Coming Soon: Seismic Performance Factors For Cross Laminated Timber Design
Oct 30, 2015

Colorado State University

Department of Civil and Environmental Engineering

Project Members

Colorado State University

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Outline

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- FEMA P695 methodology
- Index buildings
  - Archetypes
- Testing
- Modeling
- Illustrative example
- Next steps

FEMA P-695: Quantification of Building Seismic Performance Factors

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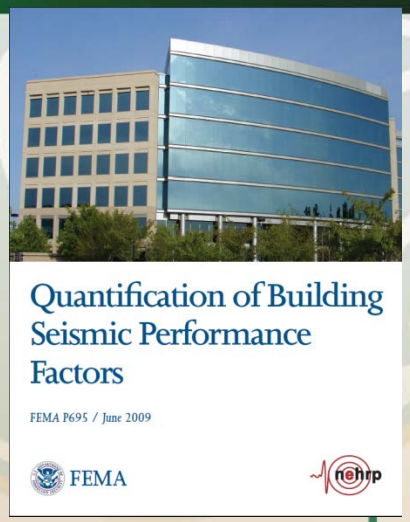
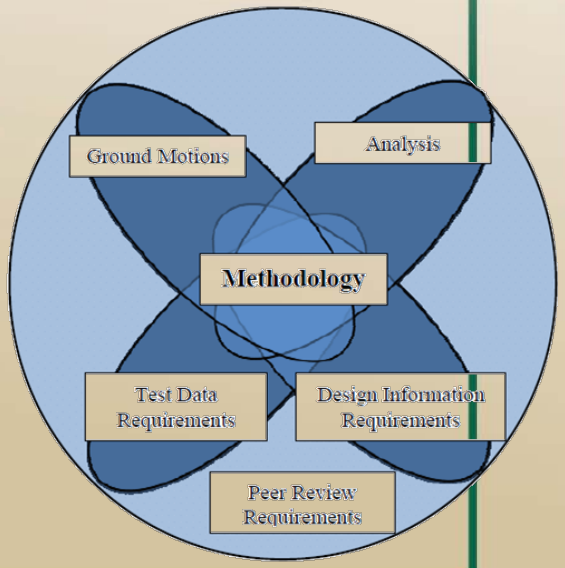
- A Methodology that allows a team to identify seismic performance factors for a new SFRS.

- The Methodology is consistent with the primary “life safety” performance objective of seismic regulations in model building codes.

- Peer review throughout is key
- Archetypes
- Design methodology
- Nonlinear time history analysis
- Performance evaluation
  - CMR





Archetype Development

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Design Space

Representative of typical residential and commercial structures in the U.S.

Archetype Configurations

Prototypical representation of a seismic-force-resisting system

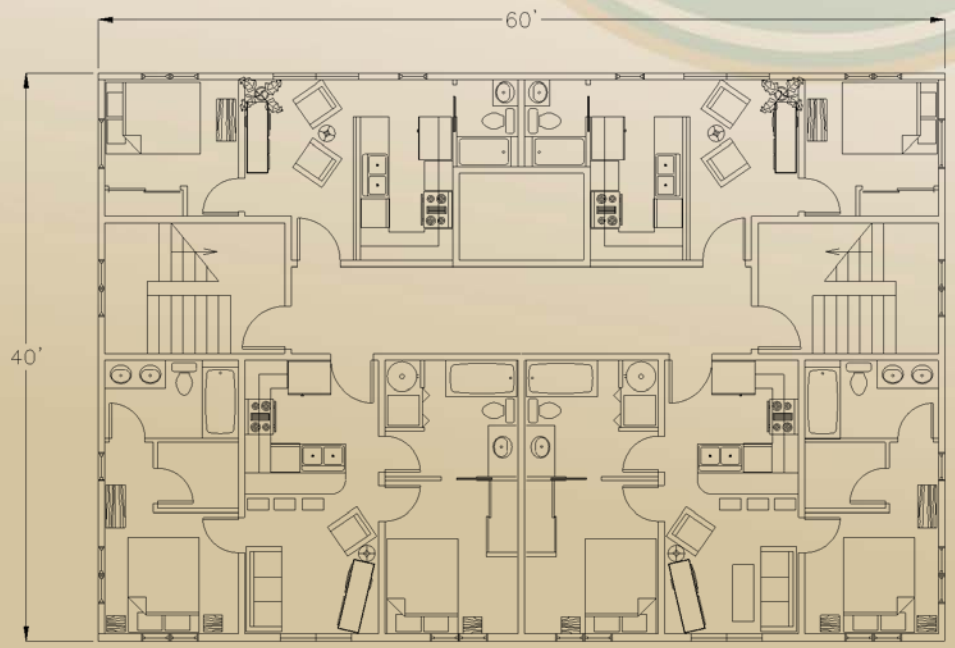
Archetype Designs

Index archetype configurations designed and detailed using the design requirements

Archetype Models

Mathematical idealization of the proposed system

Configuration Design Variables	Seismic Behavioral Effects
Occupancy and Use	Strength
Elevation and Plan Configuration	Stiffness
Building Height	Inelastic-deformation Capacity
Structural Component Type	Seismic Design Category
Seismic Design Category	Inelastic-system Mobilization
Gravity Load	



Index Buildings

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Index Bldg.	Type	Stories
1	Single Family (SF)	-
2	SF	-
3	SF	-
4	Multi-family (MF)	4, 6, 8
5	MF	2
6	MF	2
7	MF	3
8	MF	6, 8
9	MF	8, 10
10	MF	8, 10, 12
11	Commercial	8, 10, 12

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Type : Single Family Index Bldg. 1

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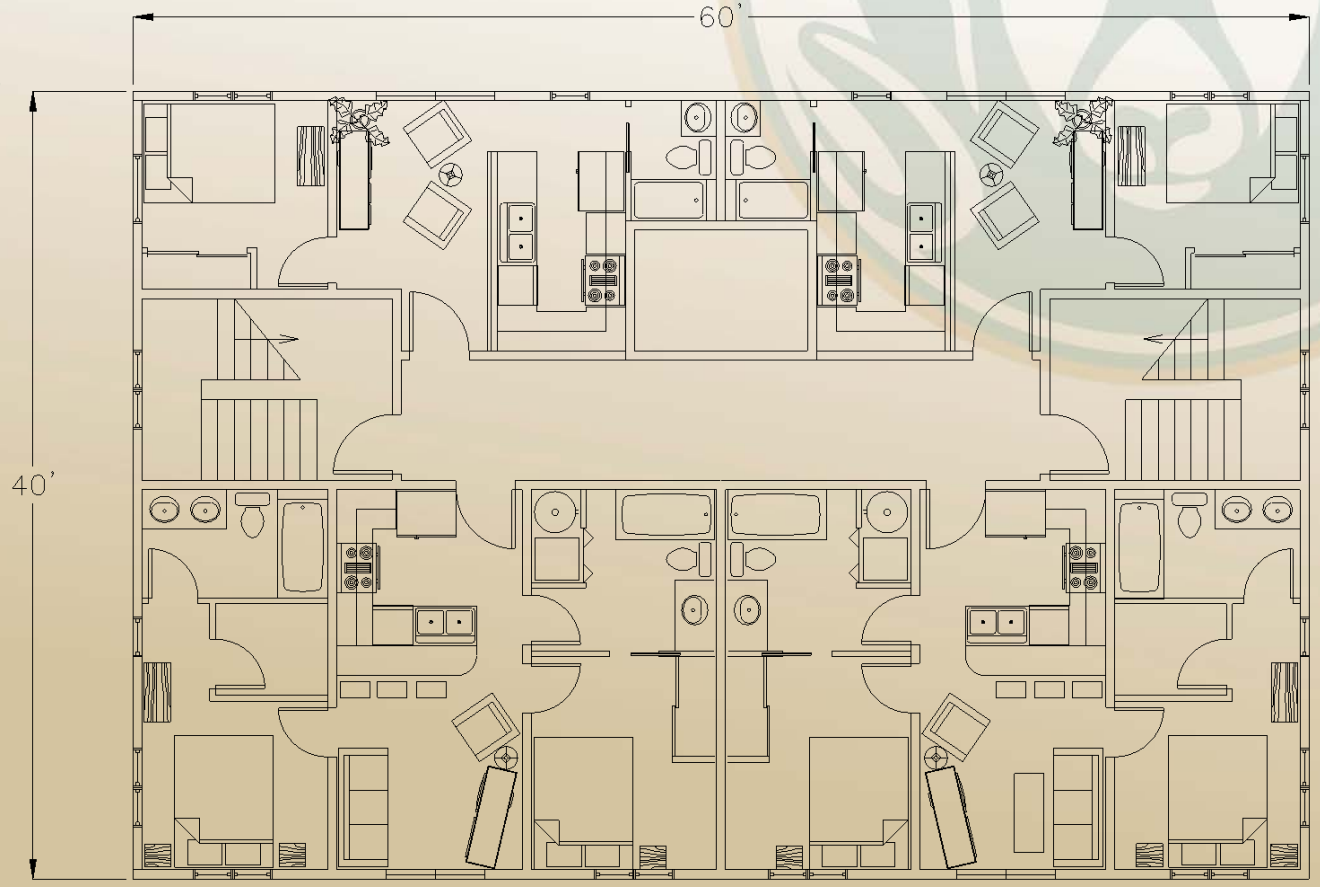
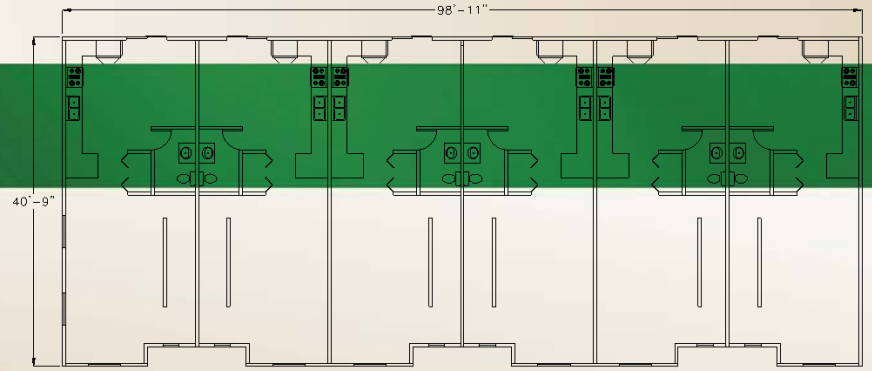
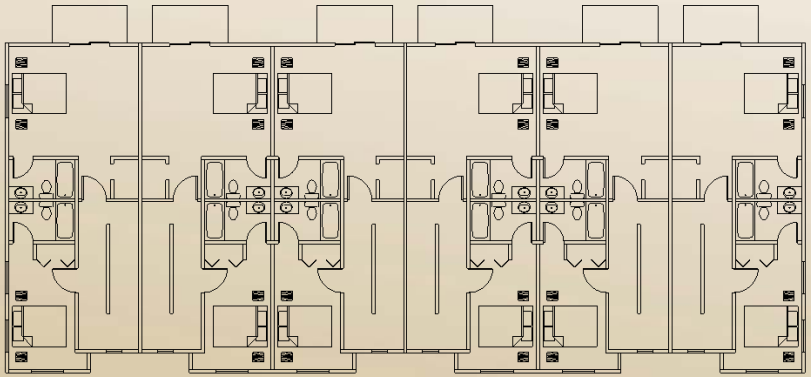
Type : Multi-family
Index Bldg. 4
Stories:4, 6, 8

