Seismic Behavior, Analysis and Design of Complex Wall Systems

A *Small-Group* Research Project Funded through the NSF NEES Research Program

The Research Team

- University of Washington
  - Laura Lowes, Assistant Professor
  - Dawn Lehman, Assistant Professor
  - Aaron Sterns & Paul Øyen, Graduate Student Researchers
  - Undergraduate Researchers
- University of Illinois
  - Dan Kuchma, Assistant Professor
  - Jian Zhang, Assistant Professor
  - Yuchuan Tang, Graduate Research Assistant
  - Jun Ji, Graduate Student Researcher
- External Advisory Panel
  - Ron Klemencic and John Hooper, Magnusson Klemencic Associates
  - Andrew Taylor, KPFF Consulting Engineers
  - Neil Hawkins, Professor Emeritus, University of Illinois

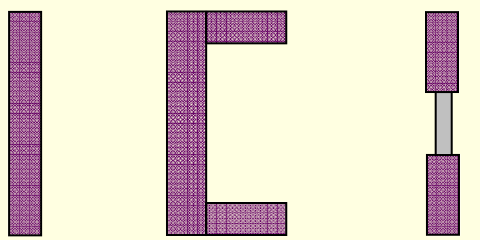
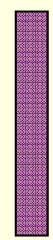
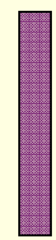
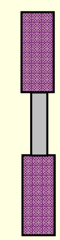
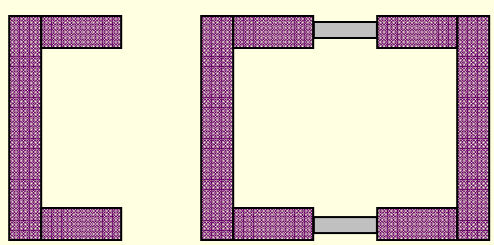
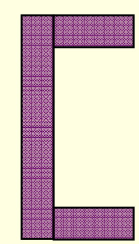
Project Basics

- Research Objectives:
  - Improve understanding of the seismic behavior of complex reinforced concrete walls including soil-structure interaction and develop tools to enable performance-based seismic design of these components.
- Project Scope:
  - Experimental investigation of slender walls with complex configurations using the UIUC MUST-SIM NEES facility.
  - Development of numerical models and modeling recommendations to enable simulation of the seismic response of buildings with walls, including foundation flexibility.
  - Development of damage-prediction models and performance-based design recommendations

Seismic Behavior of Walls

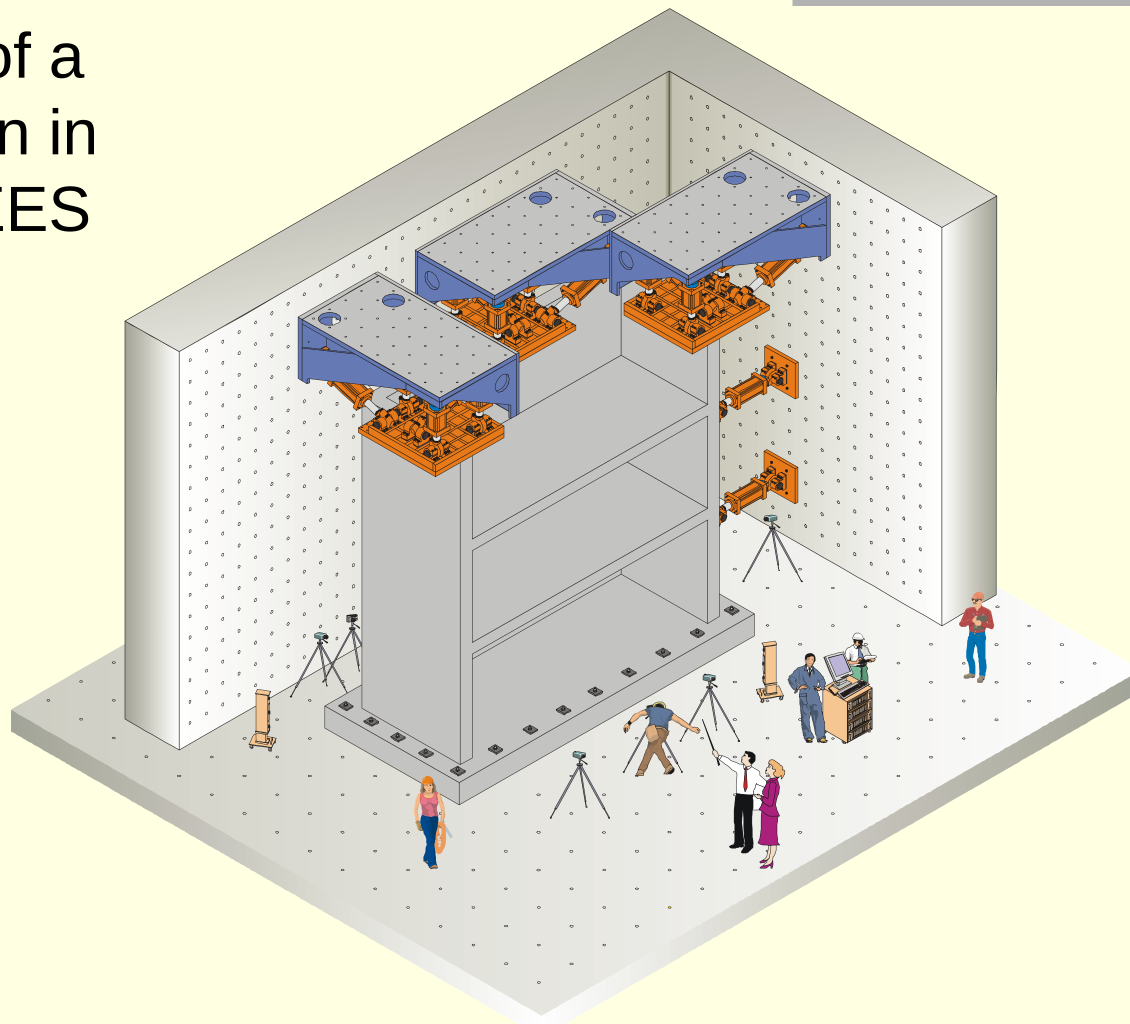
- Laboratory testing of wall sub-assemblages to generate data to support development of
  - Numerical models for use by practicing engineers to predict load and deformation demands on walls with realistic foundation boundary conditions,
  - Numerical models for behavior of structural concrete,
  - Performance-prediction models for use in design.
- Experimental testing to be conducted using the UIUC NEES facility. This facility enables
  - Testing of wall sub-assemblages with realistic configurations at moderate scales (~1/3)
  - Simulation of the load distribution that develops in the critical region at the base of the wall in buildings of moderate height.
  - Testing of representative foundation boundary conditions.
  - High-resolution measurement of the specimen displacement and strain fields.

