Journey Through a Project: Shake-table Test of a Reinforced Masonry Structure

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Research Project

Enhancement of the Seismic Performance and Design of Partially Grouted Reinforced Masonry Buildings (UC San Diego, Drexel U. & U. of Minnesota)

Objectives:

- Understand system-level performance of Partially Grouted Masonry (PGM) buildings.
- Develop cost-efficient design details to improve their performance.
- Develop accurate computational models to predict their capacity and behavior.
- Develop improved shear-strength formula for design.

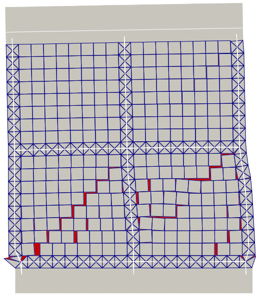
Scope of Project and Approach

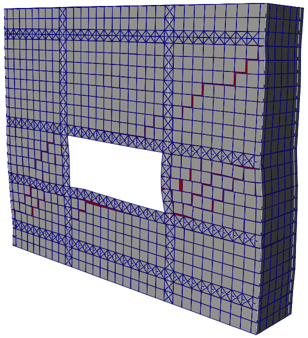
Quasi-static cyclic tests of PGM walls

Planar wall tests
(Drexel)

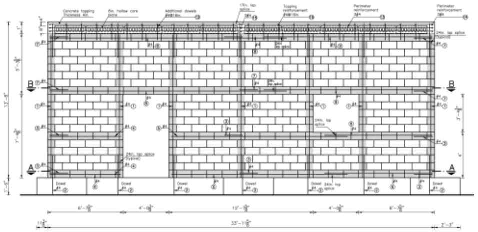
Flanged-wall tests
(Minnesota)

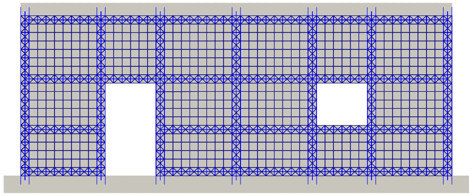
Development and calibration of finite element models





Design of shake-table experiment





- Design of test specimen
- Selection of ground motion records
- Pretest analyses
- Development of instrumentation plan

Shake-table testing

- Construction and instrumentation
- Testing
- Analysis of test data

Design of Shake-table Experiment

- Determined the structural configuration for the prototype building.
  - Representative of actual buildings
- Designed the shake-table test structure.
  - Conforming to current codes
  - Consulting data from quasi-static tests and analytical models
  - Scaling of the structure (the dimension and/or the mass as needed) to fit the shake-table size and capacity
- Selection and scaling of ground motions.
  - Amplitude and time scaling to meet the similitude requirements
  - Determined the loading protocol (test sequence)
- Conducted pretest analyses.
  - To identify base-shear capacity of the test structure
  - To confirm the loading protocol
- Developed instrumentation plan

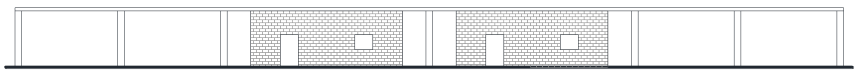
Selection of Prototype Building

Prototype configuration was determined with the following criteria:

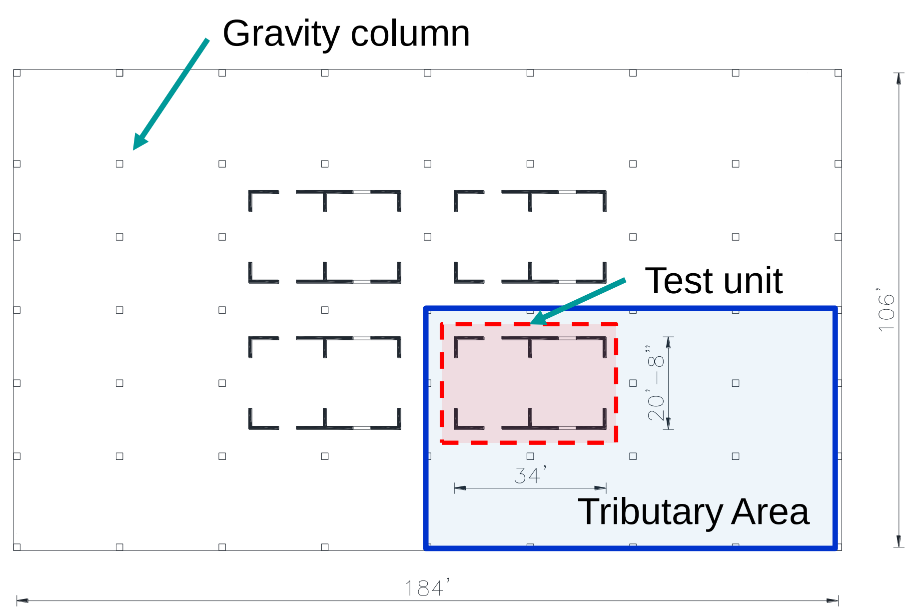
- Representative of commercial or industrial buildings.
- Large tributary seismic mass so that the shear walls would reflect a "minimum" design.

