ACI 374

Seismic Shear Force Amplification in Concrete Shear Walls

Performance Based Seismic Design vs Code Level Design

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Introduction

- **Building height is limited to 240’** per current code if the concrete shear walls are used as the lateral force resisting system (LFRS) for buildings in high seismic regions.
- **Performance Based Seismic Design (PBSD**) is often used for concrete shear wall structures that is taller than 240’ because it is considered to be more economical than moment frames or a dual system.

Introduction

- **In the city of Seattle, it is required to design the building for code level force in addition to PBSD**, which is not necessarily the case in other jurisdictions. As a result, there are a lot data to compare the code level seismic demands vs the demands predicted by using the PBSD approach.
- **The shear amplification factor can easily be 3 or more.** This is one of the common observation comparing the shear demands predicted by the nonlinear time history analysis at Maximum Considered Earthquake (MCE) level to that in a code analysis at the Design Earthquake (DE) level.

Introduction

- **Amplifying the shear demand by the over strength factor Ω_o =2.5, for a building taller than 160'** The city of Seattle changed its building code in 2016, under the advisory of a group experts in PBSD, to have additional requirements for concrete shear wall structure, including the increase of shear demands to shear walls, foundations and transfer diaphragms.

- **There are no guidelines for determining shear capacity** when checking against the amplified shear demand required by the 2016 Seattle building code.

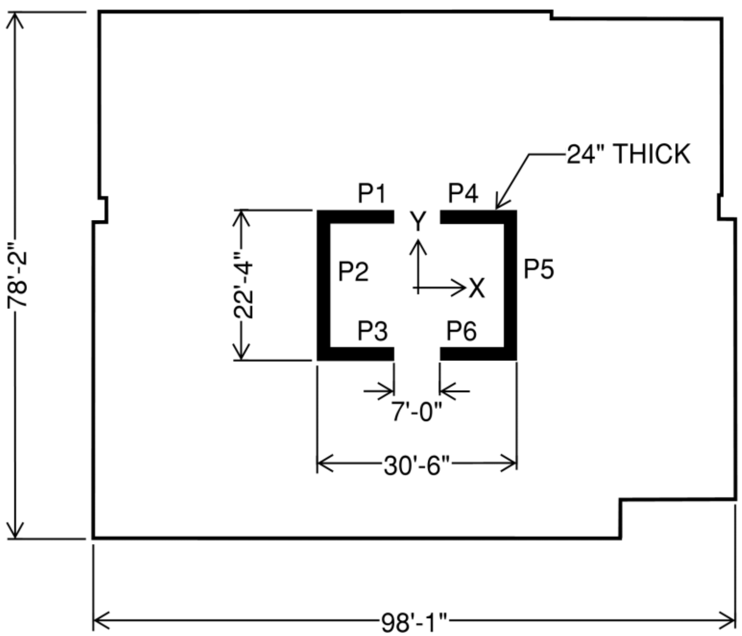
Introduction

- **Two concerns about this code change:**

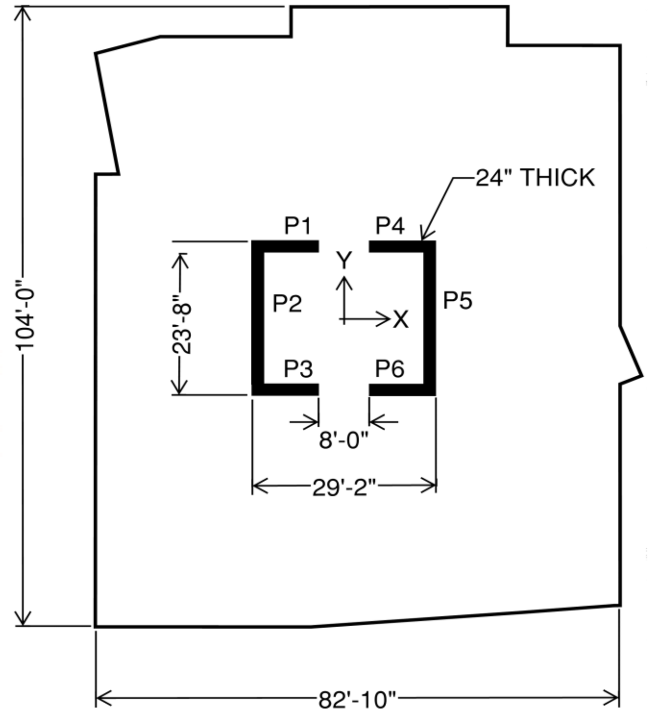
1) **Is the shear demand increase appropriate for buildings between 160' and 240'?** The shear demand increase is largely based on the observation of PBSD for buildings much taller than 240'. No specific study is done for buildings between 160' and 240'.

2) **How to determine the shear capacity using ACI 318 if the shear demand is increased by the over-strength factor, Ω_o?** In a PBSD, expected material properties, not nominal design properties, are used in analysis and design. Strength reduction factor **ϕ=1.0** is also used in a PBSD design at MCE level. What strength factor should be used in ACI 318 to check against the increased shear demand?

Building Design Information



Building-A



Building-B

Building Design Information

- **Two buildings are used in this study:**

1) **Building A**
   - **Building Height : 240'**
   - **Seismic Design Category: D**
   - **Cracked Properties: Walls 70%, Link beams: 15%-20%**
   - **Fundamental Period: 1.71 second (ELF) vs 3.54 second (MRS)**
   - **Base Shear Scaling: up to 85% per ELF procedure**
   - **Total Base Shear: 5.1% of building weight**
   - **Design Concrete Strength: 8,000 psi**
   - **Shear Strength Reduction Factor: ϕ = 0.75 (ACI 318)**
   - **Redundancy Factor: ρ = 1.3 is not applied**
   - **Shear Amplification: Ω_o = 2.5 is applied in both directions**

Building Design Information

- **Two buildings are used in this study:**

2) **Building B**

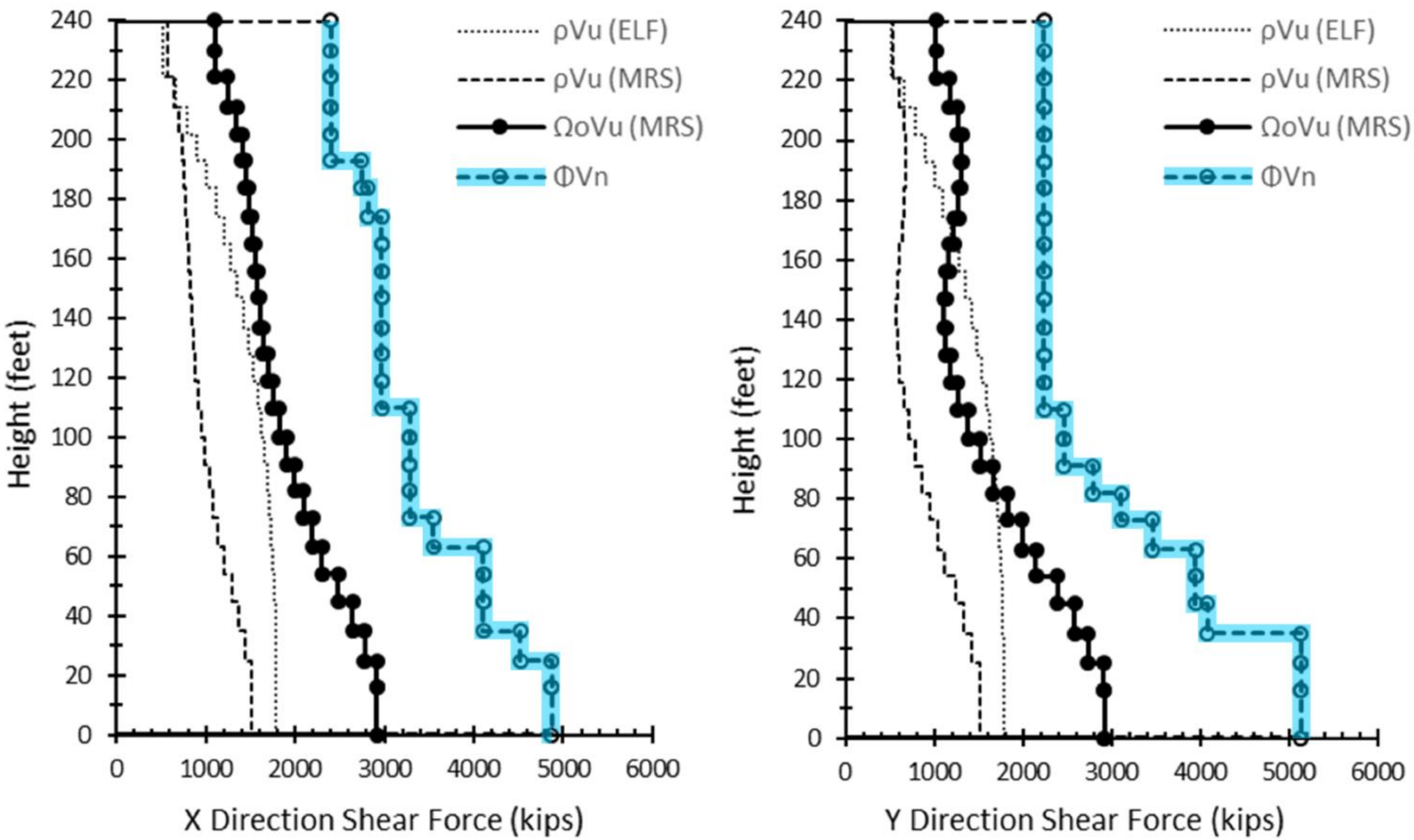
- **Building Height : 159'**
- **Seismic Design Category: D**
- **Cracked Properties: Walls 70%, Link beams: 15% - 20%**
- **Fundamental Period: 1.33 second (ELF) vs 2.11 second (MRS)**
- **Base Shear Scaling: up to 90% per ELF procedure**
- **Total Base Shear: 5.3% of building weight**
- **Design Concrete Strength: 7,000 psi**
- **Shear Strength Reduction Factor: $\phi = 0.6$ (ACI 318)**
- **Redundancy Factor: $\rho = 1.3$ is applied in both directions**
- **Shear Amplification: $\Omega_o = 2.5$ is not applied**

