Full-Scale Shear Wall Tests for Force Transfer Around Openings

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Learning Objectives

At the end of this program, participants will have:

1. *Investigated past and current methods for determining force transfer around opening for wood shear walls*
2. *Compared the effects of different size of openings, size of full-height piers, and the relationships to the three industry standards for calculation of force transfer around openings*
3. *Observed how the study examines the internal forces generated by reviewing the full-scale wall tests*
4. *Concluded that research results obtained from this study can be used to support different design methodologies in estimating the forces around the openings accurately.*

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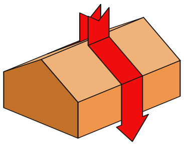
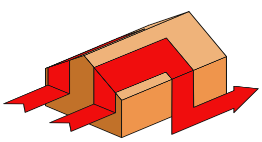
Introduction

"Any system of method of construction to be used shall be based on a rational analysis in accordance with well established principles of mechanics. Such analysis shall result in a system that provides a complete load path capable of transferring loads from their point of origin to the load-resisting elements."

(IBC 2009 1604.4)



VERTICAL



HORIZONTAL

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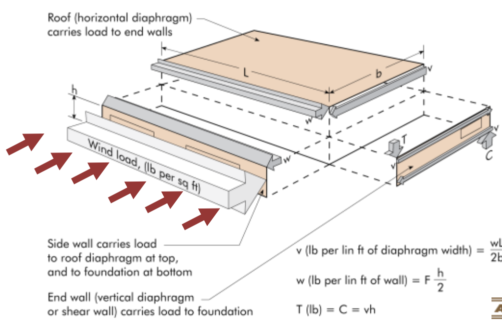
General Lateral Load Path



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Research Overview

Joint research project

- APA - The Engineered Wood Association (Skaggs & Yeh)
- University of British Columbia (Lam & Li),
- USDA Forest Products Laboratory (Rammer & Wacker)

Study was initiated in 2009 to:

- Examine the variations of walls with code-allowable openings
- Examines the internal forces generated during full-scale testing
- Evaluate the effects of size of openings, size of full-height piers, and different construction techniques
- Create analytical modeling to mimic testing data

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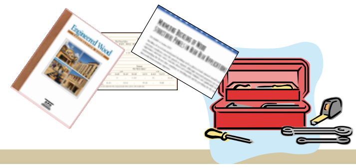
Research Overview

Study results will be used to:

- Support design methodologies in estimating the forces around the openings
- Develop rational design methodologies for adoption in the building codes
- Create new tools/methodology for designers to facilitate use of FTAO



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Introduction

- Wood structural panel shear walls are the primary lateral force resisting system for most light framed buildings
- Architectural characteristics demand many large openings and limit available shear wall
- IBC/code supplements permit three solutions for walls with openings
  - Ignore openings (Segmented Shear)
  - Empirical Approach (Perforated Shear AF&PA SDPWS)
  - Rational Approach (Force Transfer Around Openings)

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Design Methods
(SDPWS 4.3)

1. Segmented Shear Walls
2. Shear Walls with Openings
   - a. force transfer around openings
   - b. perforated shear walls

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Shear Wall Design

Segmented

1. Aspect Ratio for seismic 2:1
2. Aspect ratio up to 3.5:1, if allowable shear is reduced by 2w/h

Force Transfer

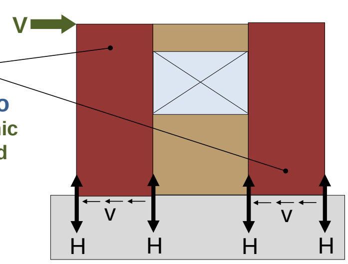
1. Code does not provide guidance for this method
2. Different approaches using rational analysis could be used

Perforated

1. Code provides specific requirements
2. The capacity is determined based on empirical equations and tables

Segmented (Traditional) Wood Shear Walls

- Only full height segments are considered
- Max aspect ratio
  - 2:1 – for seismic
  - 3.5:1 – for wind
- Current Code design values based on data dating back to 1950's.



