Precast Concrete Diaphragm Design – New Provisions

October 8, 2019

Blue Ridge Design, Inc.

ASCE 7-16 Seismic Design Methodology

- A new alternative design method is included in ASCE 7-16
- The method is optional for reinforced concrete, timber construction, and precast concrete in SDC B.
- The method is mandatory for precast concrete in SDC C, D, E an F.
- The method does not apply the steel deck

Current Precast Diaphragm Seismic Design

- ACI 318 11 and before
  - 21.11 Structural diaphragms and trusses
    - Structures assigned to SDC D, E & F
    - 21.11.4 Cast-in-place composite topping slab diaphragms
    - 21.11.5 Cast-in-place topping slab diaphragms (non-composite)

History of Precast Diaphragm Seismic Design

- ACI 318 14
  - Chapter 12 Diaphragms
    - (a) Diaphragms that are cast-in-place slabs
    - (b) Diaphragms that comprise a cast-in-place topping slab on precast elements
    - (c) Diaphragms that comprise precast elements with end strips formed by either a cast-in-place concrete topping slab or edge beams
    - (d) Diaphragms of interconnected precast elements without cast-in-place concrete topping
- No Seismic Provisions

Current Precast Diaphragm Seismic Design

- ACI 318 14
  - Section 18.12 Diaphragms and trusses
  - 18.12.4 Cast-in-place composite topping
  - 18.12.5 Cast-in-place non-composite topping slab diaphragms

Brief History

- 1994 Northridge Earthquake
  - Northridge Fashion Center

Brief History

- 1994 Northridge Earthquake
  - CSU Northridge

Brief History

- 1994 Northridge Earthquake
  - Kaiser Permanente Garage (CIP-PT)

Brief History

- ACI 318-99
  - 21.7.1 Structural diaphragms and trusses changed
  - 21.7.5.1 “Where welded wire fabric is used as the distributed reinforcement in topping slabs placed of precast floor and roof elements, the wires parallel to the span of the precast elements shall be spaced not less than 10 in. on center.”

Brief History

- PCI Diaphragm Seismic Design Methodology DSDM
  - 2003 to 2012
  - Lehigh University: connection qualification
  - UCSD: shake table testing
  - University of Arizona: analysis and lead

Shake Table Test

Seismic Design Methodology for Precast Concrete Floor Diaphragms

2012 PCI National Convention

PRECAST/PRESTRESSED CONCRETE INSTITUTE

Dr. Robert B. Fleischman
University of Arizona

The Charles Pankow Foundation

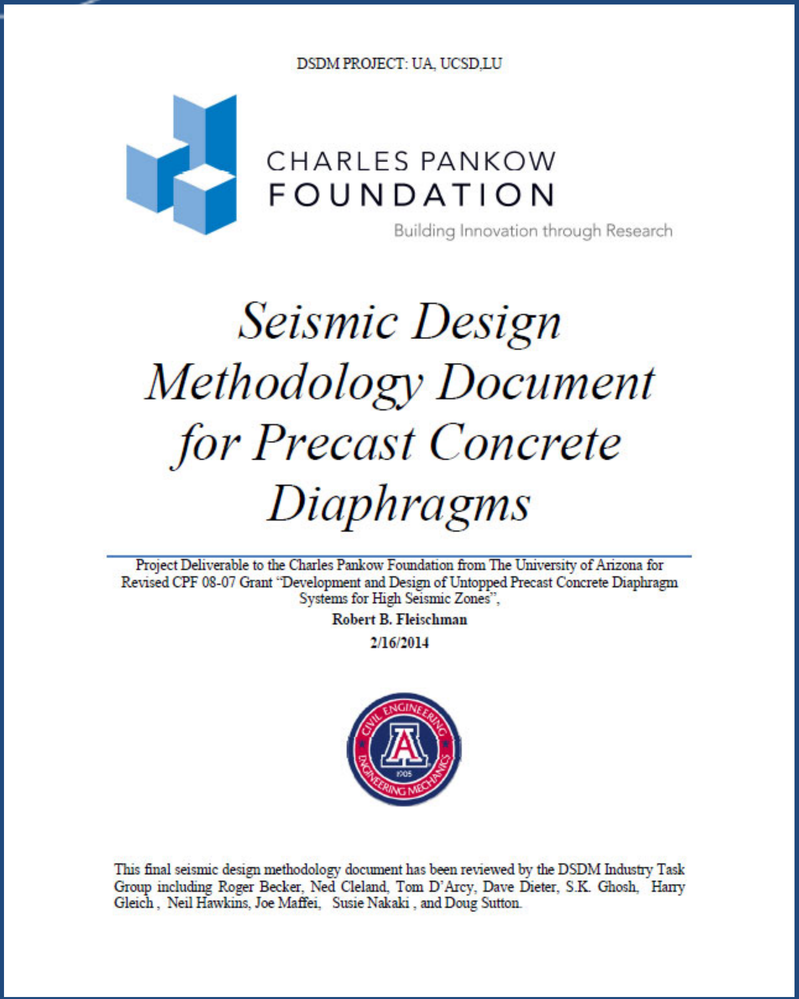
NEES

Brief History

- Building Seismic Safety Council (BSSC) Issue Team 6 on diaphragms formed in 2011
- Included <u>all</u> diaphragm materials
- Intent to write a Part 3 resource paper on diaphragm design
- Changed to include a Part 1 code change proposal

Brief History

- 2014 BSSC IT 6 completes report with code change proposal
- 2014 DSDM Report updated
- Code change submitted to ASCE 7


DSDM PROJECT: UA, UCSD,LU

CHARLES PANKOW FOUNDATION
Building Innovation through Research

Seismic Design Methodology Document for Precast Concrete Diaphragms

Project Deliverable to the Charles Pankow Foundation from The University of Arizona for Revised CPF 08-07 Grant “Development and Design of Untopped Precast Concrete Diaphragm Systems for High Seismic Zones”,

Robert B. Fleischman

2/16/2014

This final seismic design methodology document has been reviewed by the DSDM Industry Task Group including Roger Becker, Ned Cleland, Tom D’Arcy, Dave Dieter, S.K. Ghosh, Harry Gleich , Neil Hawkins, Joe Maffei, Susie Nakaki , and Doug Sutton.

Brief History

- Code change adopted into ASCE 7 as voluntary option for cast-in-place concrete, non-composite topping on precast, and wood.
- Alternative is mandatory for precast concrete diaphragms in SDC C, D, E, and F
- ASCE 7 adopted by reference into IBC 2018

ASCE 7-16

- Chapter 12
  - 12.10.3 alternative Design Provisions fro Diaphragms Including Chords and Collectors: Adopted into IBC 2018
- Chapter 14
  - 14.2.4 Additional Design and Detailing Requirements for Precast concrete Diaphragms: Not Adopted into Sec. 1905

ACI 318 -19

- 18.12.1.2 for precast diaphragms
- 18.12.11 Precast concrete diaphragms
  - ACI 550.5-18: Code Requirements for the Design of Precast Concrete Diaphragms for Earthquake Motions
  - ACI 550.4-18: Qualification of Precast Prestressed Concrete Diaphragm Connector and Reinforcement at Joints for Earthquake Loading

Global (ASCE 7) Issues

Diaphragms, Chords, and Collectors

12.10.1.1 Diaphragm Design Forces. Floor and roof diaphragms shall be designed to resist design seismic forces from the structural analysis, but not less than the following forces:

$$0.2S_{DS}Iw_{px} \le F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px} \le 0.4S_{DS}Iw_{px}$$

Where

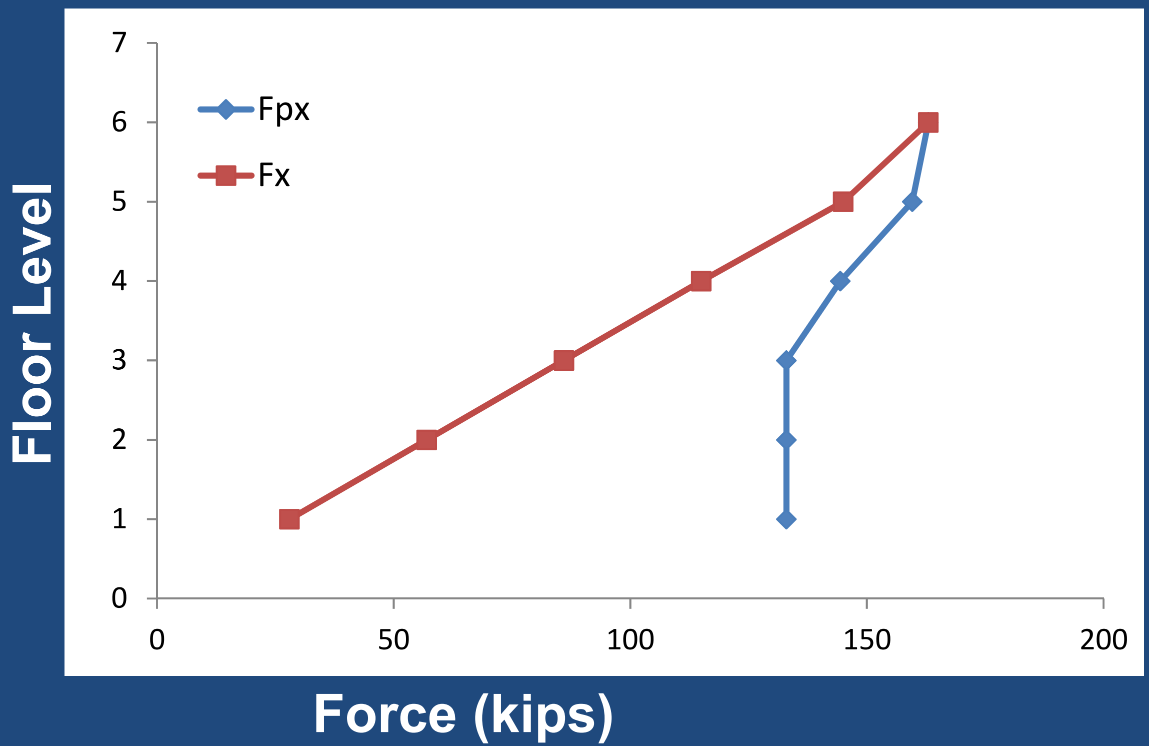
F_{px} = the diaphragm design force

F_i = the design force applied to Level i

w_i = the weight tributary to Level i

w_{px} = the weight tributary to the diaphragm at Level x

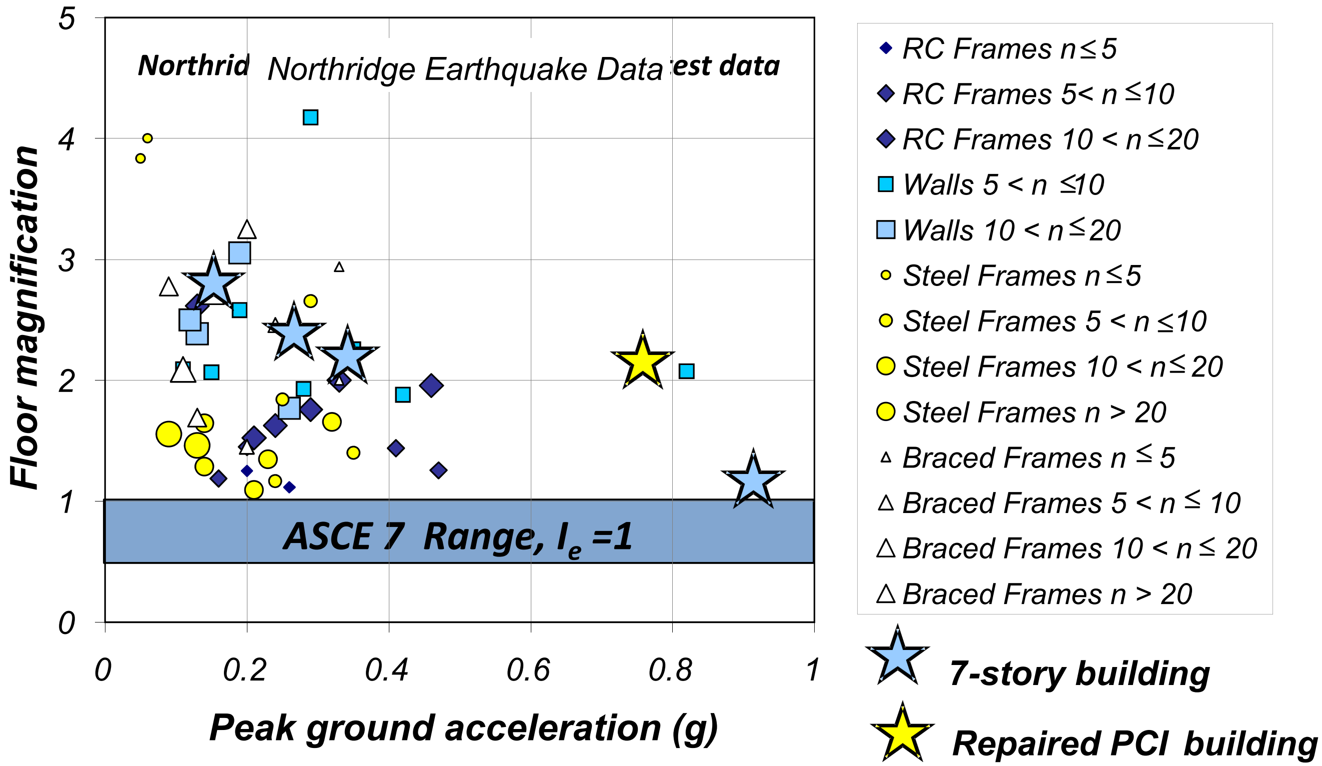
Diaphragm Design Forces



Floor Accelerations for Diaphragm Design

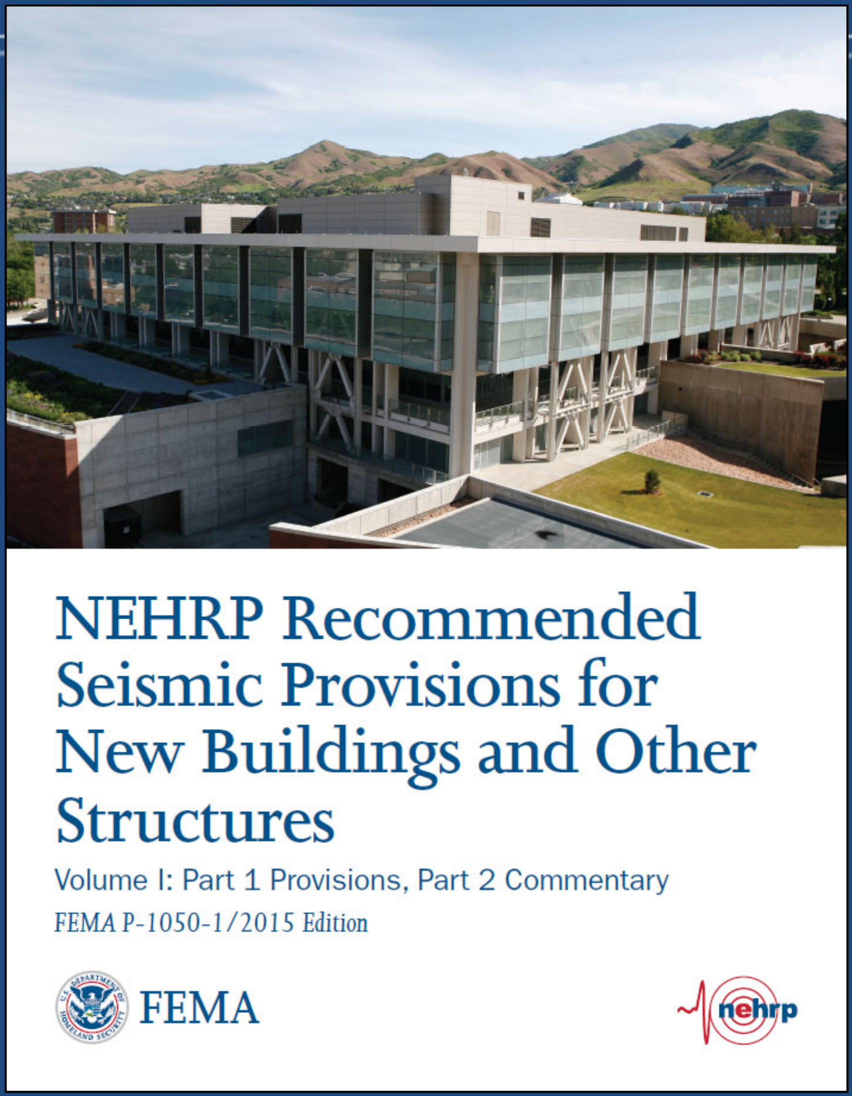
ASCE 7 Method

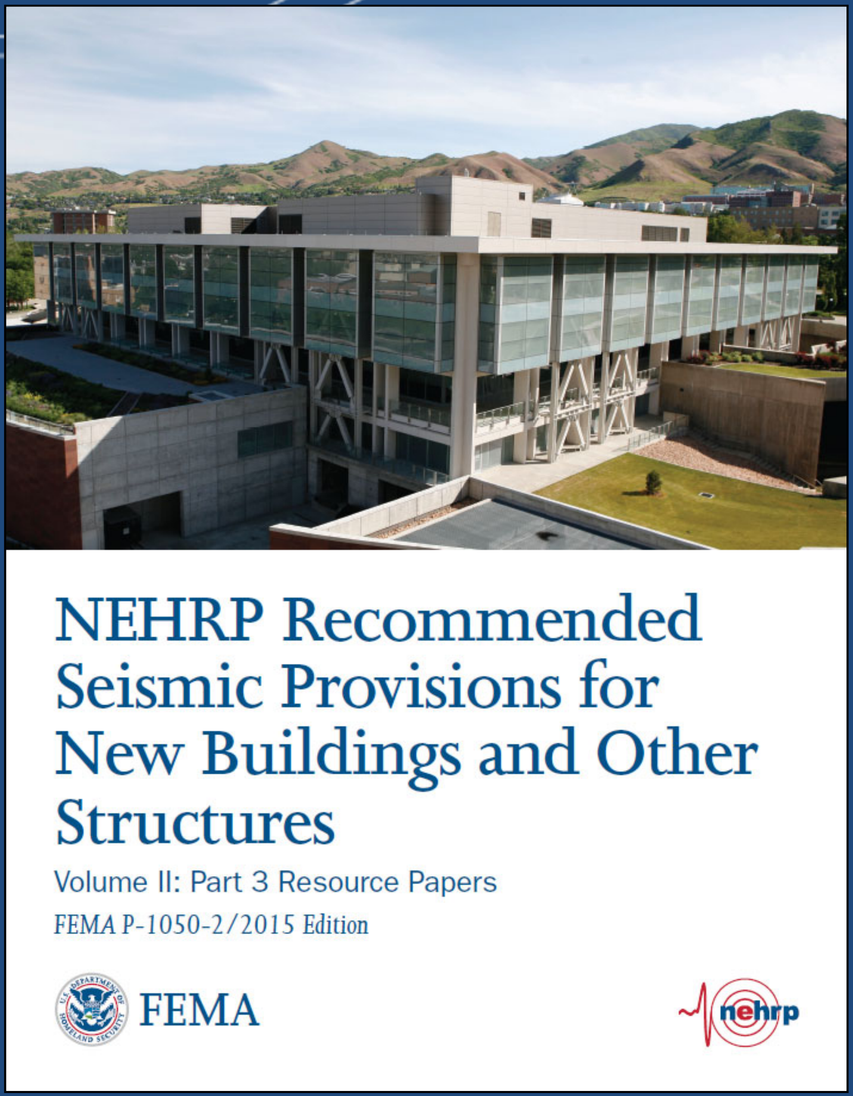
$0.5\,I_e \leq$ Acceleration "Magnification" $\leq 1.0\,I_e$ **?**



