Assessment of the Collapse Potential of Reinforced Masonry Structures using Finite Element Models

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PEER 2019 Annual Meeting
January 17-18, 2019, UCLA

Reinforced Masonry (RM) Structures

- Reinforced masonry (RM) is commonly used for low-rise construction in North America.


Commercial buildings


Office buildings


Residential buildings


Warehouse buildings

The photos are courtesy of Dr. G. Kingsley

- Walls are the primary load resisting members.

Reinforced Masonry Construction

Reinforced masonry walls consist of:

- Hollow concrete masonry blocks
- Mortar joints
- Grout (full or partial grouting)
- Steel reinforcing bars

RM wall layout

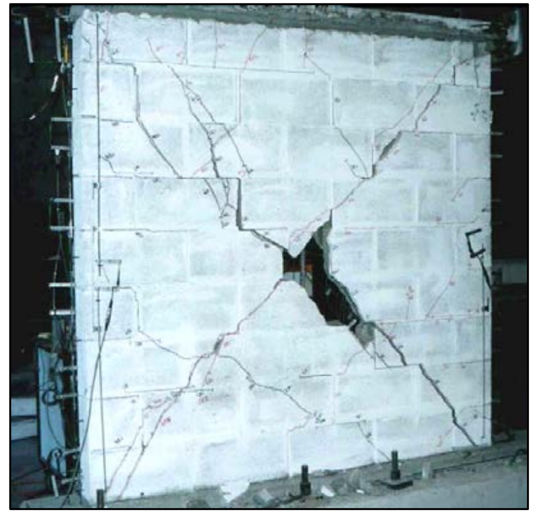
Similar to RC walls but:

- More heterogeneous
- More complex seismic behavior
- Restricted spacing of reinforcement – bars cannot be placed less than 8 in. apart.
- No confinement reinforcement

RM wall grouting

Damage and Failure of RM Structures

Courtesy of M. Mavros



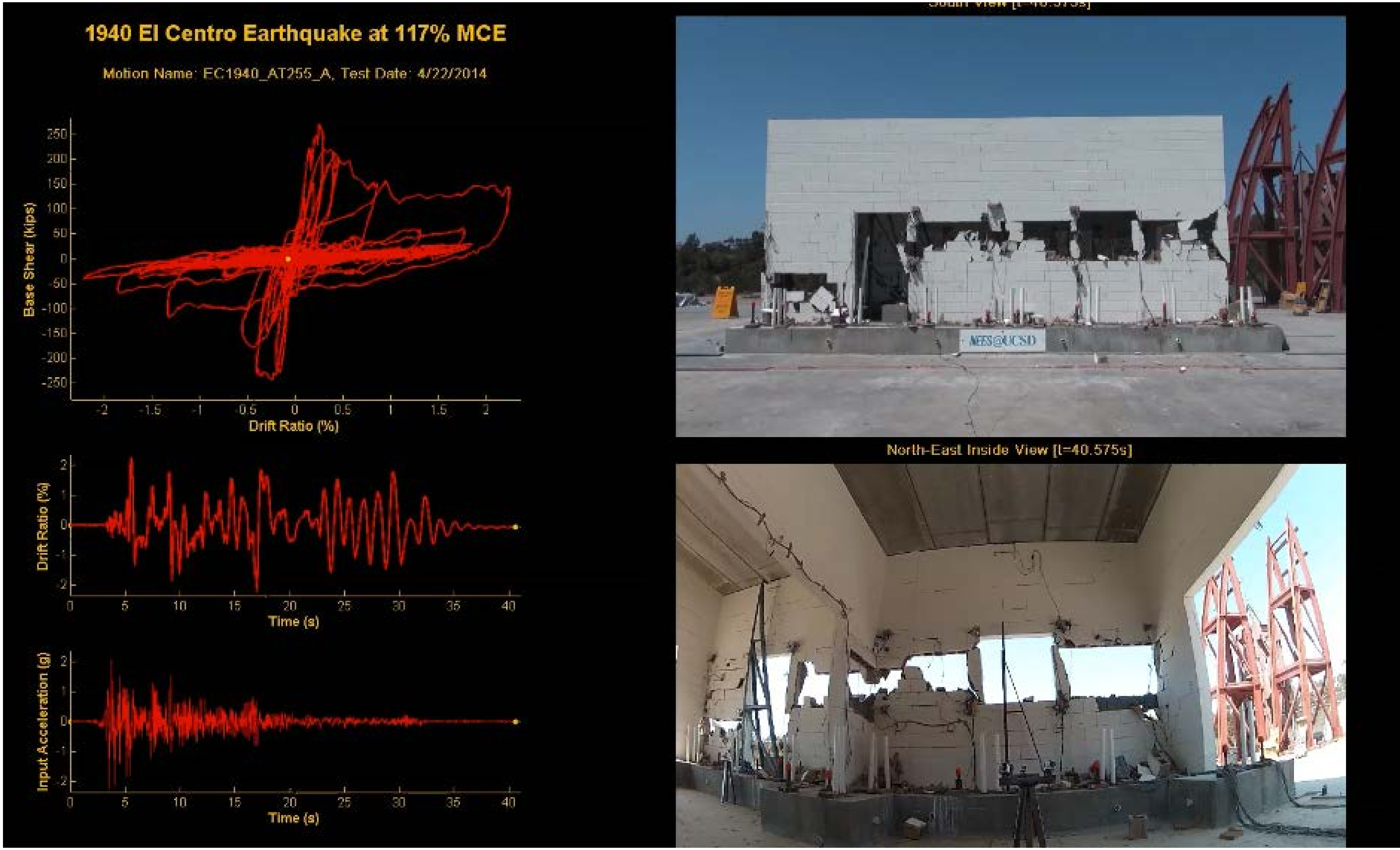
Courtesy of J. Ingham

Courtesy of J. Sherman

RM damage after the 2011 Christchurch Earthquake

Partially Grouted Masonry Building Test

- Koutras and Shing, 2014

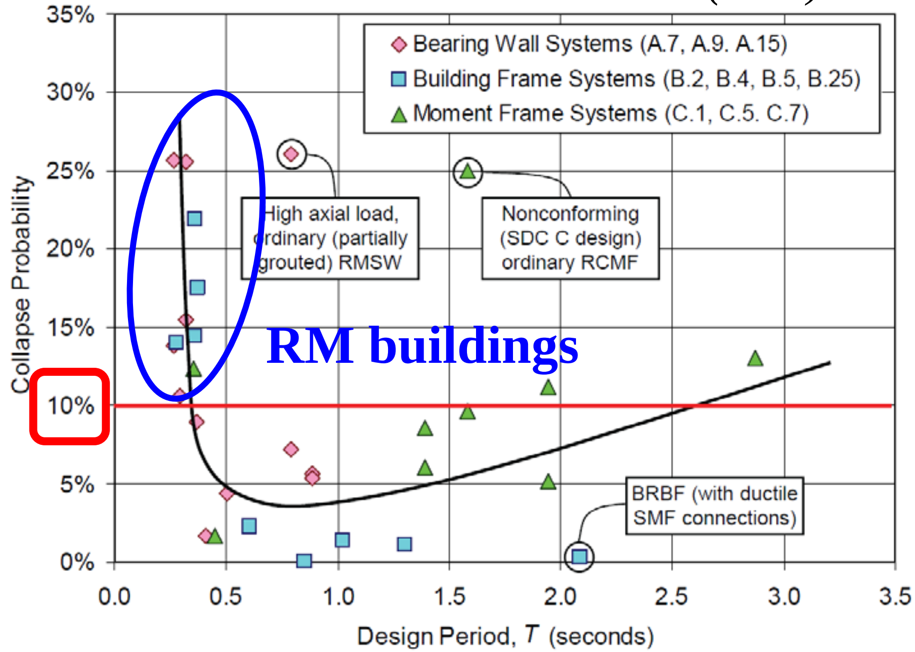


Seismic Performance of RM Buildings

Previous numerical study under ATC 76 following the FEMA P-695 Methodology:

Source: NIST GCR 12-917-20 (2012)

- Low-rise RM structures **did not satisfy** the design code **safety threshold** of 10% probability of collapse during an MCE event (2500-year return period)!