***Tributary roof seismic mass** was 4.5 times the **gravity mass**.*

Prototype Building



Elevation view

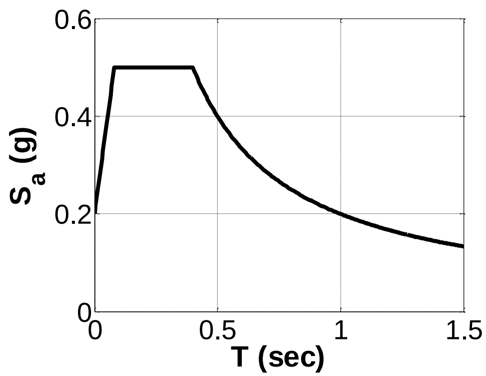


Plan view

Design of Test Structure

Forced-based Design Approach (ASCE 7-10 and TMS 402-13)

- Seismic Design Category: $\mathbf{C_{max}}$ (FEMA P695)



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

- Fundamental period:

$$T_a = \frac{0.0019}{\sqrt{C_w}} h_n = 0.024\,\text{sec}$$

h_n : structural height

C_w : depends on the footprint of the structure and shear wall dimensions

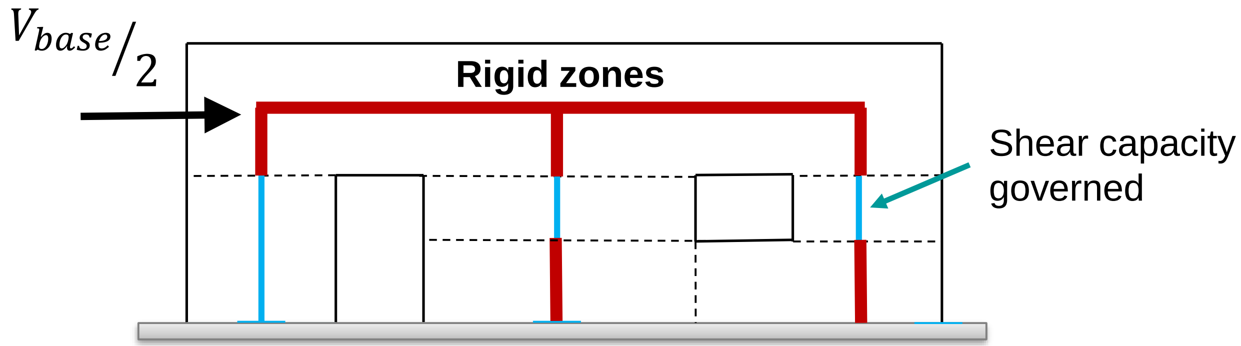
- Design Base Shear :

$$V_{base} = \frac{S_{DS} \cdot W}{Rg} = 102 kips$$ ($R = 2$ for Ordinary RM shear walls)

Design of Test Structure

Simplified model for design:

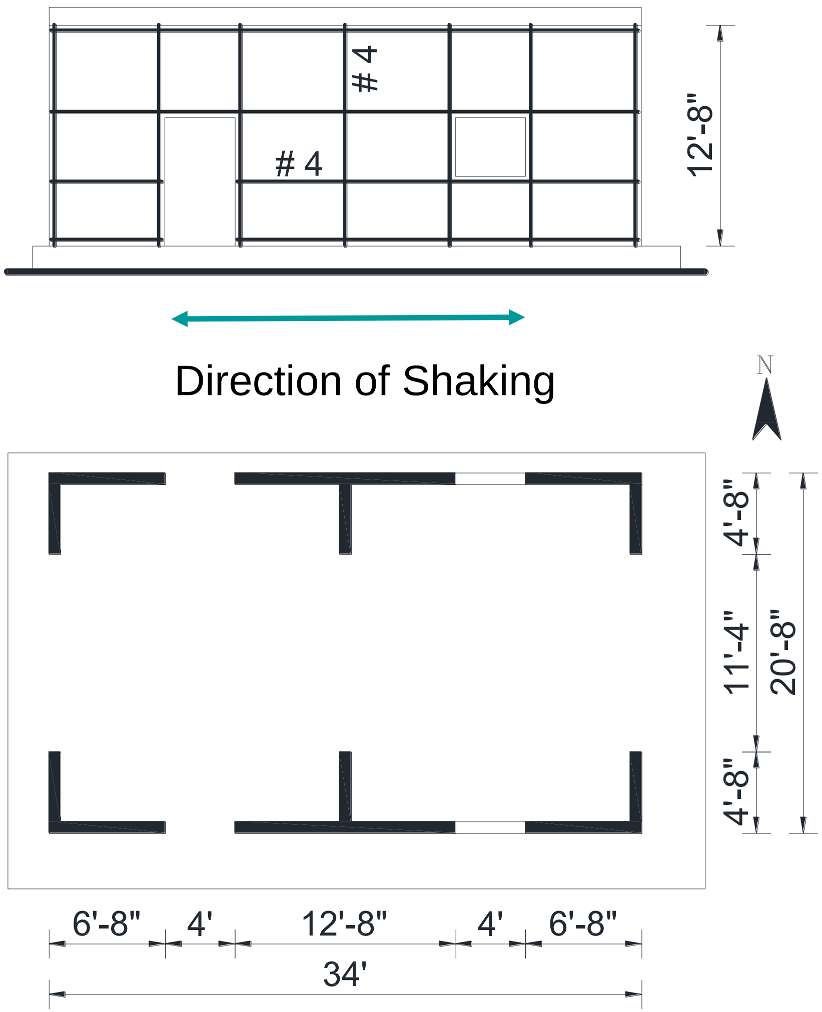
- Elastic plane frame representing one-half of the structure.
- Shear deformation was accounted for by using Timoshenko beam elements.



- Flexural and shear capacities of masonry walls were calculated according to TMS 402-13.

Design of Test Structure

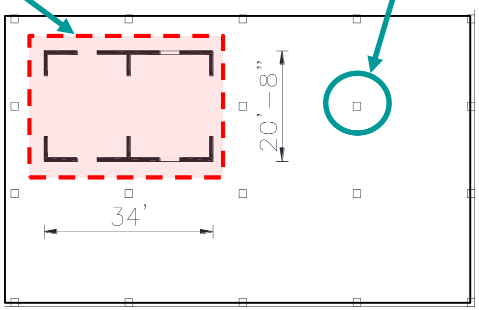
Design was accomplished with the minimum reinforcement prescribed by the code.



Seismic Mass of Test Structure

- Tributary roof seismic mass was 4.5 times the gravity mass.
- Not able to include the entire tributary roof area because of the space and cost.
- Thickness of the roof slab was slightly increased to provide the exact tributary gravity mass.
- Test specimen had seismic mass smaller than the design (prototype) seismic mass.

