Design, Similitude Scaling, and Simulation of a Shake-Table Test Structure

- A single-story reinforced masonry building

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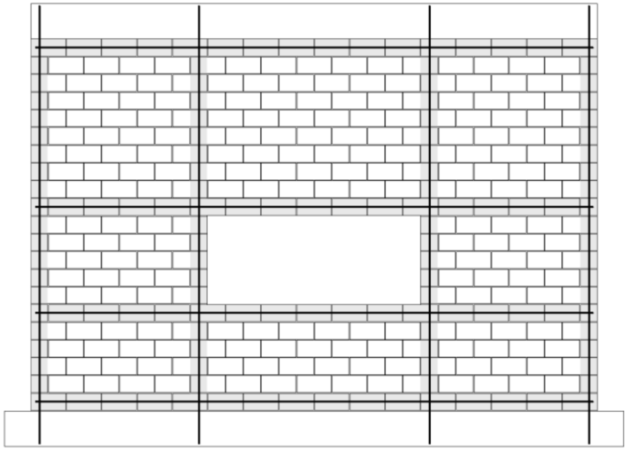
Research Project

Enhancement of the seismic performance and design of Partially Grouted Reinforced Masonry Buildings

<u>Project Objectives:</u>

- Study the system-level performance of Partially Grouted Masonry (PGM) buildings.
- Propose economically competitive design details to improve their performance.
- Develop accurate computational tools that predict their capacity and behavior.
- Evaluate the accuracy of the shear-strength design formula and propose an improved one.



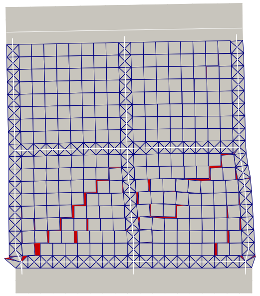
Research Approach

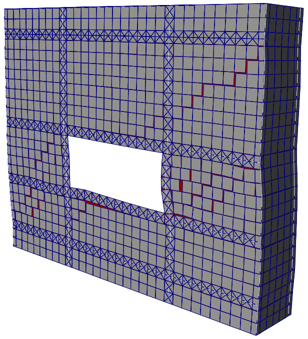
- **Quasi-static cyclic tests of PGM walls**

Planar wall tests (Drexel)

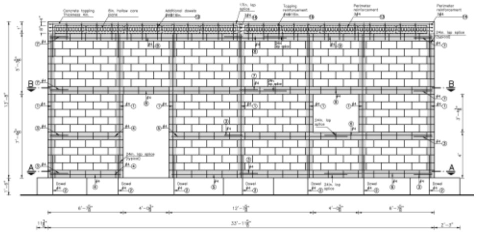
Flanged-wall tests (Minnesota)

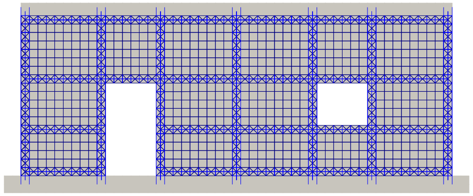
- **Development and calibration of finite element models**





- **Experiment planning**
- **Design of shake-table specimens**
- **Pretest analyses**





- **Shake-table testing**
- **Processing and interpretation of recorded data**
- **Refinement of finite element model**

Design of Experiment

Steps for designing a shake-table test:

- Identify structural system, concept to be tested.
- Design of the prototype structure.
- Design of the shake-table test structure.
- Selection and scaling of ground motions.
- Estimation of the specimen's base-shear capacity, and conduction of pretest analyses.

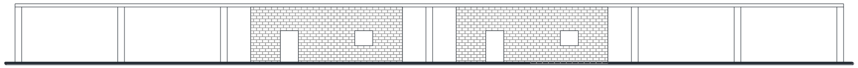
Design of Prototype Structure

Selection of a prototype configuration based on the research objectives:

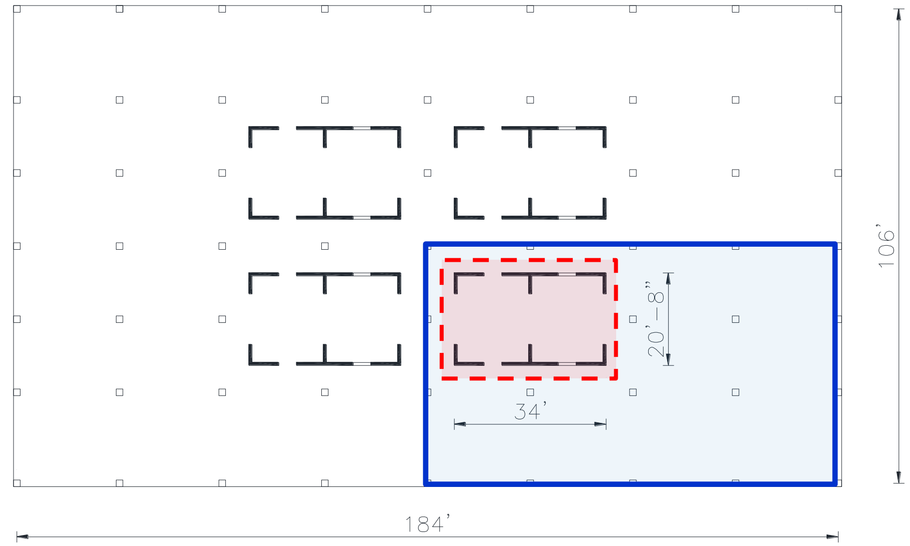
- Configuration that represents a commercial or industrial building in the East Coast.
- Consists of PGM shear walls and gravity columns.
- The large tributary area is necessary so that the shear walls will be a "minimum" design.

Seismic tributary area *is 4.5 times larger than the* ***gravity tributary area*** *for each PGM wall system.*

<u>Prototype Building</u>



Elevation view



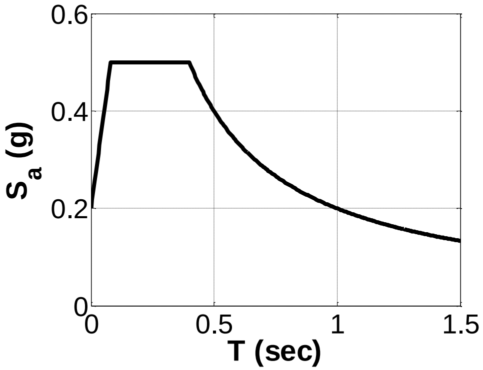
Plan view

Design of Prototype Structure

Conventional Forced-based Design Approach

- Seismic Design Category: **C_{max}** (FEMA P695)

$$S_{DS} = 0.50\text{g}$$
$$S_{D1} = 0.20\text{g}$$



- Approximate fundamental period of the prototype configuration:
  - Calculation using the Eq. 12.8-9 of ASCE/SEI 7-10: $T_a = \frac{0.0019}{\sqrt{C_w}} h_n = 0.024\text{sec}$

    h_n : structural height

    C_w : quantity that depends on the dimensions of the prototype

- Calculation of Design Base Shear :

