Determination of Seismic Performance Factors For Cross Laminated Timber Shear Wall System Based on FEMA P695 Methodology

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Department of Civil and Environmental Engineering

Proposal No. 43 CLT shear wall

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SECTION 12.2: Add line items to Table 12.2-1 on Bearing Wall Systems featuring cross-laminated timber (CLT) shear walls.

Seismic Force-Resisting System	ASCE 7 Section Where Detailing Requirements Are Specified	R	Ω_0	C_d	Structural System Limitations Including Structural Height, h_n (ft) Limits[d]				
					Seismic Design Category				
					B	C	D	E	F
A. BEARING WALL SYSTEMS									
…									
19. Cross laminated timber shear walls	14.5	3	3	3	65	65	65	65	65
20. Cross laminated timber shear walls with shear resistance provided by high aspect ratio panels only	14.5	4	3	4	65	65	65	65	65
…									

Cross Laminated Timber (CLT)

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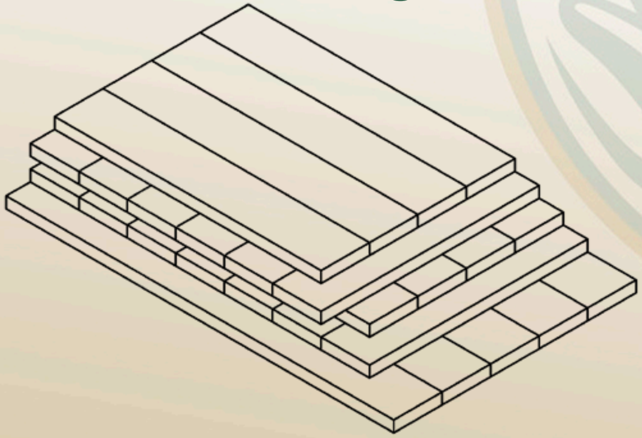
- Usually 3, 5 or 7 layers of dimensional lumber stacked in alternating directions and bonded together with adhesive



- Research and development for CLT began in the early 1990s in Europe
- The first production facilities established in 1994 in Austria, Germany and Switzerland
- The term coined in 2000 at the COST E5 conference in Italy

- Stadthaus, London, 2009
- Residential
- 9 stories
- 9 weeks of CLT construction
- 4 laborers
- 1 supervisor

Photo credit: Will Pryce

Photo credit: Popsci.com

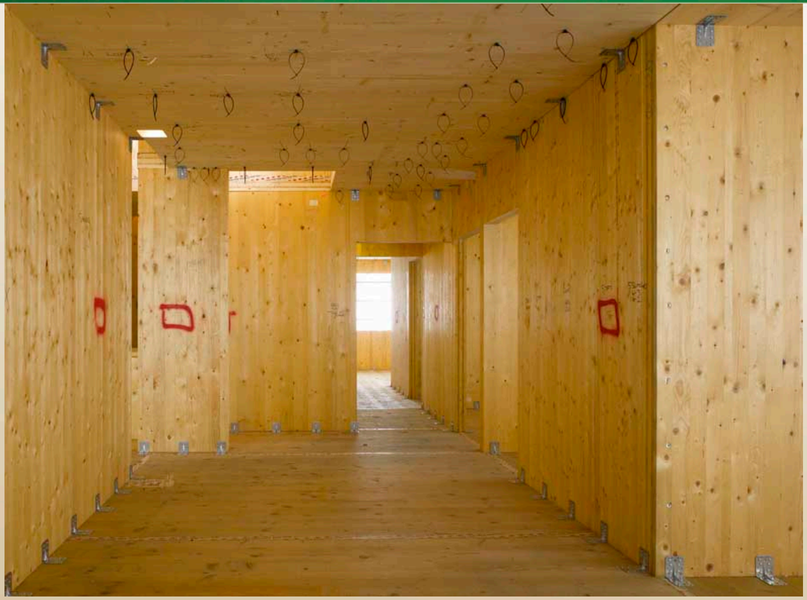


Photo credit: Will Pryce and Lendlease

- Bridport House, London, 2010
- Residential
- 8 story and 5 story
- 12 weeks of CLT construction
- 4 laborers
- 1 supervisor

Photo credit: Karakusevic Carson Architects

- Forte building, Melbourne, 2012
- 9 stories (105 ft)
- 12 weeks of CLT construction
- 5 laborers
- 1 supervisor
- 1 trainer

Photo credit: Lend Lease Architects

Ft. Drum, NY (4-story), 2017; Courtesy Jeff Morrow, Lendlease

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Ft. Jackson, SC (5-story), 2019; Courtesy Jeff Morrow, Lendlease

FEMA P-695: Quantification of Building Seismic Performance Factors

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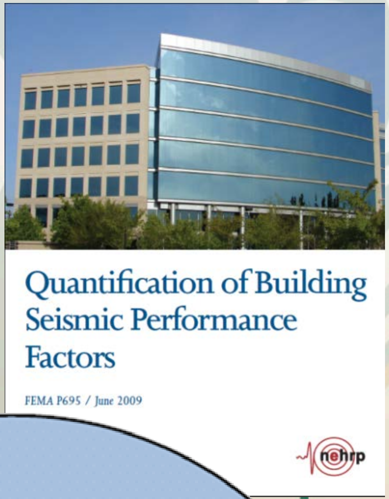
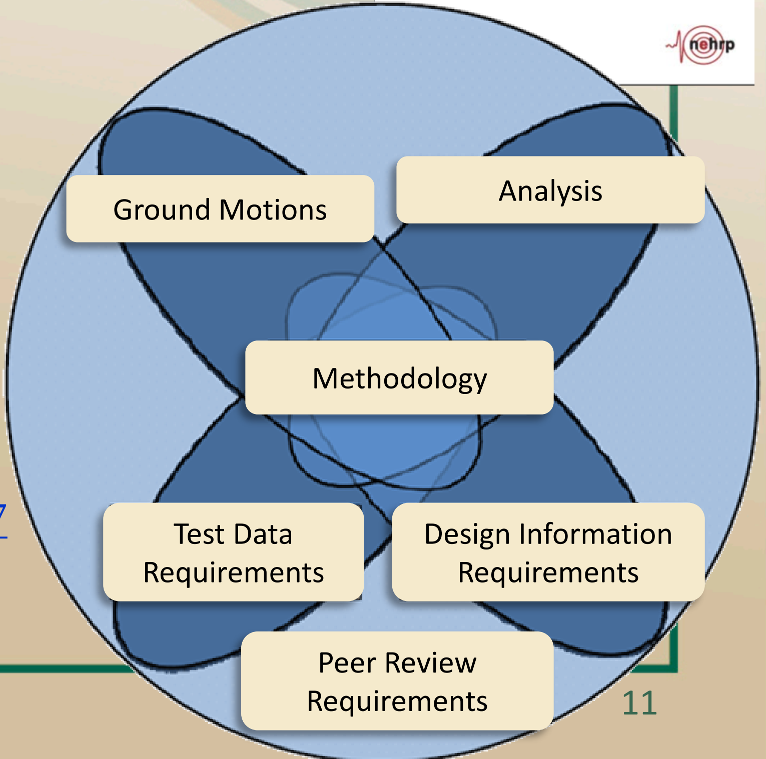
- A Methodology that allows a team to identify seismic performance factors for a new SFRS.
- The Methodology is consistent with the primary "life safety" performance objective of seismic regulations in model building codes.
- Peer review throughout is key
- Archetypes
- Design methodology
- Nonlinear time history analysis
- Performance evaluation (CMR & ACMR)