Aspect ratio applies to full height segment (dotted)

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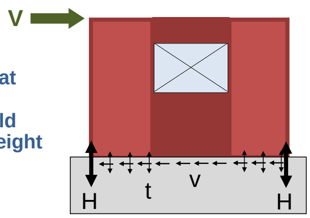
Shear Wall With Opening – Perforated Shear Wall

- Openings accounted for by empirical adjustment factor
- Hold-downs only at ends
- Uplift between hold downs, t, at full height segments is also required
- Limited to 870 plf



Aspect ratio applies to full height segment (dotted)

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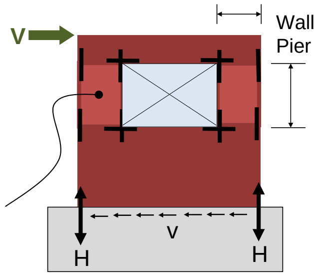
Shear Wall With Opening – Force Transfer Around Opening

- Openings accounted for by strapping or framing
  - "based on a rational analysis"
- H/w ratio defined by wall pier



Aspect ratio applies to wall pier segment (dotted)

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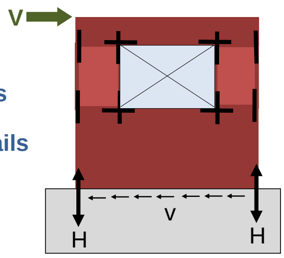
Shear Wall With Opening – Force Transfer Around Opening

- Hold-downs only at ends
- Extra calculations and added construction details (connections & blocking)
  - Uses traditional design values



Aspect ratio applies to wall pier segment (dotted)

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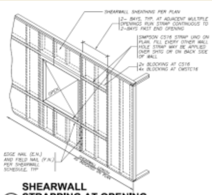
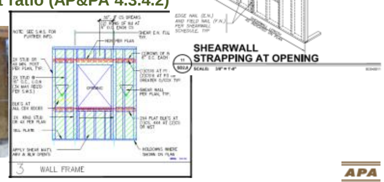
Introduction

- What is FTAO?
  - Monolithic shear wall with opening
    - Straps/studs transfer shear flow around opening
  - Use entire shear wall to resist load
  - Address aspect ratio (AP&PA 4.3.4.2)





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Introduction

- Why use FTAO?
  - Architectural limitations
    - Lack of available shear wall length
    - Openings at critical locations
    - Avoidance of specific wall sections

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Introduction

- Why use FTAO?
  - Value proposition
    - Reduction in number of shear walls
    - In some cases it can provide an alternative to manufactured walls

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FTAO Examples So. Ca. 18+ Sites: Los Angeles, Orange & San Diego Counties

TYPICAL FTAO APPLICAITON

Random Survey September of 2010

- Multi-Family
  - 40-90% of all shear applications utilized FTAO
- Single-Family
  - 80% Minimum 1-application on front or back elevation
  - 70% Multiple applications on front, back or both
  - 25% Side wall application in addition to front or back application

Residential - Segmented

ALL ELEVATIONS OF THIS PLAN HAVE FTAO APPLICATIONS

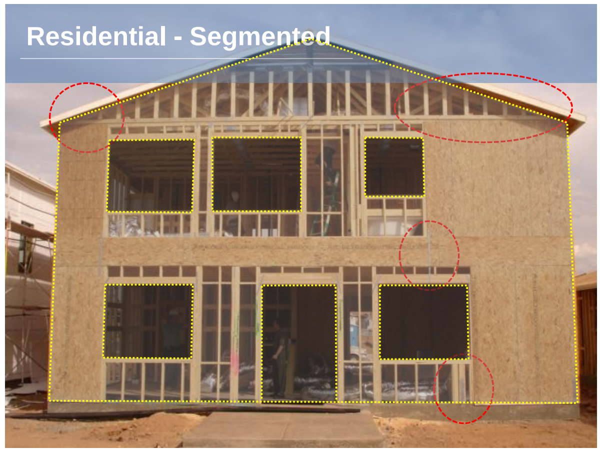
Residential - Segmented

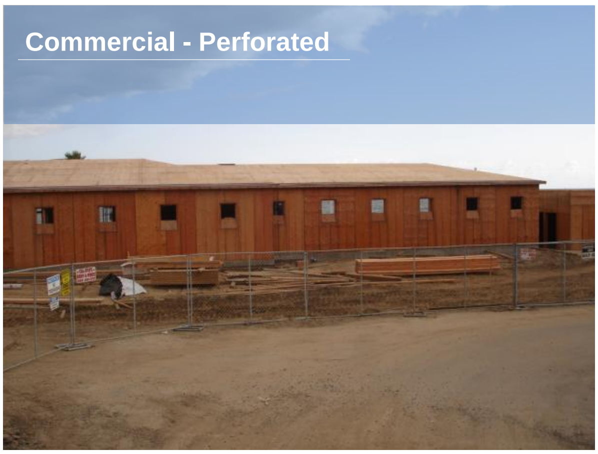
ENTIRE ELEVATION OF THIS SINGLE FAMILY HAS FTAO