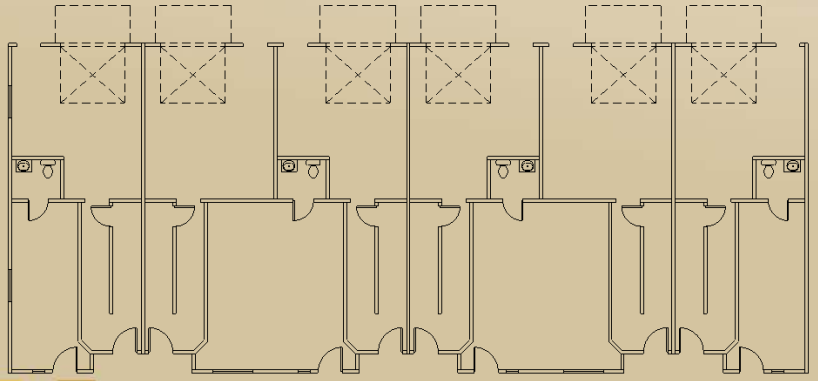




THIRD FLOOR



SECOND FLOOR



LOWER FLOOR

Type : Multi-family
Index Bldg. 7
Stories: 3
Possibly mixed-use

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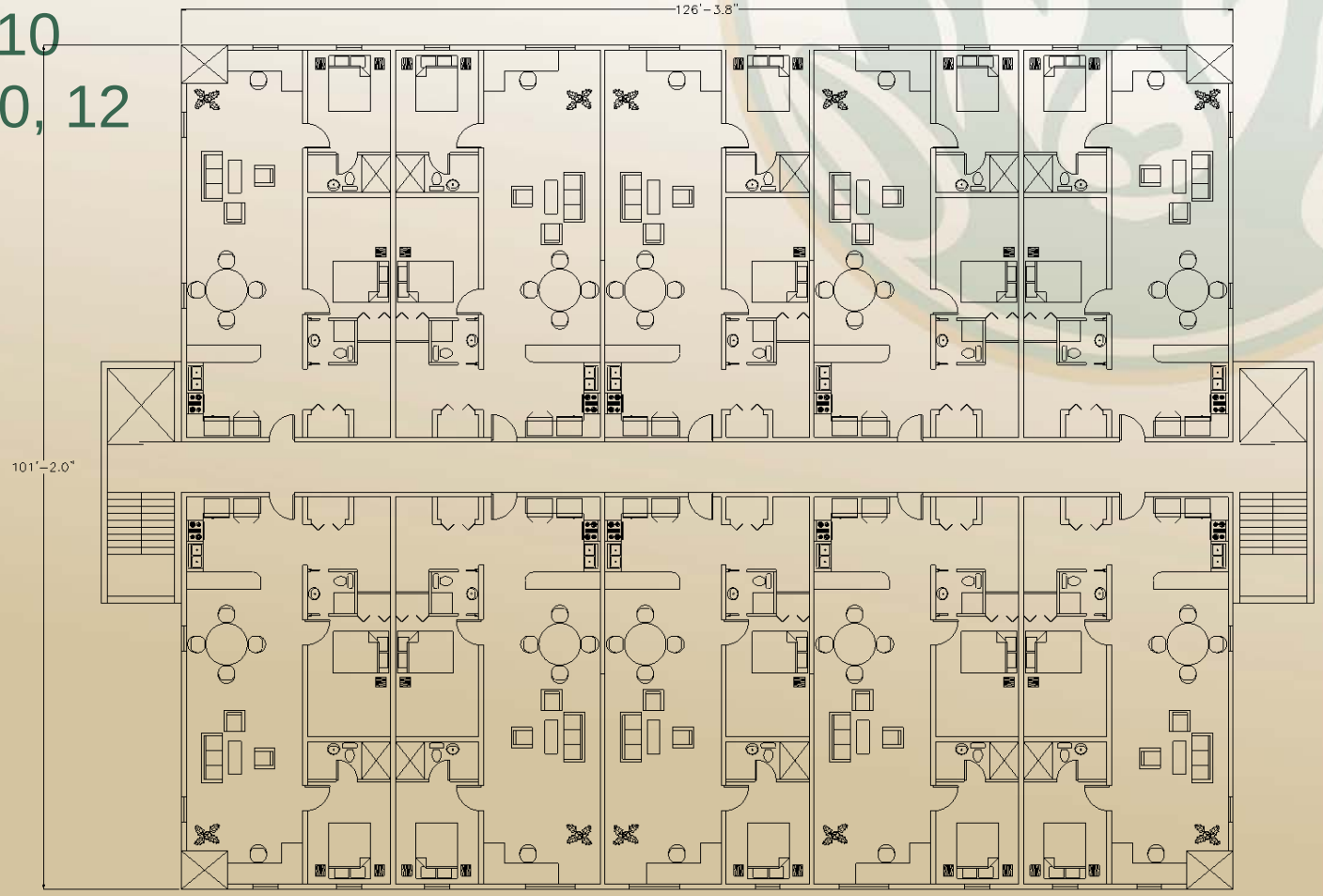
Type : Multi-family
Index Bldg. 10
Stories: 8, 10, 12



Performance groups

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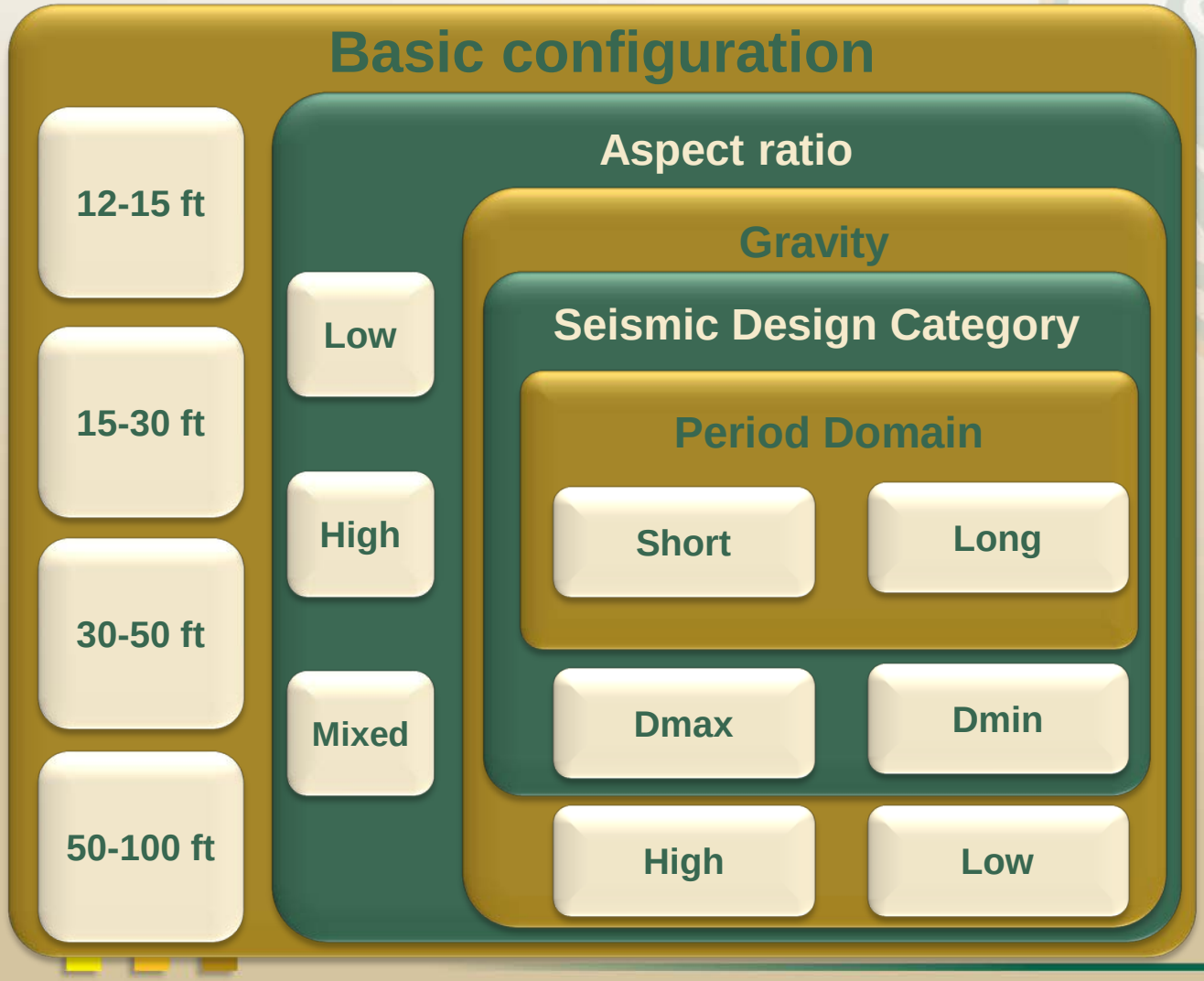

- Min. of 3 archetype per performance group
- Total= 96 performance group that is 288 archetypes

Performance groups

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Group No.	Grouping Criteria: Basic Config.		Design Load Level: Gravity	Design Load Level: Seismic	Period Domain	Archetype description
PG-65	30-50 ft wall	Mixed aspect ratio panels	High	SDC Dmax	Short	Index building 1, 3 stories
						Index building 4, 4 stories
						Index building 7, 3 stories
PG-66					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-67				SDC Dmin	Short	Index building 1, 3 stories
						Index building 5, 2 stories
						Index building 7, 3 stories
PG-68					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-69			Low	SDC Dmax	Short	Index building 1, 3 stories
						Index building 4, 4 stories
						Index building 7, 3 stories
PG-70					Long	Index building 4, 8 stories
						Index building 4, 6 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-71				SDC Dmin	Short	Index building 1, 3 stories
						Index building 5, 2 stories
						Index building 7, 3 stories
PG-72					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories

Reducing Archetypes

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- SDC Dmax only
- Based on the testing Low aspect ratio vs. High aspect ratio vs. Mixed aspect ratio critical case will be determined
- Calculating exact gravity loads based on architectural plans is deemed sufficient by the peer panel and there is no need to specifically consider low vs. high gravity
- Visual Inspection of some of the archetypes
- Only 8 performance groups are expected to be analyzed

Performance groups

Colorado State University

Group No.	Grouping Criteria: Basic Config.		Design Load Level: Gravity	Design Load Level: Seismic	Period Domain	Archetype description
PG-65	Example				Short	Index building 1, 3 stories
						Index building 4, 4 stories
						Index building 7, 3 stories
PG-66	30-50 ft wall	Critical aspect ratio	Calculated	SDC Dmax	Long	Index building 4, 6 stories
	Reduced					Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
PG-67	30-50 ft wall	Mixed aspect ratio panels	High	SDC Dmin	Short	Index building 1, 3 stories
						Index building 5, 2 stories
						Index building 7, 3 stories
PG-68					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories
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						Index building 5, 2 stories
						Index building 7, 3 stories
PG-72					Long	Index building 4, 6 stories
						Index building 4, 8 stories
						Index building 8, 8 stories
						Index building 9, 10 stories

Testing Program

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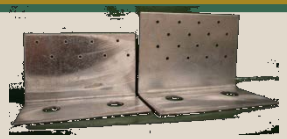
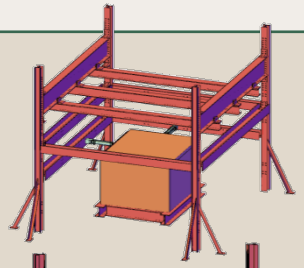
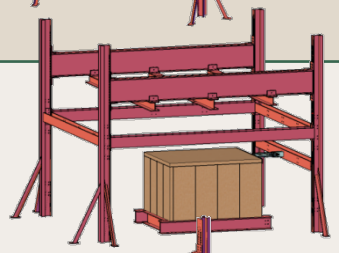
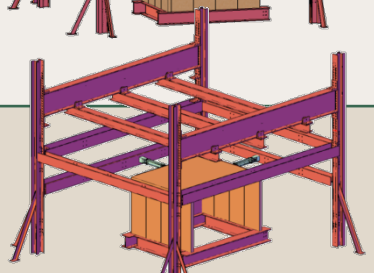
Test Type	Objective	
Connector tests	• Behavior under cyclic loading • Interpanel connector behavior	
Isolated Wall Tests	• Boundary condition • Gravity loading • Connector thicknesses • Connector type • CLT panel thickness • Connector thickness • CLT panel aspect ratio • Inter-panel connector (vertical joint) • CLT grade	
Box type configuration	• Effect of diaphragm on wall behavior • Diaphragm behavior • Effect of out-of-plane loading on the connector • Effect of bi-directional loading • Holddowns in the corners • Stability of the walls	
Box type configuration with multiple panel walls	• Effect of out-of-plane loading on the connector • Effect of bi-directional loading • Holddowns in the corners • Stability of the walls • Vertical joints between perpendicular walls will also be investigated	
3-sided wall with a diaphragm	• Effect of diaphragm rotation • Combined loading on the connectors	