Building Design Information

Building Period and Design Base Shear

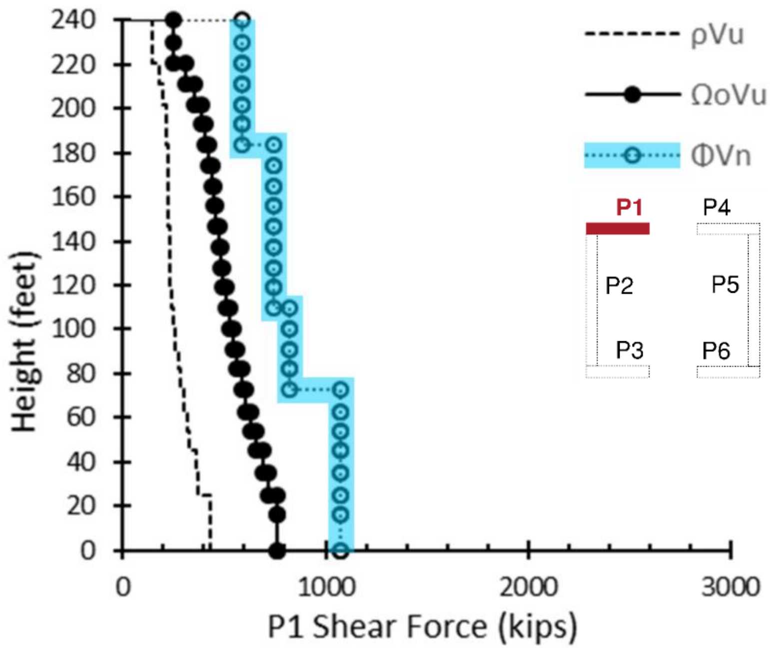
Building	Direction	Aspect Ratio H/L	Period ELF (CuTa) Seconds	Period MRS Seconds	Base Shear ρVu (ELF) Kips	Base Shear ρVu (MRS) Kips	Base Shear ΩoVu (MRS) Kips
A	X	7.9	1.71	3.29	1785	1516	2915
	Y	10.8	1.71	3.54	1785	1516	2915
B	X	5.6	1.33	2.11	1518	1290	2481
	Y	6.3	1.33	1.38	1518	1290	2481

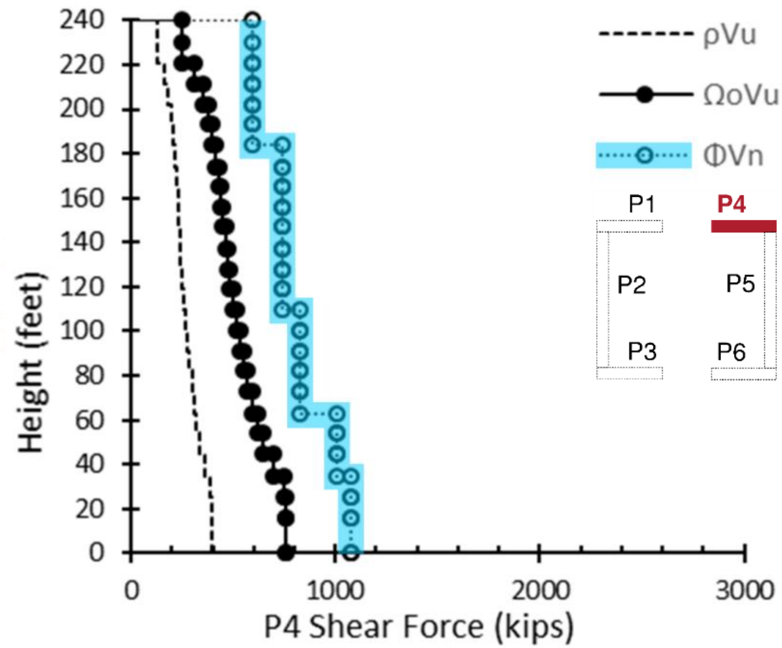
Building Design Information



Building-A Story shear demand and capacity (elastic analysis at DE level)

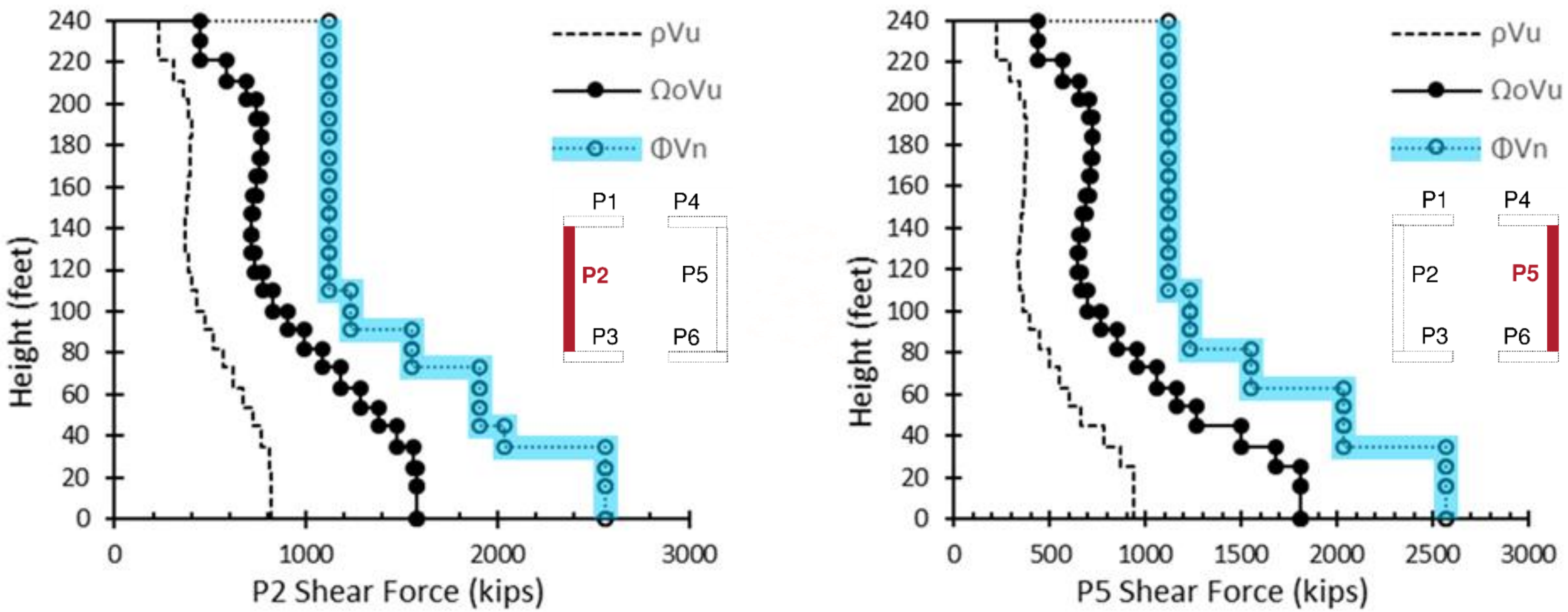
Building Design Information





Building-A Wall pier shear demand and capacity (Code design at DE level)