Residential - Segmented

Residential - Segmented


Residential - Segmented
FTAO
FTAO
FTAO
FTAO


Residential - Segmented


Commercial - Perforated


Commercial – Fully Sheathed/FTAO
FTAO


Commercial – Segmented/FTAO
FTAO


Commercial – Fully Sheathed/FTAO

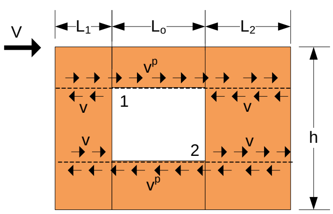
Industrial – Fully Sheathed/FTAO

Different Techniques for FTAO

- 3 Common rational analysis methods
  - Drag Strut Analogy
  - Cantilever Beam Analogy
  - Diekmann (Other: Bryer/Cobeen/Thompson)

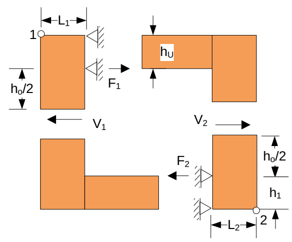
Different Techniques for FTAO

- Drag Strut Analogy
  - Forces are collected and concentrated into the areas above and below openings
  - Strap forces are a function of opening and pier widths



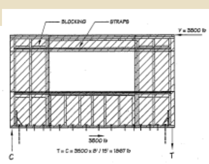
Different Techniques for FTAO

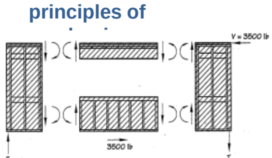
- Cantilever Beam Analogy
  - Forces are treated as moment couples
  - Segmented panels are piers at sides of openings
  - Strap forces are a function of height above and below opening and pier widths

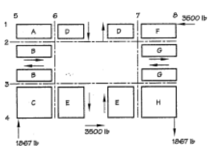


Different Techniques for FTAO

- Diekmann
  - Assumes wall behaves as monolith
  - Internal forces resolved via principles of

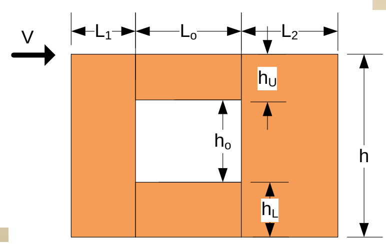






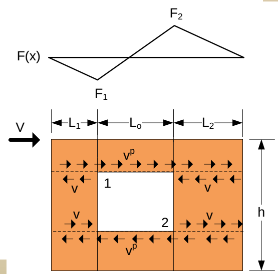
Design Examples

- V = 2,000 lbf
- L_1 = 2.3 ft
- L_O = 4 ft
- L_2 = 4 ft
- L = 10.3 ft
- h_U = 2 ft
- h_O = 4 ft
- h_L = 2 ft
- h = 8 ft



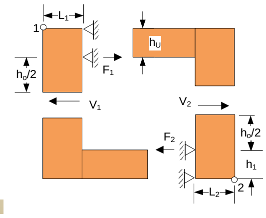
Ex. 1 – Drag Strut Analogy

- v^p = 2,000/(10.3) = 194 plf
- v = 2,000/(2.3 + 4) = 317 plf
- F_1 = (317-194)*2.3 = 284 lbf
- F_2 = (317-194)*4 = 493 lbf



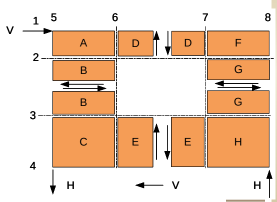
Ex. 2 – Cantilever Beam Analogy

- v = 2,000/(2.3 + 4) = 317 plf
- V_1 = 317 * 2.3 = 730 lbf
- V_2 = 317 * 4 = 1,270 lbf
- F_1 = (730 * 4)/2 = 1,460 lbf
- F_2 = (1,270 * 4)/2 = 2,540 lbf



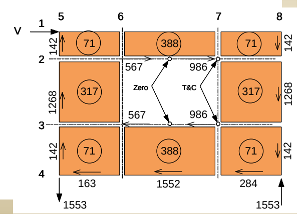
Ex. 3 – Diekmann Technique

- H = (2,000 * 8)/10.3 = 1,553 lbf
- $V_D = V_E$ = 1,553/(2+2) = 388 plf
- $V_B = V_G$ = 2,000/6.3 = 317 plf



