Slender Wall Behavior & Modeling

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with contributions from
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Presentation Overview

- FEMA 356 Requirements
  - General requirements
  - Modeling approaches
    - Beam-column, fiber, general
  - Stiffness, strength
- Experimental Results
  - Model Assessment
    - Rectangular, T-shaped cross sections
  - FEMA backbone relations
    - Flexure dominant walls

FEMA 356 – Nonlinear Modeling for Buildings with Slender RC Walls

FEMA 356 – RC Walls

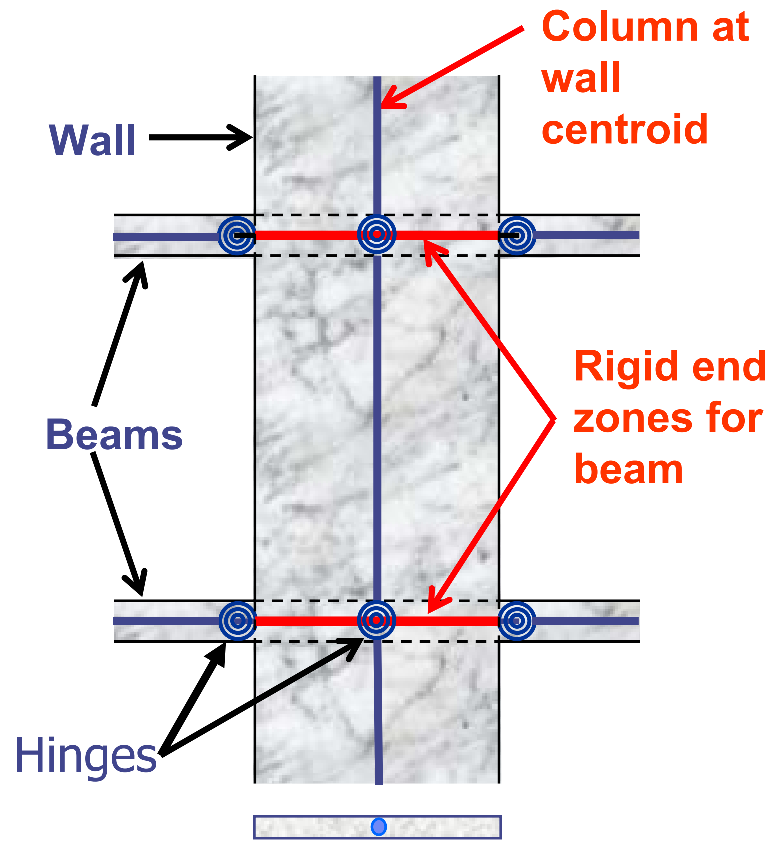
- General Considerations – 6.8.2.1
  - Represent stiffness, strength, and deformation capacity
  - Model all potential failure modes anywhere along the wall (member) height
  - Interaction with other structural and nonstructural elements shall be considered
  - So, we must consider any and everything

Wall Modeling Approaches

- Equivalent beam-column model
  - $h_w/l_w \geq 3$
- Modified equivalent beam-column
  - Rectangular walls ($h_w/l_w \leq 2.5$)
  - Flanged walls ($h_w/l_w \leq 3.5$)
- Multiple-line-element and Fiber models
  - Concrete and rebar material models
- General wall model

Equivalent Beam-Column Model

- $h_w/l_w \geq 3$:
  - Use of equivalent beam-column permitted
  - Neutral axis migration not considered
  - Interaction with in- and out-of-plane elements not properly considered
  - Axial load Impacts
    - Stiffness (EI)
    - Strength (P-M)
  - L- or T-shaped walls
    - Where to locate the element?
    - Elastic centroid?



$$A_{column} = t_w l_w$$

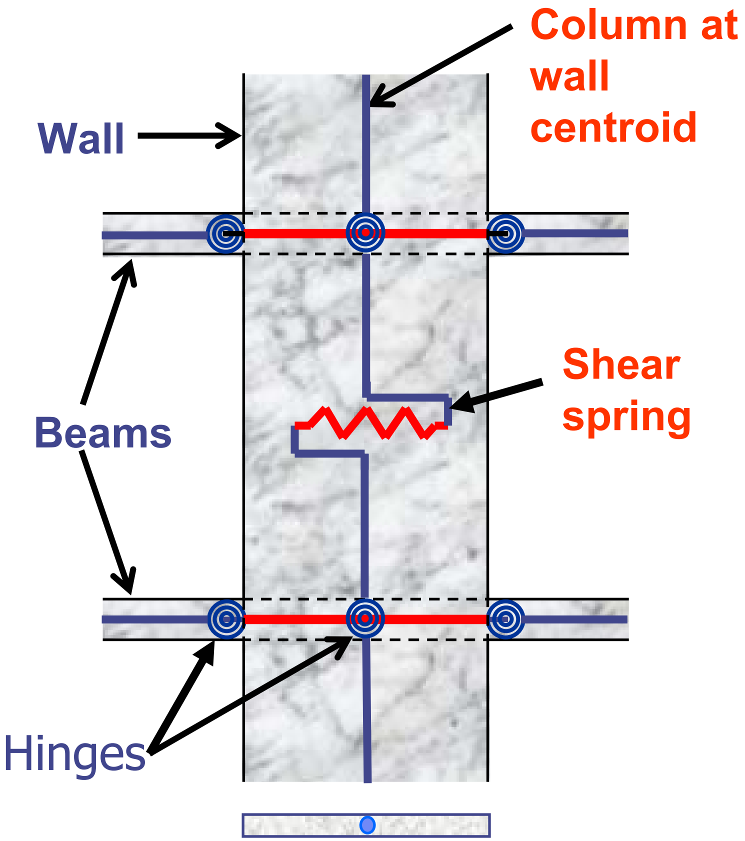
$$I_{column} = \alpha_{cracking}\left[\frac{1}{12} t_w l_w^3\right]$$

Modified Beam - Column Model

- Rectangular walls ($h_w/l_w \leq 2.5$) & Flanged walls ($h_w/l_w \leq 3.5$):

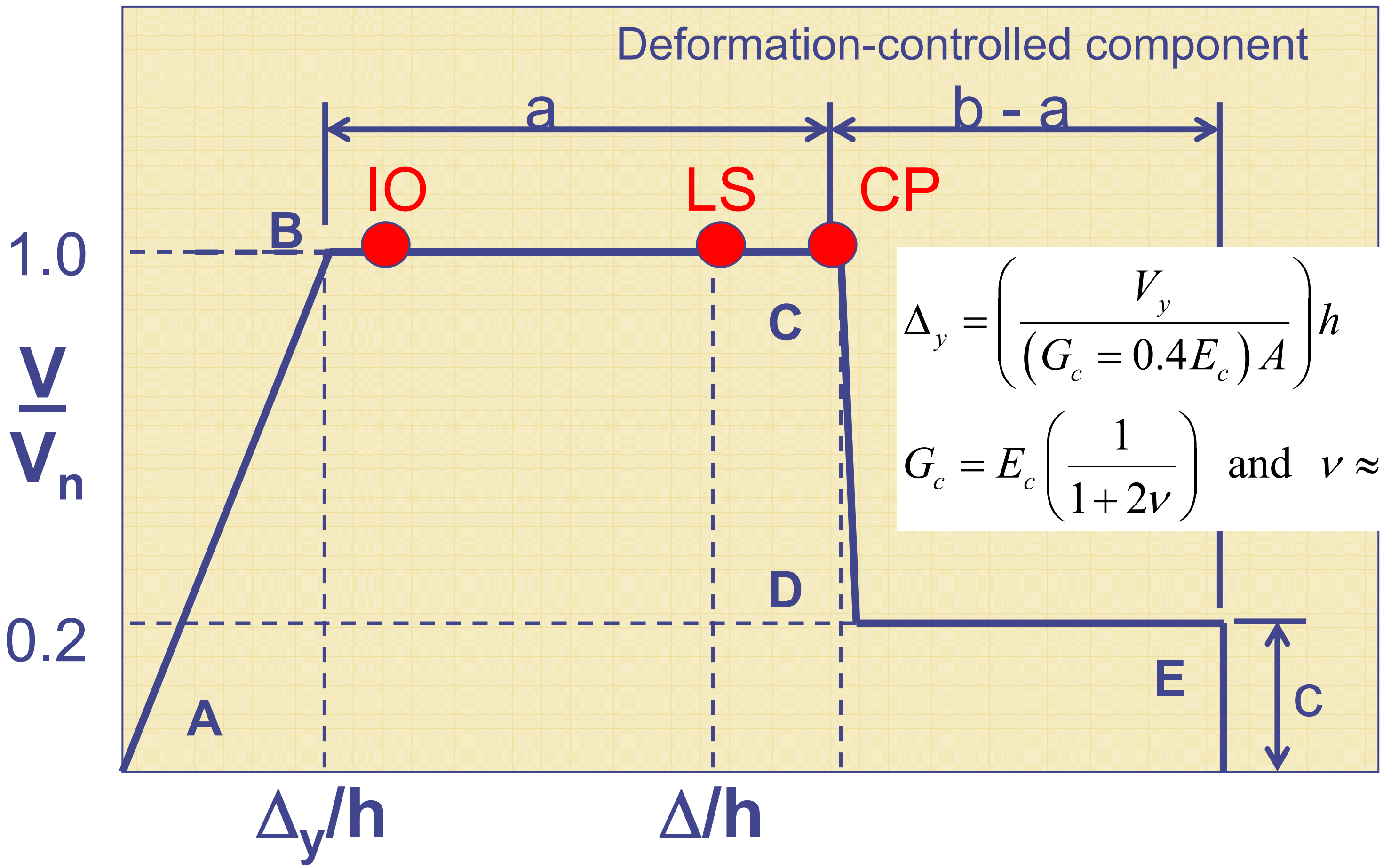
Use of modified beam-column element with added shear spring

Nonlinear flexure/shear are uncoupled using this approach



Modified Beam - Column Model

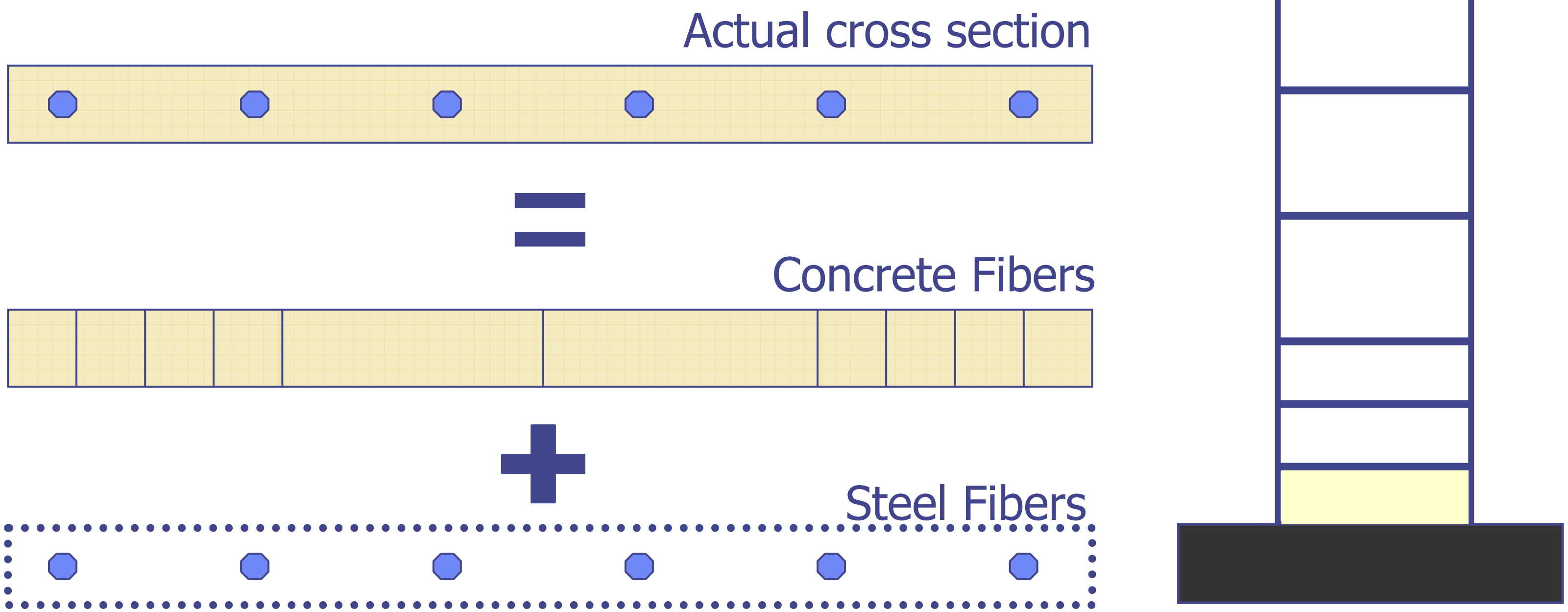
- Shear force – deformation properties



$$\Delta_y = \left(\frac{V_y}{\left(G_c = 0.4E_c\right) A} \right) h$$

$$G_c = E_c \left(\frac{1}{1+2\nu} \right) \quad \text{and} \quad \nu \approx 0.2$$

Fiber Section Model



- Typically use a more refined mesh where yielding is anticipated; however,
- Nonlinear strains tend to concentrate in a single element, thus, typically use an element length that is approximately equal to the plastic hinge length (e.g., $0.5l_w$). Might need to calibrate them first (this is essential).
- Calibration of fiber model with test results, or at least a plastic hinge model, is needed to impose a “reality” check on the element size and integration points used.

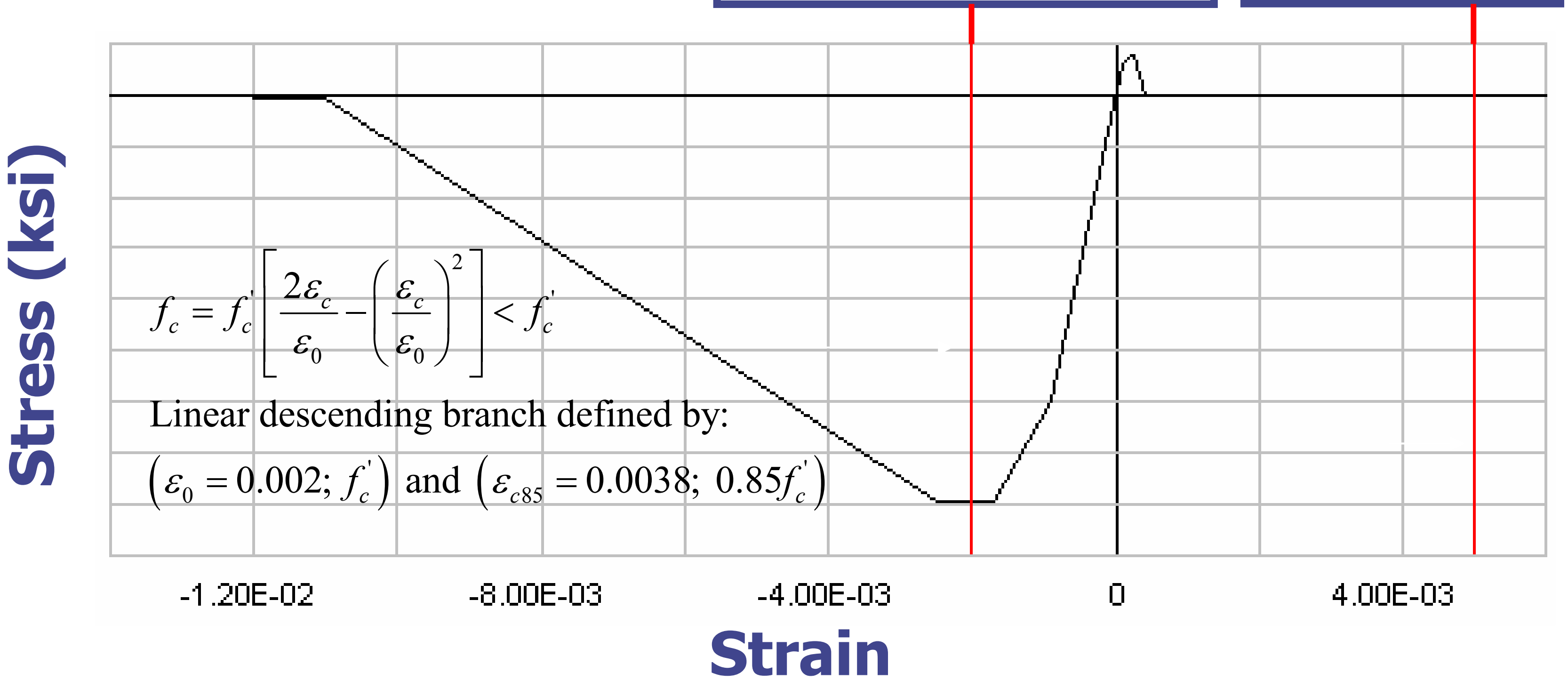
Materials

- Unconfined Concrete

Maximum permissible compressive strain for unconfined concrete (FEMA 356 S6.4.3.1)

ε = 0.002 or 0.005

Limit state associated with crack width



In the absence of cylinder stress-strain tests, Saatcioglu & Razvi (ASCE, JSE, 1992) recommend relation based on work by Hognestad.

