Guidance on Nonlinear Modeling of RC Buildings

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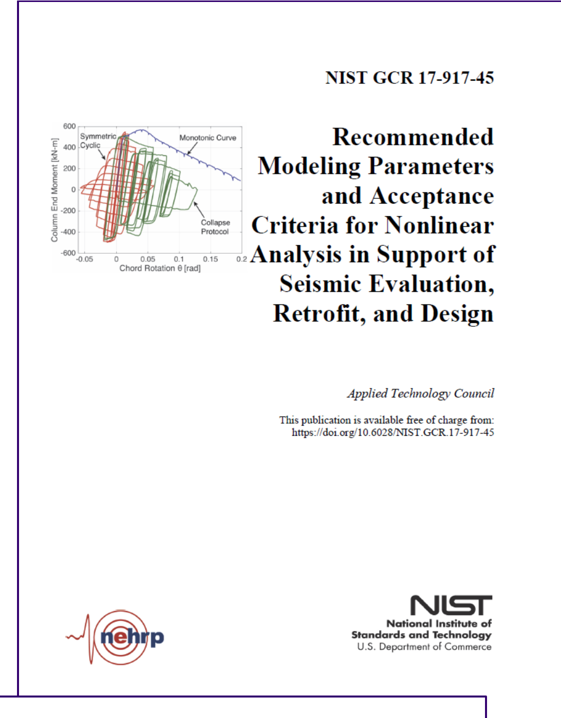
ATC 114 Project

> Funded by NIST
> Objective: provide recommendations for updating ASCE 41



NIST GCR 17-917-45

Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit, and Design

Applied Technology Council

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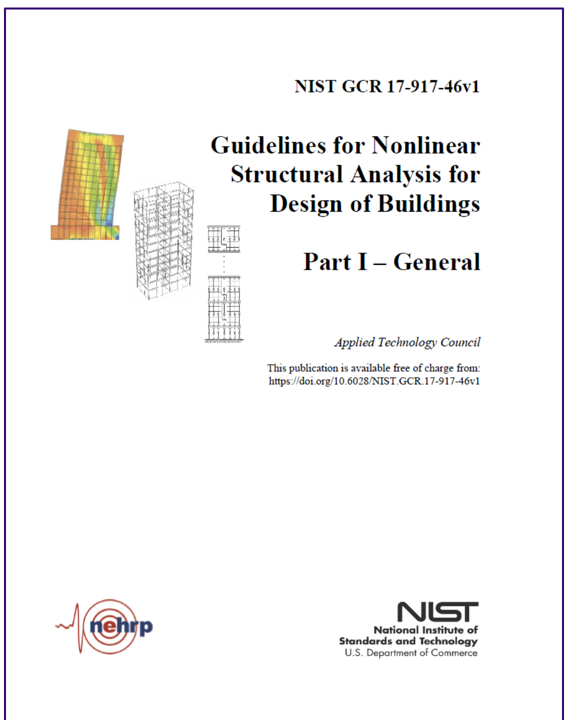

NIST GCR 17-917-46v1

Guidelines for Nonlinear Structural Analysis for Design of Buildings

Part I – General

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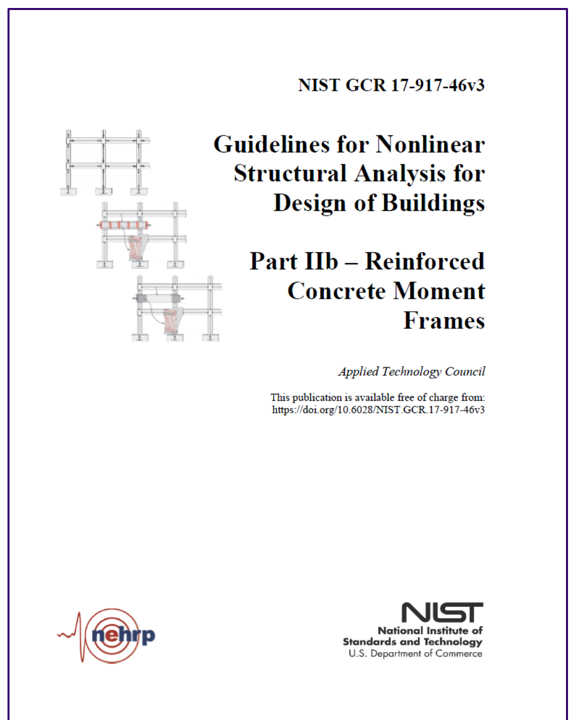