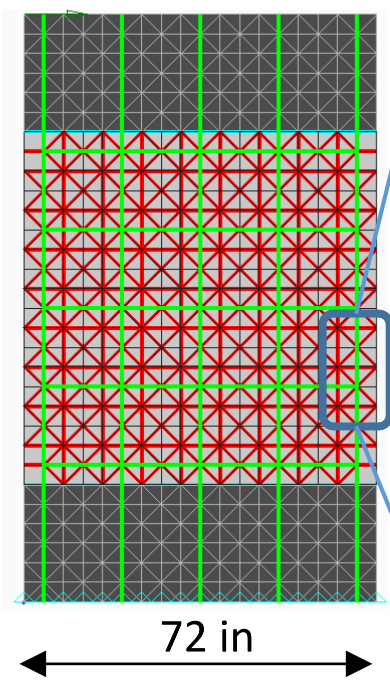


- **However**, the **models** used for that study were **overly simplified** and **too conservative**.
- The development of numerical models that can **reliably assess the collapse potential** of RM building systems is of utmost importance.

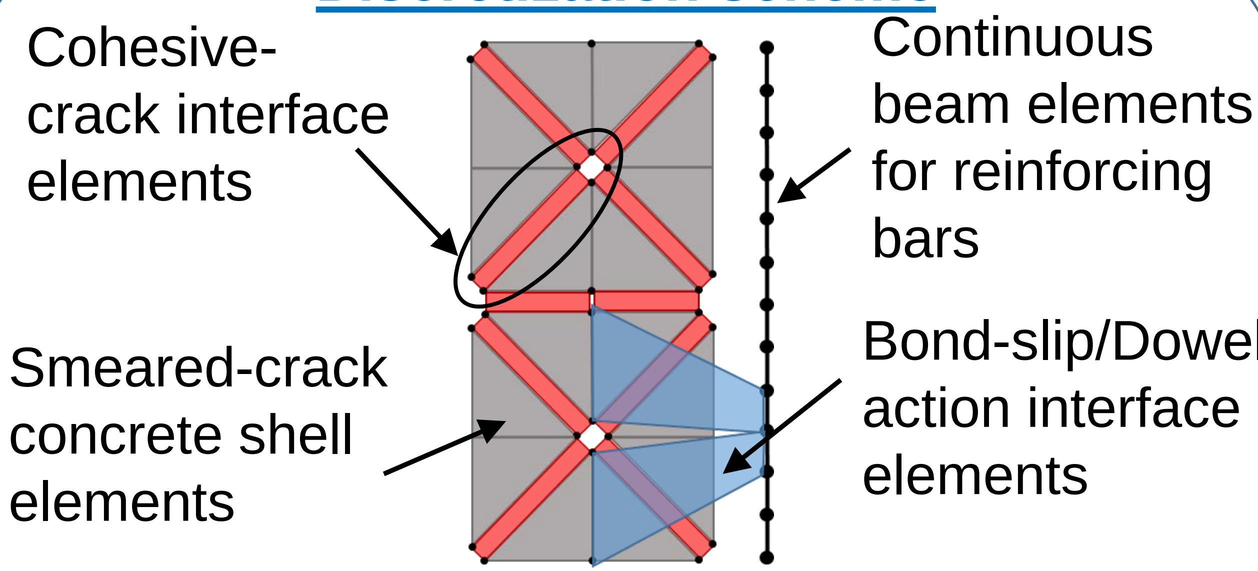
Modeling Approach

- Although a number of approaches with various degrees of complexities have been proposed, **nonlinear finite element (FE) analysis** is still the most powerful tool.
- **Concrete shell** elements are combined with **cohesive crack interface** elements (extension of Mavros 2015).

FE mesh of a RM wall



Discretization scheme

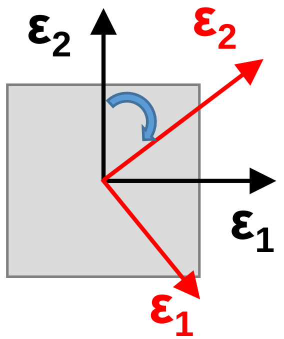


The FE analysis software LS-DYNA is used as the analysis platform for this study.

Concrete/Masonry Model

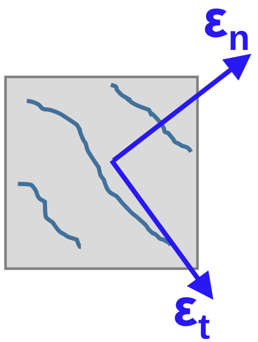
➢ A simple **orthotropic material** model was developed.

a) Uncracked stage

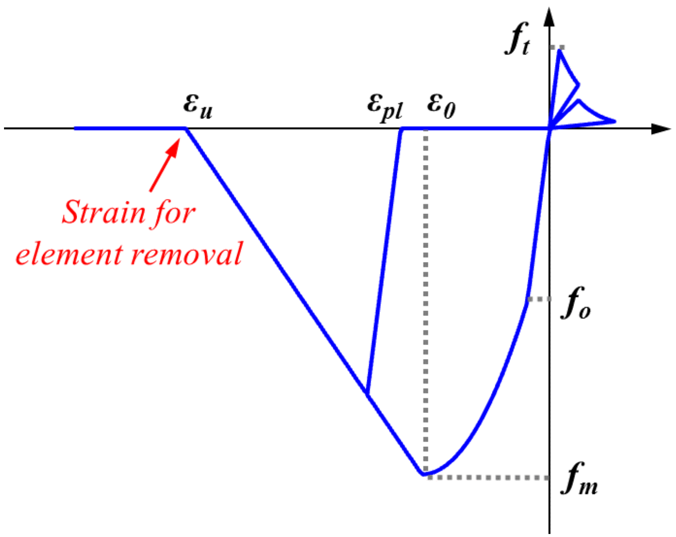


Axes of orthotropy rotate together with the axes of principal strains

b) Cracked stage



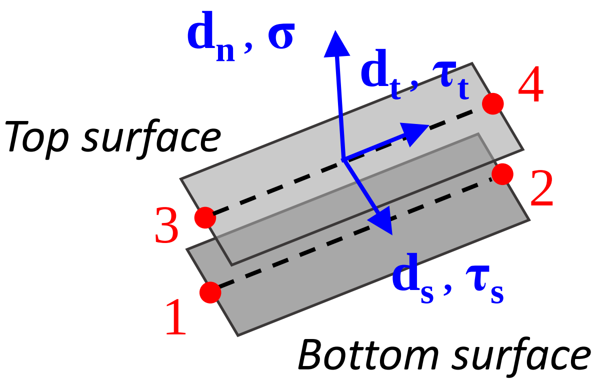
Axes of orthotropy remain fixed, parallel and normal to the direction of the first crack.



Stress – strain law in each direction of orthotropy

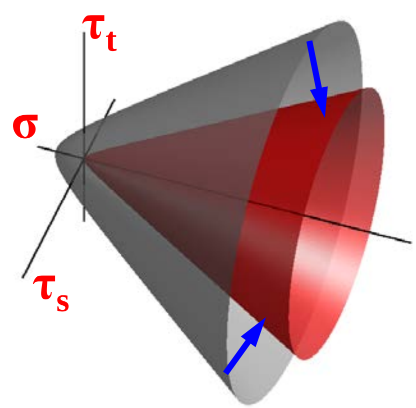
Cohesive Crack Interface Model

Interface element configuration



It is implemented in a line interface element.

3D yield surface for mixed-mode fracture



Softening rules

$$s = s_o\left(1 - \frac{\kappa_1}{G_f^I} - \frac{\kappa_2}{G_f^{II}}\right)$$

$$\mu = (\mu_o - \mu_r)\cdot e^{-\alpha\cdot\kappa_3} + \mu_r$$

$$r = (r_o - r_r)\cdot e^{-\beta\cdot\kappa_3} + r_r$$

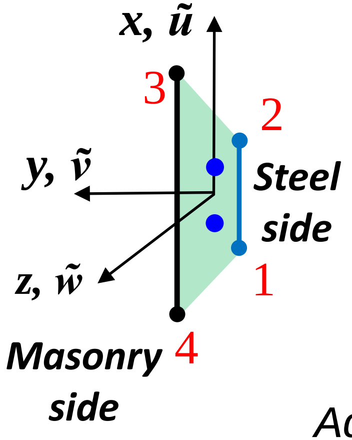
$$F = \tau_s^2 + \tau_t^2 - \boldsymbol{\mu}^2\cdot(\sigma - \boldsymbol{s})^2 - 2\cdot\boldsymbol{r}\cdot(\sigma - \boldsymbol{s}) = 0$$

Based on Kottari 2016 (Ph.D. Thesis)

- The model can capture **crack opening and closing**, reversible joint **dilatation**, and irreversible joint **compaction** under cyclic loading (Koutromanos and Shing, 2012).