Project Documents:
https://drive.google.com/drive/folders/1W2GSdZ4ePMMvZIz7mDOUj6MKB1168e49?usp=sharing





Numerical Modeling

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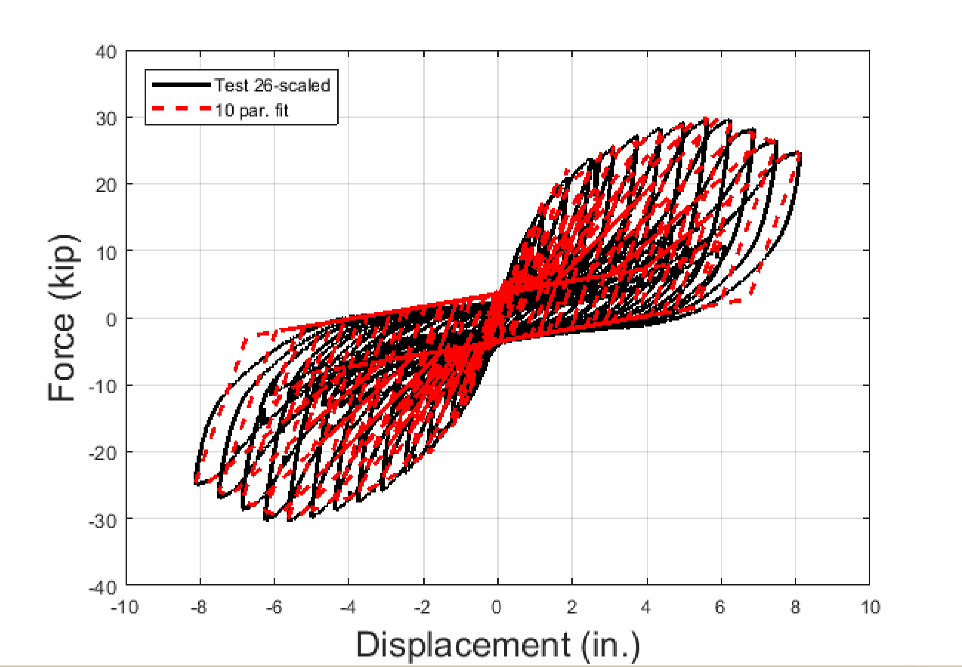

Note: Scaled results

Shake Table Testing

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Design Method

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- *National Design Specification® for Wood Construction* (*NDS®*) including Appendix E
- ASCE/SEI 7-16, *Minimum Design Loads for Buildings and Other Structures*
- Capacity based design procedure
- Platform construction
- CLT wall panels of aspect ratio (h/b_s) between 2:1 and 4:1
- *Shear resisted by prescribed nailed metal connectors*
- *Overturning induced uplift resisted by hold-downs*

Design Method

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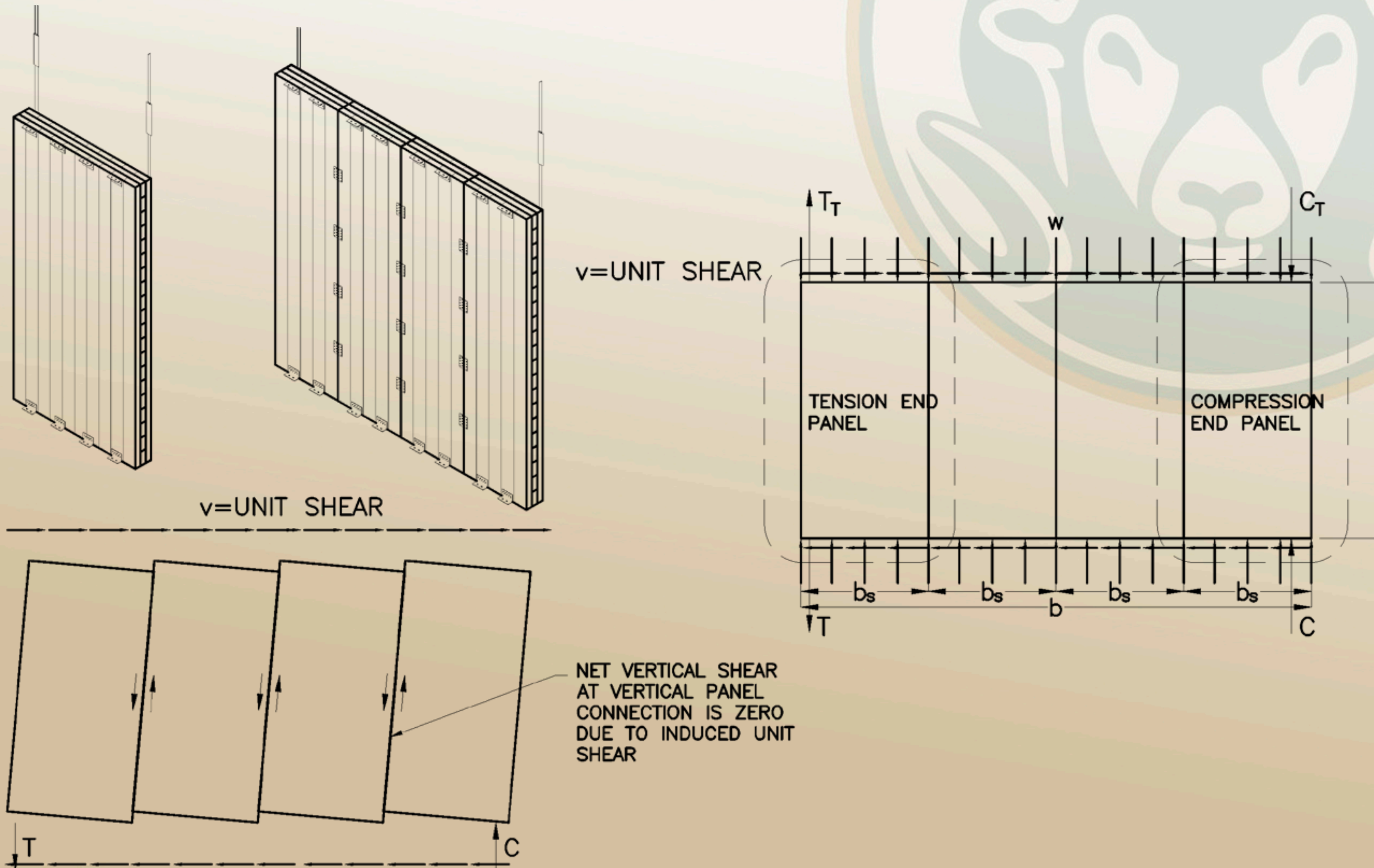

System Requirements

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- CLT wall panels that are not part of the designated seismic force resisting system requirements:

  - Effect of CLT wall panels not part of the designated seismic force resisting system on the design of the structural system shall be considered (e.g. force distribution and potential to create structural irregularities such as weak story or torsional irregularity)

  - CLT wall panels not part of the designated seismic force resisting system required to meet same detailing (i.e. connectors and panel aspect ratio not less than 2:1)

CLT Shear Walls – High AR Only

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14.5.2.3.7 CLT shear walls with shear resistance provided by high aspect ratio panels only

CLT shear walls with shear resistance provided by high aspect ratio panels only shall meet all requirements applicable for CLT shear walls and the following:

a) All CLT panels used as part of the designated seismic force resisting system shall have aspect ratio h/b_s, equal to 4:1; and

b) All CLT panels that are not part of the designated seismic force resisting system shall have aspect ratio h/b_s, not less than 4:1

Acknowledgements

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Structurlam Products LP and Nordic Structures

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Thank you!