Ex. 3 – Diekmann Technique

- F = 388 * 4 = 1,552 lbf
- F_1 = 1,552 * 2.3/(2.3 + 4) = 567 lbf
- F_2 = 1,552 * 4/(2.3 + 4) = 986 lbf
- $V_A = V_C = V_F = V_H$ =
  F&H: Horizontal v
  567/2.3 = 246 plf
  986/4 = 246 plf
  317 plf – 246 plf = 71 plf



Design Example Summary

Drag Strut Analogy

- F_1 = 284 lbf
- F_2 = 493 lbf

Cantilever Beam Analogy

- F_1 = 1,460 lbf
- F_2 = 2,540 lbf

Diekmann Method

- F_1 = 567 lbf
- F_2 = 986 lbf

References

Drag Strut Analogy

- Martin, Z.A. 2005. Design of wood structural panel shear walls with openings: A comparison of methods. Wood Design Focus 15(1):18-20

Cantilever Beam Analogy

- Martin, Z.A. (see above)

Diekmann Method

- Diekmann, E. K. 2005. Discussion and Closure (Martin, above), Wood Design Focus 15(3): 14-15
- Breyer, D.E., K.J. Fridley, K.E. Cobeen and D. G. Pollock. 2007. Design of wood structures ASD/LRFD, 6th ed. McGraw Hill, New York.

SEAOC/Thompson Method

- SEAOC. 2007. 2006 IBC Structural/Seismic Design Manual, Volume 2: Building Design Examples for Light-frame, Tilt-up Masonry. Structural Engineers Association of California, Sacramento, CA

Test Data

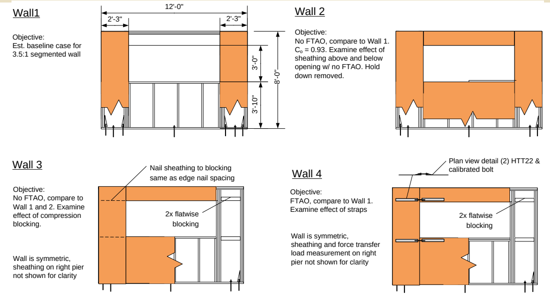
Test Plan

- Examine forces in straps above and below openings
  - Allow simple comparison of test values to measured forces
- Examine failure modes
- Test walls that could be modeled

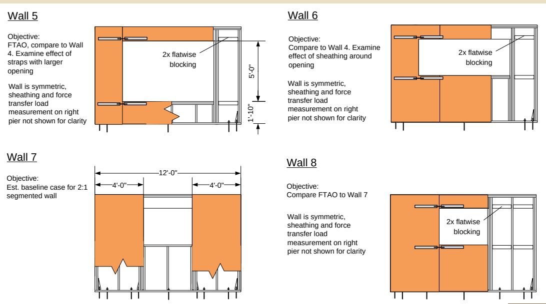
Test Plan

- 12 wall configurations tested (with and without FTAO applied)
- Wall nailing; 10d commons (0.148” x 3”) at 2” o.c.
- Sheathing; 15/32 Perf Cat oriented strand board (OSB) APA STR I
- All walls were 12 feet long and 8 feet tall
- Cyclic loading protocol following ASTM E2126, Method C, CUREE Basic Loading Protocol

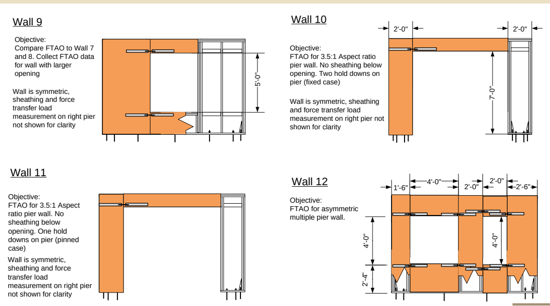
Test Plan



Test Plan

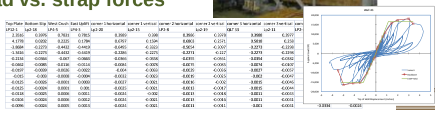


Test Plan



Test Plan

- Information obtained
  - Cyclic hysteretic plots and various cyclic parameters of the individual walls
    - Hold down force vs. load
    - Anchor bolt vs. load
    - Load vs. displacement
    - Load vs. strap forces



