Displacement-based Seismic Design of Shear Wall Structures

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project participants

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earthquakes, engineering, and masonry

- "earthquakes don't kill people, masonry buildings that aren't properly designed kill people"

2003 Bam City, Iran
December 26, 2003
lasted 12 seconds
about 50,000 dead

2010 Haiti

12 January 2010
lasted less than 1 minute
about 250,000 dead

- over 80% of the buildings in the world are built of masonry, with no design code!

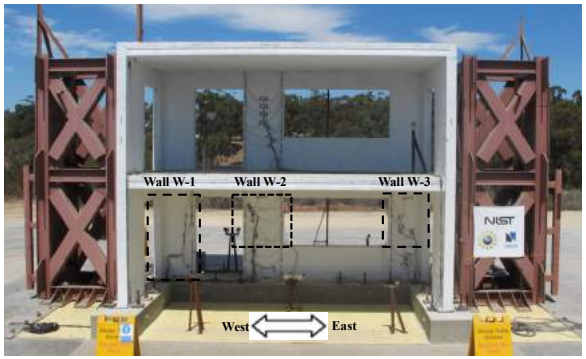
important points of this presentation

- current seismic design does not always work well for shear-wall structures

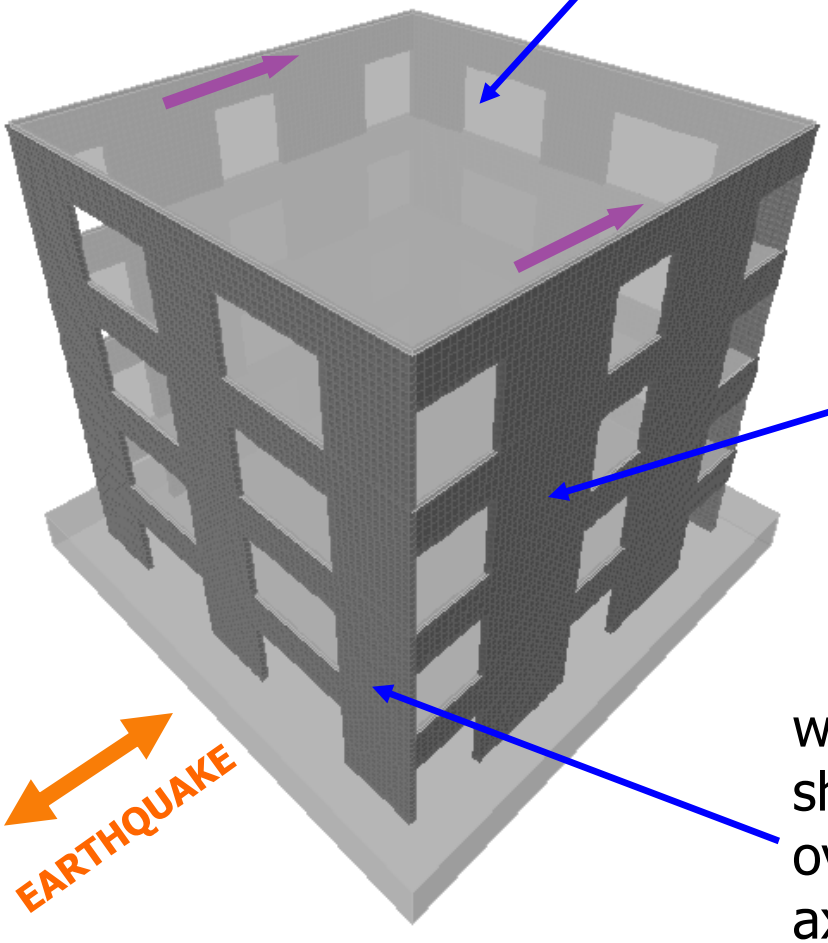
- proposed displacement-based seismic design works well for shear wall structures
  - produces structures that behave reliably in strong earthquakes
  - more consistent and more transparent than current seismic design

contents of presentation

- review current seismic design of masonry shear wall structures
- develop proposed displacement-based design
- conduct cyclic-load tests on masonry walls
- improve analytical models
- check and validate displacement-based seismic design



seismic response of masonry structures



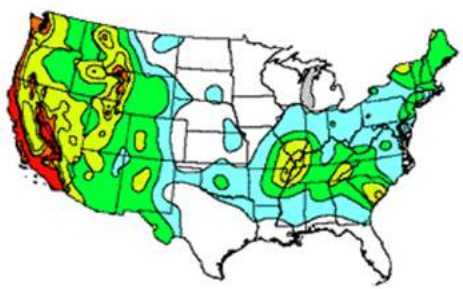
diaphragms are effectively rigid in their own planes

walls parallel to shaking resist overturning by their flexural and shear capacity

walls perpendicular to shaking resist overturning by their axial capacity

current force-based design approach …

- determine seismic design category (SDC) based on geographic location and soil
  - select from ASCE 7 list of permitted structural systems
  - special, intermediate reinforced masonry shear walls
  - prescribed detailing for each wall segment

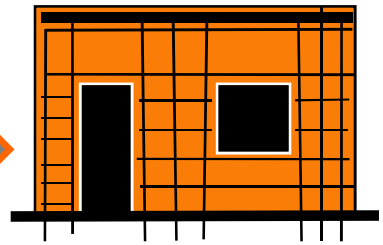


SDC

TABLE 12.2-1 DESIGN COEFFICIENTS AND FACTORS FOR SEISMIC FORCE–RESISTING SYSTEMS

Seismic Force–Resisting System	ASCE 7 Section where Detailing Requirements are Specified	Response Modification Coefficient, R^a	System Overstrength Factor, $\Omega_0{}^g$	Deflection Amplification Factor, $C_d{}^b$	Structural System Limitations and Building Height (ft) Limit[c]				
					Seismic Design Category				
					B	C	D[d]	E[d]	F[e]
A. BEARING WALL SYSTEMS									
1. Special reinforced concrete shear walls	14.2 and 14.2.3.6	5	2½	5	NL	NL	160	160	100
2. Ordinary reinforced concrete shear walls	14.2 and 14.2.3.4	4	2½	4	NL	NL	NP	NP	NP
3. Detailed plain concrete shear walls	14.2 and 14.2.3.2	2	2½	2	NL	NP	NP	NP	NP
4. Ordinary plain concrete shear walls	14.2 and 14.2.3.1	1½	2½	1½	NL	NP	NP	NP	NP
5. Intermediate precast shear walls	14.2 and 14.2.3.5	4	2½	4	NL	NL	40[i]	40[i]	40[i]
6. Ordinary precast shear walls	14.2 and 14.2.3.3	3	2½	3	NL	NP	NP	NP	NP
7. Special reinforced masonry shear walls	14.4 and 14.4.3	5	2½	3½	NL	NL	160	160	100
8. Intermediate reinforced masonry shear walls	14.4 and 14.4.3	3½	2½	2¼	NL	NL	NP	NP	NP
9. Ordinary reinforced masonry shear walls	14.4	2	2½	1¾	NL	160	NP	NP	NP
10. Detailed plain masonry shear walls	14.4	2	2½	1¾	NL	NP	NP	NP	NP
11. Ordinary plain masonry shear walls	14.4	1½	2½	1¼	NL	NP	NP	NP	NP
12. Prestressed masonry shear walls	14.4	1½	2½	1¾	NL	NP	NP	NP	NP
13. Light-framed walls sheathed with wood structural panels rated for shear resistance or steel sheets	14.1, 14.1.4.2, and 14.5	6½	3	4	NL	NL	65	65	65
14. Light-framed walls with shear panels of all other materials	14.1, 14.1.4.2, and 14.5	2	2½	2	NL	NL	35	NP	NP

ASCE 7 list of permitted systems



prescriptive reinforcement

… current force-based design approach

- based on structural system, assign seismic design factors (R, C_d, Ω_0)
  - design for elastic forces divided by *R*
  - design for elastic displacements multiplied by C_d
  - design elements that must remain elastic for elastic forces divided by *R* and multiplied by Ω_0

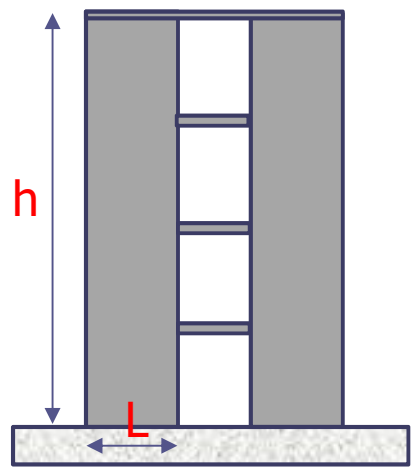
Seismic-Load Resisting Systems	*R*	C_d	Ω_0
Special RM Load Bearing Shear Walls	**5**	**3 1/2**	2 1/2
Intermediate RM Load Bearing Shear Walls	3 1/2	2 1/4	2 1/2

force-based design does not always work well

- final behavior is not always consistent with design intent

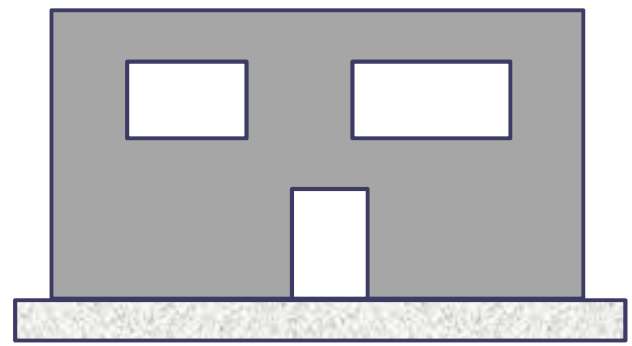
$$\textbf{aspect ratio} = \frac{\text{wall height}}{\text{wall length}}$$

easy to design



weakly coupled walls

may be impossible to design rationally

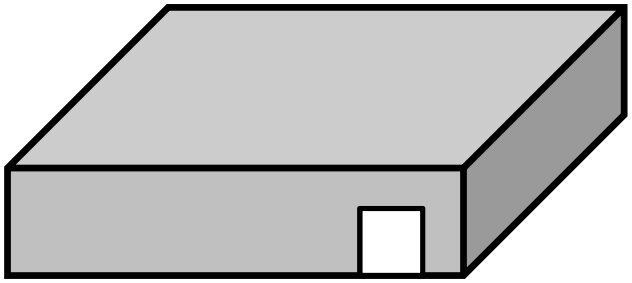


irregular openings

- current code requirements and design procedure will not result in predictable inelastic behavior

force-based design does not always work well

- ductility required by *R* and implied by detailing may not be available

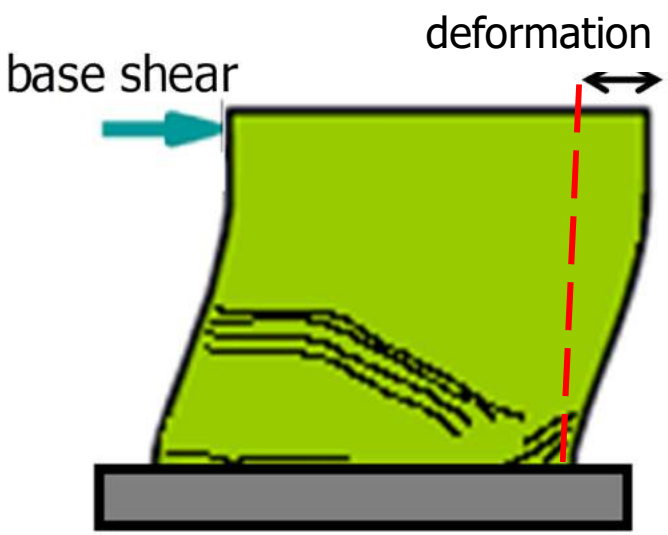


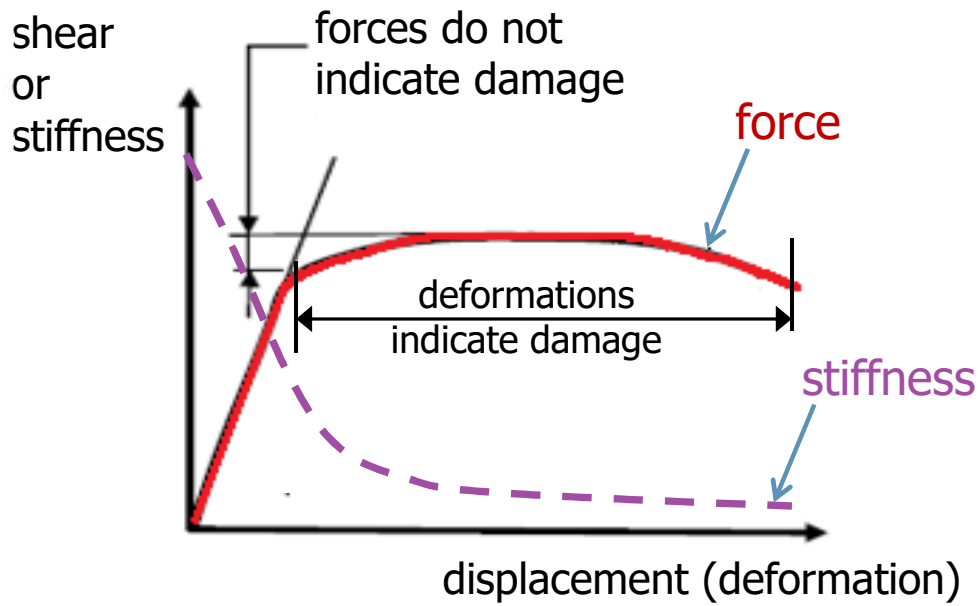
a low-rise structure in SDC D will not achieve high ductility