Building Design Information



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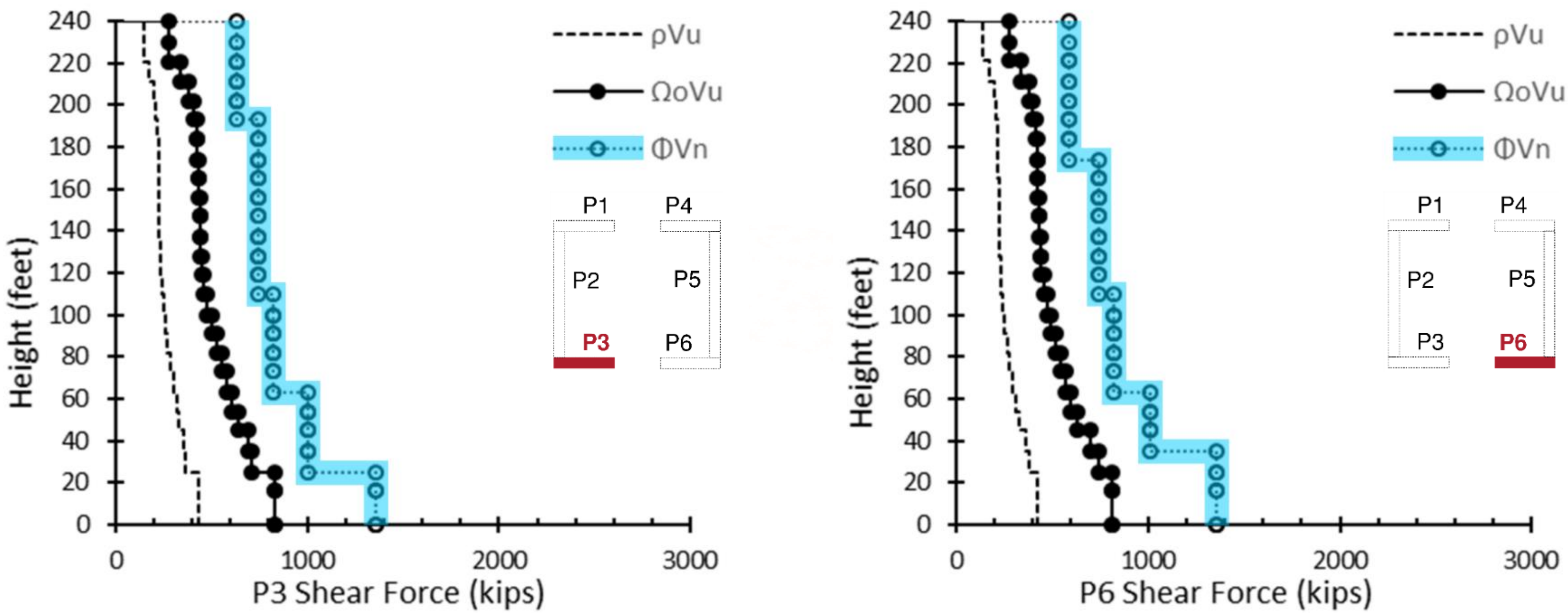

Building-A Wall pier shear demand and capacity (Code design at DE level)

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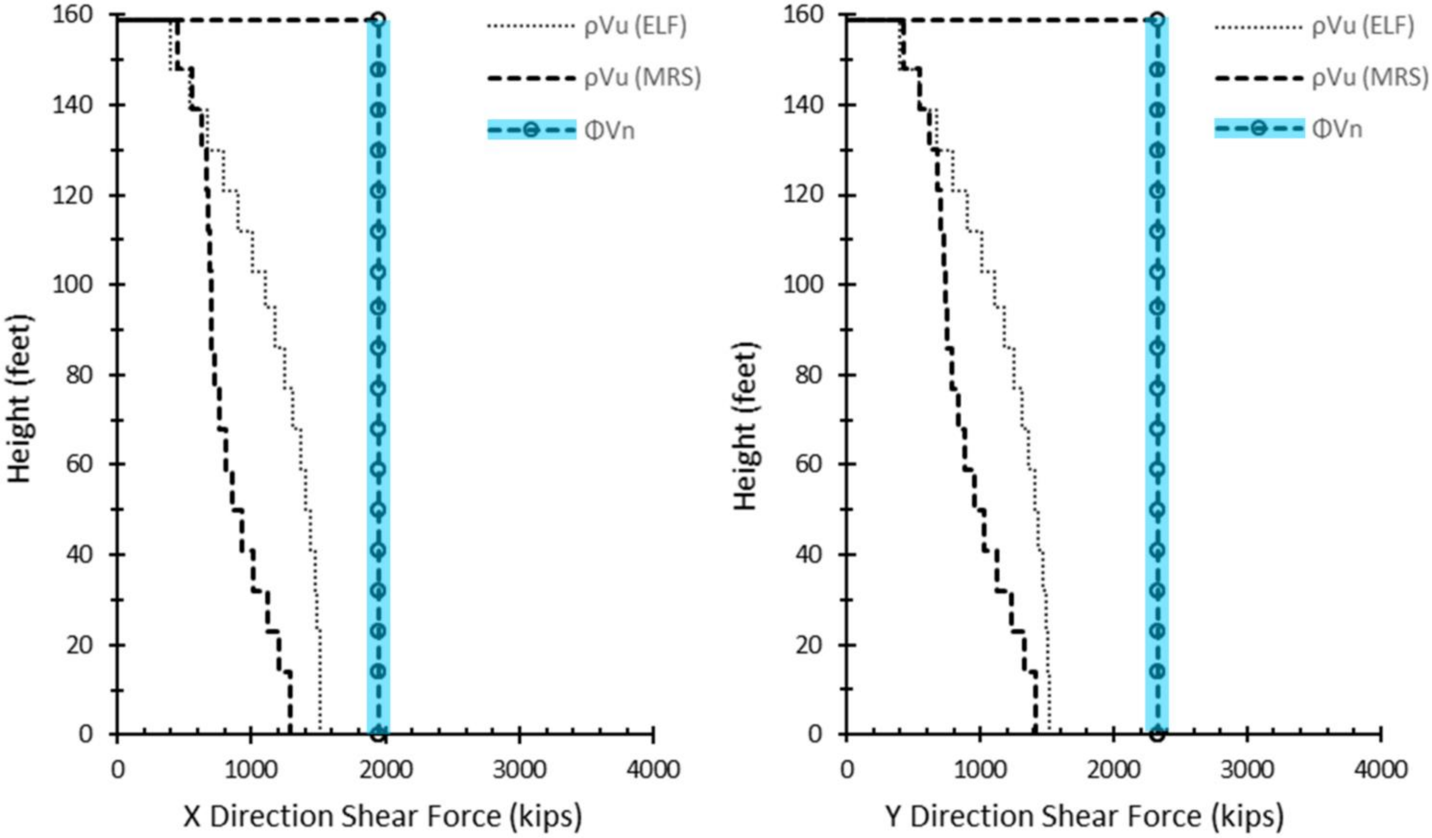
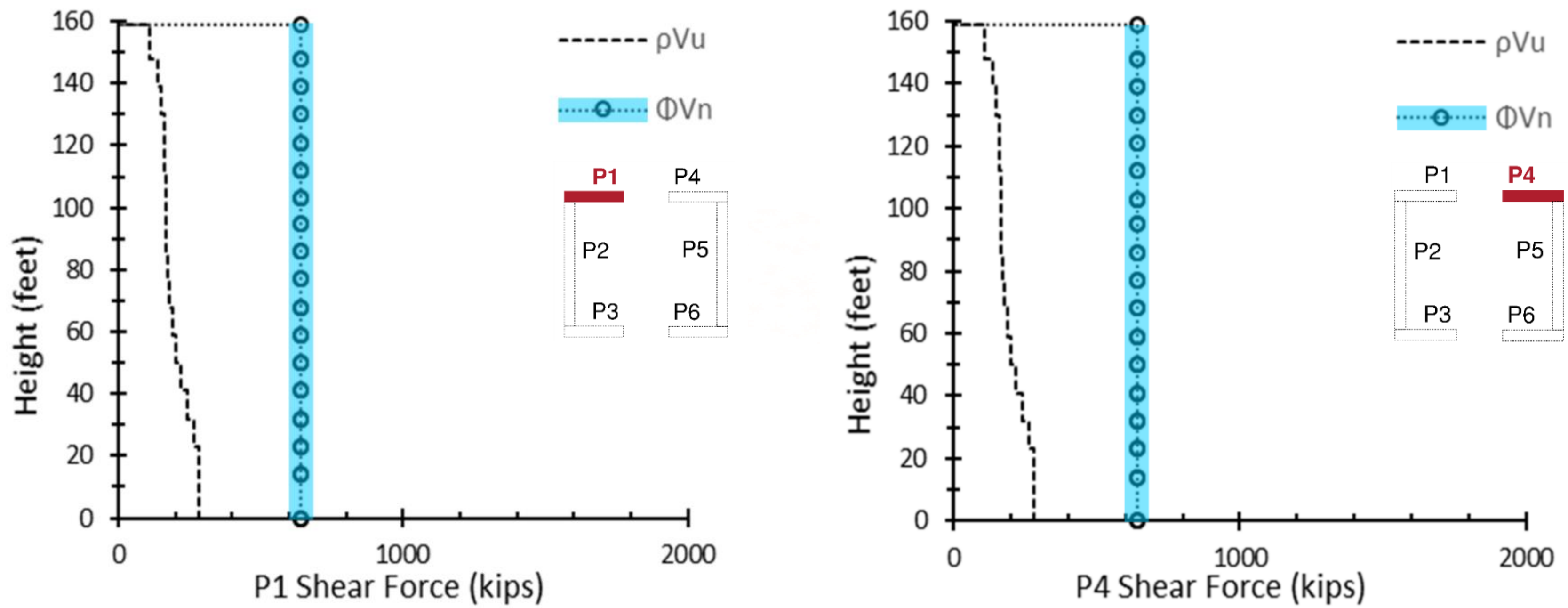