Testing Program

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Testing Program

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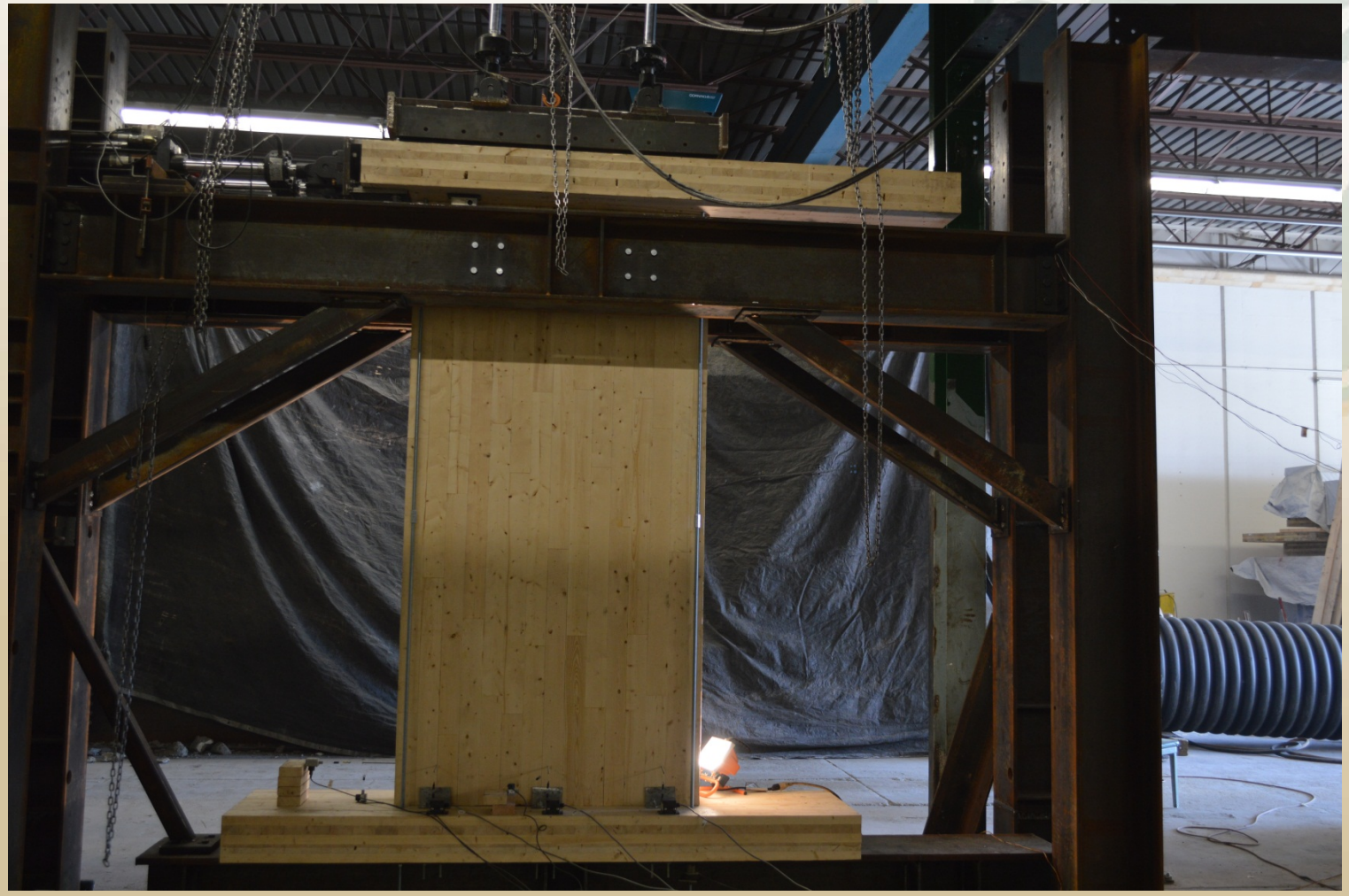

Testing Program

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Modeling

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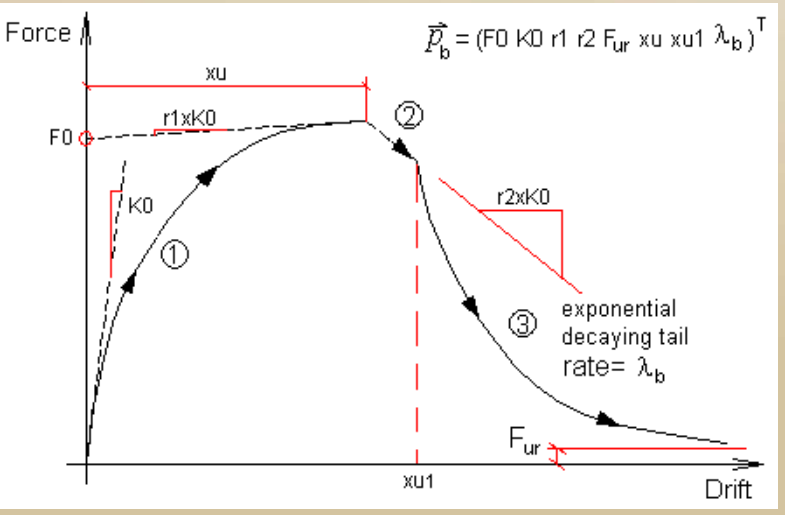
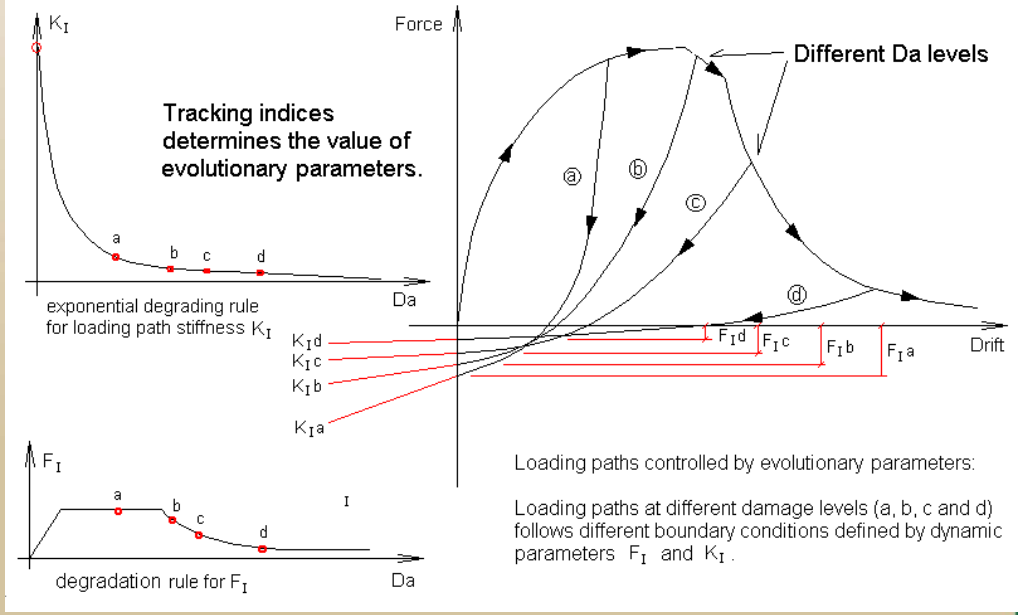
- 16-parameter hysteretic model
- Developed at CSU and TAMU
- It allows more adaptive modeling of the degradation behavior of the wood shearwall components



Backbone curve for EPHM hysteresis



Degradation of loading paths

(Pang et al, 2007; Pei and van de Lindt, 2009)

Illustrative example

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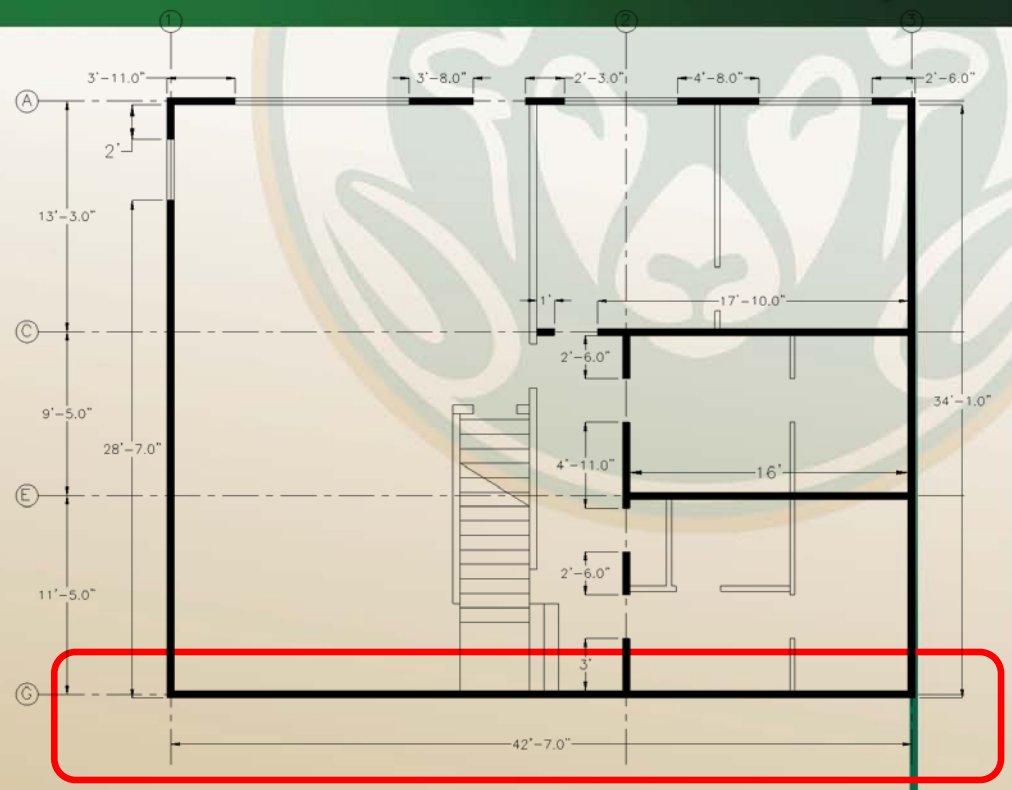
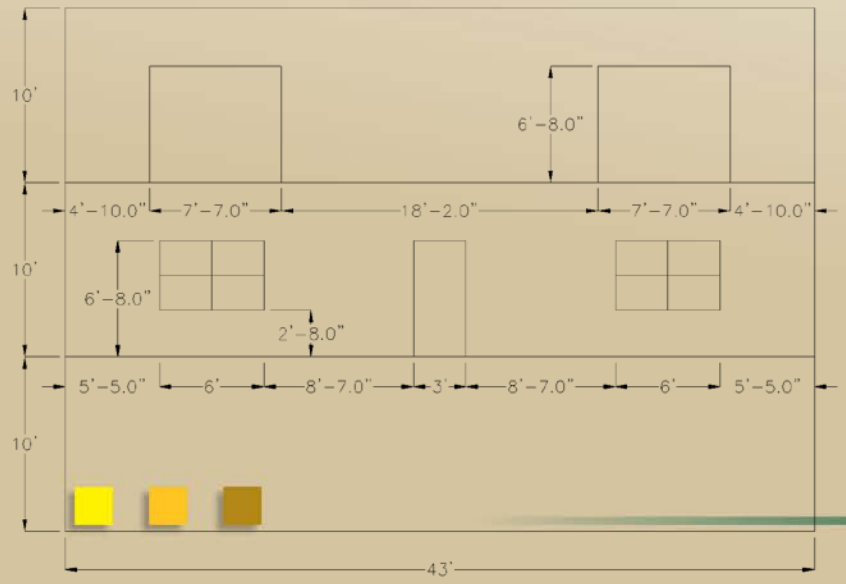
Extraction of archetypes for PG 65





Archetype 65-1

Illustrative example

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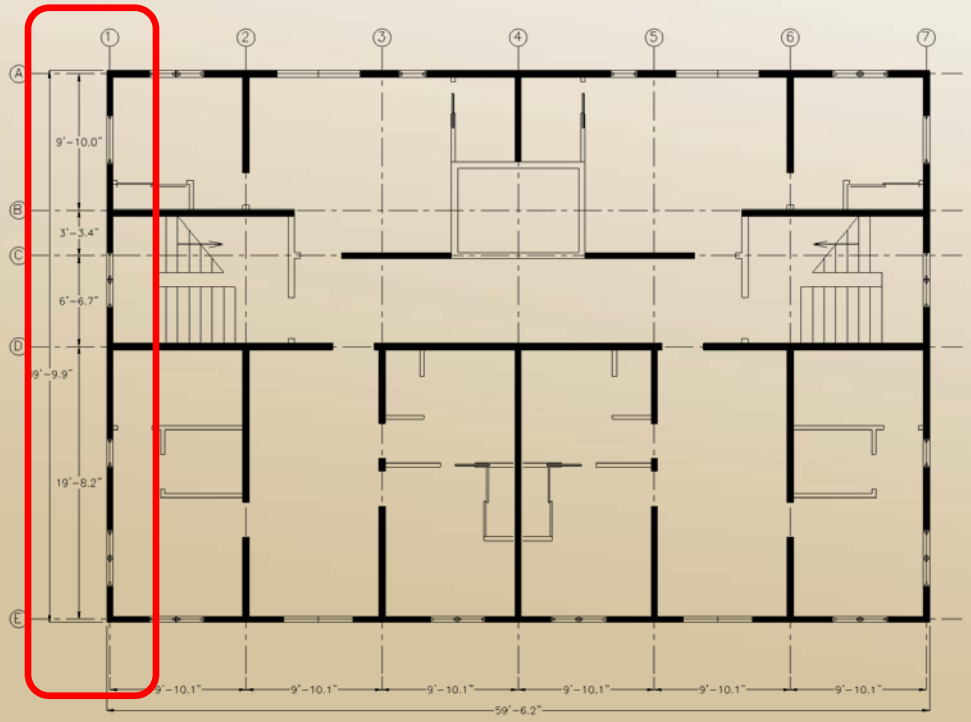