NIST GCR 17-917-46v3

Guidelines for Nonlinear Structural Analysis for Design of Buildings

Part IIb – Reinforced Concrete Moment Frames

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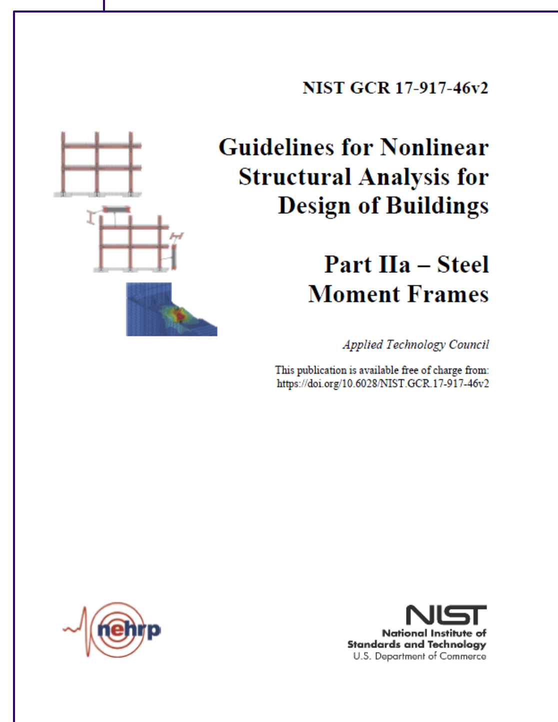

NIST GCR 17-917-46v2

Guidelines for Nonlinear Structural Analysis for Design of Buildings

Part IIa – Steel Moment Frames

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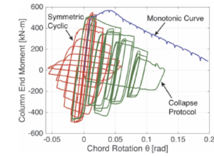

Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit, and Design

RC Frames
RC Flexure-controlled walls
RC Shear-controlled walls

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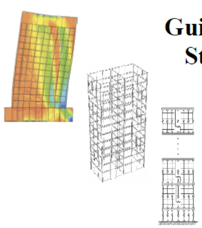

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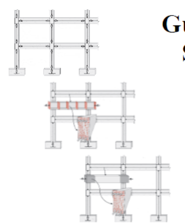

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Part IIb – Reinforced Concrete Moment Frames

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RC Frames

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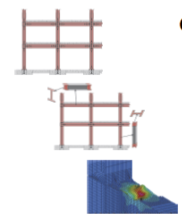

Guidelines for Nonlinear Structural Analysis for Design of Buildings

Part IIa – Steel Moment Frames

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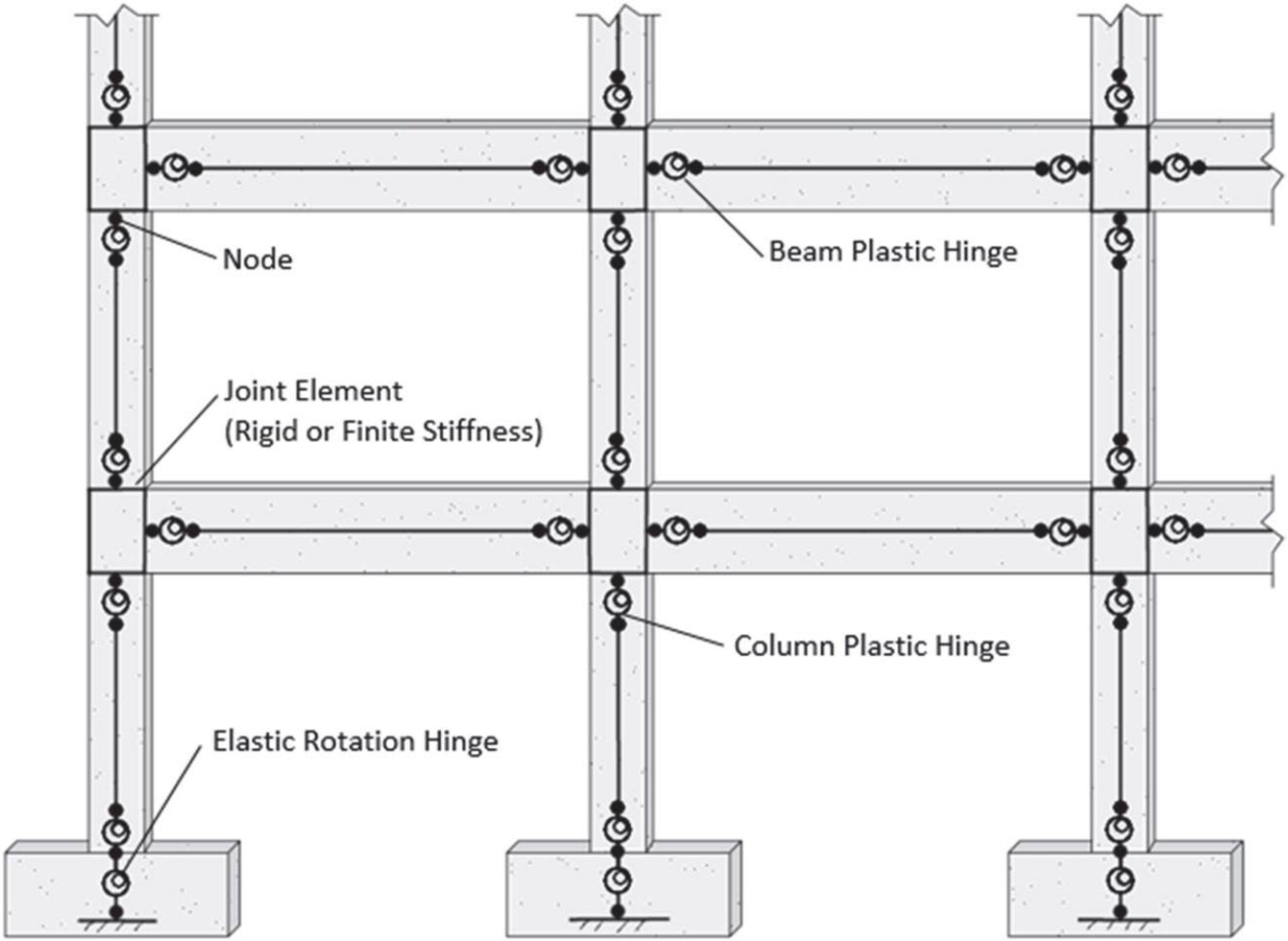
Guidelines for RC Frames