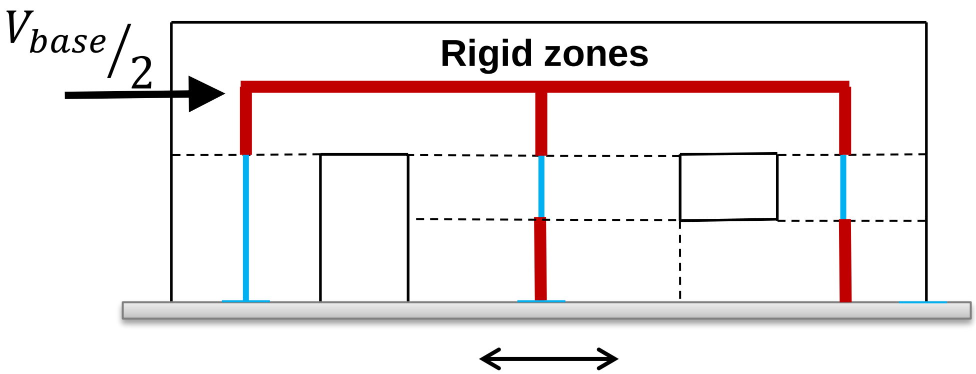
$$V_{base} = \frac{S_{DS} \cdot M_{seismic}}{R} = 102kips$$

$R = 2$: the response modification factor defined in ASCE/SEI

Design of Prototype Structure

Selection of a simplified model for the force-based design

- Use of plane frame that represents the half-structure and is assumed elastic.
- The shear deformation of the walls is considered by using Timoshenko beam elements.



- The flexural and shear capacity of the masonry walls are calculated using the standard provisions of design code MSJC 2013.

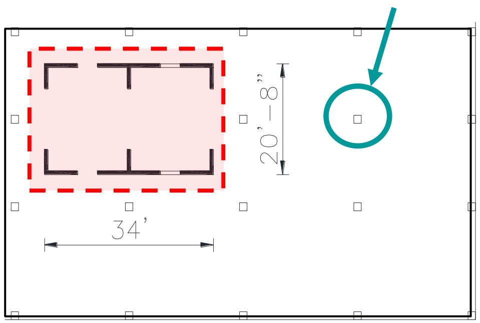
- The minimum amount of reinforcement prescribed by the code is found to be adequate for the imposed demand.

Motivation for Scaling

In general, scaling is applied when:

- Space constraints
- Limited capacity of testing apparatus
- Availability of funds
- Availability of time
- Mismatch between gravity and inertia masses

  - Not feasible to include the gravity columns in the shake-table test structure



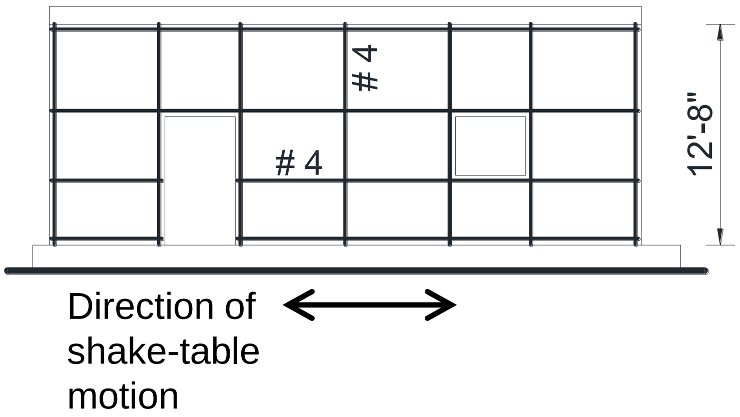
Plan view of prototype

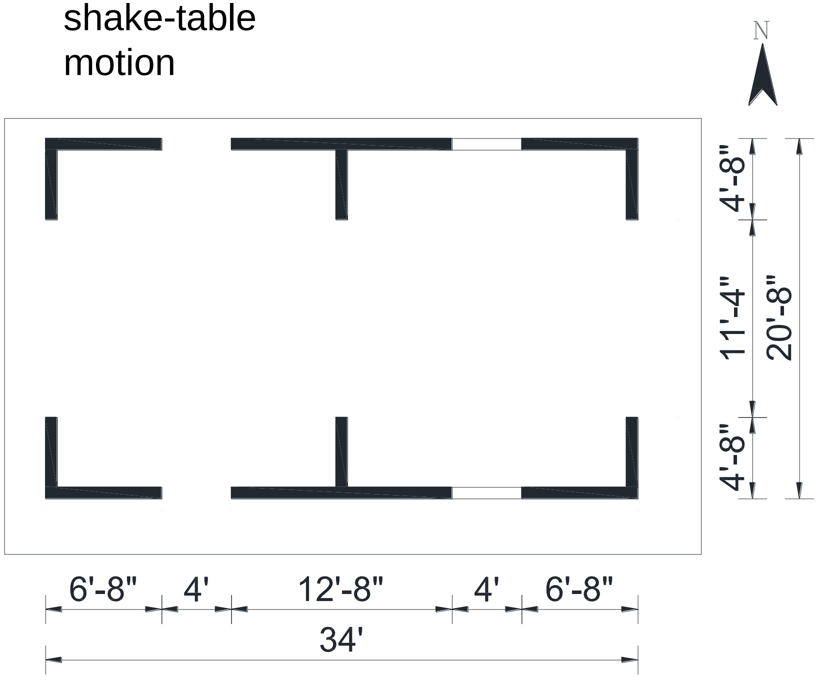
Design of Test Structure

- The shake-table test specimen represents one of the four wall assemblies in full-scale.
- The roof slab of the specimen has larger thickness to represent the actual tributary gravity load of the prototype.
- The specimen has smaller seismic mass than the prototype. The input ground motion needs to be scaled in order to satisfy the similitude law.

Ratio of seismic masses:

$$S_{SM} = \frac{M_{specimen}}{M_{prototype}} = 0.3$$





Similitude Requirements

Background

- Scaled models should satisfy **similitude requirements** so that they can replicate the response of the full-scale structures.
- The similitude requirements for consistent scaling are based on **dimensional analysis**.
- In engineering problems, the **fundamental dimensions** are:
  - Length (L)
  - Force (F) or Mass (M)
  - Time (T)
- Scale factors for 3 dimensionally independent quantities should be selected.
- Express remaining variables of the equation in terms of the selected scale factors.

Derivation of Scaling Factors

- Definition of scale factor: $S_i = \dfrac{i\ quantity\ in\ scaled\ specimen}{i\ quantity\ in\ prototype}$

Example

Given the scale factors of the seismic mass (*SM*), length (*L*), and stress (*σ*), derive the scale factor of time (*t*) in order to satisfy the similitude requirement.