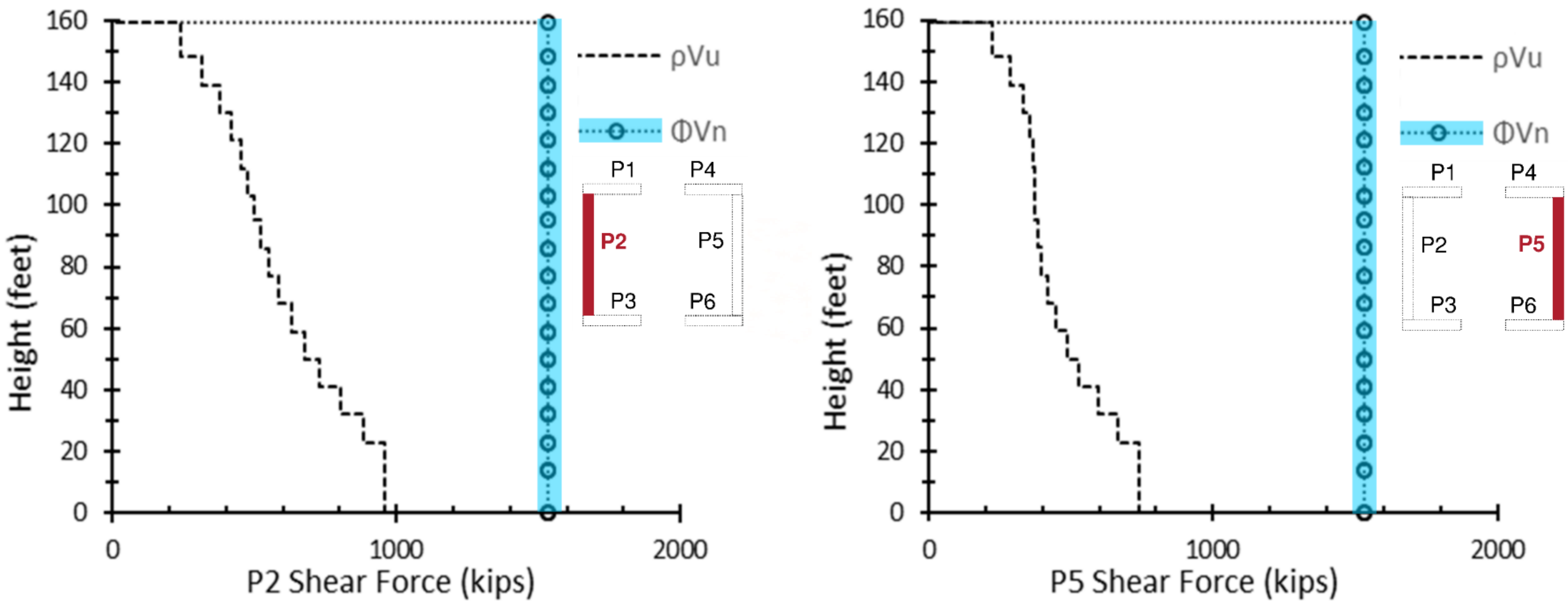
Building-B Story shear demand and capacity (elastic analysis at DE level)

Nonlinear Time History Analysis



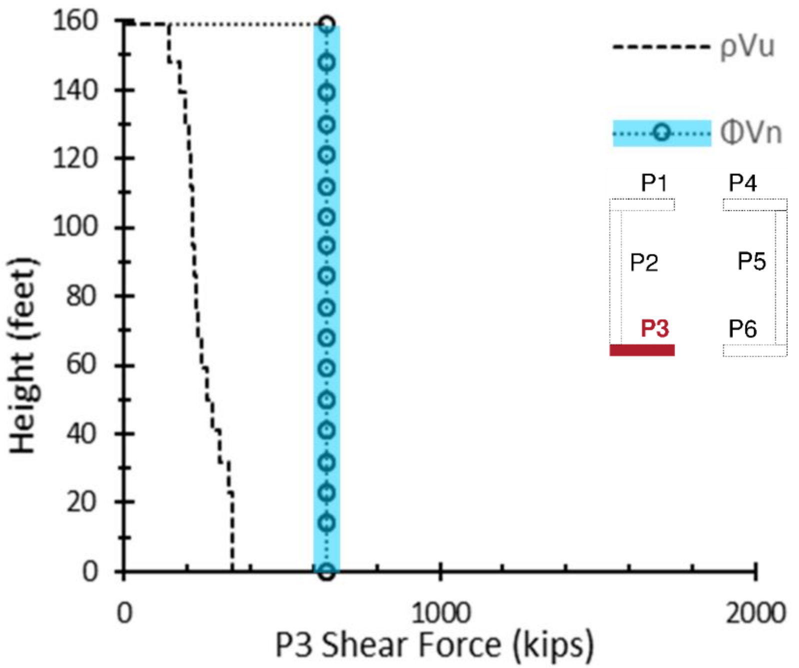
Building-B Wall pier shear demand and capacity