Experimental Test Program

	Moment – Shear Ratio	Long. Reinf. Ratio	Load History	SSI Boundary Conditions
Unidirectional Loading	 Planar (2) Flanged Coupled			
Bidirectional Loading	 Core-Wall System			

Laboratory Test Specimens

- Idealization of a test specimen in the UIUC NEES facility



Analysis of Wall Systems

- Develop recommendations for the use of simple, elastic, effective-stiffness models for performance-based design of walls.
- Develop recommendations for the use of simplified nonlinear models for performance-based design.
- Develop sophisticated nonlinear continuum models that can be used for design of special structures as well as to investigate the impact of design parameters and load history on performance.
- Develop nonlinear macroscopic models for use in simulating pile and spread-footing foundations.

Performance-Based Design Tools

- Quantify the uncertainty with which the simplified simulation models predict wall demand.
- Identify repair-specific performance states for slender wall systems.
- Develop probabilistic models linking structural performance with predicted demand.

	PS One	PS Two	PS Three	PS Four
Damage	Hairline cracking	Cracking and minimal spalling	Substantial spalling	On-set of bar buckling
Representative Damage Pattern				
Repair	No repair	Epoxy inject cracks and patch concrete	Remove and recast concrete	Replace concrete and reinforcement

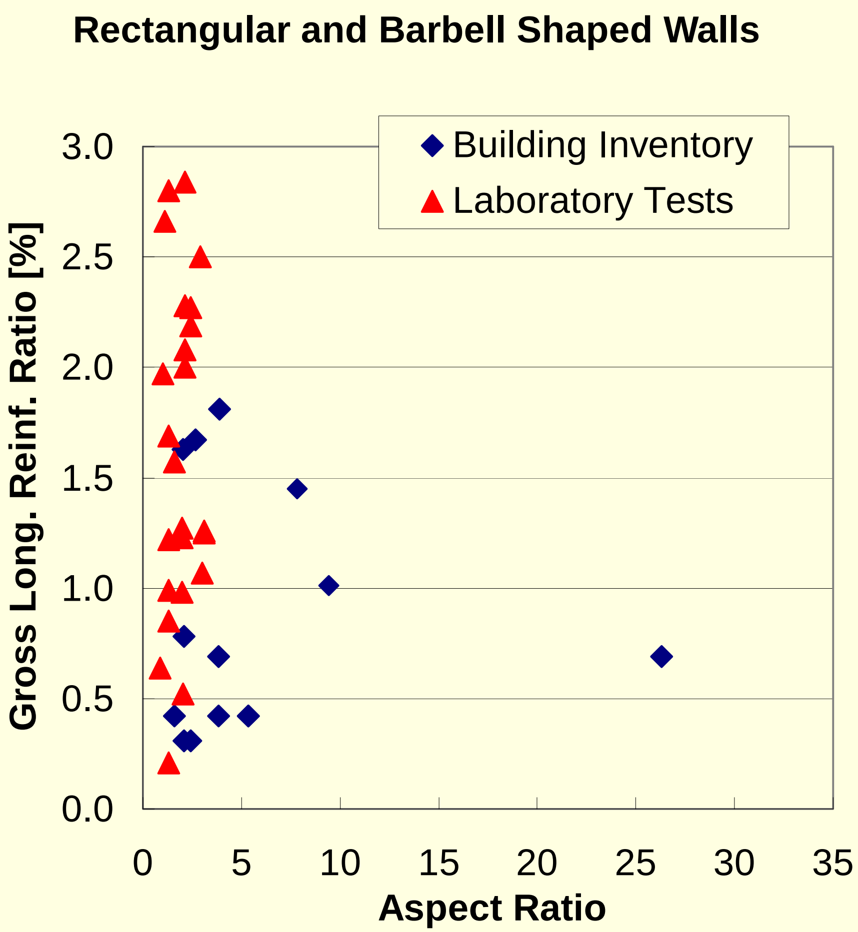
Activities to Date

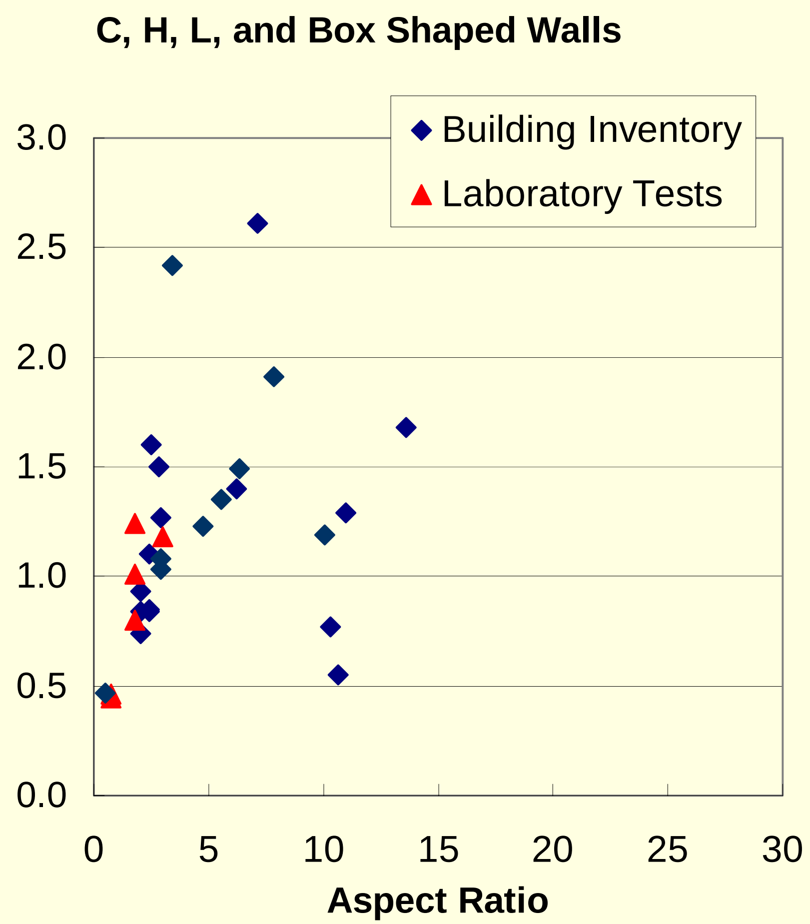
- Literature and inventory review
- Identification of prototype buildings
- Preliminary design of planar wall test program
  - Design details for prototype test specimen
  - Test matrix