Bond-Slip and Dowel Action Models

- Implemented **in a user-defined interface element**



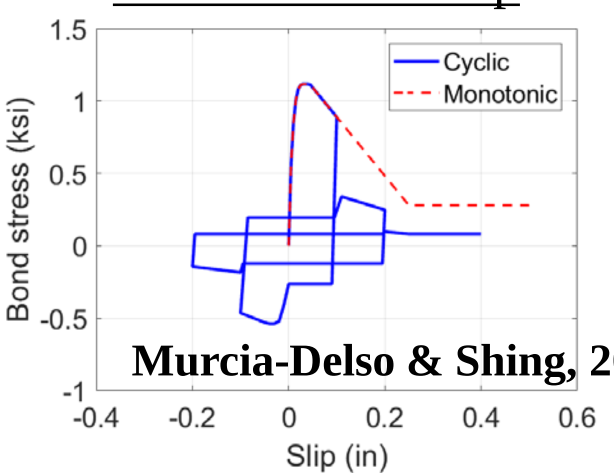
<u>Deformation components</u>

1) **Slip:** $\tilde{u} = x_{steel} - x_{masonry}$
2) **Displacements normal to slip:** $\tilde{v} = y_{steel} - y_{masonry}$, $\tilde{w} = z_{steel} - z_{masonry}$
3) **Relative twist about *x* axis:** $\tilde{\theta} = \theta_{steel} - \theta_{masonry}$

<u>Advantage</u>: allows the connection of beam elements to shell elements of a much larger size (Mavros, 2015; Kottari et al. 2016).

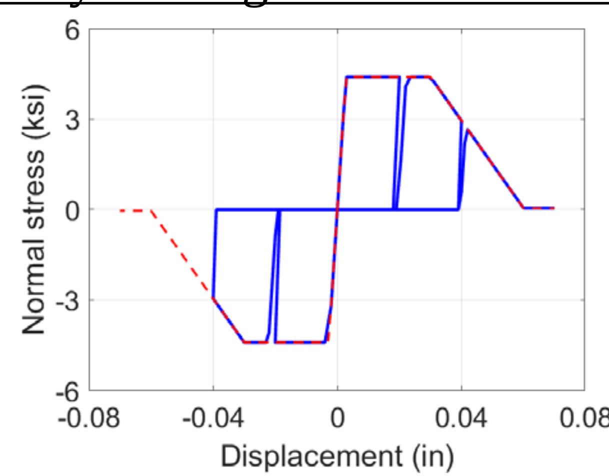
- Material laws

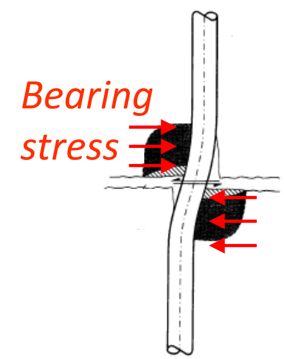
<u>Bond stress vs Slip</u>



Murcia-Delso & Shing, 2014

<u>Masonry bearing stress for dowel action</u>



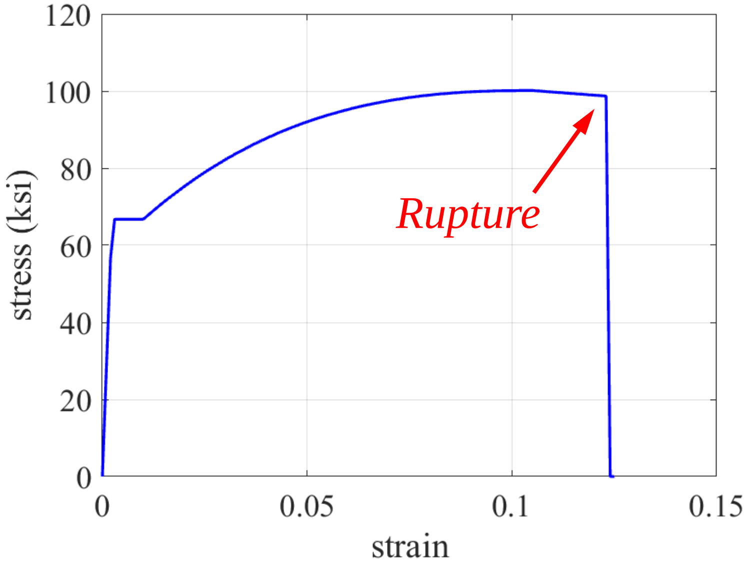


Reinforcing Steel Model

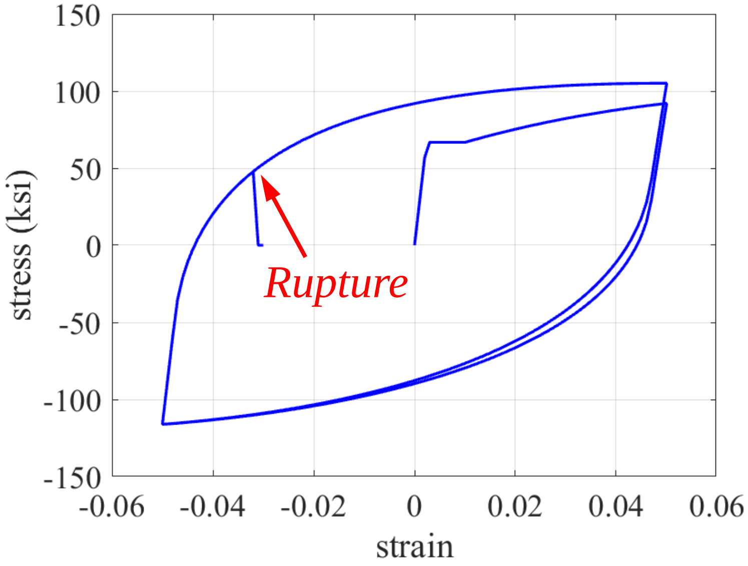
- The model developed by Kim & Koutromanos (2016) is adopted.

The model accounts for low-cycle fatigue

Monotonic response



Cyclic response



Rupture occurs when a **scalar damage parameter**, which is based on the cumulated plastic work by tensile stress, exceeds a specified **critical value**.

Element Removal Procedure

- A **non-local element removal** scheme was introduced in LS-DYNA:

  A. When a **smeared-crack** shell element satisfies the criterion of failure (compressive strain exceeds ε_u):

  1. Remove the **shell** element.
  2. Remove all the **bond-slip interface** elements connected to the deleted shell element.
  3. Remove all the adjacent **cohesive crack interface** elements.