- The upper and lower limits in ASCE7 do not seem to be rational
- The computation of floor acclerations based on the assumption that all modes are equally reduced by plasticity does not seem rational either

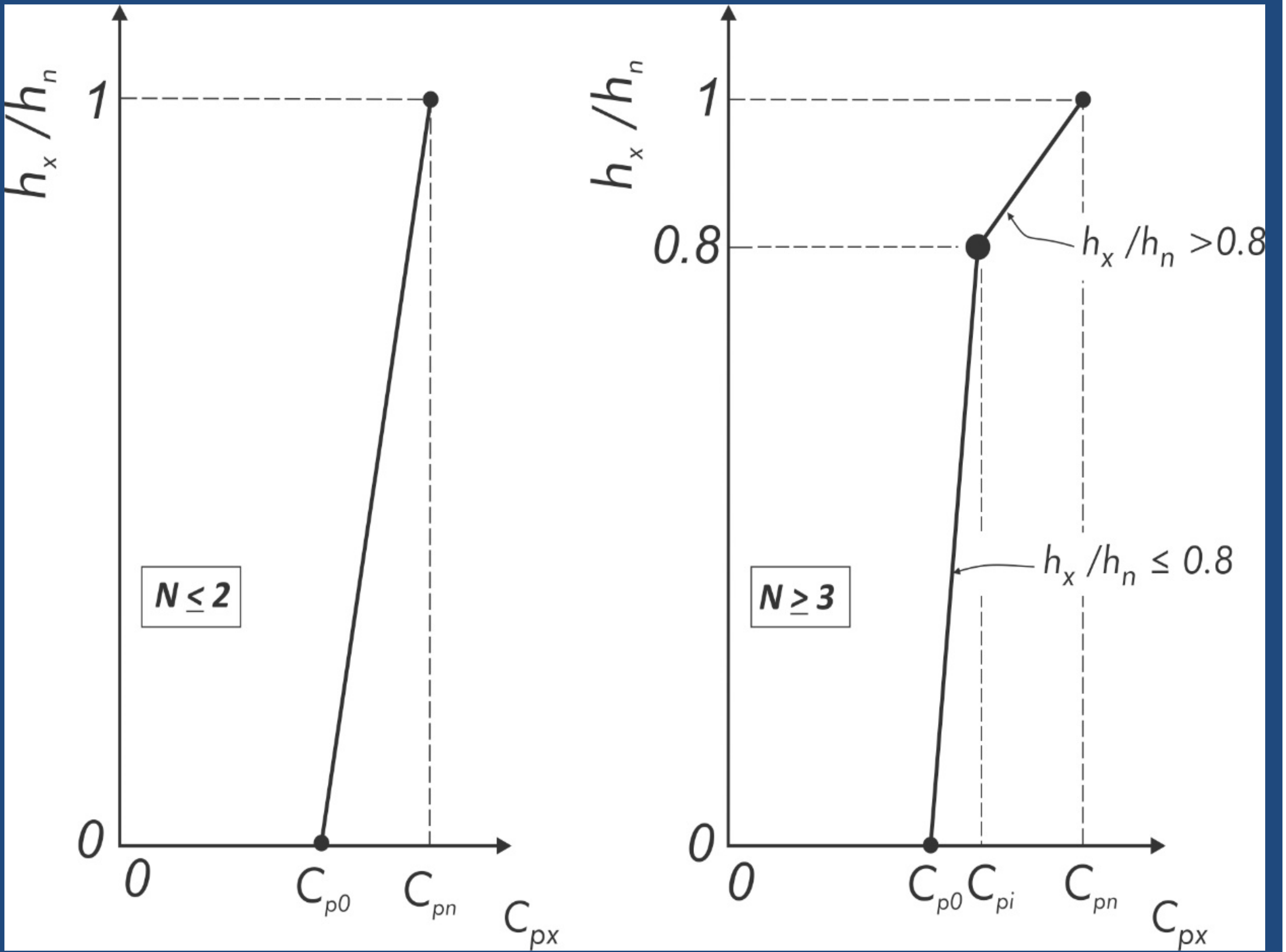
2015 NEHRP Provisions





Diaphragm Design

ASCE 7-16



Diaphragm Design

$$C_{p0} = 0.4\ S_{DS}\, I_e$$

$$C_{pn} = \sqrt{(\Gamma_{m1}\Omega_0 C_S)^2 + (\Gamma_{m2} C_{S2})^2} \ge C_{pi}$$

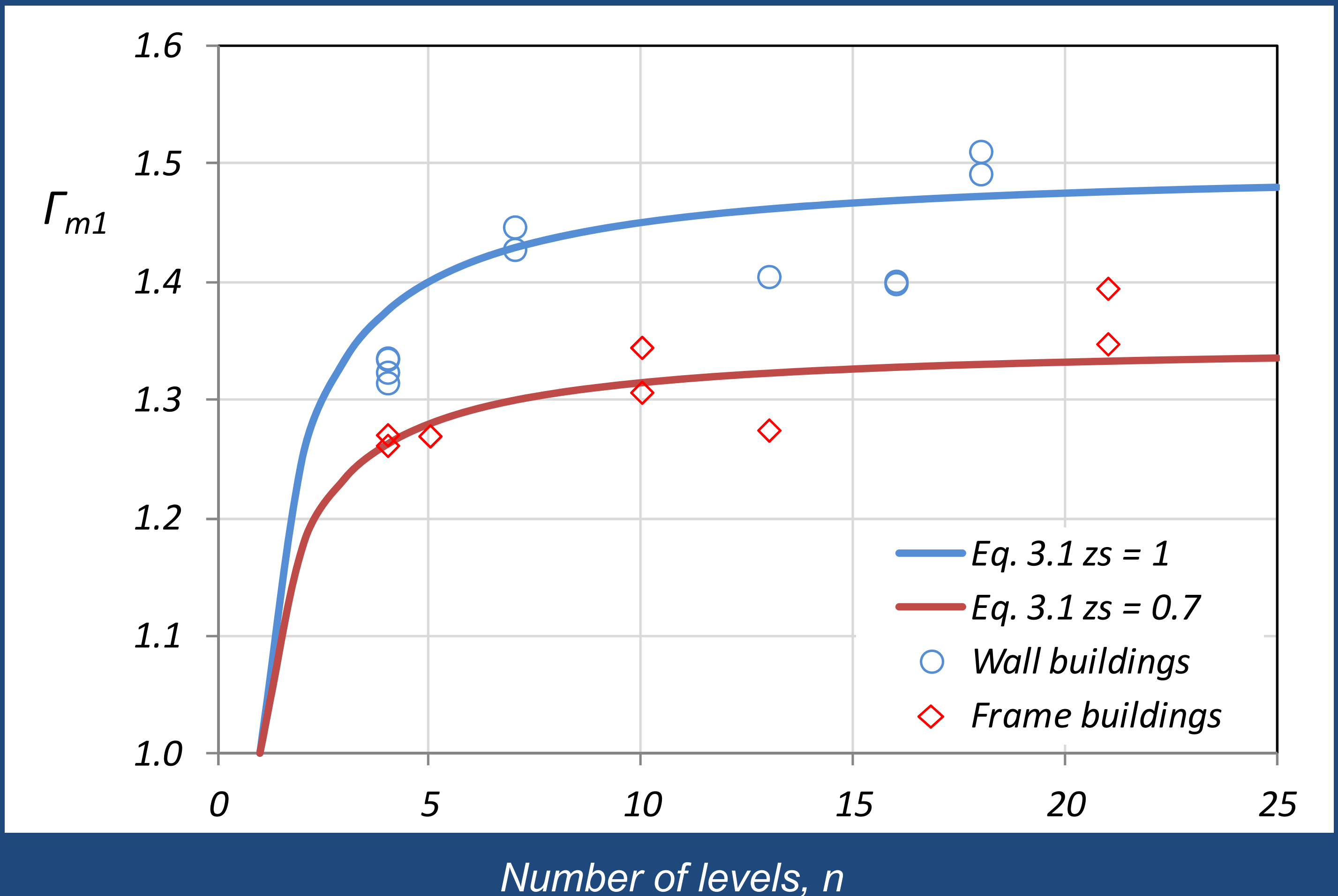
Note: The lower-bound limit on C_{pn} is in ASCE 7-16 only, not in the 2015 NEHRP *Provisions.*

Diaphragm Design

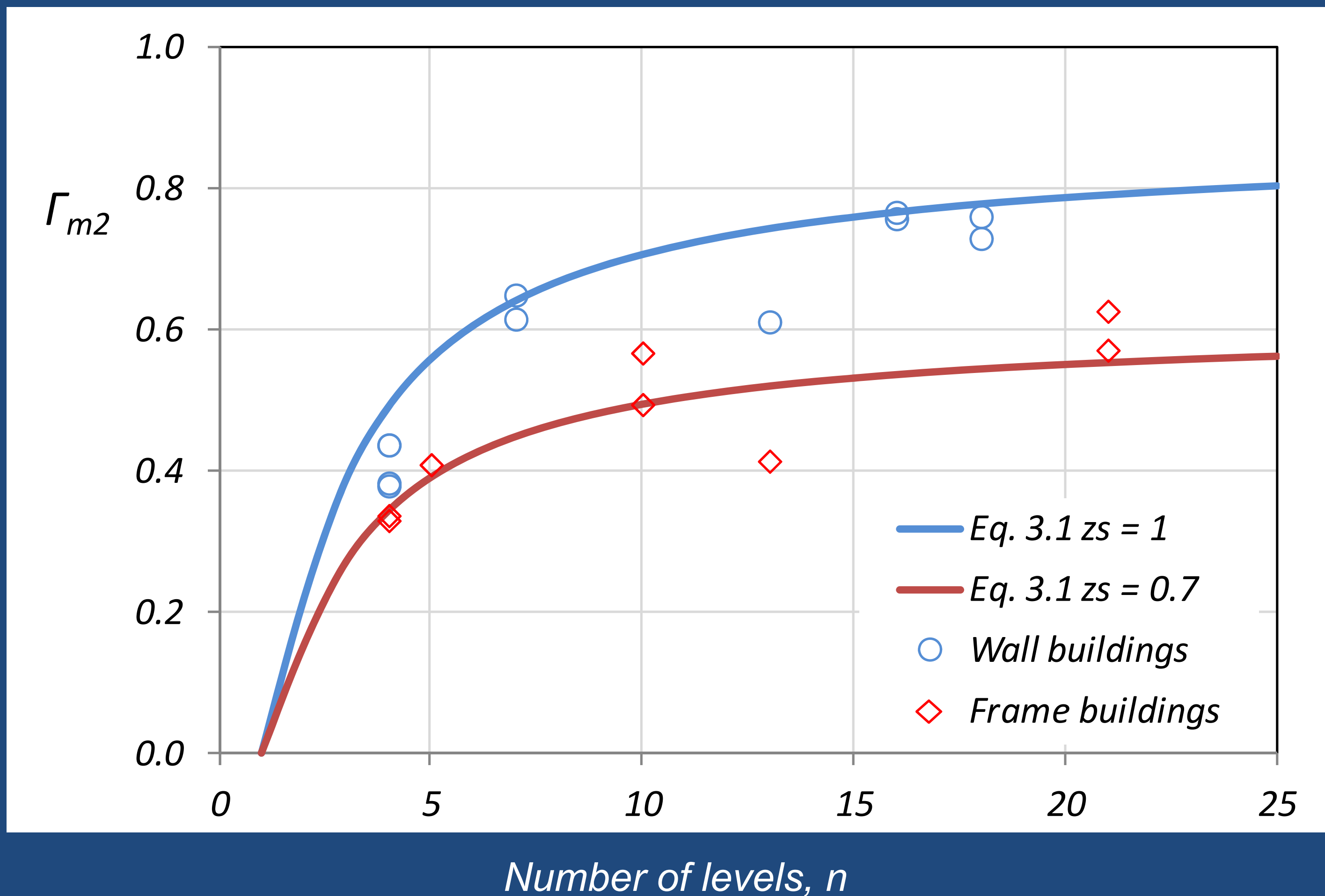
- $\Gamma_{m1} = 1 + 0.5z_s\,(1 - 1/N)$
- $\Gamma_{m2} = 0.9z_s\,(1 - 1/N)^2$

where z_s = modal contribution coefficient modifier dependent on seismic force-resisting system.

Diaphragm Design



Diaphragm Design



Diaphragm Design

C_{pi} is the greater of values given by:

$C_{pi} = C_{p0}$

$C_{pi} = 0.9\,\Gamma_{m1}\Omega_0 C_S$

Diaphragm Design

$C_S = V/W$ or V_t/W

C_{S2} = minimum of:

$(0.15N + 0.25)\, I_e\, S_{DS}$

$I_e\, S_{DS}$

$I_e\, S_{D1}/[0.03(N\text{-}1)]$ for $N \geq 2$ or 0 for $N = 1$

Diaphragm Capacity

Why are we not seeing inadequate performance of diaphragms in seismic events?

Inertial Forces in Diaphragms

Existing diaphragms may carry seismic inertial forces through:

(a) inherent overstrength in the floor system, including the floor plate and framing elements, that permit the transfer of higher than code design forces,

Inertial Forces in Diaphragms

or

(b) inherent ductility or plastic redistribution qualities within the diaphragm (or at the boundaries of the diaphragm) that limit the amount of inertial forces that can develop, without significant damage or failure.

Step-by-Step Determination of Alternative Diaphragm Seismic Design Force

Alternative– Step 1

Determine w_{px}. (Same as Traditional – Step 1)

- ASCE 7-16 Section 12.7.2 defines effective seismic weight, W.
- w_x is the portion of W that is tributary to level x.
- w_{px} is different from w_x only in that the weights of the walls parallel to the earthquake forces may be excluded from w_{px}.

Alternative– Step 2

Determine R_s, Diaphragm Design Force Reduction Factor (ASCE 7-16 Table 12.10.3.5-1)

Diaphragm System		Shear Control	Flexure Control
Precast concrete	EDO	1.0	0.7
	BDO	1.0	1.0
	RDO	1.0	1.3

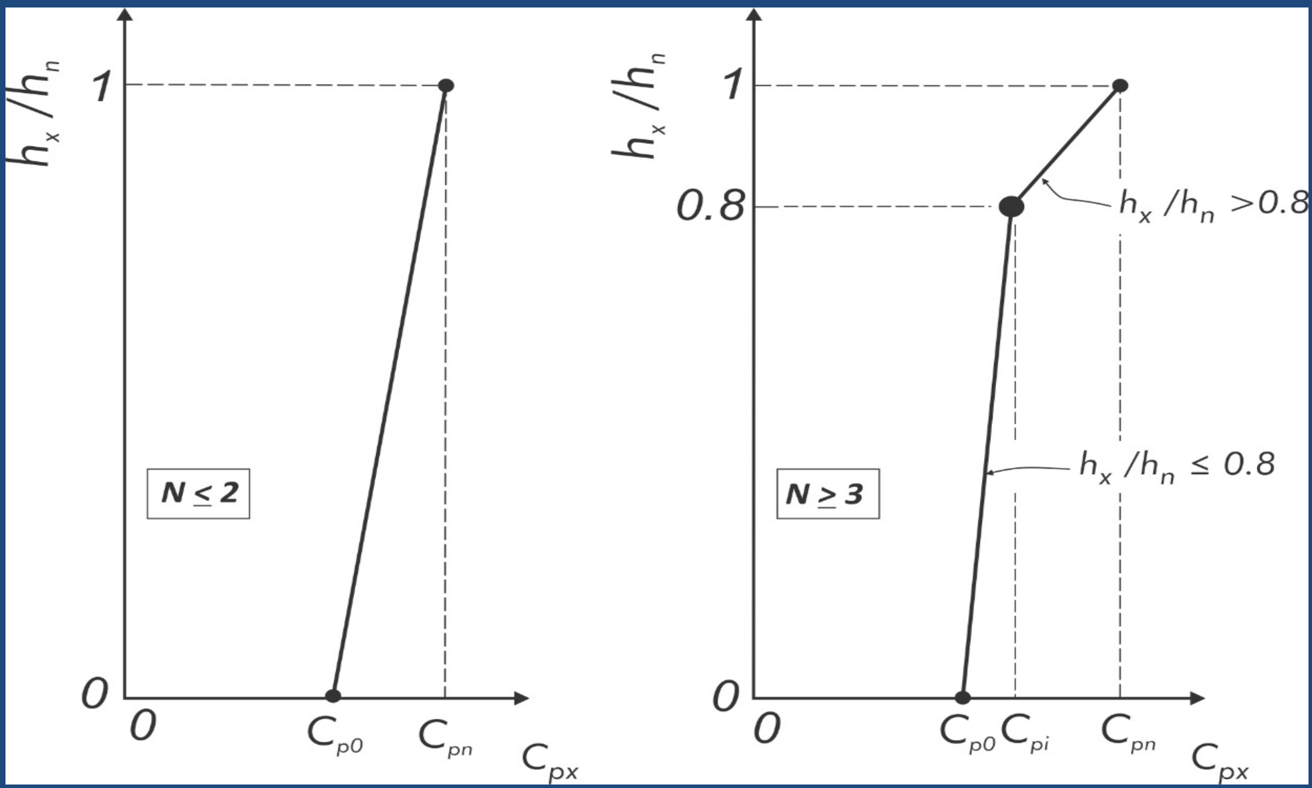
Alternative– Step 3

Determine C_{px}, Diaphragm Design Acceleration (Force) Coefficient at Level x (ASCE 7-16 Section 12.10.3.2)

- In order to determine C_{px}, C_{p0}, C_{pi}, and C_{pn} need to first be determined.