- Express time in terms of the 3 dimensionally independent quantities: $t = \sqrt{\dfrac{L}{a}} = \sqrt{\dfrac{L}{F/S\,M}} = \sqrt{\dfrac{L \cdot SM}{\sigma \cdot L^2}} = \sqrt{\dfrac{SM}{\sigma \cdot L}}$

- Calculate scale factor: $S_t = \dfrac{t_{specimen}}{t_{prototype}} = \sqrt{\dfrac{S_{SM}}{S_\sigma \cdot S_L}}$

Derivation of Scaling Factors

Scaling factors used in order to satisfy the similitude requirement:

- Definition of scale factor: $S_i = \dfrac{i\ quantity\ in\ scaled\ specimen}{i\ quantity\ in\ prototype}$

Given factors:

- Seismic mass: $S_{SM} = 0.30$
- Length: $S_L = 1.00$
- Stress: $S_\sigma = 1.00$

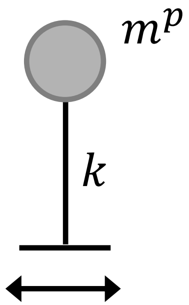
Derived factors:

- Force: $S_F = S_L^2 \times S_\sigma = 1.00$
- Moment: $S_M = S_F \times S_L = 1.00$
- Seismic Acceleration: $S_{SA} = S_F / S_{SM} = 3.33$
- Time: $S_t = \sqrt{S_L / S_{SA}} = 0.55$
- Frequency: $S_f = 1 / S_t = 1.82$

Example of Scaling Concept

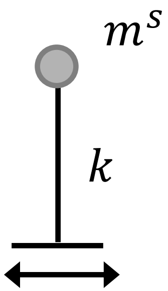
Single degree of freedom, elastic, undamped oscillators:

- **Prototype:**



$$a_b^p = a_o^p \cdot \sin\omega^p t^p$$

- **Scaled specimen:**



$$a_b^s = a_o^s \cdot \sin\omega^s t^s$$

Scale factors:

$S_{SM} = 0.30$

$S_L = 1.00$

$S_\sigma = 1.00$

- To satisfy the similitude law:

$$a_o^s = S_{SA} \cdot a_0^p = 3.33 \cdot a_0^p$$

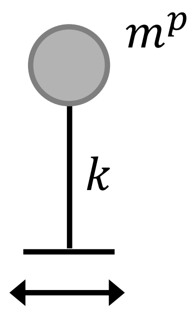
$$\omega^s = S_f \cdot \omega^p = 1.82 \cdot \omega^p$$ Excitation frequency

$$\omega_n^s = S_f \cdot \omega_n^p = 1.82 \cdot \omega_n^p$$ Natural frequency

Example of Scaling Concept

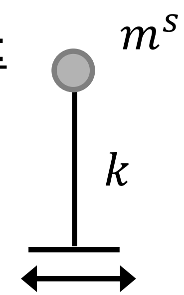
Single degree of freedom, elastic, undamped oscillators:

- <u>Prototype:</u>



$$a_b^p = a_o^p \cdot \sin\omega^p t^p$$

- <u>Scaled specimen:</u>



$$a_b^s = a_o^s \cdot \sin\omega^s t^s$$

<u>Scale factors:</u>

$S_{SM} = 0.30$

$S_L = 1.00$

$S_\sigma = 1.00$

Equation of motion:

$$m\ddot{u} + ku = -ma_o \sin\omega t$$

Assume zero initial conditions: $u(0) = \dot{u}(0) = 0$

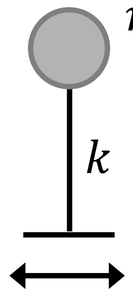
Solution:

$$u(t) = -\frac{a_0}{\omega_n^2}\frac{1}{1-(\omega/\omega_n)^2}\left(\sin\omega t - \frac{\omega}{\omega_n}\sin\omega_n t\right)$$

Example of Scaling Concept

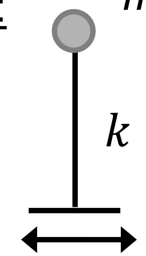
Single degree of freedom, elastic, undamped oscillators:

- <u>Prototype:</u>



$$a_b^p = a_o^p \cdot \sin\omega^p t^p$$

- <u>Scaled specimen:</u>



$$a_b^s = a_o^s \cdot \sin\omega^s t^s$$

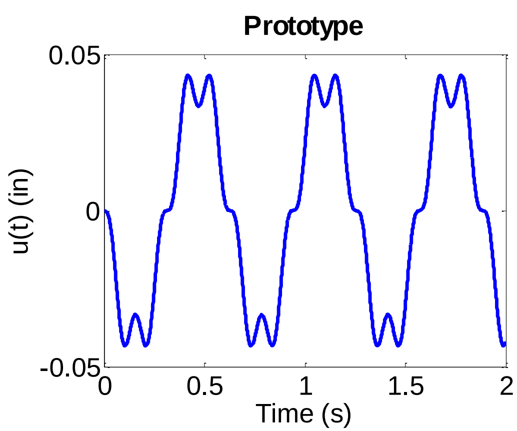
<u>Scale factors:</u>

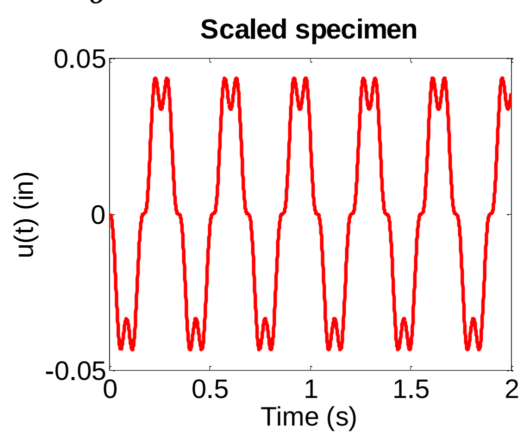
$S_{SM} = 0.30$

$S_L = 1.00$

$S_\sigma = 1.00$

For: $\omega_n^p = 50\ \mathrm{rad/s}$ $\omega^p = 10\ \mathrm{rad/s}$ $a_o^p = 100$ in/s^2