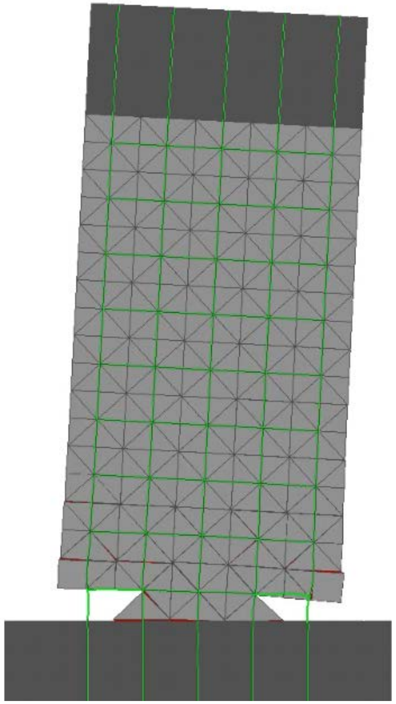
  B. When a **reinforcement beam** element satisfies the criterion of rupture:

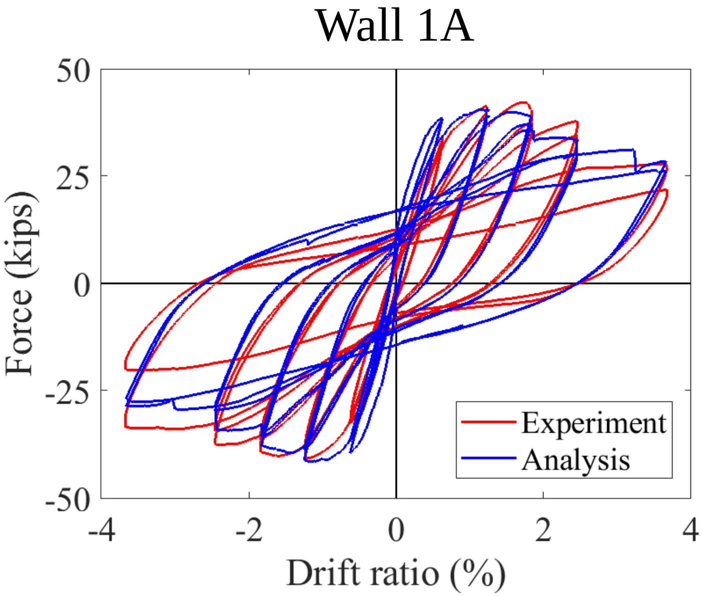
  1. Remove the **reinforcement beam** element.
  2. Remove the adjacent **bond-slip interface** element.

Flexure-dominated Wall Test

Flexure-dominated wall tested by Sherman (2011)

Damage in test

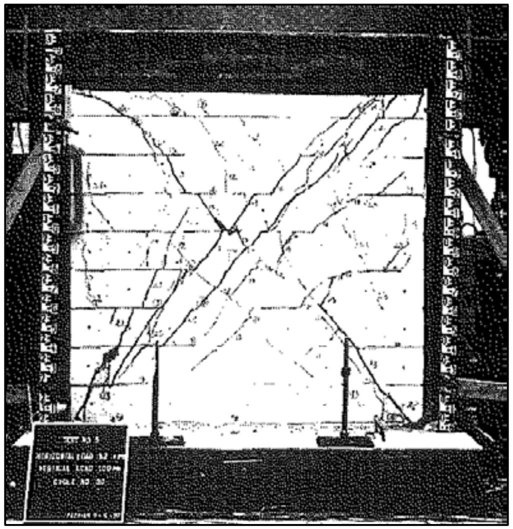




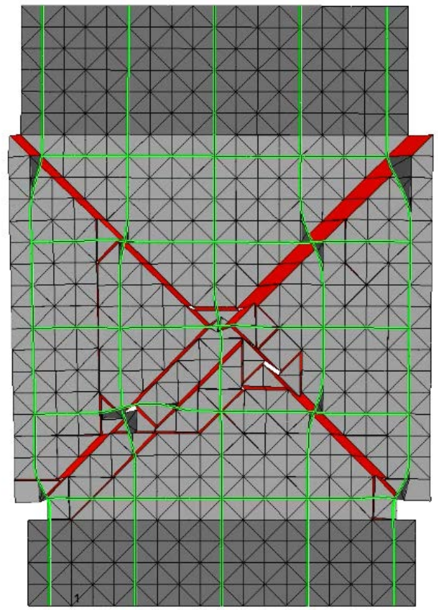
Dimensions: 40 in x 72 in.
Boundary conditions: Cantilever.
Reinforcement: Vertical 5#6, Horizontal 9#4.
Applied vertical stress : 160 psi.

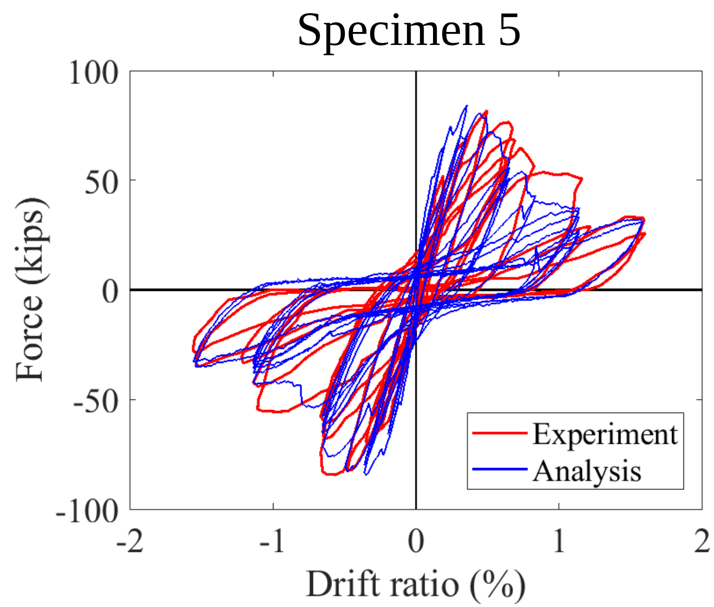
Shear-dominated Wall Test 1

Shear-dominated wall Specimen 5 tested by Shing (1991)



Damage in test



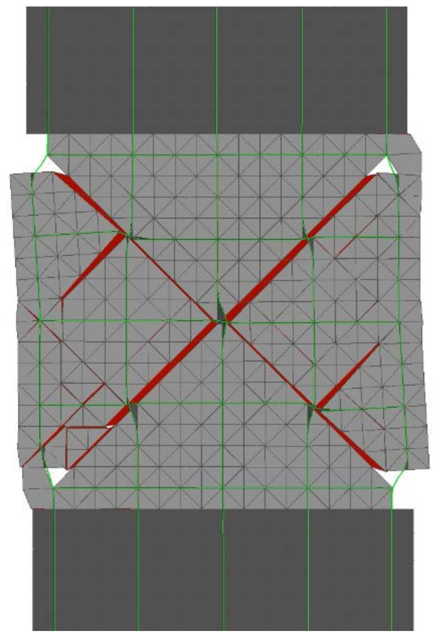


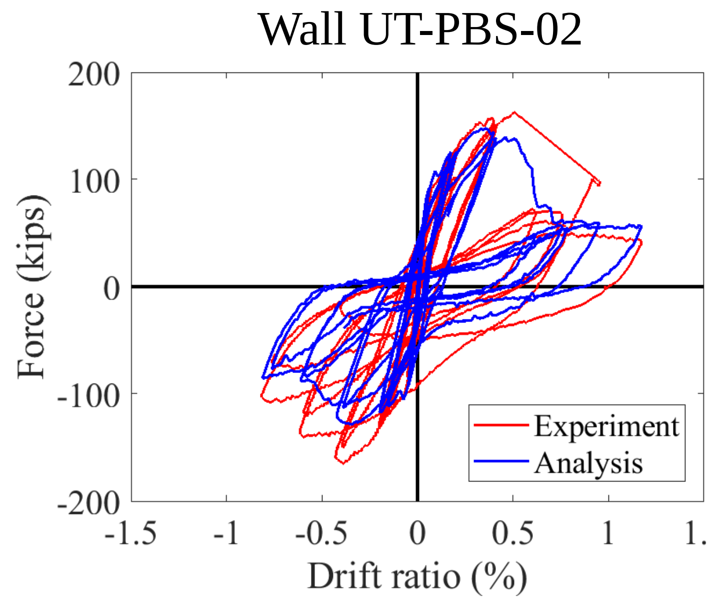
Dimensions: 72 in x 72 in.
Boundary conditions: Cantilever.
Reinforcement: Vertical 5#7, Horizontal 5#3.
Applied vertical stress: 100 psi.