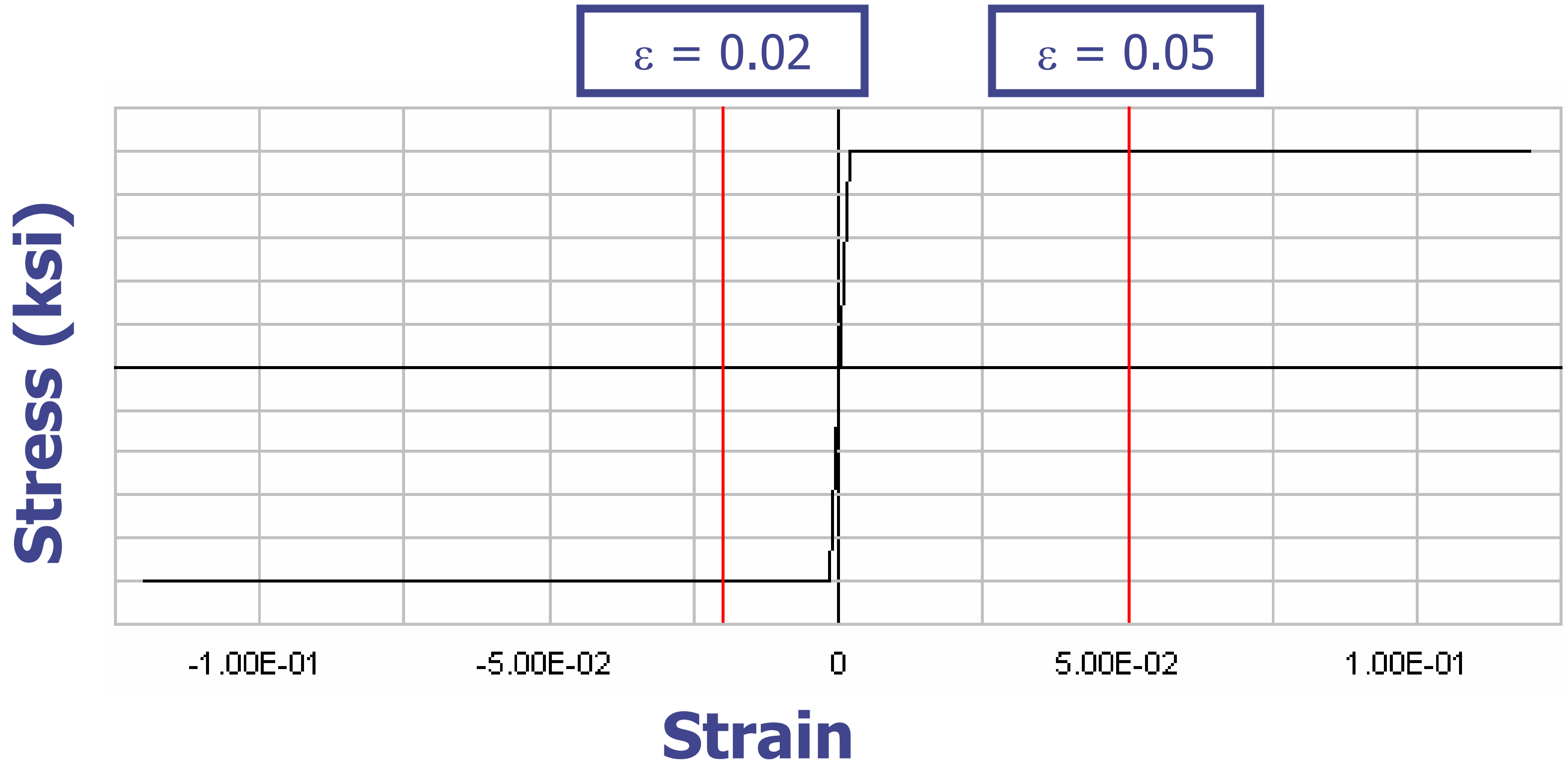
Materials

- Confined Concrete (FEMA 356 6.4.3.1)
  - Use appropriate model, e.g.:
    - Saatcioglu & Razvi (ASCE JSE, 1992, 1995)
    - Mander (ASCE JSE, 1988)
    - Modified Kent & Park (ASCE JSE, 1982)
      - For reference
  - FEMA 356 Qualifications:
    - Maximum usable compression strain based on experimental evidence and consider limitations posed by hoop fracture and longitudinal bar buckling.

Materials

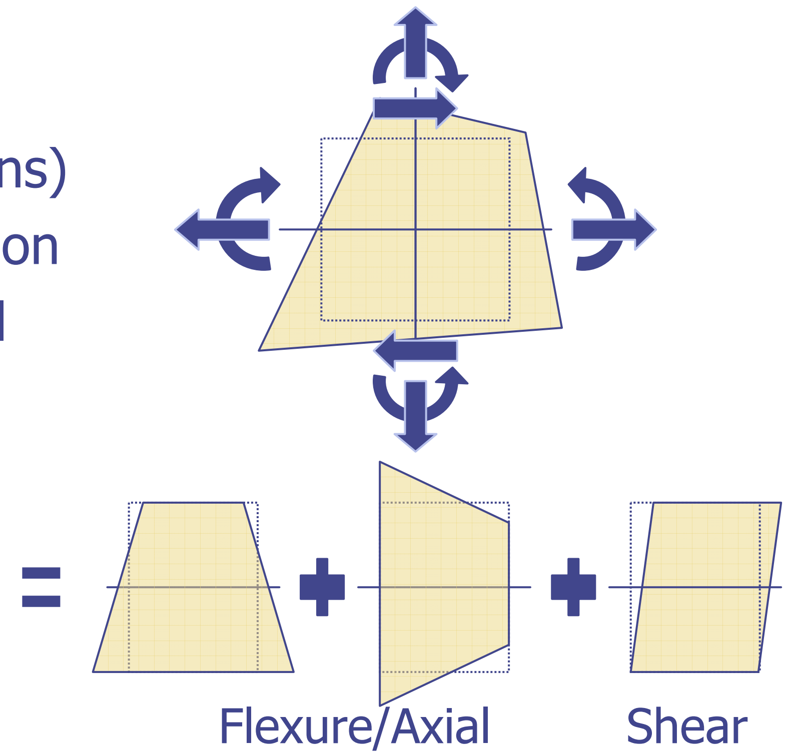
- Steel Material:

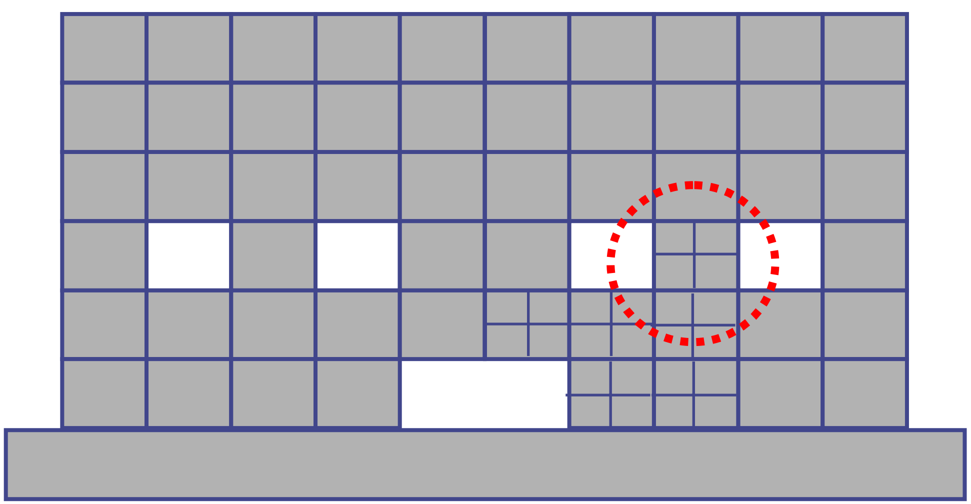
Maximum usable strain limits per FEMA 356 S6.4.3.1

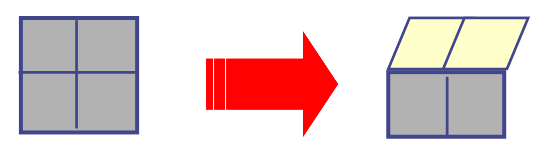


General Wall Models/FE Models

- e.g., RAM-PERFORM:
  - Flexure - fiber model (2-directions)
  - Shear - Trilinear backbone relation
  - Flexibility to model complex wall geometry
  - Mesh refinement issues



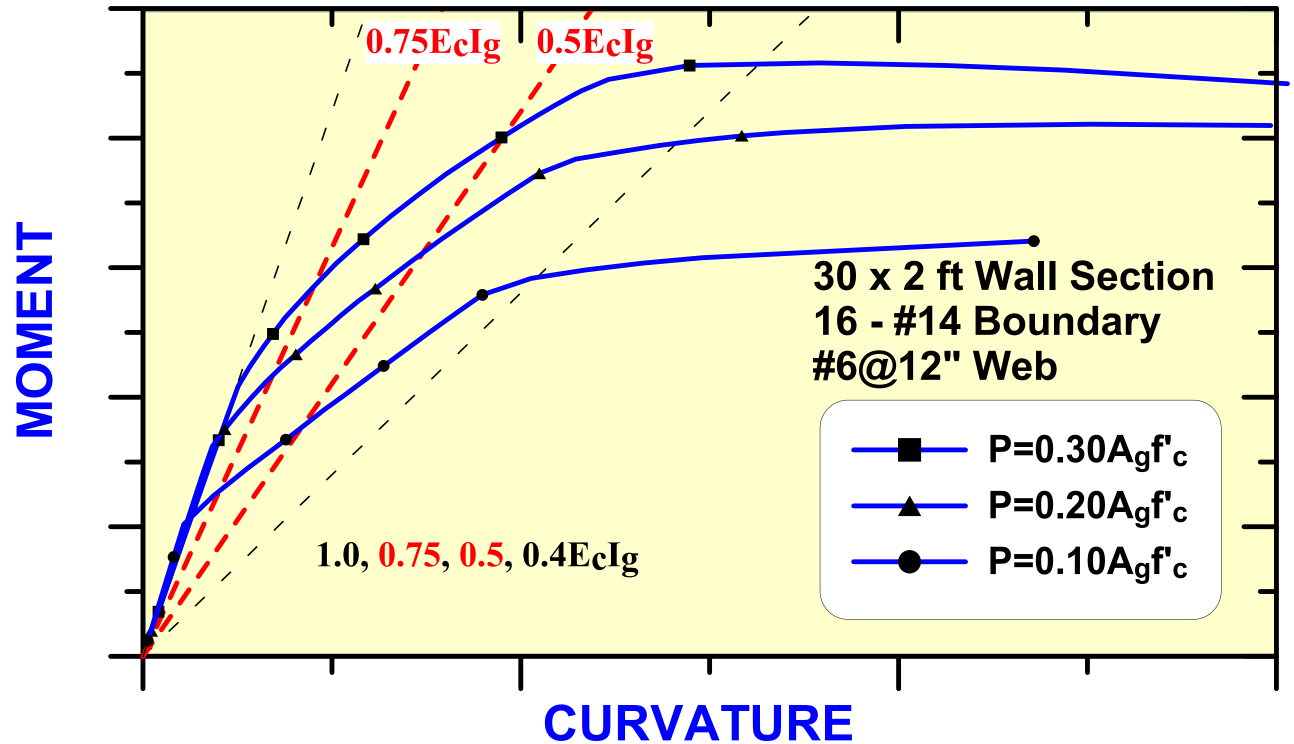




Concentration of nonlinear
Deformations in one element

Stiffness Modeling

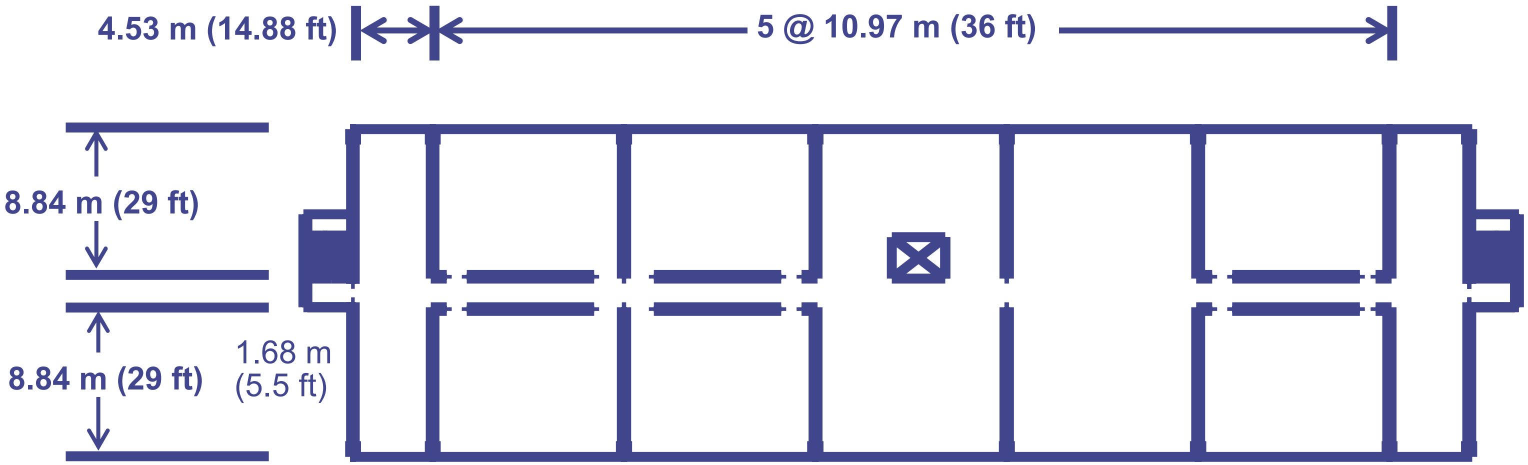
- FEMA 356 Section 6.8.2.2 – Use Table 6.5
  - Uncracked: $EI_{effective} = 0.8EI_g$
  - Cracked: $EI_{effective} = 0.5EI_g$



Wallace, et al., 4NCEE, Vol. 2, pp 359-368, 1990.

Response Correlation Studies

- Ten Story Building in San Jose, California
- Instrumented: Base, 6th Floor, and Roof
- Moderate Intensity Ground Motions – Loma Prieta



PLAN VIEW: CSMIP BUILDING 57356

Response Correlation Studies

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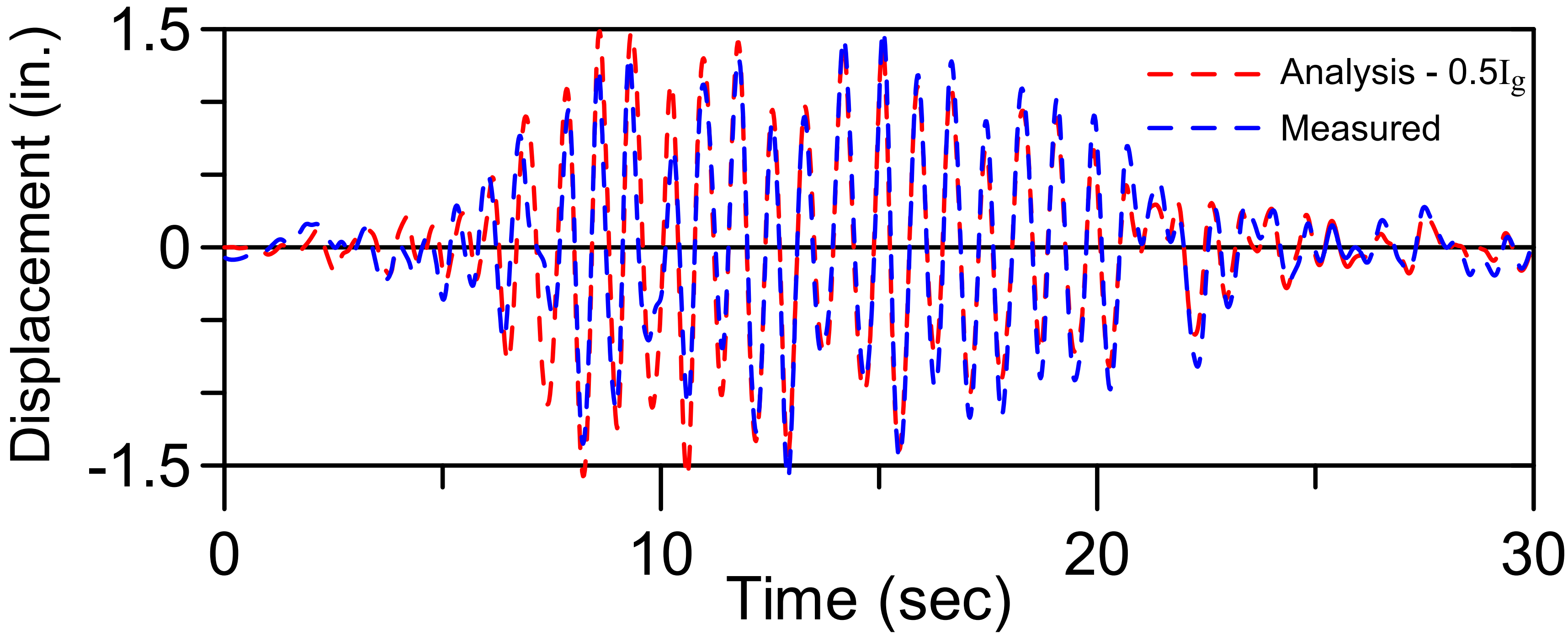


Strength Requirements

- ACI 318 Provisions
  - P_n- M_n
    - For extreme fiber compression strain of ε_c =0.003.
  - V_n
    - ACI 318-99,02,05 Equation 21-7

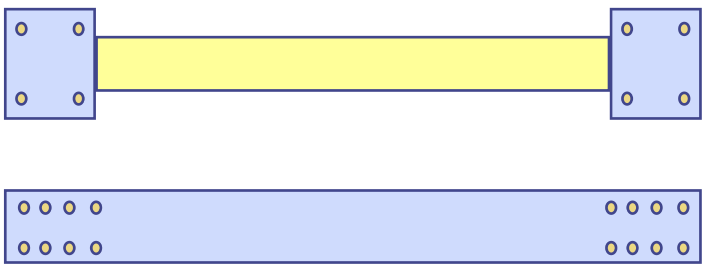
$$V_n = A_{cv}\left[\alpha_c\sqrt{f_c'} + \rho_t f_y\right]$$

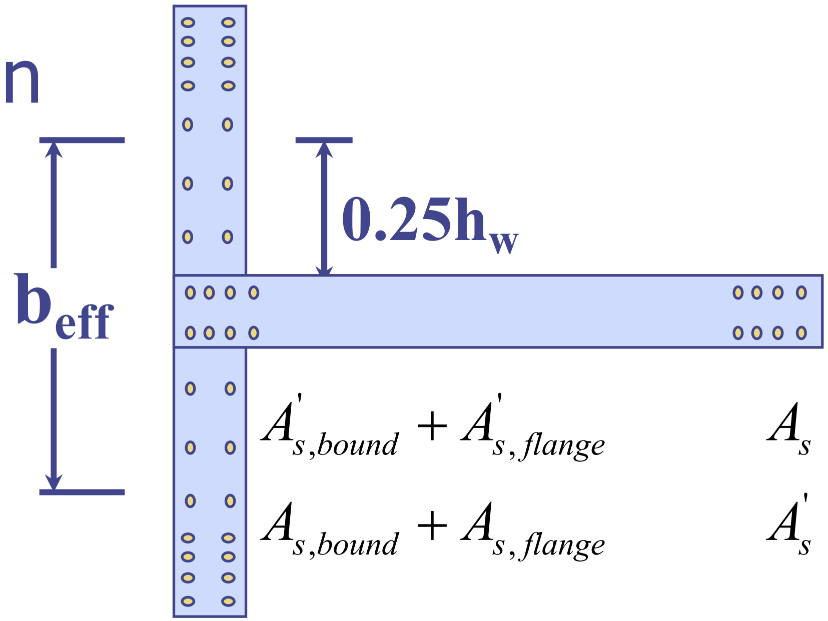
$$\left.\begin{aligned}\alpha_c &= 3.0 \quad \text{for } h_w / l_w \le 1.5\\ \alpha_c &= 2.0 \quad \text{for } h_w / l_w \ge 2.0\end{aligned}\right\}$$