CUREE Basic Loading Protocol

Local Response - Instrumentation

Anchor Instrumentation

Wall ID	Outboard Hold down Force (lbf)	Inboard Hold down Force (lbf)
Wall 1a	7,881	5,313
Wall 1b	6,637	6,216
Wall 2a	2,216	
Wall 2b	3,248	
Wall 3a	2,602	
Wall 3b	4,090	
Wall 4a	1,140	
Wall 4b	3,674	
Wall 4c [5]	1,336	
Wall 4d	1,598	
Wall 5b	5,216	
Wall 5c [5]	4,795	
Wall 5d	4,413	
Wall 6a	1,573	
Wall 6b	1,285	
Wall 7a	6,024	3,677
Wall 7b	6,577	3,844
Wall 8a	4,805	
Wall 8b [6]	5,548	
Wall 9a	4,679	
Wall 9b	5,212	
Wall 10a	5,311	5,690
Wall 10b	4,252	3,731
Wall 11a	6,449	
Wall 11b	5,843	
Wall 12a	2,856	
Wall 12b	3,458	

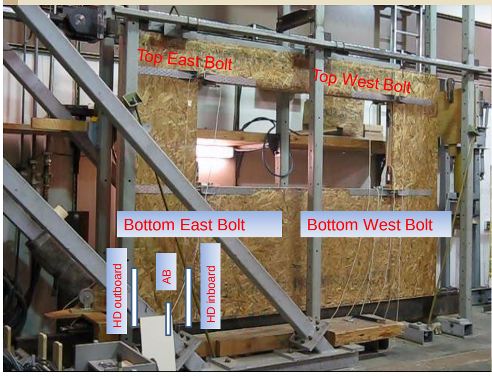
Anchor bolt forces not shown in table

Anchor Instrumentation

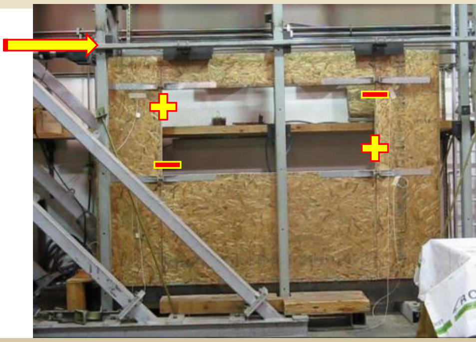
- Individual Pier

- Composite Wall

Data Notation – Opening Load Bolts

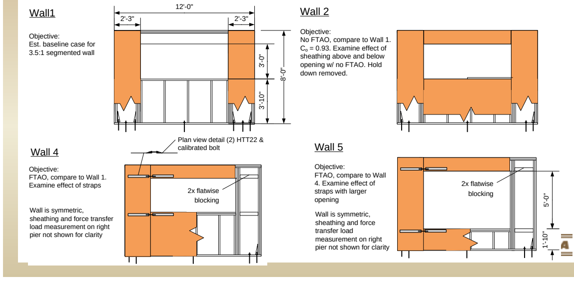


Tracking of Loads



Testing Observations

- Wall comparisons
  - Effects of shear
  - Effects of openings/straps



Global Wall Response

Wall ID	ASD Unit Shear[1], V (plf)	Effective Wall Length[2] (ft)	Wall Capacity[3] (lbf)	Average Applied Load to Wall (lbf)	ASD Load Factor[4]	Outboard Hold down Force (lbf)	Inboard Hold down Force (lbf)
Wall 1a	870	4.5	3,915	5,421	1.4	7,881	5,313
Wall 1b		4.5	3,915	5,837	1.5	6,637	6,216
Wall 2a		4.5	3,631	7,296	1.9	2,216	
Wall 2b		4.5	3,631	6,925	1.8	3,248	
Wall 3a		4.5	3,631	10,370	2.6	2,602	
Wall 3b		4.5	3,631	8,955	2.3	4,090	
Wall 4a		4.5	3,915	14,932	3.8	1,140	
Wall 4b		4.5	3,915	17,237	4.4	3,674	
Wall 4c [5]		4.5	3,915	17,373	4.4	1,336	
Wall 4d		4.5	3,915	15,328	3.9	1,598	
Wall 5b		4.5	3,915	13,486	3.4	5,216	
Wall 5c [5]		4.5	3,915	11,887	3.0	4,795	
Wall 5d		4.5	3,915	11,682	3.0	4,413	
Wall 6a		4.5	3,915	11,948	3.1	1,573	
Wall 6b		4.5	3,915	13,582	3.5	1,285	
Wall 7a		8	6,960	12,536	1.8	6,024	3,677
Wall 7b		8	6,960	10,893	1.6	6,577	3,844
Wall 8a		8	6,960	15,389	2.2	4,805	
Wall 8b [6]		8	6,960	15,520	2.2	5,548	
Wall 9a		8	6,960	15,252	2.2	4,679	
Wall 9b		8	6,960	16,647	2.4	5,212	
Wall 10a		4	3,480	7,473	2.1	5,311	5,690
Wall 10b		4	3,480	6,976	2.0	4,252	3,731
Wall 11a		4	3,480	6,480	1.9	6,449	
Wall 11b		4	3,480	5,669	1.6	5,843	
Wall 12a		6	5,220	16,034	3.1	2,856	
Wall 12b		6	5,220	15,009	2.9	3,458	

[1] Typical tabulated values are based on allowable stress design (ASD) unit shear.