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



Plan view

Scaling of ground motion was necessary to achieve dynamic similitude because of the mismatch between the design seismic mass and the specimen seismic mass.

Similitude Requirements

Equation of motion:

$$a + 2\xi\omega v + \frac{f_s}{M} = -a_g$$

The following three dimensionally independent fundamental quantities are selected for the scaling of the ground motions:

M, σ, and L (seismic mass, stress, and length)

The values of their scaling factors are determined by the properties of the test structure:

$$S_{SM} = \frac{M_{specimen}}{M_{prototype}} = 0.3 \qquad S_{\sigma} = \frac{\sigma_{specimen}}{\sigma_{prototype}} = 1 \qquad S_L = \frac{L_{specimen}}{L_{prototype}} = 1$$

Similitude Requirements

Dimensionless parameters in terms of the fundamental quantities and remaining variables:

$$\pi_1 = \frac{aM}{\sigma L^2} \qquad \pi_2 = \frac{\omega M^{0.5}}{\sigma^{0.5} L^{0.5}} \qquad \pi_3 = \frac{f_s}{\sigma L^2} \qquad \pi_4 = \frac{t\sigma^{0.5} L^{0.5}}{M^{0.5}}$$

Similitude requirements:

$$\pi_{i,specimen} = \pi_{i,prototype}$$

Hence,

$$S_{accel} = \frac{S_L^2 S_\sigma}{S_{SM}} = 3.333 \qquad S_\omega = \sqrt{\frac{S_L S_\sigma}{S_{SM}}} = 1.826$$

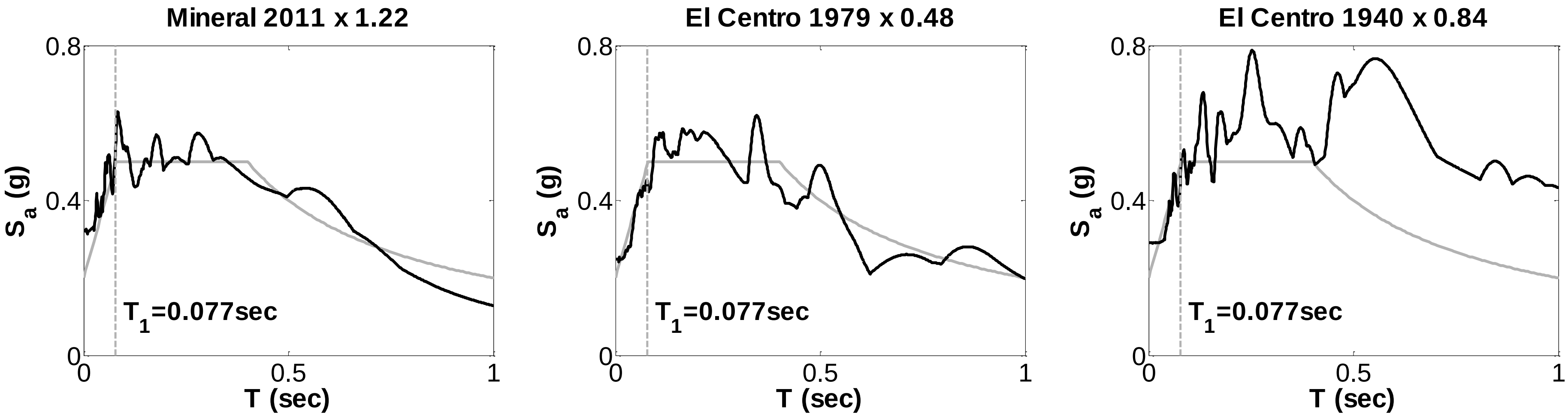
$$S_f = S_L^2 S_\sigma = 1 \qquad S_t = \sqrt{\frac{S_{SM}}{S_L S_\sigma}} = 0.5477$$

Selection and Scaling of Ground Motions

The fundamental period of the prototype was estimated with a finite element model:

$$T_1 = 0.077\ sec$$

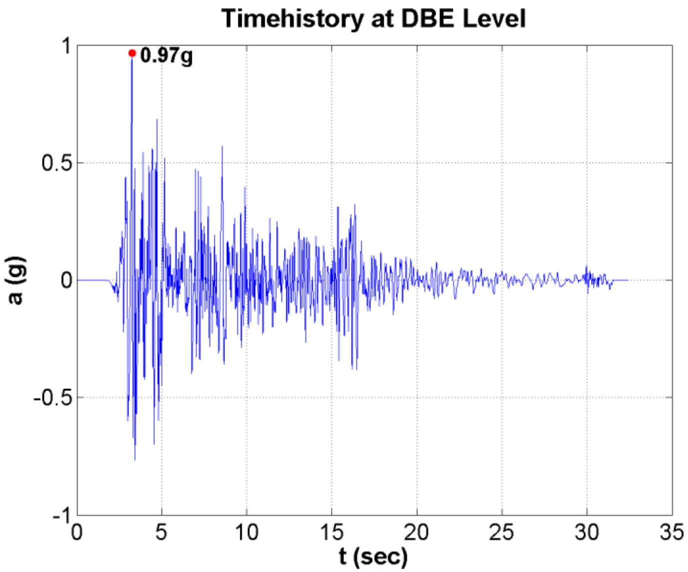
Scaling the input motion to the design-level earthquake, the amplitude of the motion was scaled so that its spectral intensity matched that of the Design Earthquake at the predicted fundamental period of the structure.