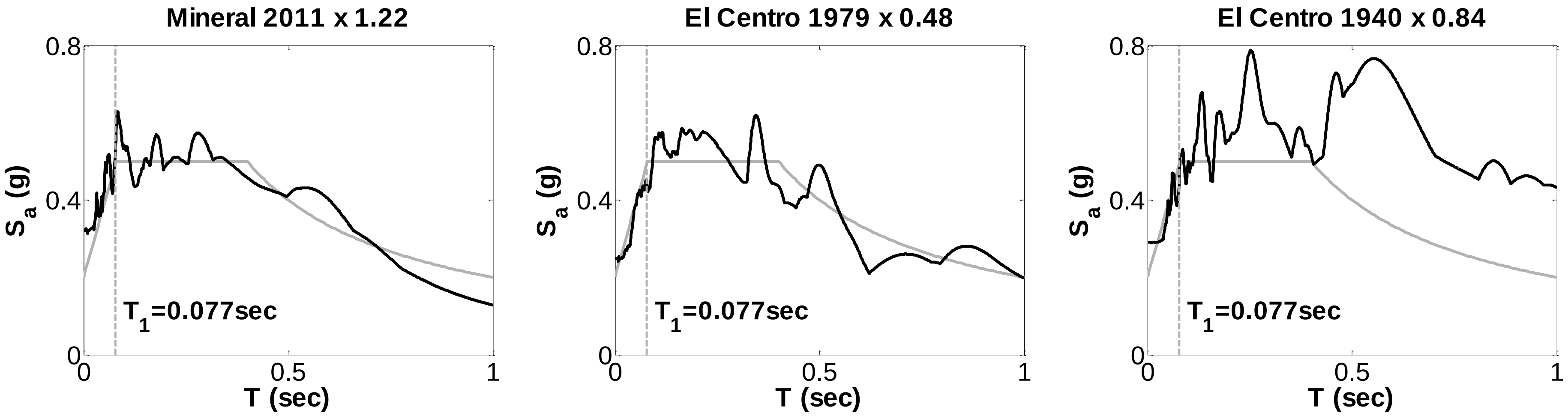


Selection and Scaling of Ground Motions

- A finite element model of the structure was developed. The fundamental period of the prototype was estimated through modal analysis:

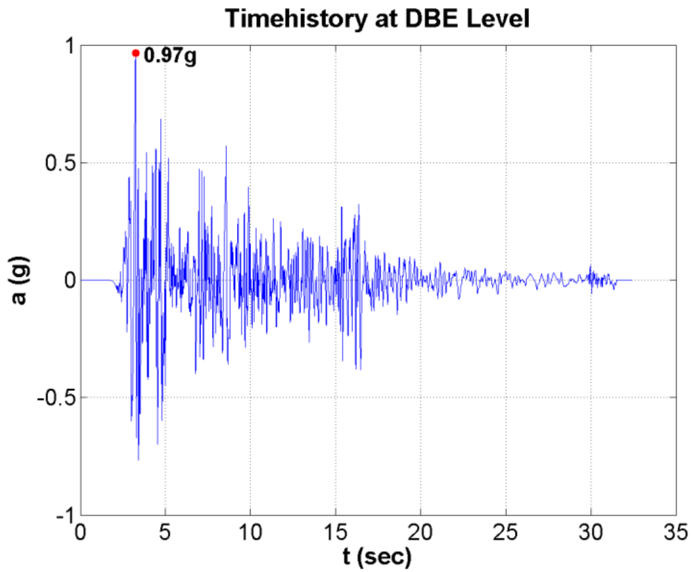
$$T_1 = 0.077sec$$

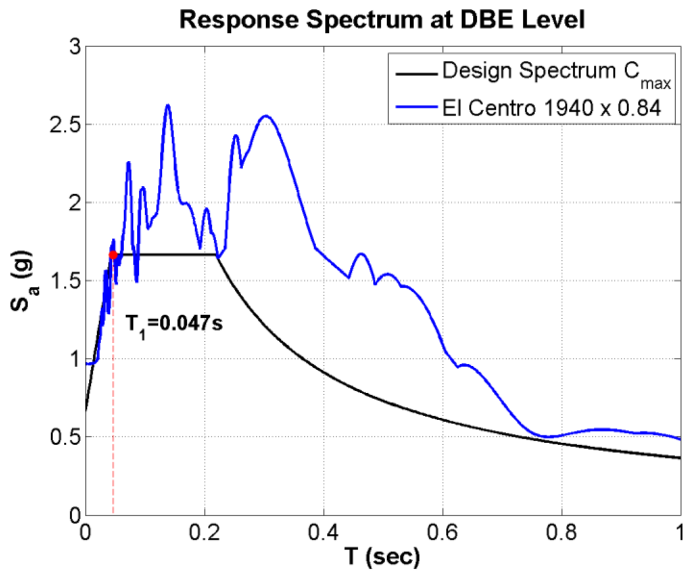
- Scaling of ground motion records to the level of the Design Earthquake for periods near the fundamental period.



Scaling of Ground Motions for Similitude

The input shake-table motions need to be scaled consistently to satisfy the similitude requirement.





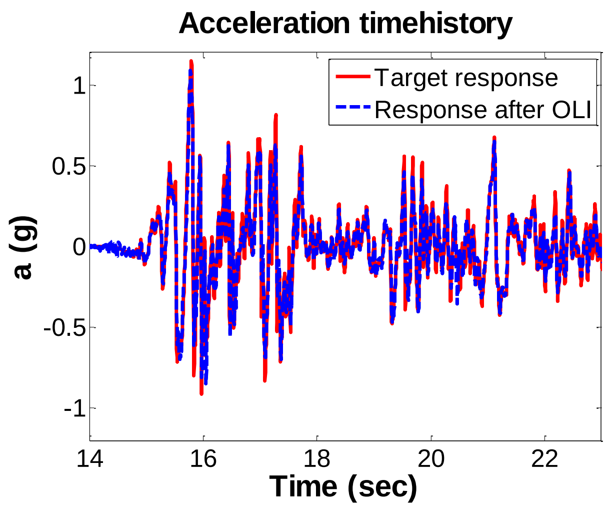
- Similitude Scaling:

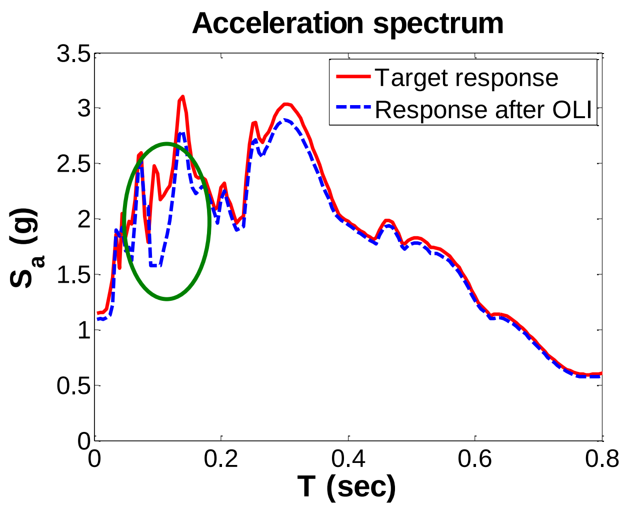
Amplification of the acceleration by the factor: $S_{SA} = S_F / S_{SM} = 3.33$

Compression of the time by the factor: $S_t = \sqrt{S_L / S_{SA}} = 0.55$

Tuning of the Shake-Table

➢ Tuning of the shake-table system for the given scaled records at bare table condition (On-Line Iterative compensation method – OLI).