[2] Based on sum of the lengths of the full height segments of the wall.

[3] The shear capacity of the wall, V, is the sum of the full height segments times the unit shear capacity. For "perforated shear walls" (Walls 2 & 3), this capacity was multiplied by $C_o = 0.93$. No reduction was taken based on aspect ratio of the walls.

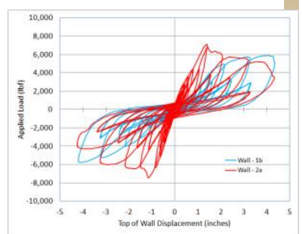
[4] Wall capacity divided by the average load applied to the wall.

[5] Monotonic test.

[6] Loading time increased by 10x

Local Response

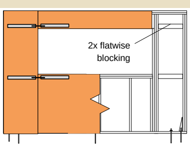
- The response curves are representative for wall 1 & 2
- Compares segmented piers vs. sheathed with no straps
- Observe the increased stiffness of perforated shear (Wall 2) vs. the segmented shear (Wall 1)

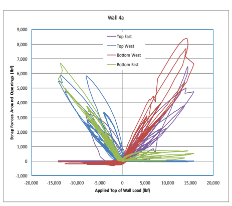


Testing Observation

Wall 4

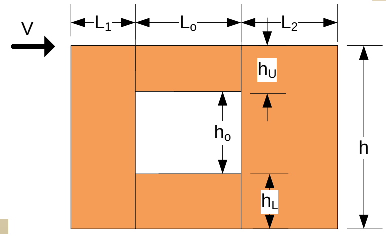
- Narrow piers
- Deep sill





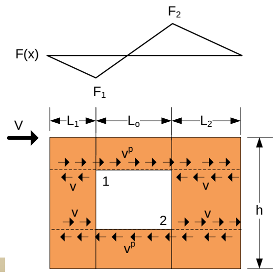
Design Examples

- $V = 3{,}915$ lbf
- $L_1 = 2.25$ ft
- $L_O = 7.5$ ft
- $L_2 = 2.25$ ft
- $L = 12$ ft
- $h_U = 1.17$ ft
- $h_O = 3$ ft
- $h_L = 3.83$ ft
- $h = 8$ ft



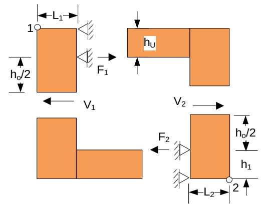
Wall 4 – Drag Strut Analogy

- v^p = 3,915/(12) = 326 plf
- v = 3,915/(2.25 + 2.25) = 870 plf
- F_1 = (870-326)*2.25 = 1,224 lbf
- $F_2 = F_1$



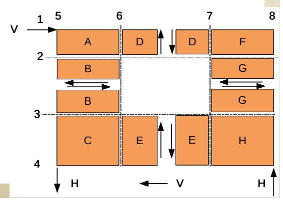
Wall 4 – Cantilever Beam Analogy

- v = 3,915/(2.25 + 2.25) = 870 plf
- V_1 = 870 * 2.25 = 1,957 lbf
- $V_2 = V_1$
- F_1 = (1,957 * (1.17+3/2))/1.17 = 4,474 lbf
- F_2 = (1,957 * (3.83+3/2))/3.83 = 2,724 lbf



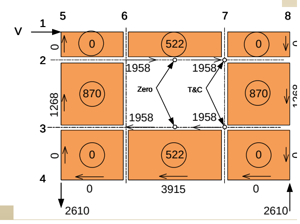
Wall 4 – Diekmann Technique

- H = (3,915 * 8)/12 = 2,610 lbf
- $V_D = V_E$ = 2,610/(1.17 + 3.83) = 522 plf
- $V_B = V_G$ = 3,915/4.5 = 870 plf



Wall 4 – Diekmann Technique

- F = 522 * 7.5 = 3,915 lbf
- F_1 = 3,915 * 2.25/(2.25 + 2.25) = 1,957 lbf
- $F_2 = F_1$
- $V_A = V_C = V_F = V_H = 0$



Local Response

Wall 4

Wall ID	Predicted Strap Forces at ASD Capacity (lbf)						
	Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 4	1,223	1,223	4,474	2,724	1,958	2,792	1,703

