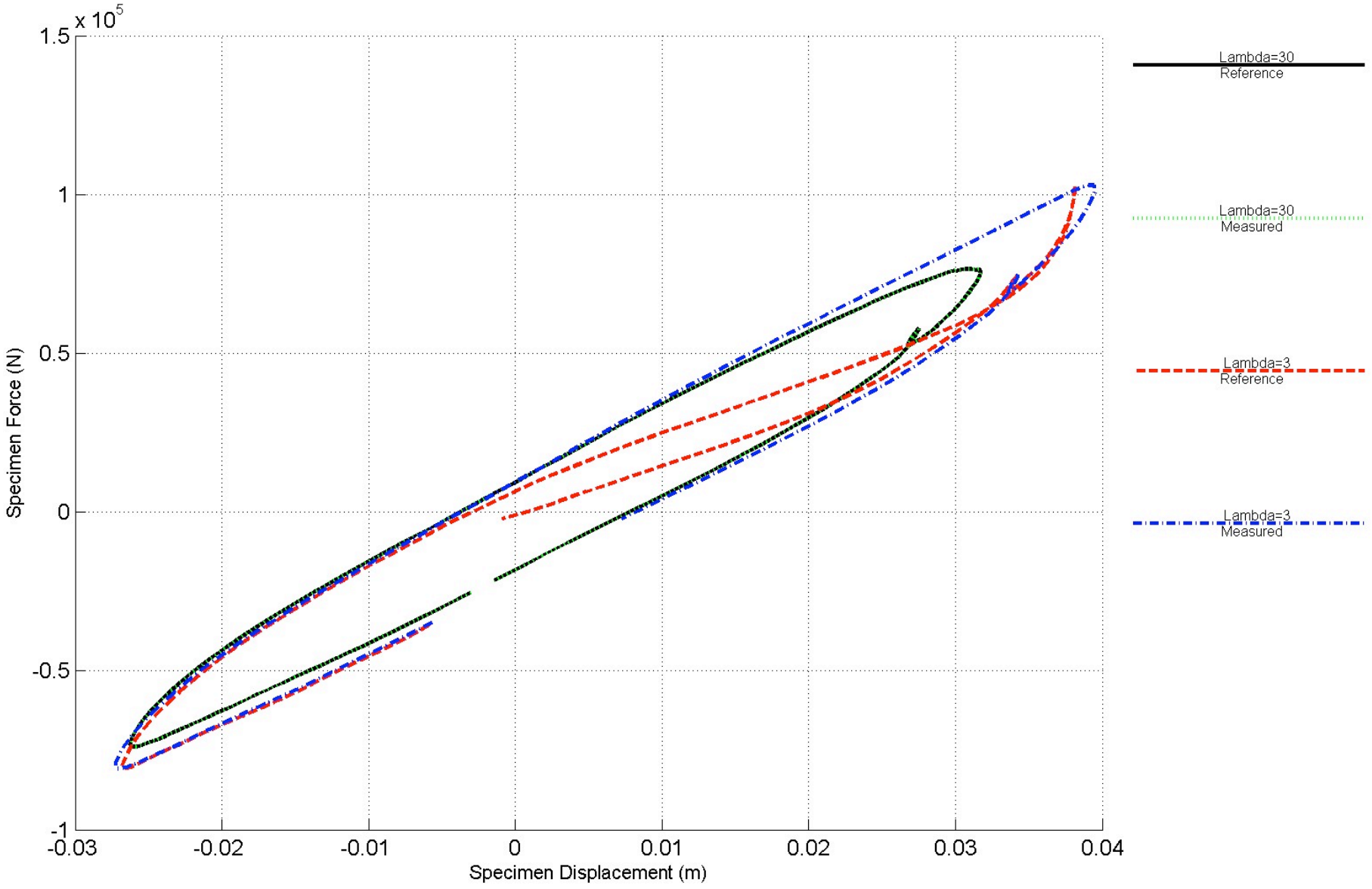






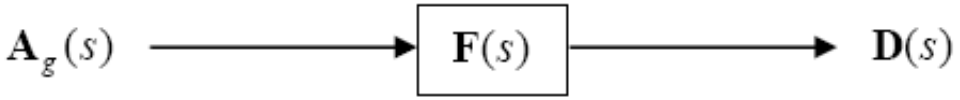


Pseudo-dynamic test of a 4-storey building with base isolation

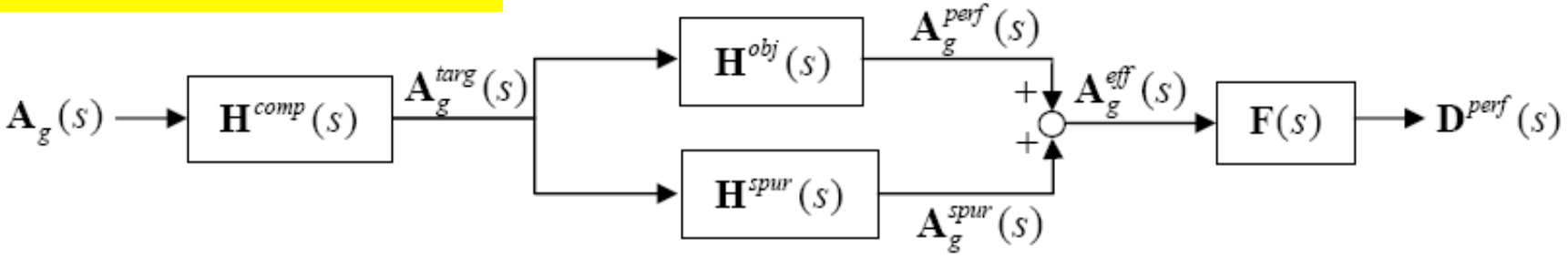


Shaking-Table Test

PROTOTYPE SYSTEM



EXPERIMENTAL SYSTEM



$$\mathbf{D}^{perf}(s) = \mathbf{F}(s)\mathbf{A}_g^{eff}(s)$$

$$\mathbf{D}^{perf}(s) = \mathbf{F}^{exp}(s)\mathbf{A}_g^{perf}(s)$$

Filter Model
Least-Squares Estimation

Reliable experiment?

$\approx$

$$s_i, s_i^* = \omega_i(-\zeta_i \pm j\sqrt{1-\zeta_i^2})$$

$$s_i^{exp}, s_i^{exp*} = \omega_i^{exp}(-\zeta_i^{exp} \pm j\sqrt{1-\zeta_i^{exp2}})$$

