Evaluation of Wall Anchorage Force Provisions in Rigid Wall – Flexible Diaphragm Buildings

Maria Koliou, Ph.D., E.I.T., Post-doctoral Researcher, University at Buffalo

John Lawson, S.E., Associate Professor, California Polytechnic State University-San Luis Obispo

Dominic J. Kelly, P.E.,S.E., Eng., Principal Simpson Gumpertz & Heger

Andre Filiatrault, Ph.D., Eng., Professor, University at Buffalo & University Institute of Advanced Studies, Pavia, Italy

Abstract

Heavy concrete and masonry walled buildings with lightweight steel or wood flexible roof diaphragms are a common type of construction in North America. Failures of the out-of-plane wall anchorage of these roof systems and the resulting partial roof collapses during past earthquakes have led to repeated revisions to the seismic design provisions in the United States. The force levels considered in the current design provisions have remained largely unchanged since their introduction in the 1997 Uniform Building Code. However these provisions have not been validated by strong ground motions in the field. Using a two dimensional numerical framework, a series of nonlinear time history analyses on various building archetypes were conducted to evaluate the validity of the current wall anchorage design force levels. The results of this study reveal that the current wall anchorage design forces are generally appropriate, but with some very significant exceptions.

Introduction

- Rigid Wall – Flexible Diaphragm (RWFD) structures are buildings framed with:
  - Exterior concrete (cast-in-place or precast) or masonry walls
  - Interior columns
  - Horizontal roof diaphragms (steel deck or wood structural panel)
- Rigid Wall – Flexible Diaphragm (RWFD) structures → **Structures with large footprint !!!**
- Applications:
  - Light industrial and low-rise commercial construction (i.e. warehouses, storage units & shopping complexes)

Problem statement & Research objectives

- **Problem Statement**:
  - RWFD buildings during past earthquakes suffer from poor response of out-of-plane wall anchorage attaching the heavy walls to the lightweight roof diaphragms
  - Wall anchorage damage can be attributed to inadequate connection overstrength for forces generated from roof accelerations and excessive deformations of the wall anchor system
  - Post-earthquake investigations & research findings:
    - Rooftop accelerations → three to four times higher than the amplitude of the ground acceleration & insufficient overstrength or ductility was accounted for in the connection design
  - Current wall anchorage provisions (ASCE 7-10 & 2012 IBC) prescribe the maximum expected design forces without relying on the connector ductility
  - Design force levels and detailing requirements associated with the out-of-plane wall anchorage have not changed since they were first introduced into the 1997 Uniform Building Code (UBC) and have not been tested under a strong earthquake event
- **Research Objectives**:
  - Develop simplified numerical models of RWFD buildings with relatively good accuracy and efficient computational overhead
  - Evaluate the wall anchorage forces for a representative set of building archetypes located in high seismicity zones accounting for:
    - Wall anchorage force variation along the roof diaphragm span
    - Wall anchorage force variation for small and large RWFD buildings
  - Compare the variations on wall anchorage forces to current design provisions

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Evolution of wall anchorage requirements

- Design provisions for anchorage of heavy walls to flexible diaphragms evolved steadily over the last forty years → to address the reoccurring poor performance of these systems during significant earthquakes
- Trial & error attempts leading to ever higher design forces and detailing restrictions to prevent repeat failures
- Current design force levels (originally introduced almost 20-years ago): raise the design to maximum expected forces without a reliance on ductility
- This brute force approach was based on amplifications observed on only a handful of instrumented RWFD buildings
- Current ASCE 7-10 wall anchorage force formula (eq. 12.11-1)