Linear interpolation allowed for intermediate values

Definition of Wall Cross Section

- Cross-Section Definition

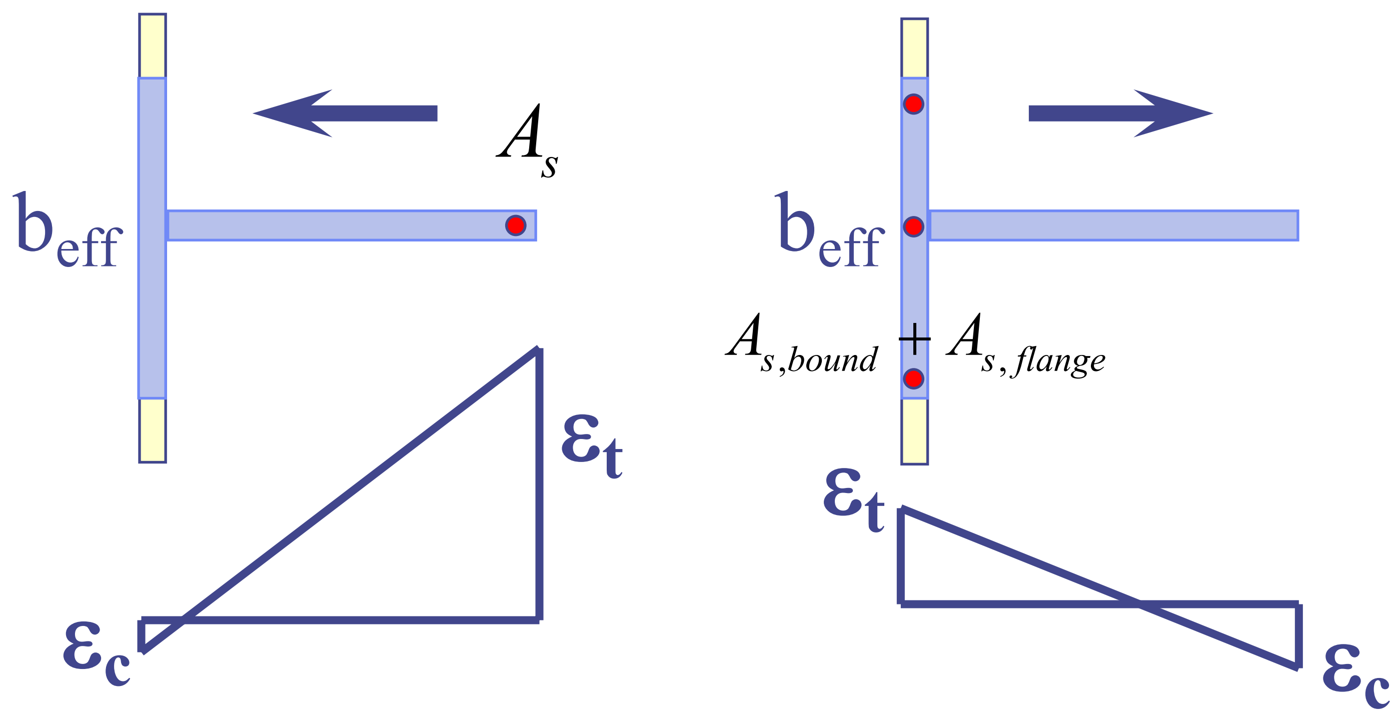




- Flexural strength
  - Consider all vertical reinforcement within web and within the effective flange width
- Consider the influence of openings on the strength and detailing requirements
  - ACI 318-02, 05 Appendix A – Strut & Tie Approach

Behavior of Flanged Walls

- Flange Compression versus Tension



Flange Compression
Low compressive strain
Large curvature capacity
M_n & V_u similar rectangle

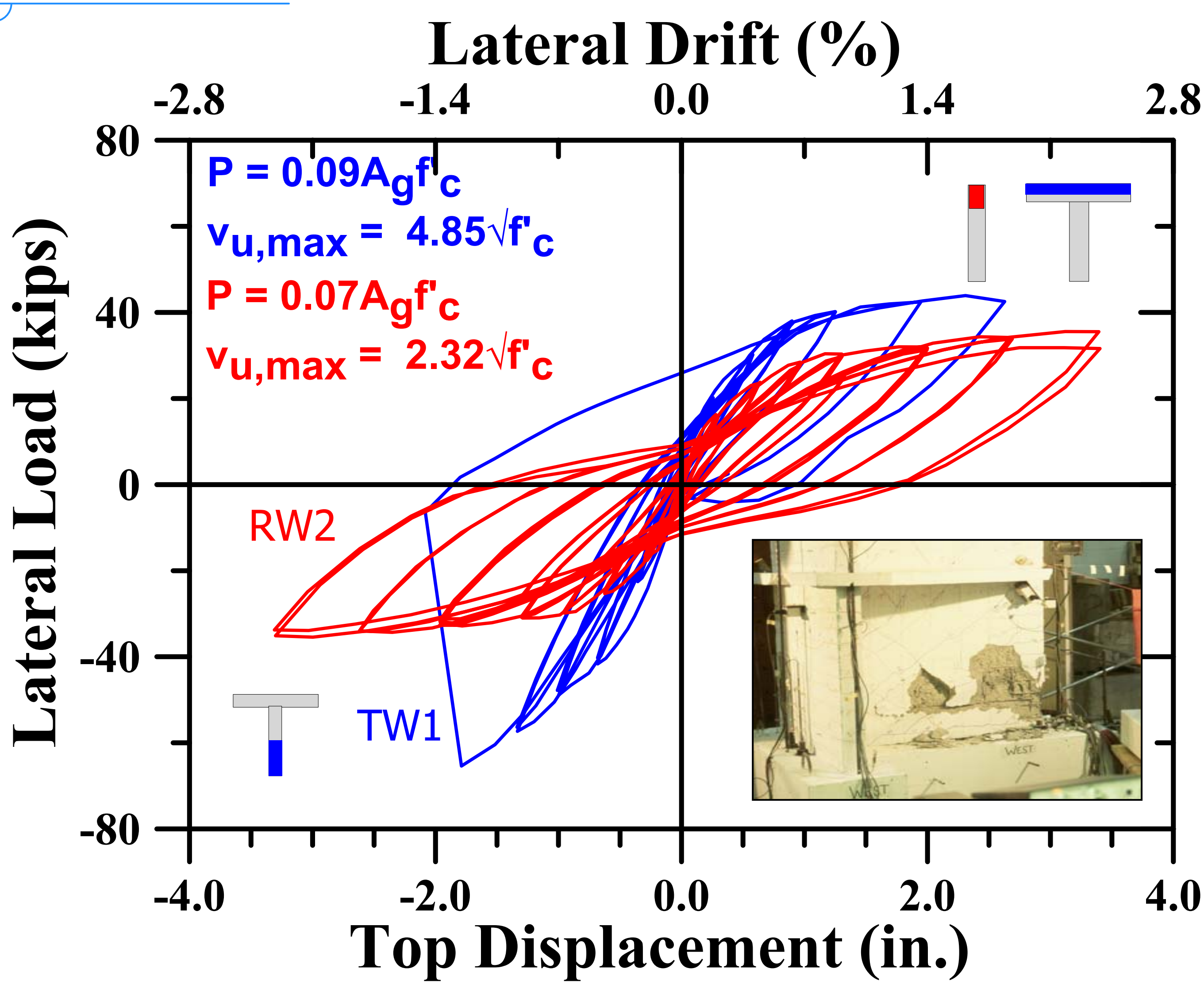
Flange Tension
Large compressive strain
Less curvature capacity
$M_n \Uparrow$ $V_u \Uparrow$

Experimental Results

- RW2 & TW1: ~ ¼ scale tests

Thomsen & Wallace, ASCE JSE, April 2004.

Experimental Results



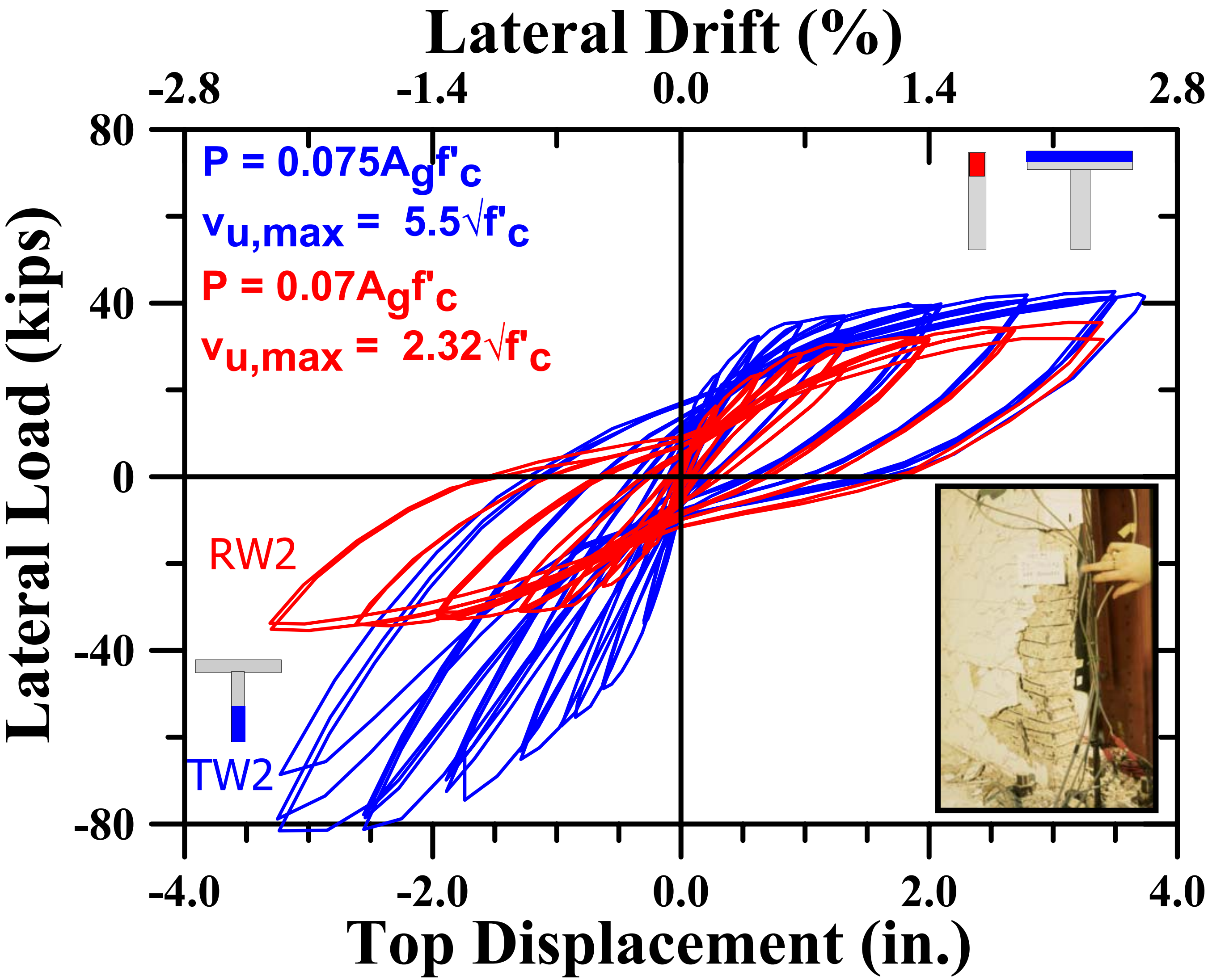
Abrupt Lateral Strength loss Due to buckling; Axial load Maintained

Experimental Results

- RW2 & TW2: ~ ¼ scale tests

Thomsen & Wallace, ASCE JSE, April 2004.

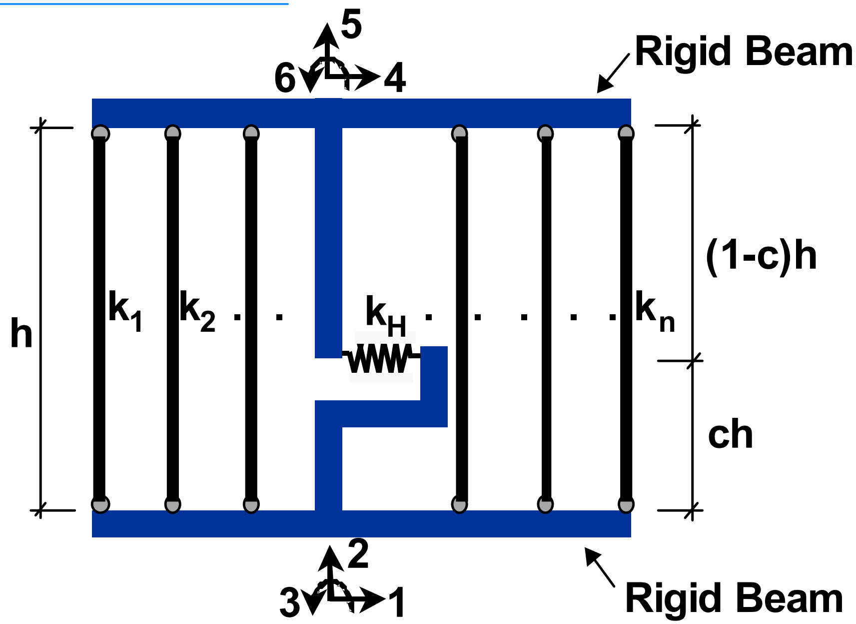
Experimental Results

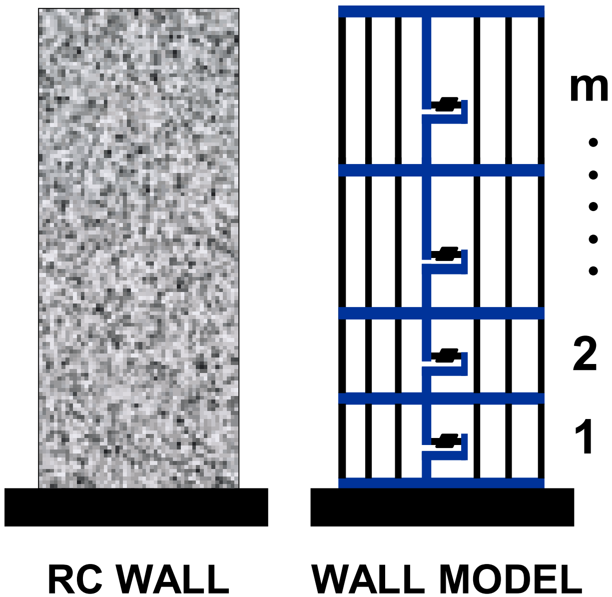


Lateral strength loss due to lateral Instability due to spalling; Axial load maintained

Model Assessment – Comparison of Analytical and Experimental results

MVLE (Fiber) Model





Basic assumptions:

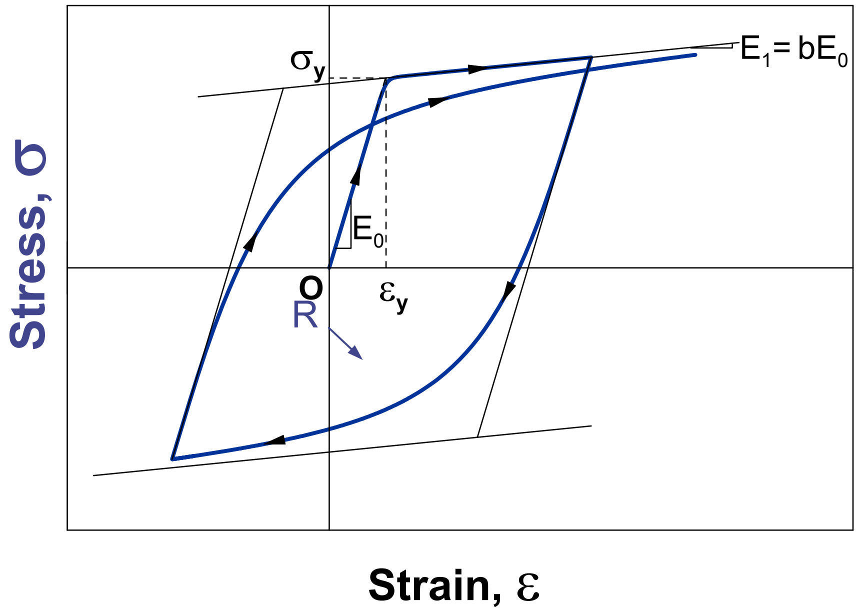
- Plane sections (rigid rotation of top/bottom beams
- Uniaxial material relations (vertical spring elements)

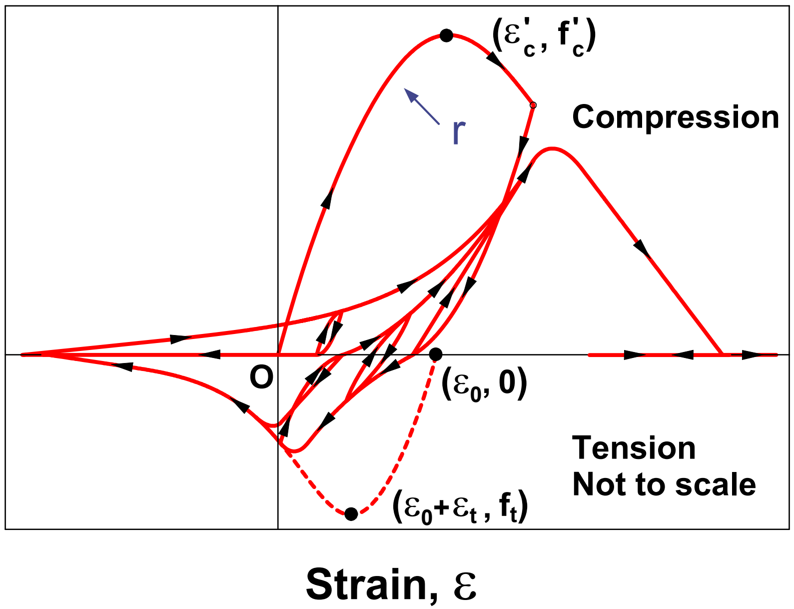
MVLE Model versus Fiber Model:

- Similar to a fiber model except with constant curvature over the element height (vs linear for fiber model)

Orakcal, Wallace, Conte; ACI SJ, Sept-Oct 2004.