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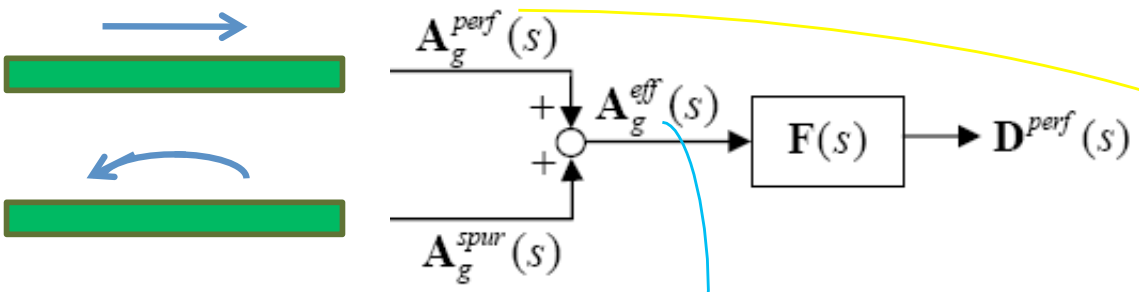
Shaking-table test on SDoF steel frame

Shaking-table test on SDoF steel frame

Performed translation

Spurious rotation



$$\mathbf{D}^{perf}(s) = \mathbf{F}(s)\mathbf{A}_g^{eff}(s)$$

$$\mathbf{D}^{perf}(s) = \mathbf{F}^{exp}(s)\mathbf{A}_g^{perf}(s)$$

Filter Model
Least-Squares Estimation

$\omega = 2.5Hz$

$\zeta = 0.015$

$\omega^{\exp} = 2.5Hz$

$\zeta^{\exp} = 0.025$

The shaking table response was acceptably reproduced by a PsD test based on the effective input given by the table (translation + rotation)