$$F_p = 0.4 S_{DS} k_a I_e W_p \geq 0.2 k_a I_e W_p$$

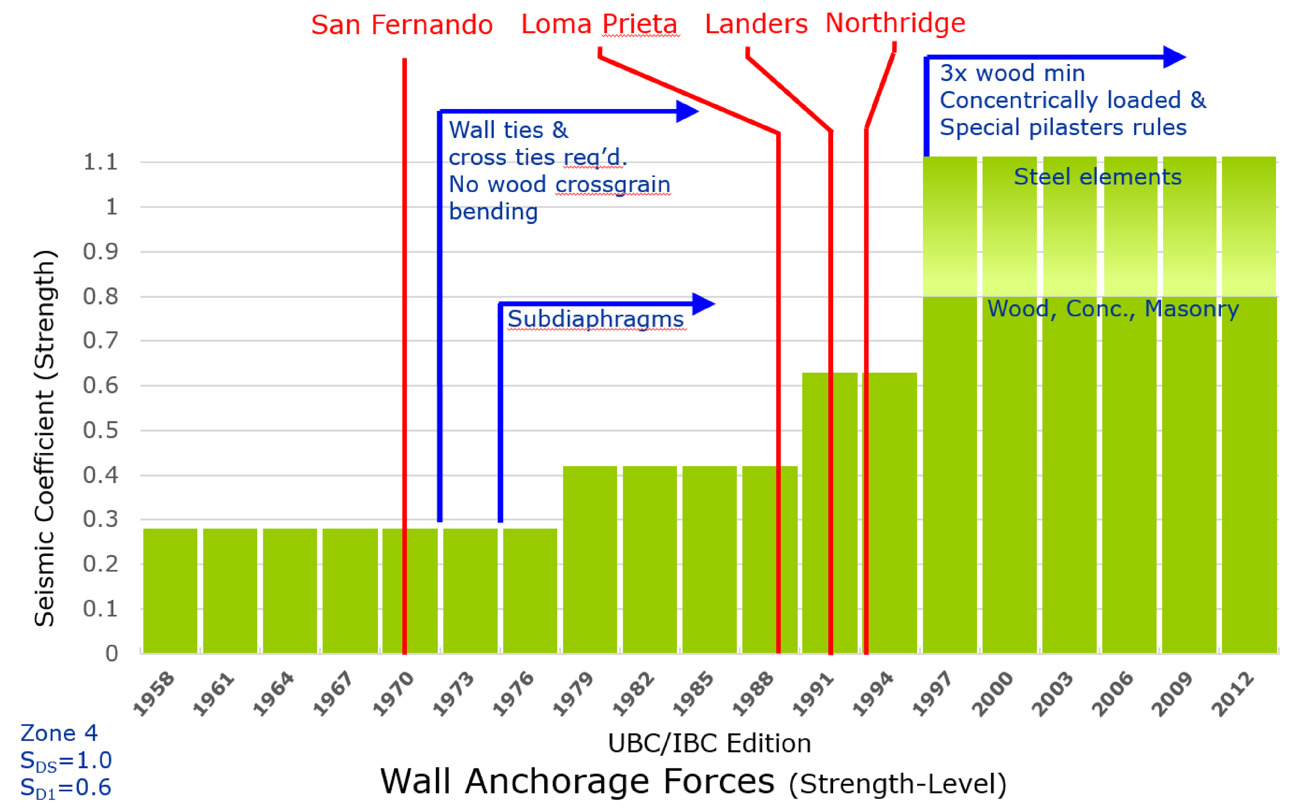
S_{DS} is the design spectral response acceleration parameter at short periods = 1.0g for this case study

I_e is the importance factor = 1.0 for this study

W_p is the weight of the wall tributary to the anchor

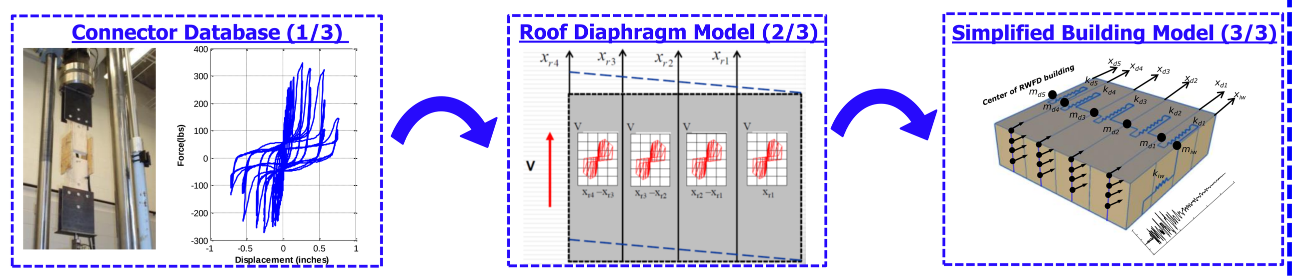
k_a is the amplification factor for diaphragm flexibility computed as $k_a = 1.0 + \frac{L_f}{100}$

L_f is the span of the flexible diaphragm that provides the lateral support for the wall in feet (200, 400 or 100 ft. in this study)



Numerical framework

- 2D numerical framework based on a three step sub-structuring approach:
  - **Step 1**: hysteretic response database for roof diaphragm connectors
  - **Step 2**: 2D inelastic diaphragm model incorporating local hysteretic connector responses
  - **Step 3**: 2D simplified building model incorporating global hysteretic diaphragm model responses