Inventory and Literature Review

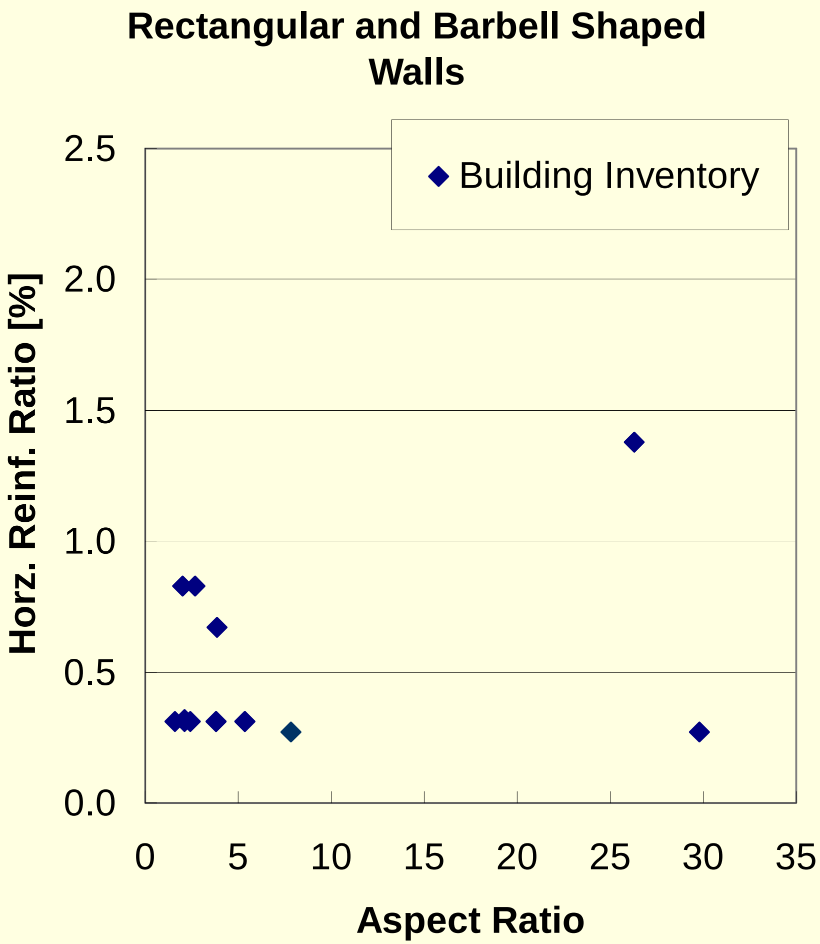
- Literature and inventory review
  - Review of drawings of 10 buildings designed for construction on the West Coast, primarily designed using UBC 91 and UBC 97.
  - Questionnaires sent to 30 consulting engineering firms. To date, we've received "replies" from 5 engineers.
  - Review of 17 experimental investigations conducted from 1985 – 2002
- Issues investigated in the inventory review
  - Gross dimensions: length, thickness, aspect ratio
  - Longitudinal reinforcement ratio: gross, in boundary elements, at mid-span
  - Horizontal reinforcement ratio at mid-span
  - Boundary element confinement: transverse reinforcement ratio, height of bound element confinement
  - Configuration including presence of coupling beams
- Additional issues considered in review of the experimental research
  - Axial load
  - Displacement history

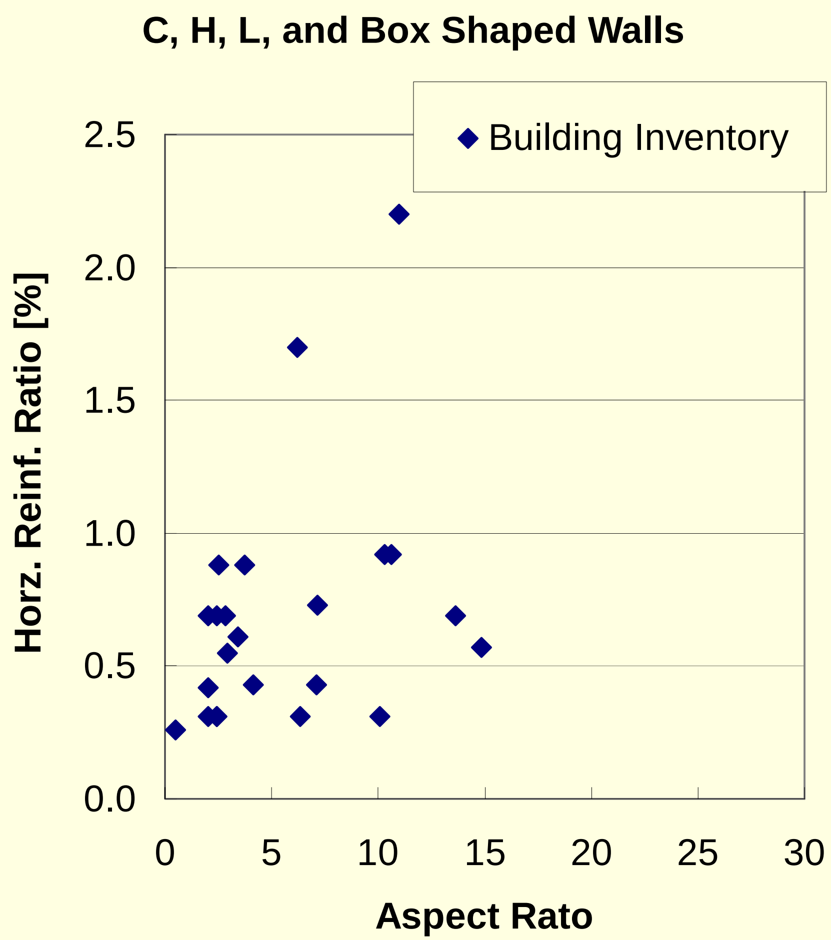
Inventory and Literature Review: Longitudinal Reinforcement Ratio