- Multiple types of models addressed
  - Concentrated-hinge component models
    - Beams, columns, joints, gravity system connections
  - Fiber-type component models
    - Section modeling
    - Material modeling
    - Shear & bond-slip deformations
  - Continuum modeling (discussed)
- New and existing construction are addressed

New

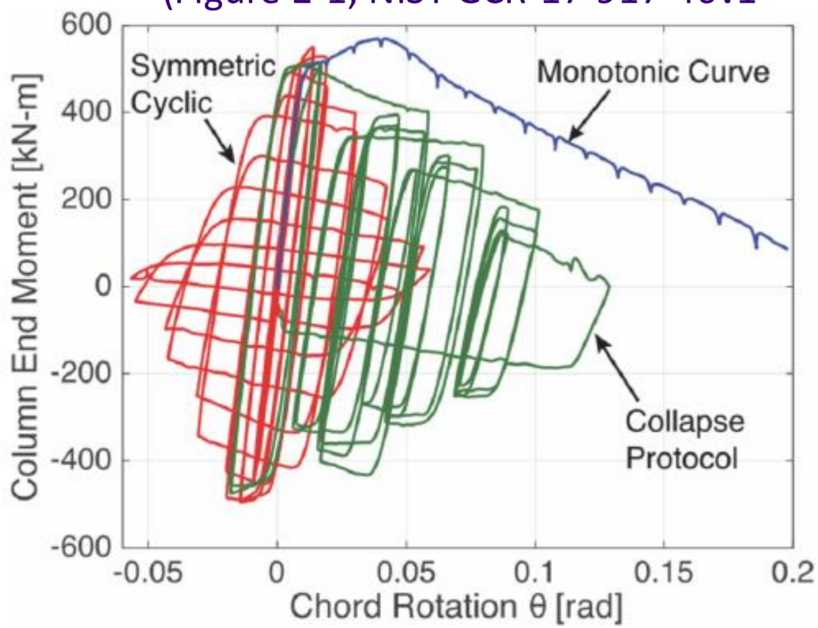
Concentrated Hinge Models



(Figure 31, NIST GCR 17-917-46v3)