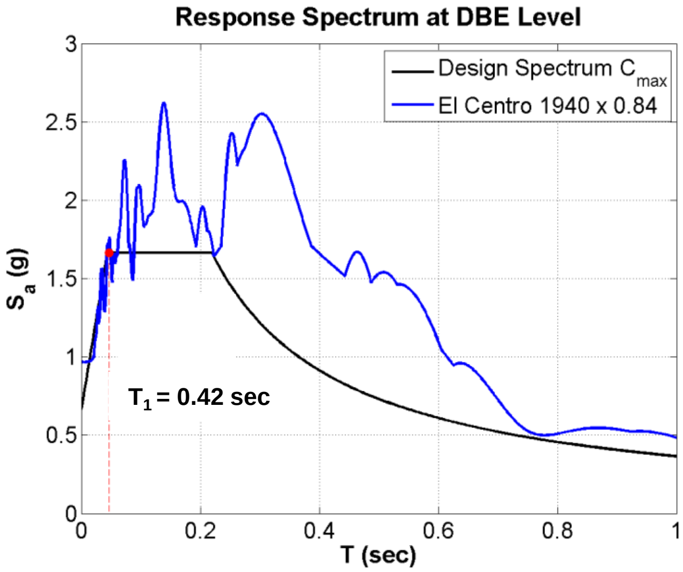


Scaling of Ground Motions for Similitude

Ground motions were scaled to satisfy the similitude requirements.

El Centro 1940



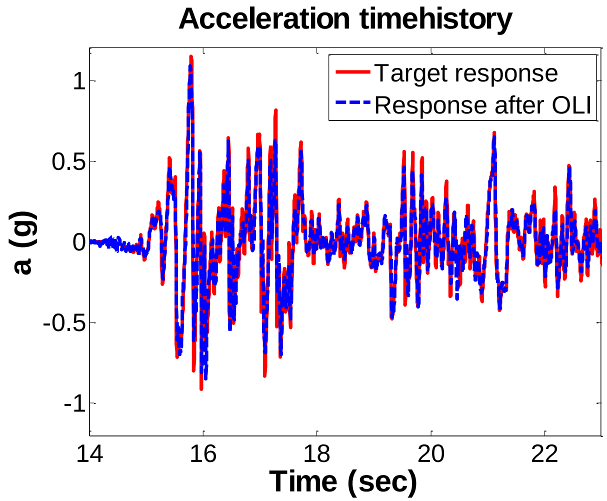


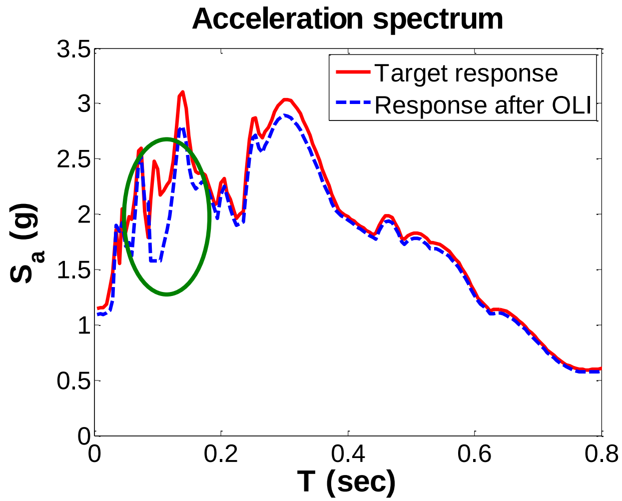
Amplified the acceleration by $S_{accel} = 3.333$

Compress the time by $S_t = 0.5477$

Tuning of Shake-Table

Tuning of bare shake table with the selected ground motion records scaled to different levels (On-Line Iterative compensation method – OLI).





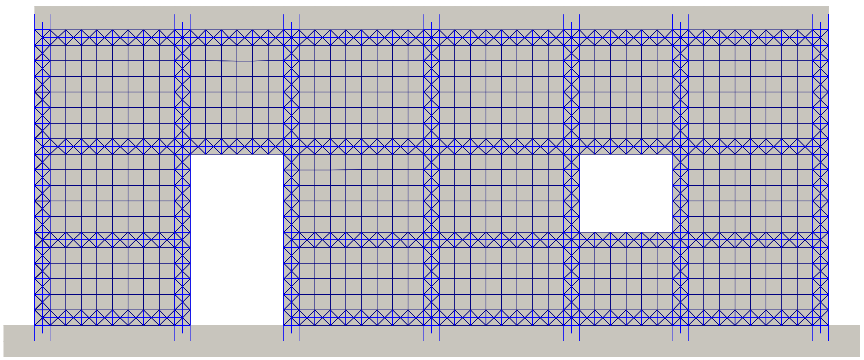
The target acceleration spectrum and the spectrum of the table motion did not match well for frequencies near 10 Hz.

This was because the oil column resonance frequency of the table was about 10 Hz. A notch filter was applied to suppress table resonance near this frequency.

Pretest Analyses

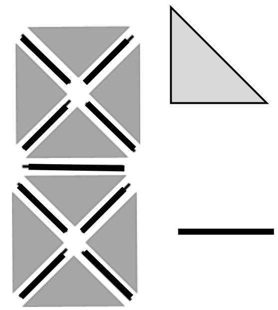
A plane stress nonlinear finite element model of the specimen was developed to simulate the shake-table tests.

Finite element modeling scheme

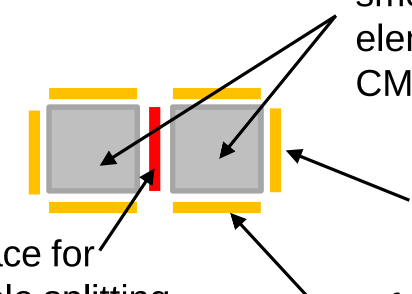


- Reinforcement:
  - Truss elements with a bilinear material law
  - Dowel effect of vertical bars was simulated by horizontal truss elements with a nonlinear material law

- Grouted Masonry:



- Ungrouted Masonry:



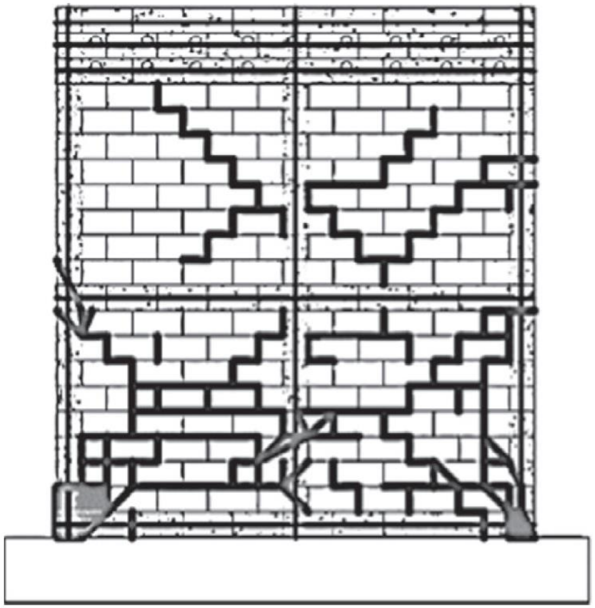
Validation Analyses

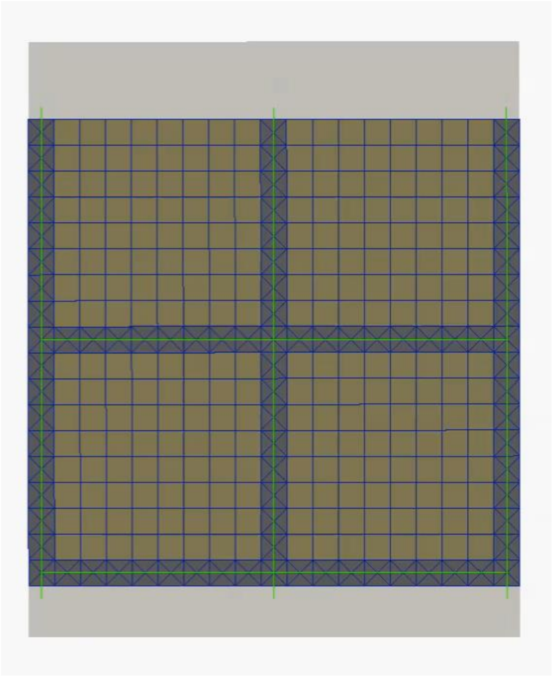
<u>Partially grouted walls tested at Drexel University</u> (Bolhassani & Hamid, 2015)

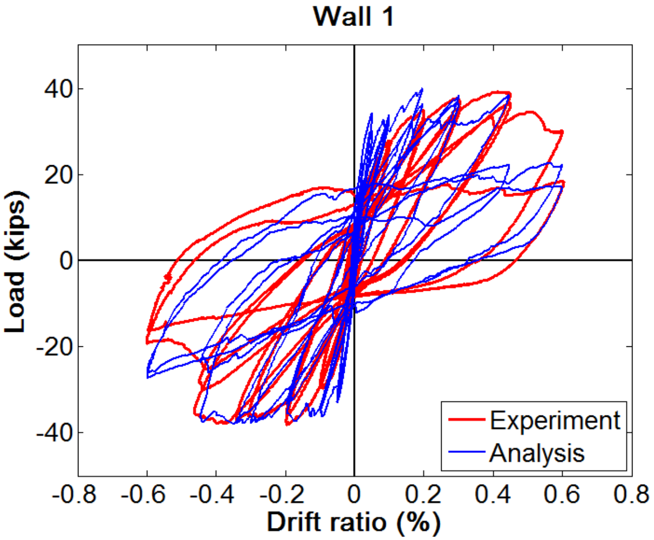
Dimensions: 152 in. x 152 in.

Reinforcement: 1 #6 bar in each grouted cell (vertical and horizontal)