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DUCTILE COUPLED REINFORCED CONCRETE SHEAR WALLS AND COUPLED COMPOSITE STEEL PLATE SHEAR WALLS

S. K. Ghosh, S. K. Ghosh Associates LLC, Palatine, IL

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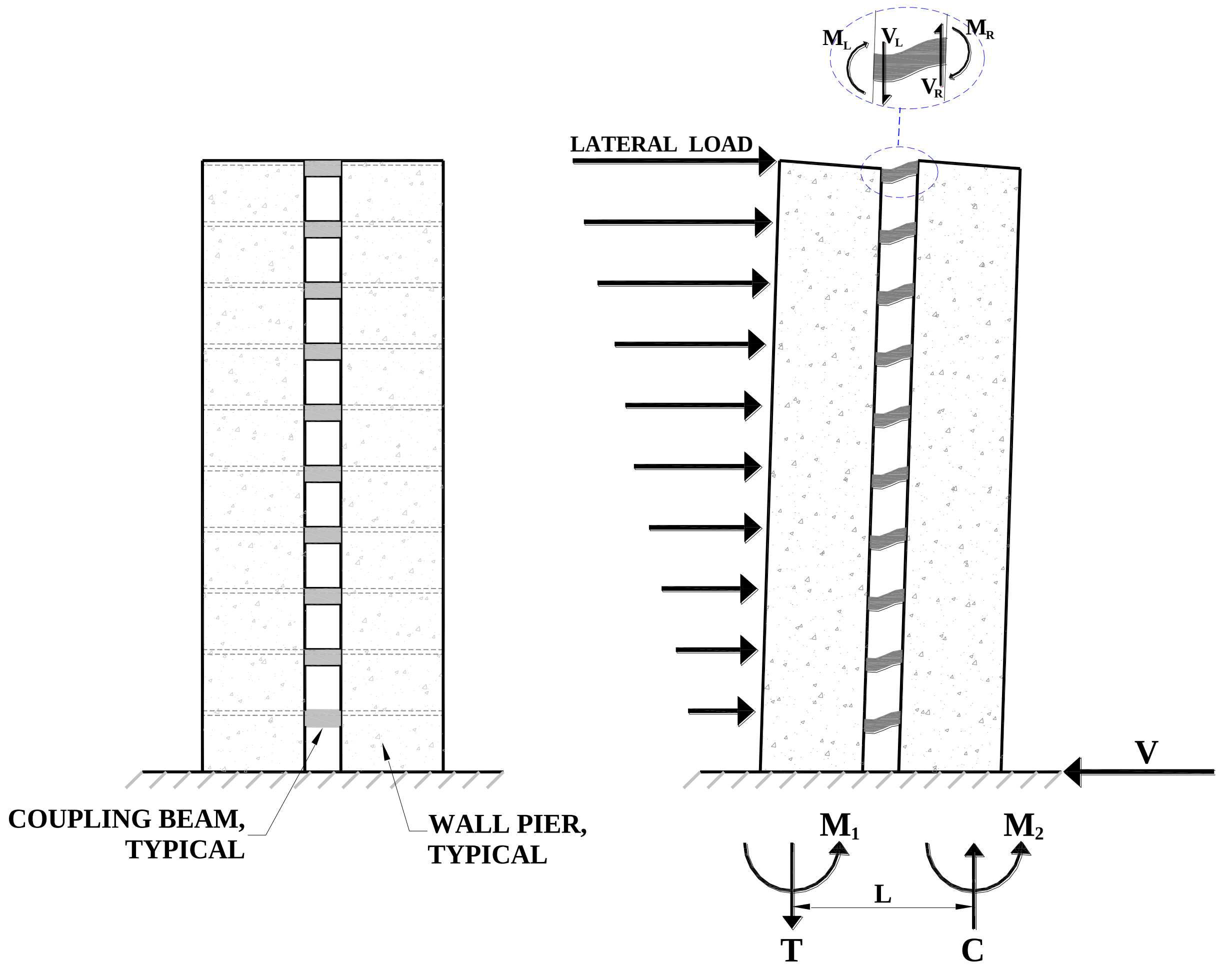
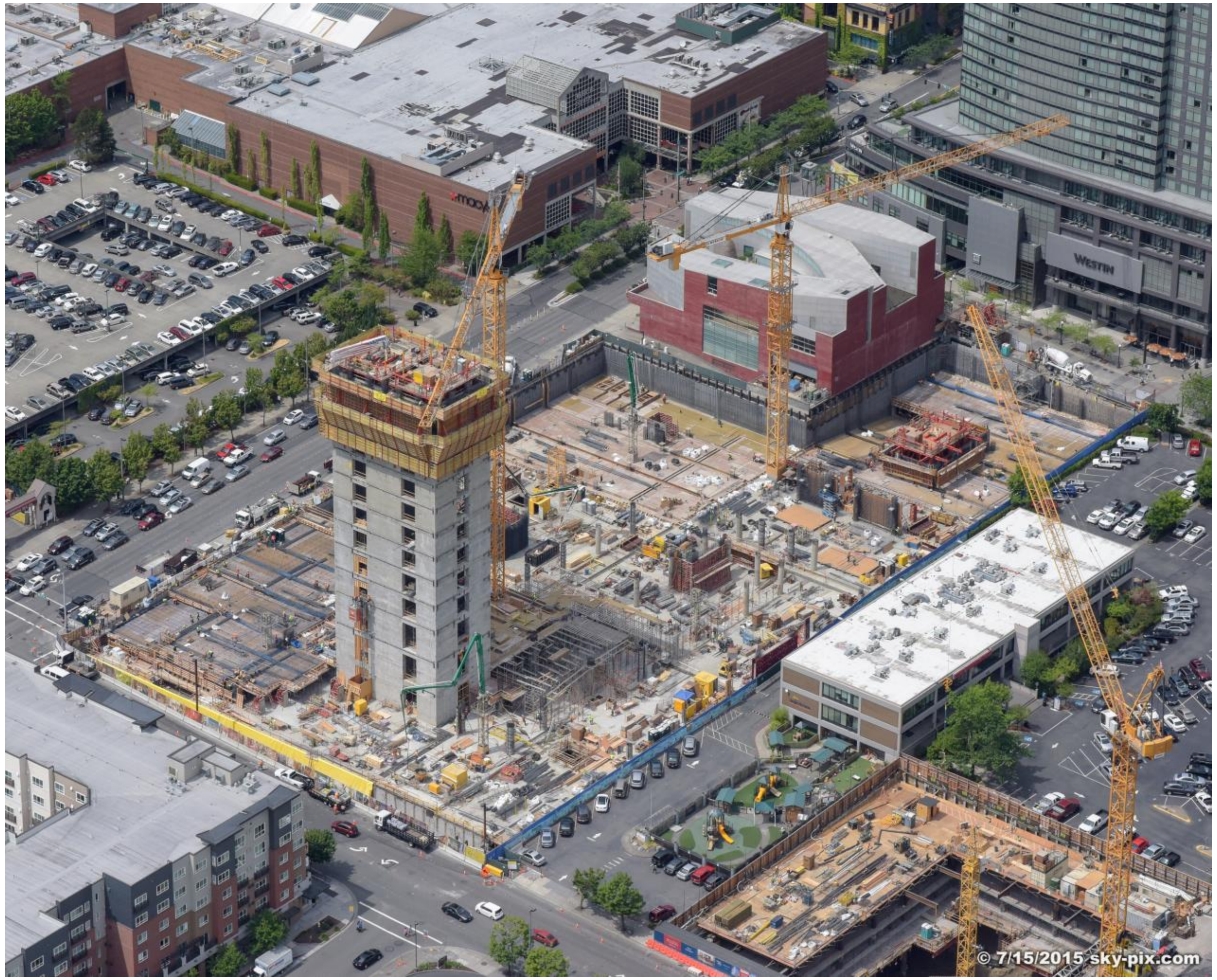
Coupled Walls