“New Ideas” for Concentrated Hinge Models

(Figure 2-1, NIST GCR 17-917-46v1



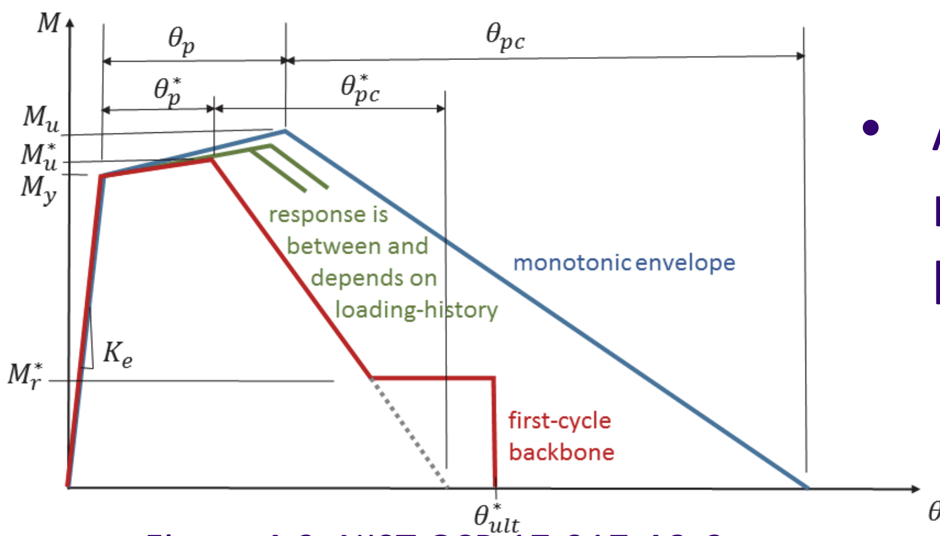
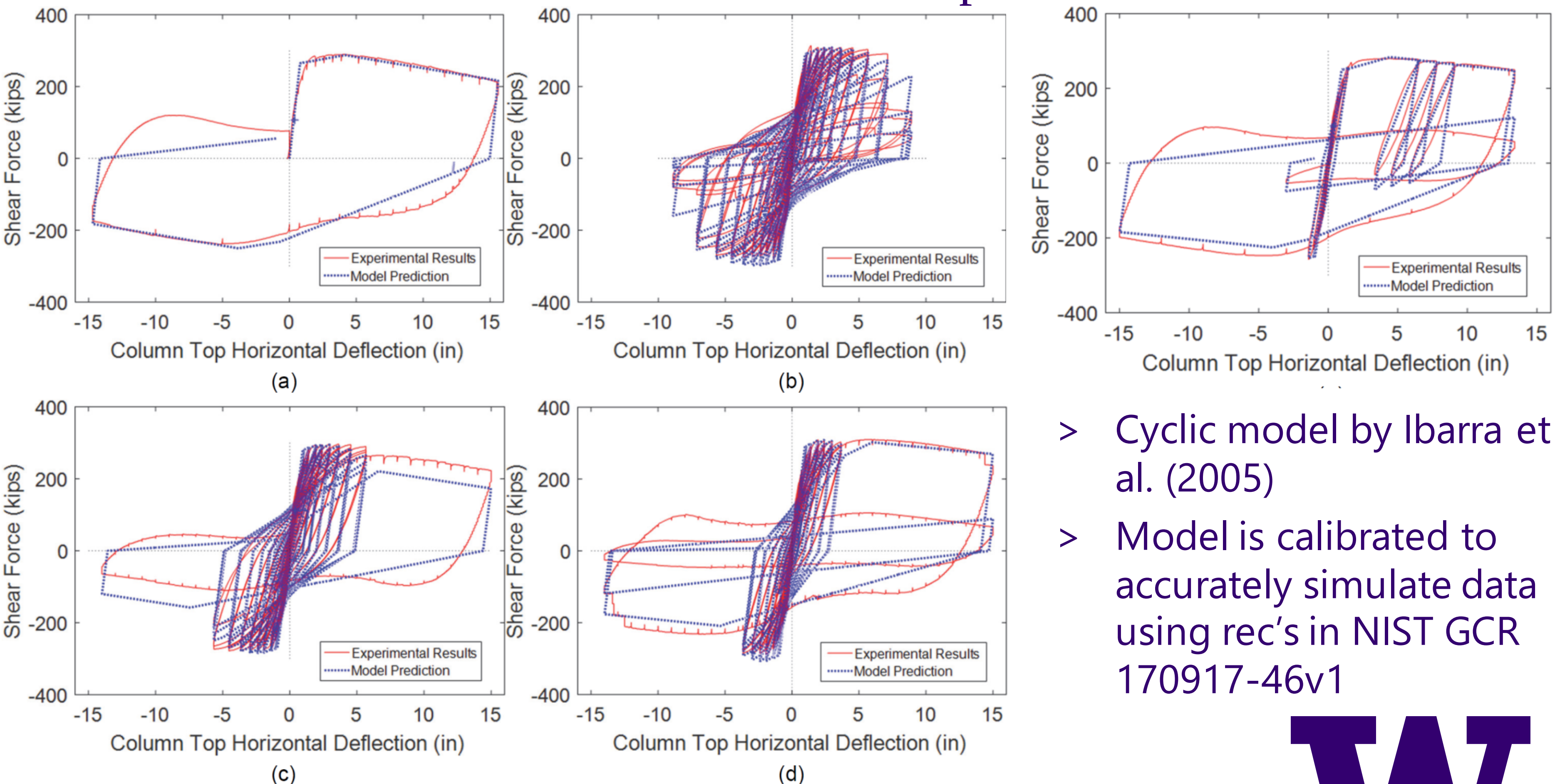


Figure 4-2, NIST GCR 17-917-46v3

- Peak strength, strength degradation and ductility are load history-dependent
- Use of cyclic backbones:
  - Conservative as to deformation capacity
  - Unconservative as to peak force demand
- Adaptive models capable of replicating different load histories are preferred
  - Green: fewer damaging cycles
  - Red: many damaging cycles

“New Ideas” for Concentrated Hinge Models

Measured and simulated column response histories



- Cyclic model by Ibarra et al. (2005)
- Model is calibrated to accurately simulate data using rec’s in NIST GCR 170917-46v1

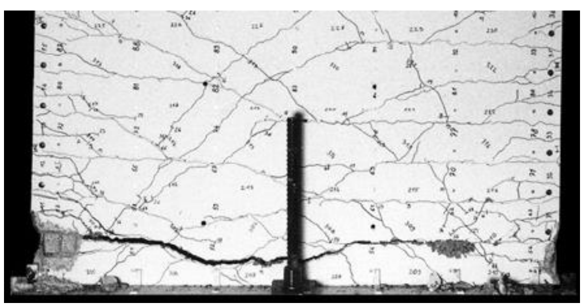
(Figure 4-7, NIST GCR 17-917-46v3; data and figures from Nojavan et al., 2014, 2016)

Guidelines for Flexural RC Walls (NIST GCR 17-917-45)

Modeling approach must simulate these failure modes
OR
Rules must define walls for which the modeling approach CAN simulate these failure modes

Tension-Controlled Flexural Failure (BR):

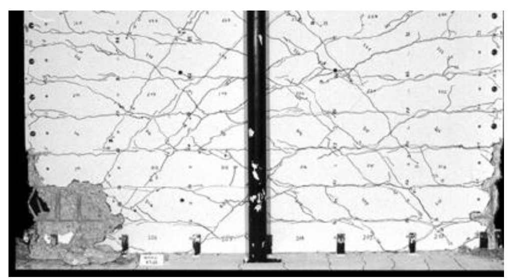
(low ρ_{long}, low axial load, low shear, low strain capacity steel)