Shear-dominated Wall Test 2

Shear-dominated wall UT-PBS-02 tested by Ahmadi (2011)

Damage in test



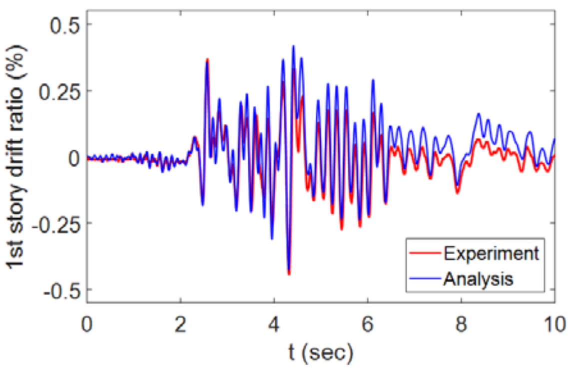


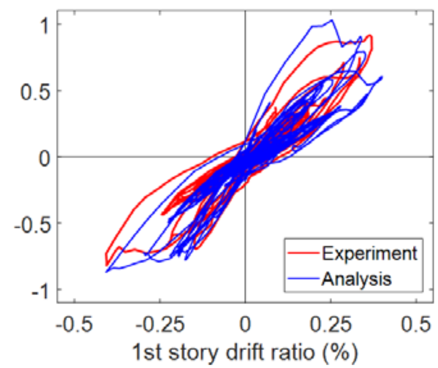
Dimensions: 72 in x 72 in.
Boundary conditions: Fixed – Fixed.
Reinforcement: Vertical 5#6, Horizontal 5#4.
Applied vertical stress : 190 psi.

2-story Shake-Table Test Structure

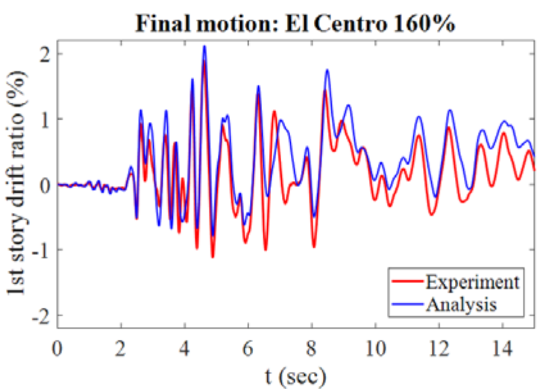
2-story shake-table structure tested by Mavros (2016)

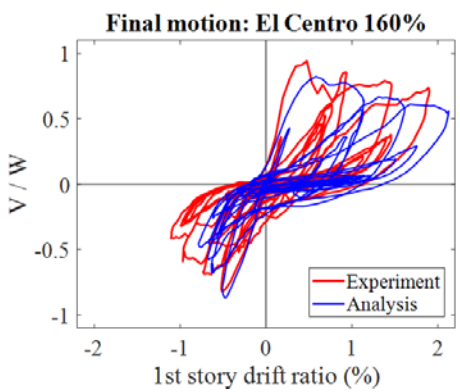
1979 El Centro 145%

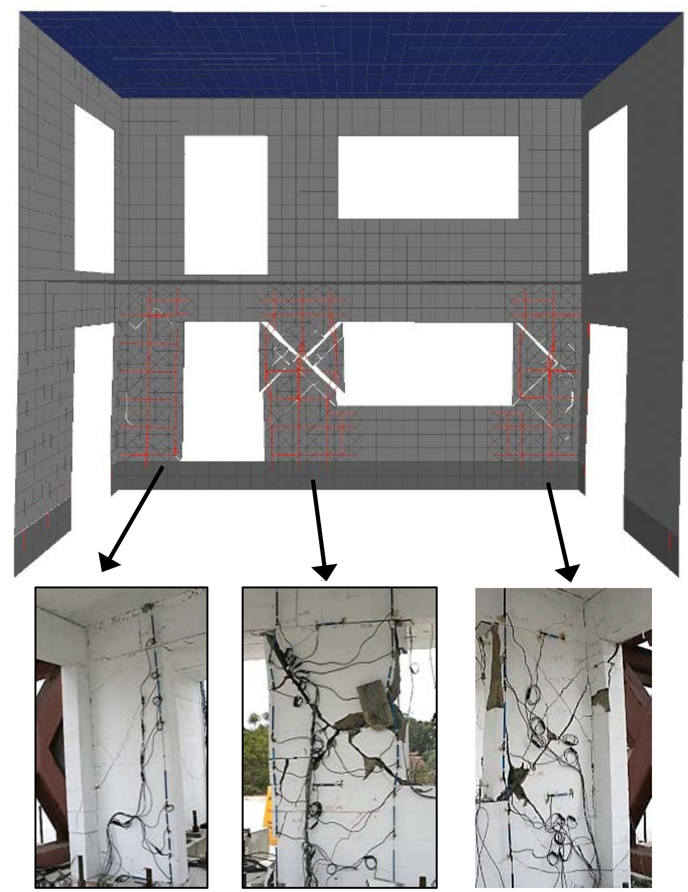




1979 El Centro 160% - Final motion







Damage at the end of the sequence

Simulation of RM through Collapse

- In all previous experimental studies, RM specimens were tested to maximum drifts of less than 3%.

Can the model also predict the response of RM structures at larger drifts and through collapse?

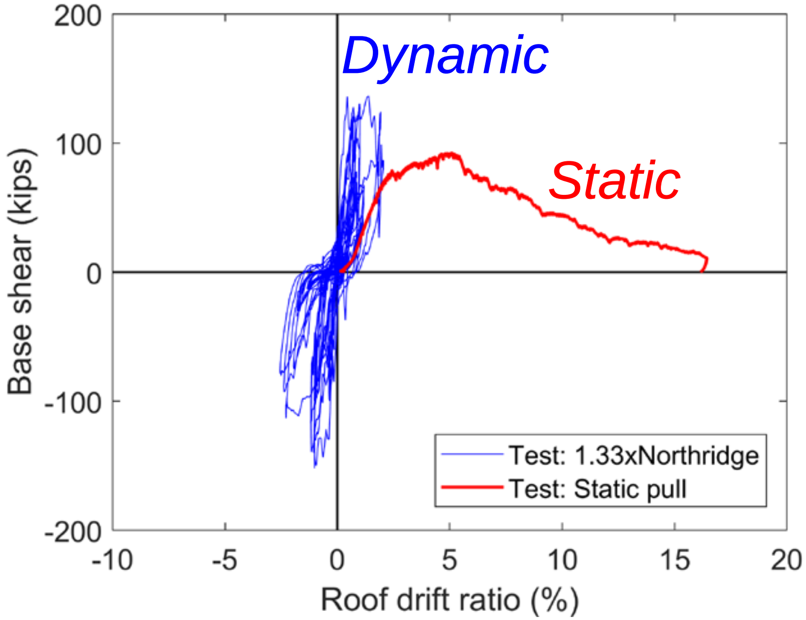
New shake-table test at UC San Diego

At 16% drift, the structure is still stable.

Will appear in: Cheng, J., Koutras, A., and Shing, P.B. (2019) “A shake-table test investigating the drift capacity of reinforced masonry wall systems.” In *13th North American Masonry Conference,* Salt Lake City, UT.

Response of Test Structure

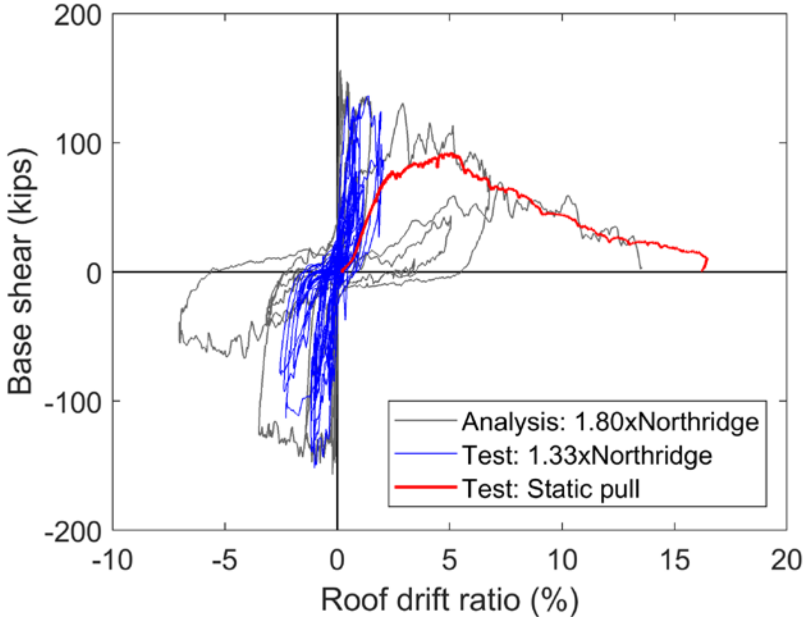
➢ Testing was conducted in two phases:



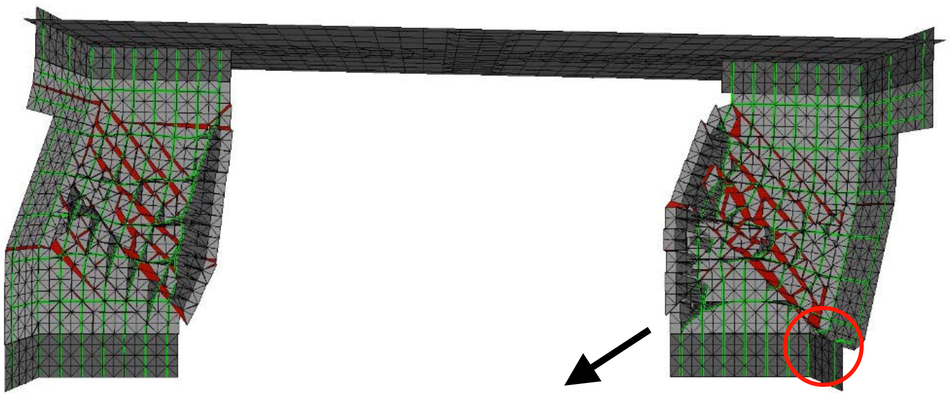
➢ Before the test, a time-history analysis was performed (pre-test analysis) as an attempt to predict the experimental response.

Response of Test Structure

- Comparison with pre-test analysis result.



Collapse mechanism in pre-test analysis



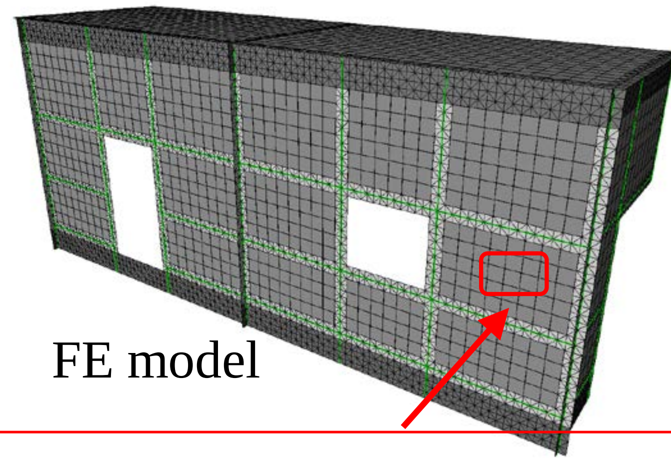
Flange crushing

Wall damage in the test

Extension to Partially Grouted Masonry

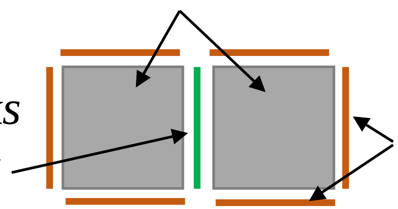
- Simulation of the one-story shake-table test structure.

Damage at the end of the test sequence



FE model

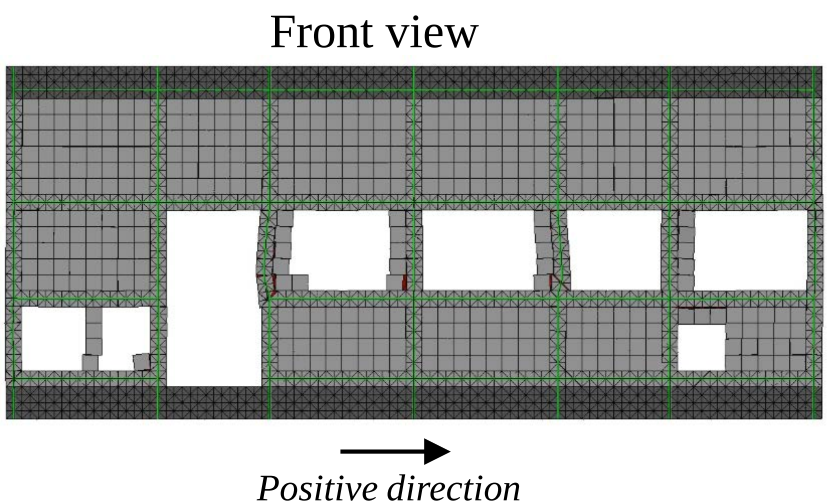
Discretization of each ungrouted masonry block:

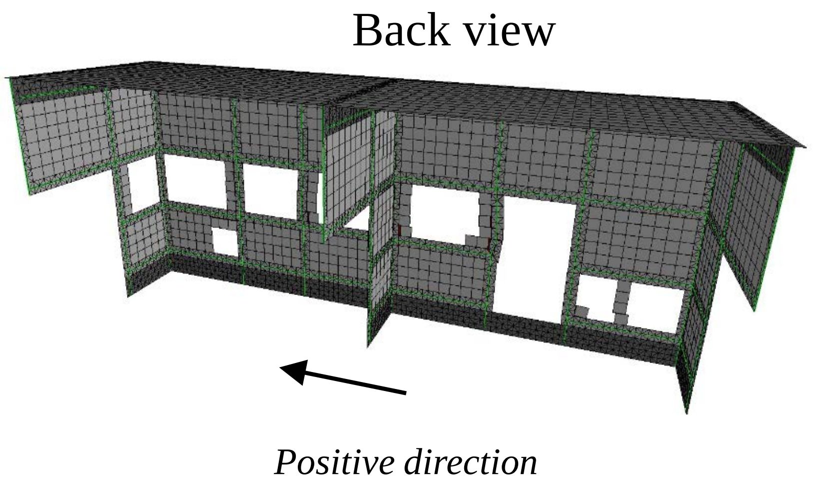


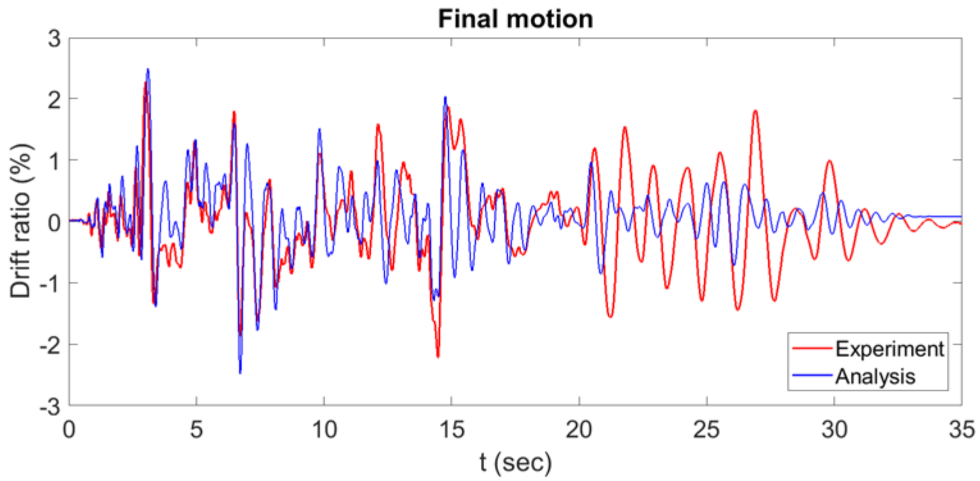
These interface **elements are removed** when the **out-of-plane sliding exceeds** the block face thickness t_{face}=1.25in.

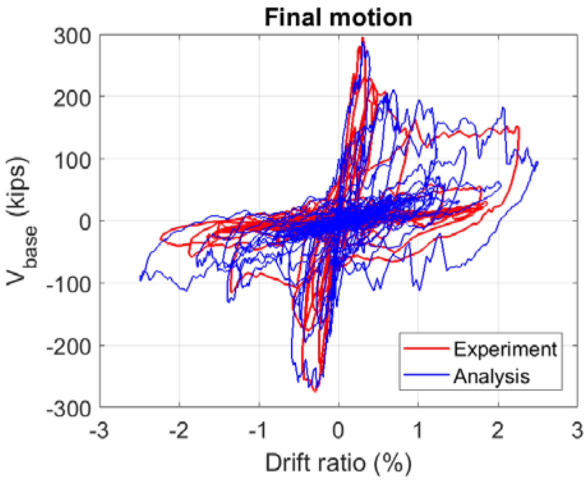
Response of the FE Model

- Last motion of the testing sequence.