Coupled Walls



Courtesy: Cary Kopczynski & Company, Bellevue, WA

Coupled Walls

Courtesy: Magnusson Klemencic Associates, Seattle, WA

Coupled Walls

Courtesy: Cary Kopczynski & Company, Bellevue, WA

Coupled Walls

Coupled Walls

Coupled shear wall systems are recognized as distinct from isolated shear wall systems in Canadian and New Zealand codes; they are also accorded higher response modification factors in view of their superior seismic performance. ASCE 7 has so far made no such distinction.

Ductile Coupled Shear Walls

Bertero wrote in 1977: “Use of coupled walls in seismic-resistant design seems to have great potential. To realize this potential it would be necessary to prove that it is possible to design and construct “ductile coupling girders” and “ductile walls” that can SUPPLY the required strength, stiffness, and stability and dissipate significant amounts of energy through stable hysteretic behavior of their critical regions.”

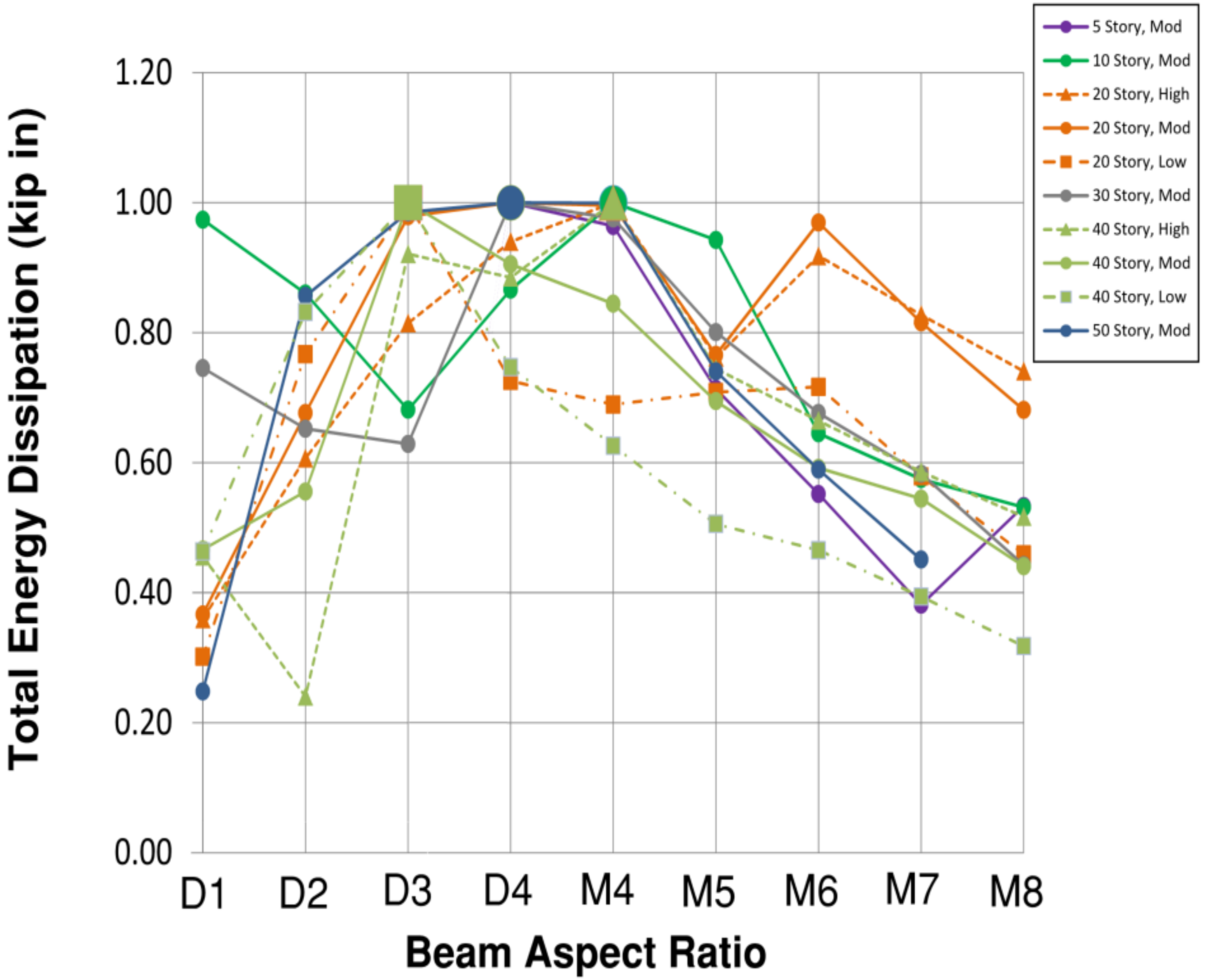
Thus, discussion needs to focus not on just coupled walls, but **ductile coupled walls** consisting of **ductile shear walls** and **ductile coupling beams**.

Energy Dissipation in Coupling Beams

MKA Study:

Non-linear response history analyses were conducted using spectrally matched ground motion records on a variety of coupled shear wall archetypes. Archetypes ranged from 5 to 50 stories in height, and considered a range of longitudinal reinforcement ratios in the coupling beams as well as the shear walls.

Energy Dissipation in Coupling Beams



Courtesy: Magnusson Klemencic Associates

ACI 318-19 18.10.9 Ductile Coupled Walls

18.10.9.1 Ductile coupled walls shall satisfy the requirements of this section.

18.10.9.2 Individual walls shall satisfy $h_{wcs}/\ell_w \geq 2$ and the applicable provisions of 18.10 for special structural walls.