Alternative– Step 3

Use Figure 12.10.3-1 to determine C_{px} (ASCE 7-16 Section 12.10.3.2)



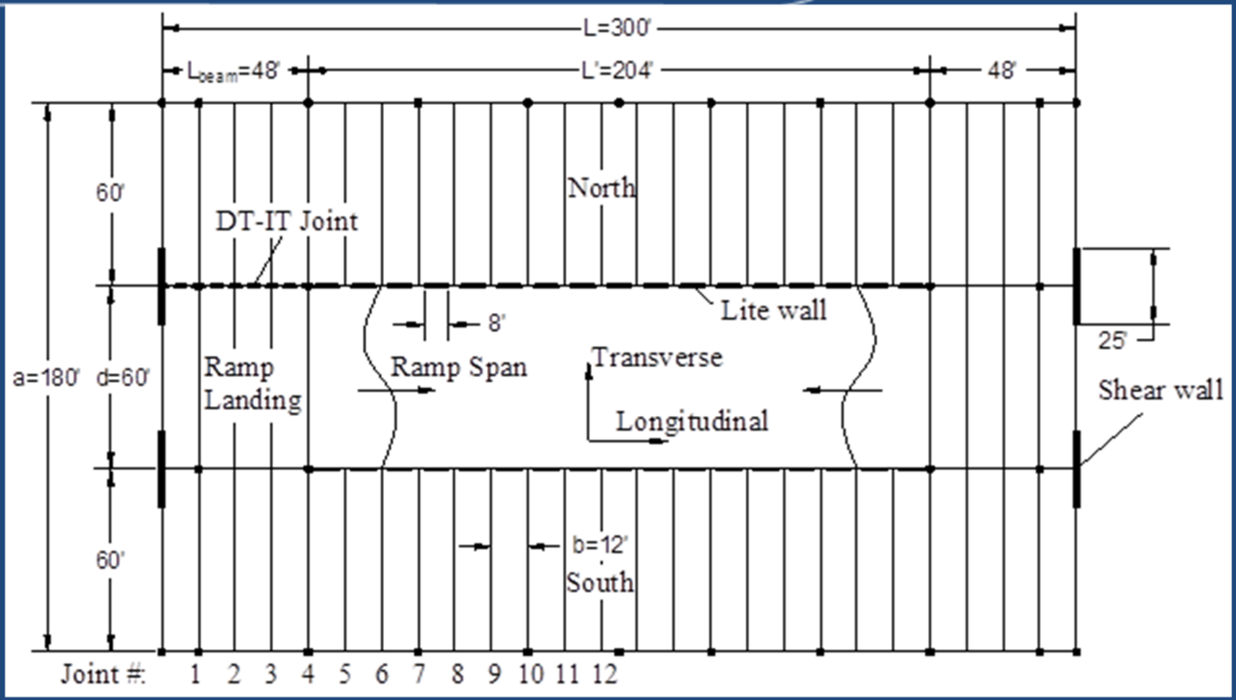
Alternative– Step 4

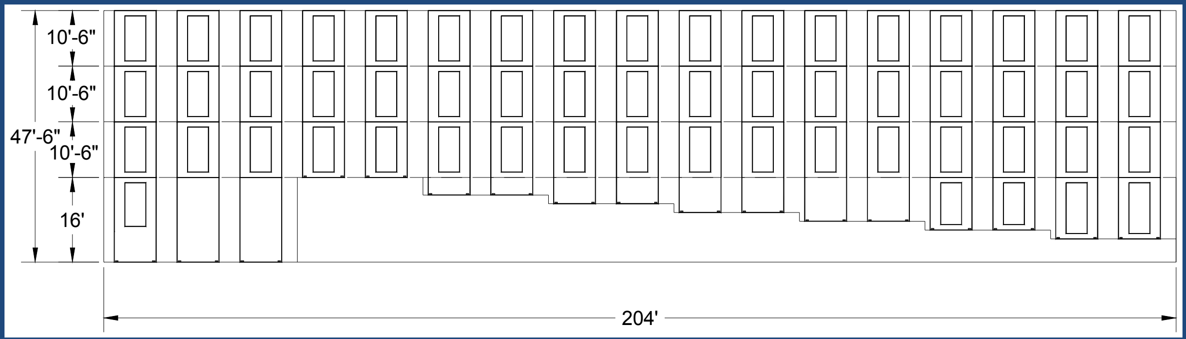
Determine F_{px}, Diaphragm Design Force at Level x (Section 12.10.3.2)

$$F_{px} = C_{px} w_{px} / R_s$$
$$\geq 0.2 S_{DS} \, I_e \, w_{px}$$

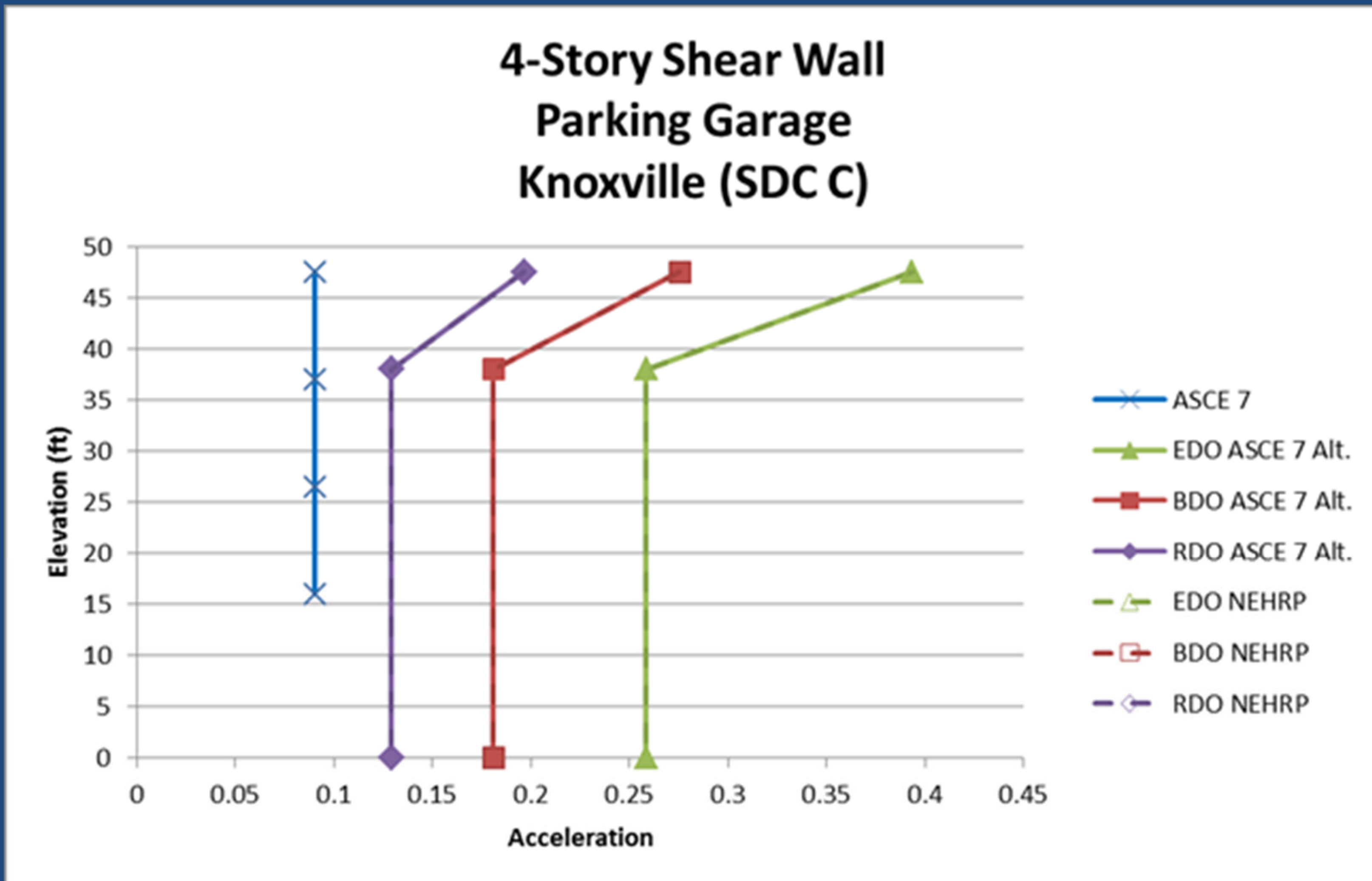
Diaphragm Design Force Level Comparisons

4-Story Perimeter Wall Precast Concrete Parking Structure (SDC C, Knoxville)

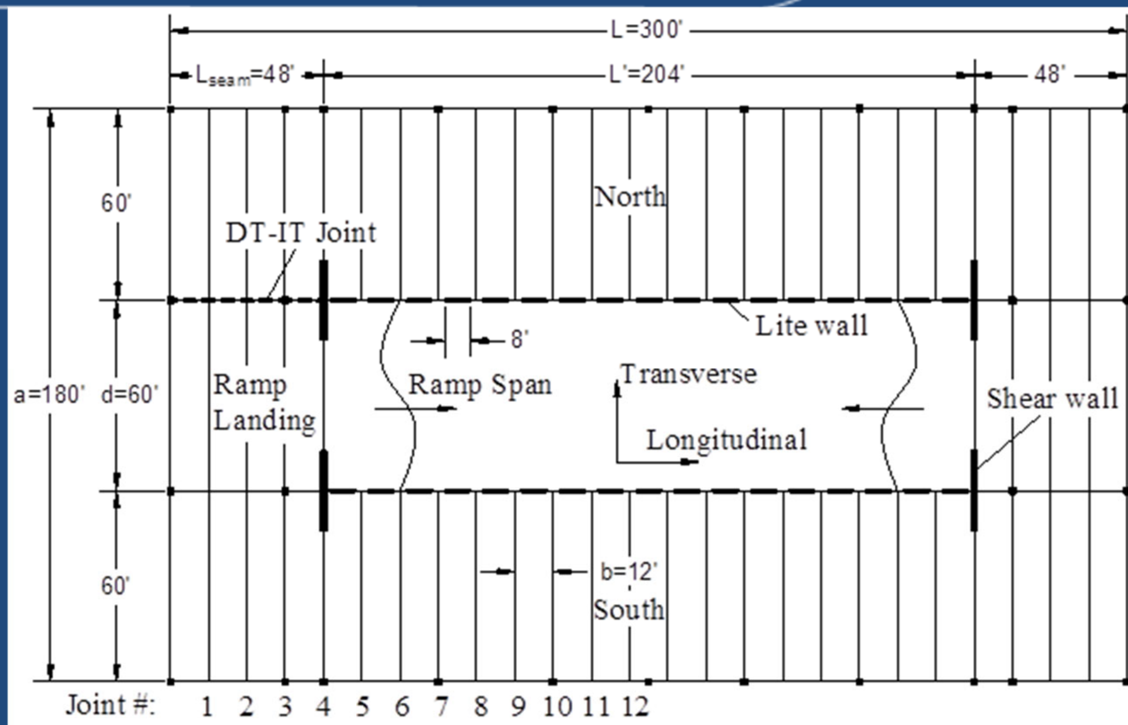


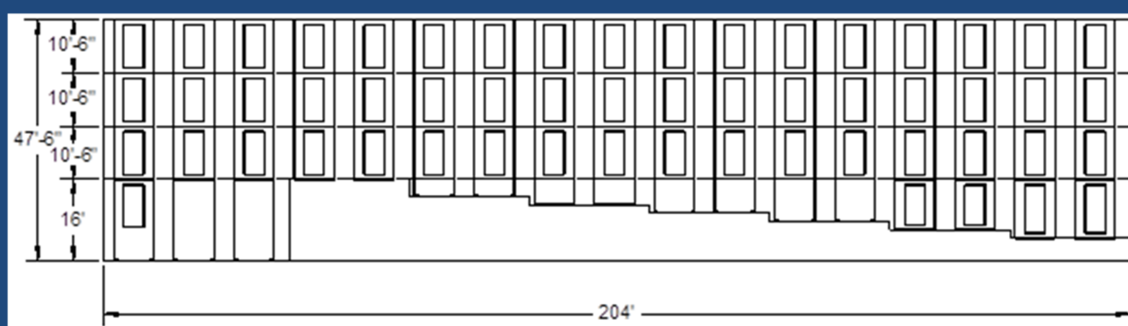


4-Story Perimeter Wall Precast Concrete Parking Structure (SDC C, Knoxville)

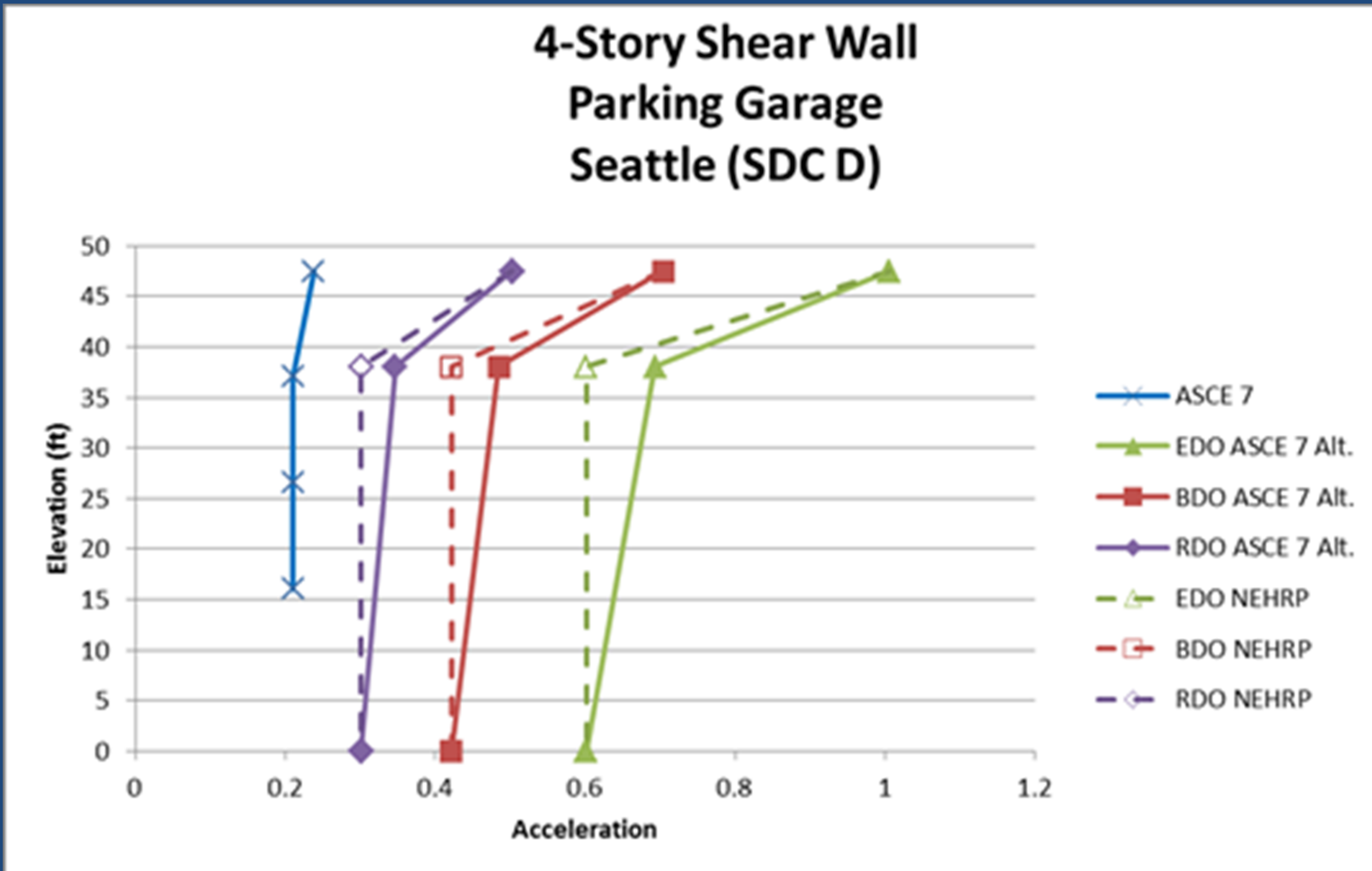


4-Story Interior Wall Precast Concrete Parking Structure (SDC D, Seattle)

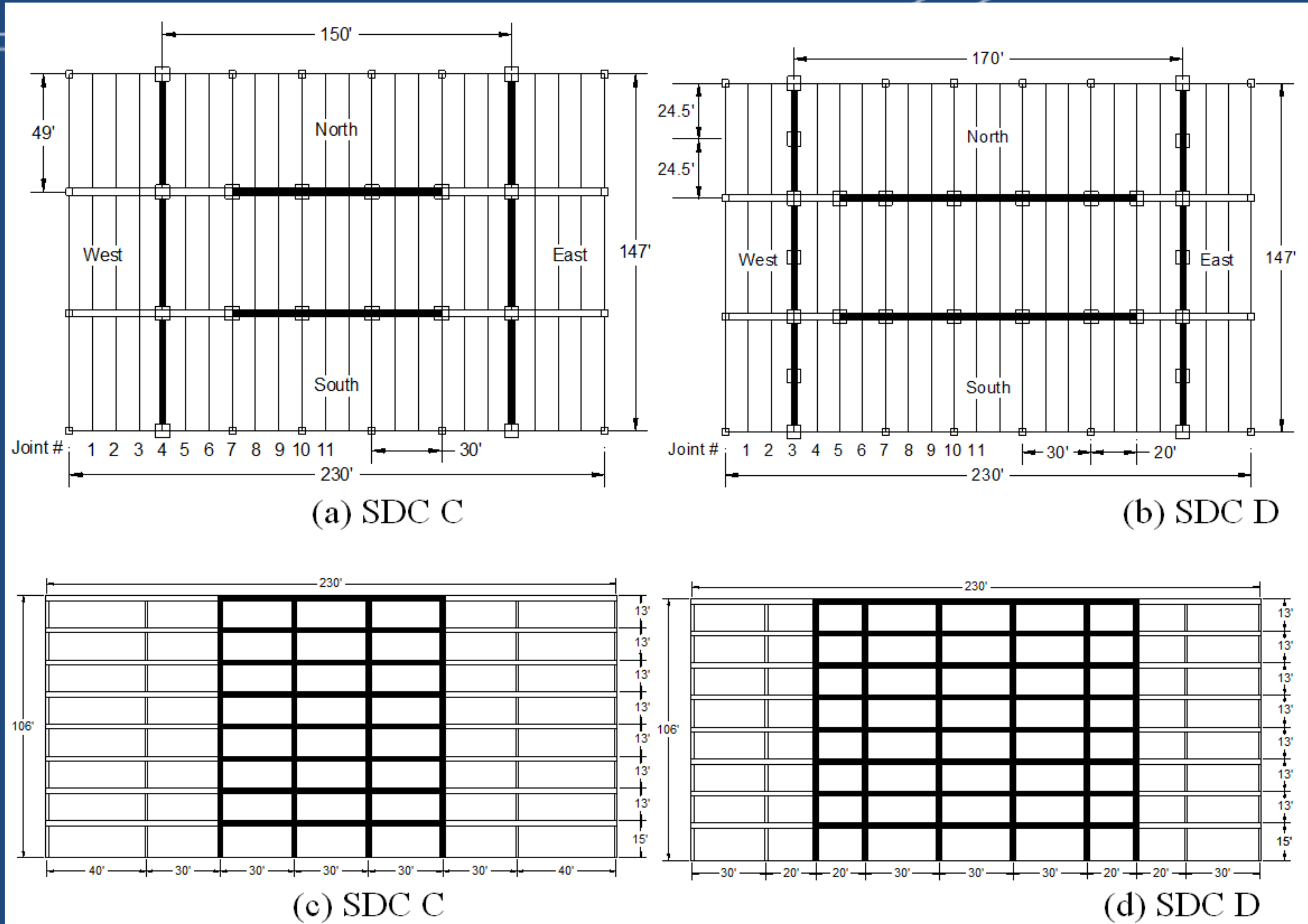




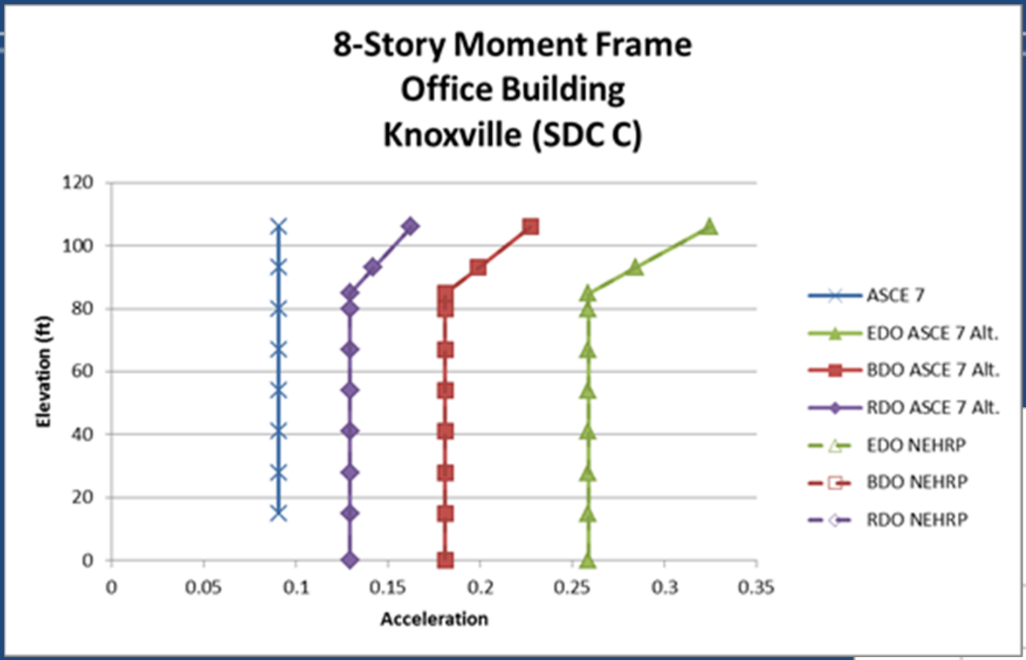
4-Story Interior Wall Precast Concrete Parking Structure (SDC D, Seattle)