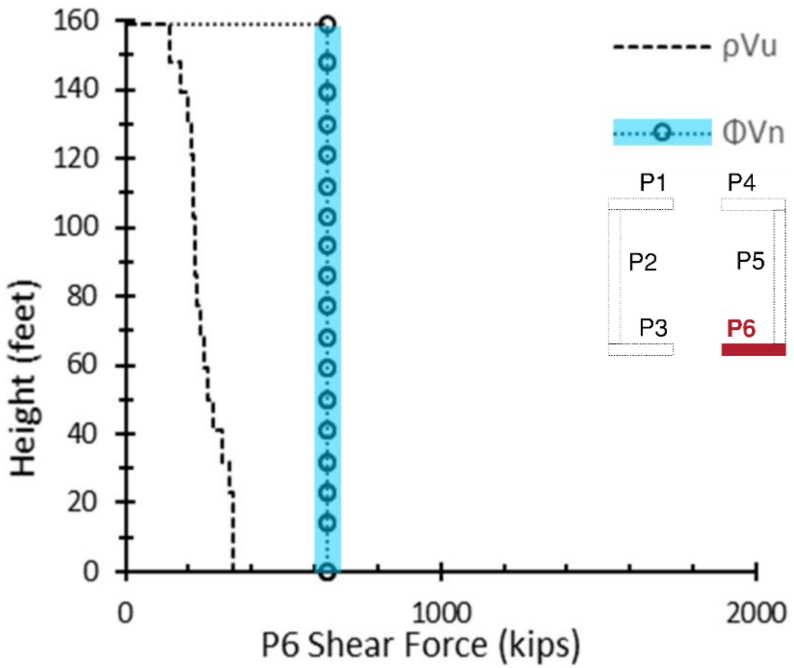
Nonlinear Time History Analysis



Building-B Wall pier shear demand and capacity

Nonlinear Time History Analysis





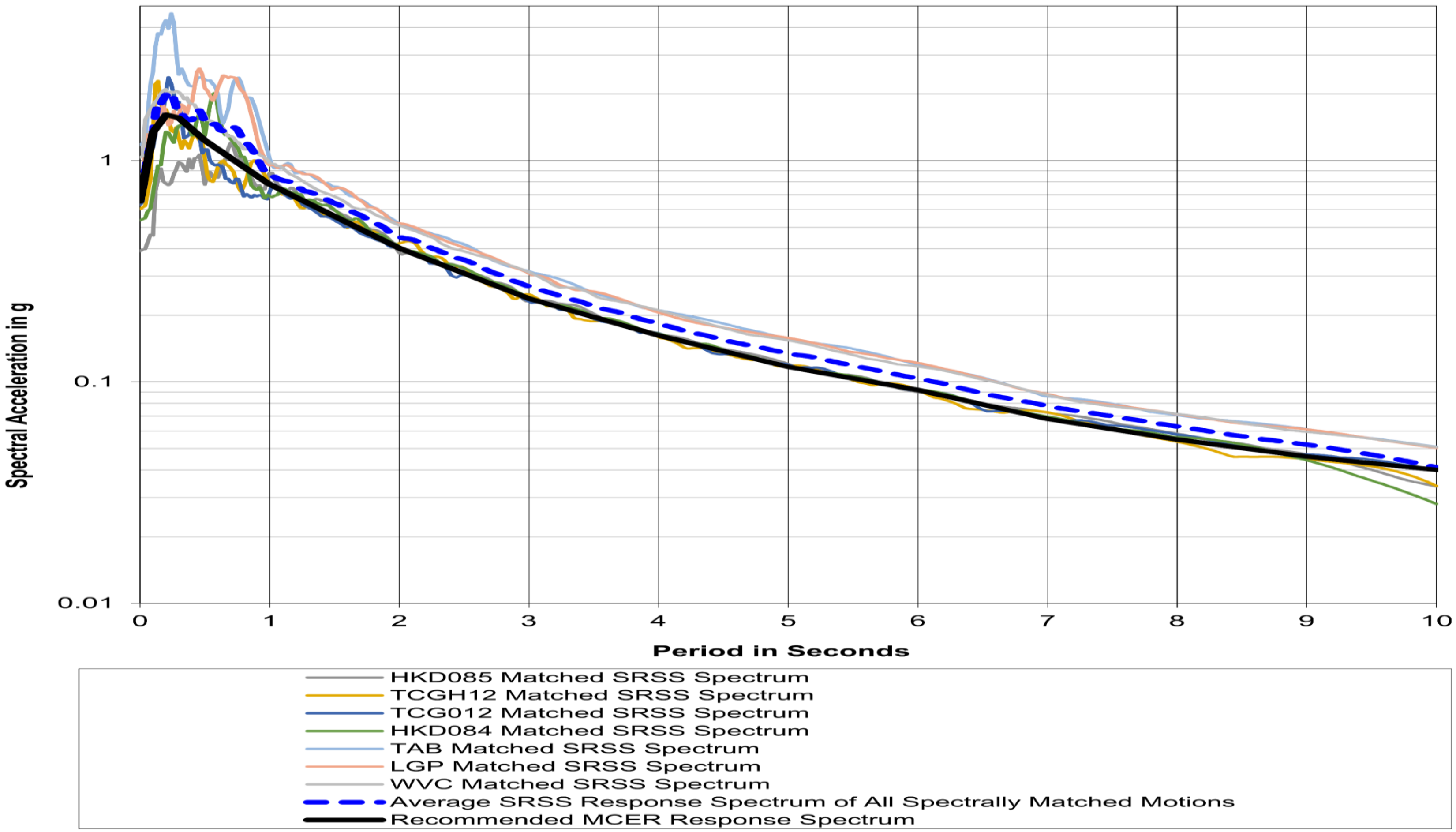
Building-B Wall pier shear demand and capacity

Ground Motion for NLTH Analysis

Seven Ground Motion Pairs Selected for the Study

HC Record ID	Earthquake	Recording Station	Magnitude	Closest Distance[a] in km	Vs30 in m/s	Max. Useable Period[b,c]	Fault Mechanism	Component 1	Component 2	Network (Reference Source)
1	2003 Tokachi-Oki	HKD084 - Akan	8.3	**146.8**	431	10	Interface Subduction	HKD084-EW	HKD084-NS	K-Net (COSMOS)
2	2003 Tokachi-Oki	HKD085 - Shiranuka	8.3	**130.3**	150	10	Interface Subduction	HKD085-EW	HKD085-NS	K-Net (COSMOS)
3	2011 Tohoku	TCG012 - Oyama	9.0	119.4	366	10	Interface Subduction	TCG012-EW	TCG012-NS	K-Net
4	2011 Tohoku	TCGH12 - Ujie	9.0	103.8	468	10	Interface Subduction	TCGH12-EW	TCGH12-NS	Kik-Net
5	1989 Loma Prieta	LGPC	6.93	3.9	478	8	Crustal - Reverse-Oblique	LGP-FN	LGP-FP	PEER
6	1989 Loma Prieta	WVC - Saratoga - W Valley Coll.	6.93	9.3	348	8	Crustal - Reverse-Oblique	WVC-FN	WVC-FP	PEER
7	1978 Tabas, Iran	TAB - Tabas	7.35	2.05	766.8	16	Crustal - Reverse	TAB-FN	TAB-FP	PEER

Ground Motion for NLTH Analysis



Nonlinear Time History Analysis

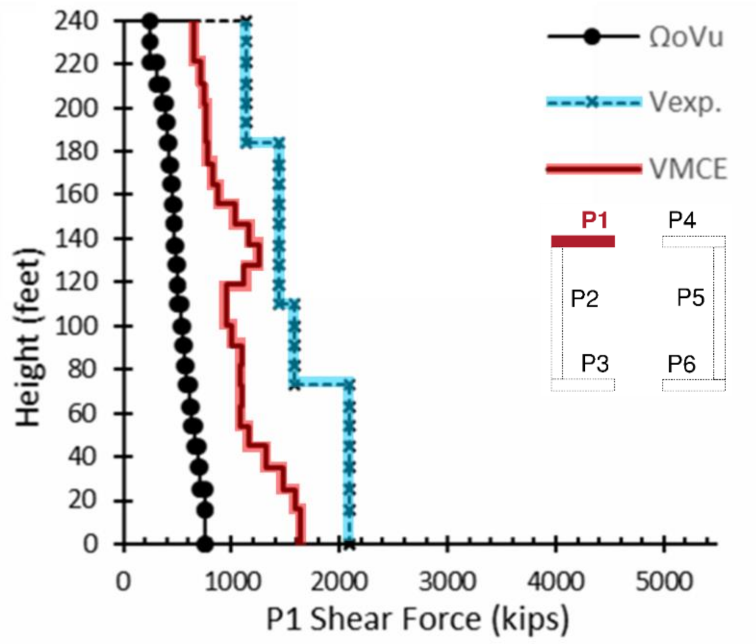
- **PERFORM-3D Modeling:**
  - **Nonlinear Elements: Core shear walls and link beams**
  - **Elastic Elements: Basement walls and diaphragms**
  - **Cracked Concrete Properties: Per ASCE 41**
  - **Damping: 2% Modal damping and 0.2% Rayleigh damping**
  - **P-Delta Effect: Included**

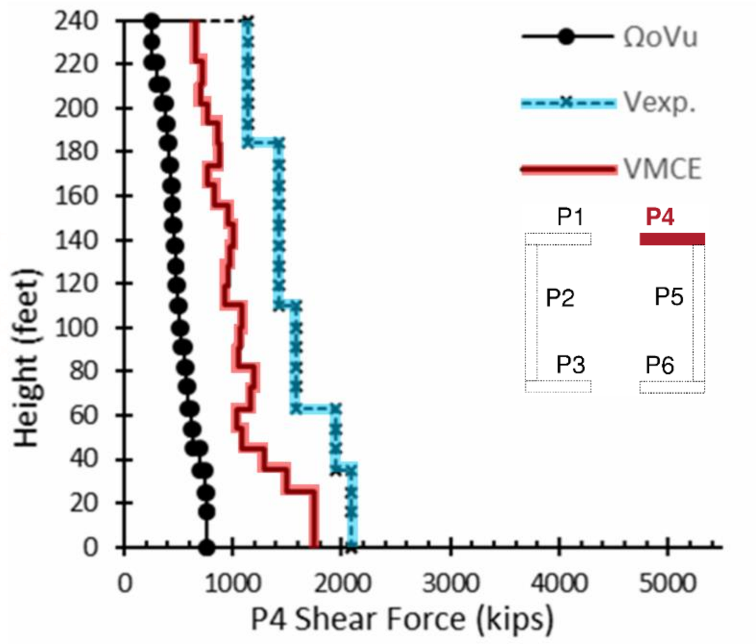
  - **Vmce – Maximum shear demand at a shear wall**
  - **- Based on upper bound models to capture the maximum shear demand in the core wall**
  - **- Used mean plus a standard deviation of the NLTH analysis results of the seven ground motions**

Nonlinear Time History Analysis

- **PERFORM-3D Modeling:**
  - **Vexp – Wall shear capacity using expected material properties**
  - **Expected Concrete Property: $f'c_{(EXP)} = 1.3f'c$**
  - **Expected Steel Property: $Fy_{(EXP)} = 1.17Fy$**
  - **Strength Reduction Factor: $\phi = 1.0$**