Axial compressive load: 34 psi based on net area

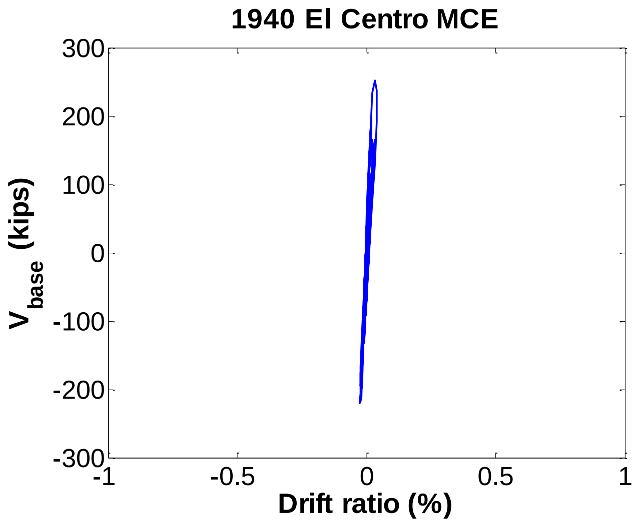


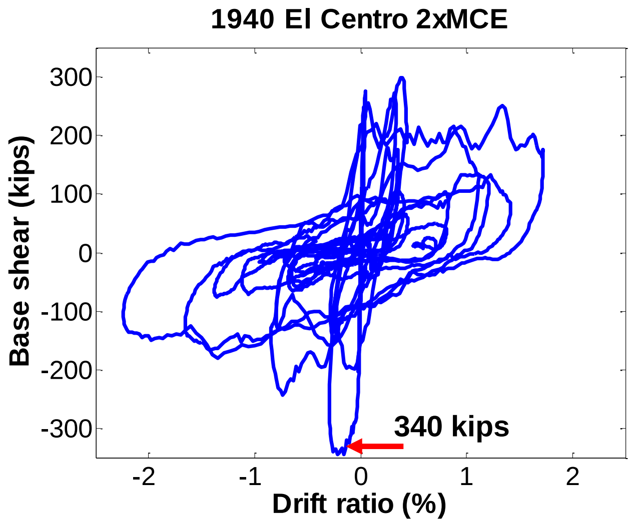




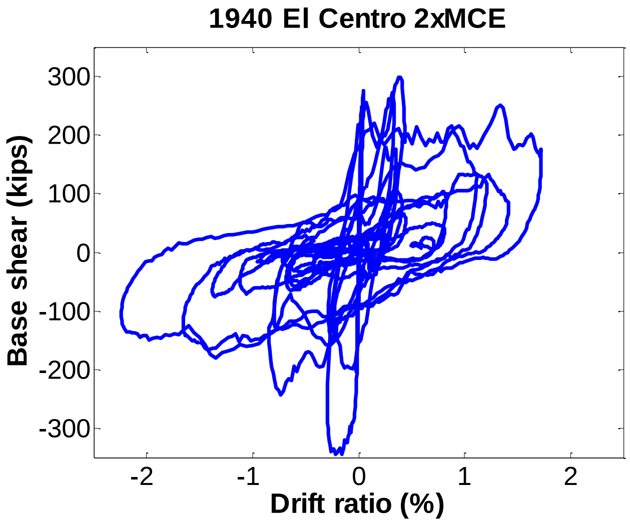
Pretest Analyses

- Pretest analyses were to estimate:
  - The base shear capacity of the specimen
  - The failure mechanism and ductility
  - The demand on the shake table (actuator force, actuator displacement and velocity)
- Results of time-history analyses using the 1940 El Centro record with intensities scaled to MCE and 2xMCE:

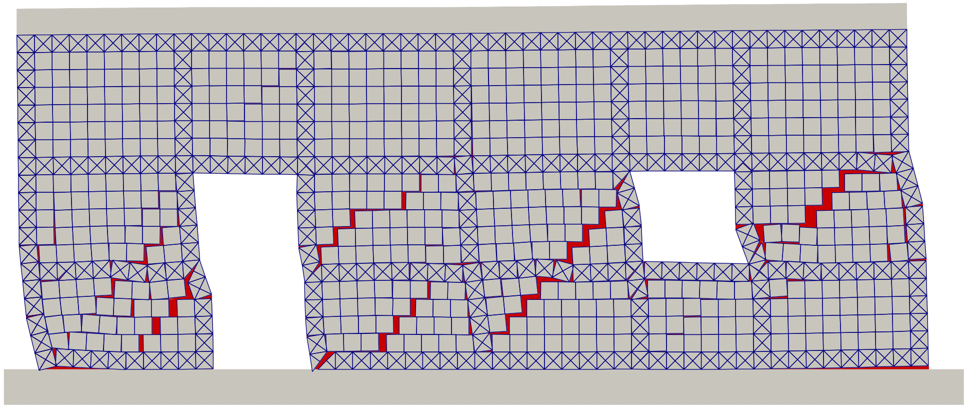




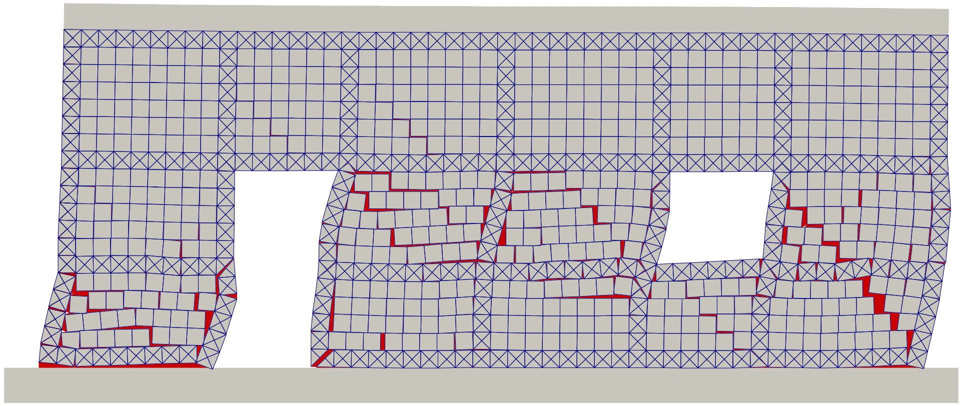
Pretest Analyses



Deformed mesh at maximum base shear



<u>In the negative direction</u>



<u>In the positive direction</u>

Construction

Instrumentation


South – East View

North – West View


North – East Interior View

Instrumentation

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

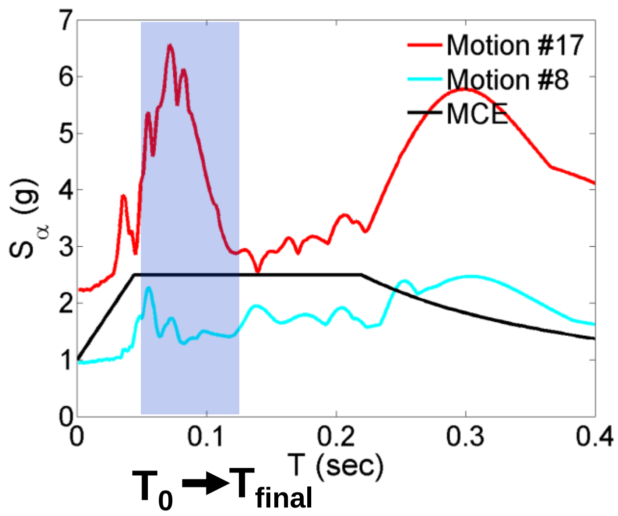
Intensity of Ground Motions

- The intensity of base excitation is quantified in terms of the spectral acceleration of the table motion as compared to that of the MCE at the natural period of the structure.