- walls can successfully resist seismic forces consistent with lower R-factors
- developed primarily based on the response of long-period structures, and were further modified by engineering judgment

force-based design requirements are not reliable

- emphasis on forces instead of deformations is misguided

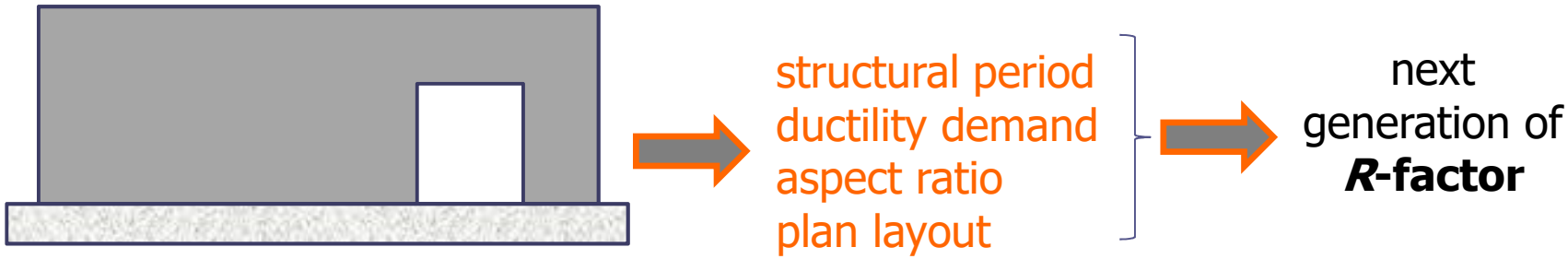




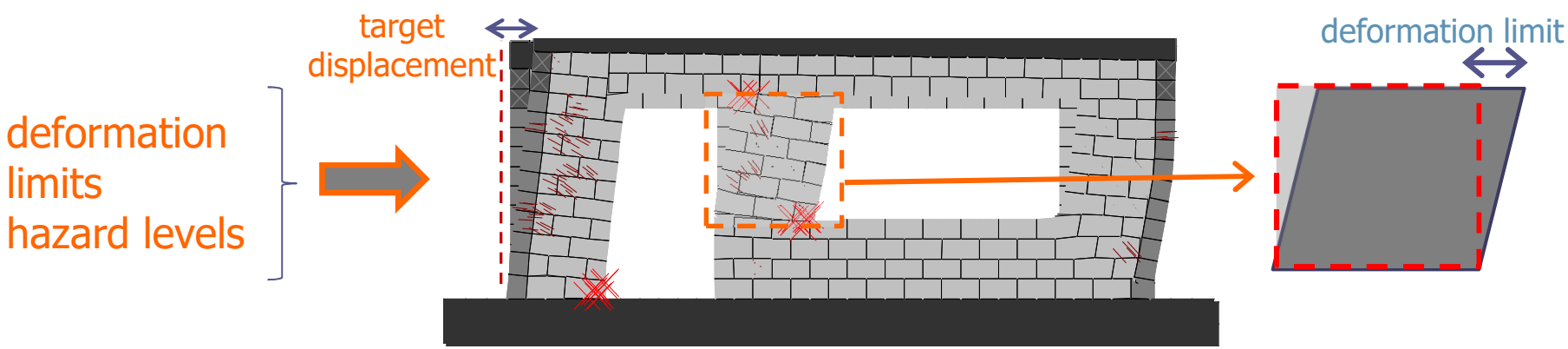
- force-based principle is not valid for short-period structures

better design approaches?

- modified force-based
  - R-factor accounts for actual system behavior

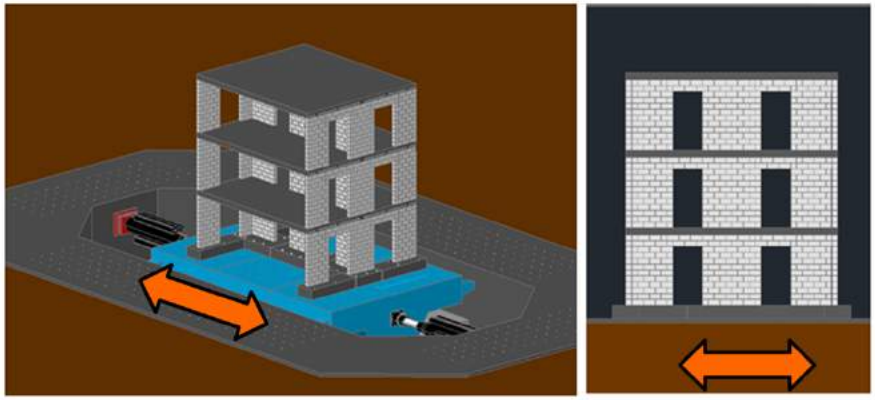


- displacement-based
  - emphasizes deformations
  - designer determines deformation limits

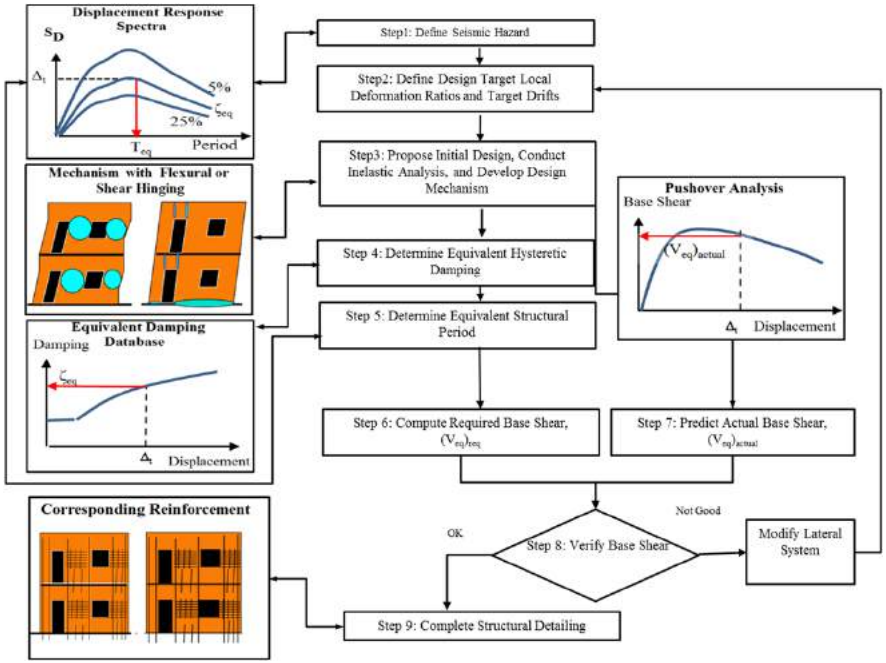


5 major tasks in this research . . .

- task 1- examined the behavior masonry buildings designed using force-based procedures

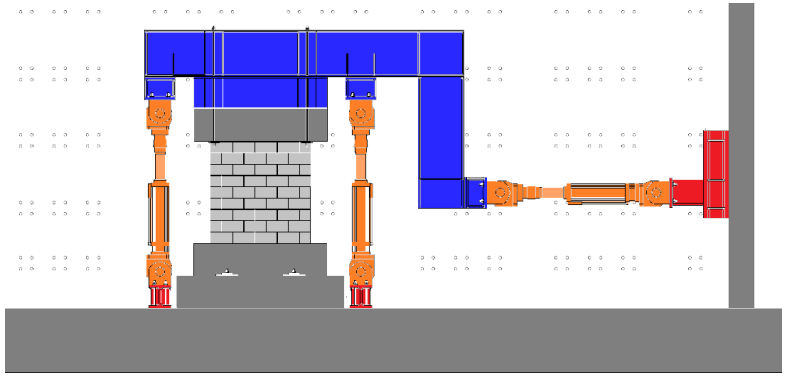


- task 2- developed displacement-based seismic design method

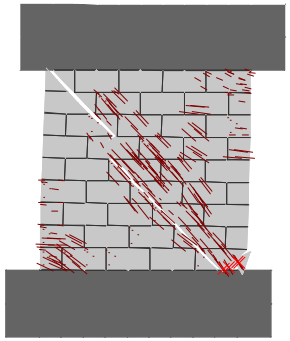


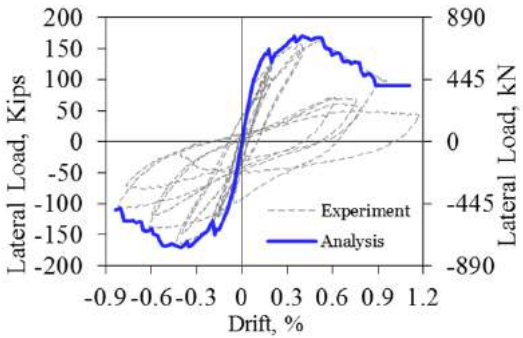
. . . 5 major tasks in this research

- task 3- conducted cyclic-load tests on masonry wall segments

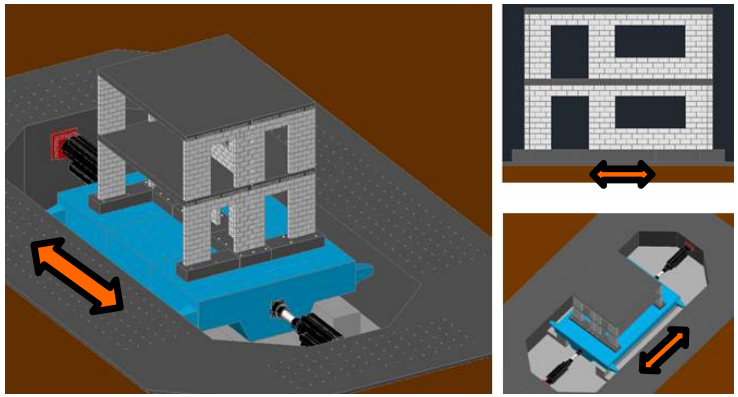


- task 4- improved analytical tools



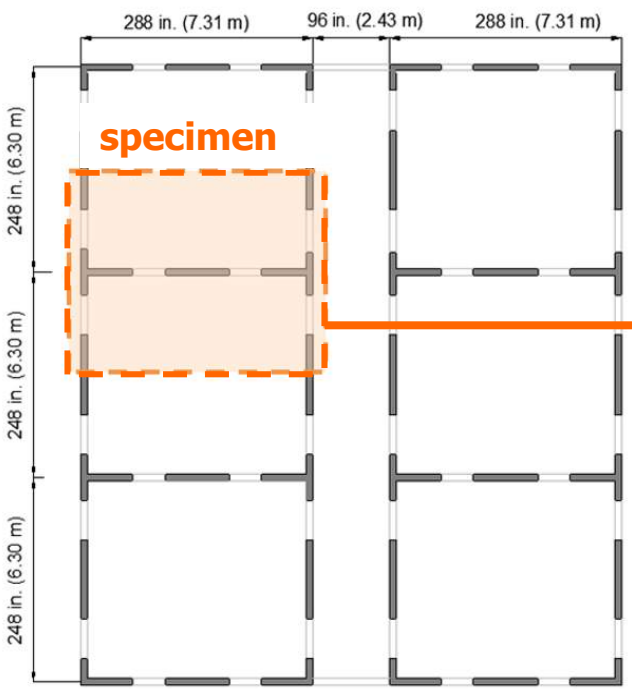


- task 5- validated displacement-based seismic design for masonry



task 1- examine force-based procedures

- used shake-table tests to examine overall and local behaviors of masonry buildings
- evaluate the performance of special reinforced masonry walls
- assess the failure mechanism of a real wall system