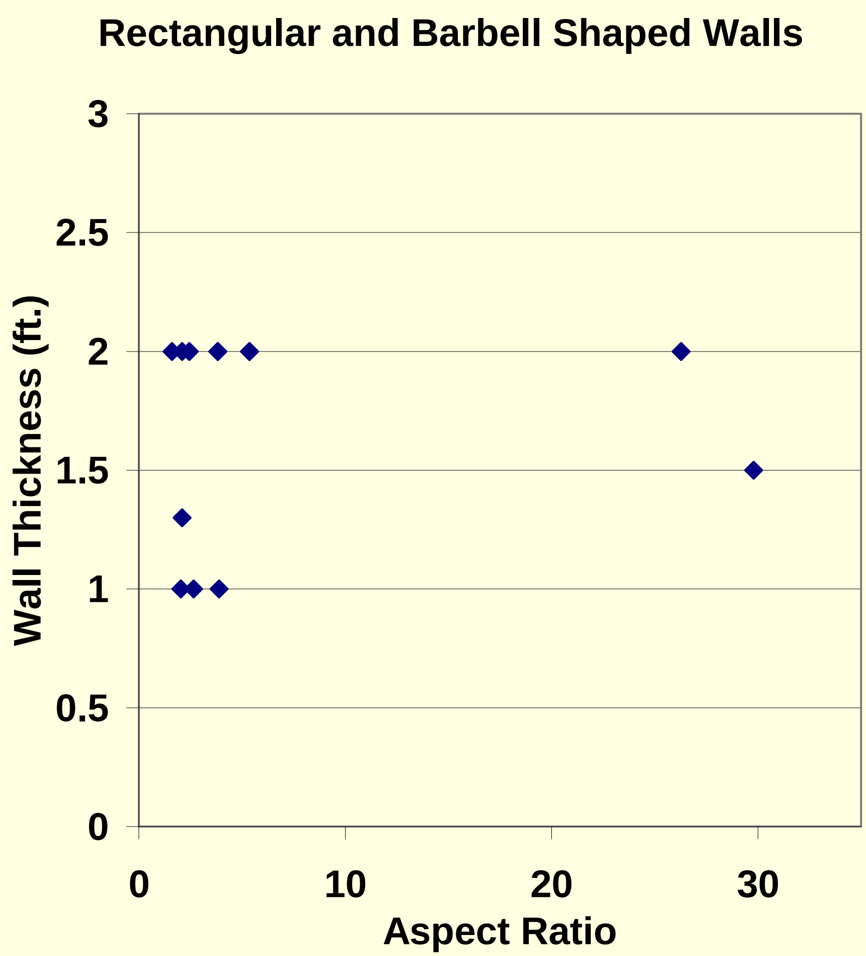


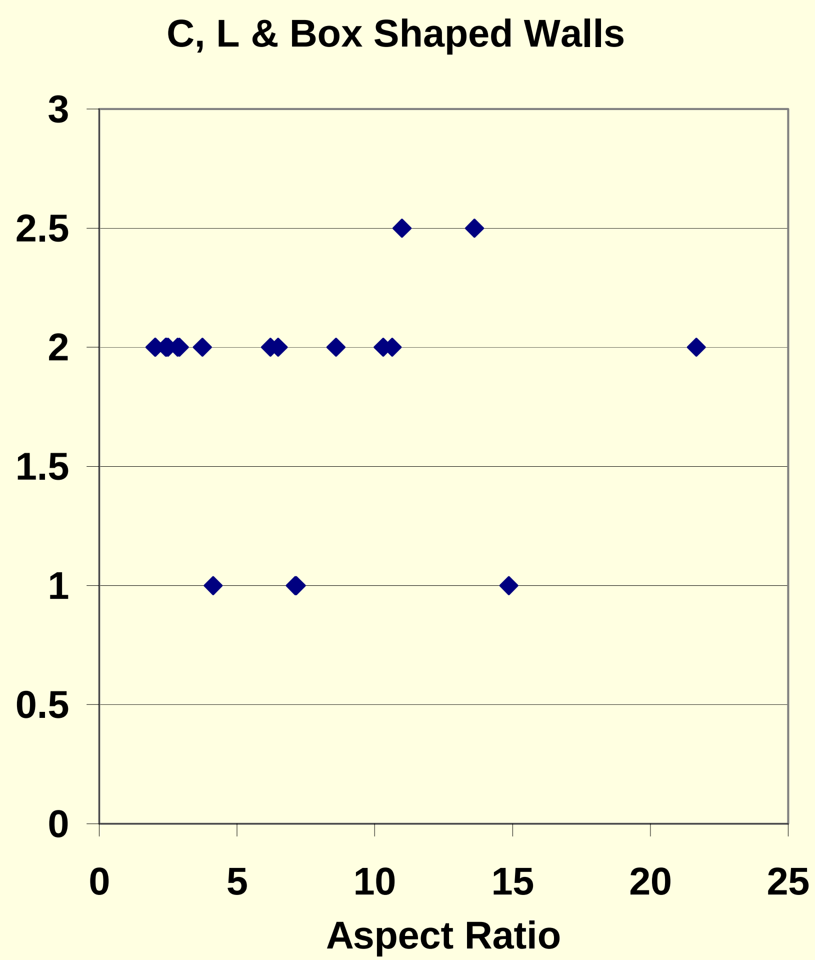
Inventory and Literature Review: Horizontal Reinforcement Ratio