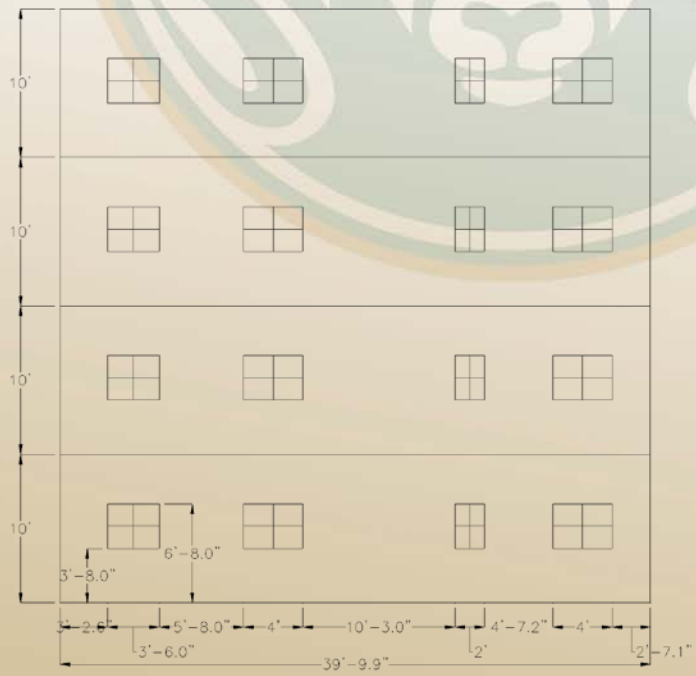

Archetype 65-2

Illustrative example

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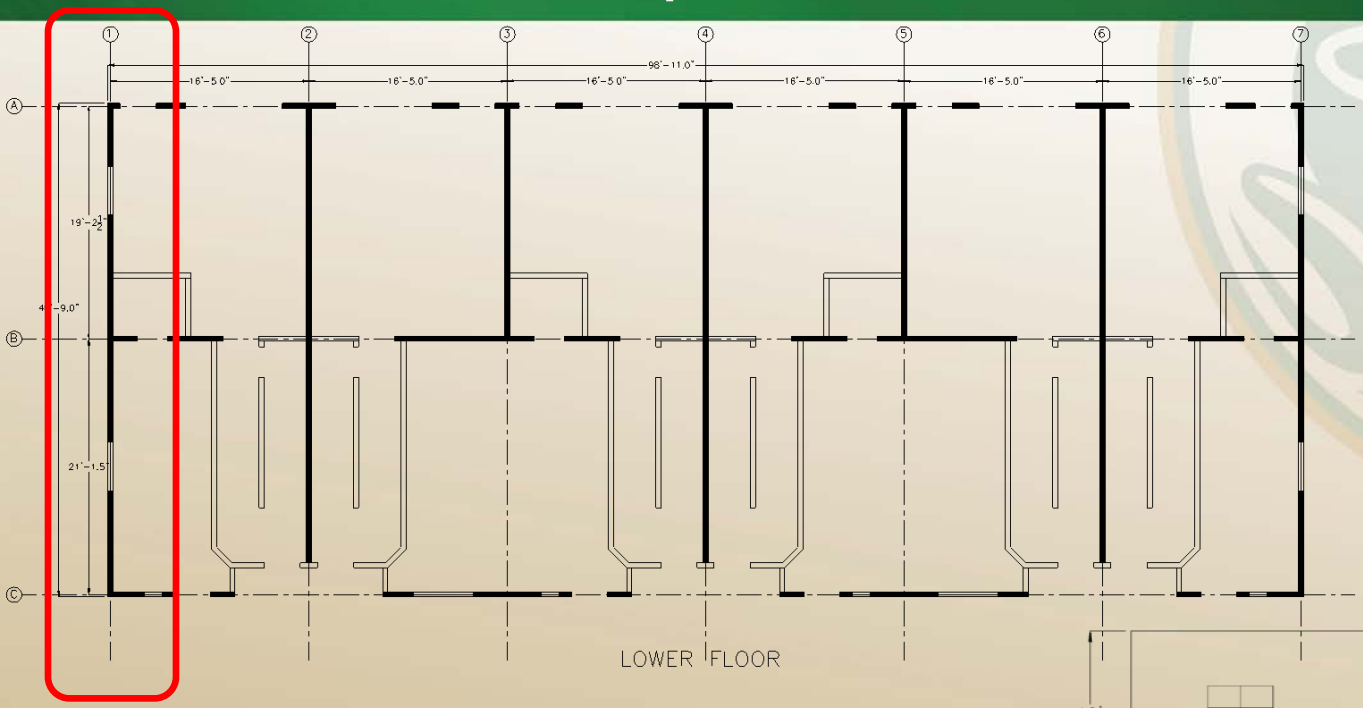

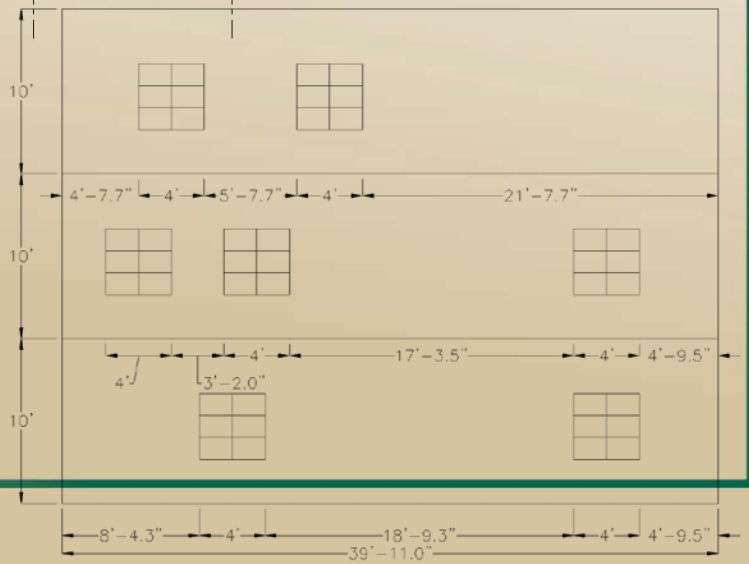

Archetype 65-3

Illustrative example

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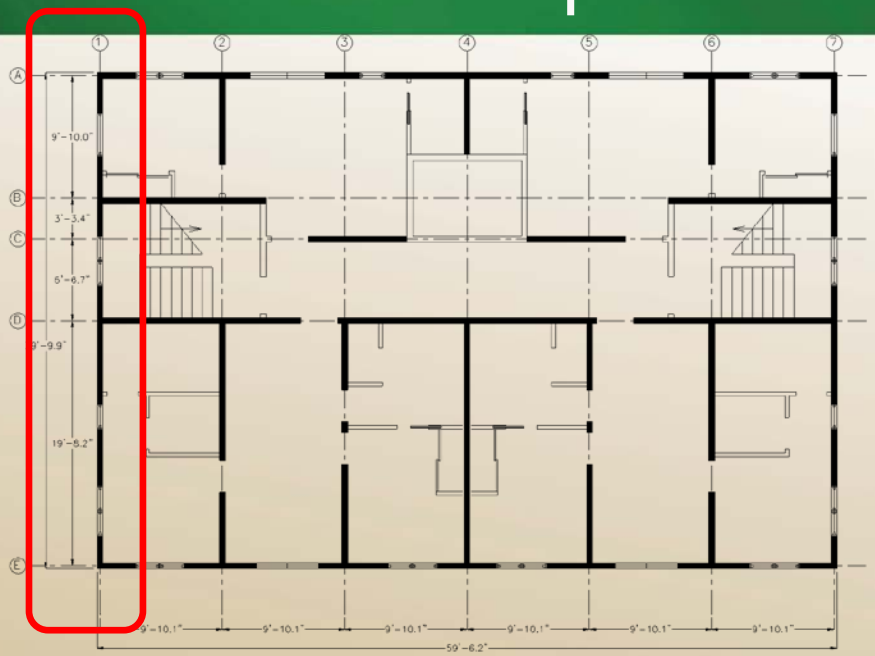