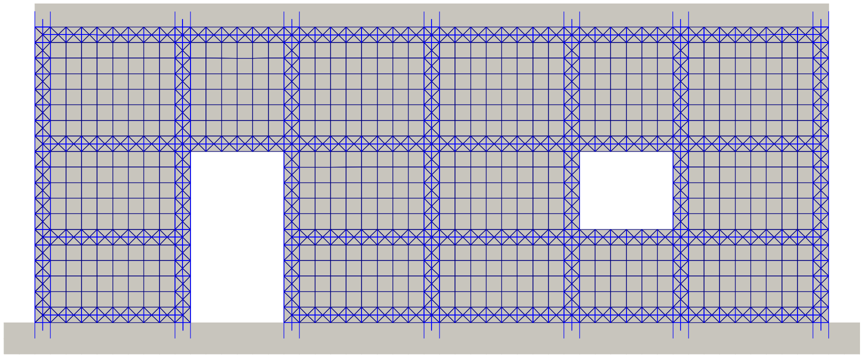
➢ The target acceleration spectrum and the feedback spectrum do not match well for frequencies in the region of 10 Hz.

➢ The oil column resonance frequency is about 10 Hz. A notch filter is applied to suppress those frequencies.

Pretest analyses

A plane stress nonlinear finite element model of the specimen was developed to simulate the shake-table tests.

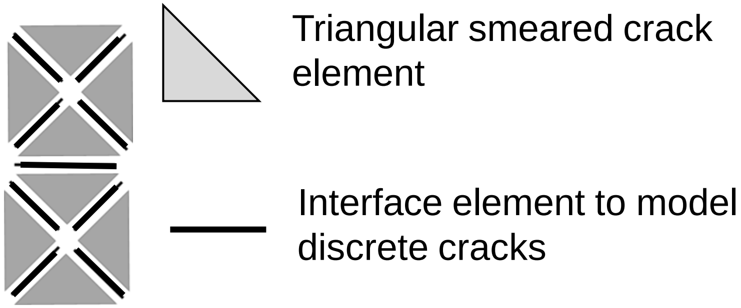
Finite element modeling scheme



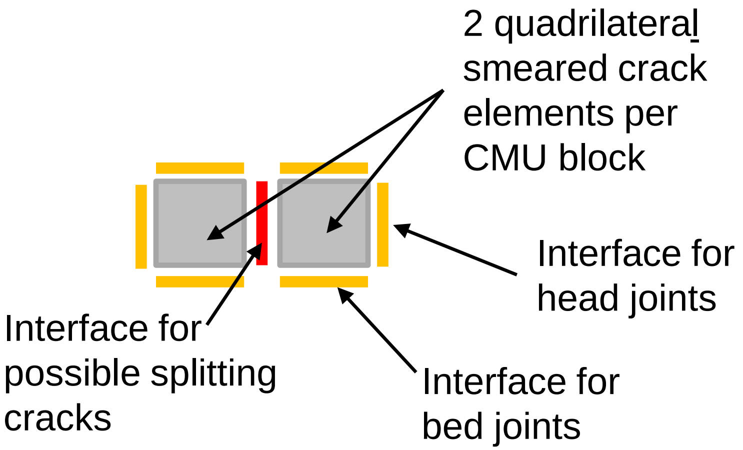
➢ Reinforcement:

- Truss elements with bilinear material
- No bond-slip is considered
- Horizontal truss elements with elastoplastic material are used to account for the dowel effect

➢ Grouted Masonry:

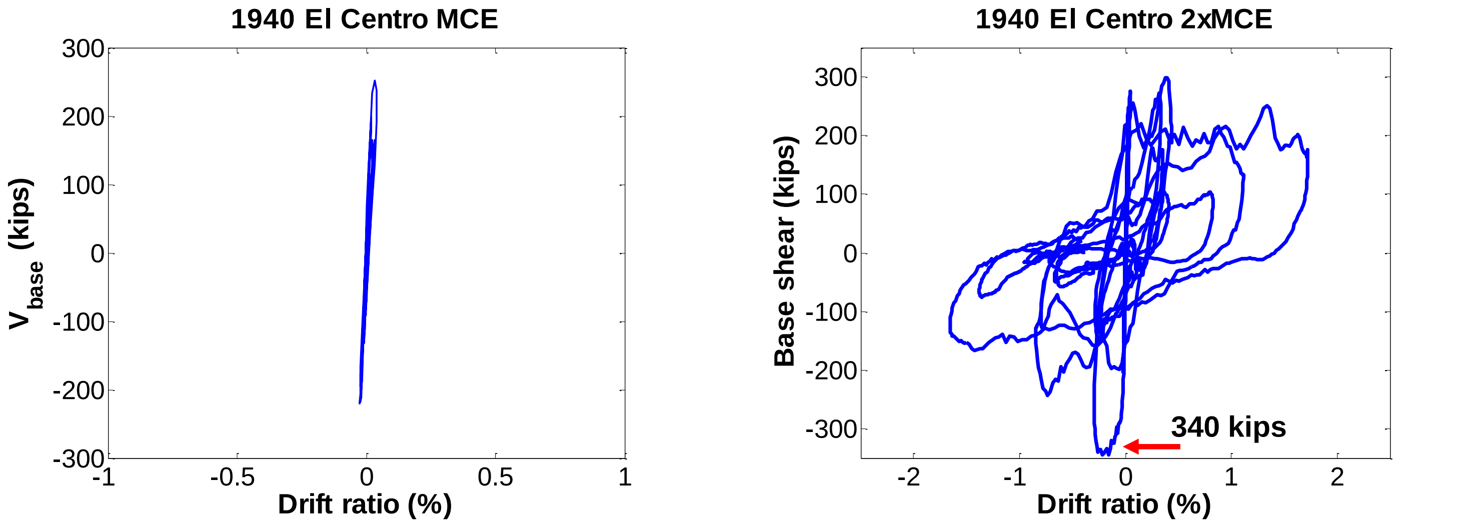


➢ Ungrouted Masonry:

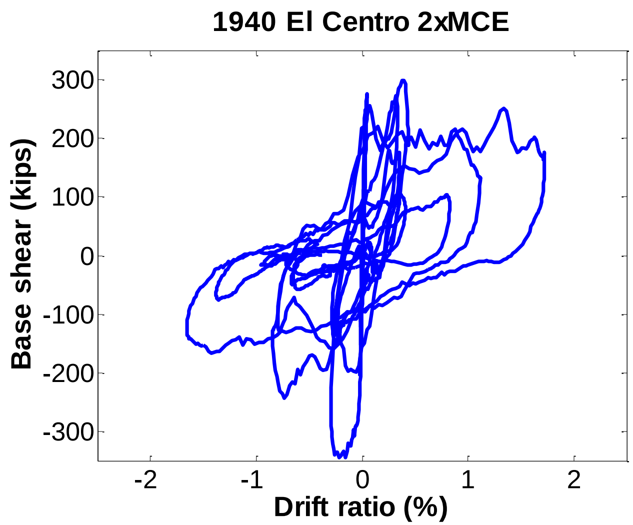


Pretest analyses

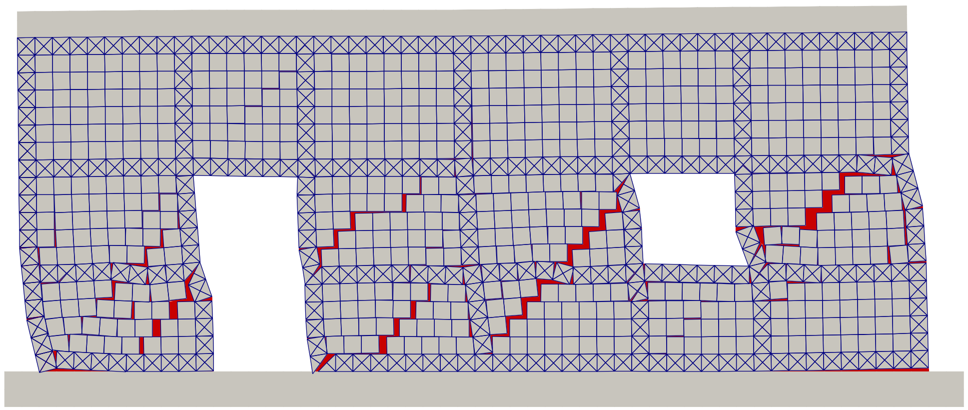
- Pretest analyses are necessary to estimate:
  - The base shear capacity of the specimen
  - The failure mechanism and ductility
  - The demand on the shake-table system (forces on actuators, max. horizontal displacement, etc)
- Time-history analyses using the 1940 El Centro record with intensities MCE and 2xMCE were performed.



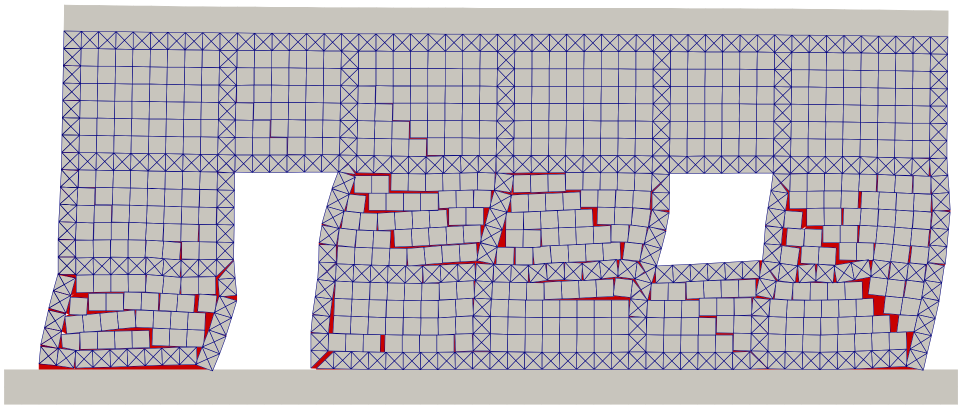
Pretest analyses



Deformed mesh at maximum base shear



In the negative direction



In the positive direction

Instrumentation

South – East View

North – West View

North – East Interior View

<u>Instrumentation</u>

- 178 strain gages
- 180 displacement transducers
- 39 accelerometers
- Non-contact measurements with DIC technology (Drexel University)

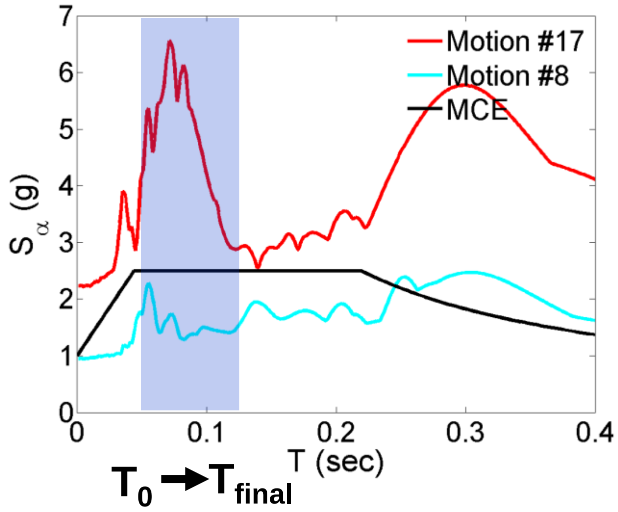
Intensity of Ground Motions

- The intensity of a base excitation is quantified in terms of the developed spectral acceleration compared to the MCE spectrum of the code.

- During a shake-table test trial, the fundamental period of the structure may shift as a result of structural damage

- Effective intensity of ground motion, I_{eff}:

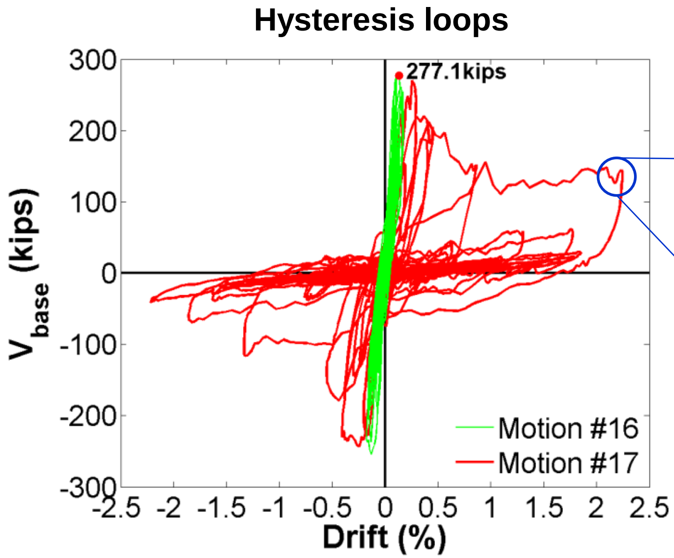
  The mean value of the ratio $\frac{S_{a,RECORD}}{S_{a,MCE}}$ *in the range of the fundamental period before and after each motion.*