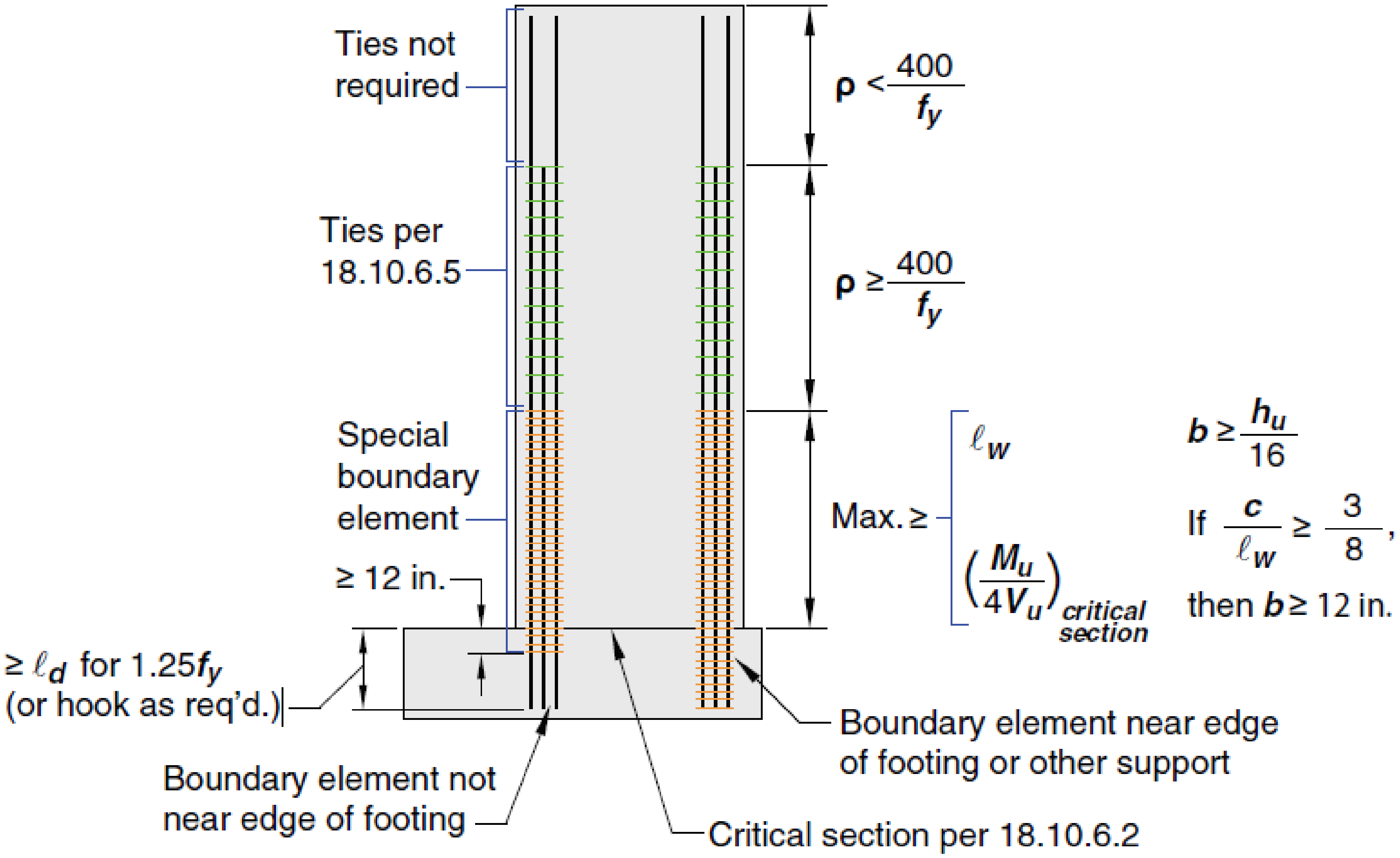
18.10.9.3 Coupling beams shall satisfy 18.10.7 [Coupling beams] and (a) through (c) in the direction considered.

(a) Coupling beams shall have $\ell_n/h \geq 2$ at all levels of the building.

(b) All coupling beams at a floor level shall have $\ell_n/h \leq 5$ in at least 90 percent of the levels of the building.

(c) The requirements of 18.10.2.5 shall be satisfied at both ends of coupling beams [reinforcement developed for $1.25f_y$].

Special Shear Walls

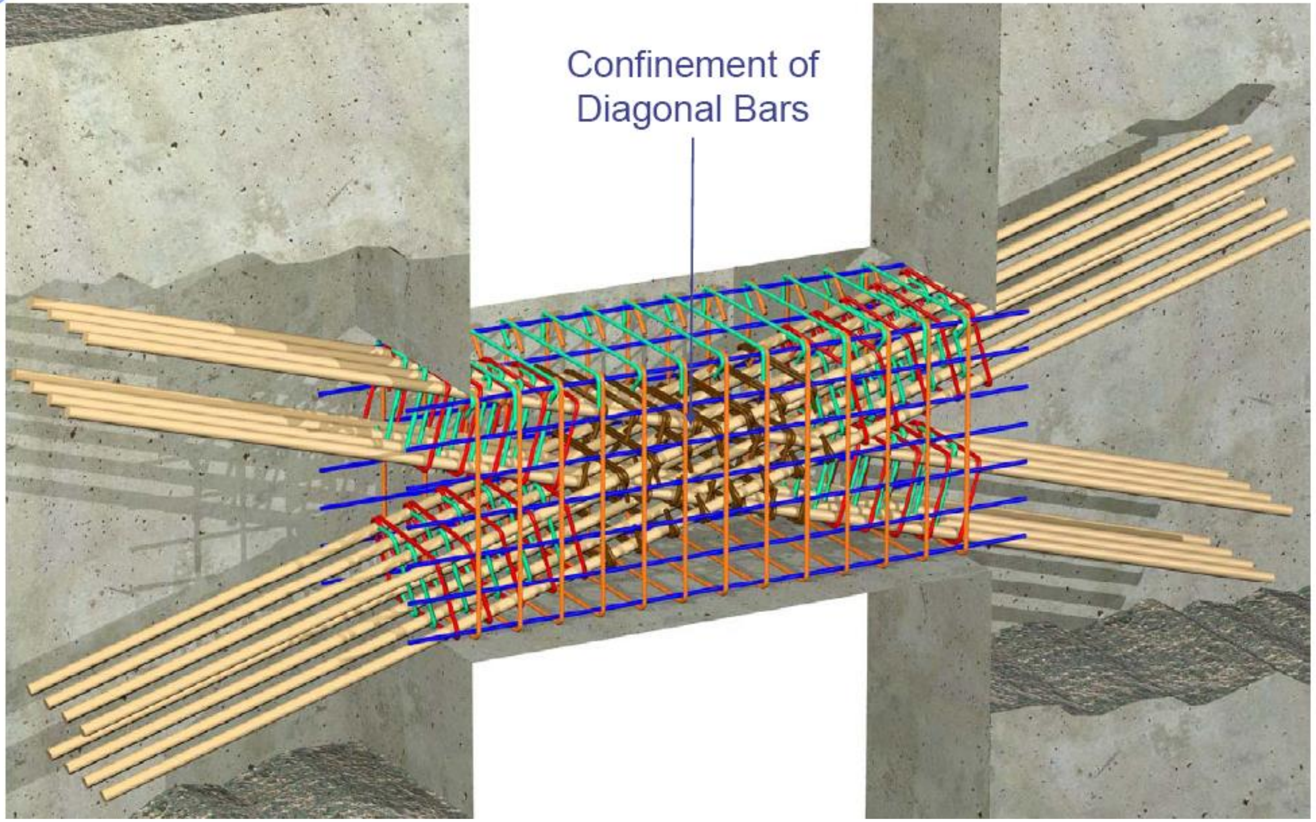


(a) Wall with $h_w/\ell_w \geq 2.0$ *and a single critical section controlled by flexure and axial load designed using 18.10.6.2, 18.10.6.4, and 18.10.6.5*