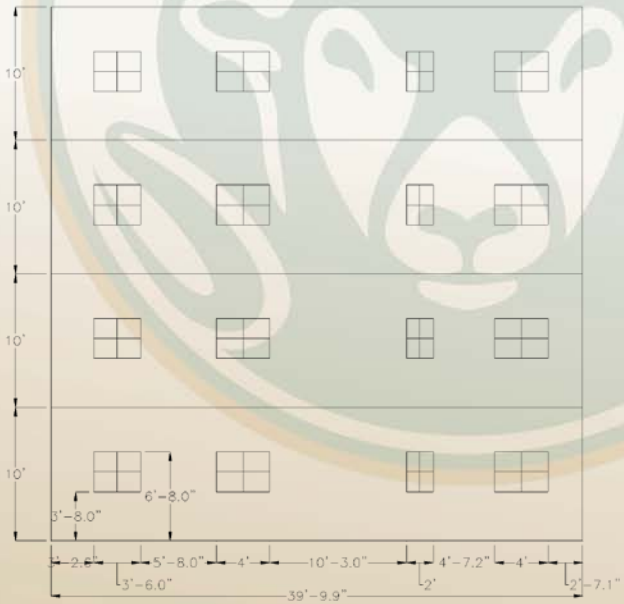

ELF

Obtain shear forces for the archetype model

Design Methodology

Design the archetype model using the design methodology

Modeling

Obtain parameters for the walls and model the building using SAPWood

Nonlinear Analysis

Static pushover and dynamic analysis

Performance evaluation

CMR and ACMR

Illustrative example

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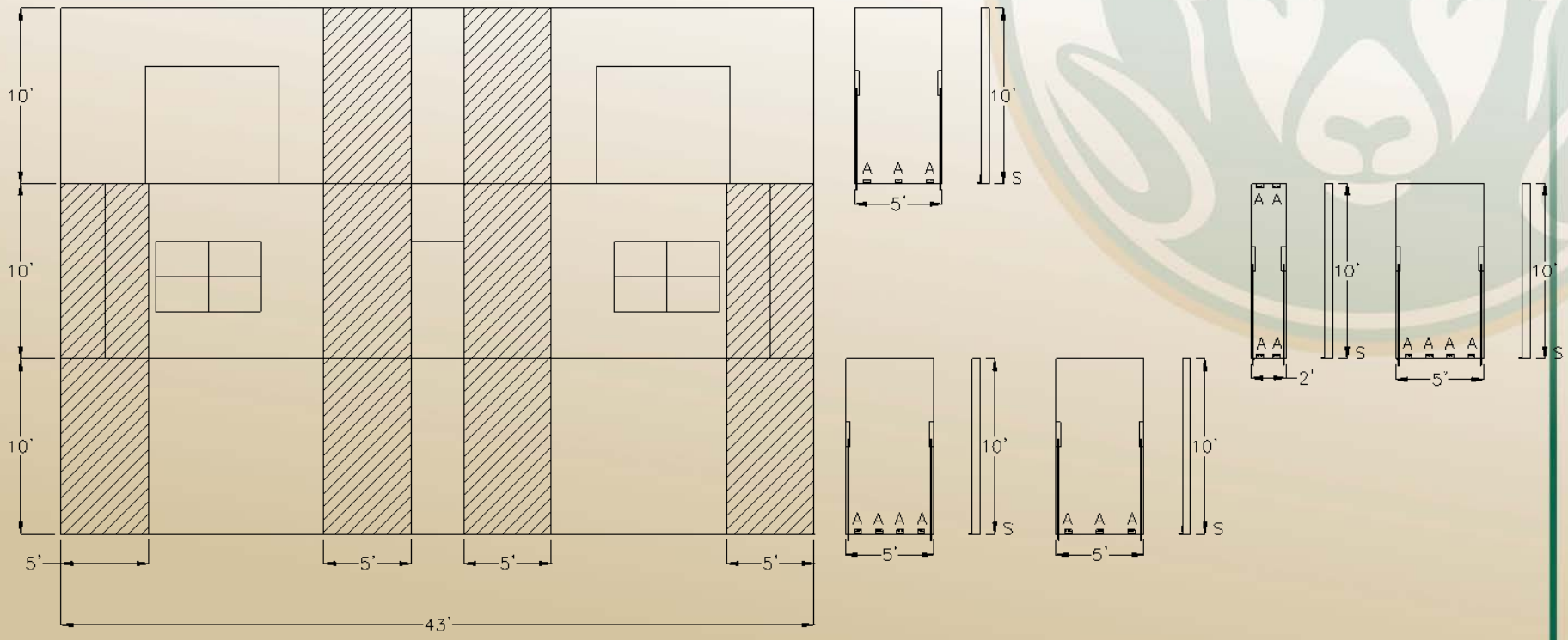
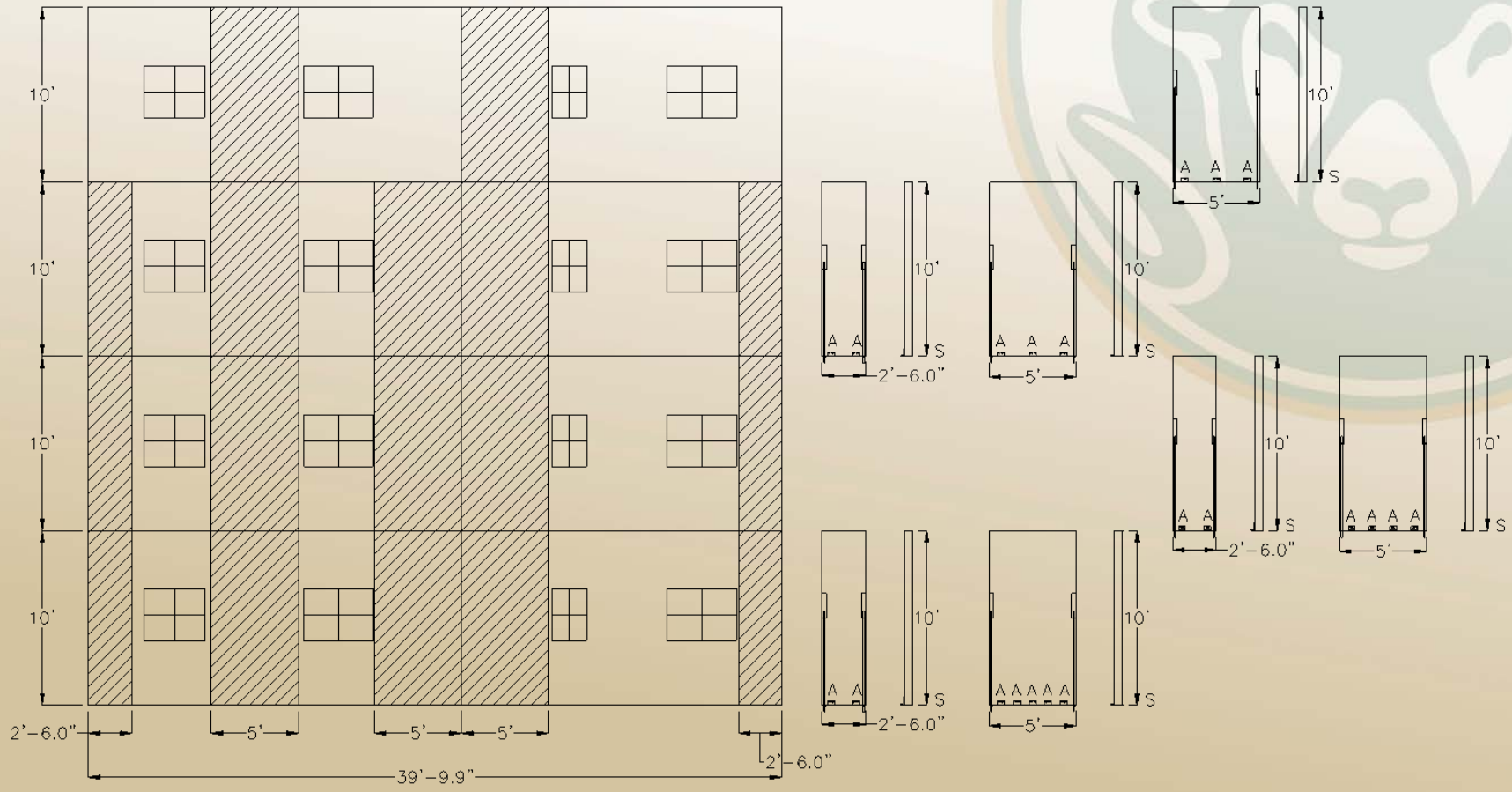


Archetype 65-1

Illustrative example

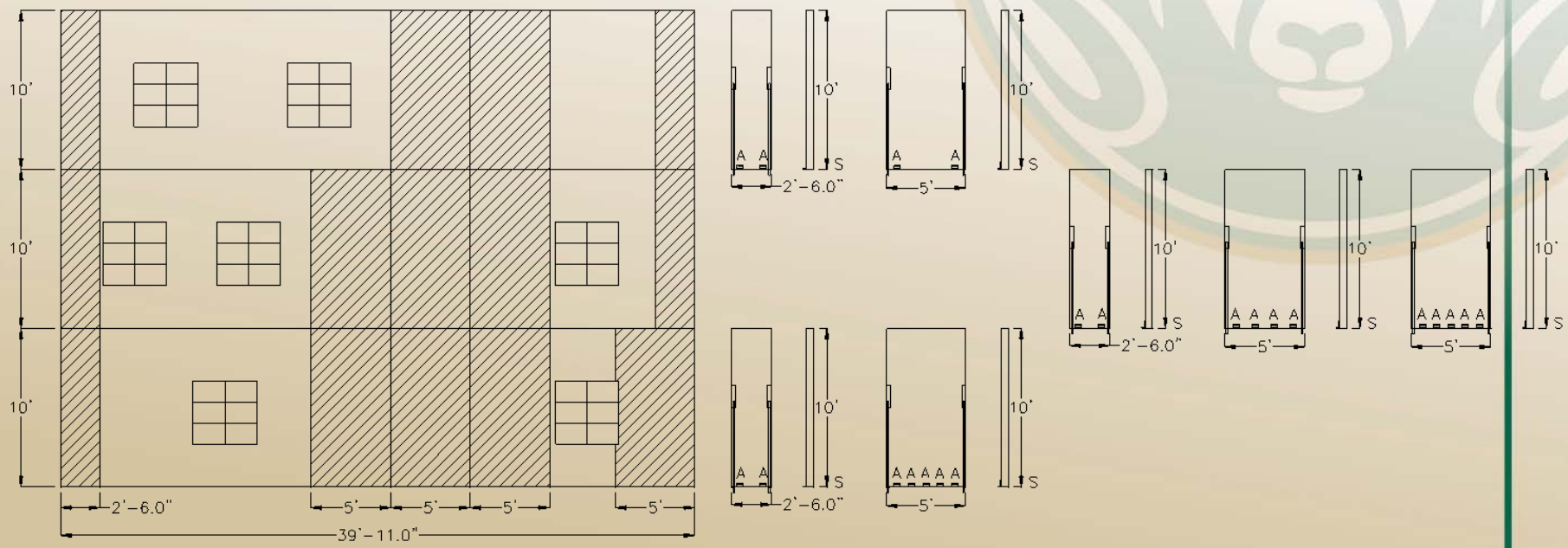
Colorado State University



Archetype 65-2

Illustrative example

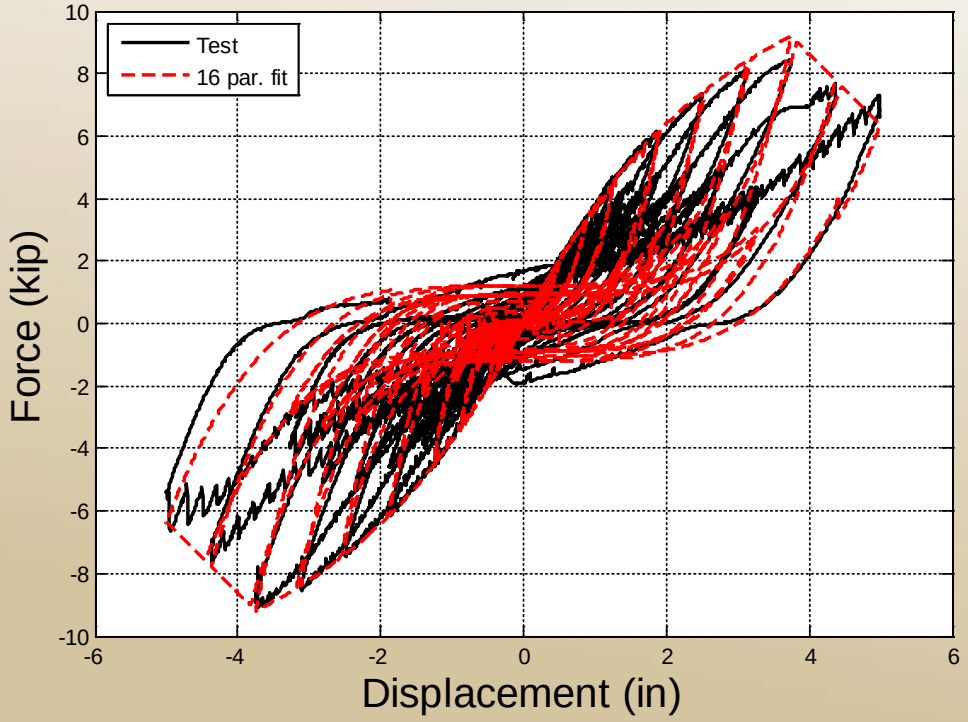
Colorado State University

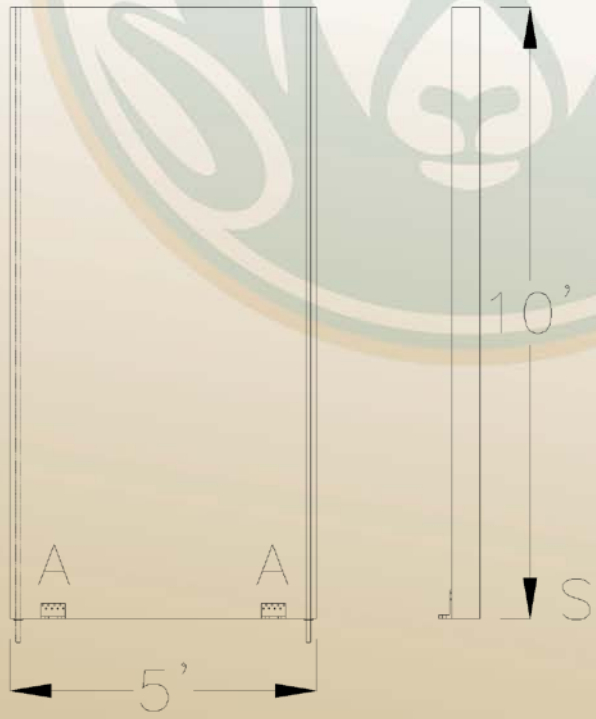


Archetype 65-3

Illustrative example

Colorado State University





Note: Scaled results

Illustrative example

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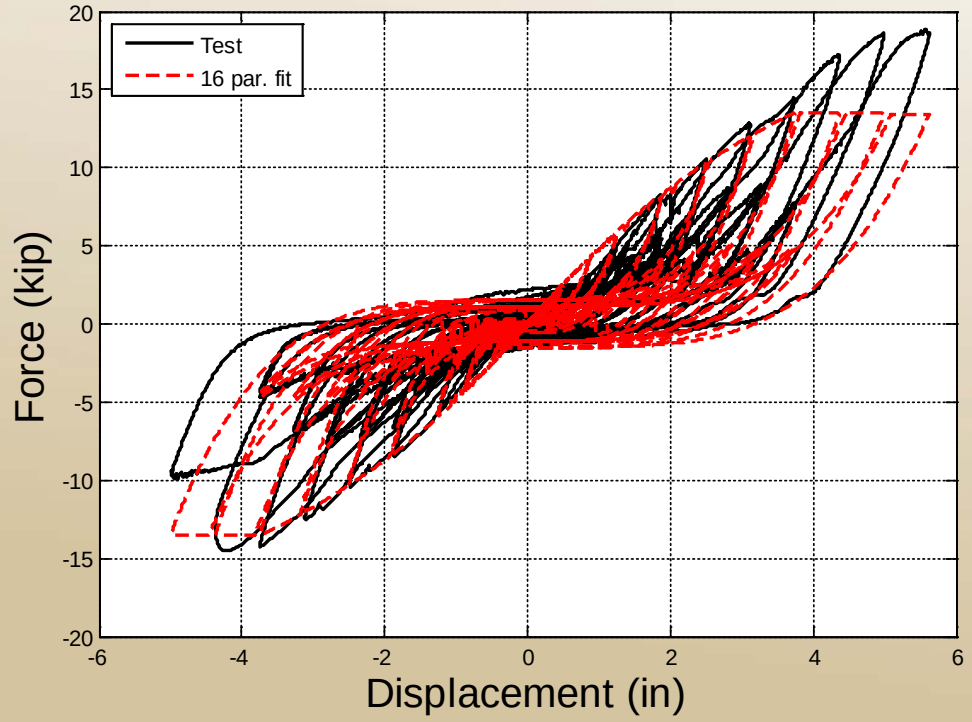