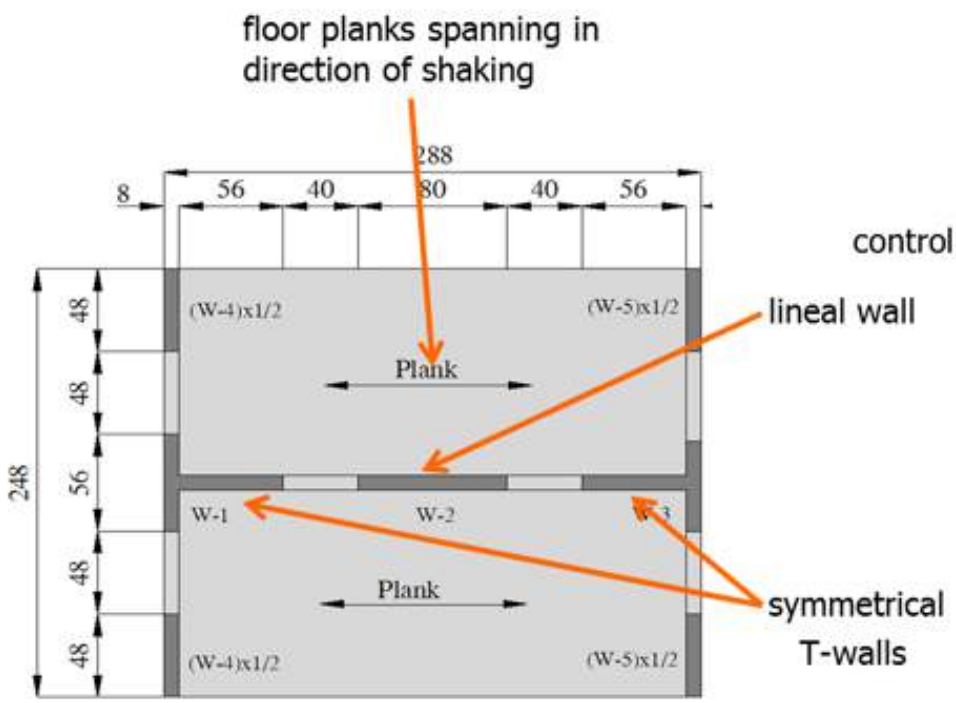
plan view of prototype building

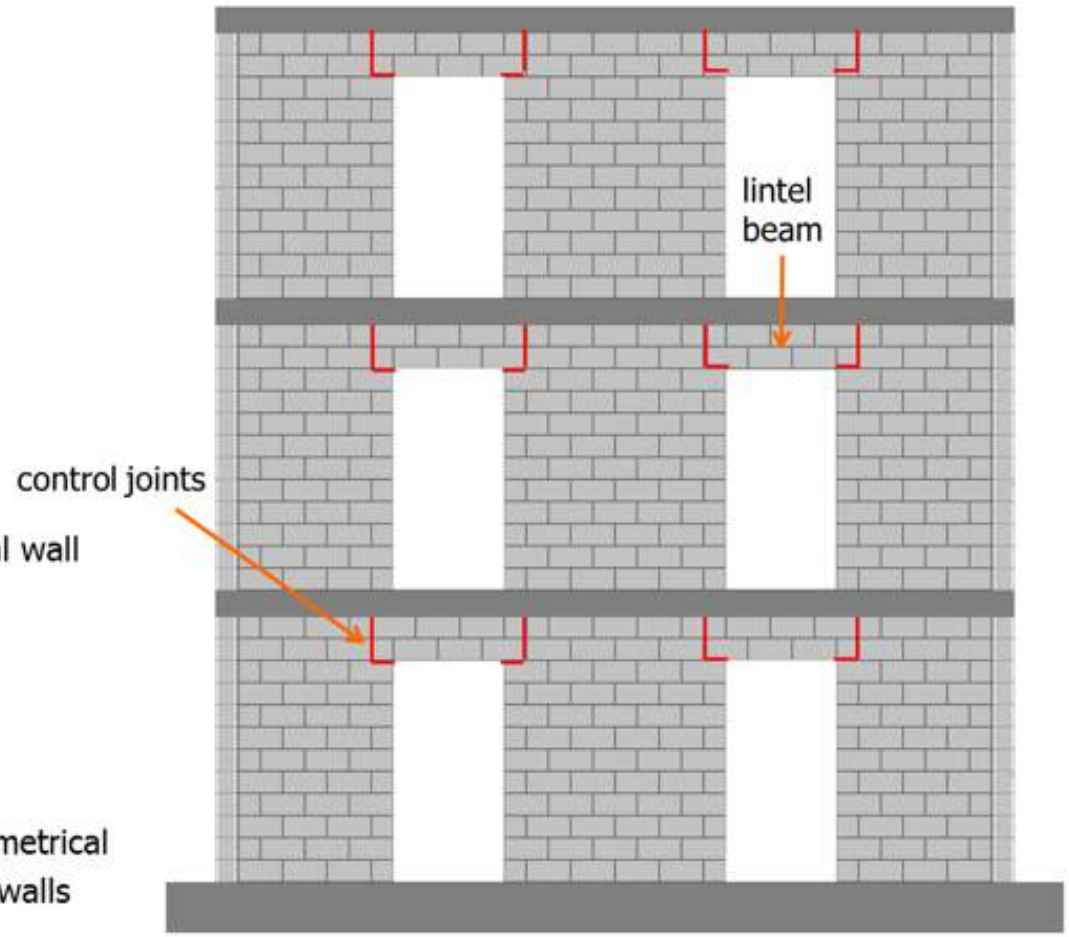
3-story specimen, UCSD-NEES

design full-scale 3-story specimen

- designed according to ASCE 7 and MSJC
  - special reinforced masonry shear wall with R=5
  - capacity design for shear
  - current requirements for prescriptive reinforcement

weakly coupled cantilever shear walls





3-story specimen behaved well

- specimen was subjected to an extended series of ground motions

Ground Motion	Scale Factor	Level of Excitation
Imperial Valley 1979 El Centro	20%	
	45%	
	90%	
	120%	DE
	150%	
	180%	MCE
	250%	above MCE
Imperial Valley 1940 El Centro #5	300%	
Northridge 1994 Sylmar	125%	MCE
	160%	1.25 MCE
Chi Chi 1999	150%	2.0 MCE

150 % Chi Chi 1990 (2 MCE)

Design Earthquake (DE),10% in 50 years

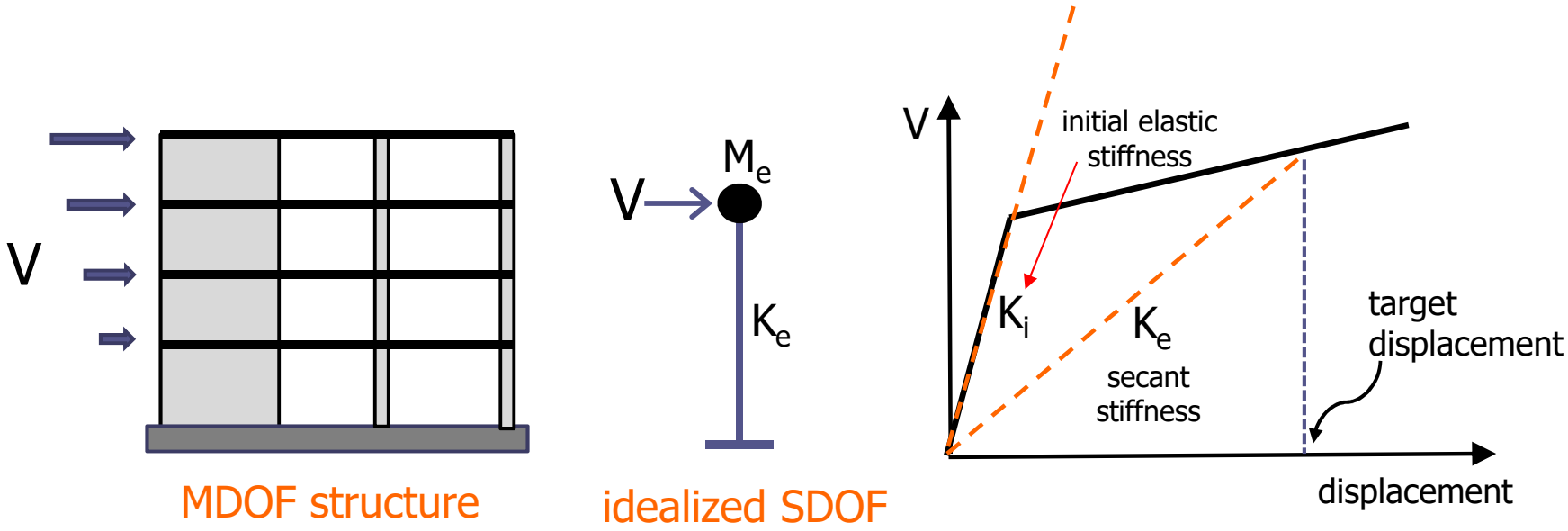
Maximum Considered Earthquake (MCE), 2% in 50 years

results were significant from a design viewpoint

- specimen was stiffer and stronger than anticipated
- final behavior was not consistent with design intent
- ductility required by R = 5 was not available

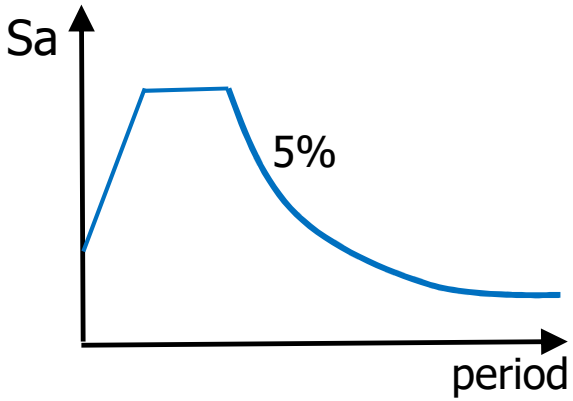
task 2- develop displacement-based design

- based on achieving specified deformation limits under selected seismic hazard levels
- fundamental difference between force-based and displacement-based design



technical basis for displacement-based method …

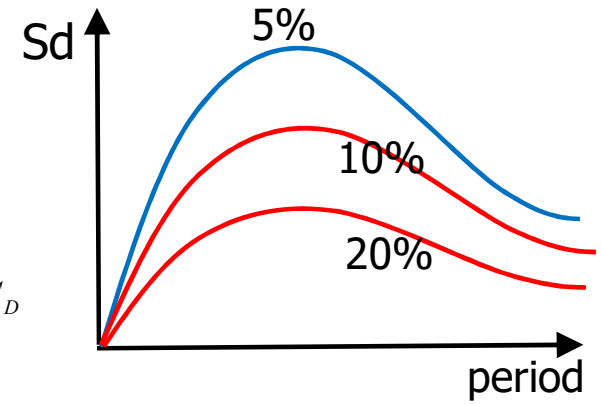
- **Step 1-** define seismic hazard levels
  - Design Earthquake (DE),10% in 50 years
  - Maximum Considered Earthquake (MCE), 2% in 50 years



design response spectrum

$$S_D = \frac{T_{eq}^2}{4\pi^2} S_a$$

$$S_{D-\xi_{eq}} = \sqrt{\frac{0.07}{0.02+\xi_{eq}}} S_D$$

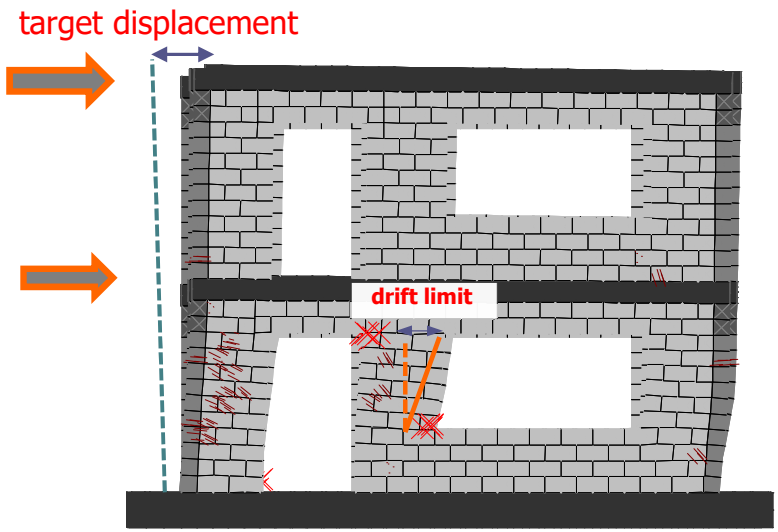


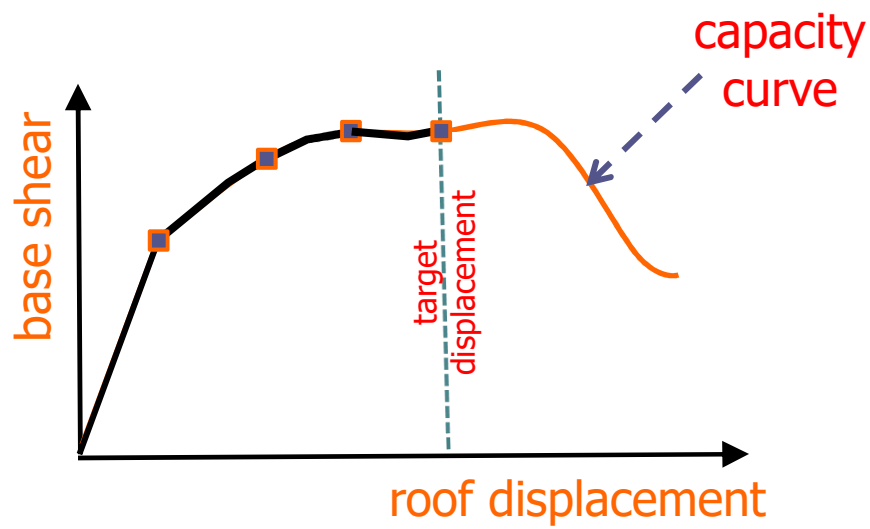
displacement response spectrum

- **Step 2-** determine design parameters (flexural and shearing) of wall segments
  - local deformation limits
  - determine damping for structural system

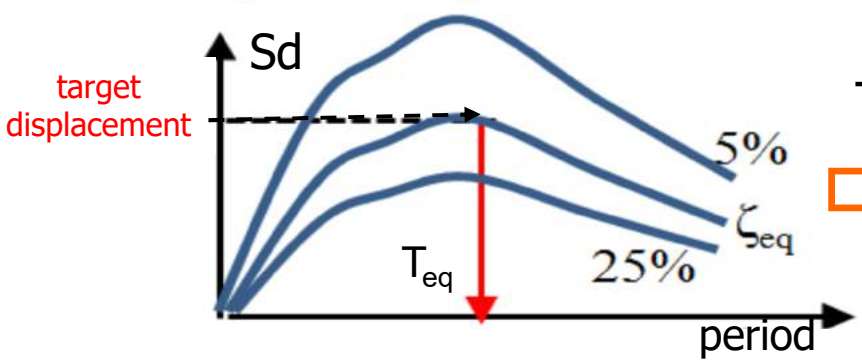
… technical basis for displacement-based method