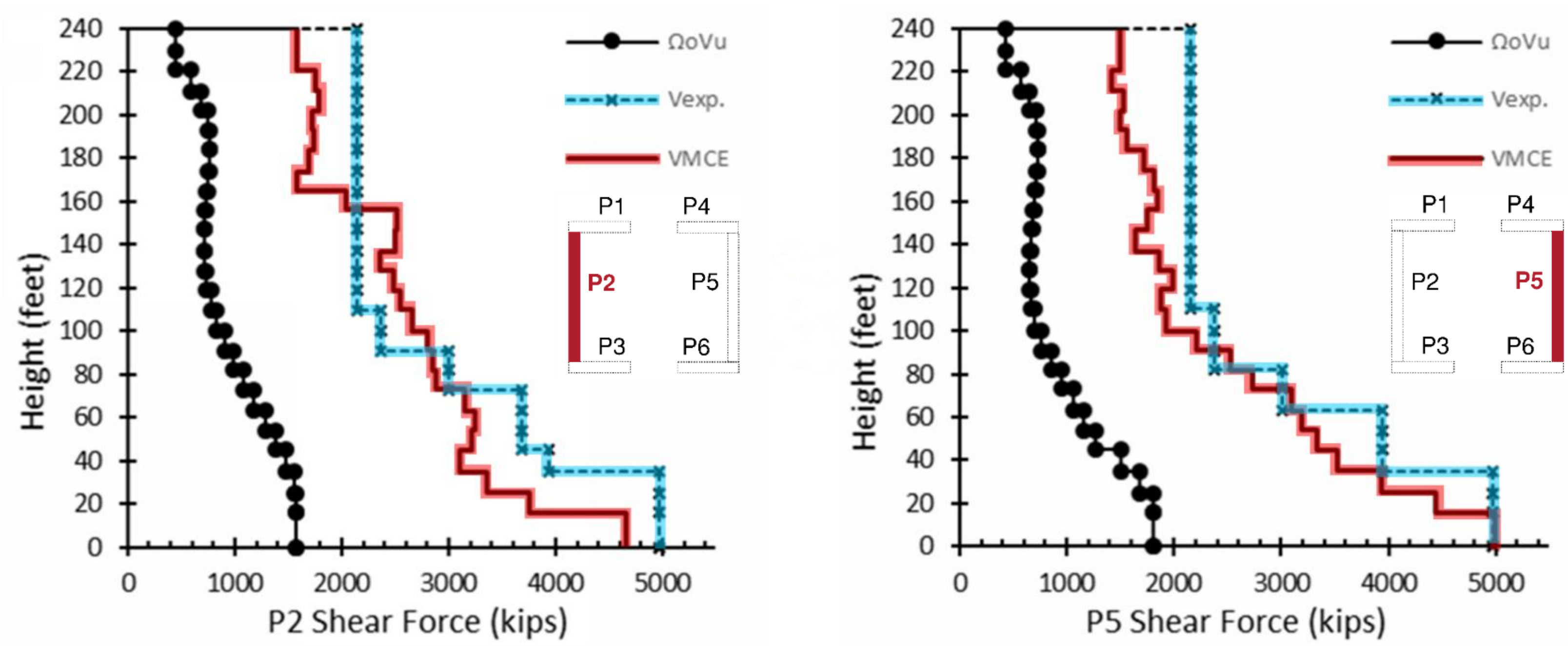
Nonlinear Time History Analysis





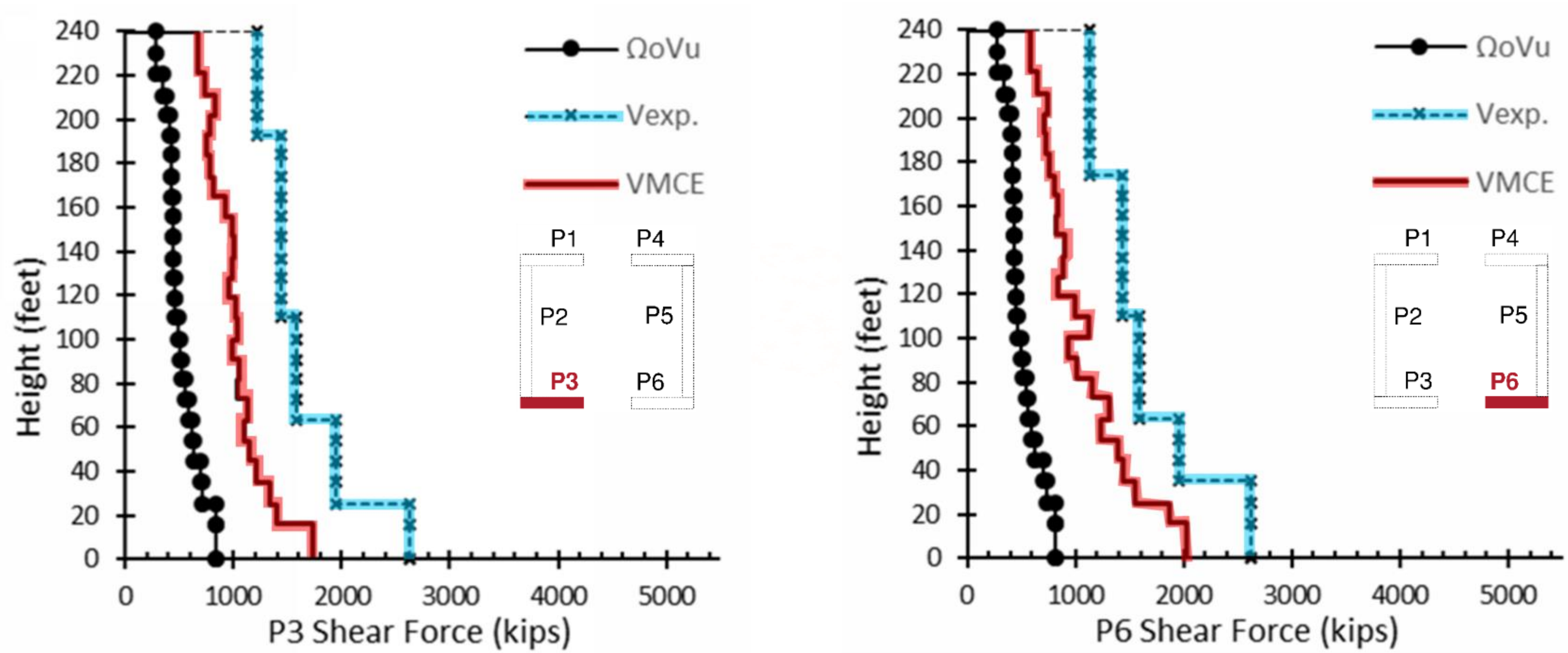
Building-A Wall pier shear demand and capacity

Nonlinear Time History Analysis



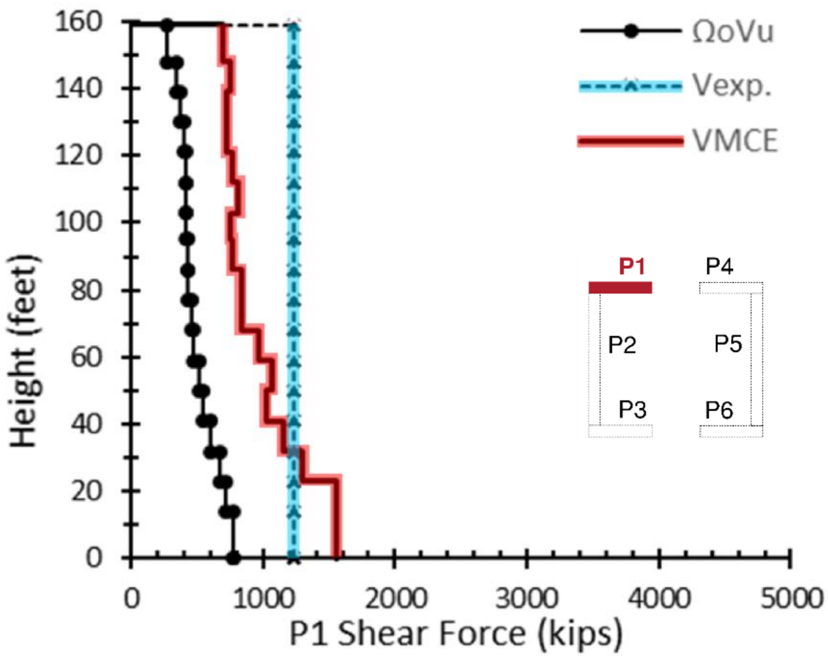
Building-A Wall pier shear demand and capacity