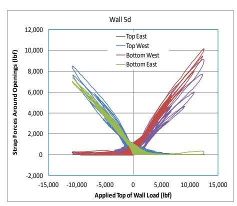
Wall ID	Measured Strap Forces (lbf) (1)		Error (2) For Predicted Strap Forces at ASD Capacity (%)						
			Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 4a	687	1,485	178%	82%	652%	183%	132%	406%	115%
Wall 4b	560	1,477	219%	83%	800%	184%	133%	499%	115%
Wall 4c (3)	668	1,316	183%	93%	670%	207%	149%	418%	129%
Wall 4d	1,006	1,665	122%	73%	445%	164%	118%	278%	102%

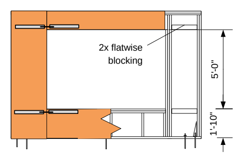
APA

Testing Observation

Wall 5

- Increased opening from Wall 4
- Shallow sill





APA

Local Response

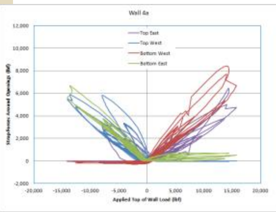
Wall ID	Predicted Strap Forces at ASD Capacity (lbf)						
	Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 5	1,223	1,223	6,151	4,627	3,263	3,838	2,895

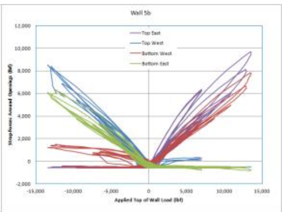
Wall ID	Measured Strap Forces (lbf) (1)		Error (2) For Predicted Strap Forces at ASD Capacity (%)						
			Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 5b	1,883	1,809	65%	68%	327%	256%	173%	204%	160%
Wall 5c (3)	1,611	1,744	76%	70%	382%	265%	187%	238%	166%
Wall 5d	1,633	2,307	75%	53%	377%	201%	141%	235%	125%

Local Response

Comparison of opening size vs. strap forces

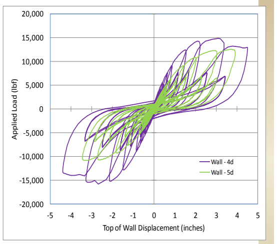
- Compared Wall 4 to 5
  - Effect of enlarged opening
  - Failure mode
  - Decreased stiffness
  - Increased strap forces





Global Response

- Comparison of opening size vs. strap forces
- Wall 4 vs. 5 reduction in stiffness with larger opening
- Wall 4 & 5d demonstrated increased stiffness as well as strength over the segmented walls 1 & 2
- Larger openings resulting in both lower stiffness and lower strength.
- Relatively brittle nature of the perforated walls
- Shear walls resulted in sheathing tearing



Measured v. Predicted Strap Forces

Cantilever Beam and Diekmann

- Not appropriate for full height openings

Drag Strut Method

- Base geometry

Wall ID	Predicted Strap Forces at ASD Capacity (lbf)						
	Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 4	1,223	1,223	4,474	2,724	1,958	2,792	1,703
Wall 5	1,223	1,223	6,151	4,627	3,263	3,838	2,895
Wall 6	1,223	1,223	4,474	2,724	1,958	2,792	1,703
Wall 8	1,160	1,160	7,953	4,842	1,856	2,647	1,614
Wall 9	1,160	1,160	7,953	6,328	3,093	3,639	2,745
Wall 10	1,160	1,160	7,830	n.a. (1)	n.a. (1)	n.a. (1)	n.a. (1)
Wall 11	1,160	1,160	7,830	n.a. (1)	n.a. (1)	n.a. (1)	n.a. (1)
Wall 12	653	1,088	4,784	4,040	1,491	n.a. (1)	n.a. (1)