- **Step 3-** conduct inelastic analysis, and select a reasonable target mechanism for each hazard level





- **Steps 4 and 5-** determine equivalent structural period, and compute required base shear



T_{eq}

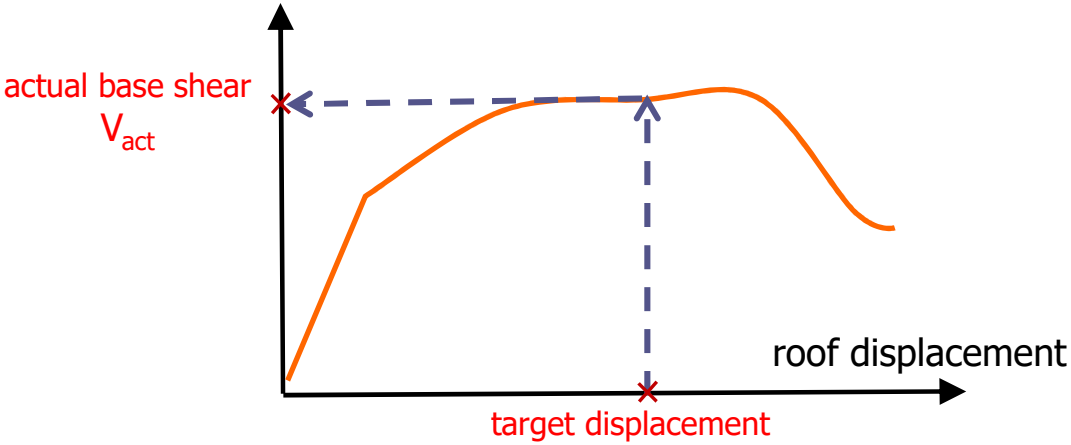
$$(k_{eq})_{req} = \frac{4\pi^2 W_{eff}}{g T_{eq}^2}$$

required base shear

$$V_{req} = (k_{eq})_{req} \Delta_{eq}$$

… technical basis for displacement-based method

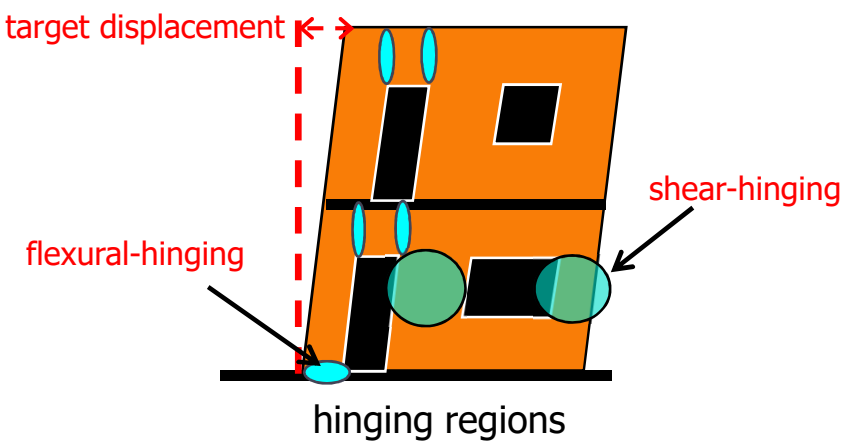
- **Steps 6 and 7-** predict base shear capacity, and verify base shear

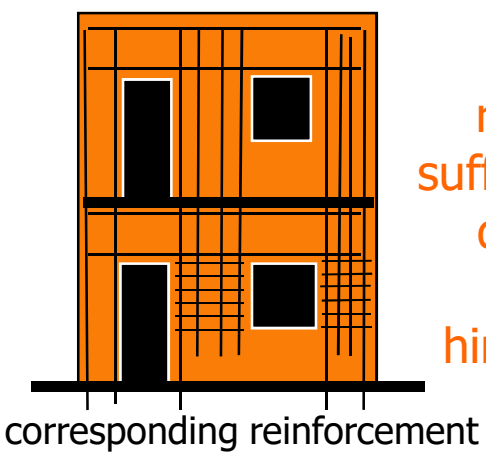


$$V_{act} \geq V_{req}$$

actual base shear — required base shear

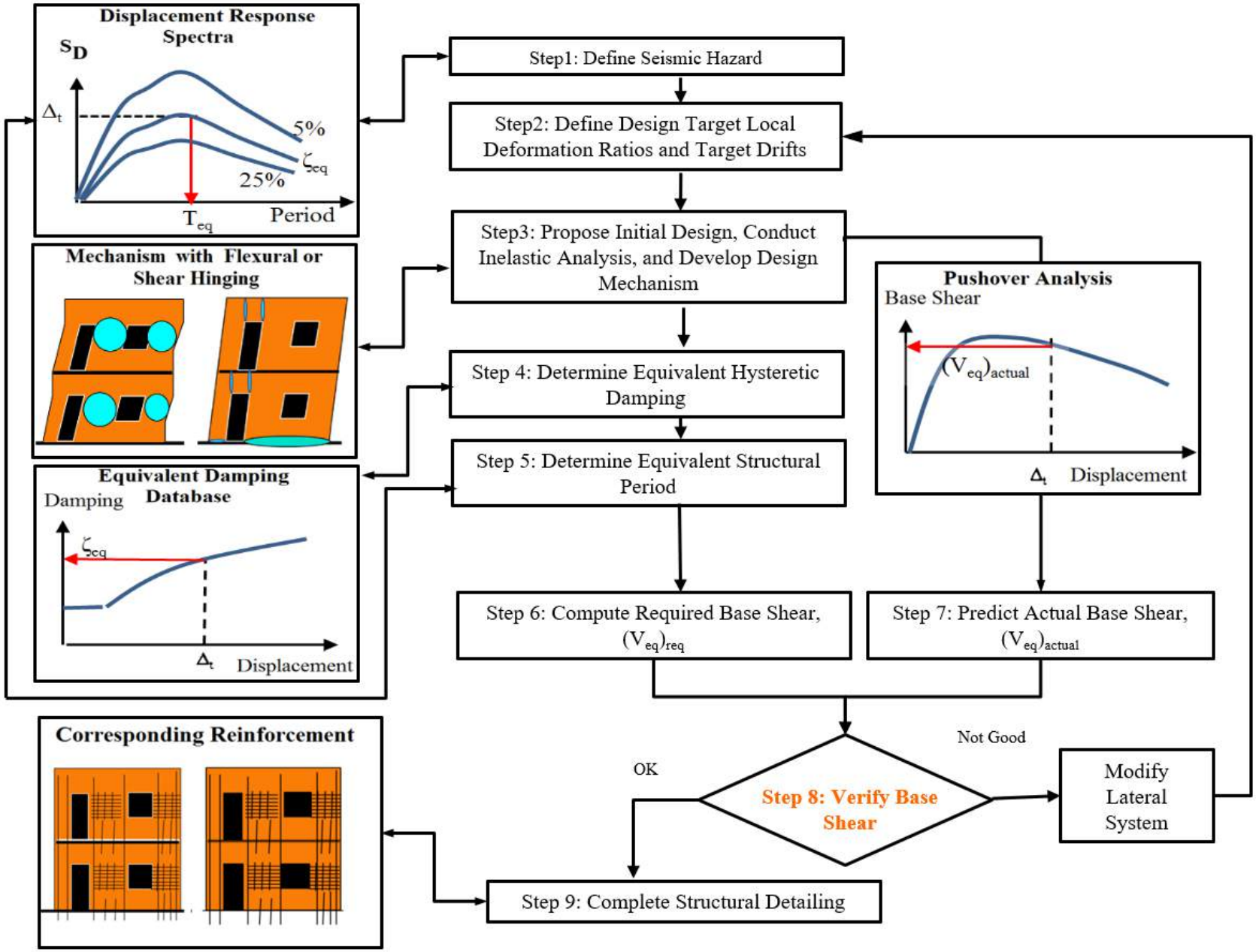
- **Step 8-** identify the inelastic deformation demands and adjust strength or detailing





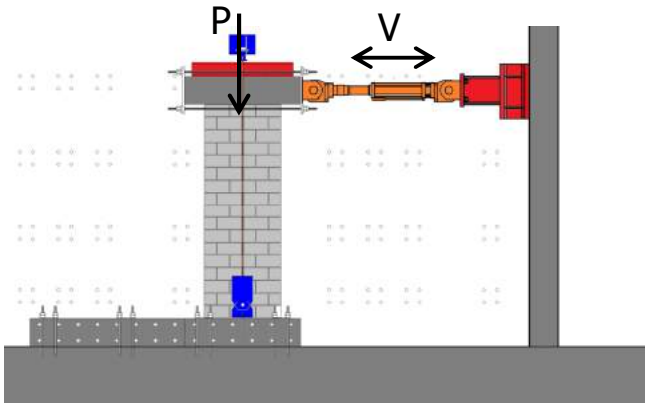
reinforce for sufficient inelastic deformation capacity in hinging regions

fundamental steps

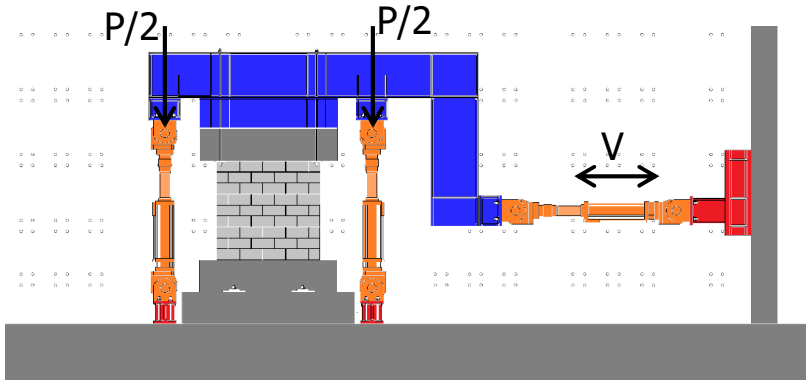


task 3- conduct cyclic-load test of shear-walls

- designed and conducted cyclic-load tests of 41 masonry shear-walls
  - test different levels of prescriptive detailing, axial loads, boundary conditions, and aspect ratios