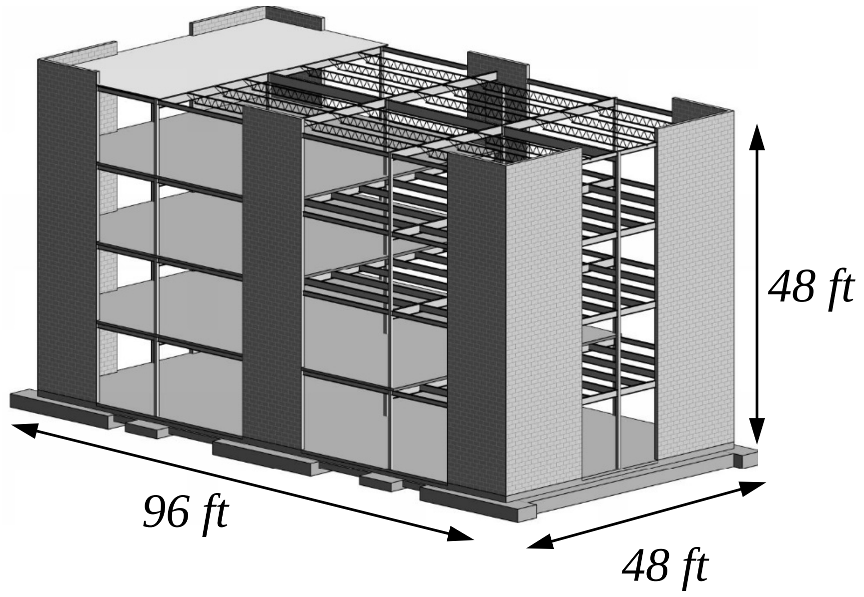


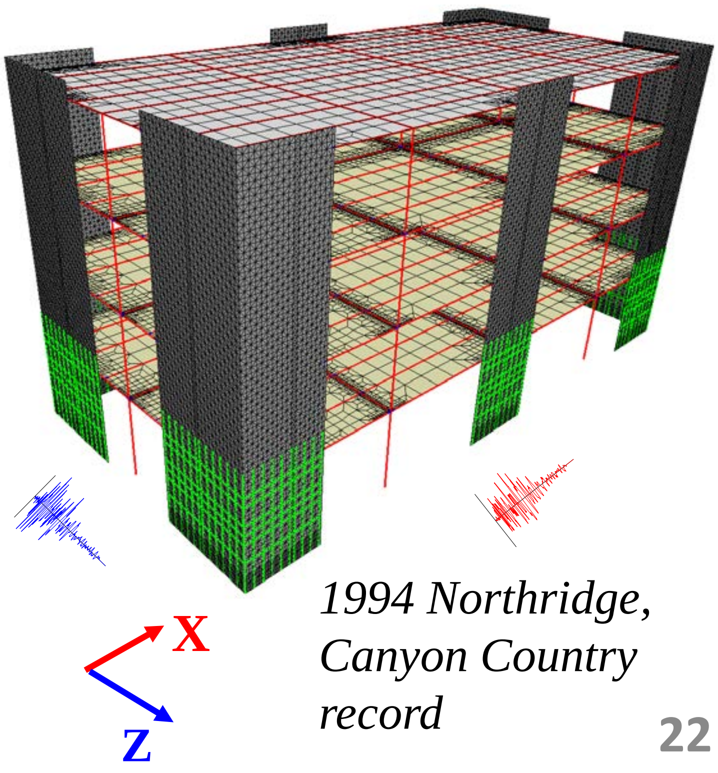


Case Study: A Commercial Building

- The FE modeling scheme is applied for the time-history analysis of a commercial building archetype designed for SDC D_{max}.

- Bi-directional excitation is used.