Inventory and Literature Review: Wall Thickness





Inventory and Literature Review: Statistics

								Boundary Ele.		Vert. Reinf.			Horz. Reinf.		
Building	**Code**	**Wall**	**Height (ft)**	**# stories**	**AspectR**	**Shape**	**t [in] Max.**	**Lb [in]**	**ρL [%]**	**ρv [%]**	**s [in]**	**ρg [%]**	**ρh [%]**	**s [in]**	**Coupled**
PAB		4	129	10	29.8	Rectang	18	12	2.89	?	?	?	0.27	18	yes
MKA#4	CA98	2	237.33	25	7.8	Rectang	18	58.52	2.56	0.93	12	1.45	0.27	18	
LDAB1	UBC97	2	67	7	2.1	Rectang	24	-	-	0.31	12	0.31	0.31	12	no
LDAB1	UBC97	7	78	7	2.4	Rectang	24	-	-	0.31	12	0.31	0.31	12	no
LDAB1	UBC97	13	91	7	5.4	Rectang	24	-	-	0.42	12	0.42	0.31	12	no
LDAB1	UBC97	14	91	7	5.4	Rectang	24	-	-	0.42	12	0.42	0.31	12	no
LDAB1	UBC97	15	52	7	1.6	Rectang	24	-	-	0.42	12	0.42	0.31	12	no
LDAB1	UBC97	16	65	7	3.8	Rectang	24	-	-	0.69	12	0.69	0.31	12	no
LDAB1	UBC97	17	65	7	3.8	Rectang	24	-	-	0.42	12	0.42	0.31	12	no
EH	UBC91	2	335	30	26.3	Rectang	24	-	-	0.69	12	0.69	1.38	4	yes
CHEM		3	75	7	3.9	Rectang	12	48	3.97	0.28	12	1.81	0.67	15	no
EH	UBC91		335	30	10.6	L/Box	24	-	-	0.55	6, 12	0.55	0.92	4	yes
PAB		2	140	10	7.1	L	18	54	4.81	?	?	?	0.43	12	yes
PAB		3	140	10	14.9	L	12	12	4.33	?	?	?	0.57	9	yes
LDAB1	0	10	91	7	3.7	L	24	-	-	1	12	1	0.88	12	no
LDAB1	0	11	91	7	2.9	L	24	-	-	1.27	6, 12	1.27	0.55	12	no
LDAB1	0	12	78	7	2.4	L	24	-	-	1.1	12	1.1	0.31	12	no
BTT	UBC91	5	260	20	21.7	L	24								yes
BTT	UBC91	6	260	20	8.6	L	24								yes
MKA#1	UBC94	1	51	5	0.5	I	20	46	1.09	0.26	12	0.47	0.26	12	
LDAB1	UBC94	9	91	7	2.8	H	24	-	-	1.5	6, 12	1.5	0.69	12	yes
MFC	UBC97	3	205	23	6.2	C	30	-	-	1.4	5, 10	1.4	1.7	5	yes
LDAB1	UBC97	1	80	7	2.5	C	24	-	-	1.6	6, 12	1.6	0.88	12	no
LDAB1	UBC97	3	65	7	2.0	C	24	-	-	0.74	12	0.74	0.69	12	yes
LDAB1	UBC97	4	65	7	2.0	C	24	-	-	0.93	6, 12	0.93	0.42	12	yes
LDAB1	UBC97	5	65	7	2.0	C	24	-	-	0.84	12	0.84	0.31	12	no
LDAB1	UBC97	6	78	7	2.4	C	24	-	-	0.85	12	0.85	0.69	12	no
LDAB1	UBC97	8	78	7	2.4	C	24	-	-	0.84	12	0.84	0.31	12	yes
EH	UBC91		335	30	10.3	C	24	-	-	0.77	6, 12	0.77	0.92	4	yes
CHEM		4	93	7	7.2	C	12	48	5.42	0.28	12	2.61	0.73	10	no
BTT	UBC91	4	260	20	6.5	C	24								yes
PAB		1	88	10	4.1	Box	18	36, 48	3.61	?	?	?	0.43	12	yes
MKA#4	CA98	3	309	32	10.1	Box	30	76.26	1.68	0.56	12	1.19	0.31	12	
MKA#4	CA98	1	237.33	25	6.3	Box	30	52.66	2.6	0.69	12	1.49	0.31	12	
MKA#3	UBC97	1	110	10	3.4	Box	24	49	3.18	2.17	6	2.42	0.61	6	
MFC	UBC97	1	449.50	23	13.6	Box	30	-	-	1.68	5, 10	1.68	0.69	5	yes
MFC	UBC97	2	449.50	23	11.0	Box	30	-	-	1.29	5, 10	1.29	2.2	5	yes
CHEM		1a	93	7	2.7	Barbell	12	36	4.7	0.97	6, 12	1.67	0.83	12	no
CHEM		1b	75	7	2.0	Barbell	12	36	4.7	0.97	6, 12	1.63	0.83	12	no
CHEM		2	93	7	2.1	Barbell	16	28	3.56	0.21	12	0.78	0.32	12	no
Average:			**151.3**		**6.7**		**22**		**3.5**	**0.8**		**1.1**	**0.6**	**10.9**	
Rect. Avg:			**116.8**		**8.4**	**Rectang**	**22**		**3.1**	**0.5**		**0.7**	**0.4**	**12.6**	
C-Shape Avg:			**132.4**		**4.4**	**C-shaped**	**23**		**5.4**	**0.9**		**1.2**	**0.7**	**10.1**	
L-Shape Avg:			**151.4**		**8.8**	**L-shaped**	**21**		**4.6**	**1.1**		**1.1**	**0.5**	**11.4**	
Box Avg:			**273.9**		**8.1**	**Box**	**27**		**2.8**	**1.3**		**1.6**	**0.8**	**8.7**	
Barbell Avg:			**87.0**		**2.3**	**Barbell**	**13**		**4.3**	**0.7**		**1.4**	**0.7**	**12.0**	