- During a shake-table test, 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 $\frac{S_{a,RECORDED}}{S_{a,MCE}}$ *calculated over the range of the fundamental period between the beginning and the end of each test.*



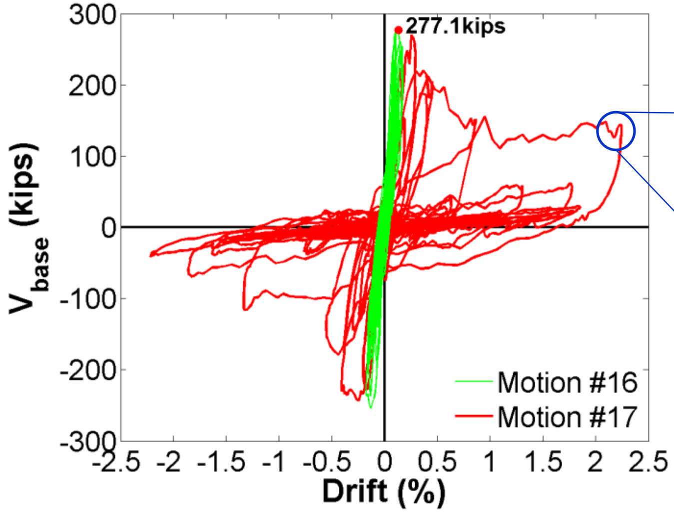
Structural Performance

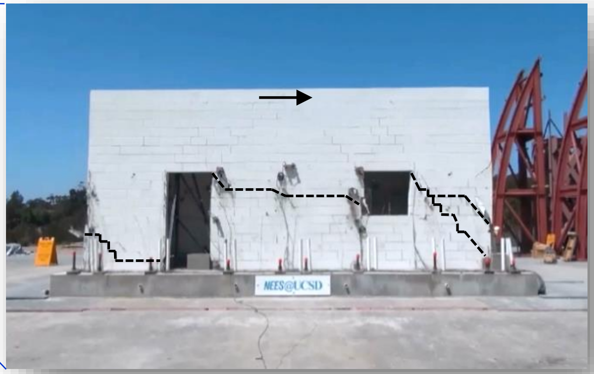
- The structure was subjected to a sequence of 17 motions. The 1940 El Centro record was used for most of the runs.
- The structure was practically elastic up to the intensity of 0.81 x MCE

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

Hysteresis loops

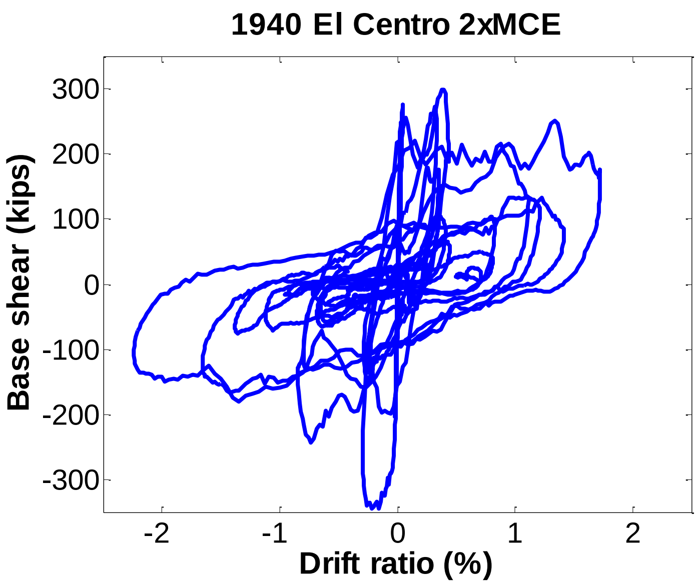




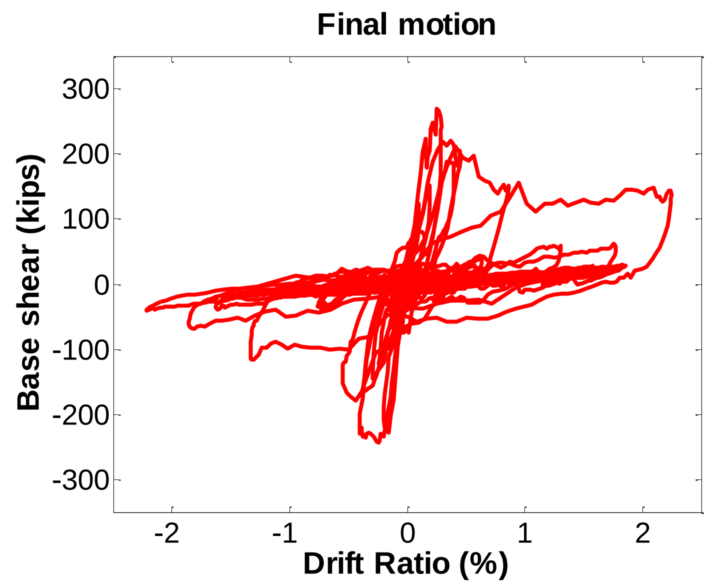
Video of the final motion

Comparison with Pretest Analysis

Pretest analysis



Experimental response



- The numerical model overestimated the maximum base shear by 23%.
- Note that the ground motion histories for the two cases are different.
- For the pretest analysis, the 1940 El Centro record scaled up by 250% was used. The intensity is 2xMCE based on the period of the undamaged structure. The analysis started with an undamaged structure.
- For the final shake-table motion, the excitation was the 1940 El Centro record scaled up by 214%. The effective intensity was 1.17xMCE.

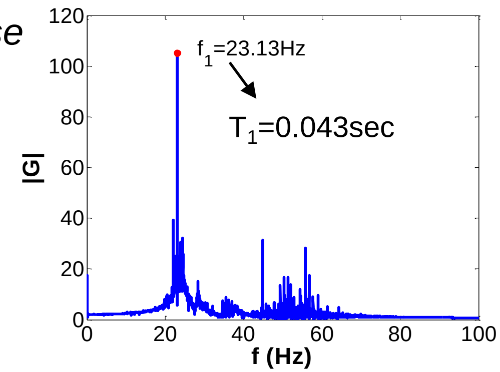
System Identification

- **White noise** tests were performed after each earthquake motion to identify the change of the fundamental period.
- For the system identification, the acceleration recorded at the base was used as the **input signal**, and the acceleration recorded at the roof of the specimen as the **output signal**.
- The **transfer function** of the structural system is estimated as the ratio of the **Fourier Amplitude** (DFT) of the output signal to that of the input signal:

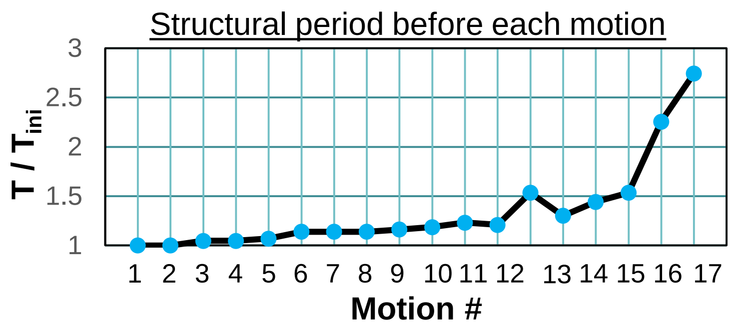
$$G\left(e^{j\omega_k}\right) = \frac{Y(\omega_k)}{U(\omega_k)} \quad \text{with} \quad U(\omega_k) = \sum_{n=1}^{N} u(t_n) \cdot e^{-j\omega_k t_n} \quad \text{and} \quad Y(\omega_k) = \sum_{n=1}^{N} y(t_n) \cdot e^{-j\omega_k t_n}$$

- Plotting the **magnitude** of the transfer function against the frequency reveals the fundamental frequency of the structure.

1st white noise test with the structure undamaged

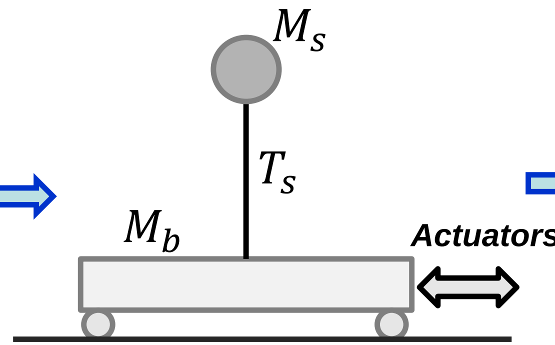


Evolution of fundamental period during testing

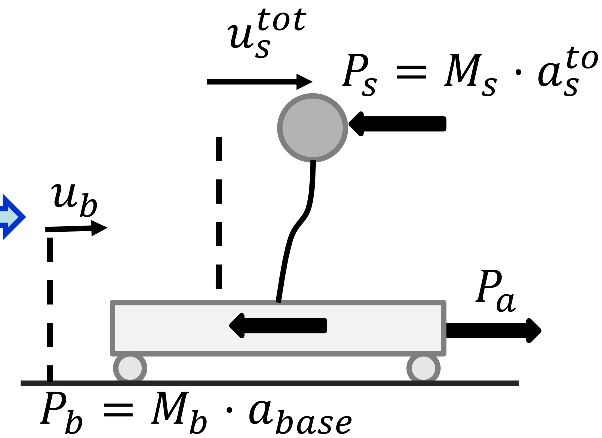


Force Demand on Table Actuators

Physical system



Idealized system

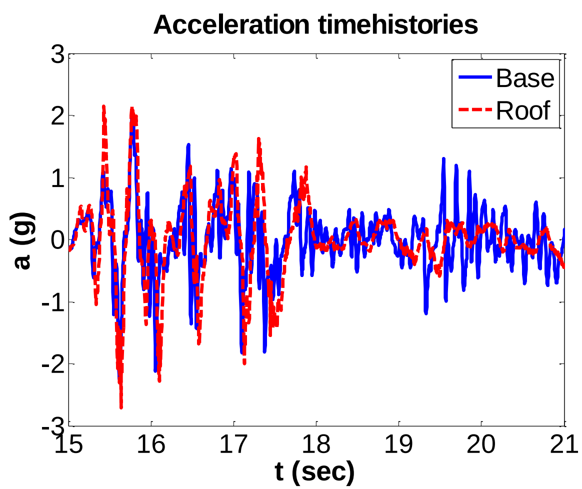


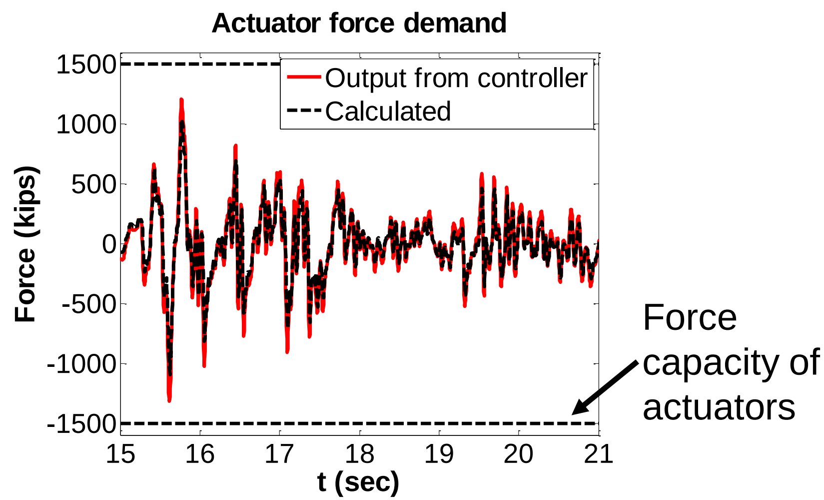
- Total force demand on the actuators: $P_a(t) = M_s \cdot a_s(t) + M_b \cdot a_{base}(t)$
- The force demand on the actuators needs to be smaller than their capacity.
- Total force demand can be determined by nonlinear time-history analysis.
- **Stiff structures** such as the masonry building considered here may impose high force demand on the actuators because **the base acceleration and the roof acceleration are likely to be in phase**

Estimation of Actuator Forces

Example

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





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

Mass of specimen: $M_s = 122 \text{ kips}$

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

Thank you!