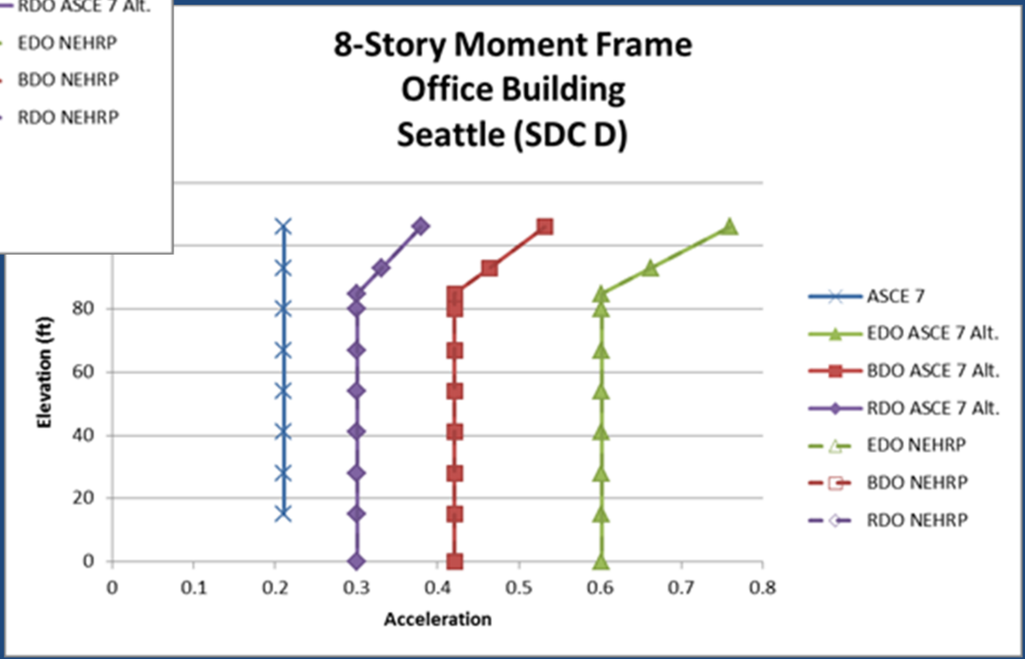


8-Story Precast Concrete Moment Frame Office Building



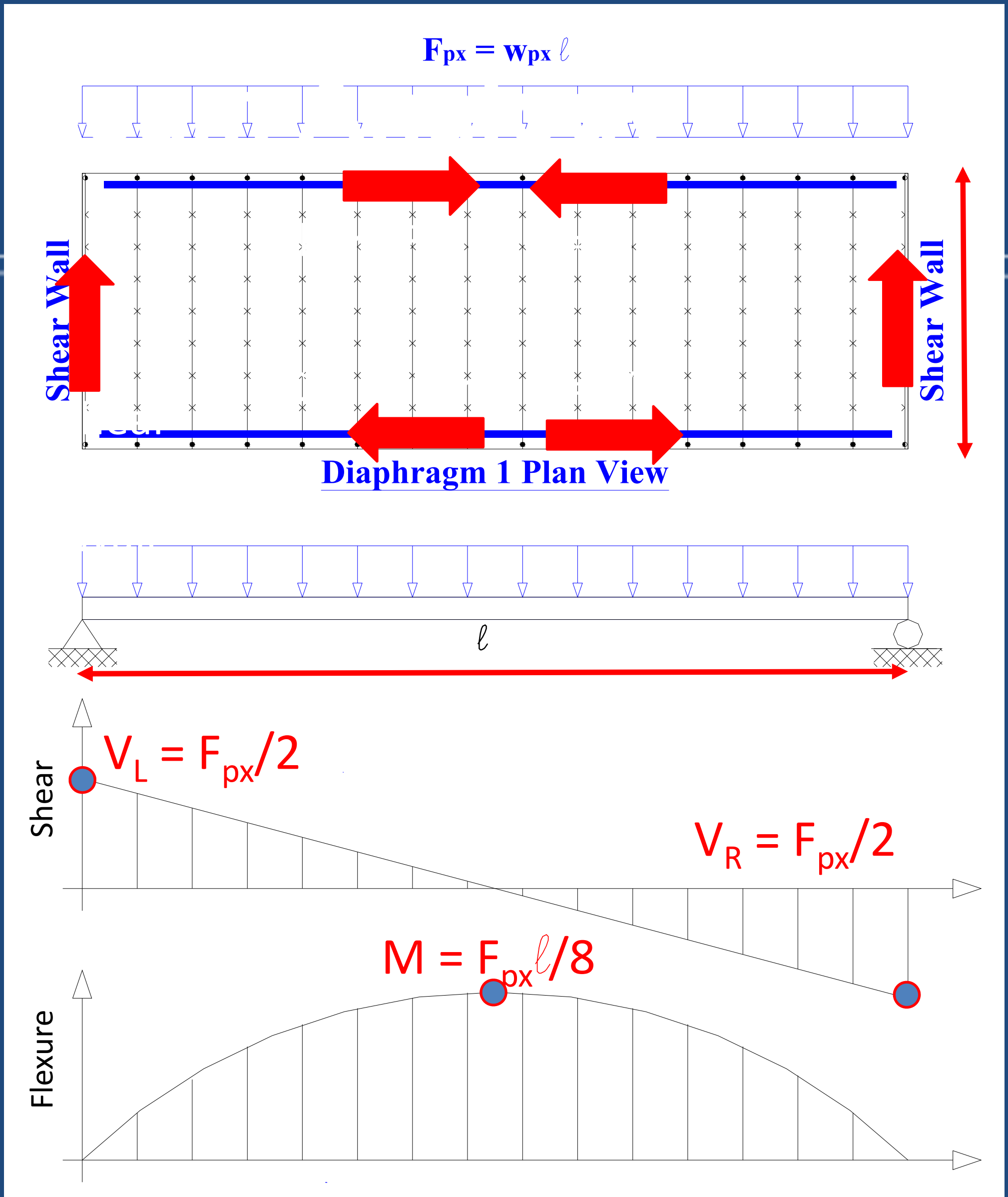
8-Story Precast Concrete Moment Frame Office Building

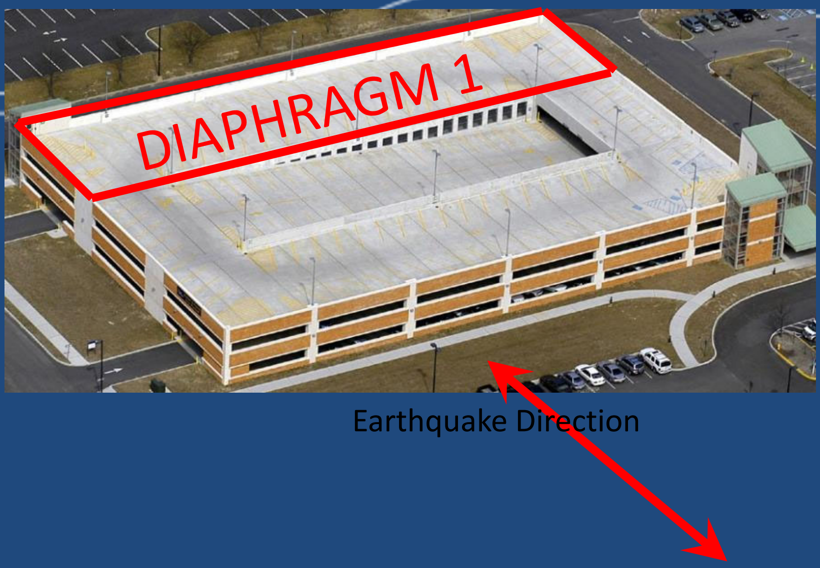




ACI 550.5-18

Connection Considerations





Beam Analogy

- Shear walls Supports
- Floor acts as beam

Shear Forces

Resisted by **WEB** Connectors

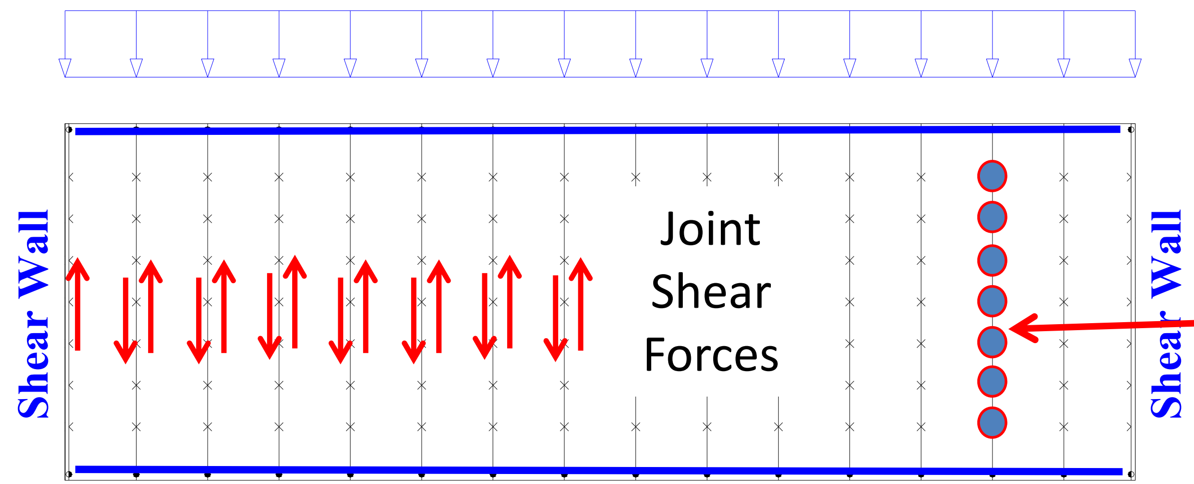
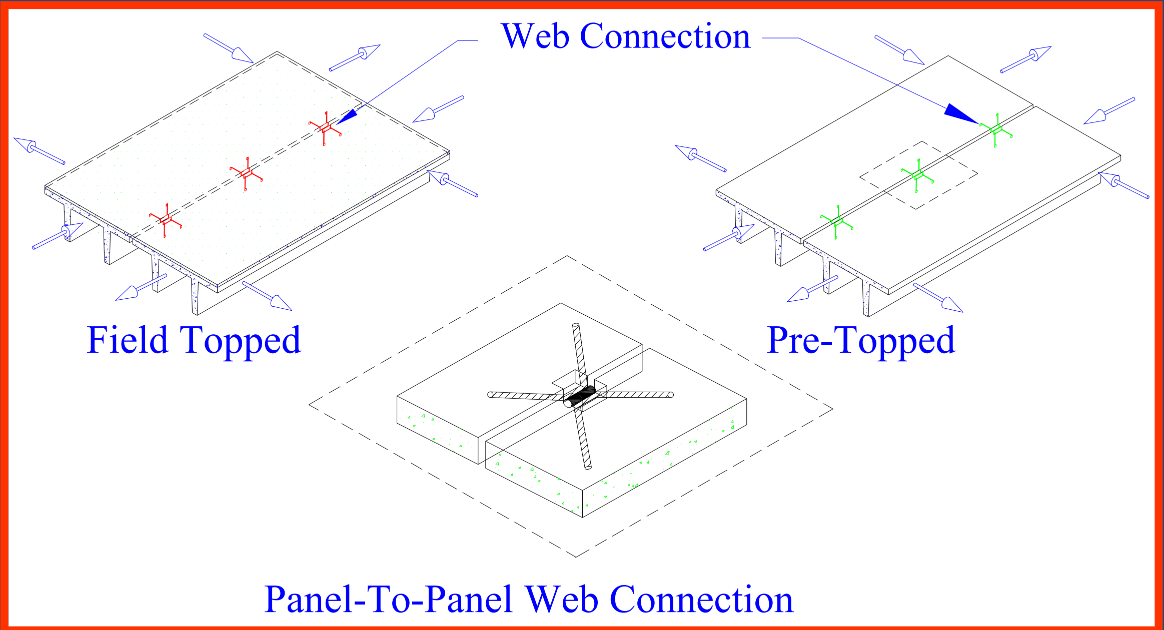
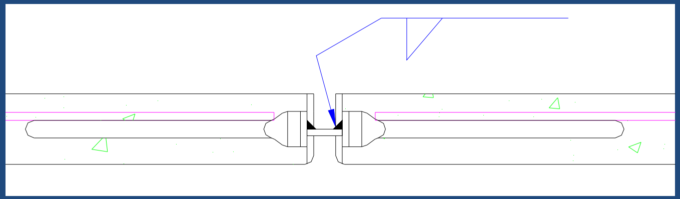
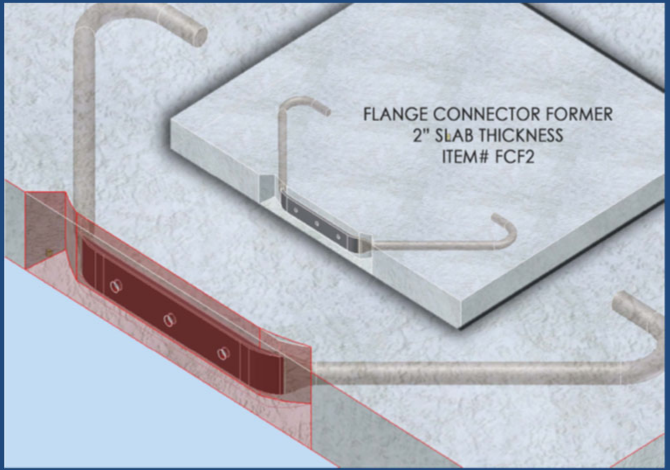