cantilever walls

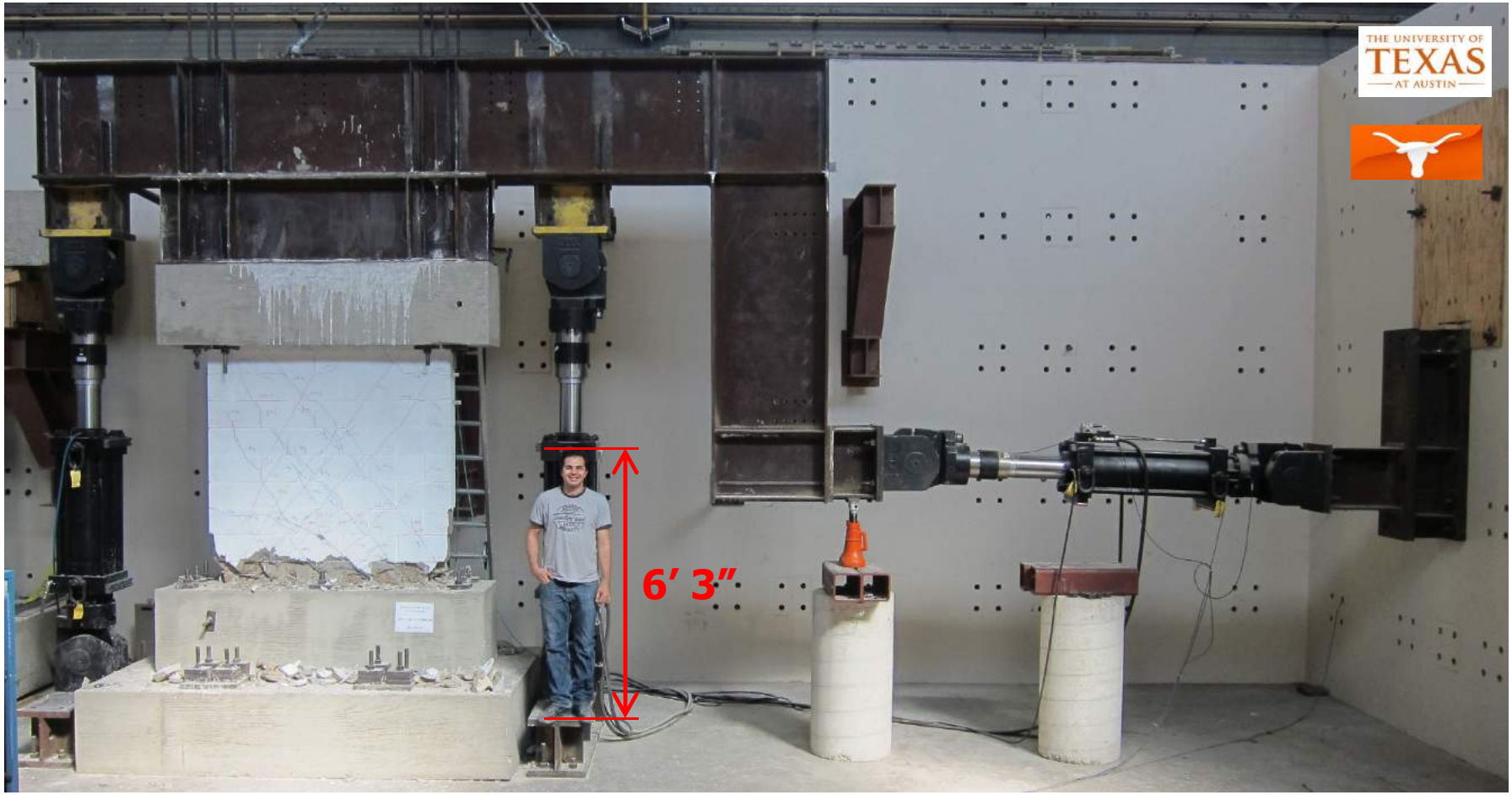


fixed-fixed walls

  - refine inelastic analytical models
  - find deformation limits

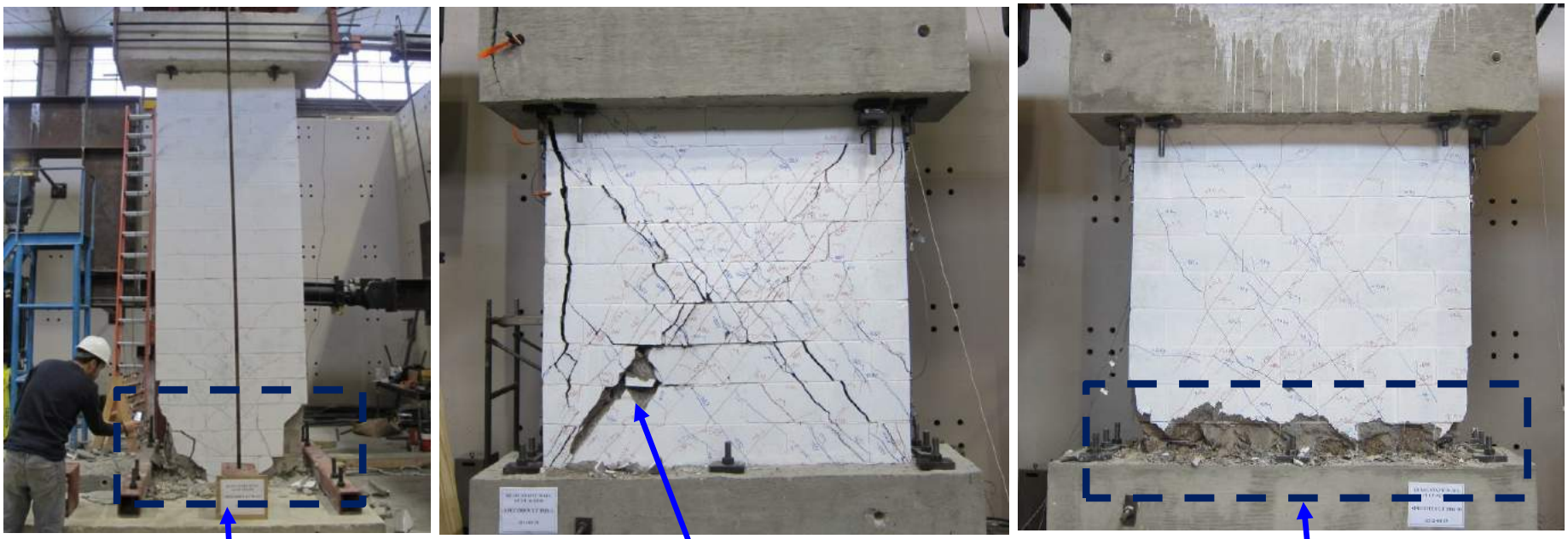
41 quasi-static test wall specimens

- test setup for cyclic-load test of masonry shear wall specimens at UT Austin



results from reversed cyclic load tests

- typical cyclic behavior of shear wall specimens
  - flexural failure
  - shear failure
  - sliding shear failure



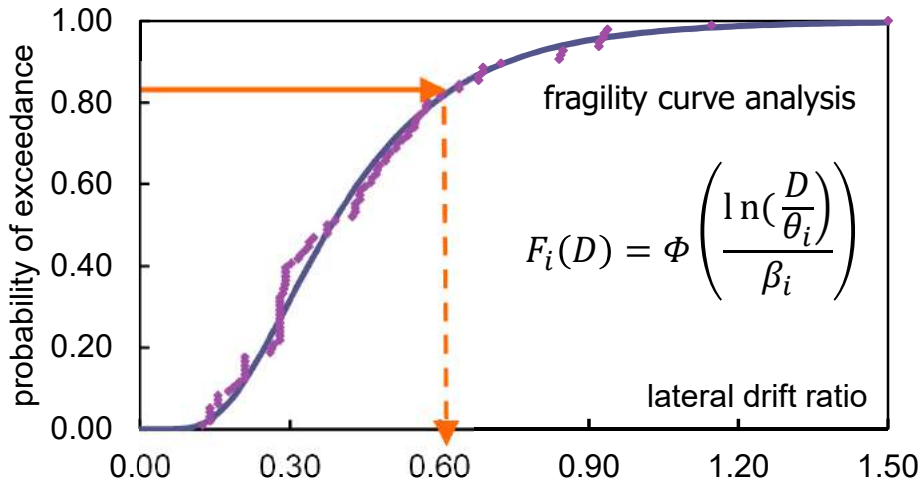
plastic hinge at the base

diagonal shear degradation

significant sliding at the base

inelastic deformation limits

- used results to find flexural and shear deformation limits
  - drift-based fragility curves



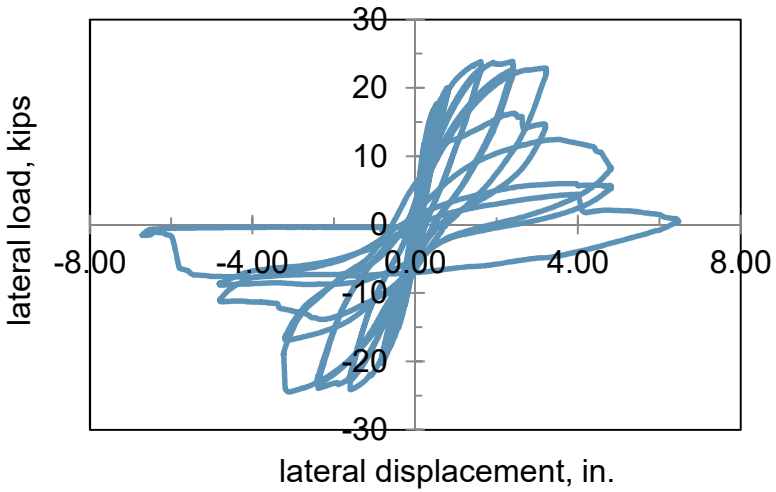
	damage state	damage description
flexure	DS-1 Safety Damage State	moderate flexure damage
flexure	DS-2 Collapse Damage State	severe flexure damage
shear	DS-3 Safety Damage State	moderate diagonal shear damage
shear	DS-4 Collapse Damage State	severe diagonal shear degradation

	aspect ratio	deformation limits	
		Safety	Collapse
flexure-controlled	4 and higher	1.50%	2.50%
flexure-controlled	between 1.0 and 4.0	1.20%	2.00%
flexure-controlled	1.0 and lower	0.80%	1.50%
shear-controlled	all cases	0.50%	1.00%

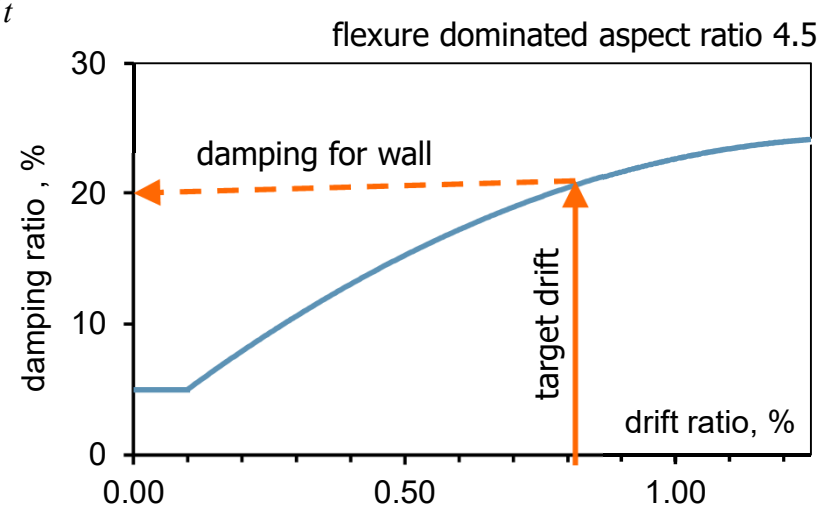
determine equivalent hysteretic damping

- damping database for structural system

$$x_{eq} = \frac{E_{DD_t}}{2pk_{eq}D_t^2} + x_0$$



using cyclic load test results

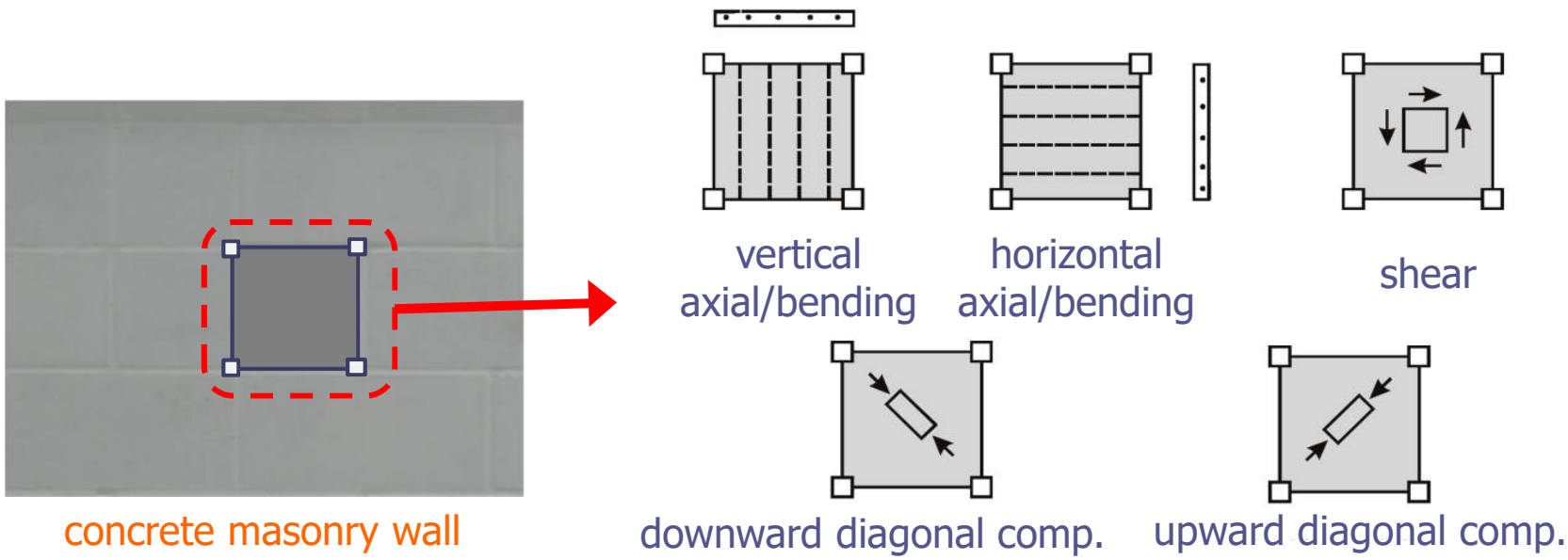


damping database for different aspect ratios and behaviors

- effective global damping can be calculated as a weighted average based on distribution of shear forces