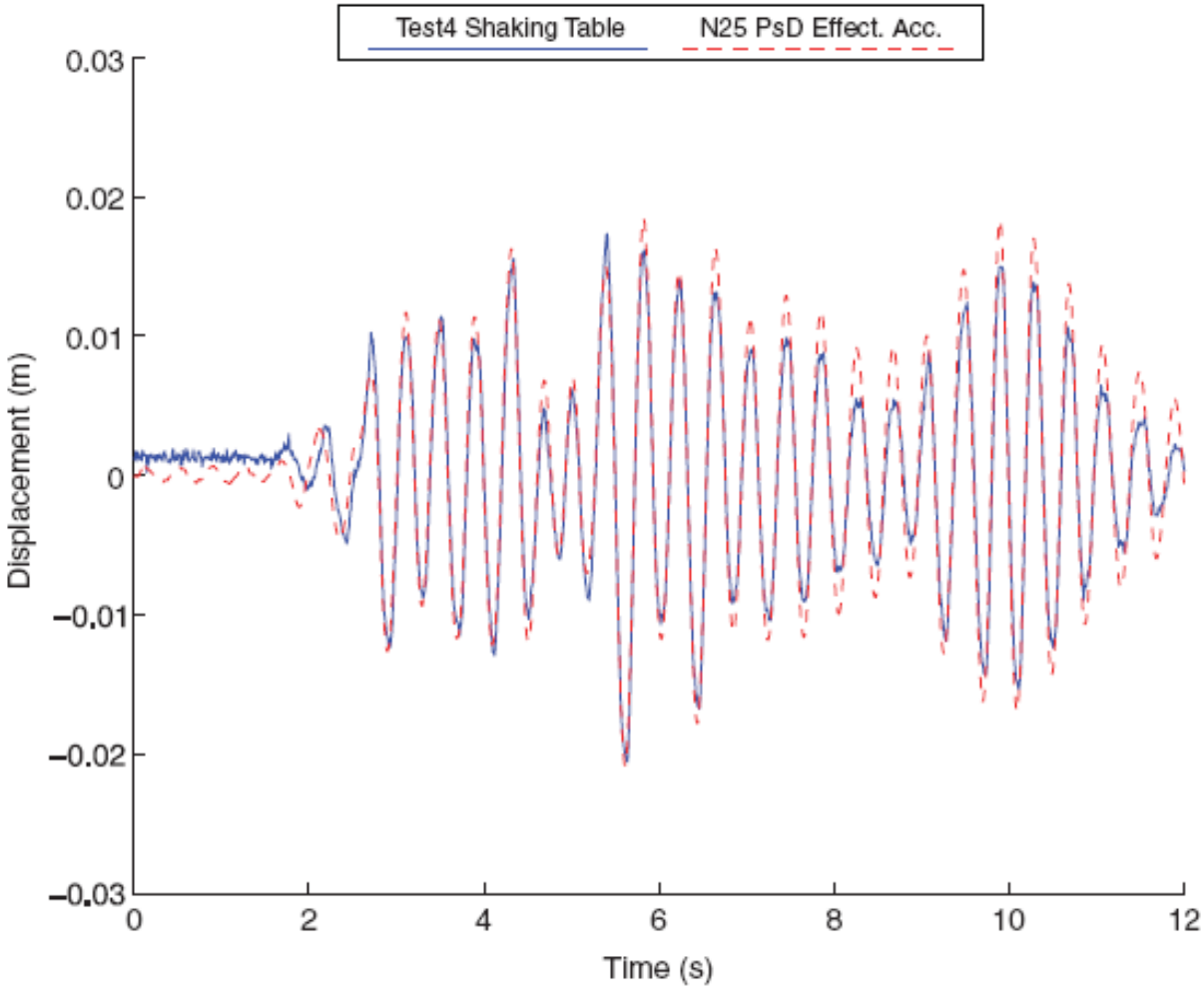


Figure 3. Comparison of PsD (from effective accelerogram) and shaking-table earthquake responses.