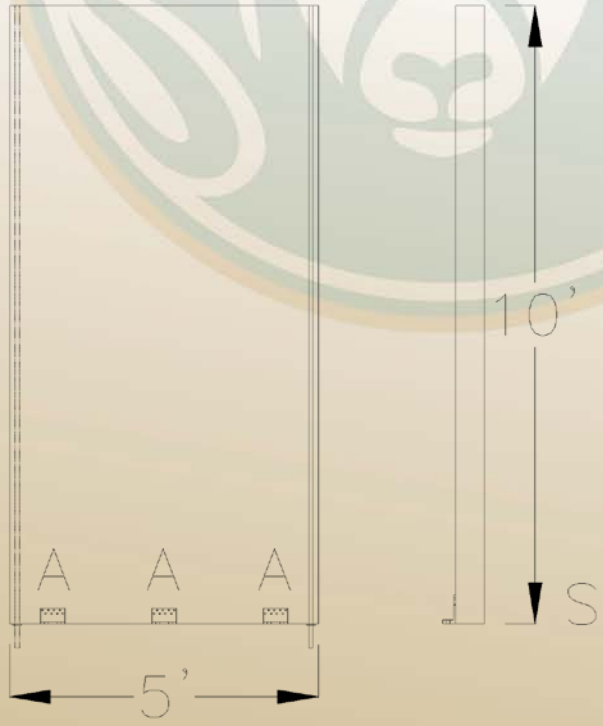

Illustrative example

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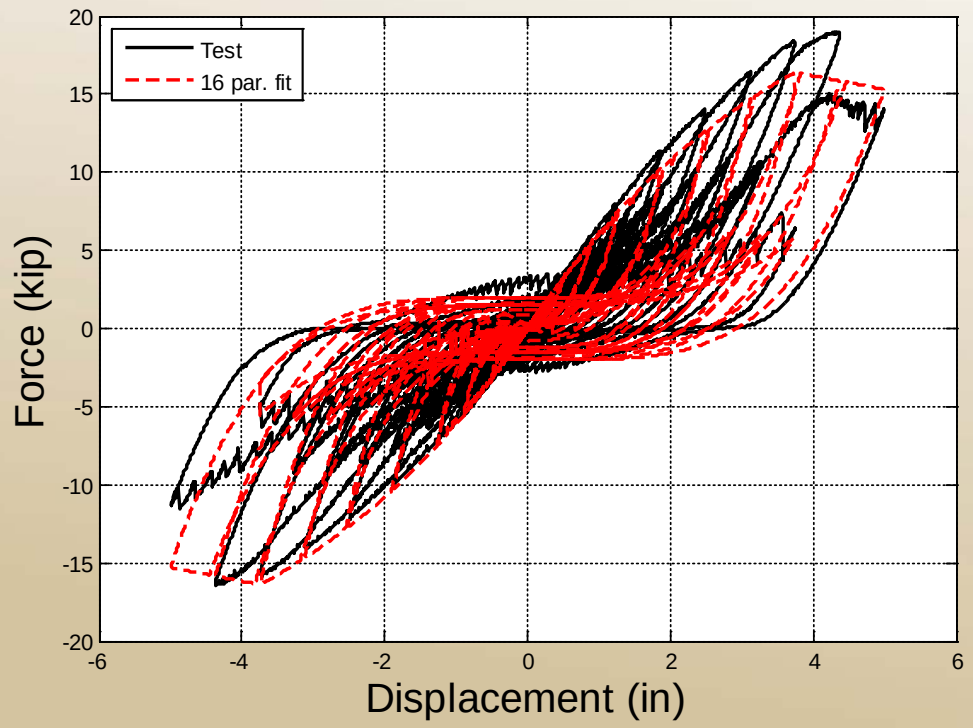

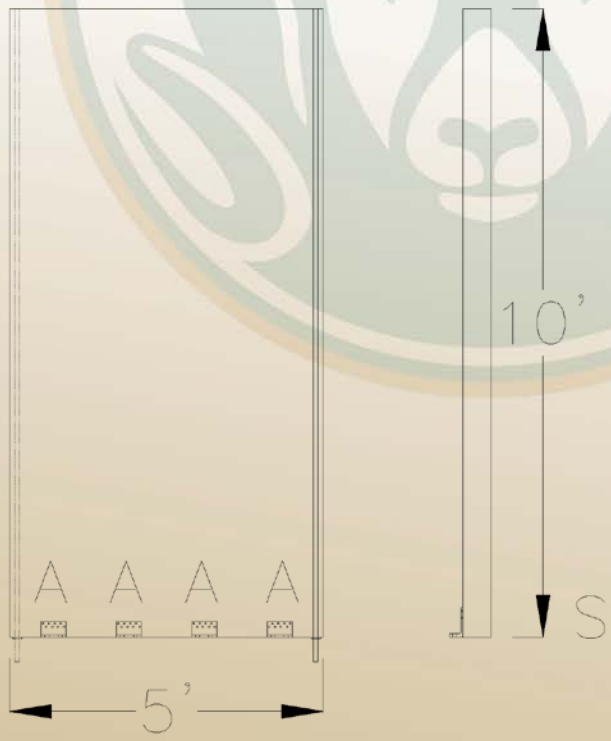

Illustrative example

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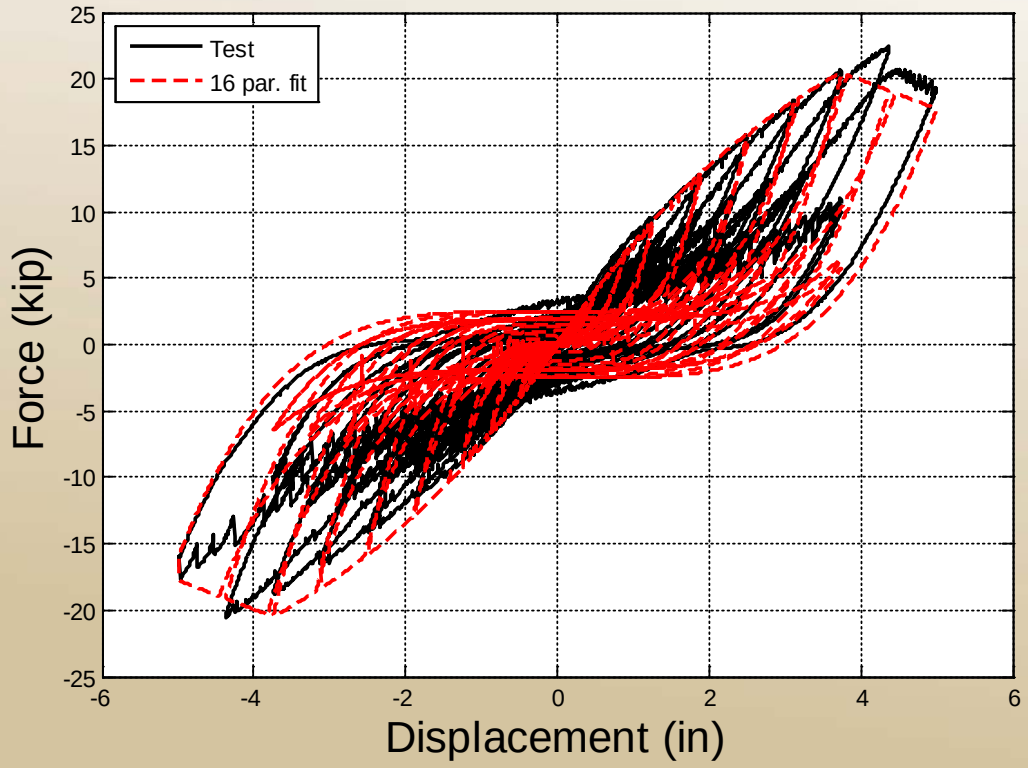

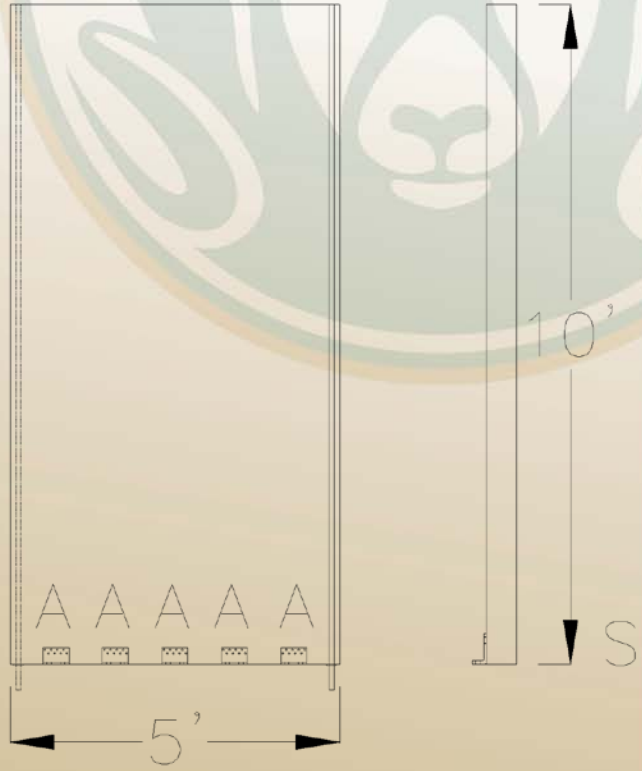

Illustrative example

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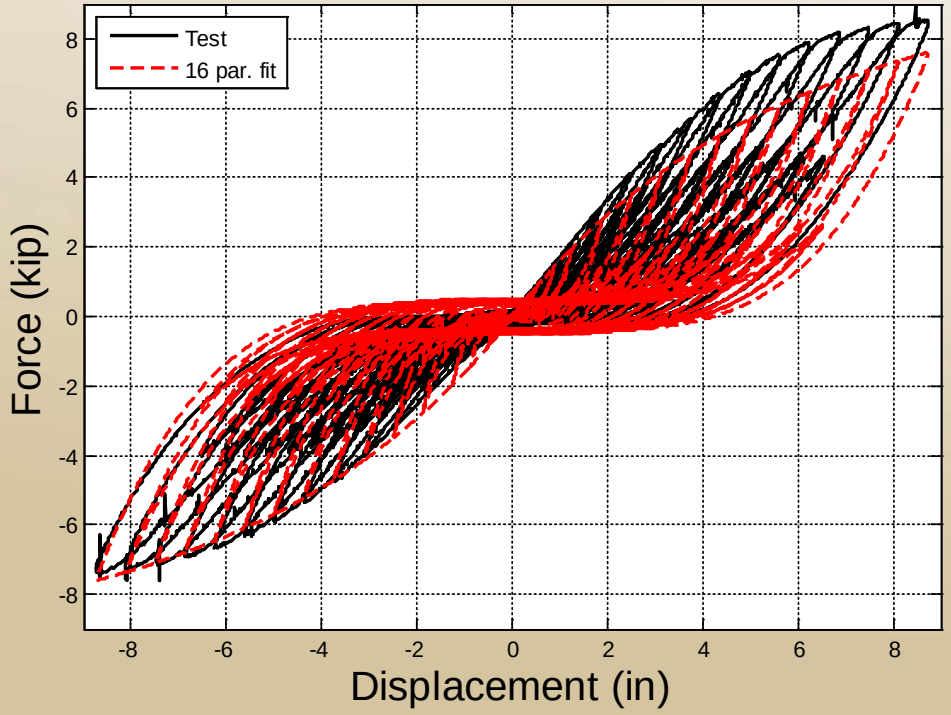

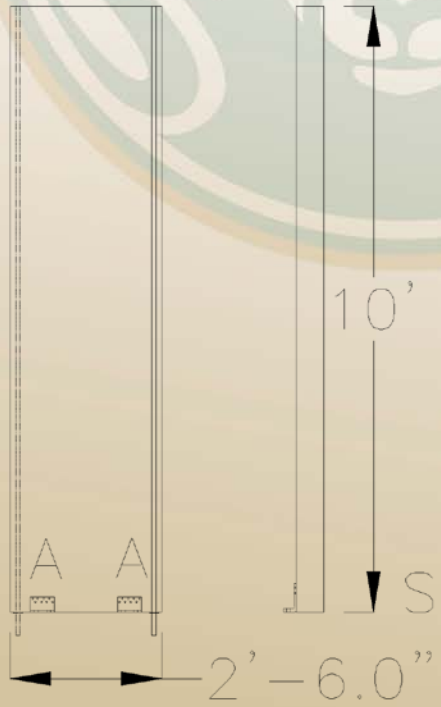

Illustrative example

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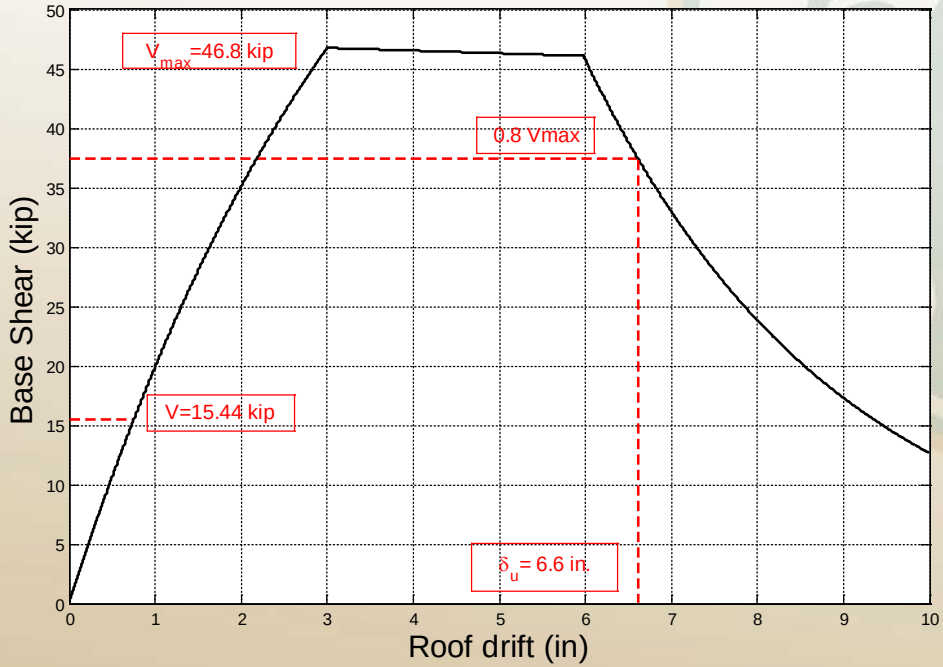
Archetype 65-1