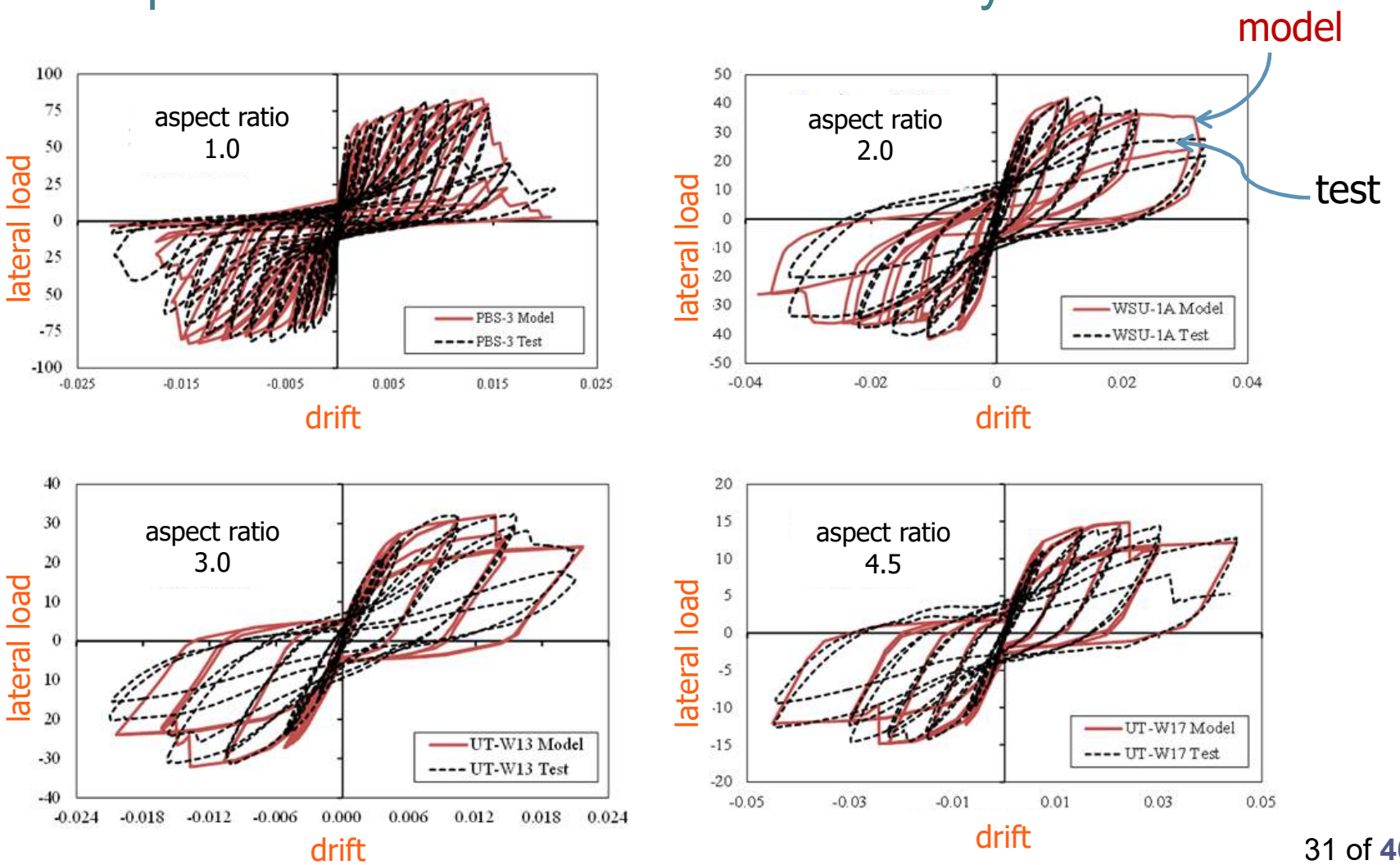
task 4- improved analytical tools

- predict nonlinear resistance and failure behavior
- predict local and global responses and deformations
- different modeling approaches were considered
  - nonlinear "macro" models



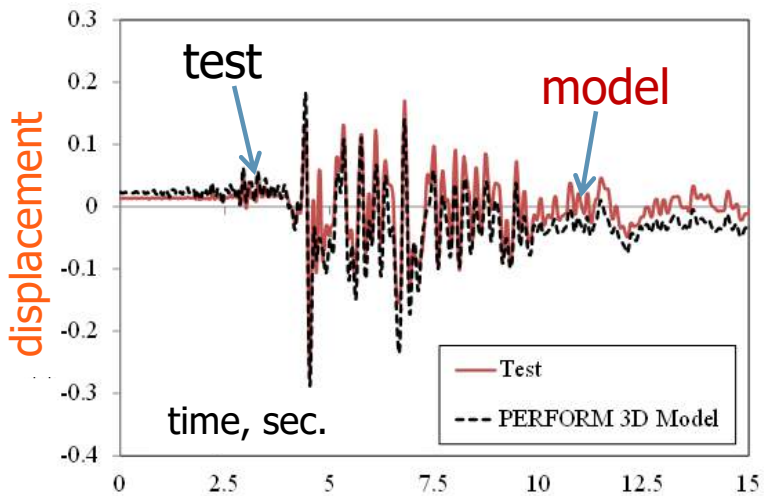
verification of models

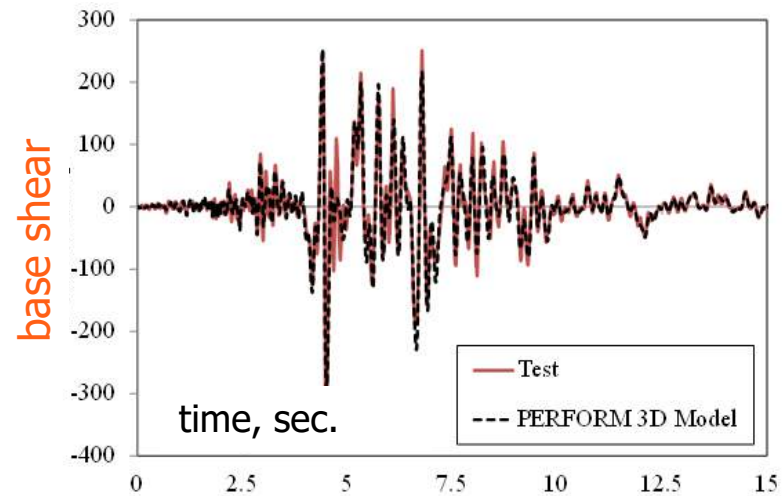
- verification of models using experimental results from masonry shear-wall specimens
  - displacement-controlled nonlinear analysis



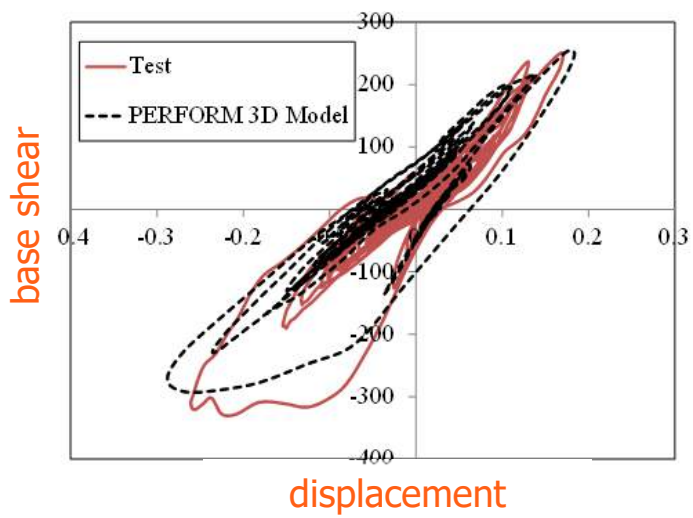
further verification of models

- used models to predict the nonlinear seismic response of 3-story specimen



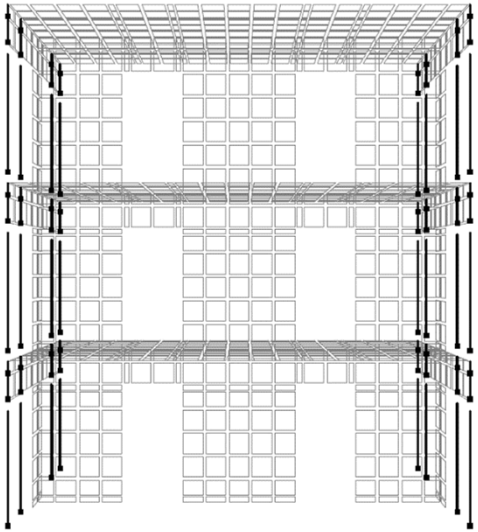


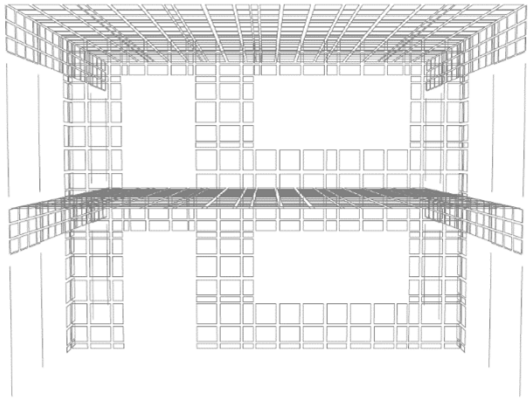
250% El Centro 1979 (MCE)



satisfactory results

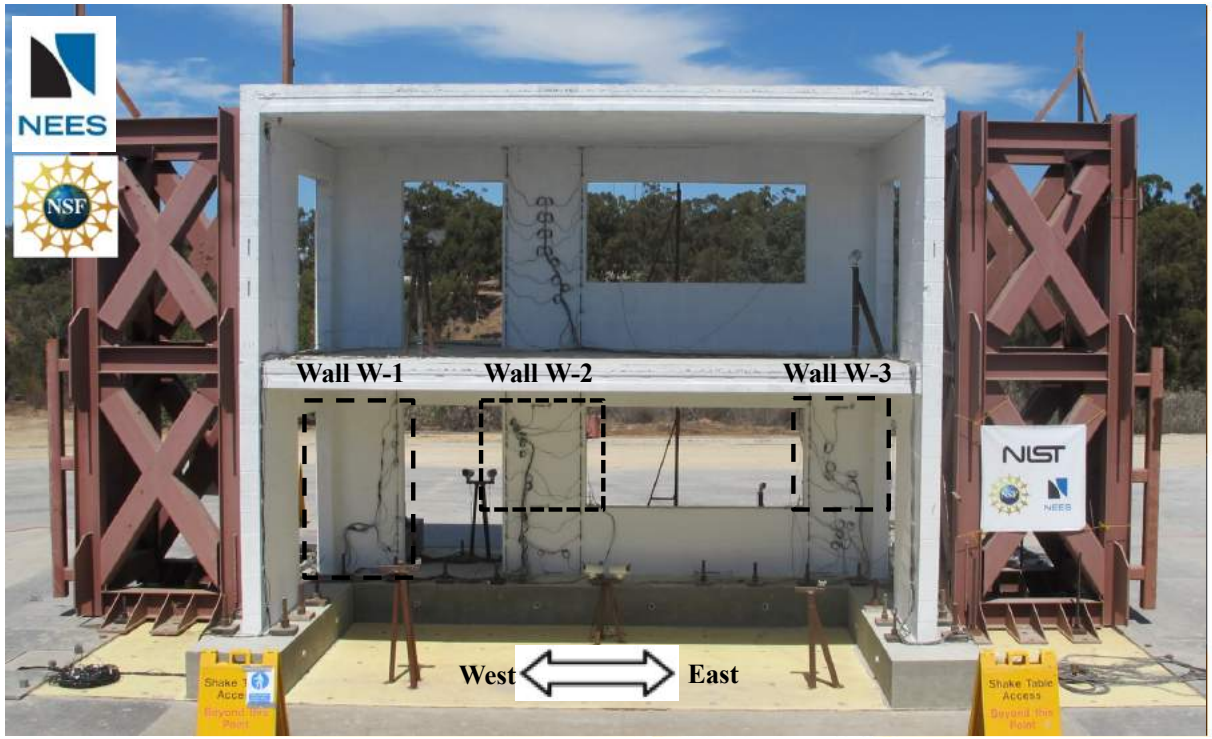
- for wall segments, proposed model accurately matched observed responses and reasonably represented cyclic properties
- at the system level, predictions agree quite well with the observed seismic responses
- models can be used as part of a systematic framework for displacement-based design