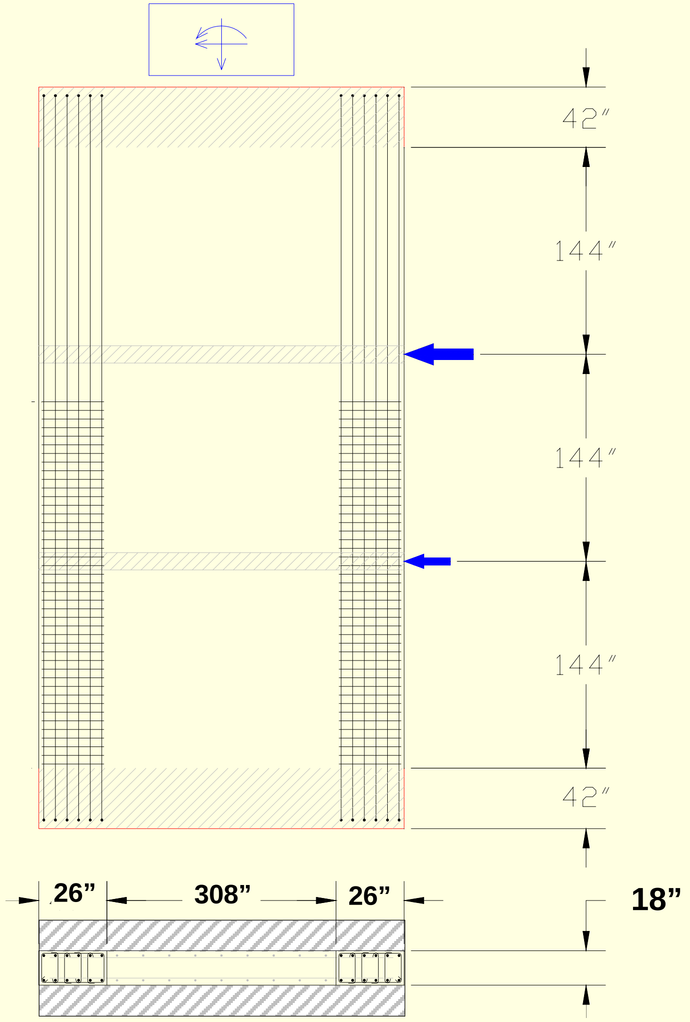
Identify Prototype Buildings

- 10-story office building in San Francisco
  - Designed by MKA per UBC 1997
  - Fairly regular layout with two core-wall systems (coupled and non-coupled)
- Would like to include
  - 4-story office building designed per code
  - 20-story office building designed per code
- Possibly will include
  - 9-story hospital in Reno
    - Designed using performance-based design criteria
    - Fairly regular layout with couple core and non-coupled walls
    - In the process of acquiring owners permission

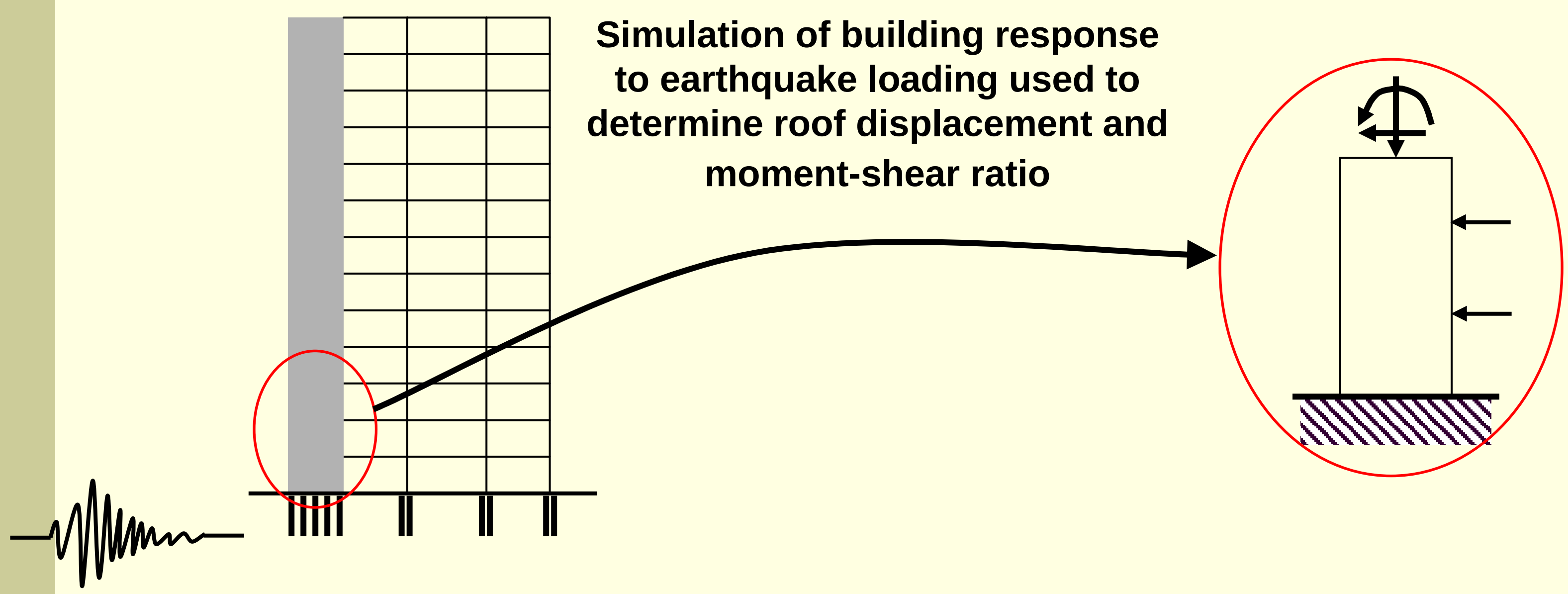
Planar Tests: Prototype Specimen

- Thickness
  - Prototype = 18 in.
  - Average from inventory review (all walls) = 22 in.
- Length
  - Prototype = 30 ft.
  - Average from inventory review (all walls) = 29.4 ft.
- Boundary Element reinforcement ratio
  - Prototype = 5%
  - Average from inventory review (rectangular walls) = 3.1%
  - Average from inventory review (all walls) = 3.5%
- Gross vertical reinforcement ratio
  - Prototype = 1%
  - Average from inventory review (rectangular walls) = 0.7%
  - Average from inventory review (all walls) = 1.1%
- Vertical (mid-span) & horizontal reinforcement ratio
  - Prototype = code minimum
  - Average from inventory review (all walls) = 0.64% (horz.), 0.8% (vert.)
  - Average from inventory review (rectangular) = 0.5% (horz.), 0.4% (vert.)