Measured vs Predicted Strap Forces

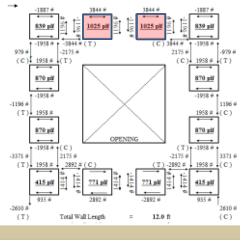
Wall ID	Measured Strap Forces (lbf) (1)		Error (2) For Predicted Strap Forces at ASD Capacity (%)						
			Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 4a	687	1,485	178%	82%	652%	183%	132%	406%	115%
Wall 4b	560	1,477	219%	83%	800%	184%	133%	499%	115%
Wall 4c (3)	668	1,316	183%	93%	670%	207%	149%	418%	129%
Wall 4d	1,006	1,665	122%	73%	445%	164%	118%	278%	102%
Wall 5b	1,883	1,809	65%	68%	327%	256%	173%	204%	160%
Wall 5c (3)	1,611	1,744	76%	70%	382%	265%	187%	238%	166%
Wall 5d	1,633	2,307	75%	53%	377%	201%	141%	235%	125%
Wall 6a	421	477	291%	256%	1063%	571%	410%	663%	357%
Wall 6b	609	614	201%	199%	735%	444%	319%	458%	277%
Wall 8a	985	1,347	118%	86%	808%	359%	138%	269%	120%
Wall 8b (4)	1,493	1,079	78%	108%	533%	449%	124%	177%	150%
Wall 9a	1,675	1,653	69%	70%	475%	383%	185%	217%	166%
Wall 9b	1,671	1,594	69%	73%	476%	397%	185%	218%	172%
Wall 10a	1,580	n.a. (5)	73%	n.a. (5)	496%	n.a. (5)	n.a. (5)	n.a. (5)	n.a. (5)
Wall 10b	2,002	n.a. (5)	58%	n.a. (5)	391%	n.a. (5)	n.a. (5)	n.a. (5)	n.a. (5)
Wall 11a	2,466	n.a. (5)	47%	n.a. (5)	318%	n.a. (5)	n.a. (5)	n.a. (5)	n.a. (5)
Wall 11b	3,062	n.a. (5)	38%	n.a. (5)	256%	n.a. (5)	n.a. (5)	n.a. (5)	n.a. (5)
Wall 12a	807	1,163	81%	94%	593%	348%	128%	n.a. (5)	n.a. (5)
Wall 12b	1,083	1,002	60%	109%	442%	403%	138%	n.a. (5)	n.a. (5)

(1)Reported strap forces were based on the mean of the "East" and "West" recorded forces at the capacity of the walls as tabulated in Table 1.
(2)Error based on ratio of predicted forces to mean measured strap forces. For Diekmann method, the larger of the top and bottom strap forces was used for calculation. Highlighted errors represent non-conservative predictions and significant ultra-conservative prediction (arbitrarily assigned as 300%).
(3)Monotonic test (4)Loading time increased by 10x. (5)Not applicable.

Other Testing Observations

Failure modes expected (Wall 5)

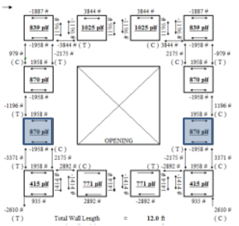
- Relatively brittle nature of the perforated walls
  - Shear walls resulted in sheathing tearing
- Concentration of forces from analysis (SEAOC/Thompson)
  - Drives shear type and nailing



Other Testing Observations

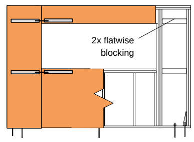
Failure modes

- Contributions of wall segments
  - Variable stiffness
  - Banging effect

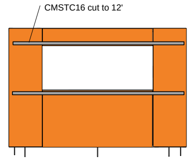


Follow-Up Testing (not reported)

Wall 4



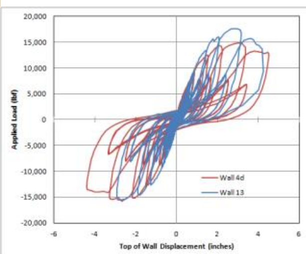
Wall 13



- Continuous strap, no instrumentation on strap

Testing Observation

Wall 13



Conclusions

- 12 assemblies tested, examining the three approaches to designing and detailing walls with openings
  - Segmented
  - Perforated Shear Wall
  - Force Transfer Around Openings
- Walls detailed for FTAO resulted in better global response

Conclusions

- Comparison of analytical methods with tested values for walls detailed as FTAO
  - The drag strut technique was consistently un-conservative
  - The cantilever beam technique was consistently ultra-conservative
  - SEAOC/Thompson provides similar results as Diekmann
  - SEAOC/Thompson & Diekmann techniques provided reasonable agreement with measured strap forces
- Better guidance to engineers will be developed by APA for FTAO
  - Summary of findings for validation of techniques
  - New tools for IRC wall bracing

Report Available

- www.apawood.org/publications
- Report is 149 pages, 28.5 MB

Enter: “force transfer” or “M410”

Final Comments

- More advanced modeling (UBC) indicate that accuracy of strap force predictions is w/in +/- 5% for most of the walls tested
- Modeling is likely too complicated for practitioners, but may lead to simplified tables or other techniques
- Modeling will also be improved, and can be used in lieu of some additional testing

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Questions?

This concludes The American Institute of Architects Continuing Education Systems Course

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WoodWorks APA