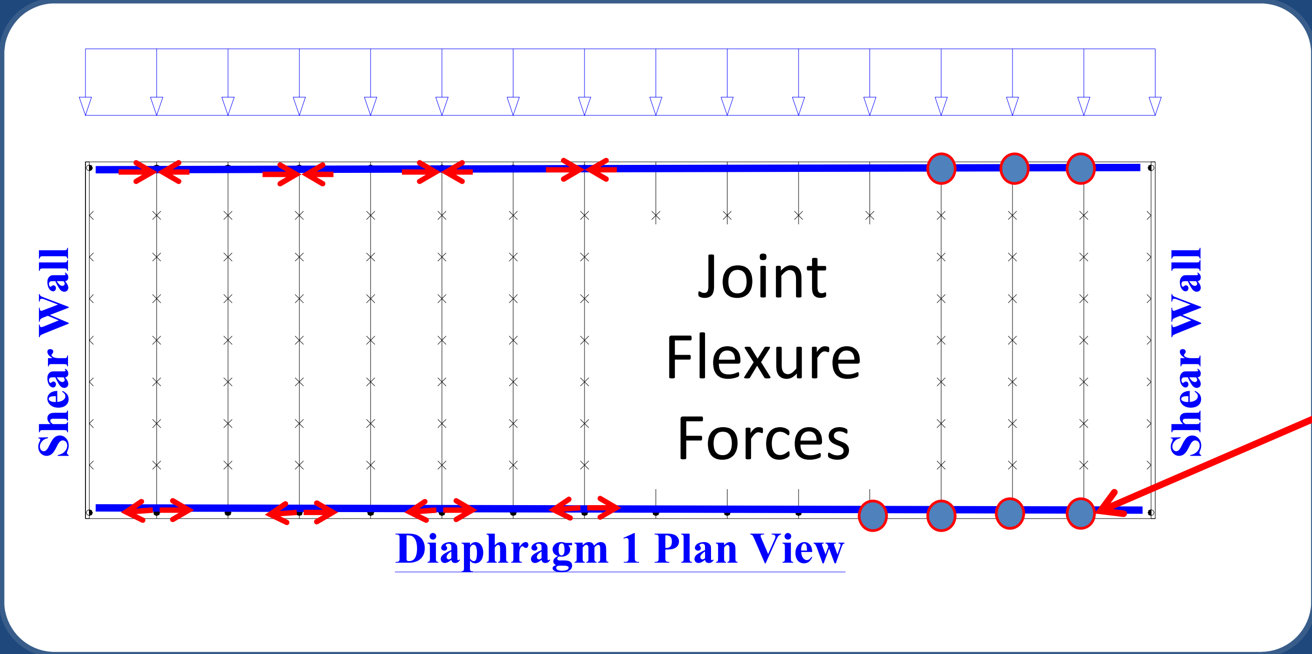
Diagram Plan View



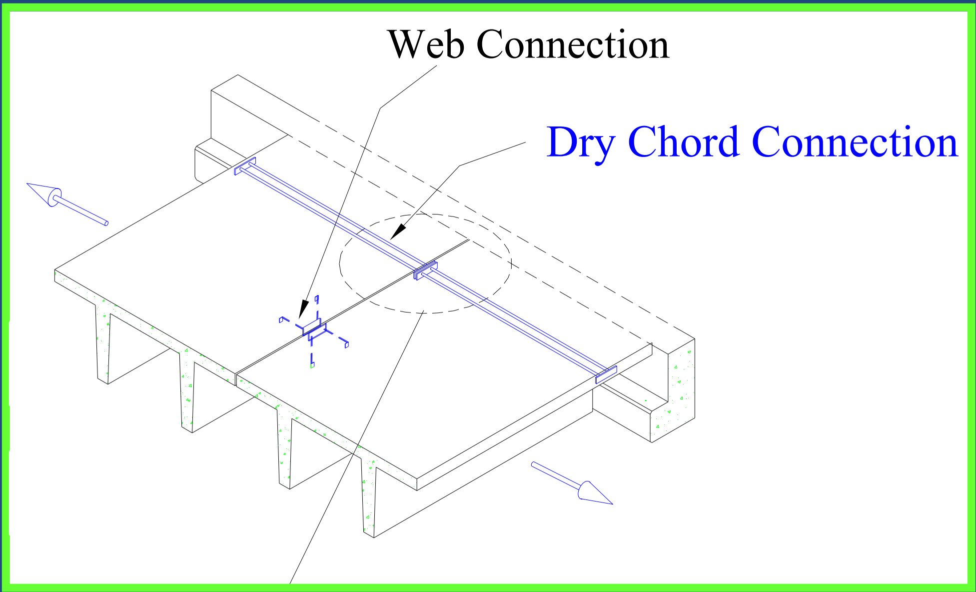


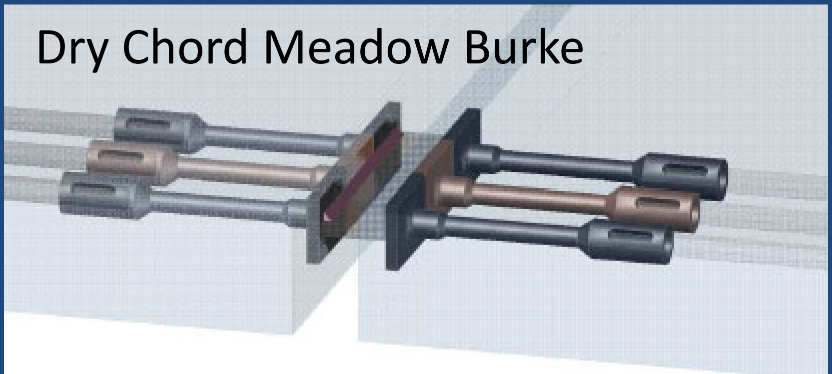


Flexure Forces

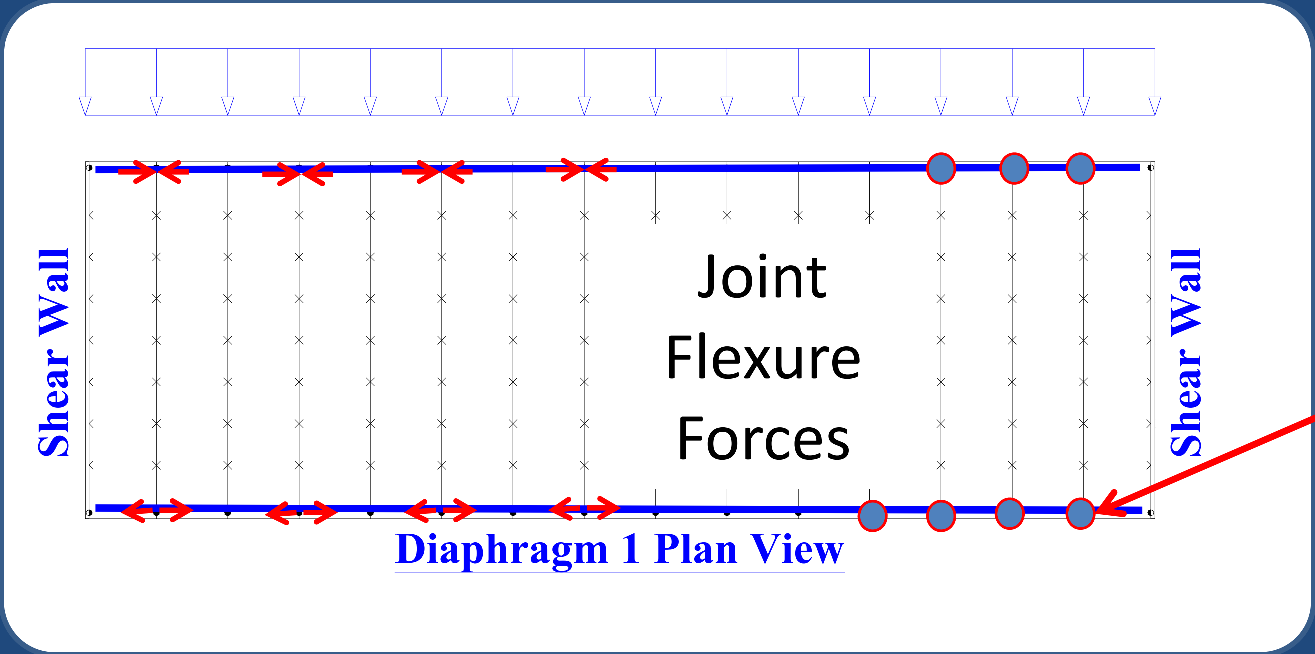


Resisted by **CHORD** Connectors

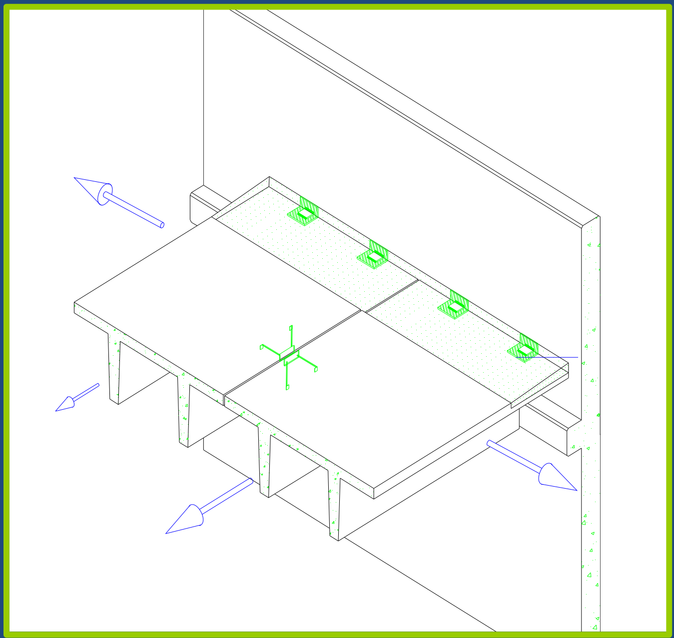




Flexure Forces

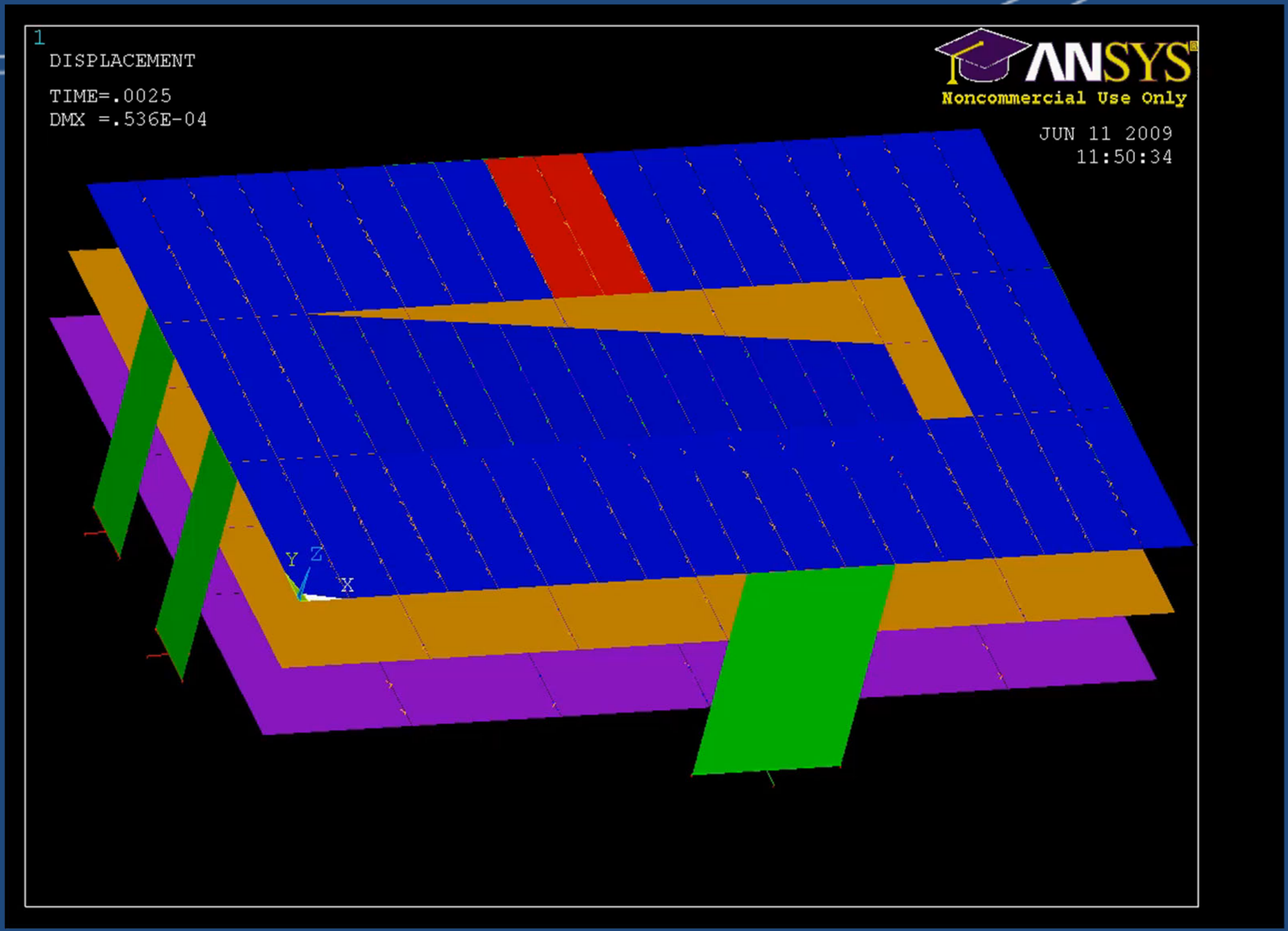


Resisted by **CHORD** Connectors



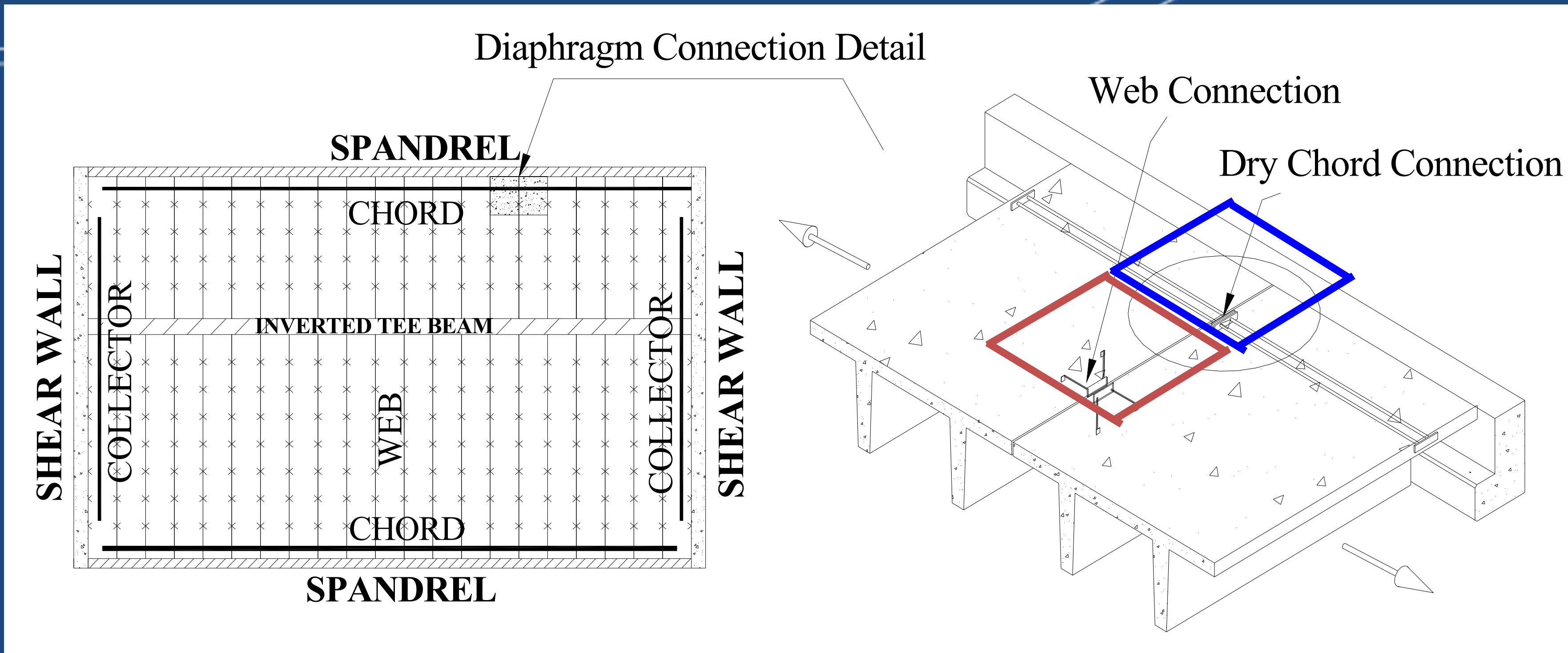
"Wet Chord" Pour Strip Detail
Concrete Placed On site

Response Under Earthquake Motion



(Fleischman – U. Arizona)

Connection Performance



- Chord Connection
  - Designed for Tension
  - Shear Neglected

Web Connection

Designed for Shear

Tension Neglected

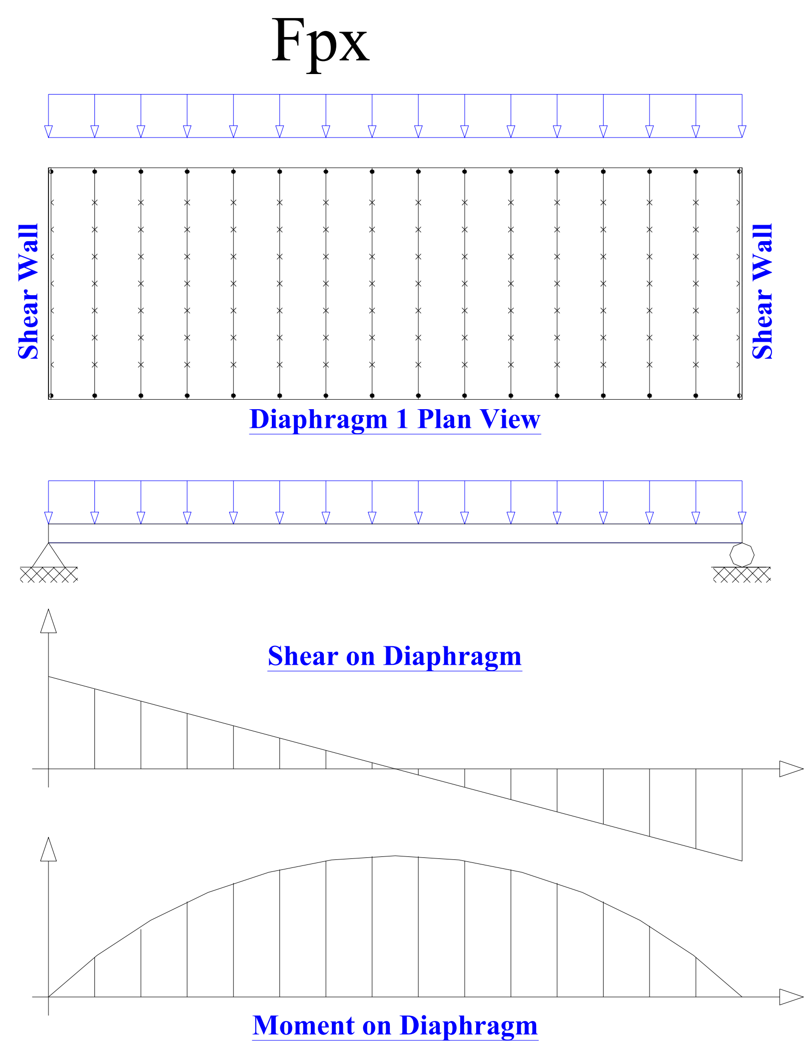
Earthquake Category

- Maximum Considered Earthquake (MCE)
  - Most severe earthquake ground motion considered at the site.
  - Eq. expected to occur once in 2500 years
  - 2% Probability of being exceeded in 50 years
- Design Basis Earthquake (DBE)
  - 2/3 that of the MCE
  - Eq. expected to occur once in 474 years
  - 10% Probability of being exceeded in 50 years

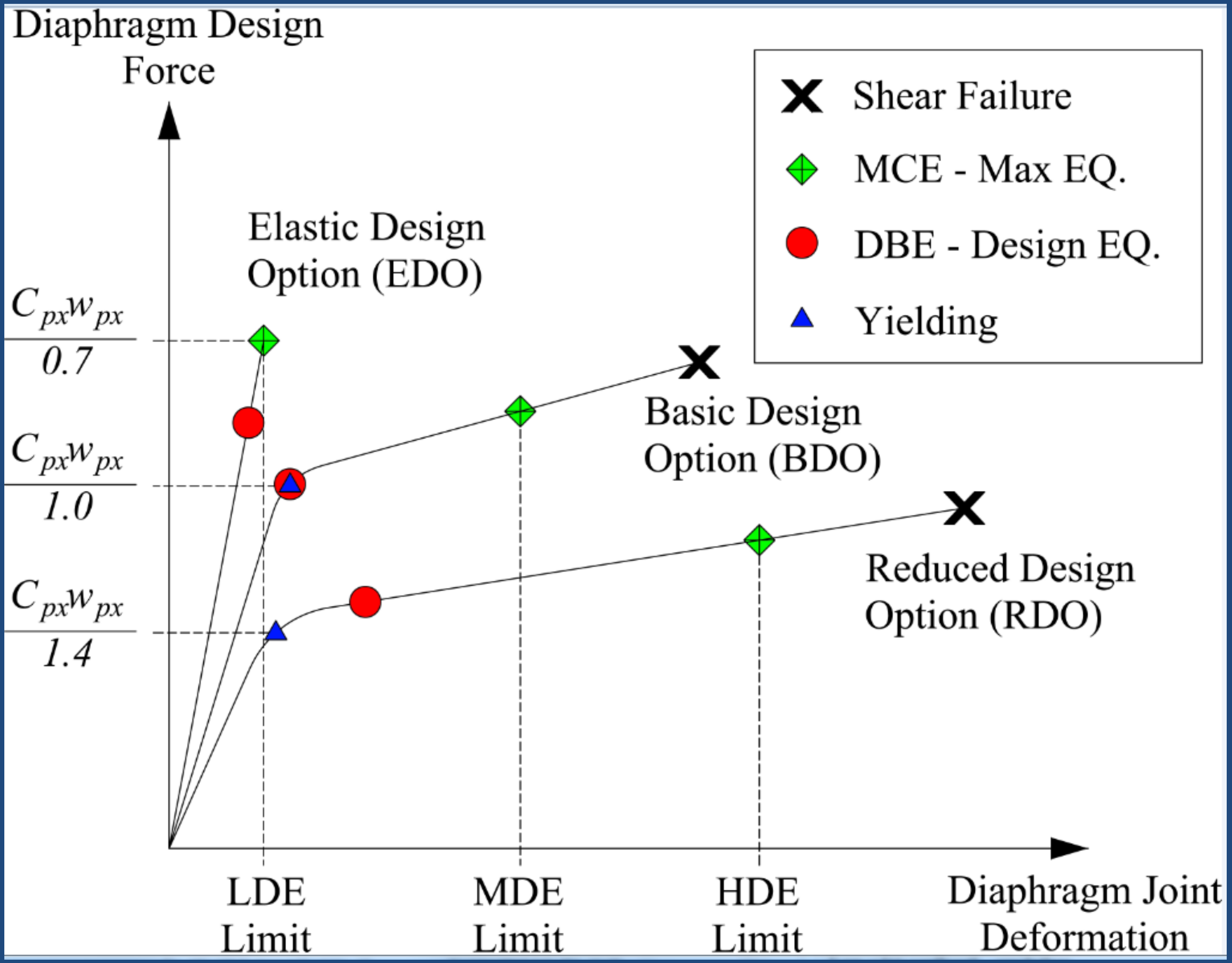
Diaphragm Seismic Design Concept

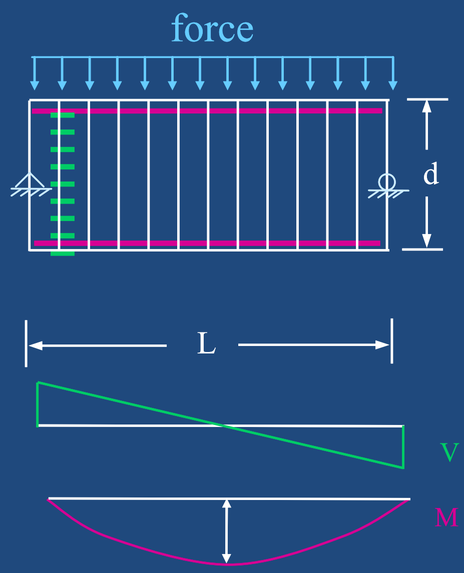
Design Method

1. Modify F_{px} to develop defined yielding under:
   - Design Basis Earthquake
   - Max Considered Earthquake
2. Prevent Shear Failure