Dazio et al. (2009)

Compression-Controlled Flexural Failure (CB):

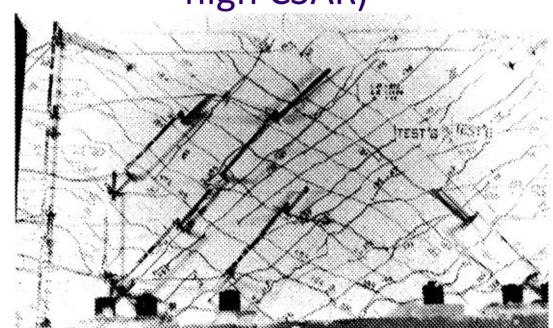
(high ρ_{long}, high axial load, low shear, low CSAR)



Dazio et al. (2009)

Compression-Shear Failure (CS):

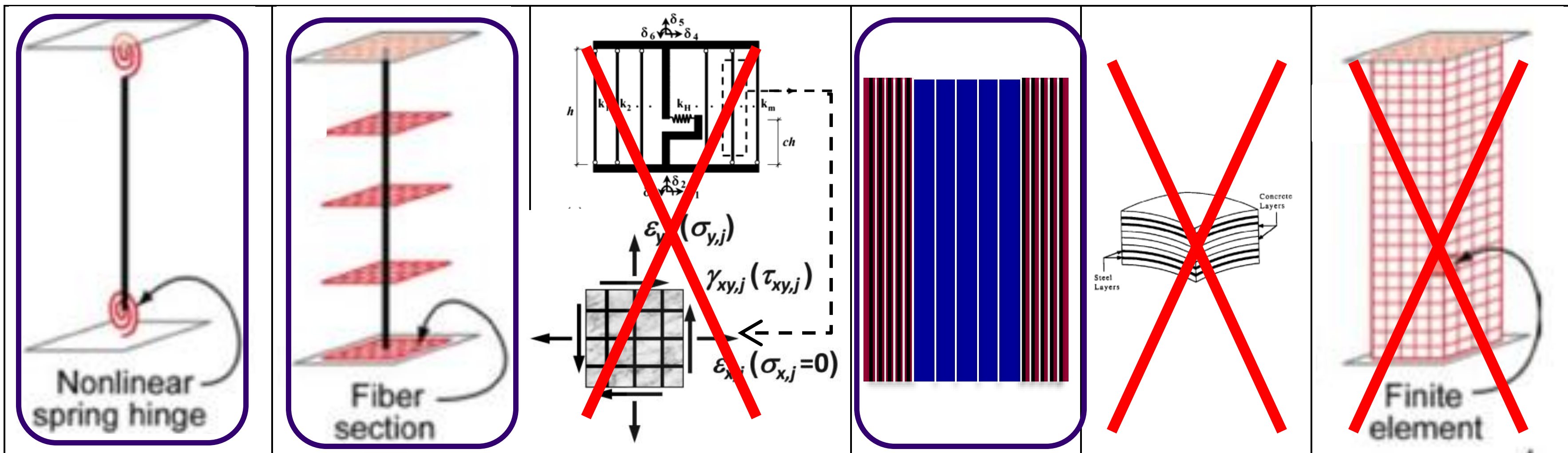
(high axial load, high shear, high CSAR)



Vallenas et al. (1979)