$$\Omega = \frac{V_{max}}{V} = 3.03$$

$$\delta_{y,eff} = C_o \frac{V_{max}}{W}\left(\frac{g}{4\pi^2}\right) * (\max(\mathrm{T}, T_1))^2 = 4.42\ in.$$

$$C_o = \phi_{1,r} \frac{\sum_1^N m_x \phi_{1,x}}{\sum_1^N m_x\, \phi_{1,x}^2}$$

$$\mu_T = \frac{6.6\ in.}{4.42\ in.} = 1.5$$

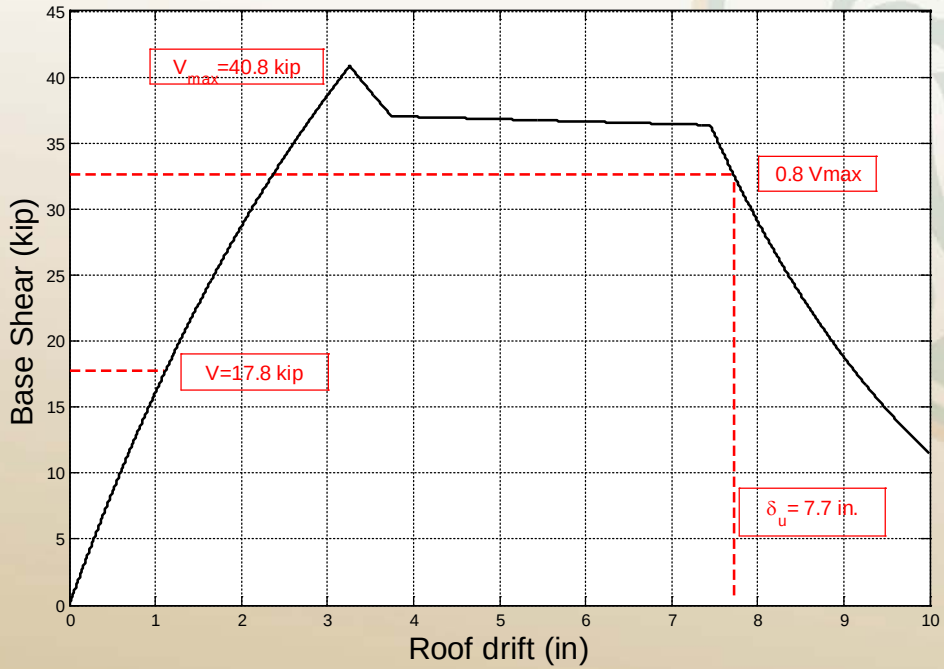
$$\mathrm{T} = 0.36\ sec$$

$$T_1 = 0.66\ sec$$

Illustrative example

Colorado State University

Archetype 65-2



$$\Omega = \frac{V_{max}}{V} = 2.29$$

$$\delta_{y,eff} = C_o \frac{V_{max}}{W}\left(\frac{g}{4\pi^2}\right) * (\max(\mathrm{T}, T_1))^2 = 4.21\ in.$$

$$C_o = \phi_{1,r} \frac{\sum_1^N m_x \phi_{1,x}}{\sum_1^N m_x\, \phi_{1,x}^2}$$

$$\mu_T = \frac{7.7\ in.}{4.21\ in.} = 1.83$$

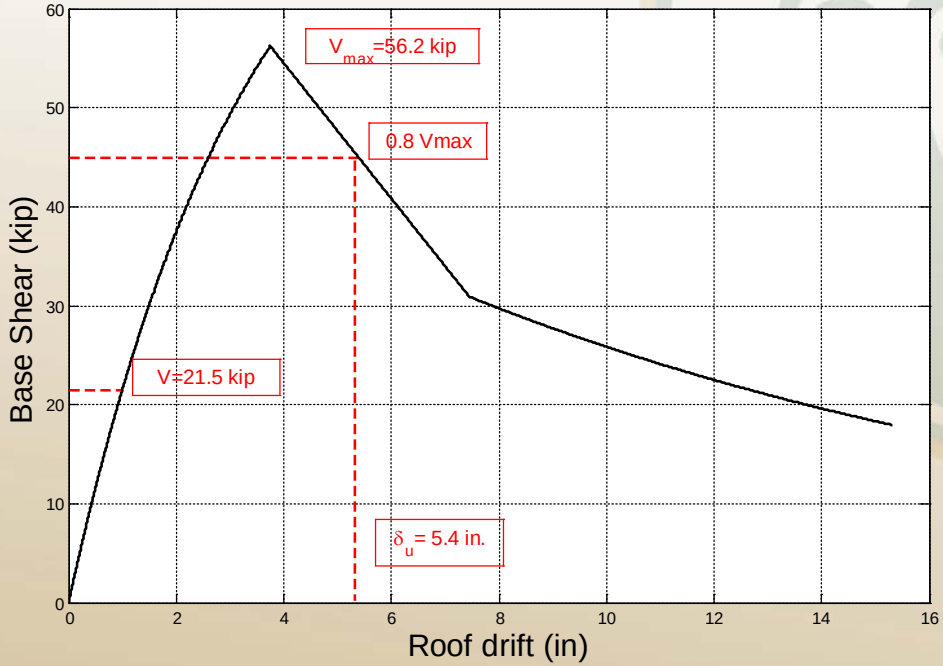
$$\mathrm{T} = 0.44\ sec$$

$$T_1 = 0.74\ sec$$

Illustrative example

Colorado State University

Archetype 65-3



$$\Omega = \frac{V_{max}}{V} = 2.61$$

$$\delta_{y,eff} = C_o \frac{V_{max}}{W}\left(\frac{g}{4\pi^2}\right) * (\max(\mathrm{T}, T_1))^2 = 3.49$$

$$C_o = \phi_{1,r} \frac{\sum_1^N m_x \phi_{1,x}}{\sum_1^N m_x\, \phi_{1,x}^2}$$

$$\mu_T = \frac{5.4\ in.}{3.49\ in.} = 1.55$$

$$T = 0.36\ sec$$

$$T_1 = 0.67\ sec$$

Illustrative example

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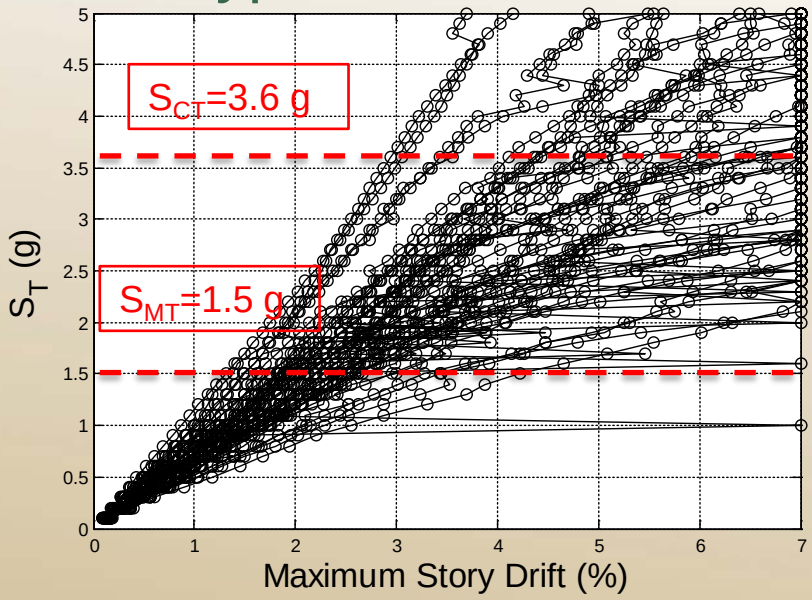
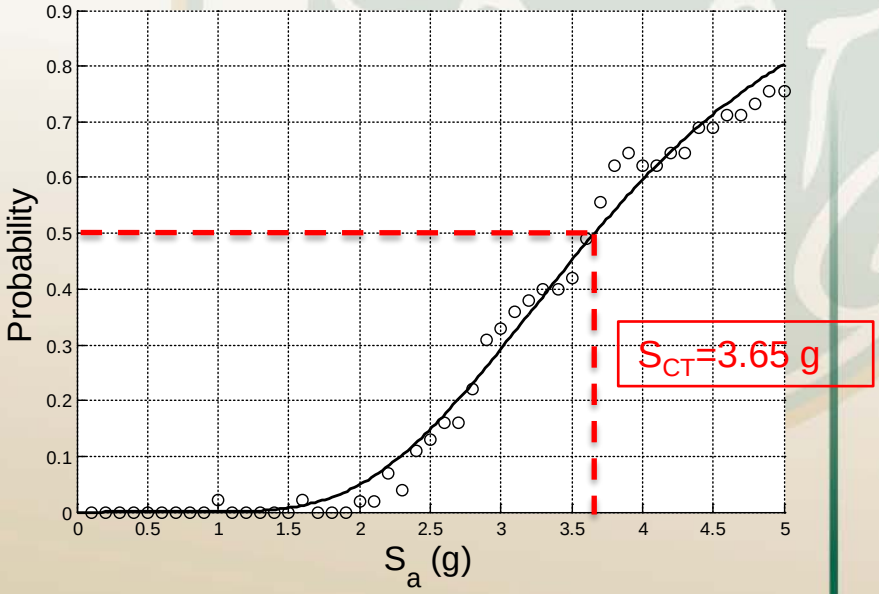
Archetype 65-1





$$CMR = \frac{S_{CT}}{S_{MT}} = \frac{3.65g}{1.5g} = 2.4$$

$$ACMR = SSF * CMR = 1.1 * 2.4 = 2.64$$

Table 7-1b Spectral Shape Factor (*SSF*) for Archetypes Designed using SDC D_{max}

T (sec.)	Period-Based Ductility, μ_T							
	1.0	1.1	1.5	2	3	4	6	≥ 8
≤ 0.5	1.00	1.05	1.1	1.13	1.18	1.22	1.28	1.33
0.6	1.00	1.05	1.11	1.14	1.2	1.24	1.3	1.36
0.7	1.00	1.06	1.11	1.15	1.21	1.25	1.32	1.38
0.8	1.00	1.06	1.12	1.16	1.22	1.27	1.35	1.41
0.9	1.00	1.06	1.13	1.17	1.24	1.29	1.37	1.44
1.0	1.00	1.07	1.13	1.18	1.25	1.31	1.39	1.46
1.1	1.00	1.07	1.14	1.19	1.27	1.32	1.41	1.49
1.2	1.00	1.07	1.15	1.2	1.28	1.34	1.44	1.52
1.3	1.00	1.08	1.16	1.21	1.29	1.36	1.46	1.55
1.4	1.00	1.08	1.16	1.22	1.31	1.38	1.49	1.58
≥ 1.5	1.00	1.08	1.17	1.23	1.32	1.4	1.51	1.61