Diaphragm Seismic Design Concept



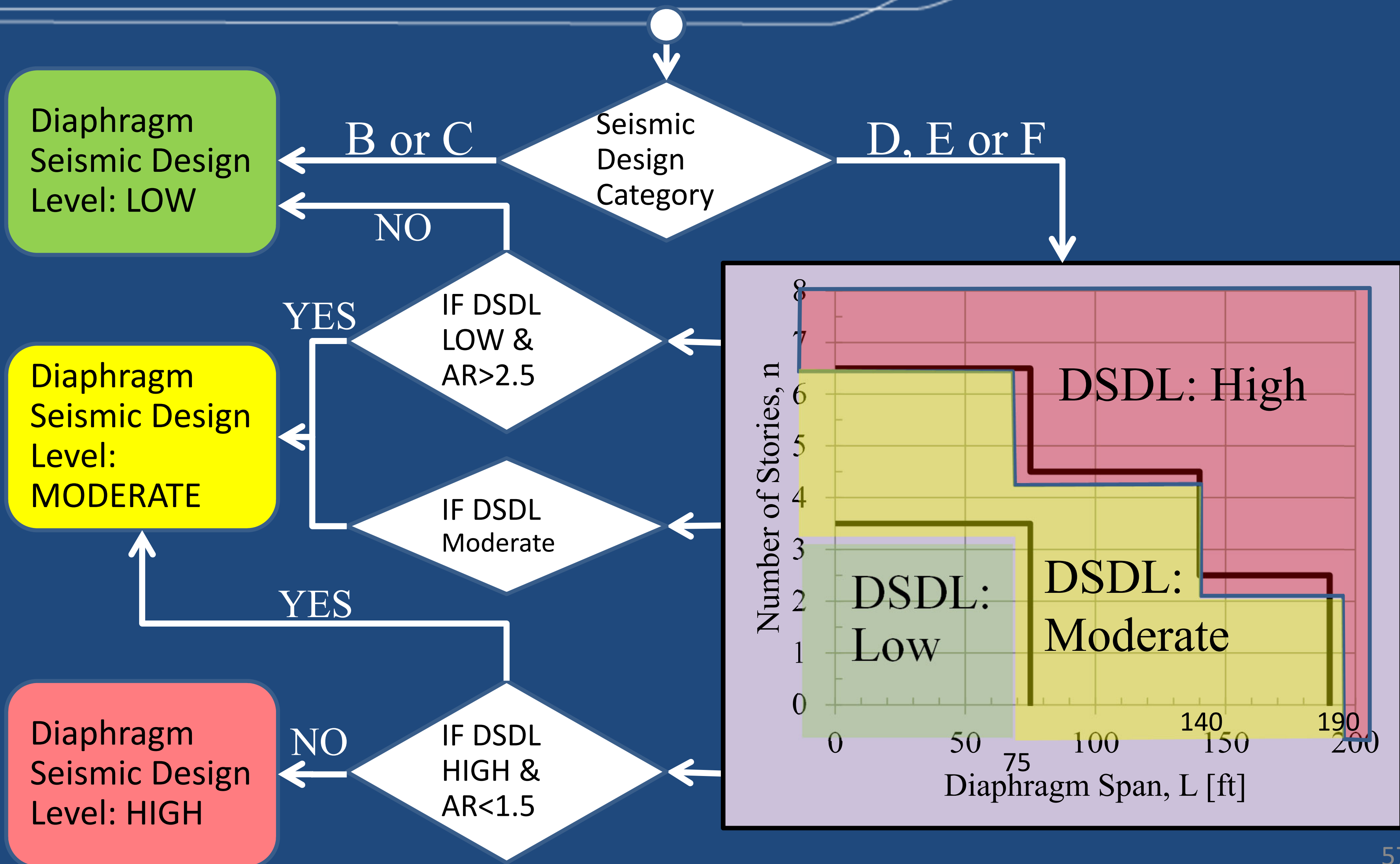


Diaphragm Design Options

Elastic Design Option (EDO)	Basic Design Option (BDO)	Reduced Design Option (RDO)
Diaphragm remain elastic in DBE and MCE	Diaphragm remain elastic in DBE but Not Necessarily in MCE	Some Diaphragm yielding in DBE, significant in MCE
Highest diaphragm design force	Lower diaphragm design force than EDO	Lowest diaphragm design force
Connections can include LDE, MDE and HDE	Connections can include MDE and HDE	Connections must be High Deformation Elements (HDE)
No shear overstrength needed since elastic design	Shear overstrength factor is needed	Shear overstrength factor is needed

Diaphragm Seismic Design Level (DSDL)

Determine Diaphragm Seismic Design Level (DSDL)



Seismic Design Option

Determine Diaphragm Design Option

Diaphragm Seismic Design Level: LOW

Diaphragm Seismic Design Level: MODERATE

Diaphragm Seismic Design Level: HIGH

Design Option	Diaphragm Seismic Demand level		
	Low	Moderate	High
Elastic	Recommended	With Penalty*	Not Allowed
Basic	Alternative	Recommended	With Penalty*
Reduced	Alternative	Alternative	Recommended

Penalty* = Diaphragm design force shall be increased by 15%.

Choose Design Option: Elastic / Basic / Reduced

Connection Element

Recommended Factors

Diaphragm Seismic Design Level (DSDL)	Diaphragm Force Reduction Factor, R_S	Diaphragm Reinforcement Classification	Reliable And Stable Maximum Joint Opening Capacity
Elastic (EDO)	0.7	Low Deformability Element	< 0.3 in.
Basic (BDO)	1.0	Moderate Deformability Element	0.3 to 0.6 in.
Reduced (RDO)	1.4	High Deformability Element	> 0.6 in.

ACI 550.5-18 Section 5.4

Determine Shear Force

- The required shear strength for diaphragm shall be amplified by the diaphragm shear overstrength factor, Ω_v

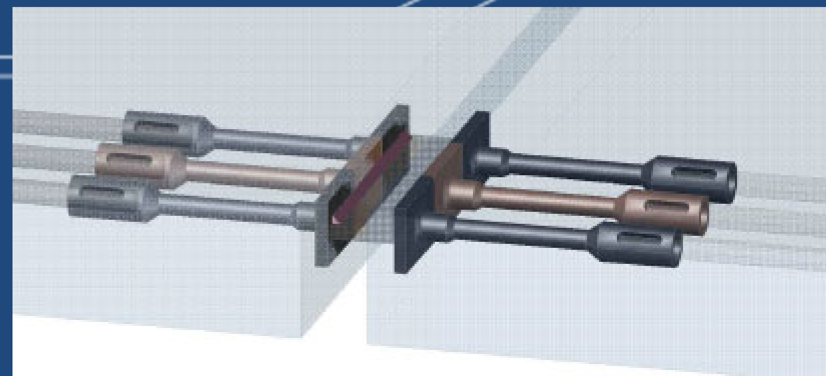
$$\Omega_v = 1.4 \cdot R_s$$

Diaphragm Seismic Design Level (DSDL)	Diaphragm Force Reduction Factor, R_s $(1/R_s)$	Diaphragm Reinforcement Classification	Shear Overstrength
Elastic (EDO)	0.7 (1.4)	Low Deformability Element	1.0
Basic (BDO)	1.0 (1.0)	Moderate Deformability Element	1.4
Reduced (RDO)	1.4 (0.7)	High Deformability Element	2.0

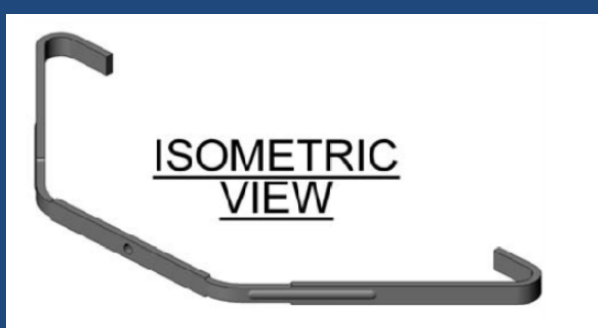
Connection Qualification Protocol ACI 550.4 -18

ACI 550.4: Definitions

- CONNECTION:



- CONNECTOR:



7.4 Classification of deformability

- 7.4.2 Low-Deformability Element (LDE) shall be connections with tension deformation less than 0.3 in.
- 7.4.3 Moderate-Deformability Element (MDE) shall be connections with tension deformation capacity greater than or equal to 0.3 in. but less than 0.6 in.
- 7.4.4 High Deformability Element (HDE) shall be connections with tension deformation capacity greater than or equal to 0.6 in.

Connectors

HDE?

MDE?

LDE?

- What connections are qualified in each category?
- Qualification testing is needed...

Qualification Procedure

- **Goal: Determine the tension deformation capacity of the connector**
- Chapter 4 – Test modules and test set-up
- Chapter 5 – Test methods
- Chapter 6 – Test report
- Chapter 7 – Interpretation of test results
  - Backbone curve
  - Classification of deformability

Subassembly Requirements 4.2

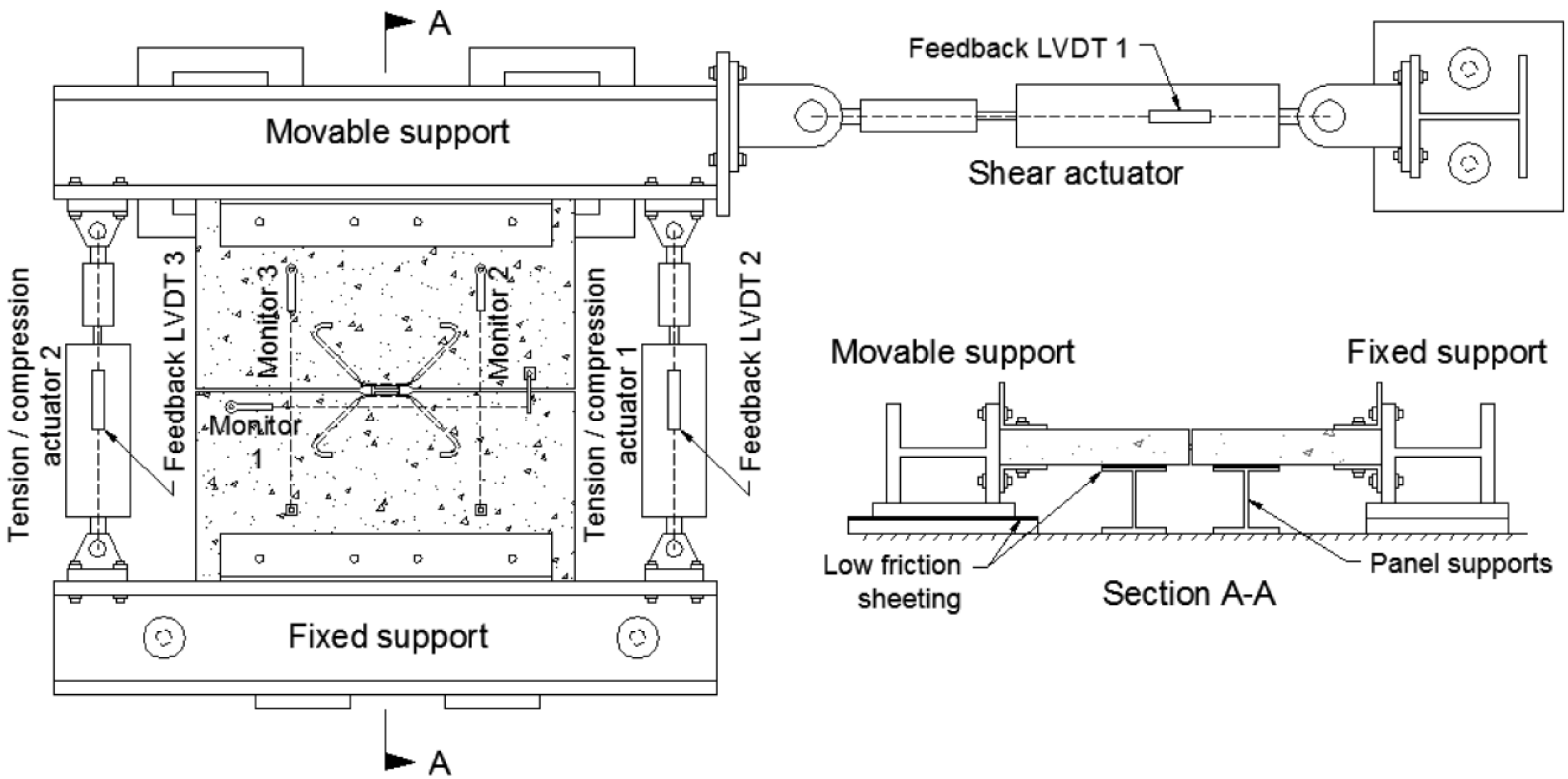
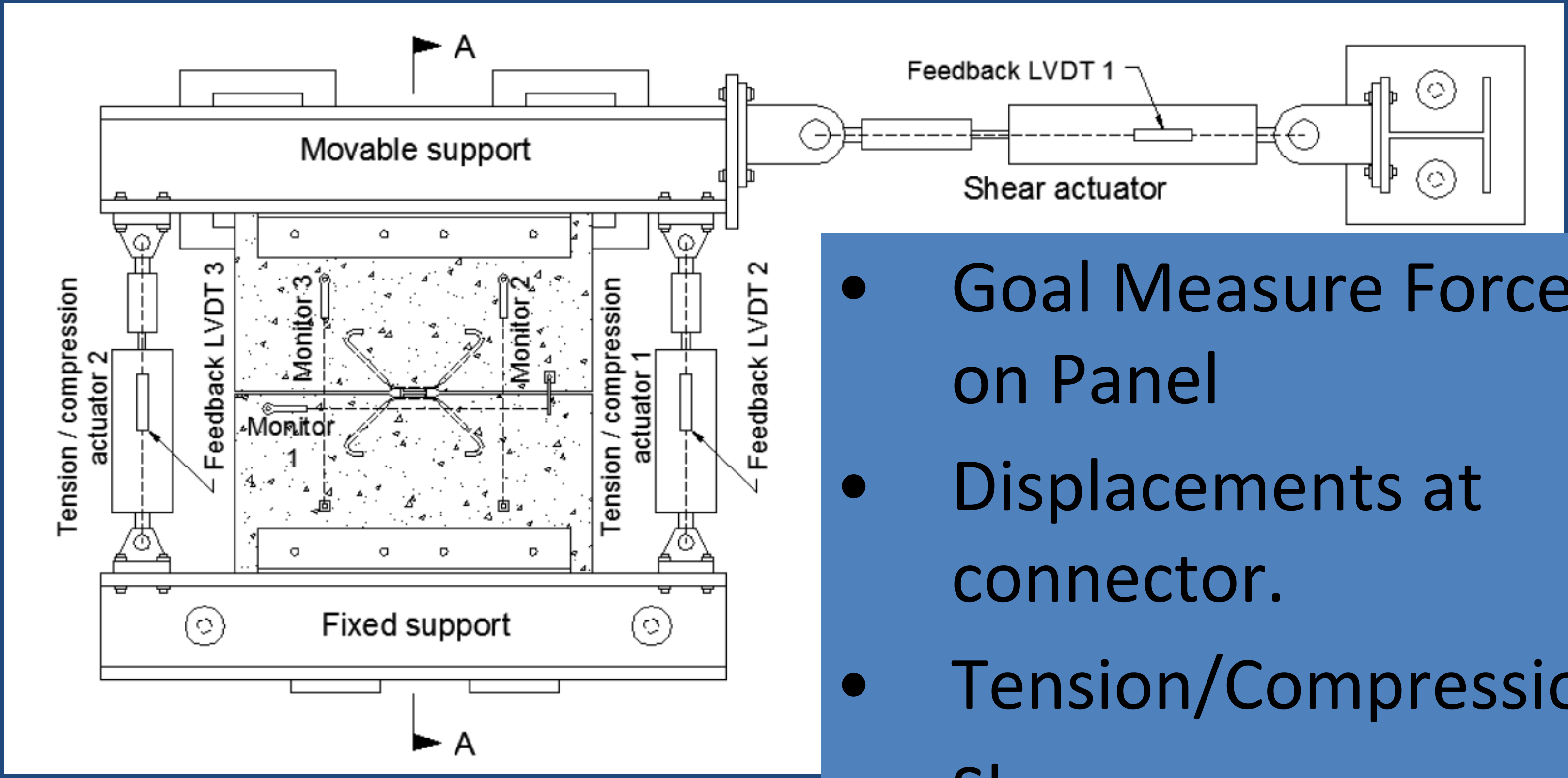


Figure C14.2.4-3 Possible test set-up.