Ductile Coupling Beams

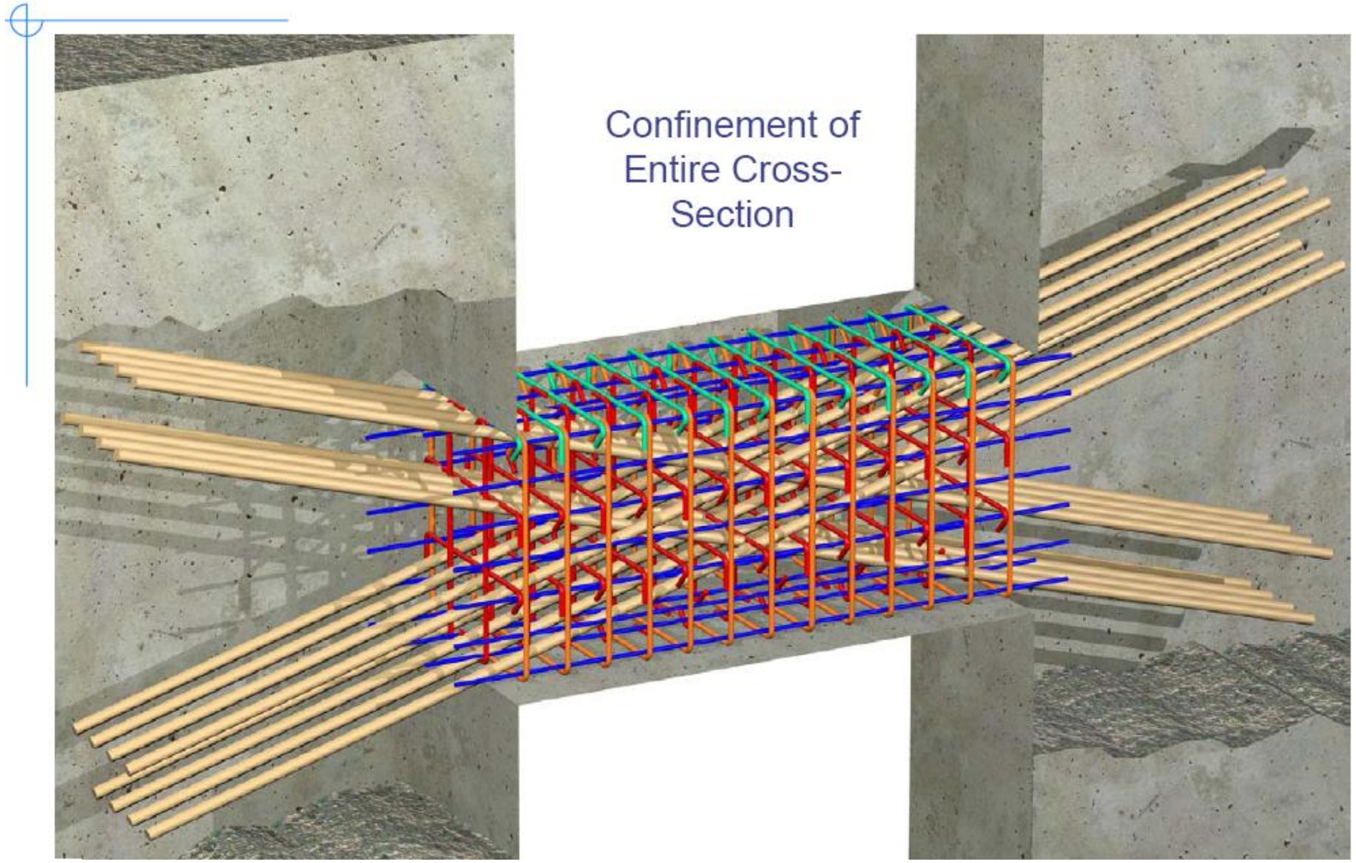
- Aspect ratio $l_n/h \geq 4$
  - Satisfy requirements of 18.6
- Aspect ratio $l_n/h < 4$
  - Permitted to be reinforced with two intersecting groups of diagonal bars
- Aspect ratio $l_n/h < 2$ and $V_u > 4\sqrt{f'_c}A_{cw}$
  - Must be reinforced with two intersecting groups of diagonal bars

Ductile Coupling Beams



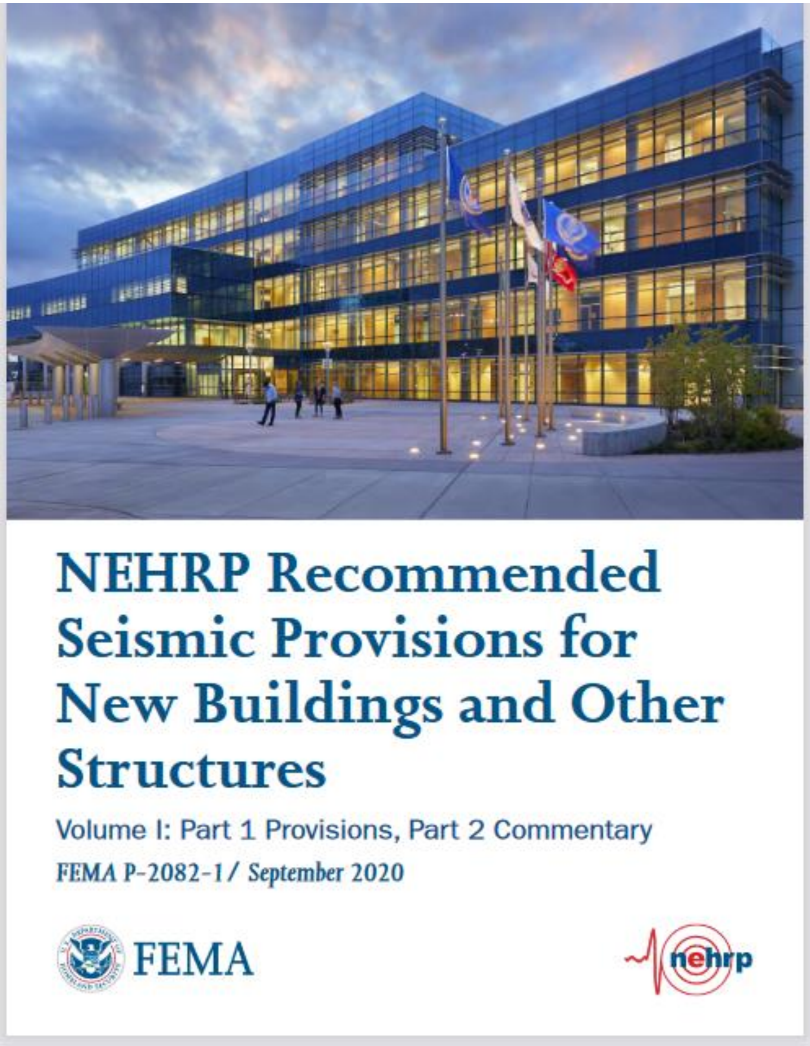
Source: http://nees.seas.ucla.edu/pankow