The shaking table response was not acceptably reproduced by a PsD test based only the translation input given by the table

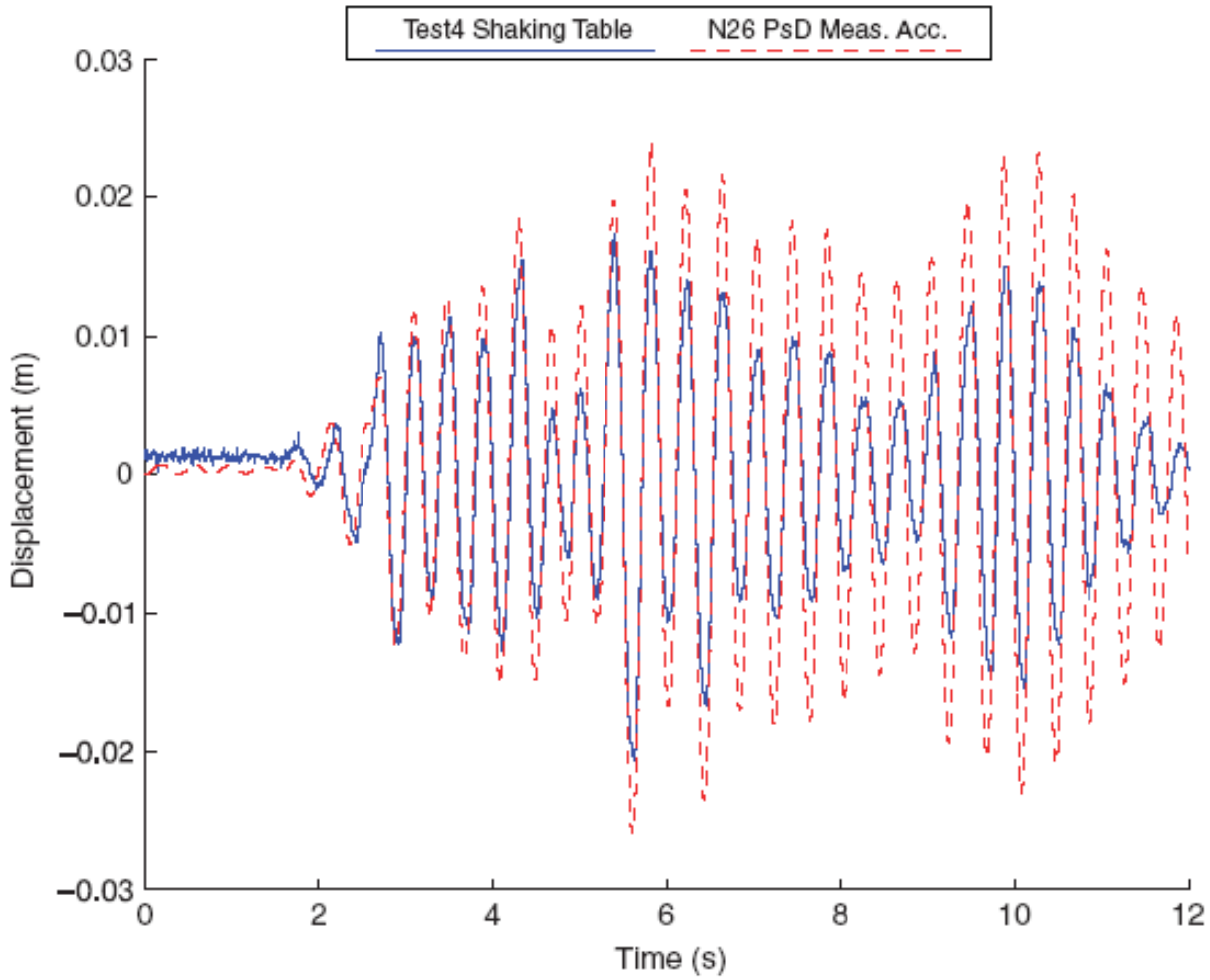


Figure 2. Comparison of PsD (from measured accelerogram) and shaking-table earthquake responses.