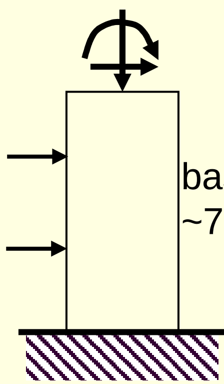
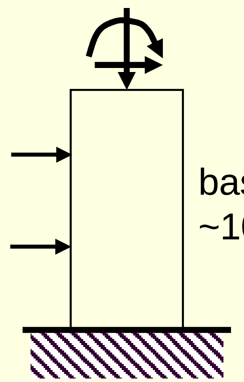
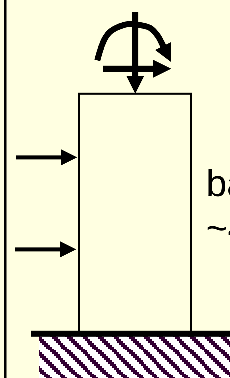
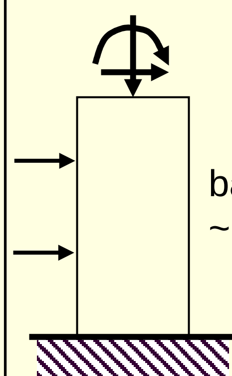
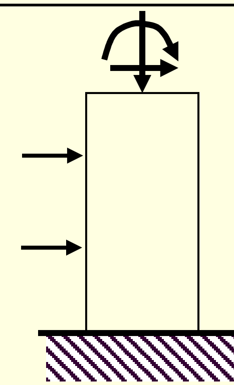
Typical Specimen



Planar Tests: Loading of Prototype Test Specimen



Planar Wall Test Matrix

design details	M/V ratio representative of			non-standard displacement history
	7-story bldg. (axial load = $0.1A_gf_c$)	4-story bldg. (axial load = $0.1A_gf_c$)	10-story bldg. (axial load = $0.1A_gf_c$)	
– ρ_l = 5% in the boundary element – ρ_h = code min. in boundary element. – ρ_v, ρ_h = code min. at mid-span	 base shear $\sim 7\sqrt{f_c}$	 base shear $\sim 10\sqrt{f_c}$	 base shear $\sim 4\sqrt{f_c}$	
– ρ_l = 2% in the boundary element – ρ_h = code min. in boundary element. – ρ_v, ρ_h = code min. at mid-span		 base shear $\sim 7\sqrt{f_c}$		

Planar Tests: Current Activities

- Review of experimental data to develop links between drift demand, damage and effective stiffness
- Analyses of prototype buildings to better determine moment-shear ratios to use in the laboratory
- Analyses of proposed test specimens to verify failure modes of laboratory test specimens
- Identify drift histories for use in laboratory testing

Research Project: Future Activities

- Planar wall tests: summer 2005
- Coupled walls
  - Design & testing: 2005-2006
- C-shaped walls
  - Design & testing: 2006
- Core wall
  - Design & testing: 2006-2007

Planar Wall Test Matrix

- Issues to be resolved in designing test matrix
  - Does the prototype specimen exhibit flexure or flexure-shear failure?
  - Does the prototype specimen have boundary elements?
  - Pseudo-dynamic testing for non-standard displacement history?
  - Is it necessary to test a wall with a steep moment gradient? If not, other potential test parameters include
    - Non-standard, pre-defined displacement histories or pseudo-dynamic displacement histories
    - Boundary zone confinement

Specimen Design

- Boundary elements
  - Vertical reinforcement ratio in boundary elements defined by moment demand (Mu).
  - Depth used for confinement is code defined (ACI 318: 21.7.6.2) and a function of drift demand: Is drift is computed using elastic effective stiffness model?
  - Transverse reinforcement for confinement as for columns (ACI 318: 21.4.1 – 21.4.3).
  - Height of boundary element is code defined (ACI 318: 21.7.6.4) and may be a function of Vu: Is Vu defined by analysis under code defined forces?
  - Bar size: Is this typically the same as in the remainder of wall?
- Mid-span
  - Vertical shear reinforcement: code defined minimum ratio (ACI 318: 11.10.9.4), code defined minimum spacing (ACI 318: 11.10.9.5).
  - Horizontal shear reinforcement: code defined minimum ratio is 0.0025, code minimum spacing (ACI 318: 11.10.9.3).