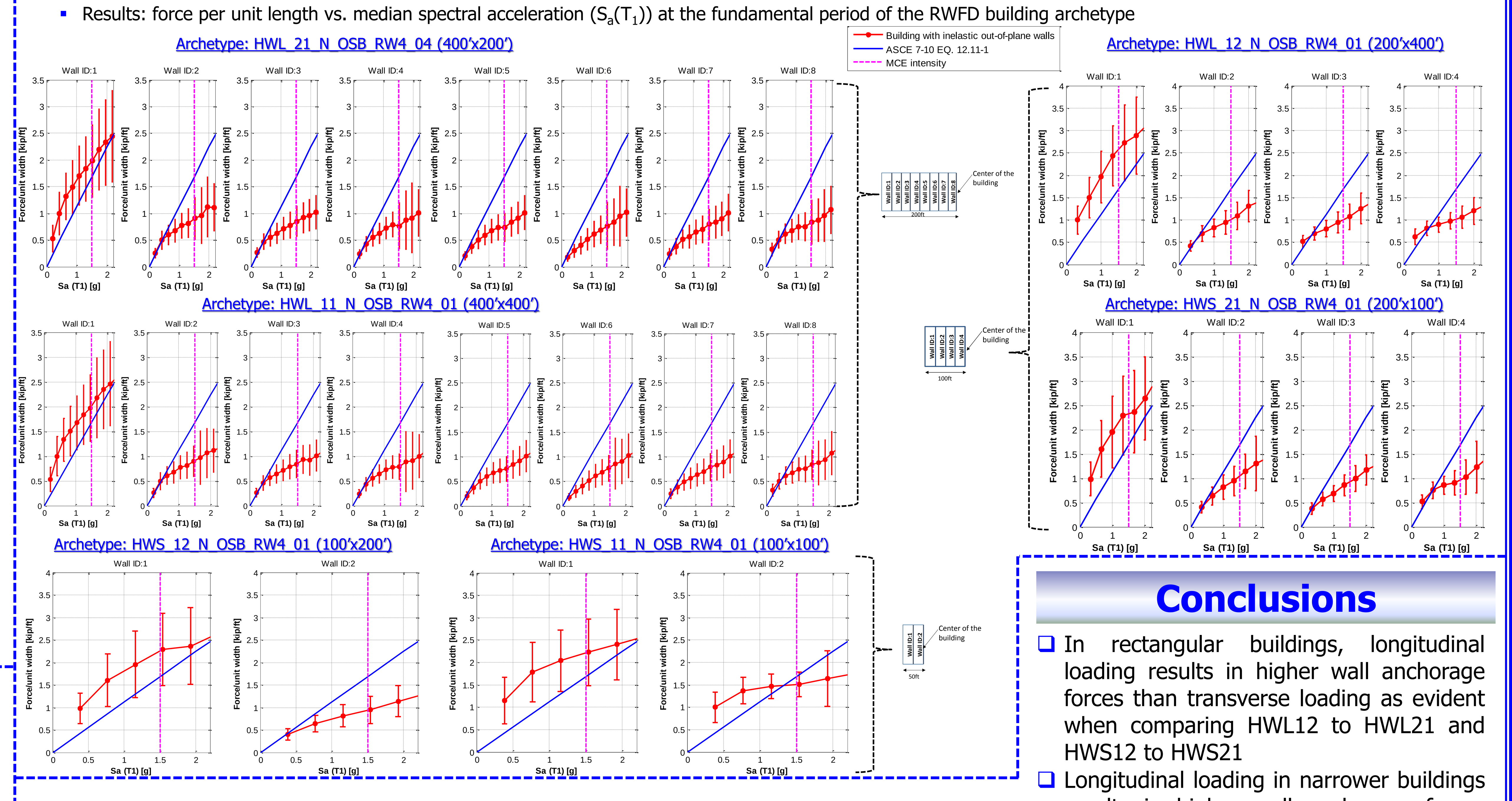


Building archetypes

- Single story concrete tilt-up buildings (located in SDC D_{max})
- **Use**: Warehouse or distribution center
- **Walls**: Precast concrete walls 30ft tall, 3ft tall parapet & 9.25in thick
- **Roof**: Panelized wood roof deck (Structural I OSB)
- **Vertical SFRS**: Intermediate precast concrete shear walls (R=4)
- **Design Code**: 2012 IBC, ASCE 7-10, ACI 318-11, 2008 NDS SDPWS
- **Fastener type**: 10d common nails
- **Plan configurations**:
  - ***Large*** RWFD buildings (400'x200', 200'x400' & 400'x400')
  - ***Small*** RWFD buildings (200'x100', 100'x200' & 100'x100')

Analysis results/findings

- Incremental dynamic analyses (IDA) conducted using the Far-Field FEMA P695 ground motion ensemble scaled for 20 different intensities
- *Median out-of-plane wall anchorage forces* taken across the ground motion ensemble several spectral acceleration intensities
  - Results: force per unit length vs. median spectral acceleration ($S_a(T_1)$) at the fundamental period of the RWFD building archetype



- There is no amplification observed in the wall anchorage forces at the center half of the diaphragm length, which further validates that provision's removal when the UBC transitioned from the 1994 to the 1997 edition
- The anchorage forces at the corner wall panels are higher than the ASCE 7-10 wall anchorage force levels for all building archetypes

Conclusions

- In rectangular buildings, longitudinal loading results in higher wall anchorage forces than transverse loading as evident when comparing HWL12 to HWL21 and HWS12 to HWS21
- Longitudinal loading in narrower buildings results in higher wall anchorage forces than in wider buildings as evident when comparing HWL11 to HWL12. This observation is in conflict with the intent of the k_a factor in ASCE 7-10 Sec. 12.11.2.1, and the factor should be removed