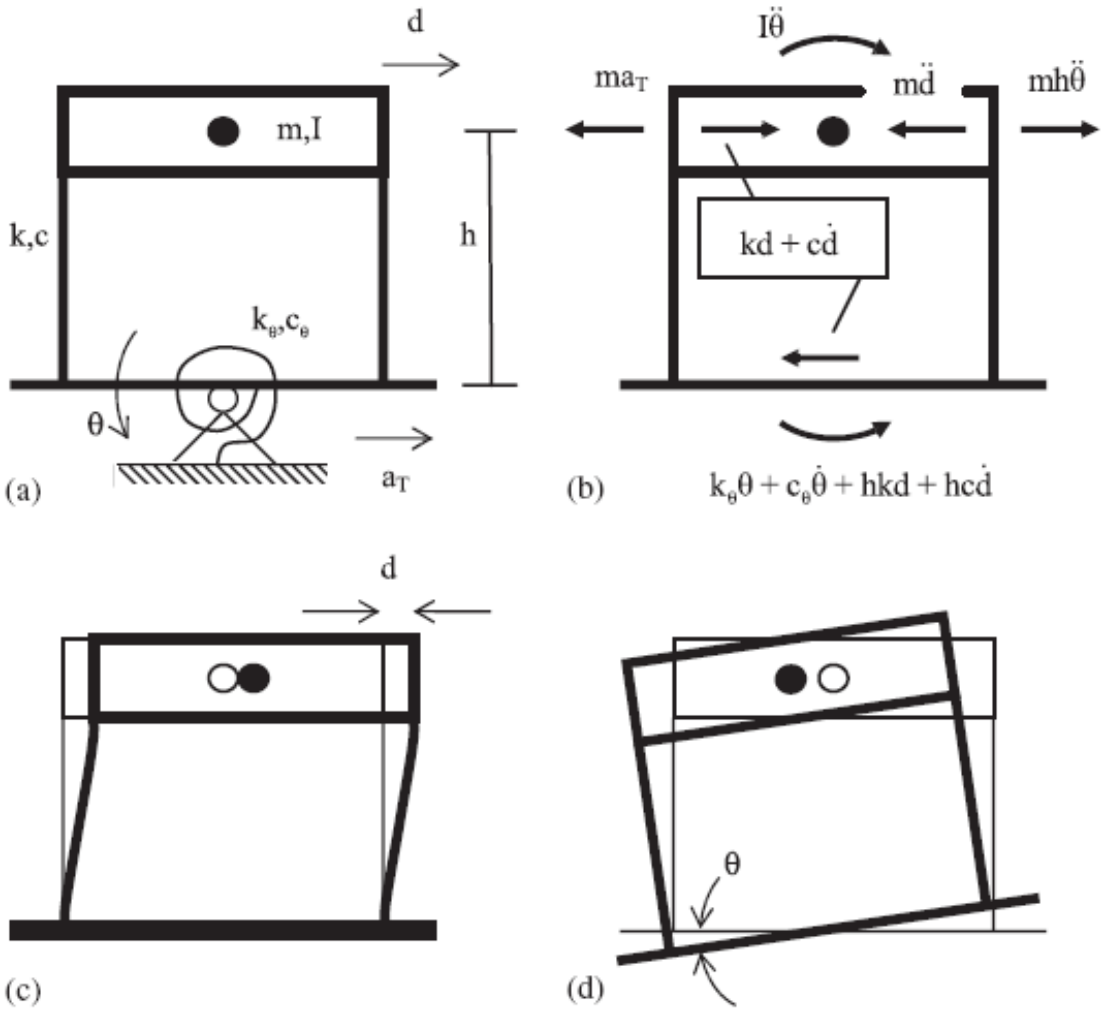


Figure 4. Simplified model including table pitching flexibility: (a) model; (b) acting forces; (c) first DoF; and (d) second DoF.

Damping increment according to the model

$$\Delta\zeta = \zeta_{SYS} - \zeta_{SP} = 0.0262 - 0.0150 = 0.0112$$

Simplified formula

$$\Delta\zeta \simeq -\frac{h^2 \,\mathrm{Im}\{\Phi(\omega_{SP})\}}{2(1/k)} = 0.0118$$

Conclusions and remarks

- "Small" control errors are not a guaranty for no disturbances in the response.
- Testing reliability should be assessed through parameters that directly estimate the disturbances in the response for every mode of vibration.
- The assessment should be based preferably only on the very measurements of the test in question.
- This assessment should be included with the results of every test in a standard manner.

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