Material (Uni-axial) Models





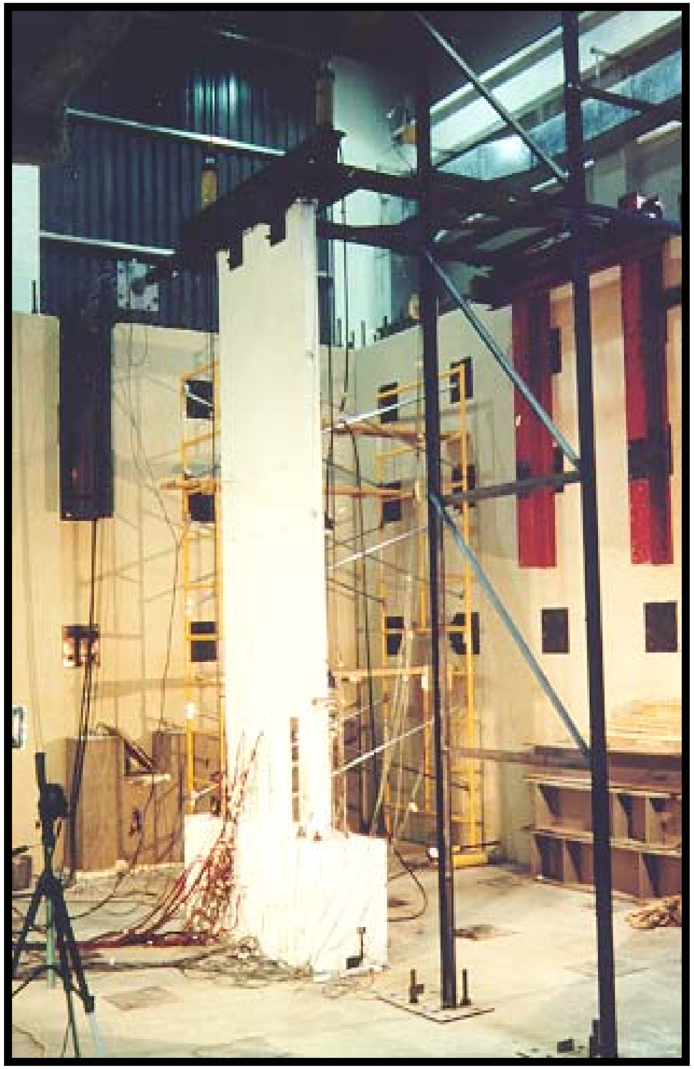
Reinforcing Steel :

- Menegotto and Pinto (1973)
- Filippou et al. (1984)
  - Simple but effective
  - Degradation of cyclic curvature

Concrete :

- Chang and Mander (1994)
  - Generalized (can be updated)
  - Allows refined calibration
  - Gap and tension stiffening

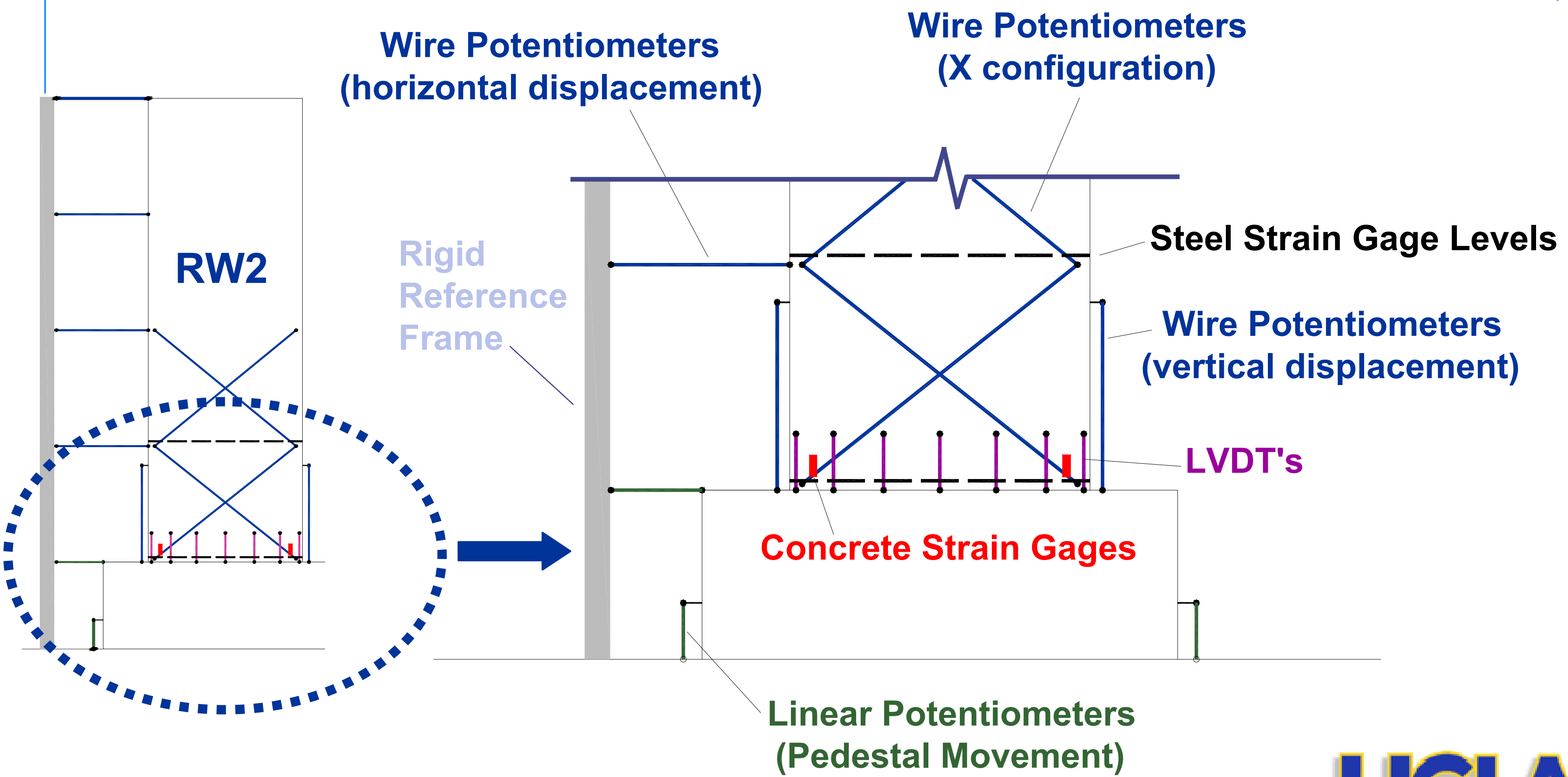
Model Assessment



- **Approximately 1/4 scale**
- **Aspect ratio = 3**
- **Displacement – based evaluation for detailing provided at the wall boundaries**
- **12 ft tall, 4 ft long, 4 inches thick**
- **#3 vertical steel, 3/16” hoops/ties**
- **#2 deformed web steel**
- **Constant axial load**
- **Cyclic lateral displacements applied at the top of the walls**

Instrumentation

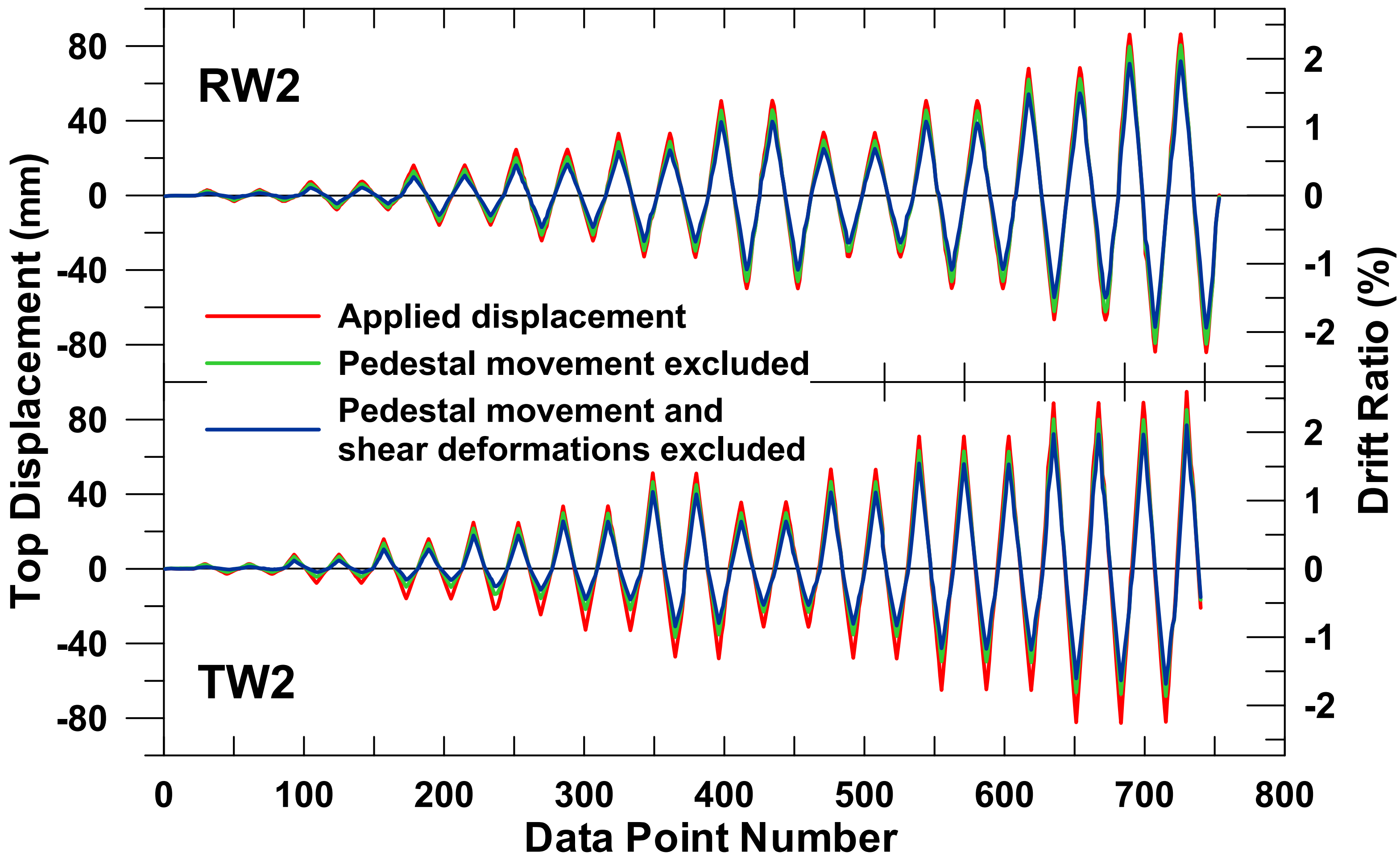
- **Extensive instrumentation provided to measure wall response at various locations**



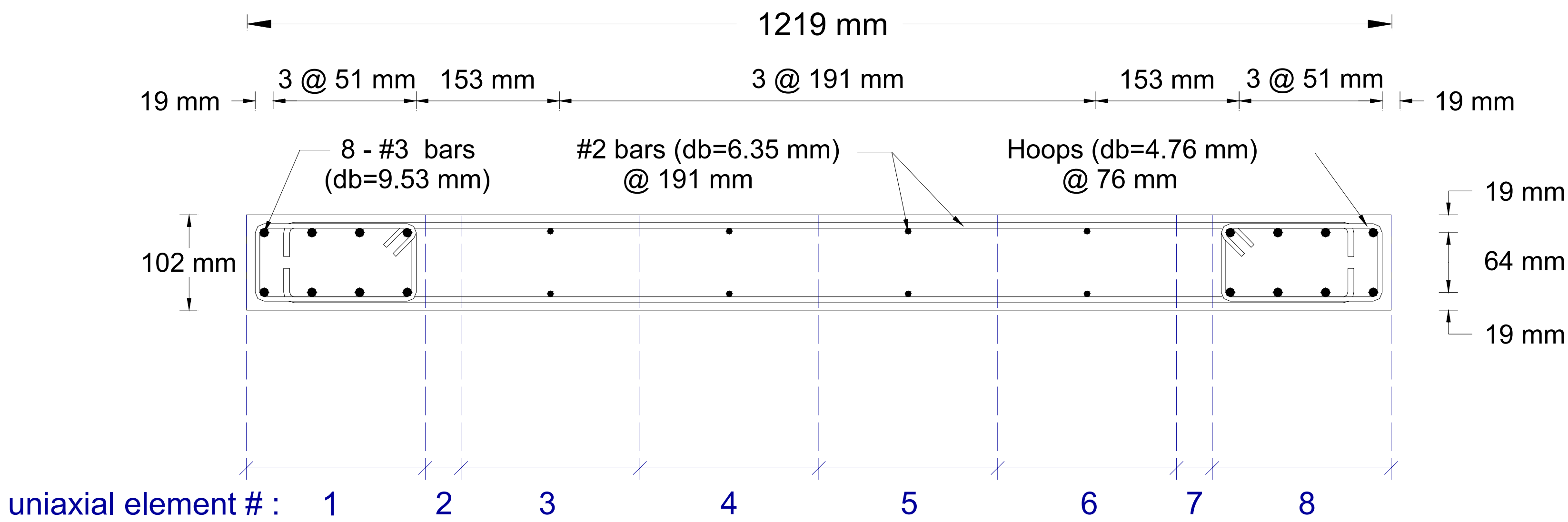
Massone & Wallace; ACI SJ, Jan-Feb 2004.