Recommendations for Modeling

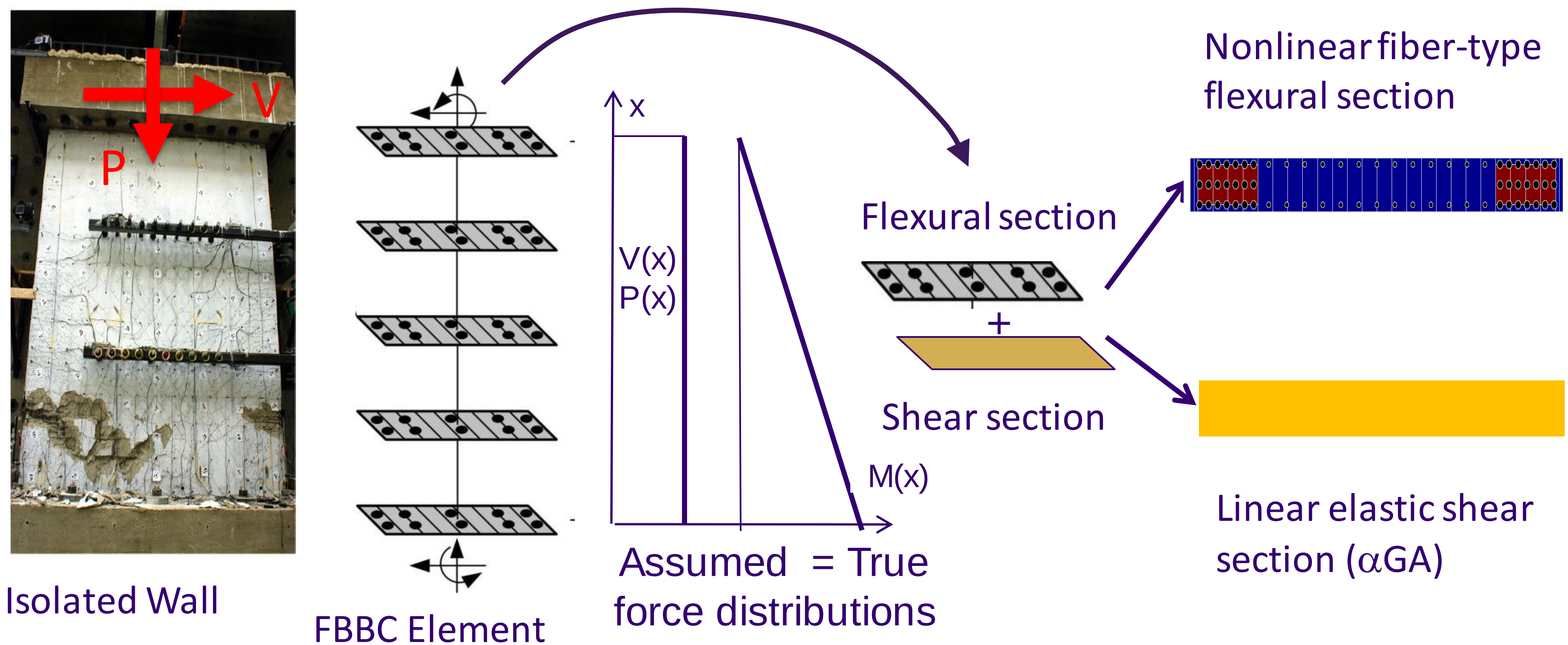
> Multiple approaches may be used to simulate flexural wall response to earthquake loading



(a) zero-length hinge model (e.g. SAP2000 or PERFORM)	(b) fiber-type beam-column element (e.g., OpenSees)	(c) beam-column element with flexure-shear interaction	(d) fiber-shell element (e.g. Perform)	(e) layered-shell element (e.g., LS Dyna or Abaqus)	(f) 3D continuum elements (e.g. Atena or Abaqus)

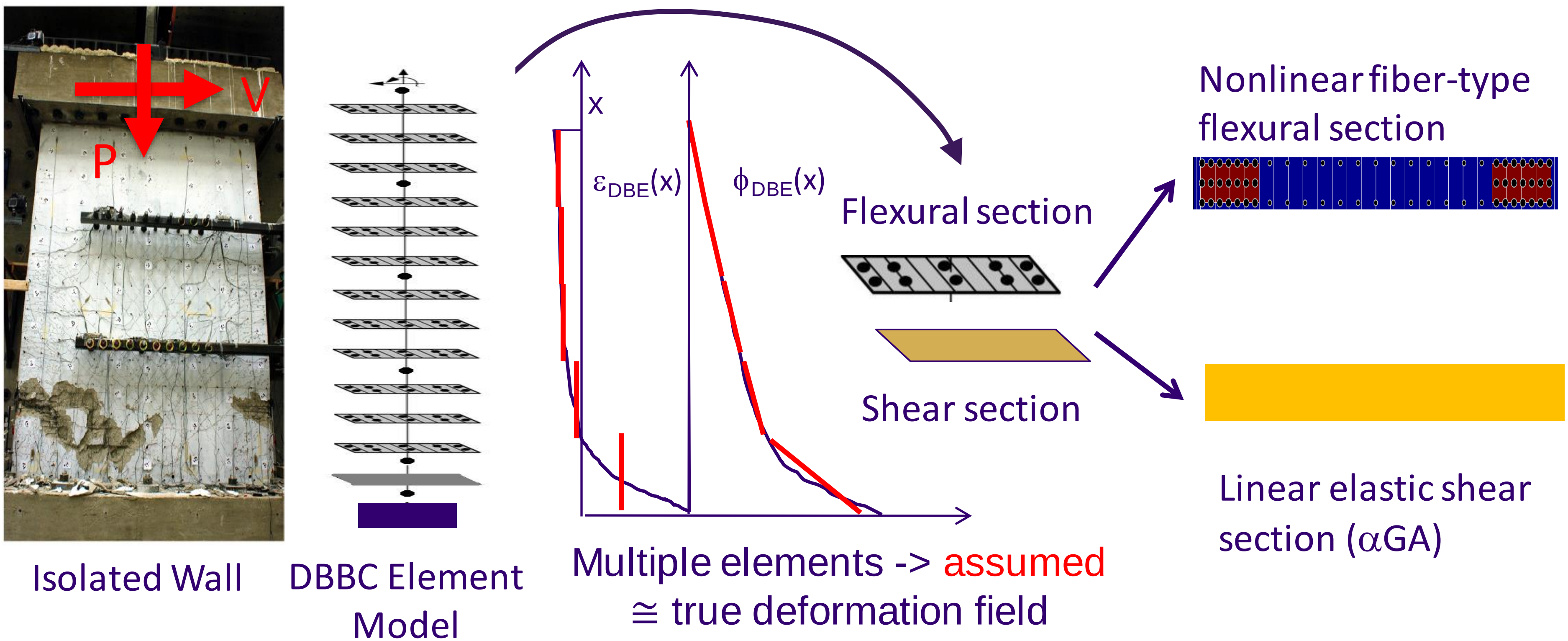
Force-Based Fiber-Type Beam-Column Element (OpenSees)

- **Force-Based Fiber-Type Beam-Column Elements Assumptions:** linear moment distribution, constant axial load -> solve for section strain and curvature to satisfy compatibility req'ts.