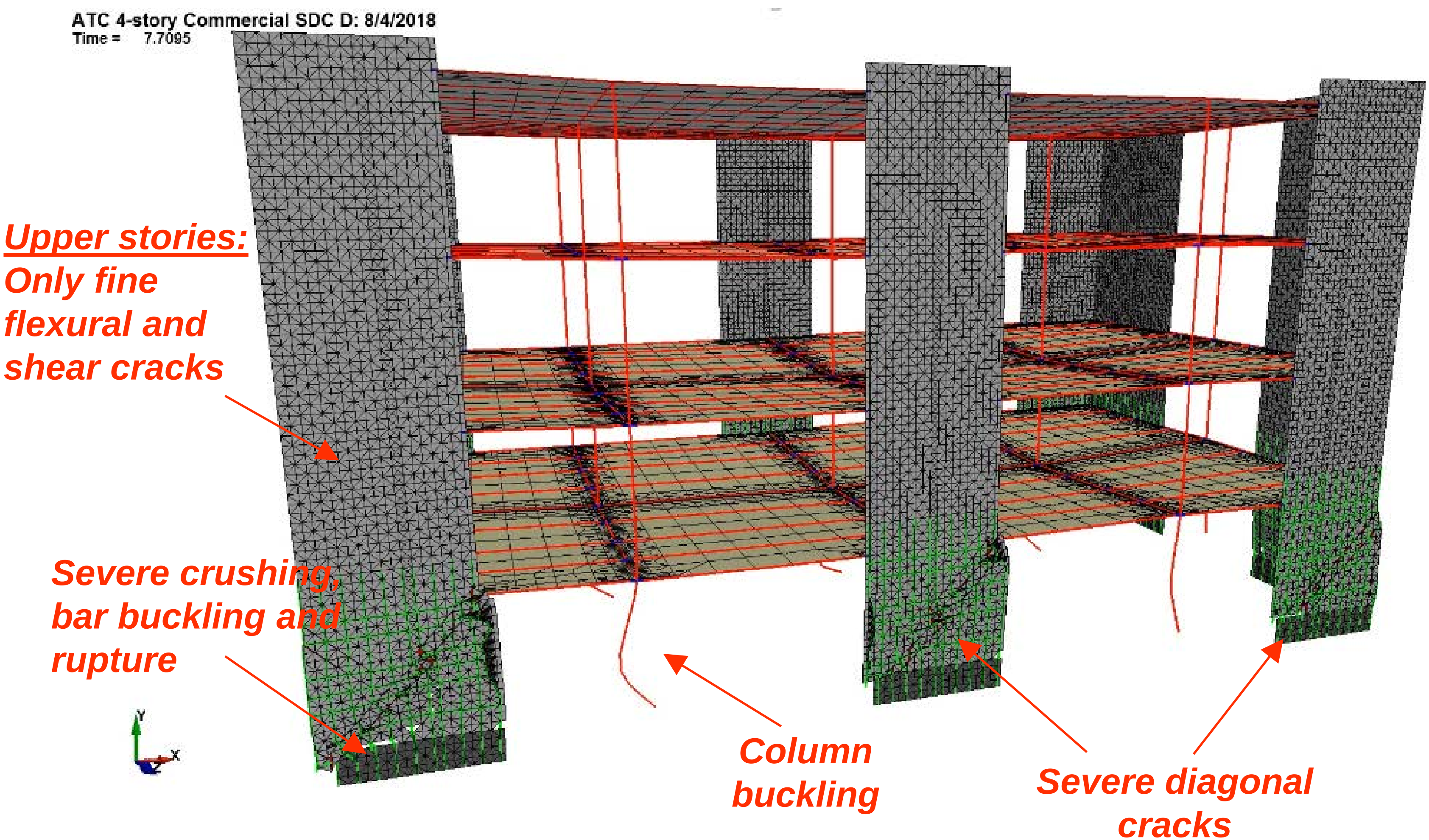




1994 Northridge, Canyon Country record

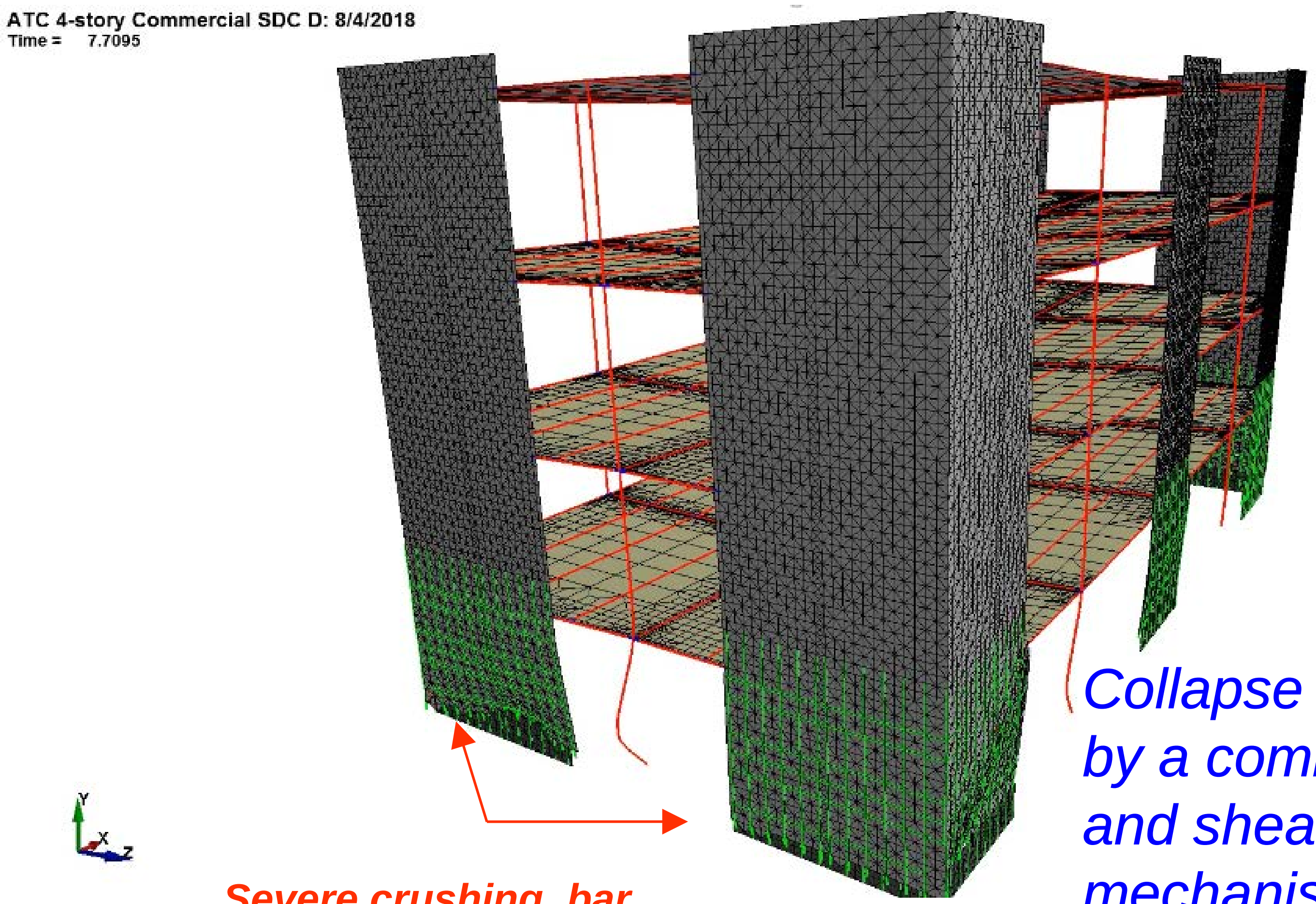
Response under an extreme 1.8xMCE

- View of longitudinal side



Response under an extreme 1.8xMCE

- View of transverse side



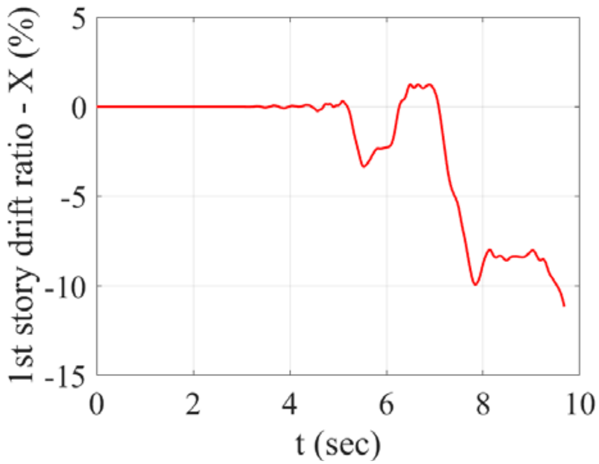
Severe crushing, bar buckling and rupture

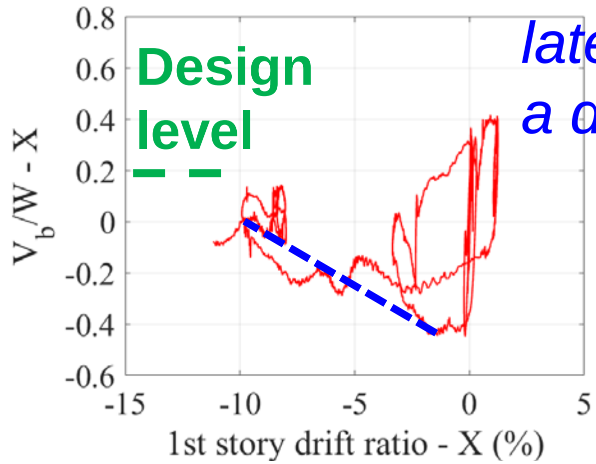
Collapse is governed by a combined flexure- and shear- dominated mechanism.

Response under an extreme 1.8xMCE

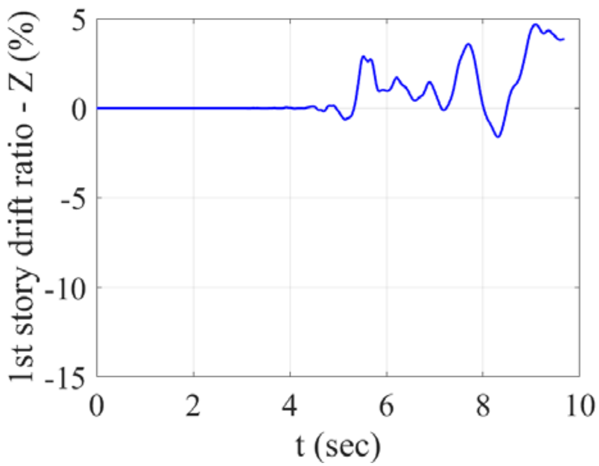
➢ Longitudinal direction - X

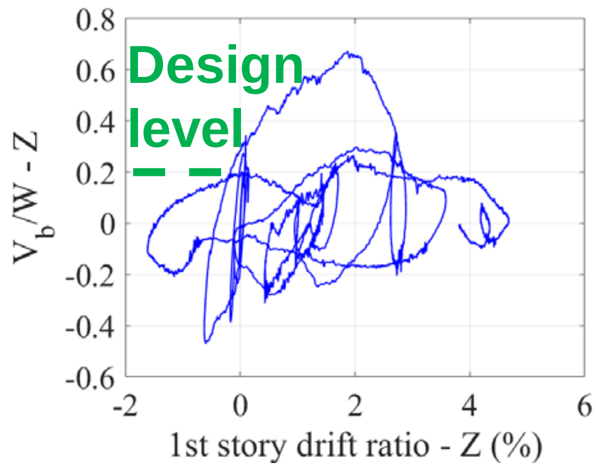
The system loses its lateral resistance at a drift ratio of 10%.





➢ Transverse direction – Z





Conclusions

The proposed FE modeling scheme can capture the seismic response of RM structures in a realistic manner. The models can be used to:

- Gain insight into the seismic behavior and collapse potential of RM building systems.
- Calibrate or validate more computational efficient simplified models.
- Assess and improve the design-code provisions.

Acknowledgements

National Science Foundation
WHERE DISCOVERIES BEGIN

FEMA

ATC
Applied Technology Council

NHERI@
UC San Diego

Any Questions?

Thank you!