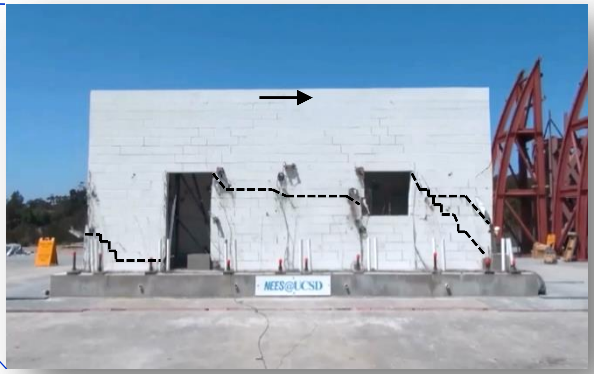


Structural Performance

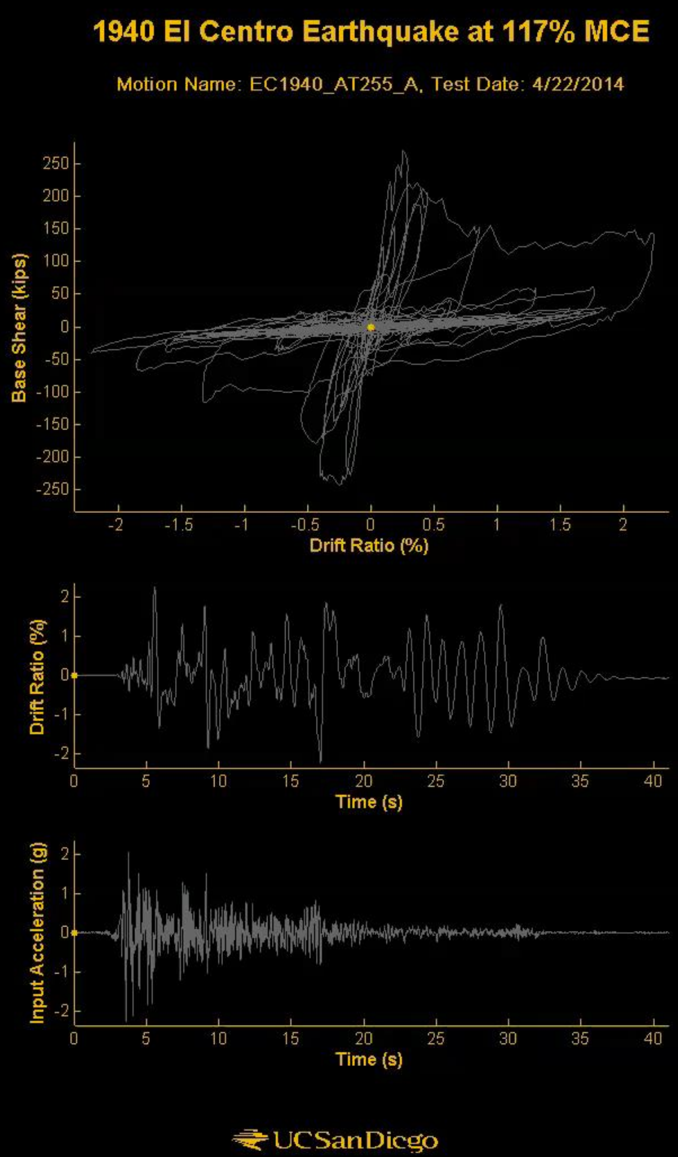
- The structure was subjected to a sequence of 17 motions. The 1940 El Centro record was mainly used.
- The structure was practically elastic up to effective motion intensity 0.81 x MCE
- Structural response quantities during the last 5 motions

Motion #	Name	I_{eff} (MCE)	Max. Drift Ratio	Max. V_{base}
13	EC1940 125%	1.52	0.058 %	242 kips
14	EC1940 164%	2.04	0.095 %	264 kips
15	EC1940 188%	2.07	0.121 %	271 kips
16	EC1940 202%	1.43	0.175 %	**277 kips**
17	EC1940 214%	1.17	2.245 %	270 kips





Video of the final motion

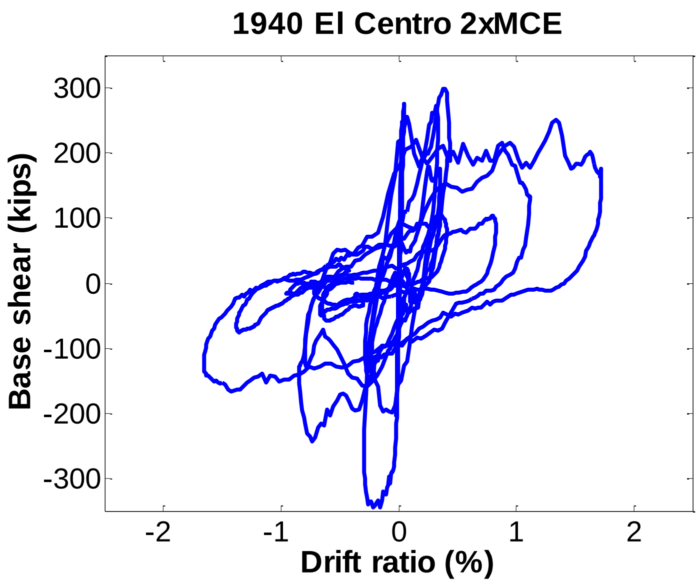


South View [t=0.033s]

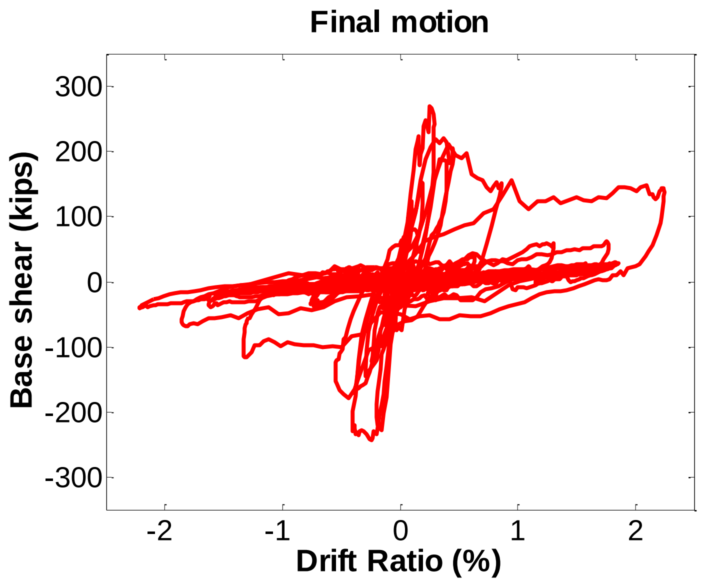
North-East Inside View [t=0.033s]

Comparison with Pretest Analysis

Pretest analysis



Experimental response



- The numerical model overestimated the maximum base shear by 20%.
- Note that, the base excitation of the two cases is different.
- For the pretest analysis, the 1940 El Centro record at 250% was used. The intensity is 2xMCE based on the period of the undamaged structure.
- For the final shake-table motion, the intended excitation was the 1940 El Centro record at 214%. The effective intensity was 1.17xMCE.