Displacement-Based Fiber-Type Beam-Column Element (OpenSees)

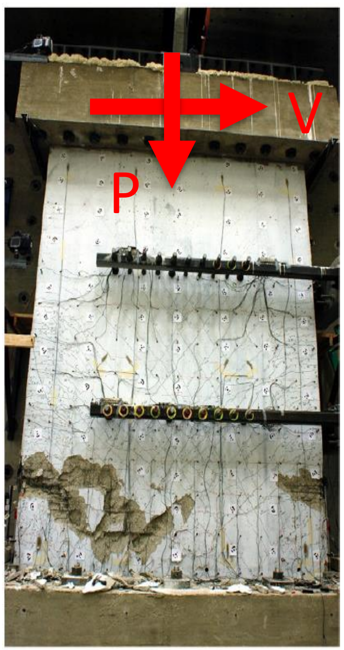
- **Assume** linear **curvature** and constant axial **strain** distribution
- **Compute** member end (nodal) forces and moments, explicitly from curvatures and strains: ϕ & ε -> section M & P -> nodal M & P & V



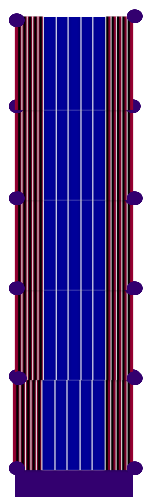
Displacement-Based Fiber-Type Wall / Planar Element (PERFORM)

- Element: assume **constant curvature** and **constant axial deformation**
- **Compute** member end (nodal) forces a explicitly from curvatures and strains: ϕ & ε -> section M & P -> nodal M & P & V

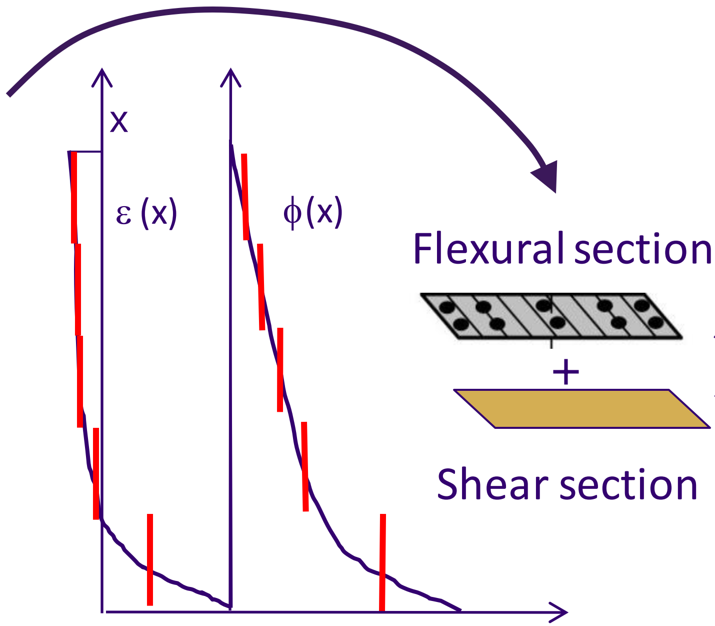
Nonlinear fiber-type flexural section



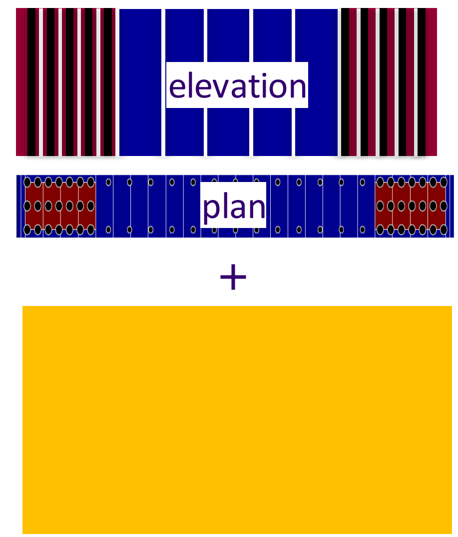
Isolated Wall



Quad element model

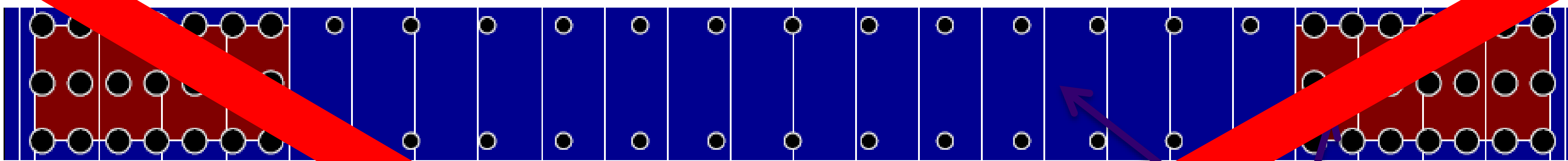


Multiple elements -> assumed ≅ true deformation field



Linear elastic shear section (αGA)