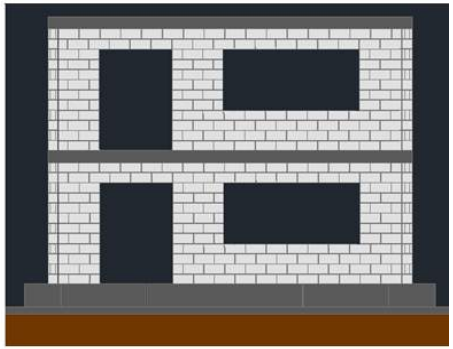


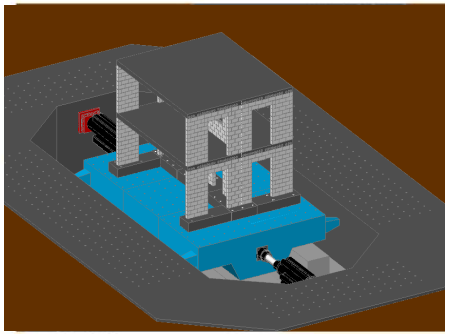


task 5- validation of displacement-based design

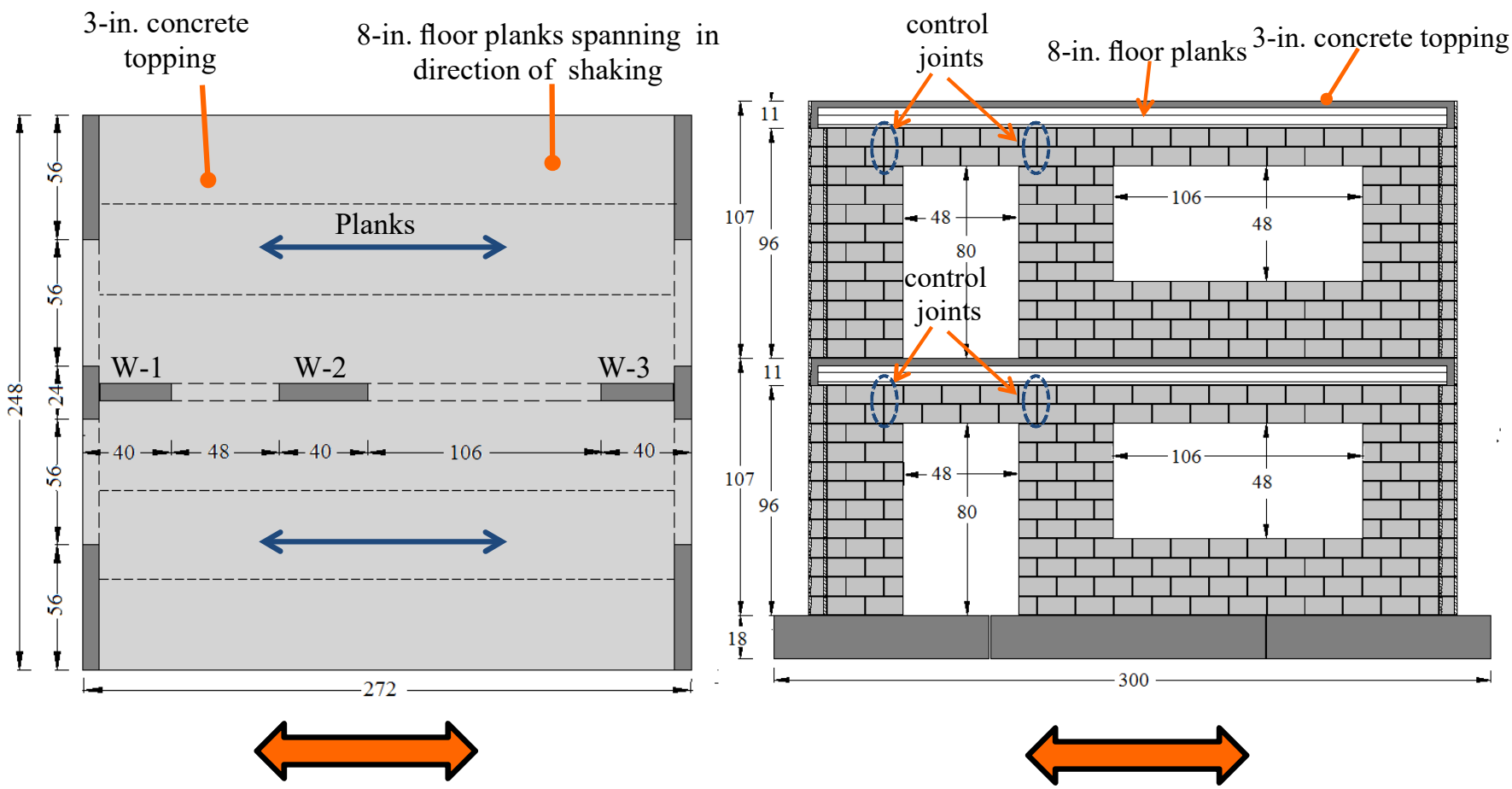
- application of proposed displacement-based design and analytical tool
- a full-scale two-story reinforced masonry shear-wall system, complex geometry of openings





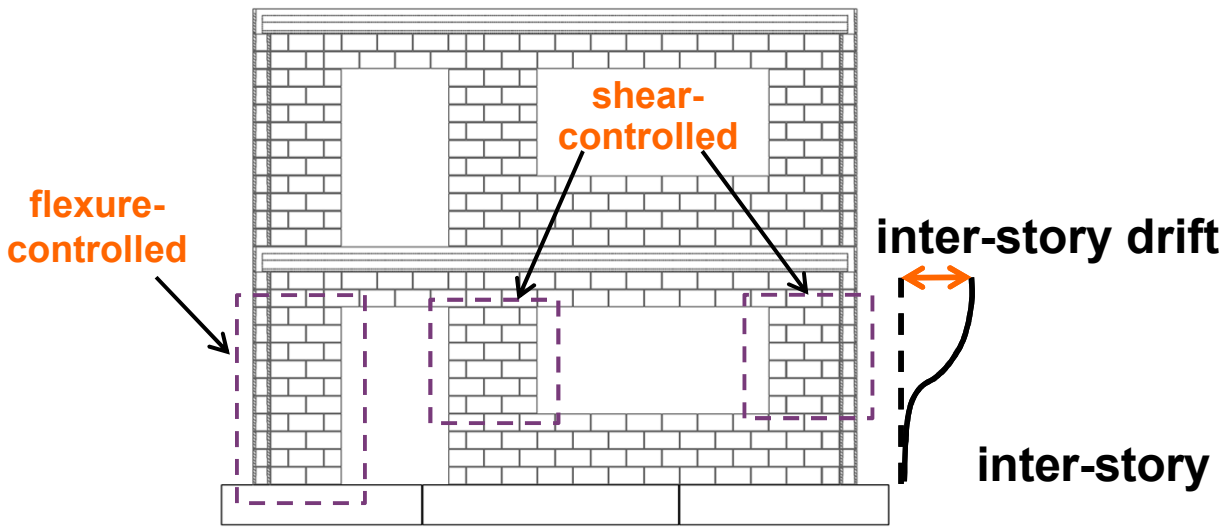


plan layout and elevation of specimen



select seismic hazard levels and target drifts

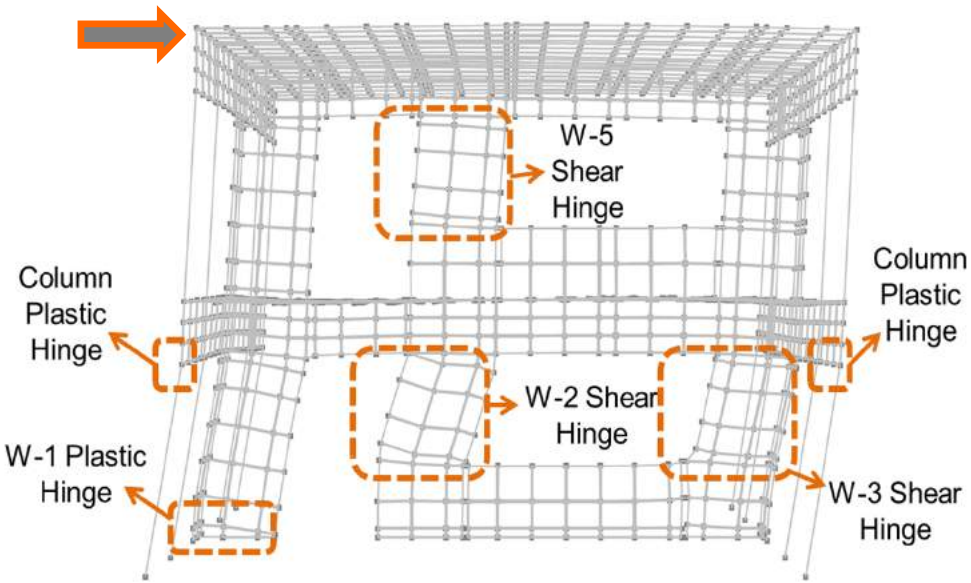
seismic hazard Level	damage state	deformation limits		corresponding inter-story drift ratios
		flexure-controlled wall segments	shear-controlled walls segments	
Design Earthquake (DE)	Safety Damage State	0.8 %	0.5 %	0.3 %
Maximum Considered Earthquake (MCE)	Collapse Damage State	1.5 %	1.0 %	0.6 %



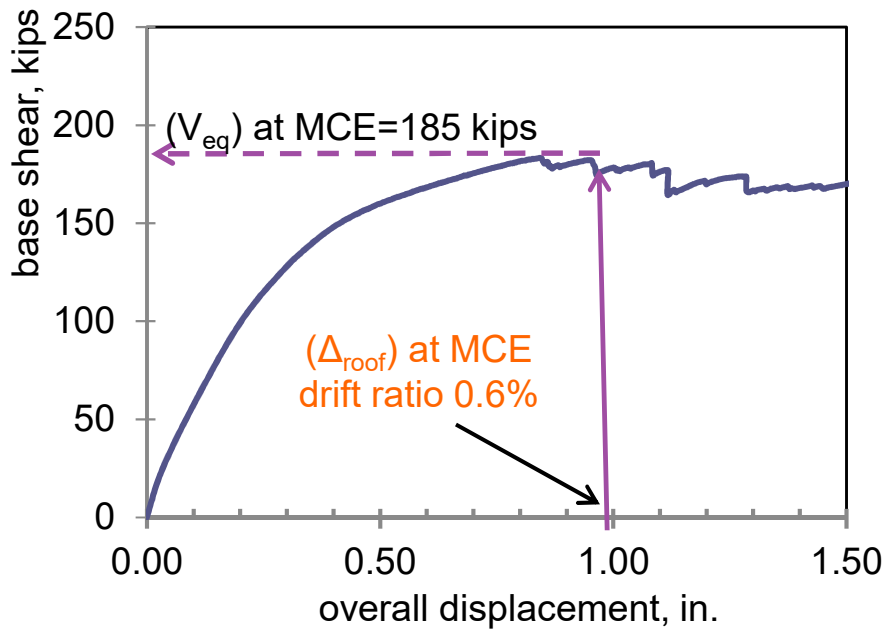
$$\text{inter-story drift ratio} = \frac{\text{inter-story drift}}{\text{story height}}$$

conduct inelastic analyses

- performed pushover analyses to determine the capacity curve and target mechanisms at selected hazard levels



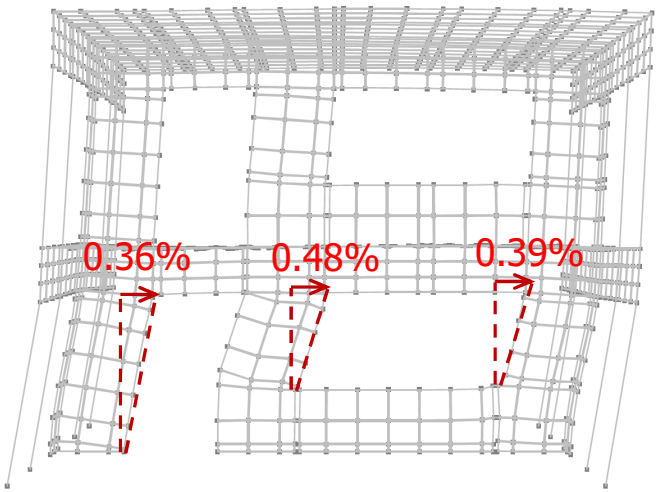
target mechanism at MCE



capacity curve and base shear at MCE level

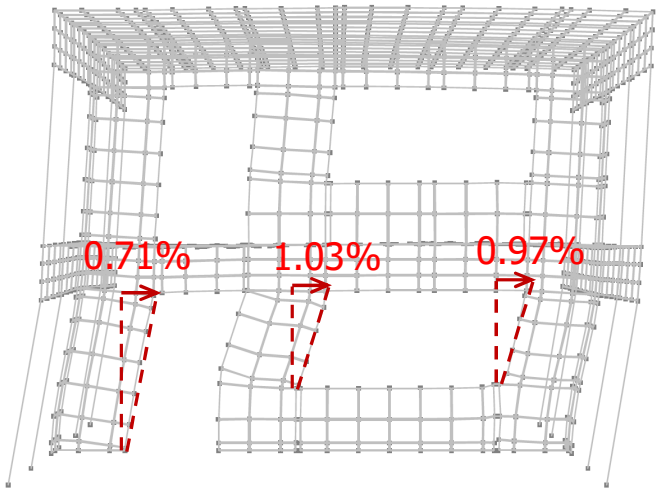
predict deformation demands in wall segments

- at DE level
  - center wall segment would be shear-dominated, and would have drift ratio of 0.48%



local drift ratios at DE

- at MCE level
  - center wall segment would be shear-dominated, and would have drift ratio of 1.03%

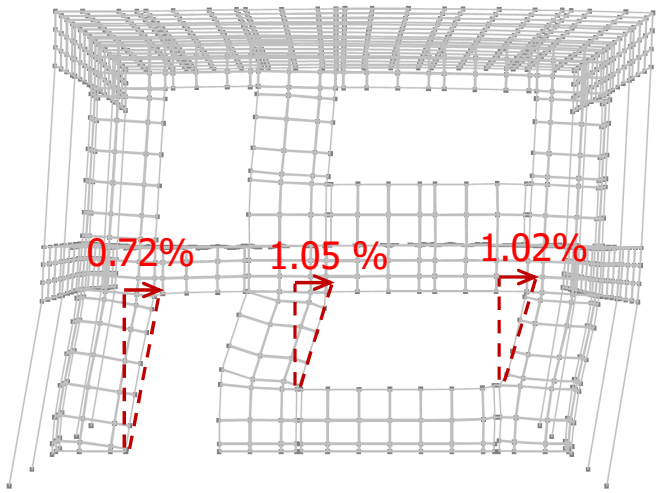


local drift ratios at MCE

predict the response of 2-story specimen

- nonlinear time-history analyses for input sequence

order	ground motion	hazard level
1	30% El Centro 1979	
2	43% El Centro 1979	0.50 DBE
3	86% El Centro 1979	0.80 DBE
4	**108% El Centro 1979**	**slightly above DE**
5	145 % El Centro 1979	slightly below MCE
6	**160% El Centro 1979**	**slightly above MCE**