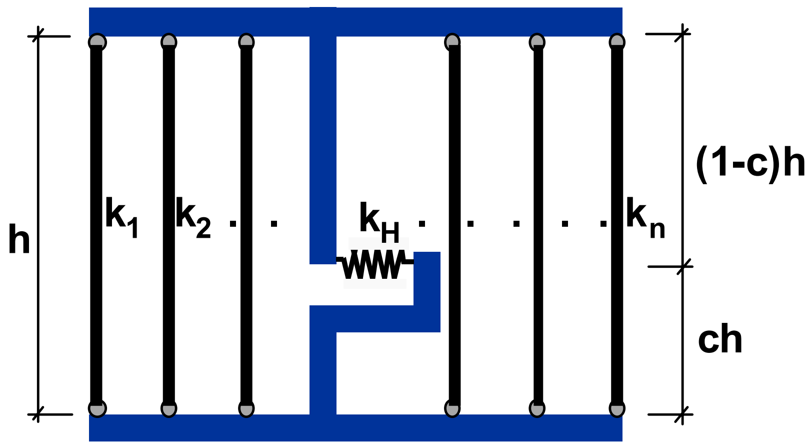
UCLA

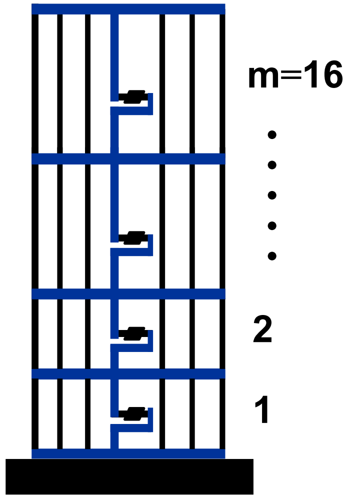
Applied Lateral Displacement



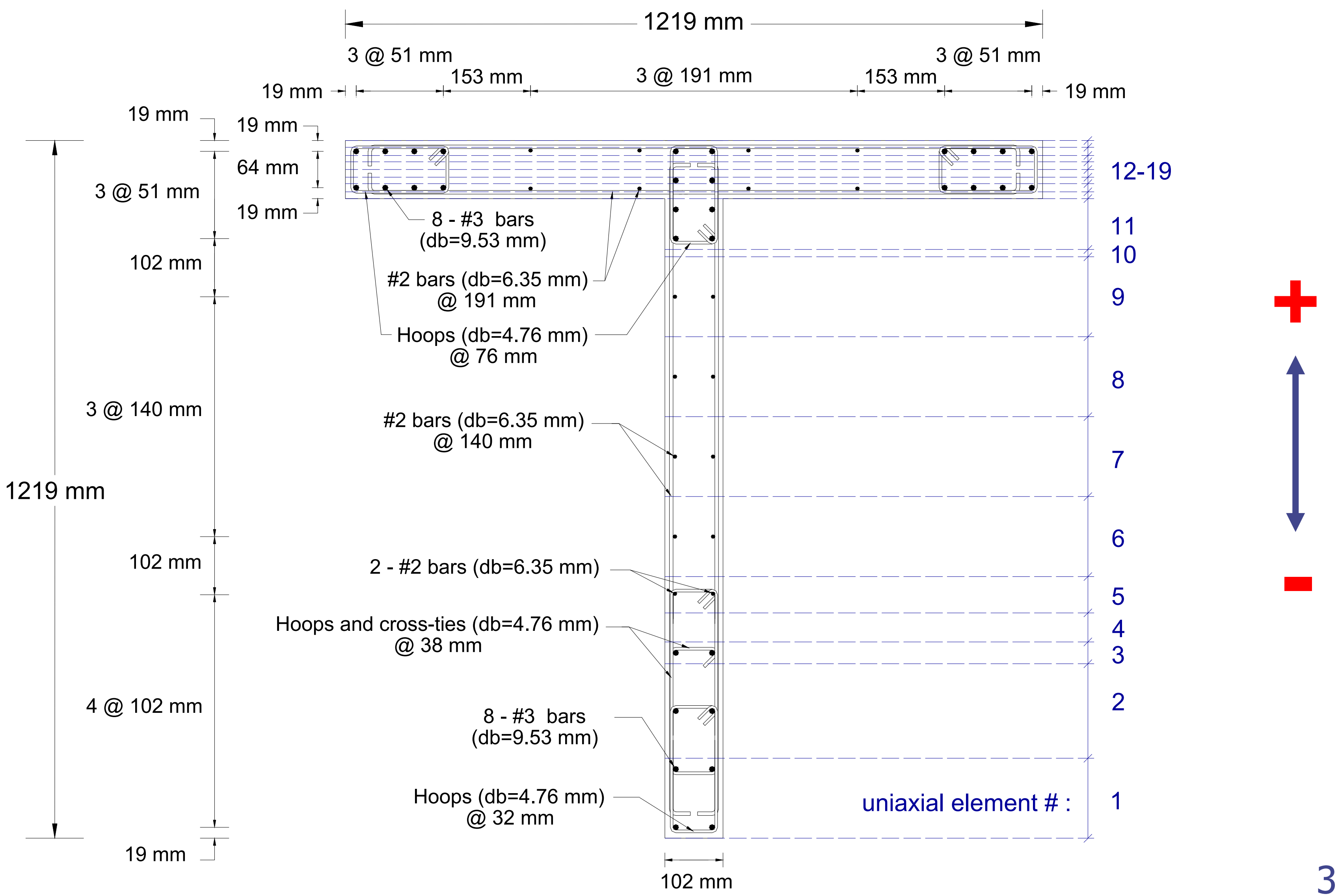
Model Details – RW2



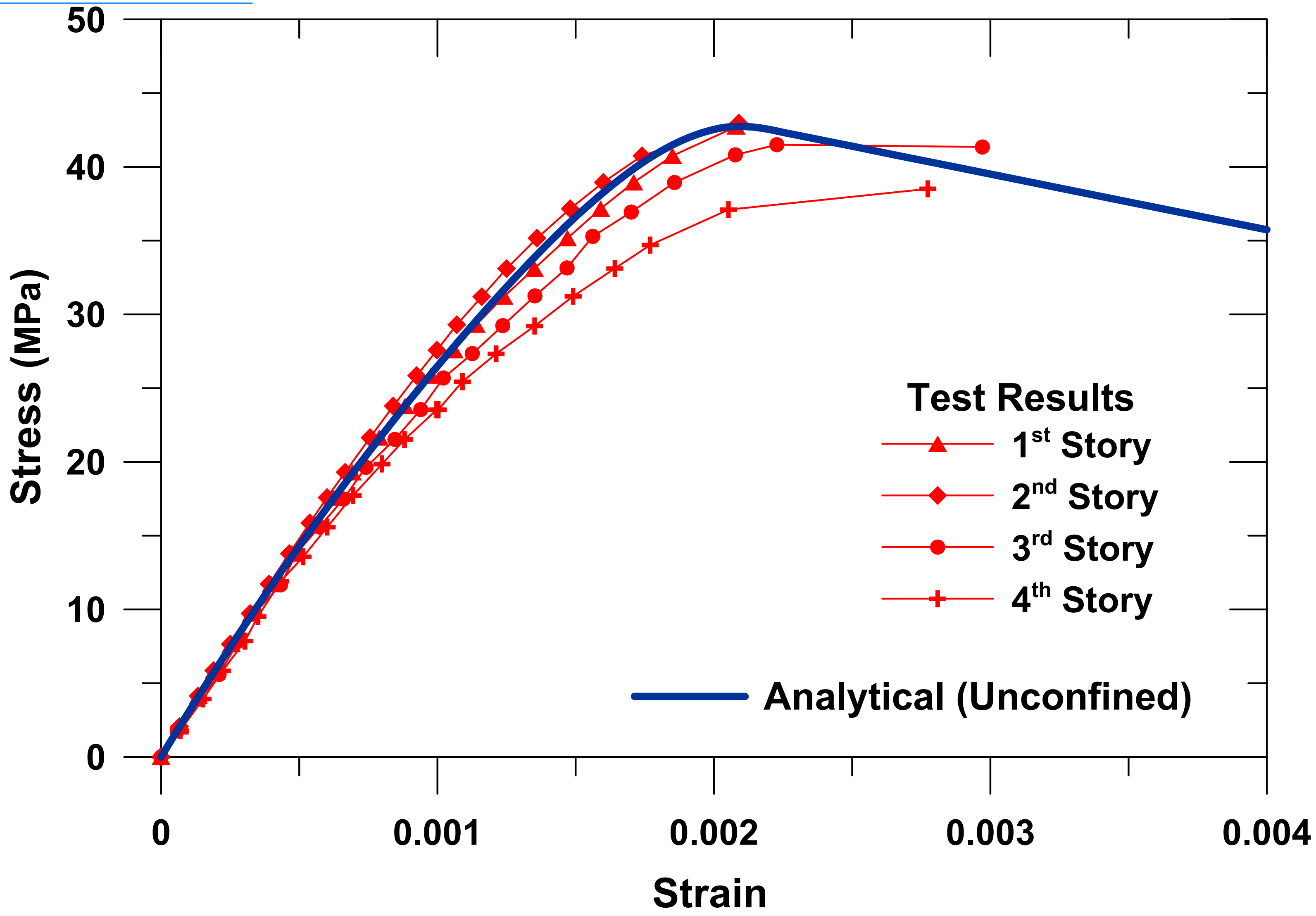




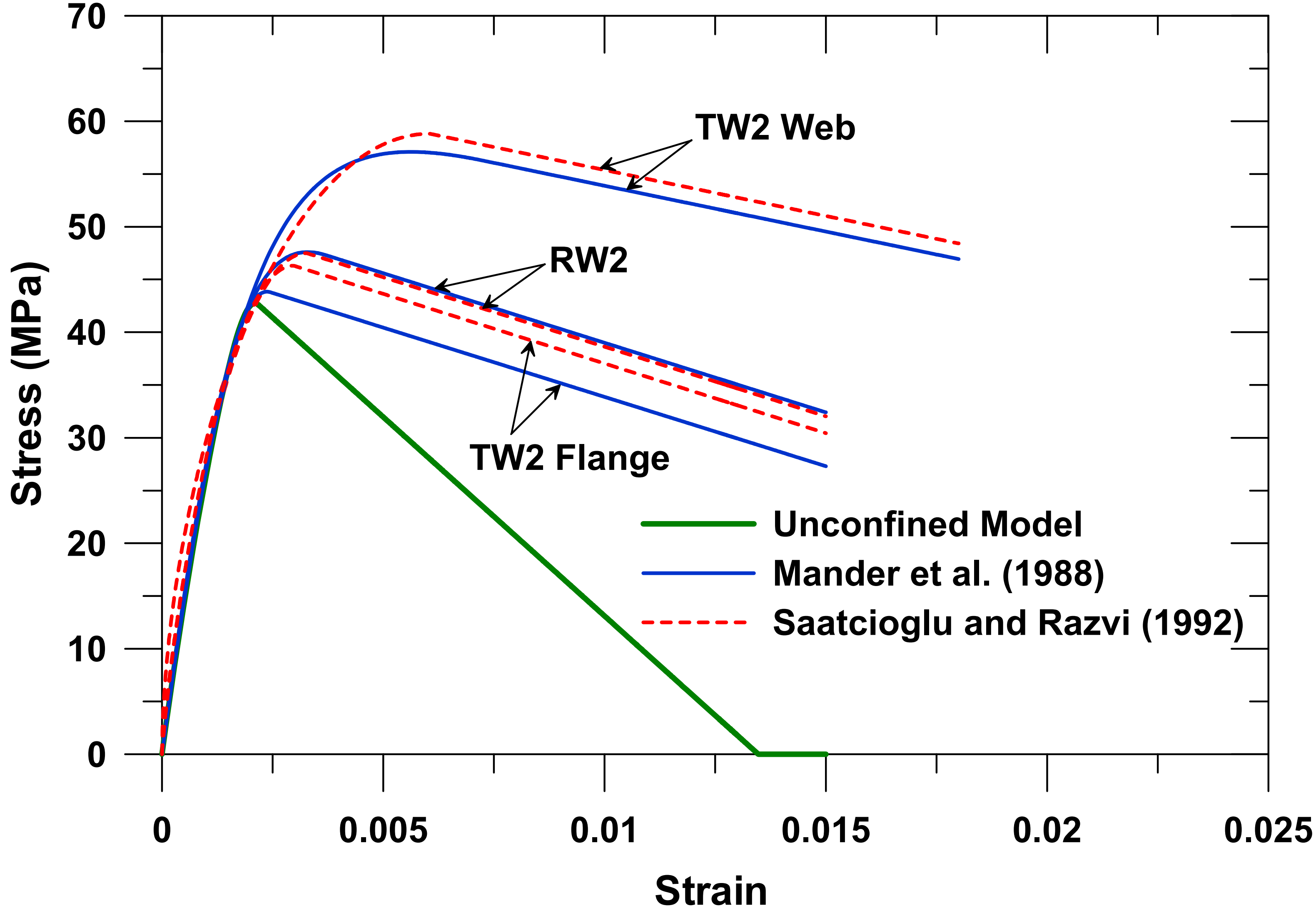
Model Details – TW2



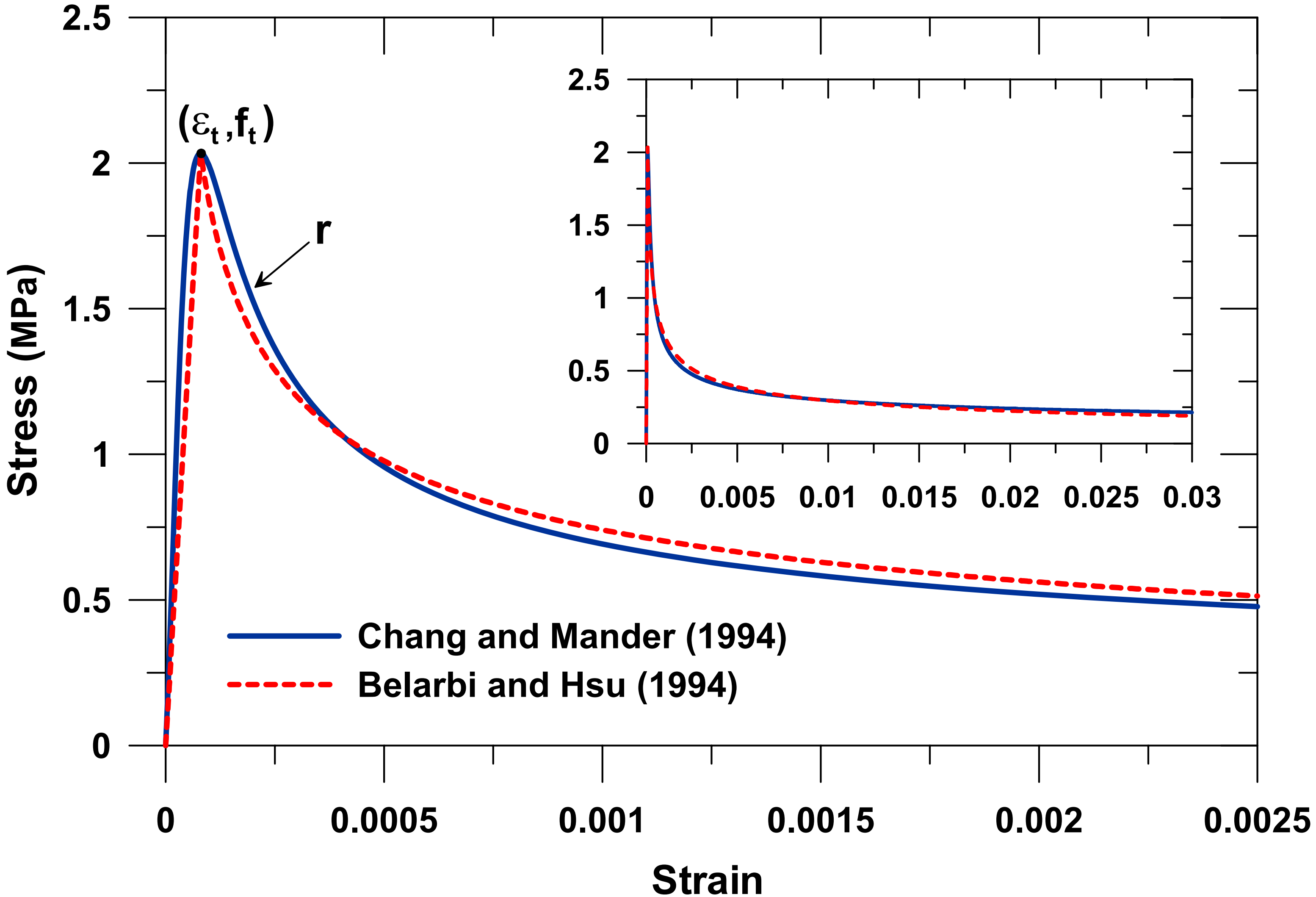
Concrete Model - Unconfined



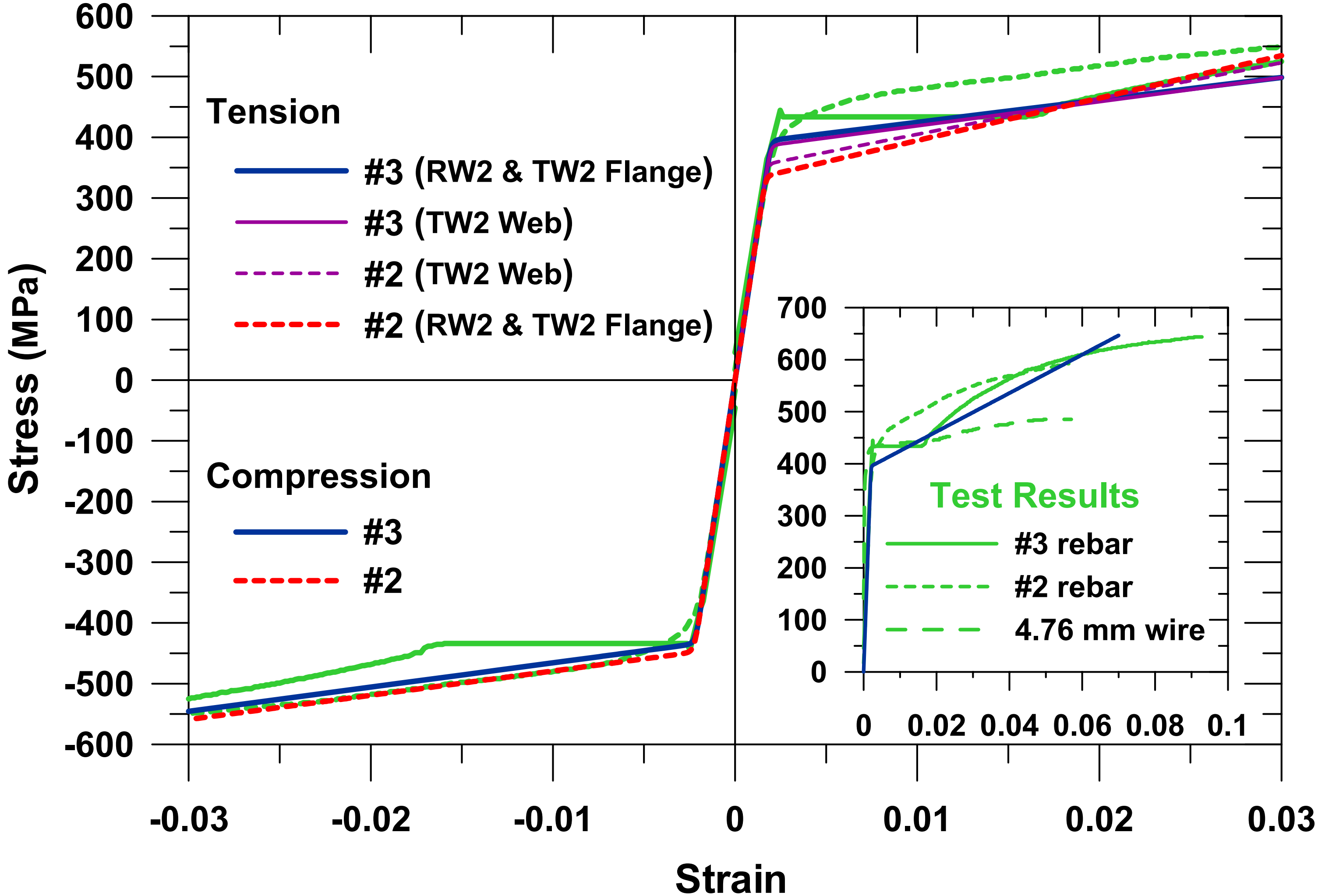
Concrete Model - Confined



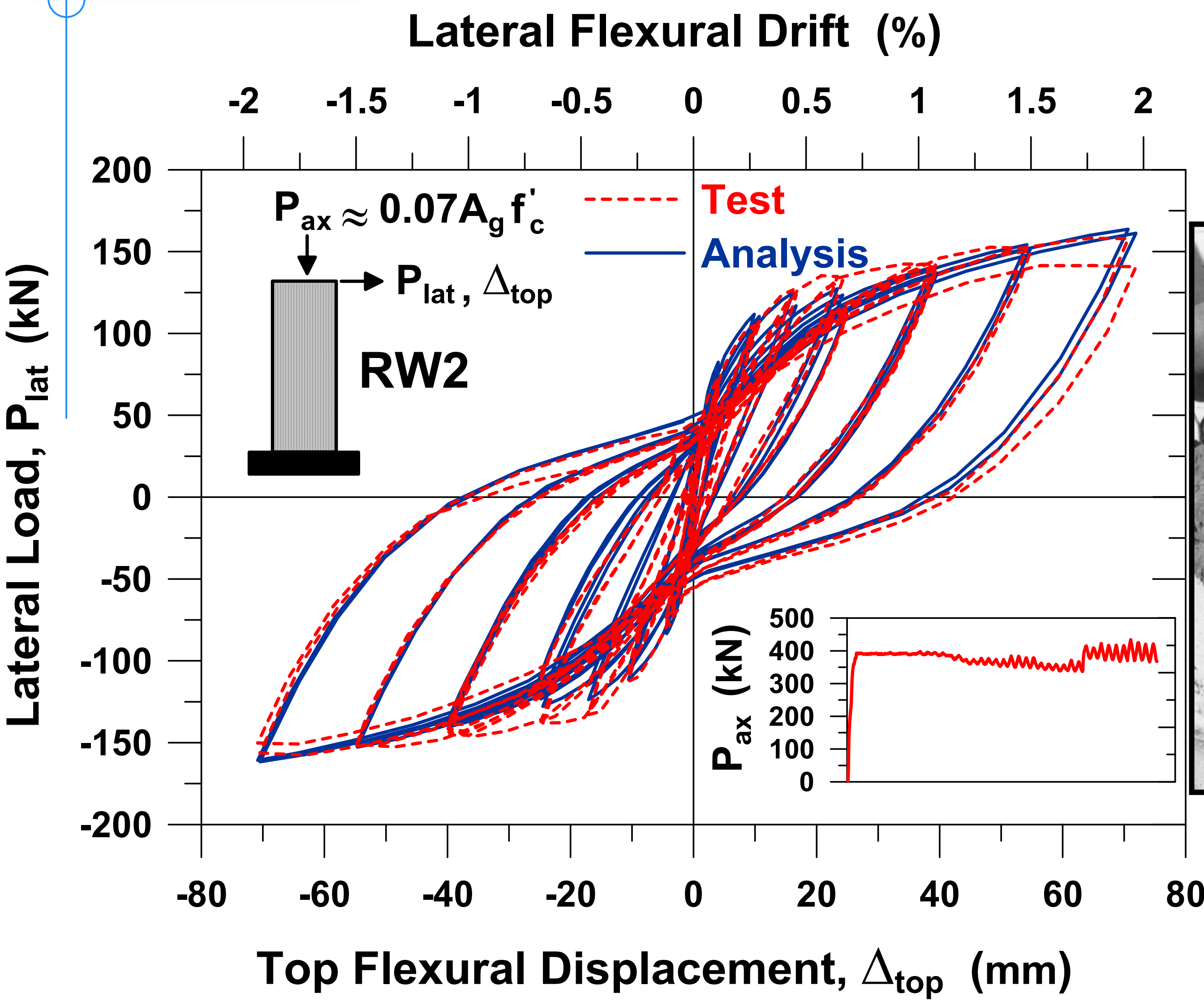
Concrete Model - Tension

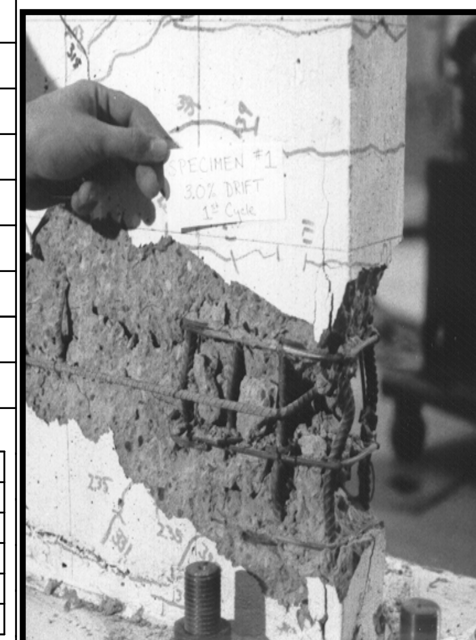


Reinforcement Material Model

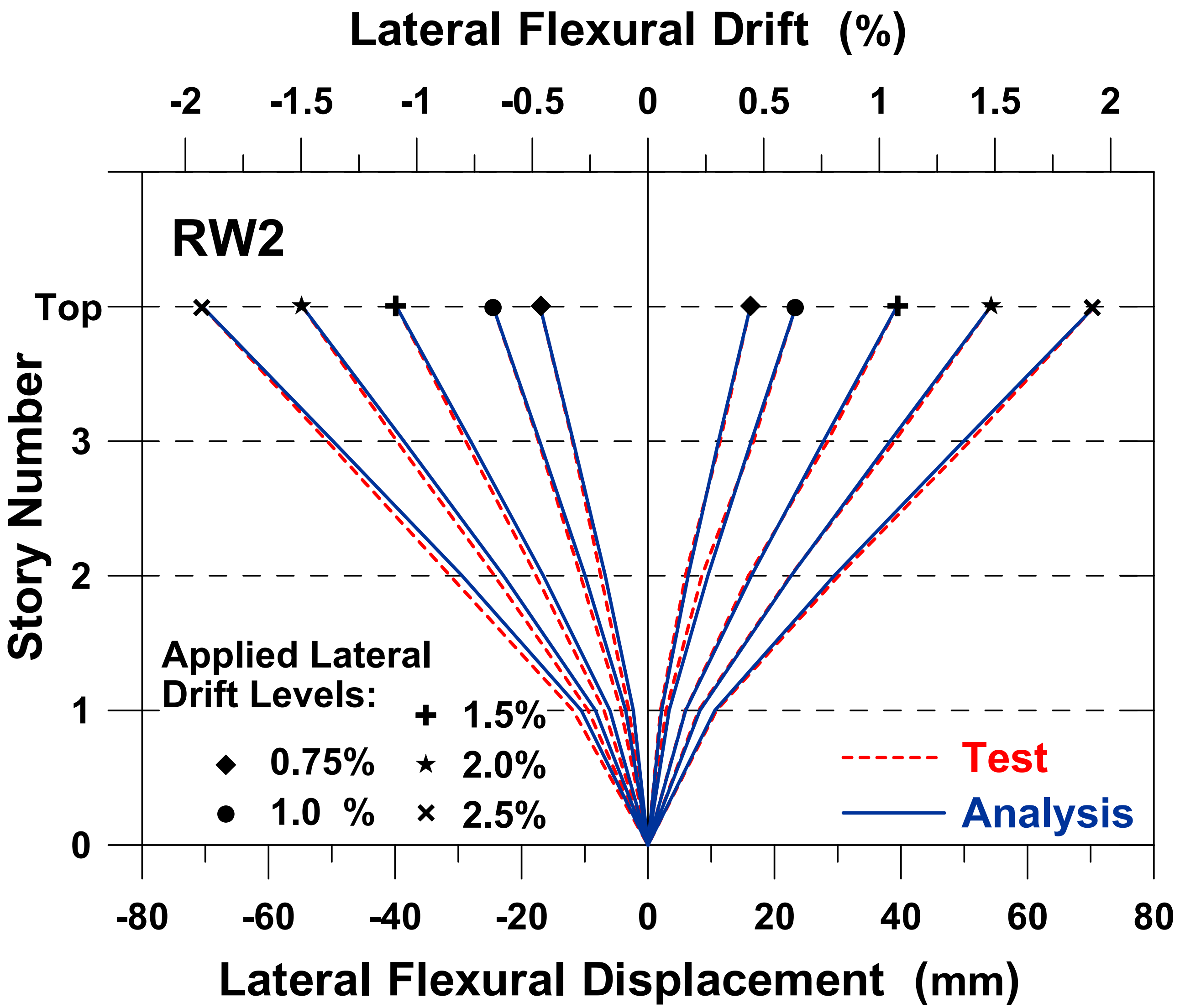