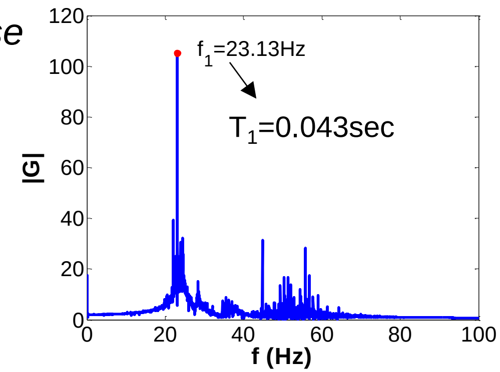
System Identification

- **White noise** tests were performed after each motion to identify the change of the fundamental period.
- For the system identification, the base acceleration was used as the **input signal**, and the recorded acceleration at the roof of the specimen as the **output signal**.
- The **transfer function** of the structural system can be estimated in the frequency domain as the ratio of the **Discrete Fourier Transform** (DFT) of the output signal over the DFT of the input signal:

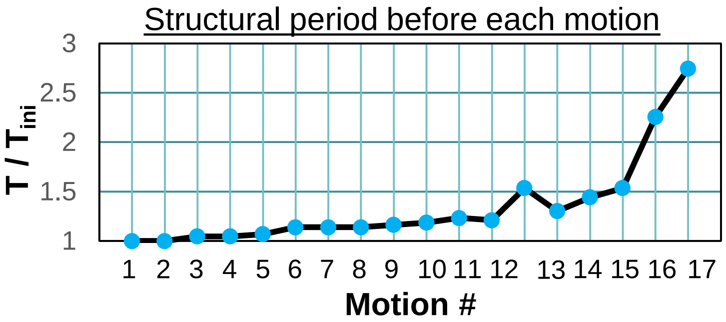
$$G\left(e^{j\omega_k}\right) = \frac{Y(\omega_k)}{U(\omega_k)} \quad \text{with} \quad U(\omega_k) = \sum_{n=1}^{N} u(t_n) \cdot e^{-j\omega_k t_n} \quad \text{and} \quad Y(\omega_k) = \sum_{n=1}^{N} y(t_n) \cdot e^{-j\omega_k t_n}$$

- Plotting the **magnitude** of the transfer function with respect to the frequency reveals the fundamental frequency of the structure.

1st white noise test with the structure undamaged

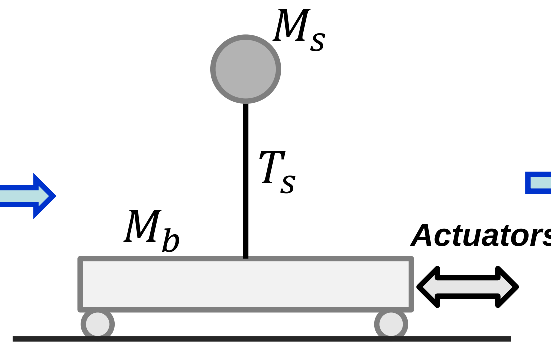


Evolution of fundamental period during testing

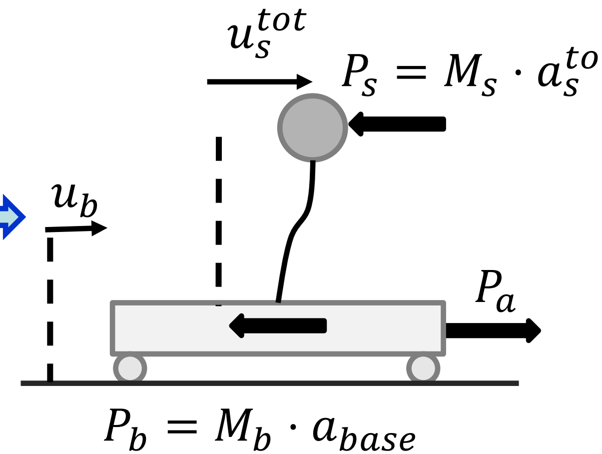


Equilibrium of Seismic Forces

Physical system



Idealized system



- By equilibrium the total force demand on the actuators is given by:

$$P_a(t) = M_s \cdot a_s(t) + M_b \cdot a_{base}(t)$$

- The force demand on the actuators needs to be smaller than their operational capacity.

- Nonlinear time-history analysis of the test structure is required in order to determine the maximum force on the table actuators.

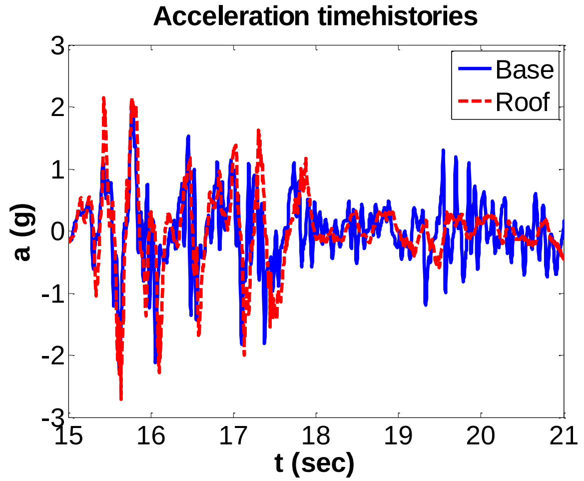
- **Stiff structures** like the masonry building presented here may lead to high demand on the actuators:

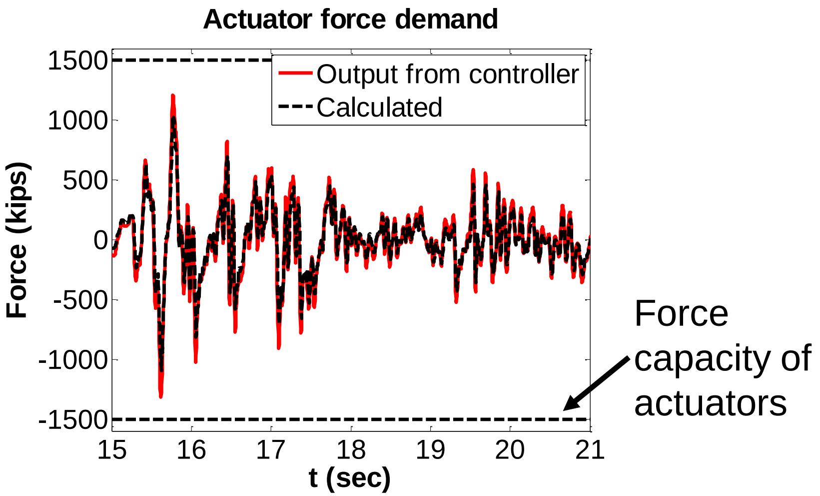
  The base acceleration and the roof acceleration is likely to be **in phase**

Equilibrium of Seismic Forces

Example

Calculation of the force developed in the actuators for the final motion (Motion #17).





Mass at the base: $M_b = M_{platen} + M_{spec.foundation} = 254 + 122 = 376kips$

Seismic mass of specimen: $M_s = 122.2kips$

$$P_a(t) = M_s \cdot a_s(t) + M_b \cdot a_{base}(t)$$

The pretest analysis at 2xMCE predicted that the required actuator force would be 1296 kips

Thank you