Subassembly Requirements 4.2

- Panels installed in testing fixture

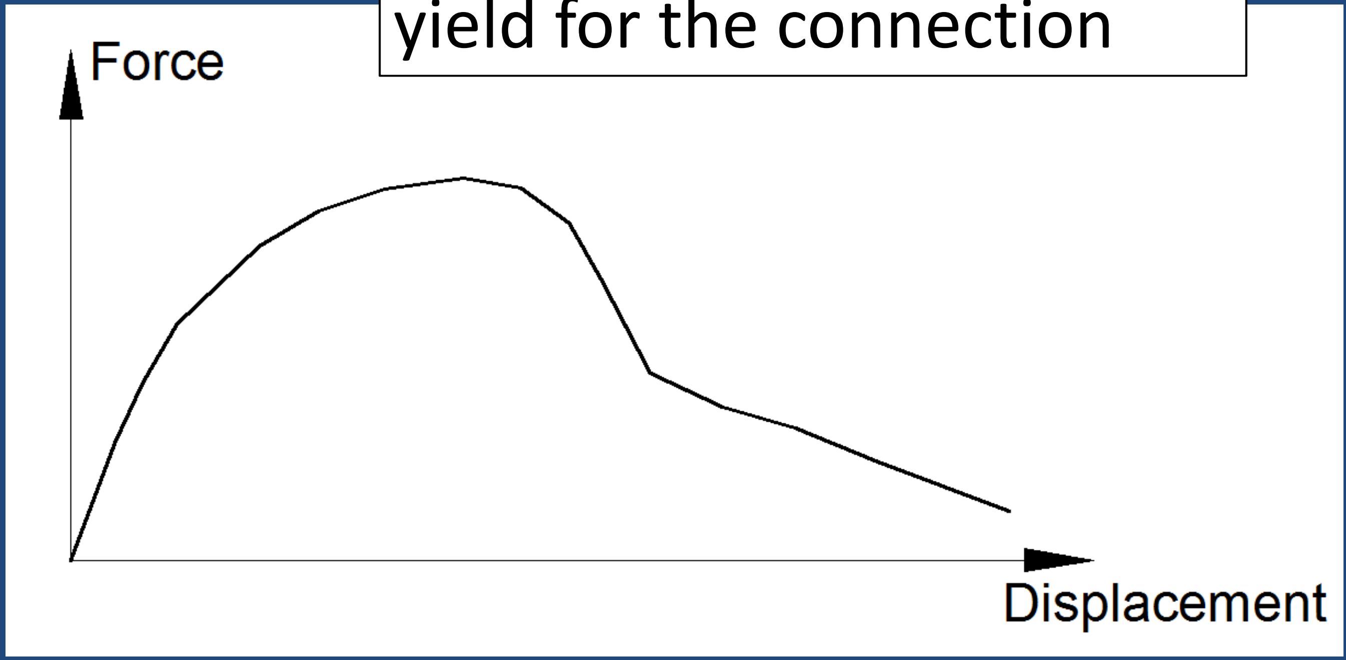


- Goal Measure Forces on Panel
- Displacements at connector.
- Tension/Compression
- Shear

5.3 Loading Protocols - Monotonic

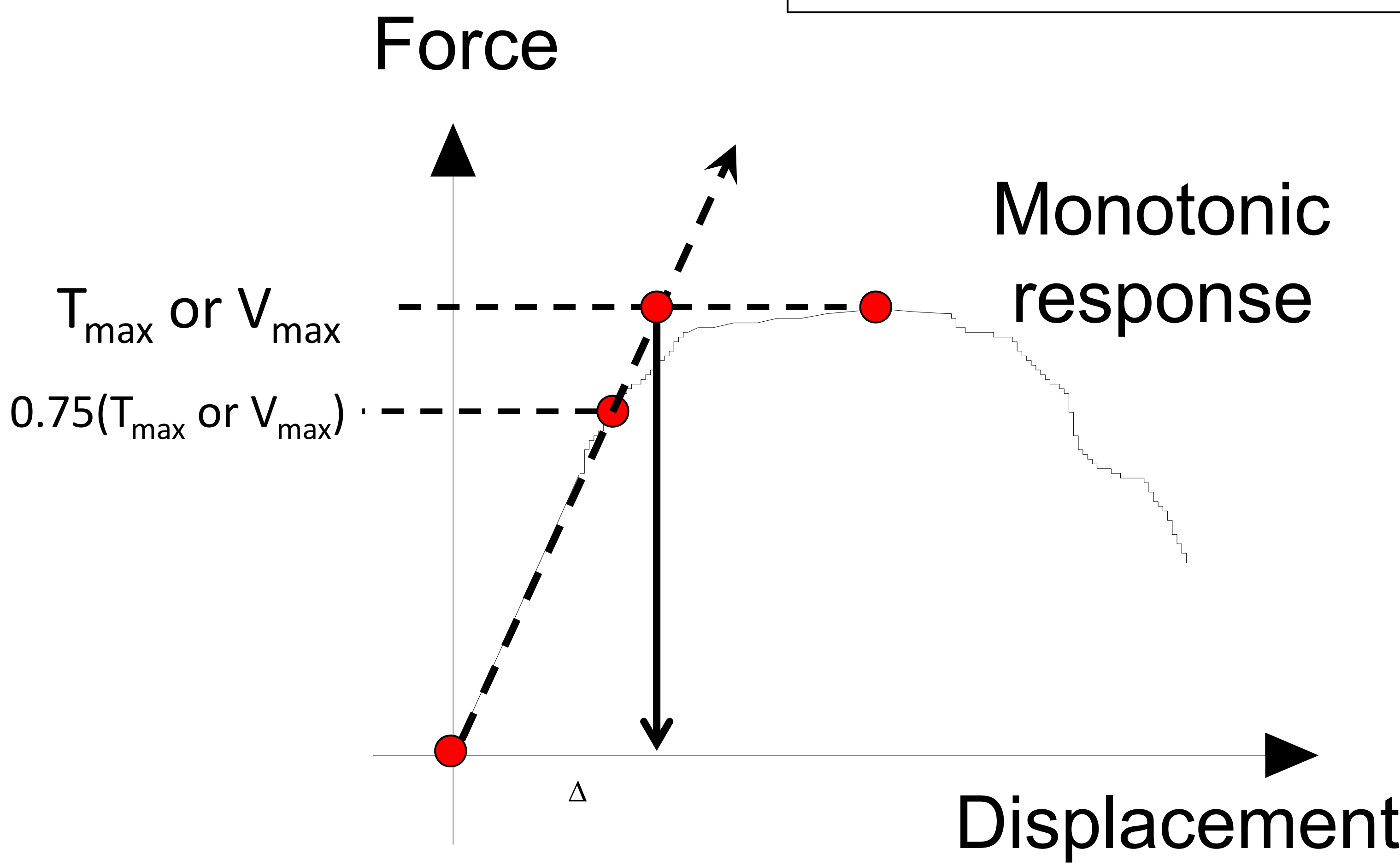
- Monotonic Test – Determine the reference deformation for the connection.

Determine an effective yield for the connection

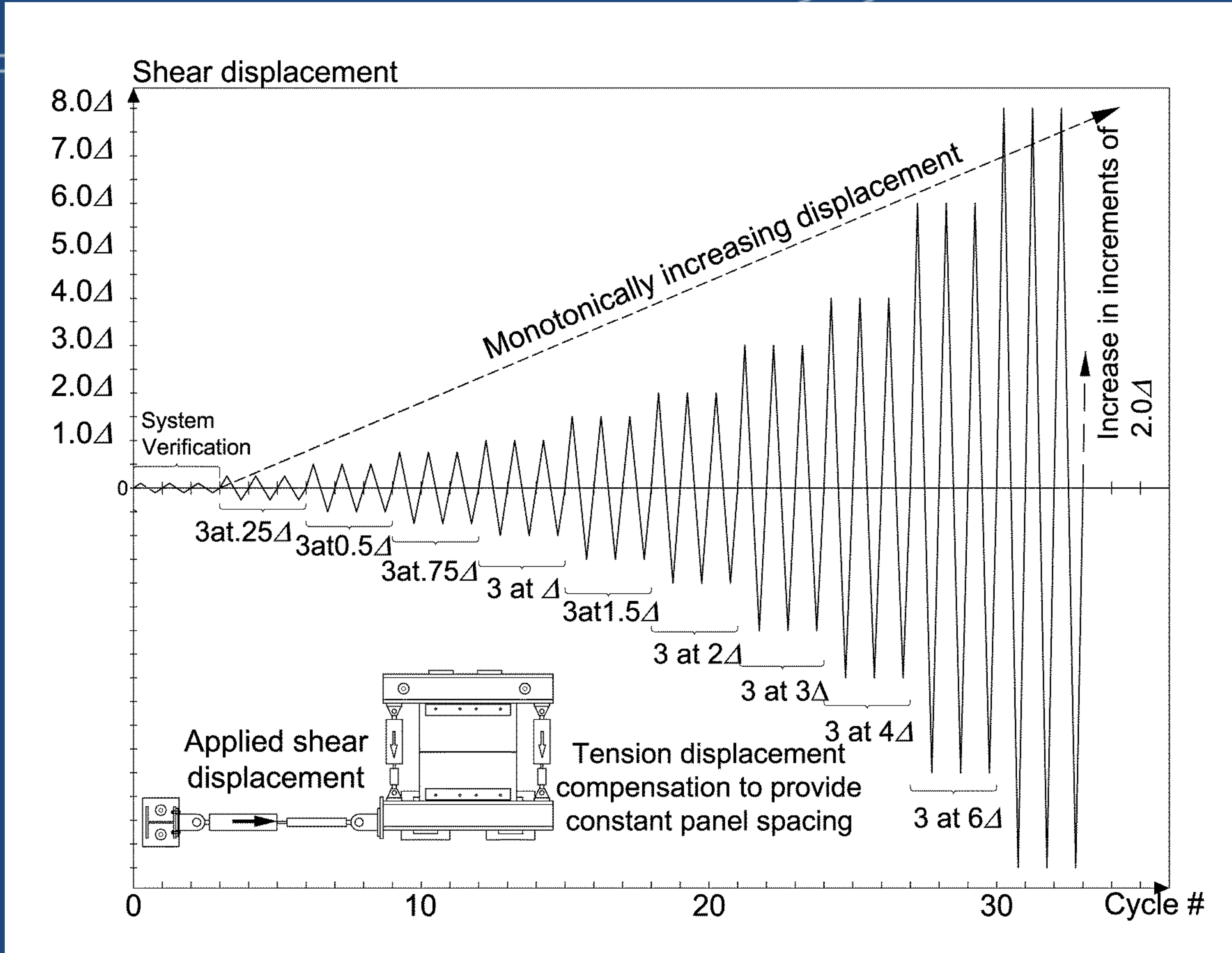


5.2 Loading Protocols - Monotonic

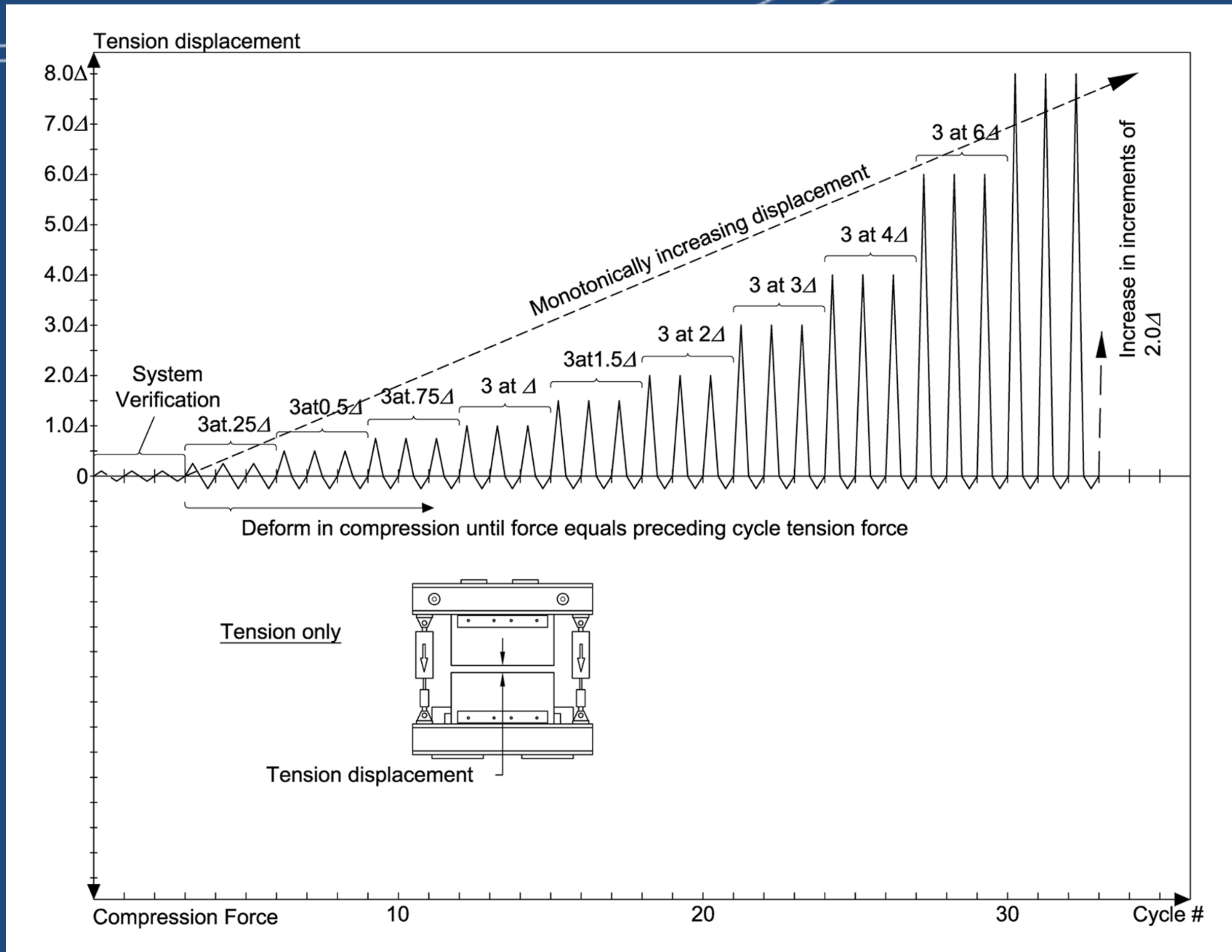
Reference Deformation, Δ



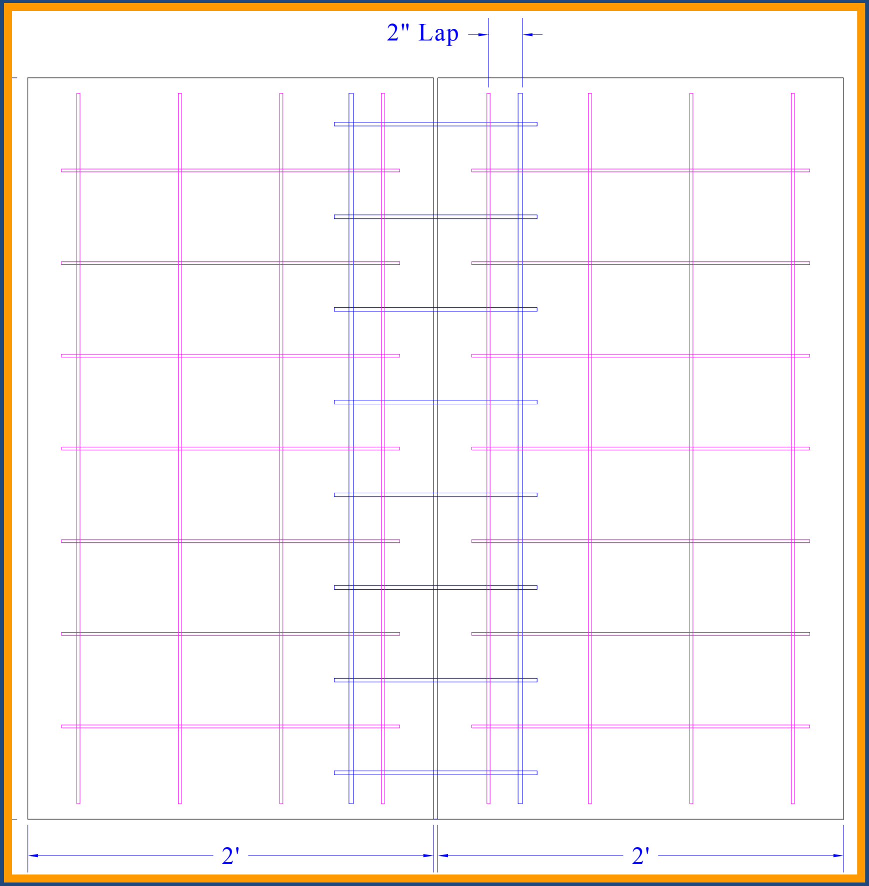
5.2 Loading Protocols – Cyclic Shear



5.3 Loading Protocols – Cyclic Tension

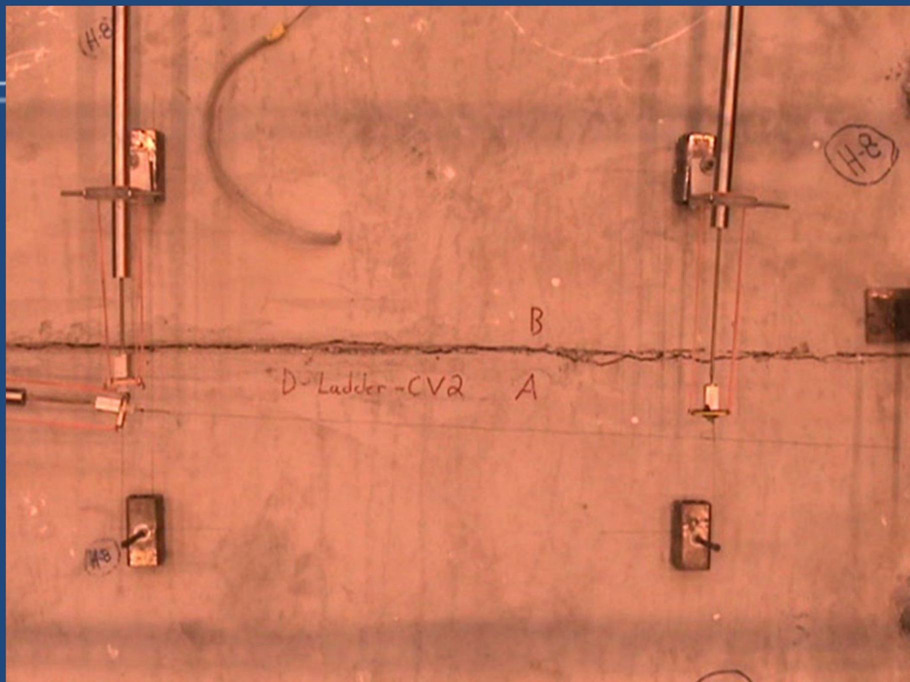


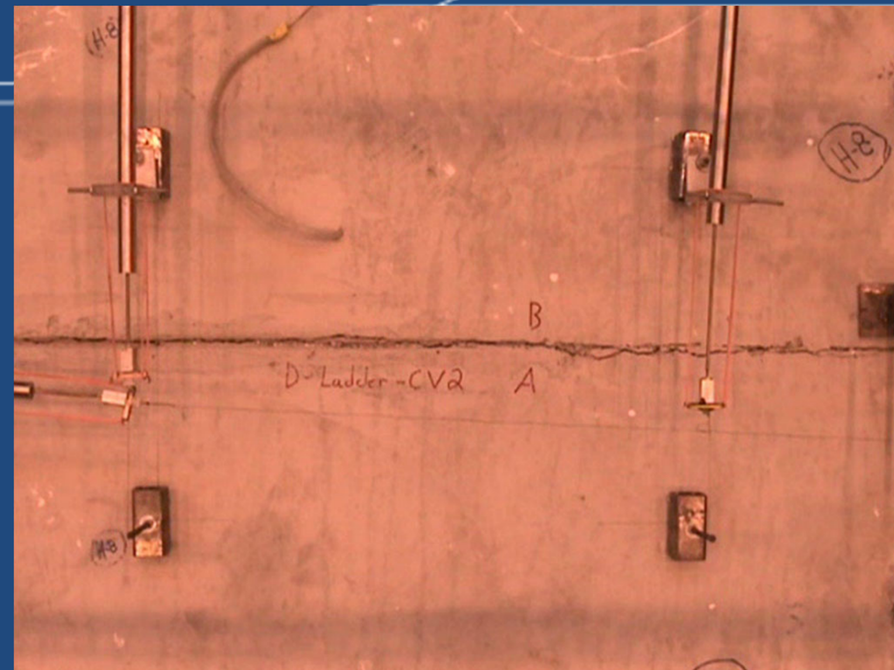
Ductile Joint Ladder Connection

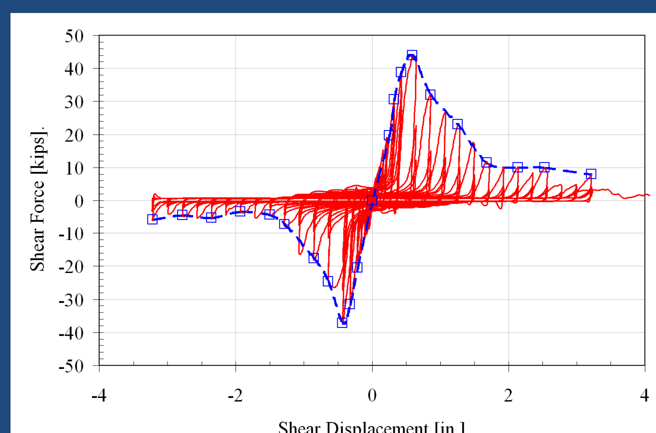


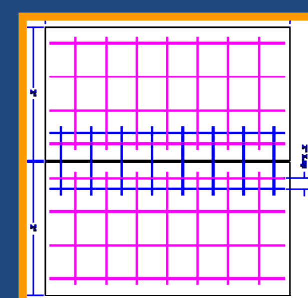
- 50 mm Lap Joint
- 1018 Steel no cold rolling
- Tension Capacity ~ 133kN
- High Deformation Connection ~ 50 mm.