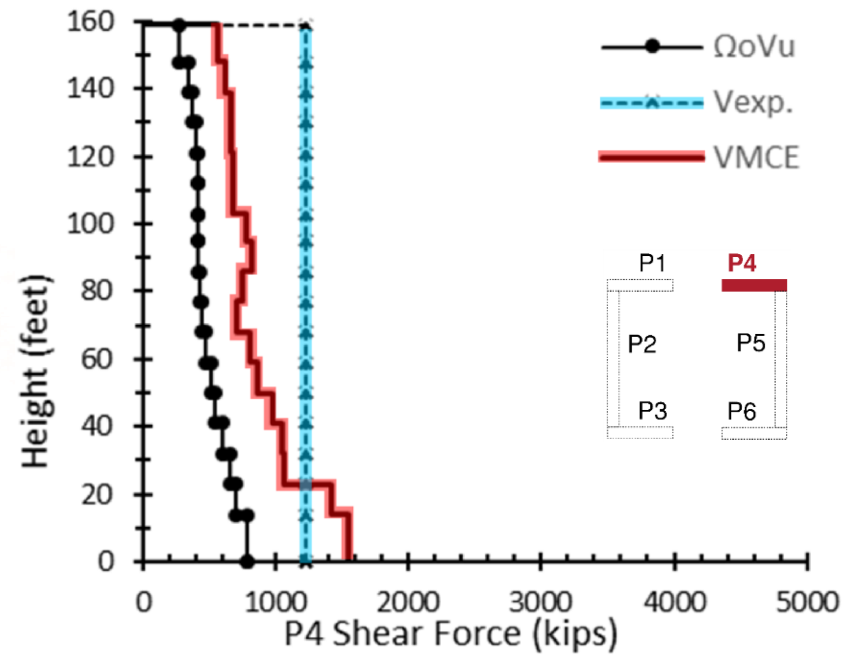
Nonlinear Time History Analysis



Building-A Wall pier shear demand and capacity

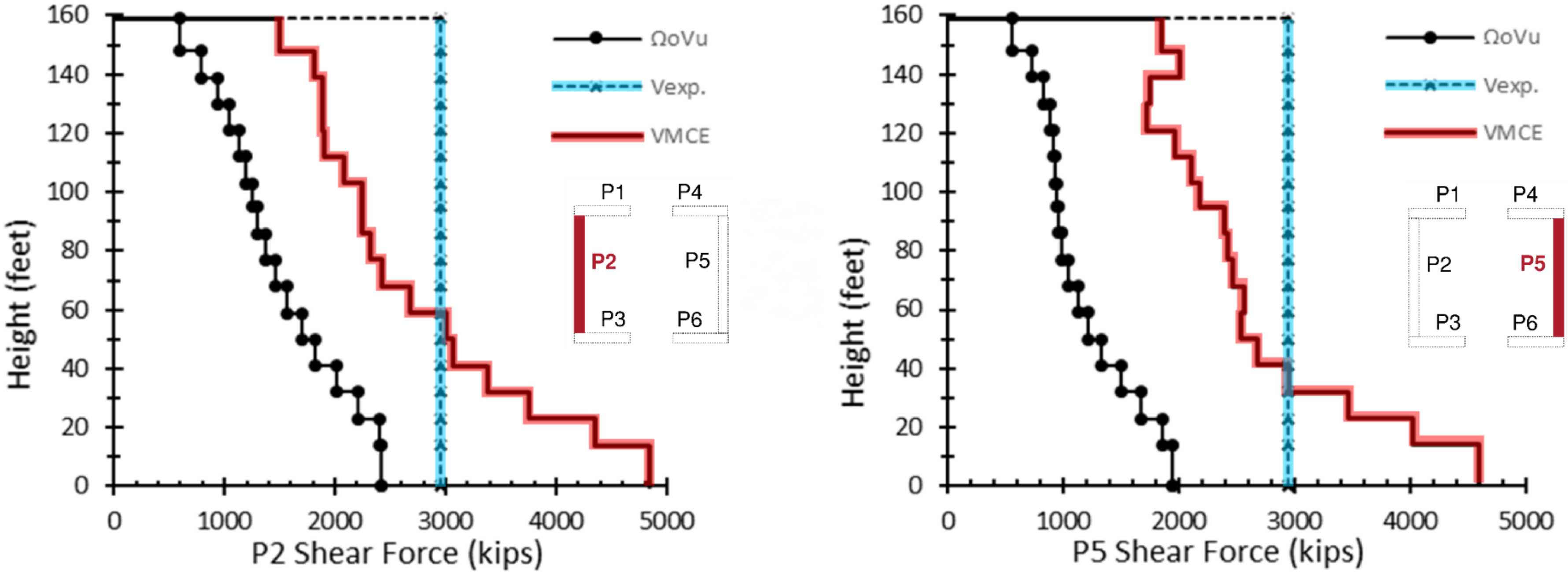
Nonlinear Time History Analysis





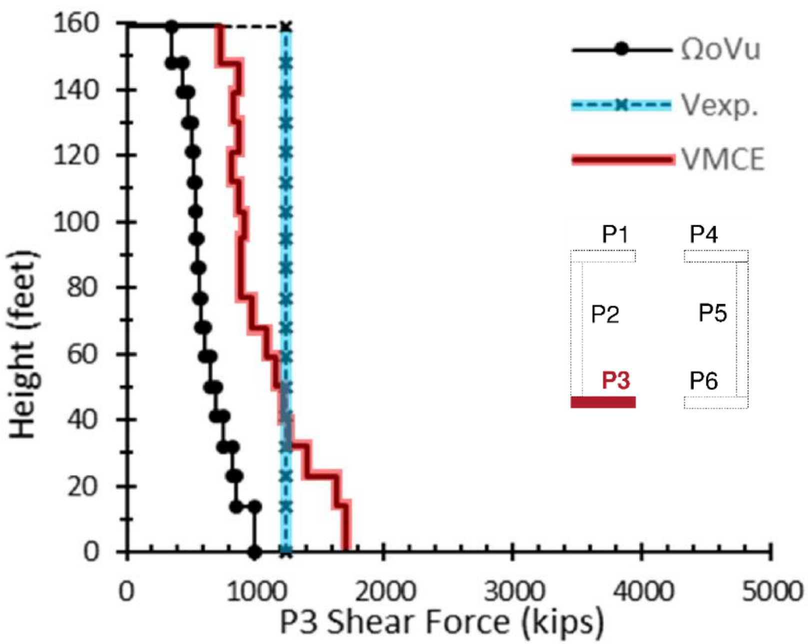
Building-B Wall pier shear demand and capacity