Ductile Coupling Beams



Source: http://nees.seas.ucla.edu/pankow

2020 NEHRP Provisions



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2020 NEHRP Provisions

- Part 1: Modifications to ASCE 7-16
- Part 2: Commentary to the Modifications
- Part 3 Resource Papers

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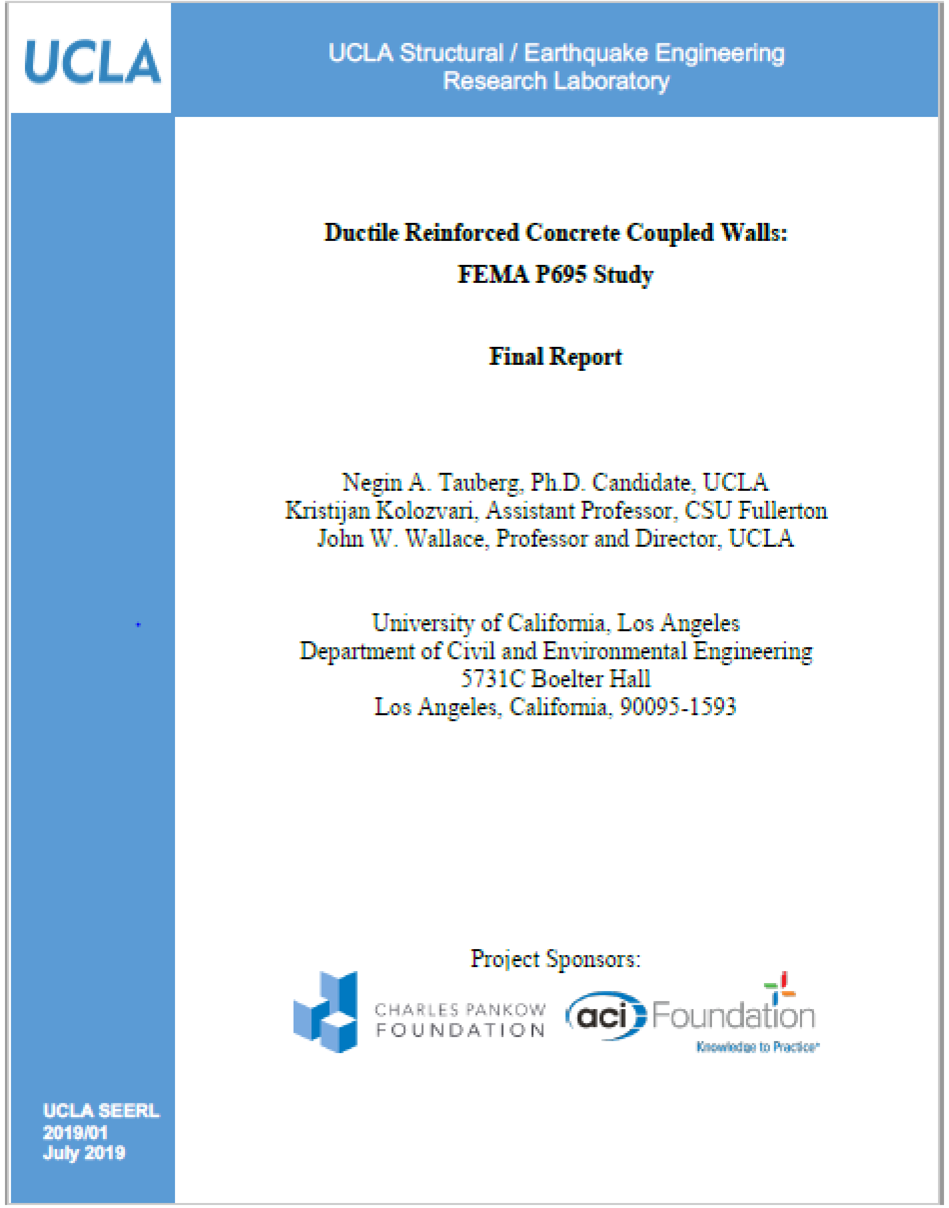
P-695 Study



UCLA

UCLA Structural / Earthquake Engineering
Research Laboratory

Ductile Reinforced Concrete Coupled Walls:
FEMA P695 Study

Final Report

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2019/01
July 2019

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Additional ACI 318-19 Changes in Special Shear Wall Design

There have been four significant ACI 318-19 code changes, all adopted in our FEMA P695 study, to address the flexural-compression wall failure issue.

(1) **18.10.3.1** (shear amplification) - would typically require design shear (required shear strength) V_u to be amplified by a factor of up to 3 (similar to New Zealand, Canada).

Additional ACI 318-19 Changes in Special Shear Wall Design

(2) **18.10.6.4** - requires improved wall boundary and wall web detailing, i.e, overlapping hoops if the boundary zone dimensions exceed 2:1, crossties with 135-135 hooks on both ends, and 135-135 crossties on web vertical bars.

(3) **18.10.6.2(b)** (Wall drift or deformation capacity check) - requires a low probability of lateral strength loss at MCE level hazard (you can think of it as requiring a minimum wall compression zone thickness), and

Additional ACI 318-19 Changes in Special Shear Wall Design

(4) **18.10.2.4** - Minimum wall boundary longitudinal reinforcement, to limit the potential of brittle tension failures for walls that are lightly-reinforced.

Shear Amplification: Concrete Shear Walls

18.10.3.1 The design shear force V_e shall be calculated by:

$$V_e = \Omega_v \omega_v V_u \leq 3V_u \qquad (18.10.3.1)$$

where V_u, Ω_v, and ω_v are defined in 18.10.3.1.1, 18.10.3.1.2, and 18.10.3.1.3, respectively.

18.10.3.1.1 V_u is the shear force obtained from code lateral load analysis with factored load combinations.

Shear Amplification: Concrete Shear Walls

18.10.3.1.2 Ω_v shall be in accordance with Table 18.10.3.1.2.

Table 18.10.3.1.2—Overstrength factor Ω_v at critical section

Condition	Ω_v	
$h_{wcs}/\ell_w > 1.5$	Greater of	M_{pr}/M_u[1]
		1.5[2]
$h_{wcs}/\ell_w \leq 1.5$	1.0	

[1] For the load combination producing the largest value of Ω_v.

[2] Unless a more detailed analysis demonstrated a smaller value, but not less than 1.0.

Shear Amplification: Concrete Shear Walls

18.10.3.1.3 For walls with $h_{wcs}/\ell_w < 2.0$, ω_v shall be taken as 1.0. Otherwise, ω_v shall be calculated as:

$$\omega_v = 0.9 + \frac{n_s}{10} \quad n_s \le 6$$
$$\omega_v = 1.3 + \frac{n_s}{30} \le 1.8 \quad n_s > 6 \qquad (18.10.3.1.3)$$

where n_s shall not be taken less than the quantity $0.007h_{wcs}$.