Sample Results

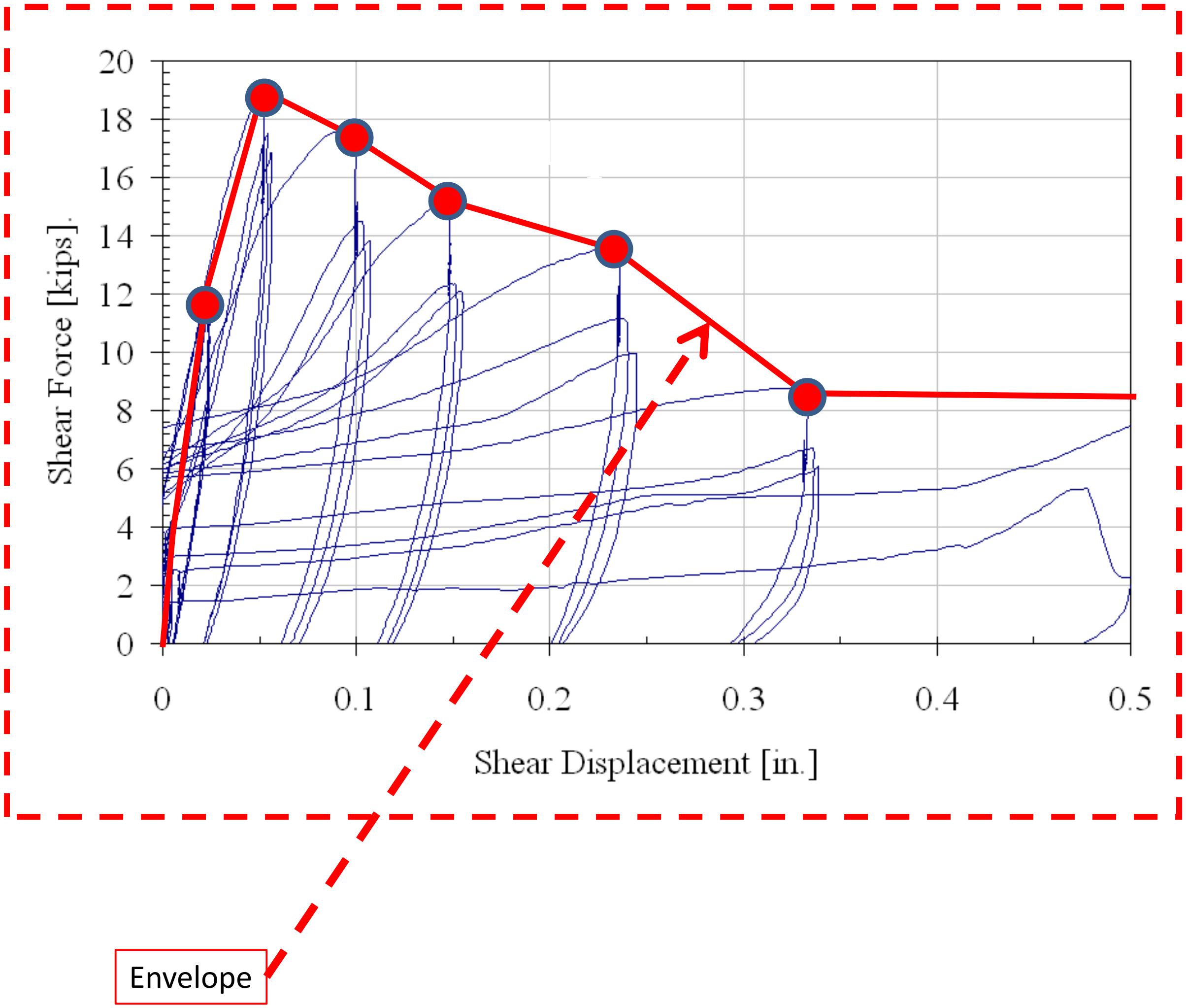


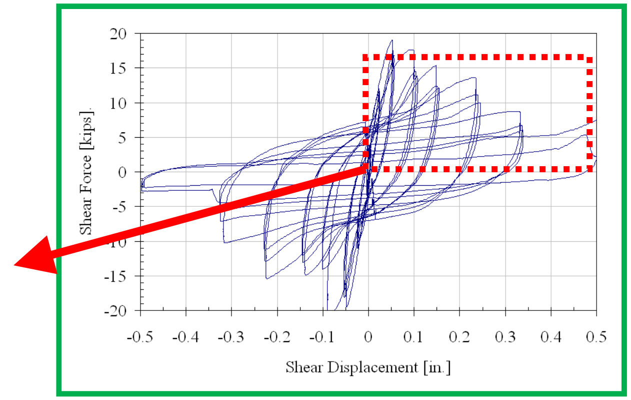






Determine Envelope of Cyclic Results

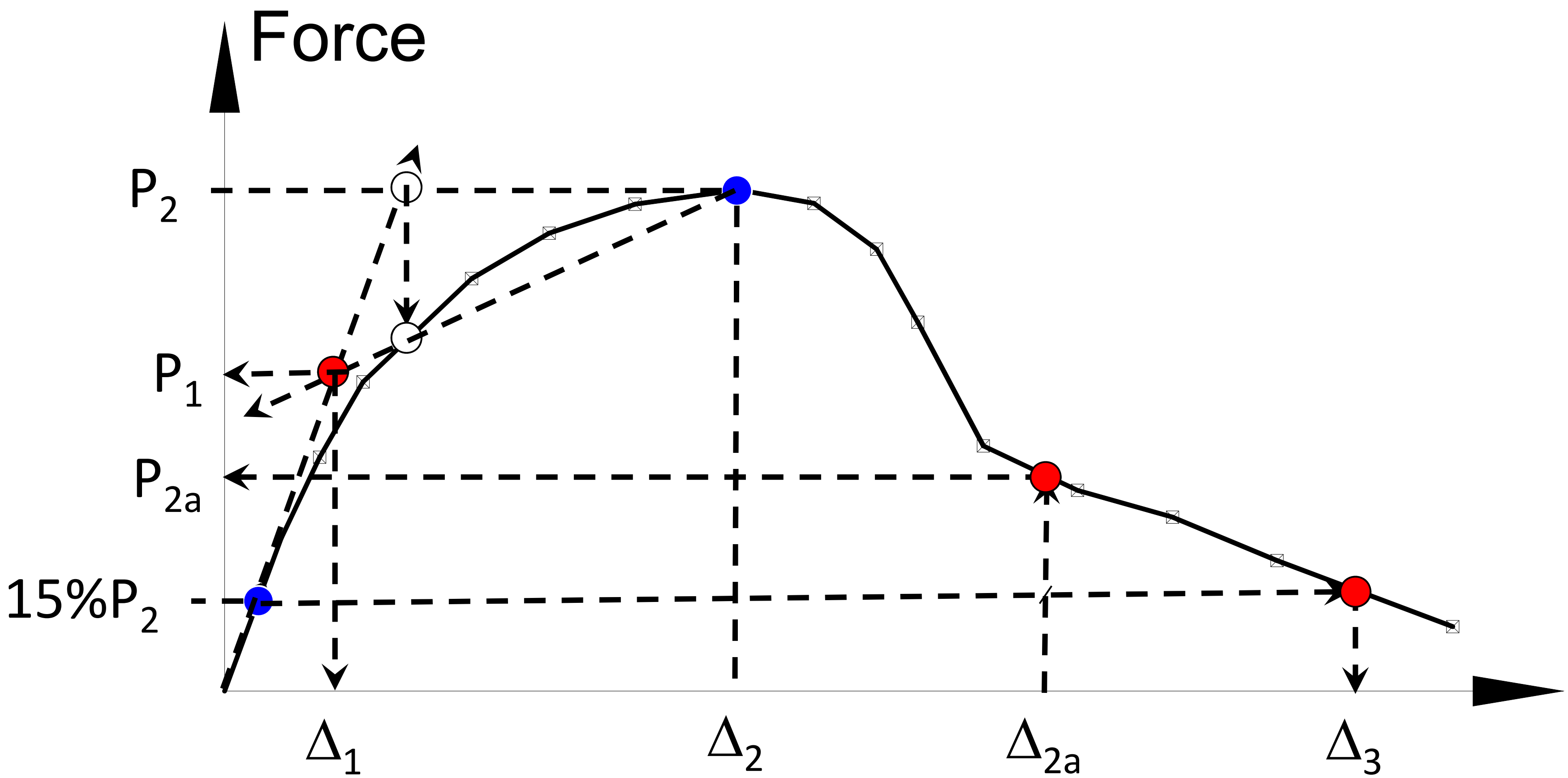




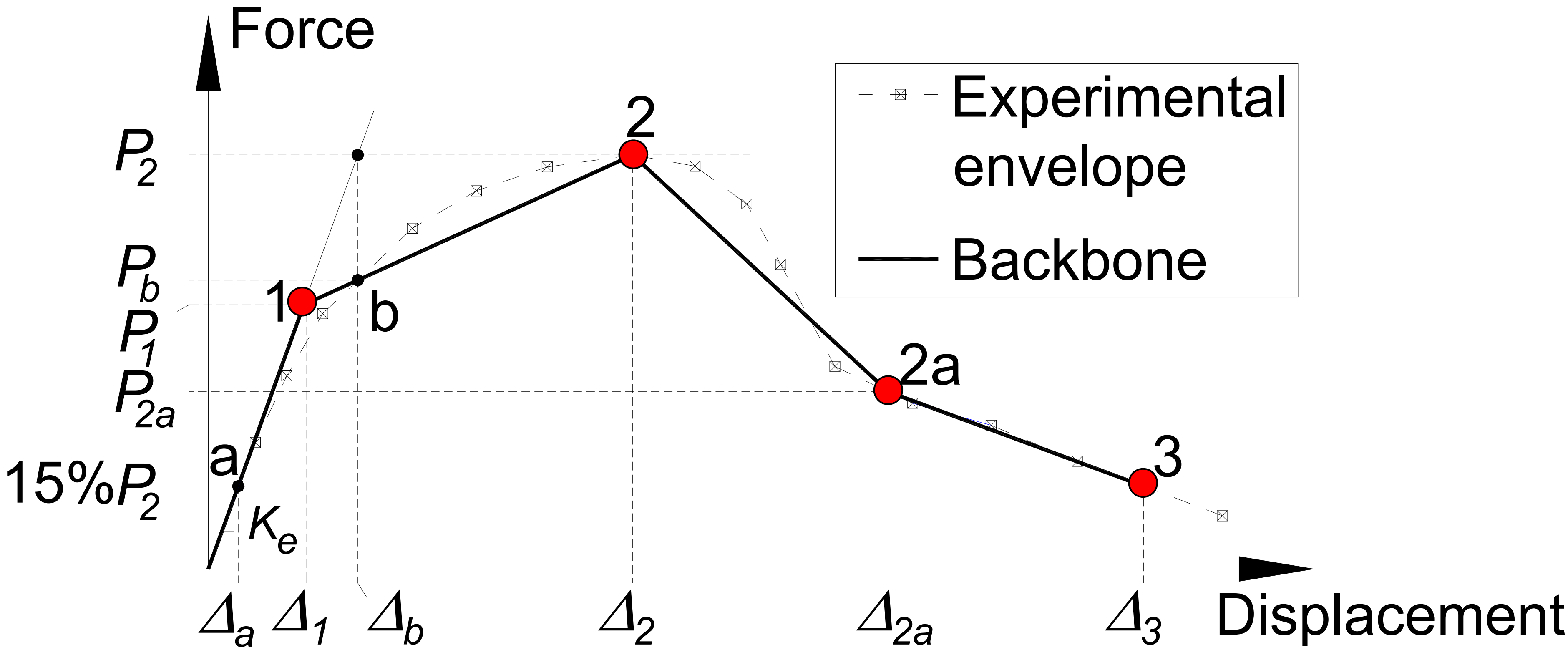
Section 7.2

Force corresponding to the peak displacement applied during the first cycle of each increment of deformation.

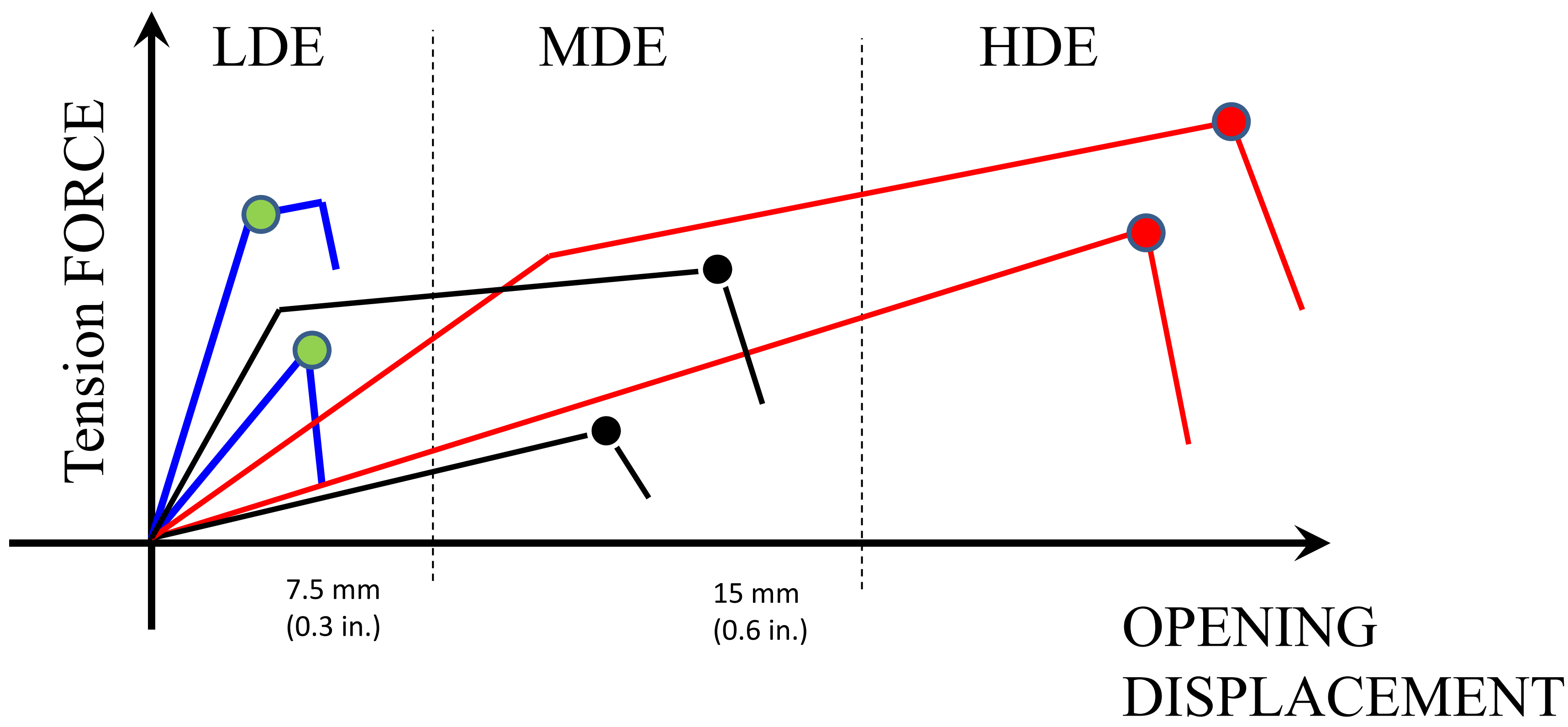
Backbone Development from Envelope



Backbone Development from Envelope



Deformation Classification



LDE – Low Deformability Element

MDE – Moderate Deformability Element

HDE – High Deformability Element

High Deformability Elements

- *14.2.4.3.5 Deformed Bar Reinforcement.* Deformed bar reinforcement (ASTM A615 or ASTM A706) placed in cast-in-place concrete topping or cast-in-place concrete pour strips and satisfying the cover, lap, and development requirements of ACI 318 shall be deemed to qualify as High Deformability Elements (HDE).

Pour Strips
HDE

High Deformability Elements

- *14.2.4.3.6 Special Inspection.* For precast concrete joint reinforcement or connector classified as a High Deformability Element (HDE), installation of the embedded parts and completion of the reinforcement or connection in the field shall be subject to continuous special inspection performed by qualified inspectors under the supervision of a licensed design professional.

HDE Requires Special Inspection

Precast Concrete Diaphragm Design

- Deficiencies revealed
- Research conducted
- Code changed
- Connections qualified
- Design procedures updated