Model Assessment – RW2

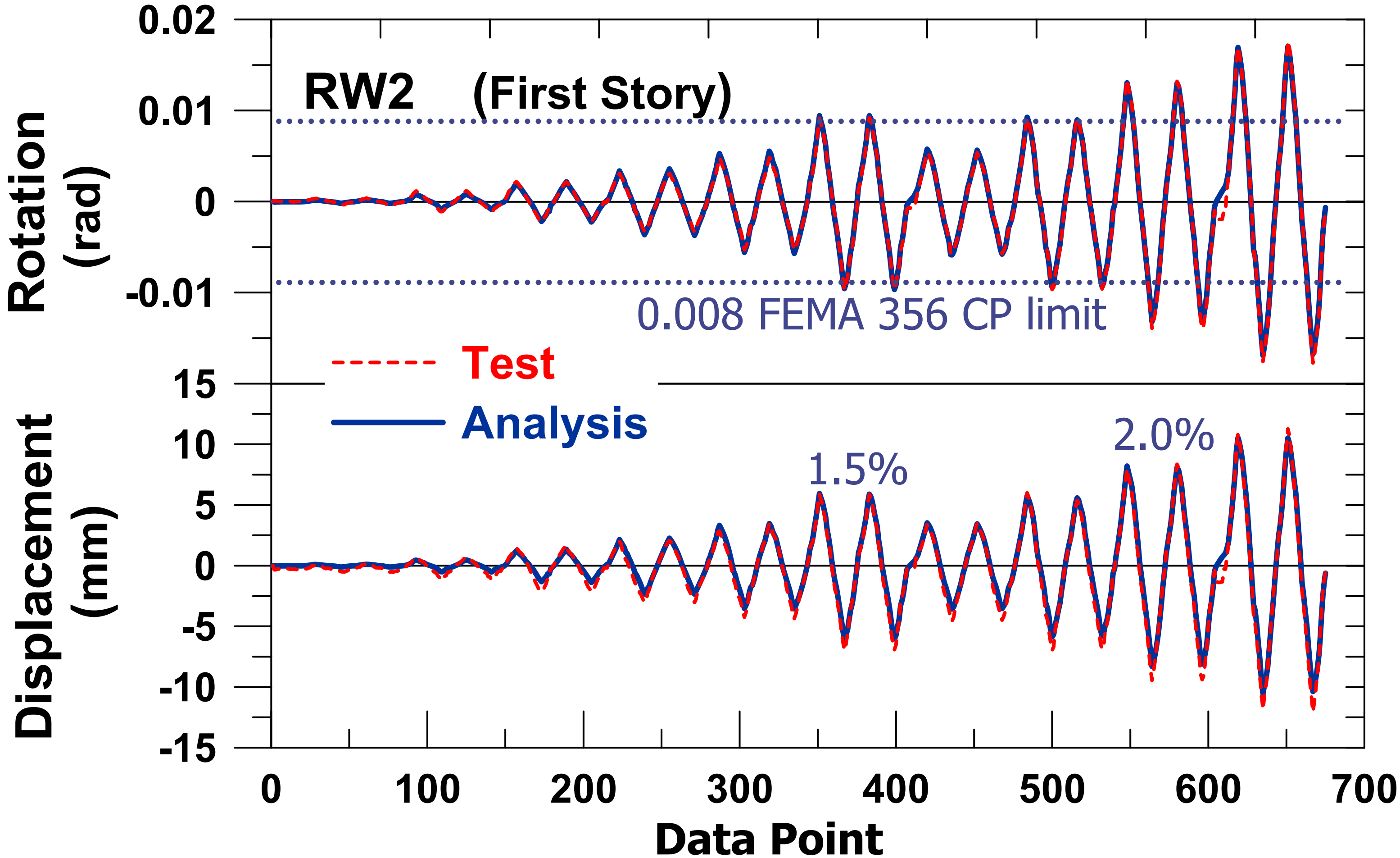




Model Assessment – RW2

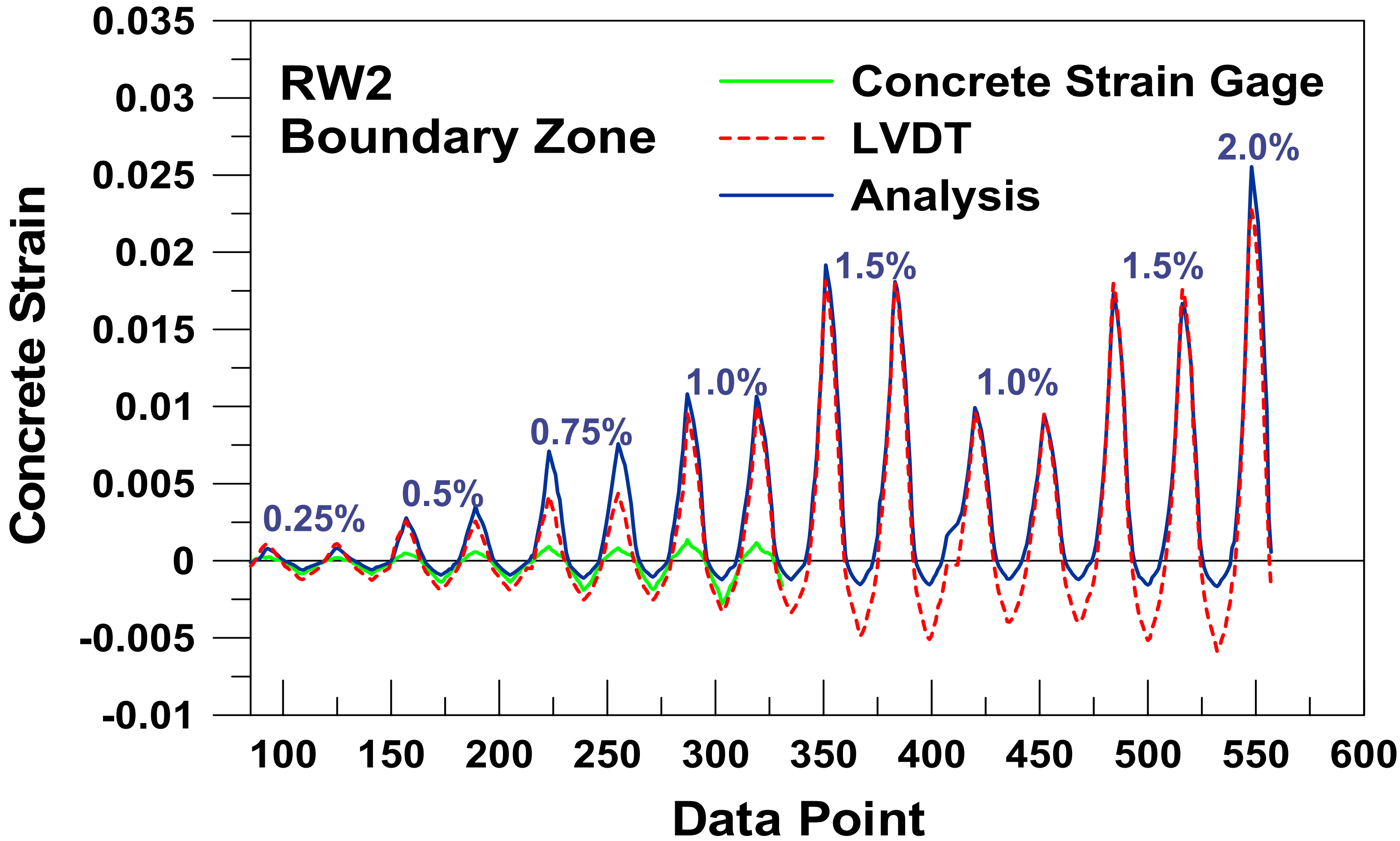


Model Assessment – RW2



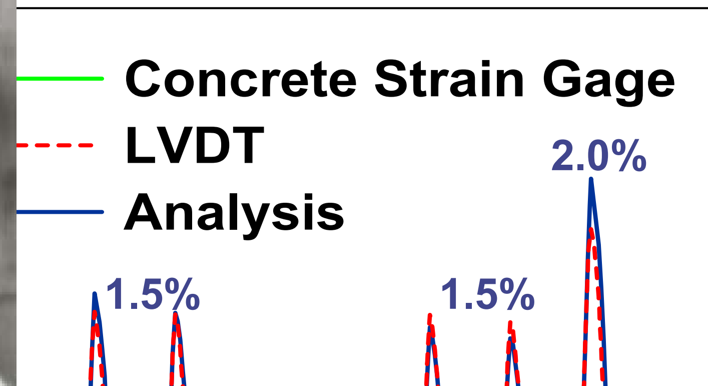
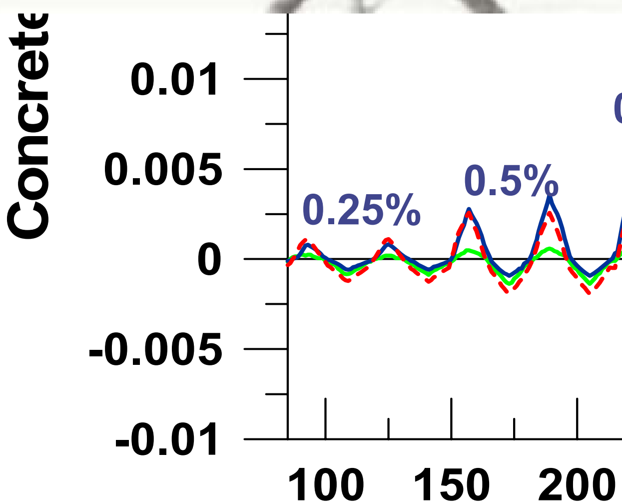
Results based on recommended values for material parameters; however, results could vary, maybe significantly, for different element lengths and material parameters (particularly if no strain hardening)

Model Assessment – RW2



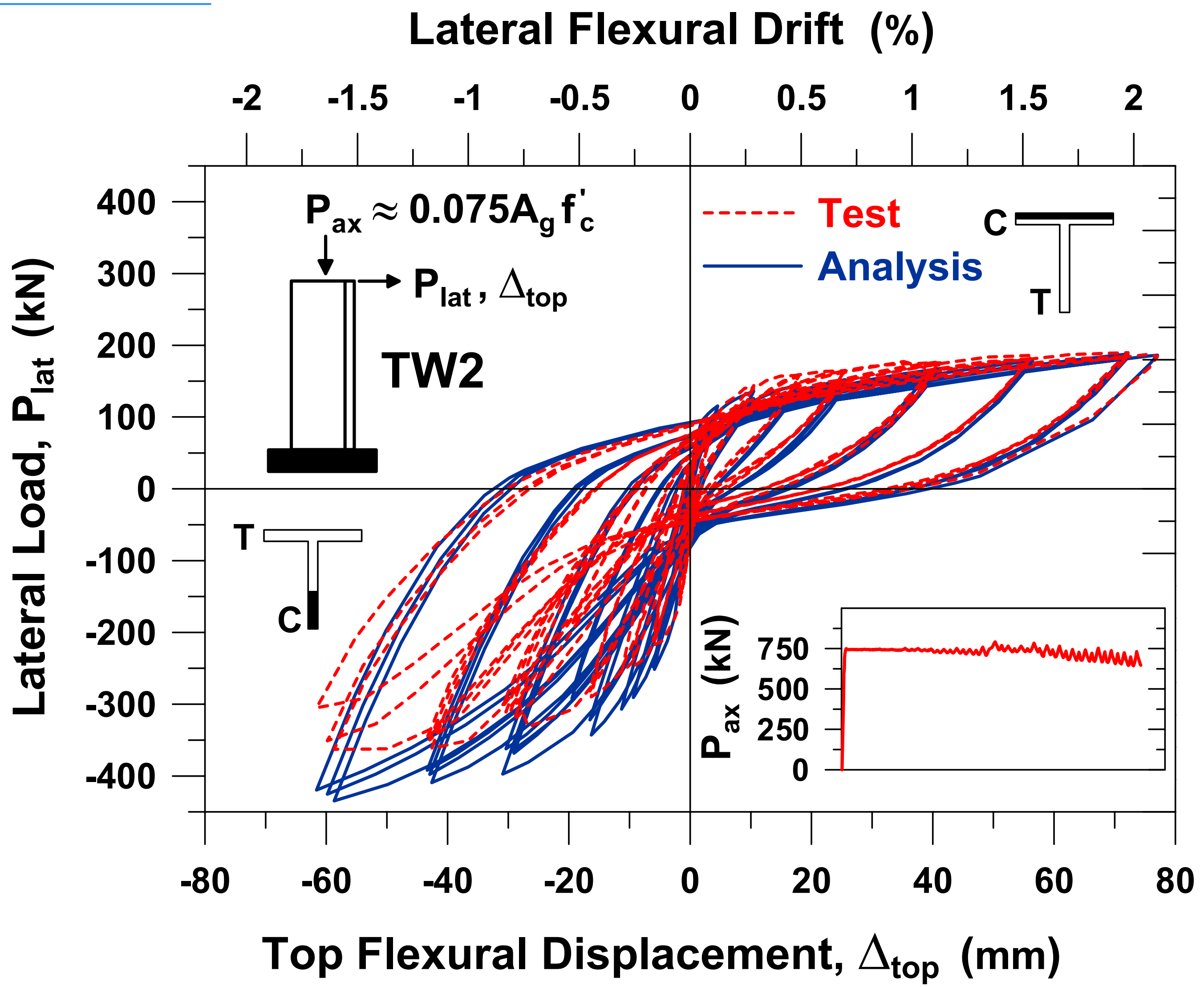
Orakcal & Wallace; ACI SJ, in-press for publication in 2006 (see 13WCEE).