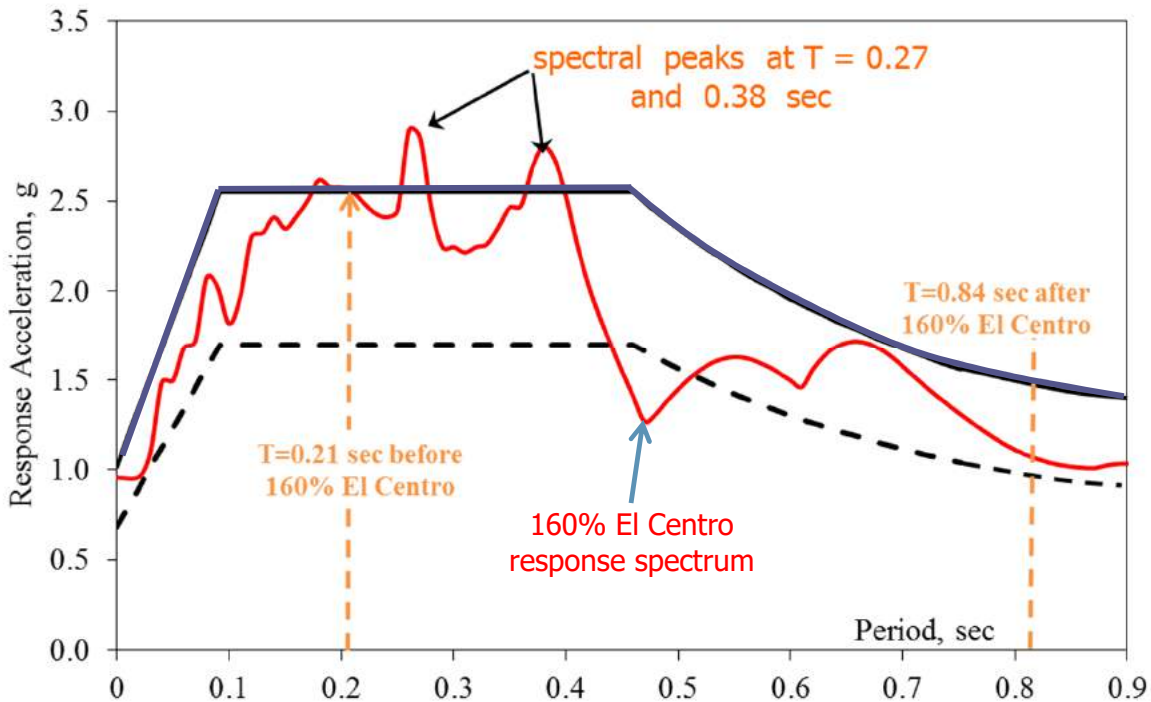
local drift ratios at MCE

- at MCE: center and right wall segments would have local drift ratios of about 1%

shake table test of 2-story specimen

- specimen was subjected to an extended series of ground motions

order	ground motion
1	30% El Centro 1979
2	43% El Centro 1979
3	86% El Centro 1979
4	108% El Centro 1979
5	145 % El Centro 1979
6	160% El Centro 1979

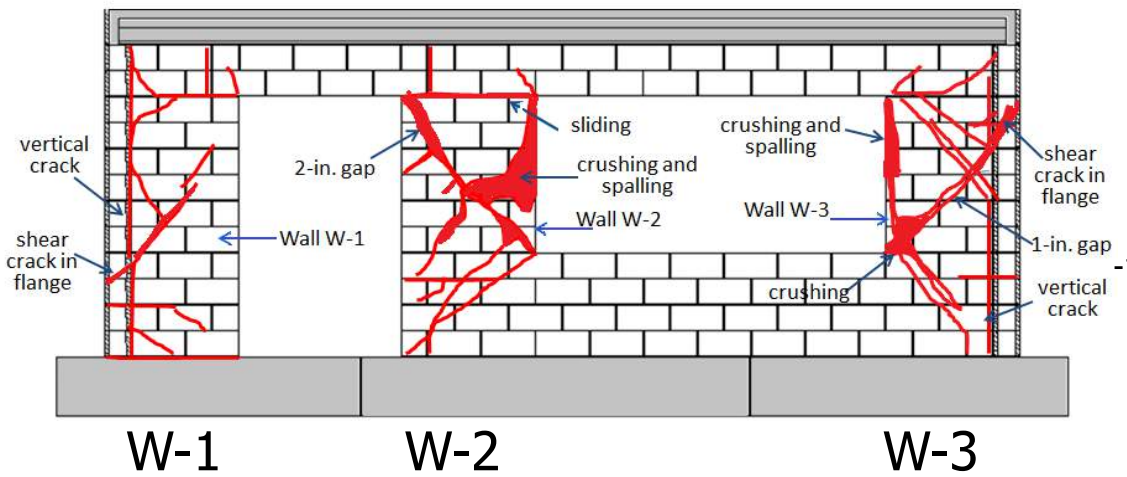


shake-table test of specimen above MCE

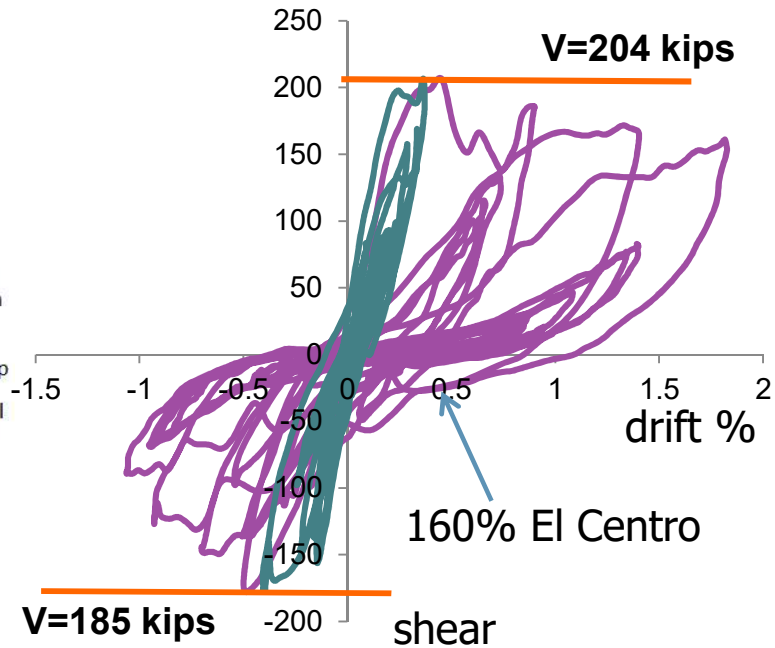
- 160 % El Centro (above MCE)

2-story specimen behaved well and as expected

- flexural hinging in W-1
- severe shearing degradation in W-2
- flexural hinging in one direction, and shear hinging in the other direction in W-3



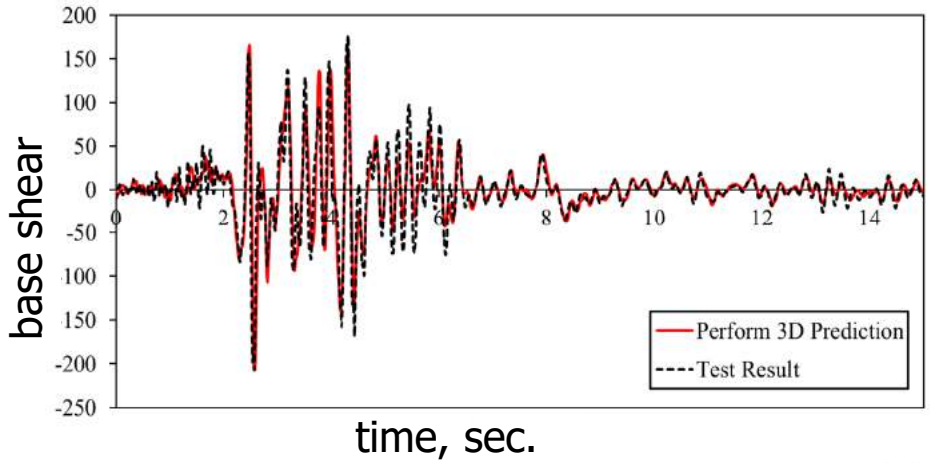
observed cracks in first story

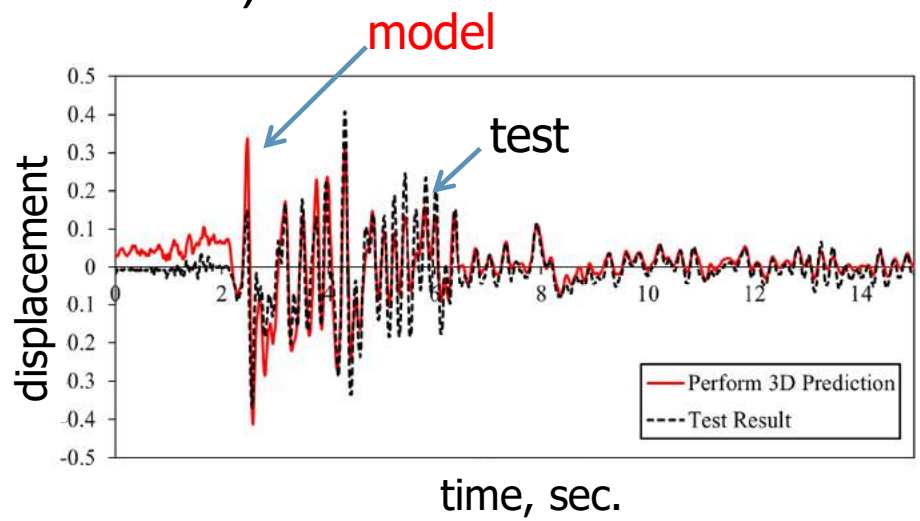


load-displacement in first story

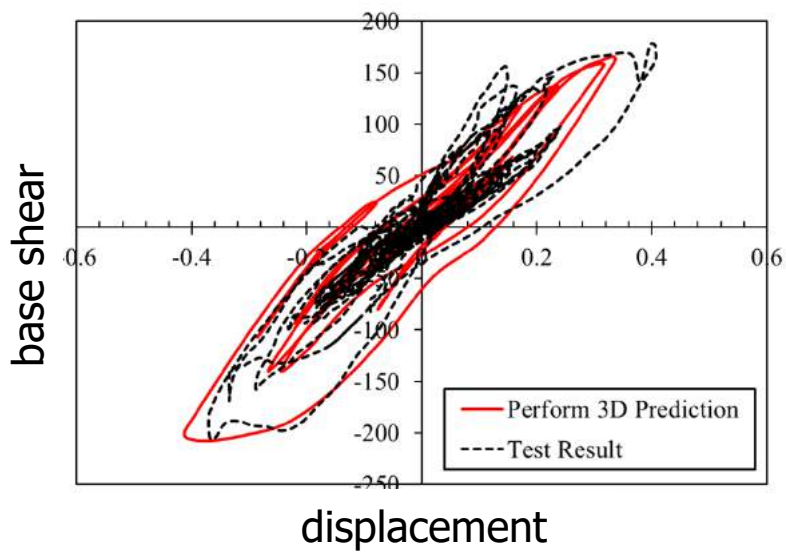
measured vs. predicted responses …

- comparison between shake-table test and numerical results, 145% El Centro (about MCE)





145% El Centro 1979 (about MCE)

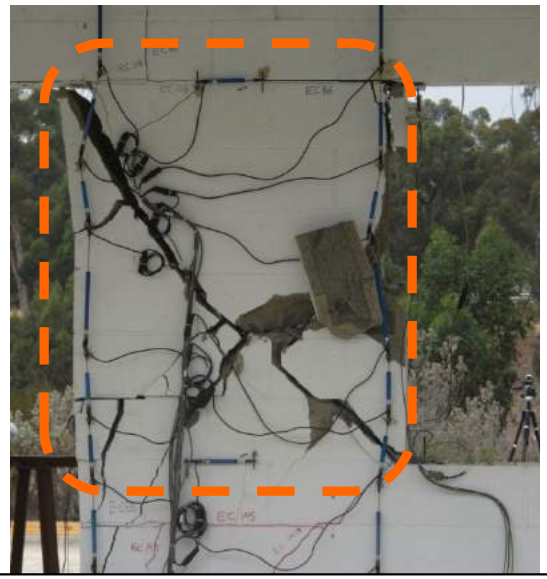


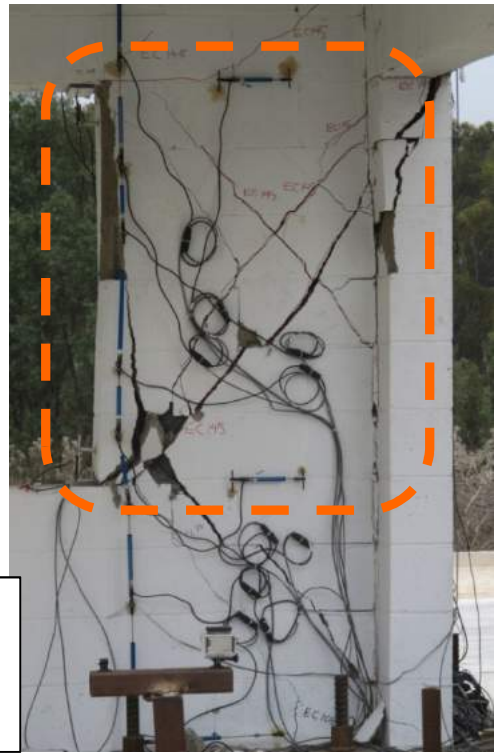
… measured vs. predicted responses

- walls exceeded expected deformation capacities

Wall W - 1 was flexure - dominated , exceeded **1%** drift ratio

Wall W - 3 was shear - dominated one way , flexure - dominated the other way , exceeded **1%** drift ratio





Wall W - 2 was shear - dominated , exceeded **1.5%** drift ratio

main tasks accomplished in this research

- developed a specific displacement-based seismic design method
- improved analytical tools for displacement-based seismic design method
- validated displacement-based seismic design method for masonry structures
- proposed provisions for displacement-based seismic design for inclusion in design codes

important points of this presentation

- current force-based seismic design does not always work well for reinforced masonry shear-wall structures

- proposed displacement-based seismic design works for masonry shear wall structures
  - it produces structures that behave reliably in strong earthquakes
  - it is more consistent and more transparent than current force-based seismic design