EARTHQUAKE FORCE-RESISTING STRUCTURAL SYSTEMS OF CONCRETE — ASCE 7-16

BASIC SEISMIC FORCE-RESISTING SYSTEM	DETAILING REF. SECTION	R	W_0	C_d	SYSTEM LIMITATIONS AND BUILDING HEIGHT LIMITATIONS (ft) BY SEISMIC DESIGN CATEGORY				
					B	C	D	E	F
A. Bearing Wall Systems									
1. Special reinforced concrete shear walls	14.2	5	$2^1/_2$	5	NL	NL	160	160	100
2. Ductile Coupled Reinforced Concrete Shear Walls	14.2	8	$2^1/_2$	8	NL	NL	160	160	100
3. Ordinary reinforced concrete shear walls	14.2	4	$2^1/_2$	4	NL	NL	NP	NP	NP
4. Detailed plain concrete shear walls	14.2	2	$2^1/_2$	2	NL	NP	NP	NP	NP
5. Ordinary plain concrete shear walls	14.2	$1^1/_2$	$2^1/_2$	$1^1/_2$	NL	NP	NP	NP	NP
6. Intermediate precast shear walls	14.2	4	$2^1/_2$	4	NL	NL	40[1]	40[1]	40[1]
7. Ordinary precast shear walls	14.2	3	$2^1/_2$	3	NL	NP	NP	NP	NP

[1]Increase in height to 45 ft is permitted for single-story storage warehouse facilities.

EARTHQUAKE FORCE-RESISTING STRUCTURAL SYSTEMS OF CONCRETE — ASCE 7-16

BASIC SEISMIC FORCE-RESISTING SYSTEM	DETAILING REF. SECTION	*R*	W_0	C_d	SYSTEM LIMITATIONS AND BUILDING HEIGHT LIMITATIONS (ft) BY SEISMIC DESIGN CATEGORY				
					B	C	D	E	F
B. Building Frame Systems									
4. Special reinforced concrete shear walls	14.2	6	$2^1/_2$	5	NL	NL	160	160	100
5. Ductile Coupled Reinforced Concrete Shear Walls	14.2	8	$2^1/_2$	8	NL	NL	160	160	100
6. Ordinary reinforced concrete shear walls	14.2	5	$2^1/_2$	$4^1/_2$	NL	NL	NP	NP	NP
7. Detailed plain concrete shear walls	14.2 and 14.2.3.2	2	$2^1/_2$	2	NL	NP	NP	NP	NP
8. Ordinary plain concrete shear walls	14.2 and 14.2.2.7	$1^1/_2$	$2^1/_2$	$1^1/_2$	NL	NP	NP	NP	NP
9. Intermediate precast shear walls	14.2	5	$2^1/_2$	$4^1/_2$	NL	NL	40[1]	40[1]	40[1]
10. Ordinary precast shear walls	14.2	4	$2^1/_2$	4	NL	NP	NP	NP	NP

[1]Increase in height to 45 ft is permitted for single-story storage warehouse facilities.

EARTHQUAKE FORCE-RESISTING STRUCTURAL SYSTEMS OF CONCRETE — ASCE 7-16

BASIC SEISMIC FORCE-RESISTING SYSTEM	DETAILING REF. SECTION	*R*	W_0	C_d	SYSTEM LIMITATIONS AND BUILDING HEIGHT LIMITATIONS (ft) BY SEISMIC DESIGN CATEGORY				
					B	C	D	E	F
D. Dual Systems with Special Moment Frames									
3. Special reinforced concrete shear walls	14.2	7	$2^1/_2$	$5^1/_2$	NL	NL	NL	NL	NL
4. Ductile Coupled Reinforced Concrete Shear Walls	14.2	8	$2^1/_2$	8	NL	NL	NL	NL	NL
5. Ordinary reinforced concrete shear walls	14.2	6	$2^1/_2$	5	NL	NL	NP	NP	NP

Composite Steel Plate Shear Walls with Coupling

The coupled steel-plate composite wall system—a sandwich of plates filled with concrete without any reinforcing steel—provides the strength, stiffness, safety and serviceability of a reinforced concrete core but is without reinforcement congestion and complex formwork.

The links between the walls are provided by composite dual-plate coupling beams.

Composite Steel Plate Shear Walls

Composite Steel Plate Shear Walls with Coupling

Courtesy: Magnusson Klemencic Associates

Composite Steel Plate Shear Walls with Coupling

Courtesy: Magnusson Klemencic Associates

Composite Steel Plate Shear Walls with Coupling

P-695 Study by Amit Varma and Michel Bruneau

http://purdue.edu/CE/Varma/secure

(UserName: varmanet - Password: boilerup2019)

EARTHQUAKE FORCE-RESISTING STRUCTURAL SYSTEMS OF CONCRETE — ASCE 7-16

BASIC SEISMIC FORCE-RESISTING SYSTEM	DETAILING REF. SECTION	*R*	W_0	C_d	SYSTEM LIMITATIONS AND BUILDING HEIGHT LIMITATIONS (ft) BY SEISMIC DESIGN CATEGORY				
					B	C	D	E	F
B. Building Frame System									
14. Steel and concrete Composite Plate shear walls	14.3	$6^1/_2$	$2^1/_2$	$5^1/_2$	NL	NL	NL	NL	NL
15. Composite Steel Plate shear walls with Coupling	14.3	8	$2^1/_2$	$5^1/_2$	NL	NL	160	160	100
16. Steel and concrete Composite special shear walls	14.3	6	$2^1/_2$	5	NL	NL	160	100	100
17. Steel and concrete Composite ordinary shear walls	14.3	5	$2^1/_2$	$4^1/_2$	NL	NL	NP	NP	NP

EARTHQUAKE FORCE-RESISTING STRUCTURAL SYSTEMS OF CONCRETE — ASCE 7-16

BASIC SEISMIC FORCE-RESISTING SYSTEM	DETAILING REF. SECTION	*R*	W_0	C_d	SYSTEM LIMITATIONS AND BUILDING HEIGHT LIMITATIONS (ft) BY SEISMIC DESIGN CATEGORY				
					B	C	D	E	F
D. Dual Systems with Special Moment Frames									
8. Steel and concrete Composite Plate shear walls	**14.2**	$7^{1}/_{2}$	$2^{1}/_{2}$	**6**	**NL**	**NL**	**NL**	**NL**	**NL**
9. Composite Steel Plate shear walls with Coupling	**14.3**	**8**	$2^{1}/_{2}$	$5^{1}/_{2}$	**NL**	**NL**	**NL**	**NL**	**NL**
10. Steel and concrete Composite special shear walls	**14.2**	**7**	$2^{1}/_{2}$	**6**	**NL**	**NL**	**NL**	**NL**	**NL**
11. Steel and concrete Composite ordinary shear walls	**14.2**	**6**	$2^{1}/_{2}$	**5**	**NL**	**NL**	**NP**	**NP**	**NP**

Composite Steel Plate Shear Walls with Coupling

Definition and detailing requirements added to ASCE 7-16 Section 14.3.5.

It is anticipated that the provisions in Section 14.3.5 will ultimately end up distributed in AISC 360 and AISC 341 (2022).

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