t – RW2

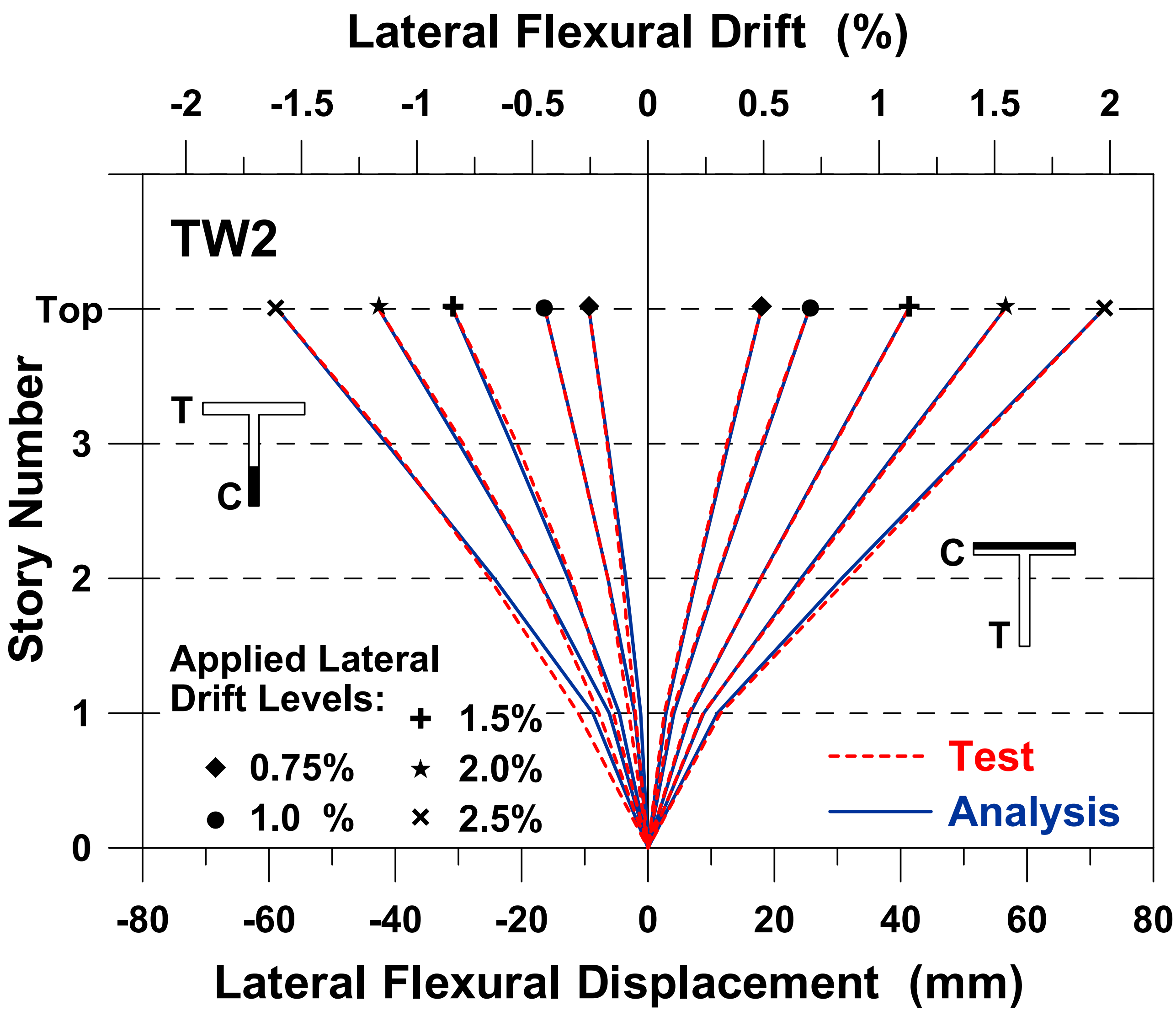



Orakcal & Wallace; ACI SJ, in-press for publication in 2006 (see 13WCEE).

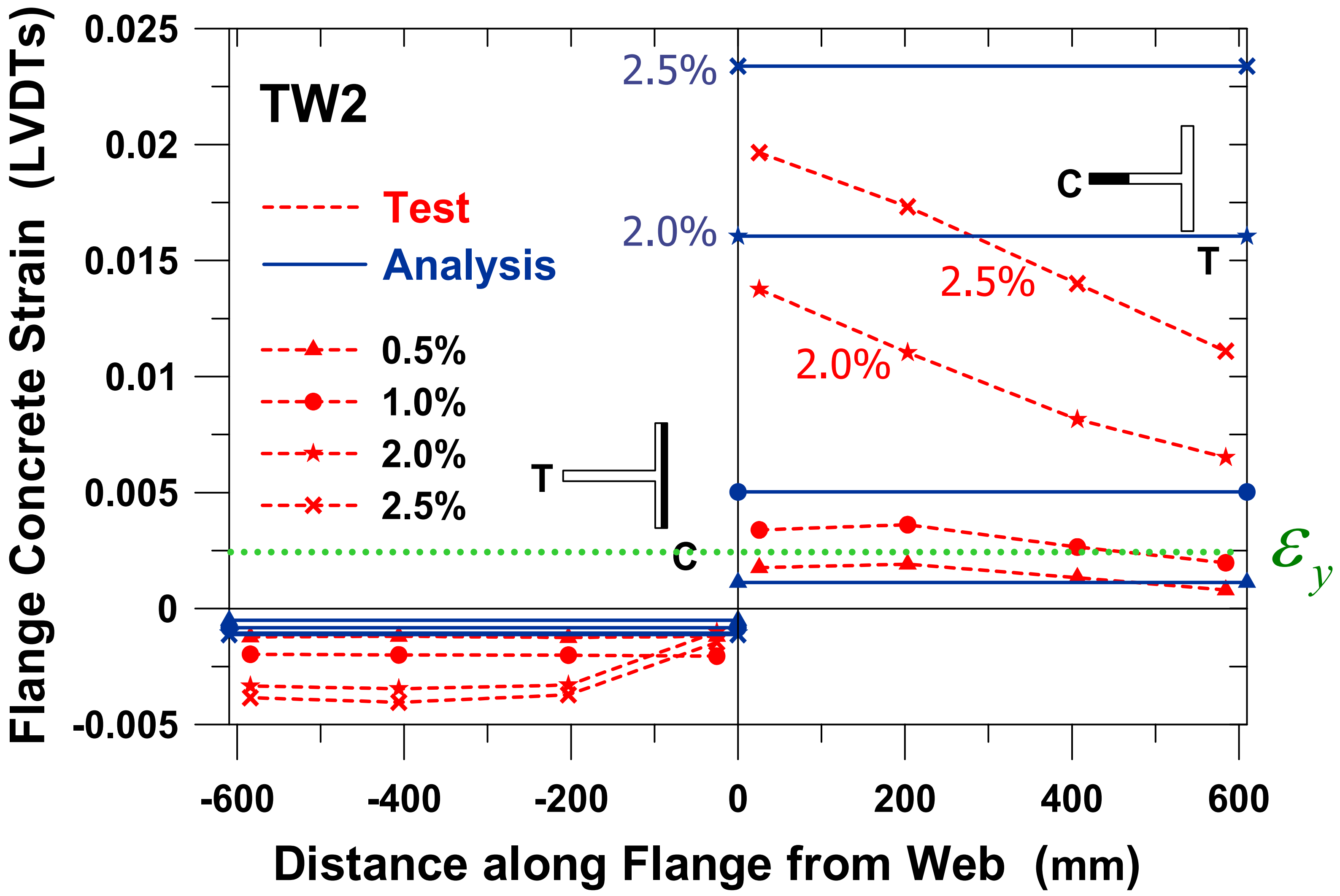
Model Assessment – TW2



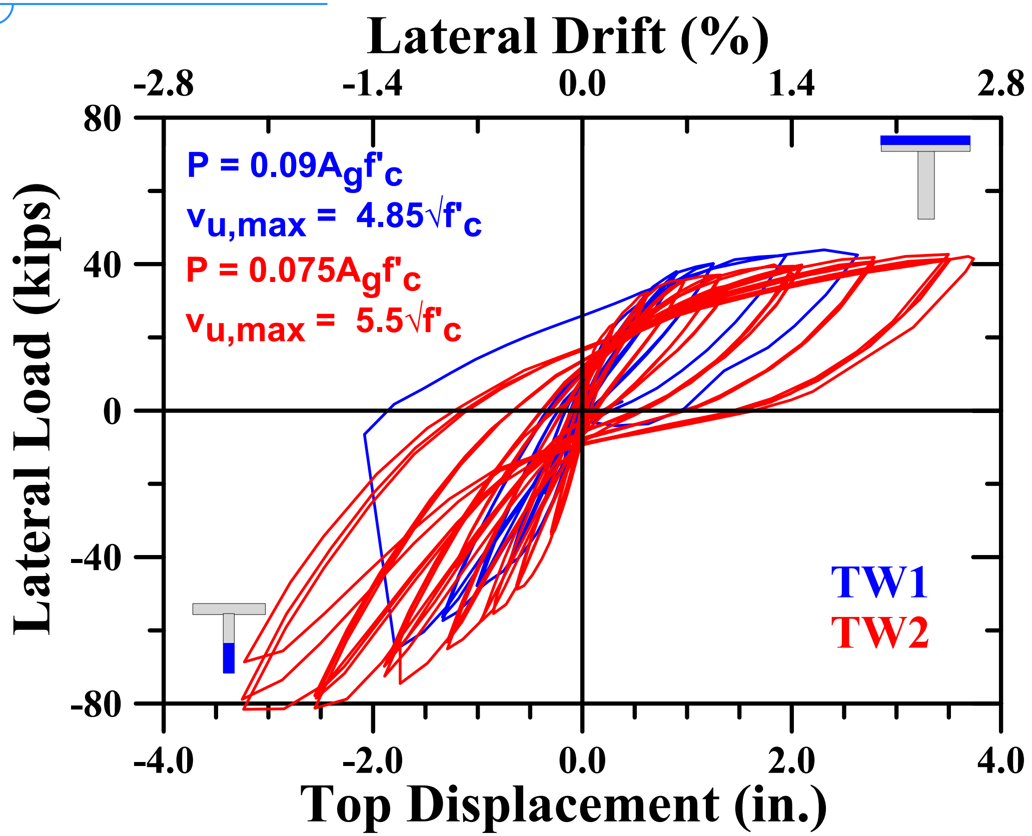
Model Assessment – TW2



Model Assessment – TW2



Model Assessment – Stability



TW1 – Abrupt failure due to buckling
TW2 – Lateral instability due to spalling and large compression

Model Assessment - Stability

Rebar Buckling at Wall Boundary

Rebar Fracture Following Buckling at Wall Boundary

Instabilities, such as rebar buckling and lateral web buckling, and rebar fracture are typically not considered in models; therefore, engineering judgment is required. Loss of lateral-load capacity does not necessarily mean loss of axial load capacity

FEMA 356 Table 6-18

Table 6-18 Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Members Controlled by Flexure

Conditions			Plastic Hinge Rotation (radians)		Residual Strength Ratio	Acceptable Plastic Hinge Rotation (radians)				
						Performance Level				
							Component Type			
							Primary		Secondary[4]	
			a	b	c	IO	LS	CP	LS	CP
i. Shear walls and wall segments										
$\frac{(A_s - A'_s)f_y + P}{t_w l_w f'_c}$	$\frac{\text{Shear}}{t_w l_w \sqrt{f'_c}}$	Confined Boundary[1]								
≤ 0.1	≤3	Yes	0.015	0.020	0.75	0.005	0.010	0.015	0.015	0.020
≤ 0.1	≥ 6	Yes	0.010	0.015	0.40	0.004	0.008	0.010	0.010	0.015
≥ 0.25	≤ 3	Yes	0.009	0.012	0.60	0.003	0.006	0.009	0.009	0.012
≥ 0.25	≥ 6	Yes	0.005	0.010	0.30	0.0015	0.003	0.005	0.005	0.010
≤ 0.1	≤ 3	No	0.008	0.015	0.60	0.002	0.004	0.008	0.008	0.015
≤ 0.1	≥ 6	No	0.006	0.010	0.30	0.002	0.004	0.006	0.006	0.010
≥ 0.25	≤ 3	No	0.003	0.005	0.25	0.001	0.002	0.003	0.003	0.005
≥ 0.25	≥ 6	No	0.002	0.004	0.20	0.001	0.001	0.002	0.002	0.004

FEMA 356 Table 6-18

Conditions			Plastic Hinge Rotation (radians)		Residual Strength Ratio
			a	b	c
i. Shear walls and wall segments					
$\frac{(A_s - A'_s)f_y + P}{t_w l_w f'_c}$	$\frac{\text{Shear}}{t_w l_w \sqrt{f'_c}}$	Confined Boundary[1]			
≤ 0.1	≤ 3	Yes	0.015	0.020	0.75
≤ 0.1	≥ 6	Yes	0.010	0.015	0.40
≥ 0.25	≤ 3	Yes	0.009	0.012	0.60
≥ 0.25	≥ 6	Yes	0.005	0.010	0.30

FEMA 356 – Modeling Parameters

WALL RW2:

$A_s = A_s'$ & $P = 0.07 A_g f_c'$ & Hoops @ 2" o.c.

$2(0.027 \text{ in}^2) = 0.09(s)(h_c = 6"+3/8"+3/16")(5 \text{ ksi}/63 \text{ ksi})$

$s < 1.2"$ Non-conforming

WALL TW2: Flange Compression

$A_s = 8$ - #3 $A_s' =$ 10 - #3 and 4 - #2 $f_y \approx 63$ ksi & Hoops/Ties @ s=4"

No special detailing required: Conforming

$$\frac{\left(A_s - A_s'\right) f_y + P}{t_w l_w f_c'} = \frac{\left[-0.42 \text{ in}^2\right]\left(63 \text{ ksi}\right)}{4"(48")(\sim 6 \text{ ksi})} + 0.075(2) = 0.127$$

$$\frac{V_u}{t_w l_w \sqrt{f_c'}} = \frac{40 \text{ kips}}{4"(48")\sqrt{6000}/1000} = 2.7$$

FEMA 356 – Modeling Parameters

WALL TW2: Flange Tension

$A_s' = 8 \text{ - \#3 \& } 2 \text{ - \#2} \qquad \text{A}_\text{s} = 24 \text{ - \#3 and } 8 \text{ - \#2} \quad \& \; f_y \approx 63 \text{ ksi}$

Hoops/Ties @ s=1.25" (5 legs and 2 legs)

$5(0.027 \text{ in}^2) = 0.09(s)(h_c = 16"+3/8"+3/16")(6 \text{ ksi}/63 \text{ ksi}) \qquad s < 1.0"$

$2(0.027 \text{ in}^2) = 0.09(s)(h_c = 2.5"+3/8"+3/16")(6 \text{ ksi}/63 \text{ ksi}) \qquad s < 2.1"$

~ Conforming

$$\frac{\left(A_s - A_s'\right) f_y + P}{t_w l_w f_c'} = \frac{\left[16(0.11) + 6(0.049)\right]\left(63 \text{ ksi}\right)}{4"(48")(\sim 6 \text{ ksi})} + 0.075(2) = 0.26$$

$$\frac{V_u}{t_w l_w \sqrt{f_c'}} = \frac{80 \text{ kips}}{4"(48")\sqrt{6000}/1000} = 5.4$$

FEMA 356 – Modeling Parameters

- Tables 6-18 (partial):

Walls Controlled by Flexure			Model Parameters, Radians		
$\frac{(A_s - A_s')f_y + P}{t_w l_w f_c'}$	Conf. Bound.	$\frac{V}{t_w l_w \sqrt{f_c'}}$	Plastic Hinge a	Plastic Hinge b	Residual Strength c
≤ 0.1	Yes	≤ 3	0.015	0.02	0.75
≤ 0.1	No	≤ 3	0.008	0.015	0.60
≥ 0.25	Yes	≥ 6	0.005	0.010	0.30
≥ 0.25	No	≥ 6	0.002	0.004	0.20