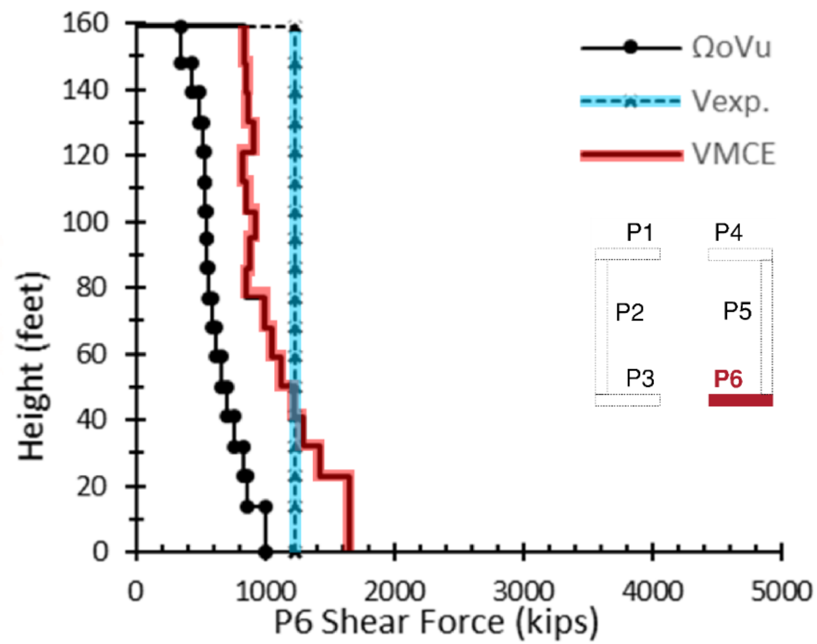
Nonlinear Time History Analysis



Building-B Wall pier shear demand and capacity

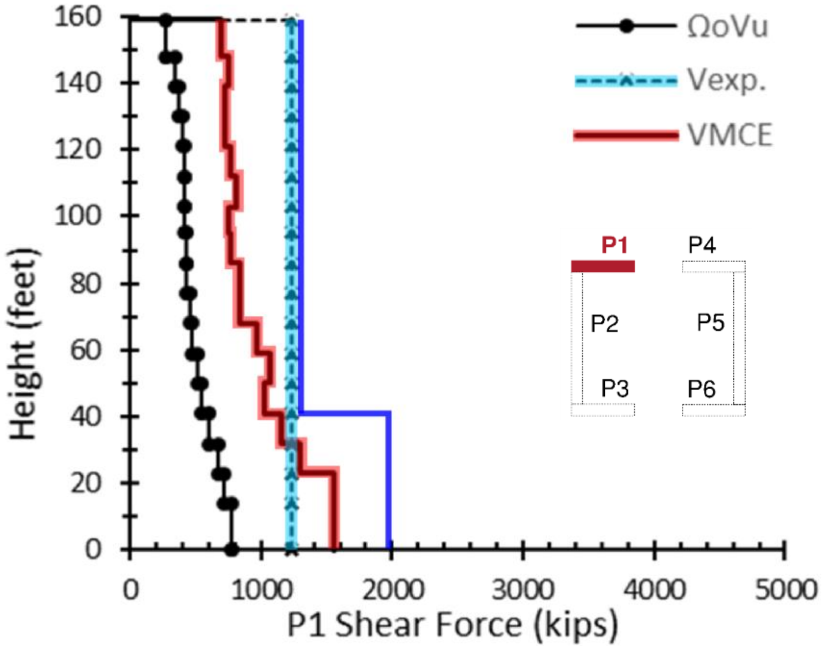
Nonlinear Time History Analysis

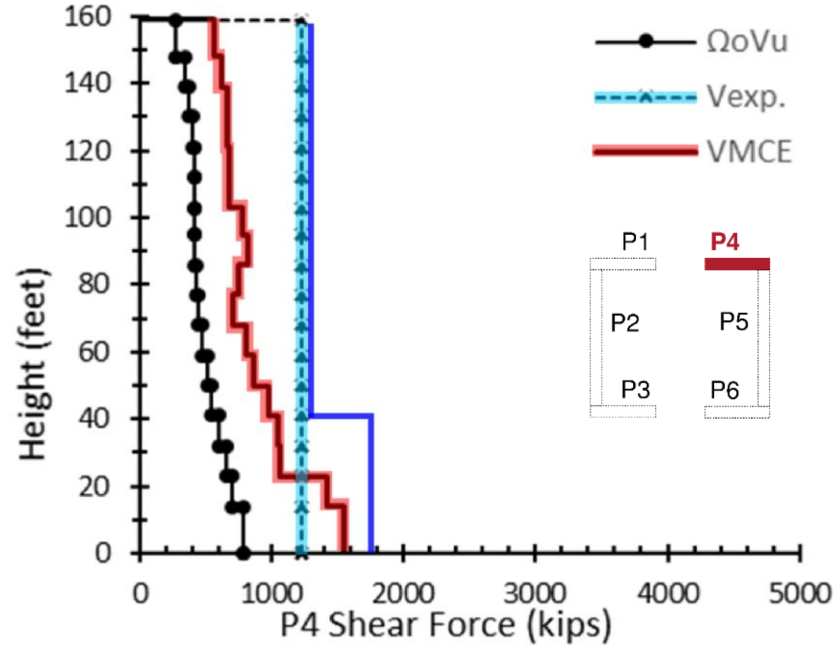




Building-B Wall pier shear demand and capacity

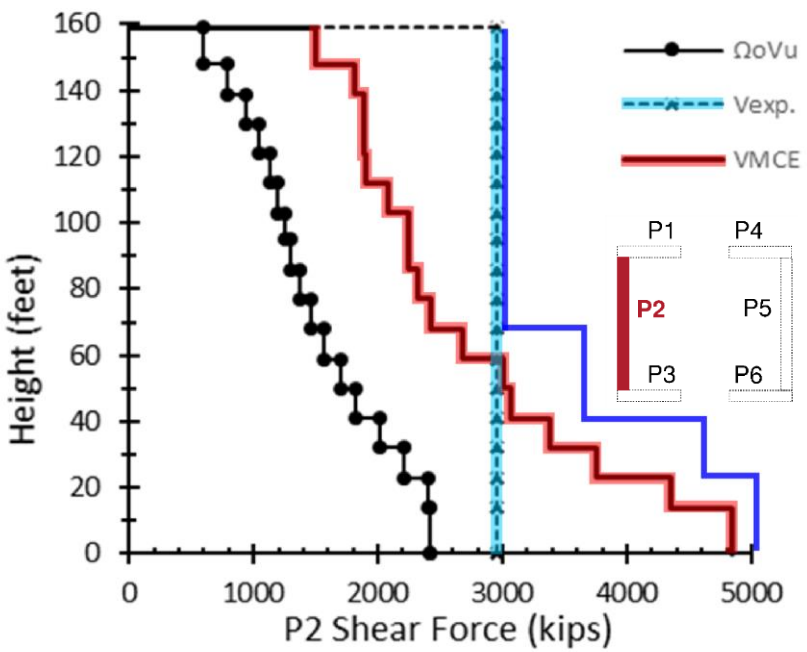
Nonlinear Time History Analysis

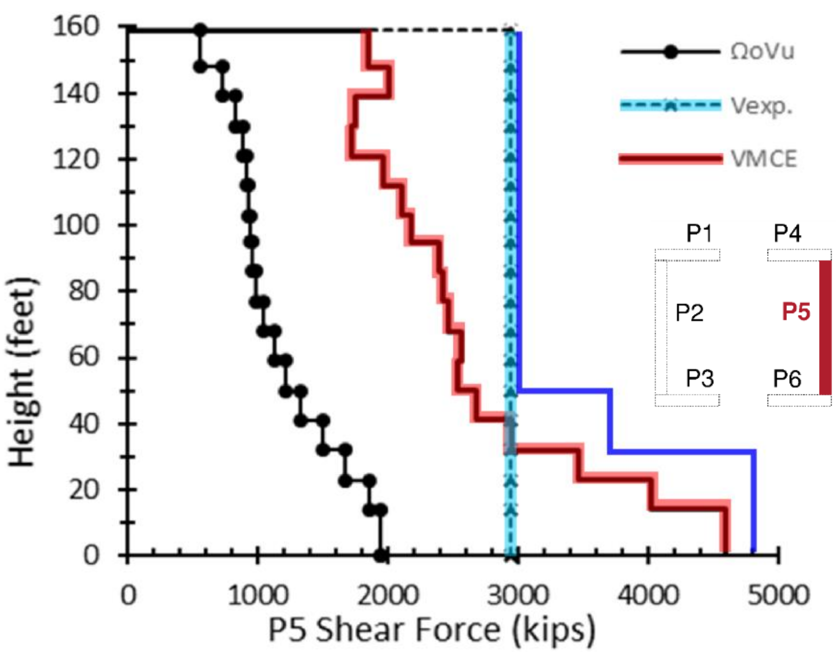




Building-B Wall pier shear demand and adjusted capacity

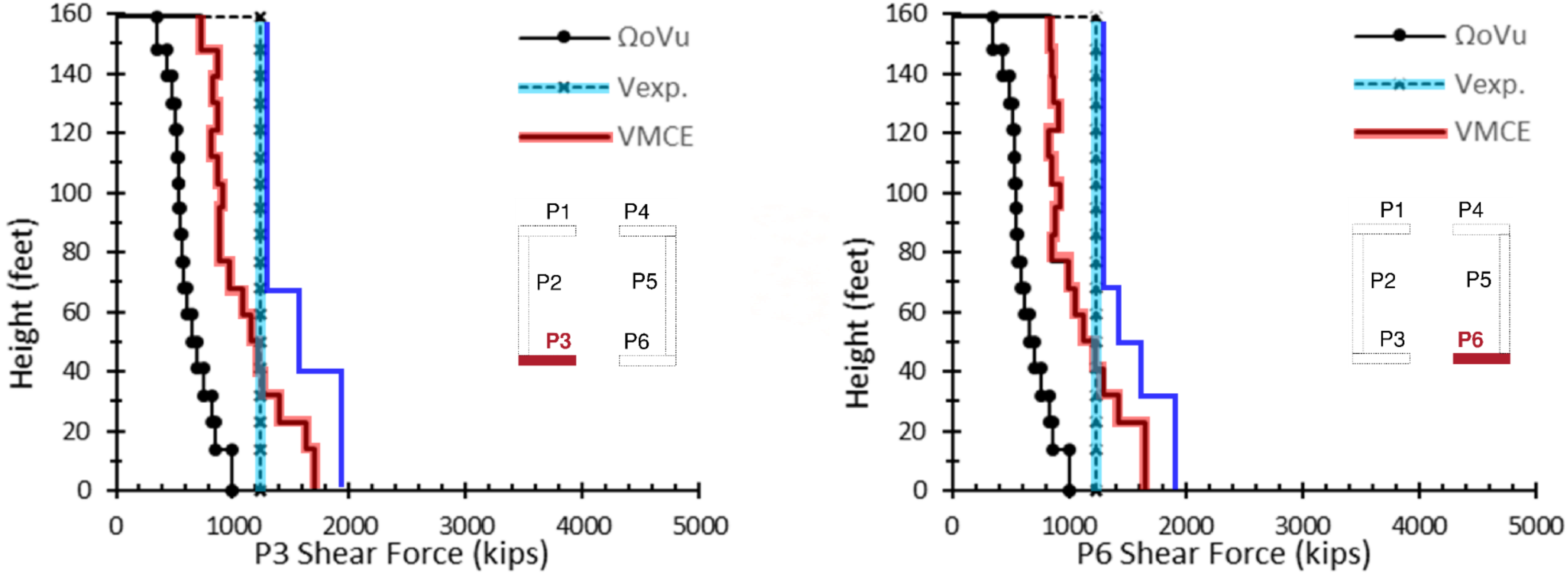
Nonlinear Time History Analysis





Building-B Wall pier shear demand and adjusted capacity

Nonlinear Time History Analysis



Building-B Wall pier shear demand and adjusted capacity

Observations and Discussions

- **NLTH analysis predicted a much higher shear demand than the design shear force per code.** The amplification factor can easily be 3 or more and is much greater than the difference between MCE (1.5 DE) and DE.

- **Using Ω_o =2.5 to estimate the shear demand amplification is a reasonable lower bound design value.**

- **It is rational to set ρ =1.0 when Ω_o =2.5 is used for shear amplification.**

Observations and Discussions

- **It is appropriate to use ϕ = 0.75 and nominal material properties per ACI 318 when checking against this amplified shear demand.**

- **NLTH analysis results indicate less shear amplification for coupled walls in comparison with non-coupled walls.**

- **Link beam inelastic energy dissipation may help to reduce the wall shear amplification. The ductile behavior of a coupled wall should be recognized in the future design code.**