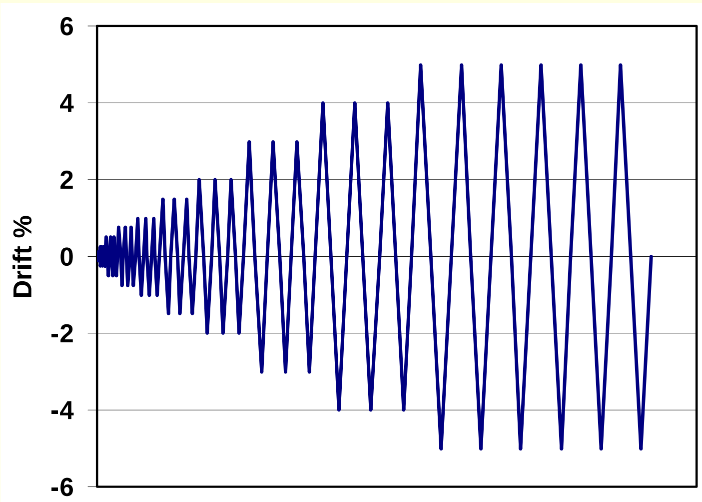
Specimen Design

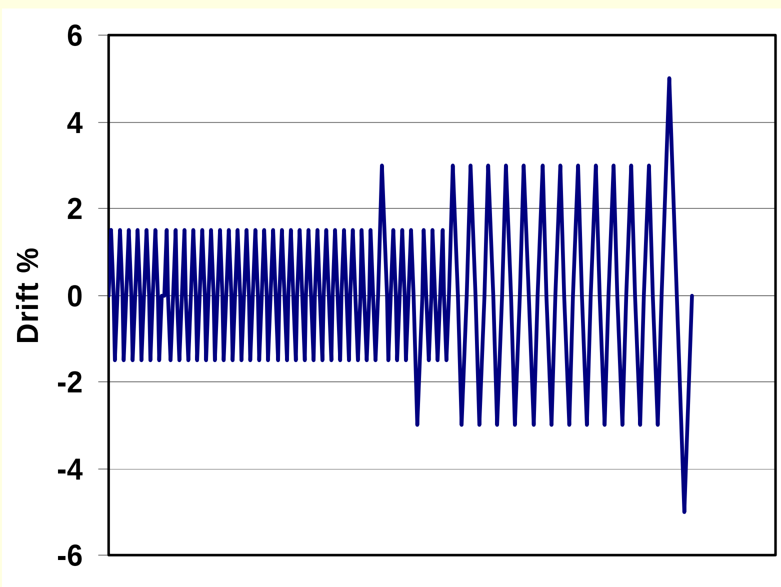
- Additional design issues
  - What criteria are used to determine the height at which boundary elements are discontinued?
  - What criteria are used to determine the height at which longitudinal reinforcement is discontinued?
  - How is a capacity design approach used in defining moment demand (Mu) and shear demand (Vu)?
  - Is there a target / typical shear demand on the wall $\left(\alpha\sqrt{f_c'}\right)$?
- Additional issues
  - Typical concrete strength?
  - Typical aggregate size?

Laboratory Load Histories

- Issues to be considered
  - Building height as defined by M-V ratio
  - Lower story shear loads
  - Non-standard displacement histories
    - Pre-defined
    - Pseudo-dynamic testing

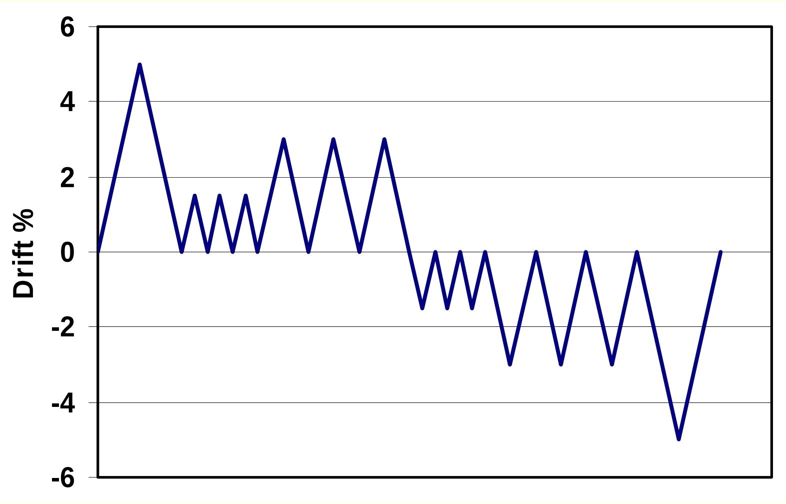
Displacement History: pre-defined





- "STANDARD"
  - Symmetric History
  - Monotonically increasing drift demands
  - 2-6 cycles per drift level
  - Comparison with previous results
- CONSTANT DRIFT
  - Long-duration effects
  - Low-cycle fatigue
  - One or more drift levels
  - Symmetric

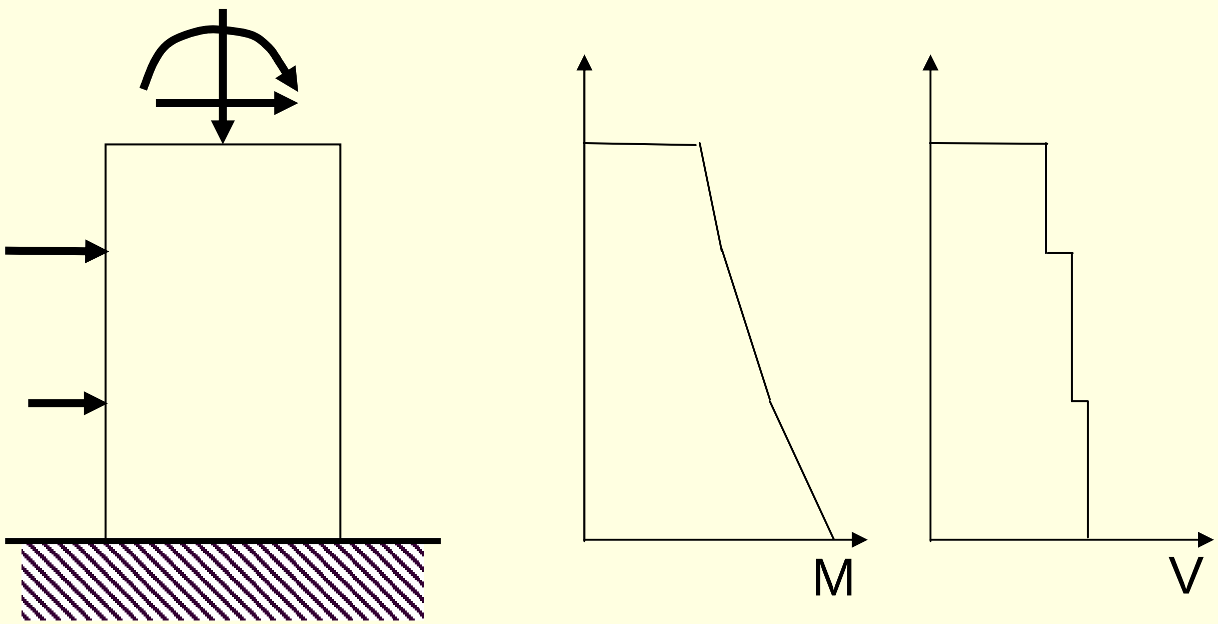
Displacement History: pre-defined



- PULSE/NON-SYMMETRIC
  - Near-fault effects
  - Analytical Model development
  - One or more drift levels
  - Not Symmetric

Lower Story Shear Load

- Inter-story shear loads
  - Analysis of wall load distribution using a UBC lateral load distribution indicates that shear loads at 1st and 2nd story represent 17% of total base shear. Therefore, include these loads:



Building Height and M-V Ratio