TW2 Flange Comp

RW2

TW2 Flange Tension

FEMA Backbone Relation – RW2

$$P_{lateral} = \frac{M_n}{h_w} = 29.4 \text{ kips}$$

$$\delta_y = \left[\frac{\left(P_{lateral} h_{load}^3 \right)}{3E_c\left(0.5I_g\right)} \right]$$

$$= \frac{29.4^k (150")^3}{3(4000^{ksi})(18,432^{in^4})} = 0.41"$$

$$\delta_a = 0.008(144") = 1.15"$$

$$\delta_b = 0.015(144") = 2.16"$$

$$P_{residual} = 0.6(29.4^k) = 17.6 \text{ kips}$$

FEMA Backbone Relations – TW2

Flange Compression

$$P_{lateral} = \frac{M_n}{h_w} = 40.2 \text{ kips}$$

$$\delta_y = \left[\frac{\left(P_{lateral} h_{load}^3\right)}{3E_c\left(0.5I_g\right)} \right]$$

$$= \frac{40.2^k(150")^3}{3(4400^{ksi})(40,700^{in^4})}$$

$$= 0.25"$$

$$I_g = 2.2\left(I_g\right)_{4x48} \qquad \overline{y} = 34.5"$$

$$\delta_a = 0.015(144") = 2.16"$$

$$\delta_b = 0.020(144") = 2.88"$$

$$P_{residual} = 0.75(40.2^k) = 30.2 \text{ kips}$$

Flange Tension

$$P_{lateral} = \frac{M_n}{h_w} = 77.0 \text{ kips}$$

$$\delta_y = \left[\frac{\left(P_{lateral} h_{load}^3\right)}{3E_c\left(0.5I_g\right)} \right]$$

$$= \frac{77.0^k(150")^3}{3(4400^{ksi})(40,700^{in^4})}$$

$$= 0.48"$$

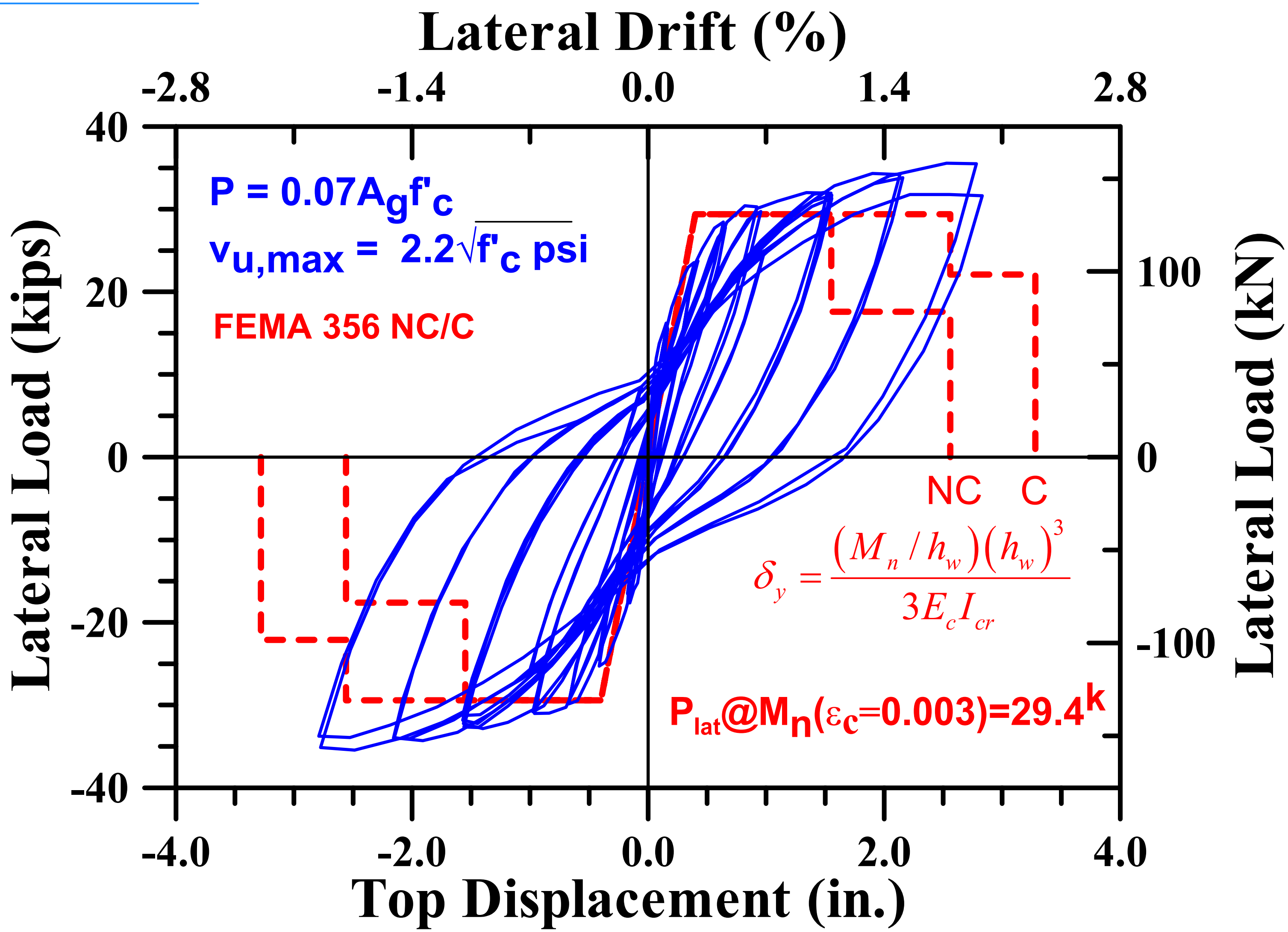
$$I_g = 2.2\left(I_g\right)_{4x48} \qquad \overline{y} = 34.5"$$

$$\delta_a = 0.005(144") = 0.72"$$

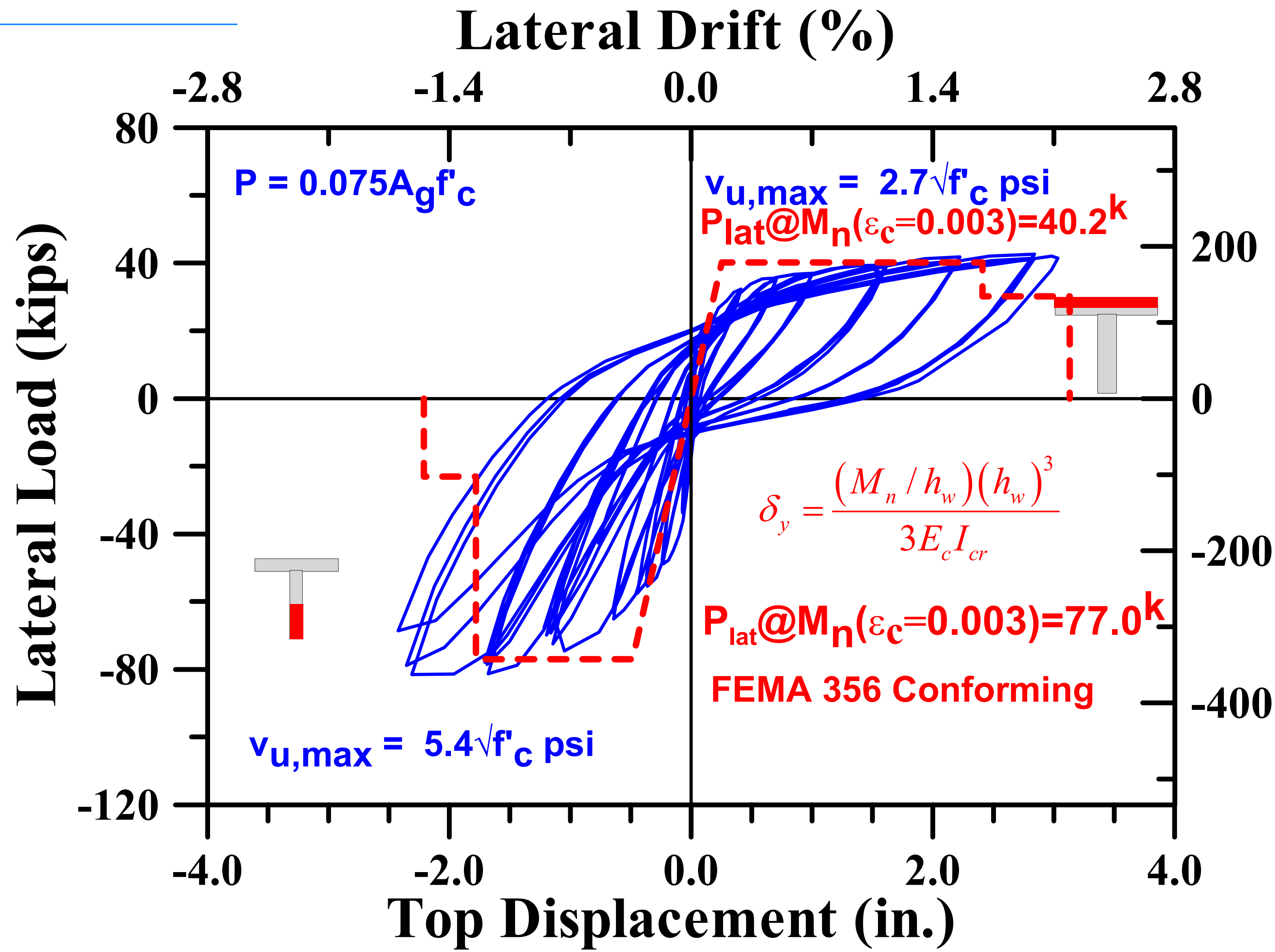
$$\delta_b = 0.010(144") = 1.44"$$

$$P_{residual} = 0.30(77.0^k) = 23.1 \text{ kips}$$

Backbone Curve – RW2



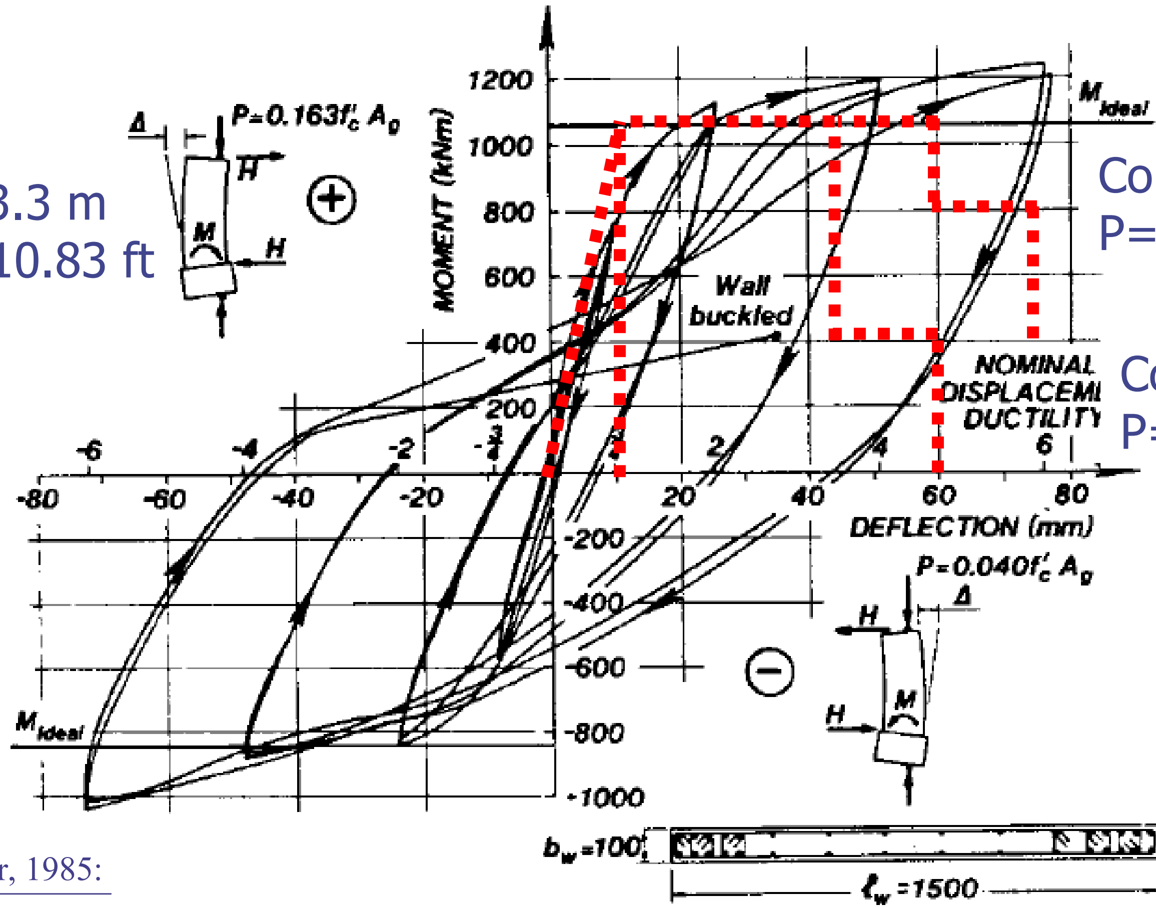
Backbone Curve – TW2



Cantilever Wall Tests

Paulay, EERI, 2(4), 1986 [Goodsir, PhD 1985 NZ]

h = 3.3 m
= 10.83 ft



Conforming
P=10%, V=3

Conforming
P=10%, V=6

(3.94”)

(59”)

WALL Goodsir, 1985:

$A_s = A_s'$ & $P = 0.163 f_c' A_g$ & Assume conforming

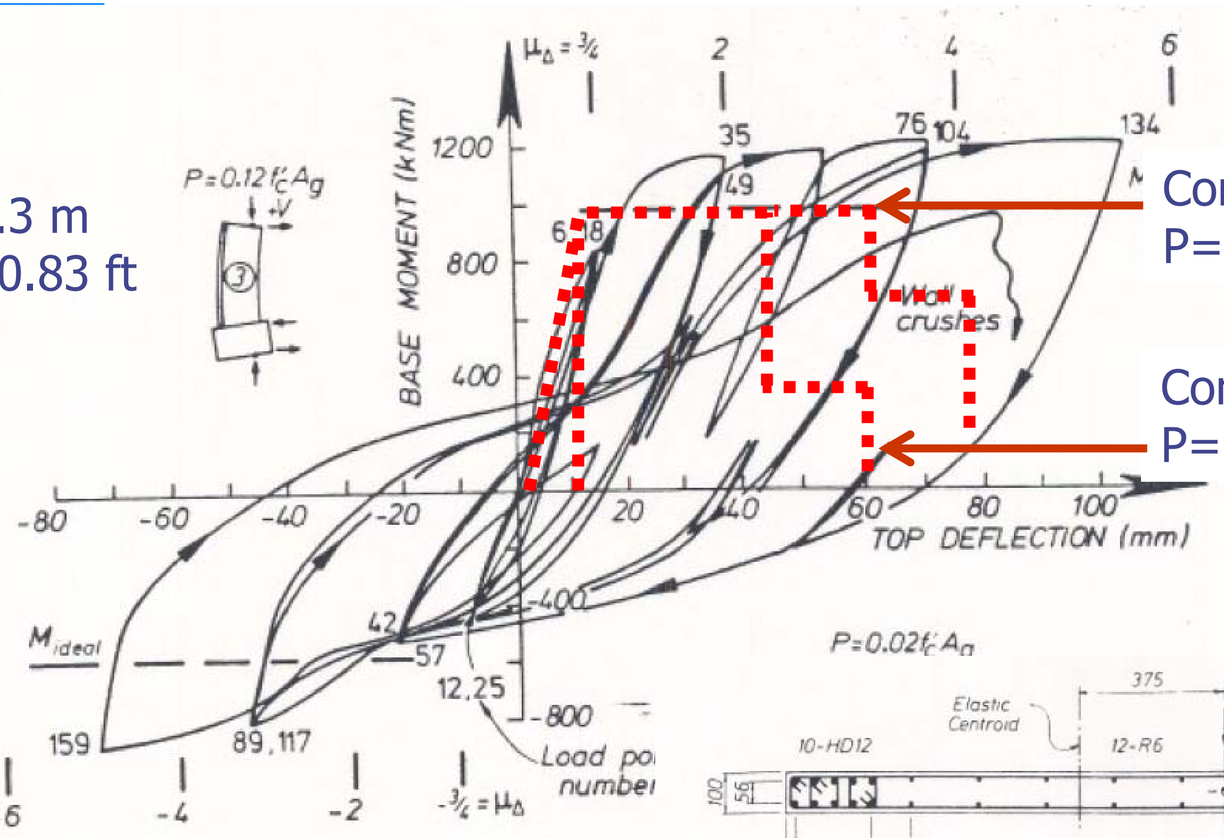
$$\delta_y = \frac{PL^3}{3E_c 0.5 I_g} = \frac{(70k)(130")^3}{3(\sim 3750ksi)(0.5)(4")(59")^3/12} = 0.4" \ (10.0mm) \qquad \frac{V_u}{t_w l_w \sqrt{f_c'}} = \frac{70k}{(4")(59")\sqrt{3750\,psi}} = 4.6$$

$\delta_a \approx 0.01(3300mm) = 33mm \qquad \delta_b \approx 0.015(3300mm) = 50mm$

Cantilever Wall Tests

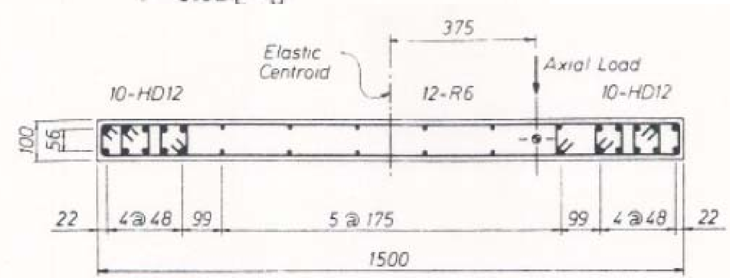
Paulay, EERI, 2(4), 1986 [Goodsir, PhD 1985 NZ]

h = 3.3 m
= 10.83 ft



Conforming
P=10%, V=3

Conforming
P=10%, V=6



WALL Goodsir, 1985:

$A_s = A_s'$ & $P = 0.12 f_c' A_g$ & Assume conforming

$$\delta_y = \frac{PL^3}{3E_c 0.5 I_g} = \frac{(70k)(130")^3}{3(\sim 3750ksi)(0.5)(4")(59")^3/12} = 0.4" \ (10.0mm)$$

$$\frac{V_u}{t_w l_w \sqrt{f_c'}} = \frac{70k}{(4")(59")\sqrt{3750 psi}} = 4.6$$

$\delta_a \approx 0.01(3300mm) = 33mm$ $\delta_b \approx 0.015(3300mm) = 50mm$

Summary

- FEMA 356 Backbone Curves
  - In general, quite conservative
  - This appears to be especially true for cases where moderate detailing is provided around boundary bars
  - Possible reformat
    - Compute neutral axis depth
    - If s <12d_b over c/2, then modest ductility
    - If s < 8d_b and transverse steel ratio is ~1/2 of ACI 318-05, then moderate ductility
    - If s < 8d_b and transverse steel ratio is > 3/4 of ACI 318-05, then high ductility
    - Do not reduce deformation capacity for shear stress below 5 roots f'_c

Shear Design

- Wall shear studies
  - Aktan & Bertero, ASCE, JSE, Aug. 1985
  - Paulay, EERI 1996; Wallace, ASCE, JSE, 1994.
  - Eberhard & Sozen, ASCE JSE, Feb. 1993
- Design Recommendations
  - Based on M_{pr} at hinge region
  - Uniform lateral force distribution

$$V_{wall} = \omega_v \left(\frac{M_{pr}}{M_u} \right) V_u \qquad \omega_v = 0.9 + n/10$$

Paulay, 1986

$$V_{wall} = V_{limit} + \left(D_m = 0.3 \right)\left(W = weight \right)\left(A_e = EPA \right)$$

Eberhard, 1993

Slender Wall Behavior & Modeling

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