Illustrative example

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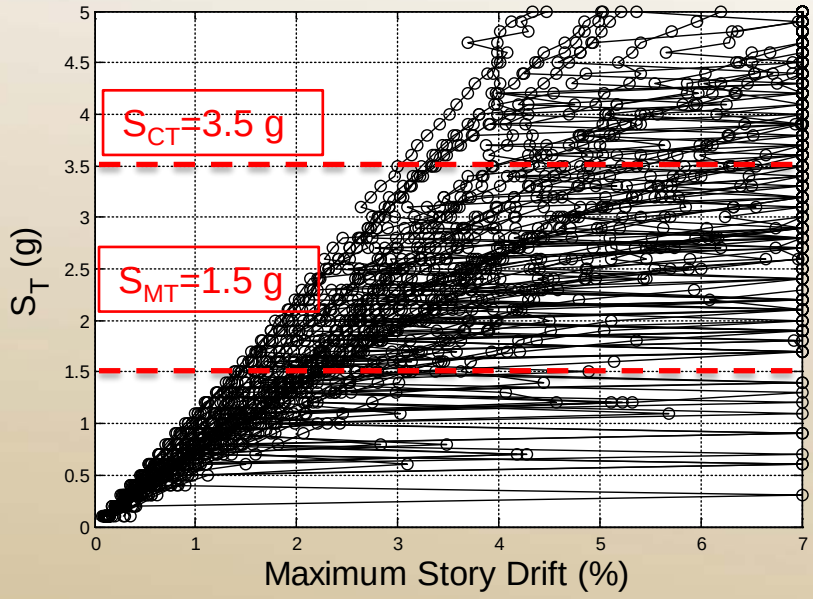
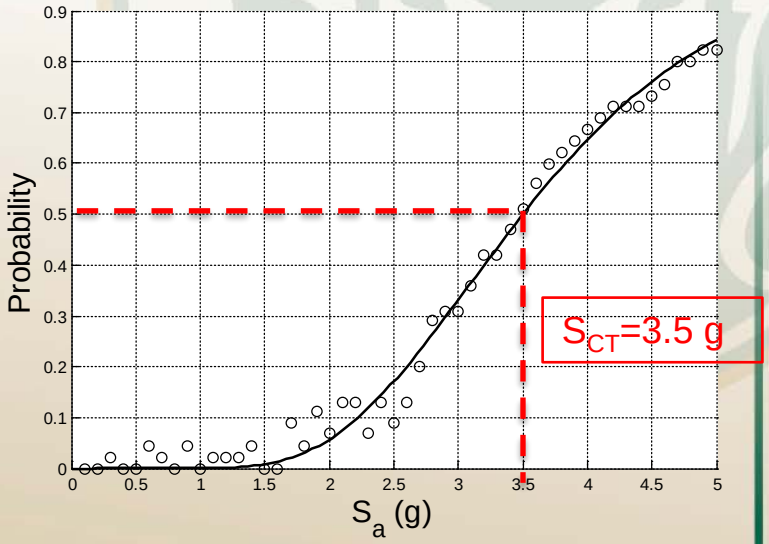
Archetype 65-2





$$CMR = \frac{S_{CT}}{S_{MT}} = \frac{3.5g}{1.5g} = 2.33$$

$$ACMR = SSF * CMR = 1.1 * 2.33 = 2.57$$

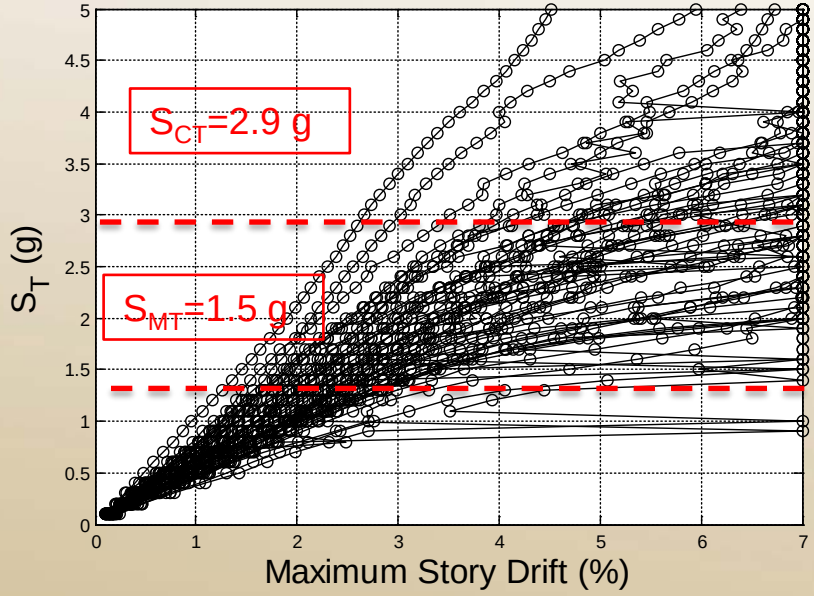
Table 7-1b Spectral Shape Factor (*SSF*) for Archetypes Designed using SDC D_{max}

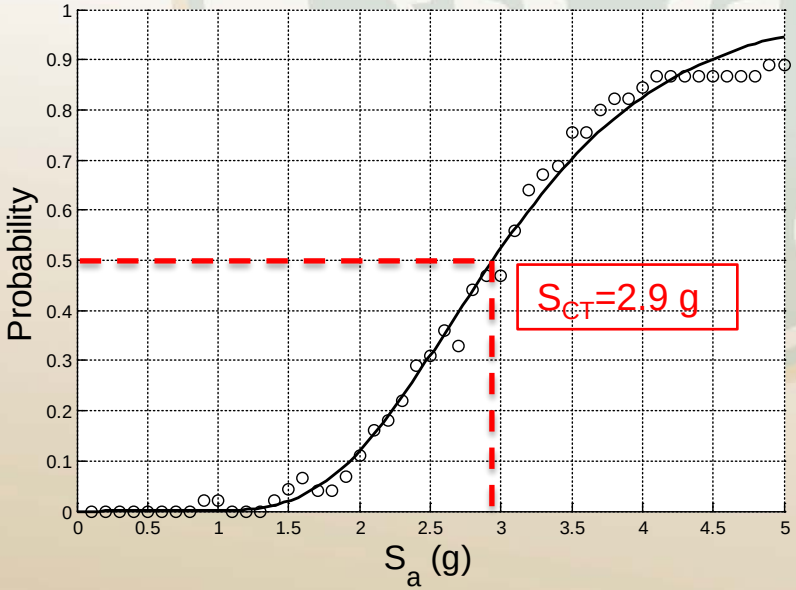
T (sec.)	Period-Based Ductility, μ_T							
	1.0	1.1	1.5	2	3	4	6	≥ 8
≤ 0.5	1.00	1.05	1.1	1.13	1.18	1.22	1.28	1.33
0.6	1.00	1.05	1.11	1.14	1.2	1.24	1.3	1.36
0.7	1.00	1.06	1.11	1.15	1.21	1.25	1.32	1.38
0.8	1.00	1.06	1.12	1.16	1.22	1.27	1.35	1.41
0.9	1.00	1.06	1.13	1.17	1.24	1.29	1.37	1.44
1.0	1.00	1.07	1.13	1.18	1.25	1.31	1.39	1.46
1.1	1.00	1.07	1.14	1.19	1.27	1.32	1.41	1.49
1.2	1.00	1.07	1.15	1.2	1.28	1.34	1.44	1.52
1.3	1.00	1.08	1.16	1.21	1.29	1.36	1.46	1.55
1.4	1.00	1.08	1.16	1.22	1.31	1.38	1.49	1.58
≥ 1.5	1.00	1.08	1.17	1.23	1.32	1.4	1.51	1.61

Illustrative example

Colorado State University

Archetype 65-3





$$CMR = \frac{S_{CT}}{S_{MT}} = \frac{2.9g}{1.5g} = 1.93$$

$$ACMR = SSF * CMR = 1.1 * 1.93 = 2.12$$

Table 7-1b Spectral Shape Factor (*SSF*) for Archetypes Designed using SDC D_{max}

T (sec.)	Period-Based Ductility, μ_T							
	1.0	1.1	1.5	2	3	4	6	≥ 8
≤ 0.5	1.00	1.05	1.1	1.13	1.18	1.22	1.28	1.33
0.6	1.00	1.05	1.11	1.14	1.2	1.24	1.3	1.36
0.7	1.00	1.06	1.11	1.15	1.21	1.25	1.32	1.38
0.8	1.00	1.06	1.12	1.16	1.22	1.27	1.35	1.41
0.9	1.00	1.06	1.13	1.17	1.24	1.29	1.37	1.44
1.0	1.00	1.07	1.13	1.18	1.25	1.31	1.39	1.46
1.1	1.00	1.07	1.14	1.19	1.27	1.32	1.41	1.49
1.2	1.00	1.07	1.15	1.2	1.28	1.34	1.44	1.52
1.3	1.00	1.08	1.16	1.21	1.29	1.36	1.46	1.55
1.4	1.00	1.08	1.16	1.22	1.31	1.38	1.49	1.58
≥ 1.5	1.00	1.08	1.17	1.23	1.32	1.4	1.51	1.61

Illustrative example

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Completeness and Robustness	Confidence in Basis of Design Requirements		
	High	Medium	Low
High. Extensive safeguards against unanticipated failure modes. All important design and quality assurance issues are addressed.	(A) Superior $\beta_{DR} = 0.10$	(B) Good $\beta_{DR} = 0.20$	(C) Fair $\beta_{DR} = 0.35$
Medium. Reasonable safeguards against unanticipated failure modes. Most of the important design and quality assurance issues are addressed.	(B) Good $\beta_{DR} = 0.20$	(C) Fair $\beta_{DR} = 0.35$	(D) Poor $\beta_{DR} = 0.50$
Low. Questionable safeguards against unanticipated failure modes. Many important design and quality assurance issues are not addressed.	(C) Fair $\beta_{DR} = 0.35$	(D) Poor $\beta_{DR} = 0.50$	--

Representation of Collapse Characteristics	Accuracy and Robustness of Models		
	High	Medium	Low
High. Index models capture the full range of the archetype design space and structural behavioral effects that contribute to collapse.	(A) Superior $\beta_{MDL} = 0.10$	(B) Good $\beta_{MDL} = 0.20$	(C) Fair $\beta_{MDL} = 0.35$
Medium. Index models are generally comprehensive and representative of the design space and behavioral effects that contribute to collapse.	(B) Good $\beta_{MDL} = 0.20$	(C) Fair $\beta_{MDL} = 0.35$	(D) Poor $\beta_{MDL} = 0.50$
Low. Significant aspects of the design space and/or collapse behavior are not captured in the index models.	(C) Fair $\beta_{MDL} = 0.35$	(D) Poor $\beta_{MDL} = 0.50$	--

Completeness and Robustness	Confidence in Test Results		
	High	Medium	Low
High. Material, component, connection, assembly, and system behavior well understood and accounted for. All, or nearly all, important testing issues addressed.	(A) Superior $\beta_{TD} = 0.10$	(B) Good $\beta_{TD} = 0.20$	(C) Fair $\beta_{TD} = 0.35$
Medium. Material, component, connection, assembly, and system behavior generally understood and accounted for. Most important testing issues addressed.	(B) Good $\beta_{TD} = 0.20$	(C) Fair $\beta_{TD} = 0.35$	(D) Poor $\beta_{TD} = 0.50$
Low. Material, component, connection, assembly, and system behavior fairly understood and accounted for. Several important testing issues not addressed.	(C) Fair $\beta_{TD} = 0.35$	(D) Poor $\beta_{TD} = 0.50$	--

$$\beta_{RTR} = 0.1 + 0.1 * \mu_T \leq 0.4$$

$$\beta_{RTR} = 0.1 + 0.1 * 1.6 = 0.26$$

$$\beta_{TOT} = \sqrt{\beta_{RTR}^2 + \beta_{DR}^2 + \beta_{TD}^2 + \beta_{MDL}^2} = 0.66$$

$$\boxed{Avg.ACMR = 2.44 > 2.38 \Rightarrow Pass}$$

Table 7-3 Acceptable Values of Adjusted Collapse Margin Ratio ($ACMR_{10\%}$ and $ACMR_{20\%}$)

Total System Collapse Uncertainty	Collapse Probability				
	5%	10% ($ACMR_{10\%}$)	15%	20% ($ACMR_{20\%}$)	25%
0.275	1.57	1.42	1.33	1.26	1.20
0.600	2.68	2.16	1.86	1.66	1.50
0.625	2.80	2.23	1.91	1.69	1.52
0.650	2.91	2.30	1.96	1.73	1.55
0.675	3.04	2.38	2.01	1.76	1.58
0.700	3.16	2.45	2.07	1.80	1.60
0.725	3.30	2.53	2.12	1.84	1.63

On average for performance group

For any one archetype

Illustrative example

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Overstrength Factor

The value of the system overstrength factor, Ωo, for use in design should not be taken as less than the largest average value of calculated archetype overstrength, Ω, from any performance group

Deflection Amplification Factor

Inherent damping may be assumed to be 5 percent of critical, and a corresponding value of the damping coefficient, $B_I = 1.0$

$$C_d = \frac{R}{B_I}$$

Table 18.6-1 Damping Coefficient, B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD}, B_{mM} (Where Period of the Structure ≥ T_0)

Effective Damping, β (percentage of critical)	B_{v+I}, B_{1D}, B_R, B_{1M}, B_{mD}, B_{mM} (where period of the structure ≥ T_0)
≤2	0.8
5	1.0
10	1.2
20	1.5
30	1.8
40	2.1
50	2.4
60	2.7
70	3.0
80	3.3
90	3.6
≥100	4.0

Next Steps

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- Wall assembly with a diaphragm
  - Low aspect ratio panels
  - High aspect ratio panels
  - 3 sided with an opening on one side

- Finalizing analyses
- Report submittal to the peer panel

Acknowledgements

Colorado State University

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Thank you!