Traditional Concrete Model

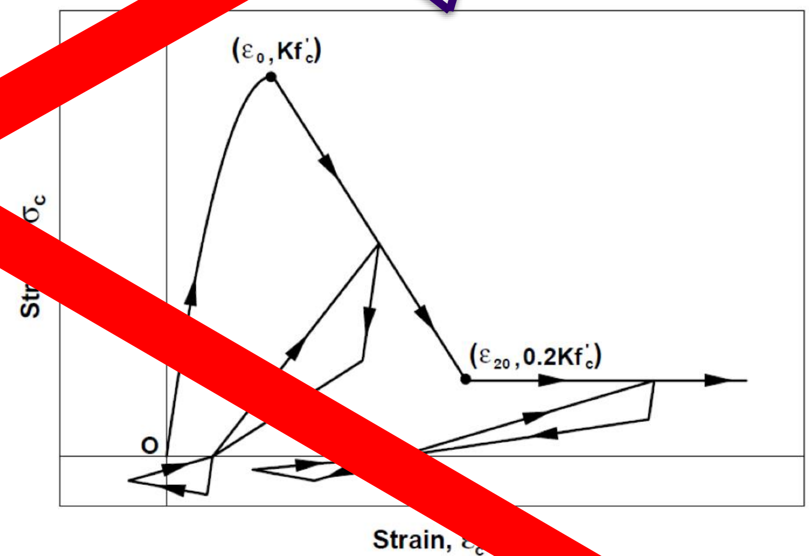


- Cyclic model per … in (1994)
- Compression:
  - Modified Kent-Park (Scott et … 982)
  - Unconfined fibers:

$$\varepsilon_0 = \frac{2f_c'}{57000\sqrt{f_c'}} \qquad \varepsilon_{20} = 0.00$$

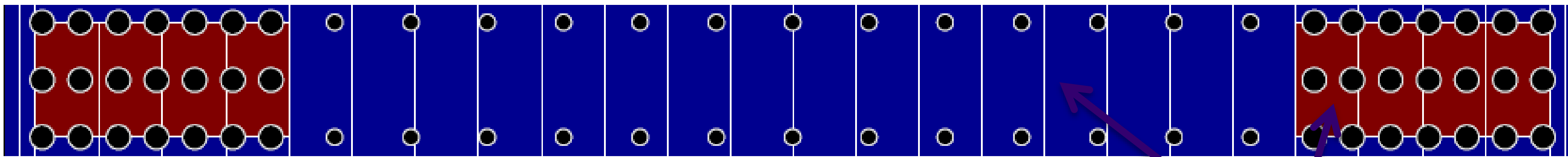
  - Confined fibers:

    K, ε_0, ε_{20} p… atcioglu and Razvi (1992)



- Tensio…
  - …astic stiffness: $E_t = E_c = 57000\sqrt{f_c}\ psi$
  - Strength per Wong and Vecchio (2006): $f_t = 4\sqrt{f_c}\ psi$
  - Post-peak stiffness per Yassin (1994): $E_{ts} = 0.05E_t$

Regularized Concrete Model

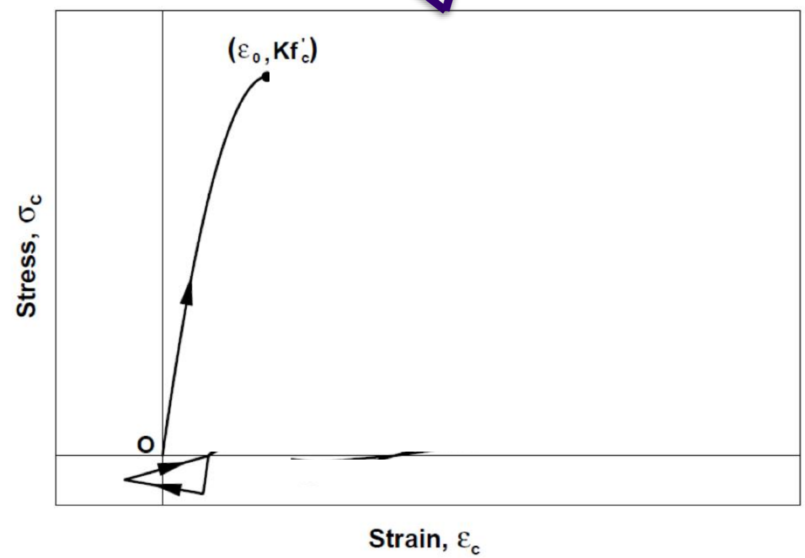


- Cyclic model per Yassin (1994)
- Compression:
  - Modified Kent-Park (Scott et al. 1982)
  - Unconfined fibers:

$$\varepsilon_0 = \frac{2f_c'}{57000\sqrt{f_c'}} \qquad \varepsilon_{20} = 0.008$$

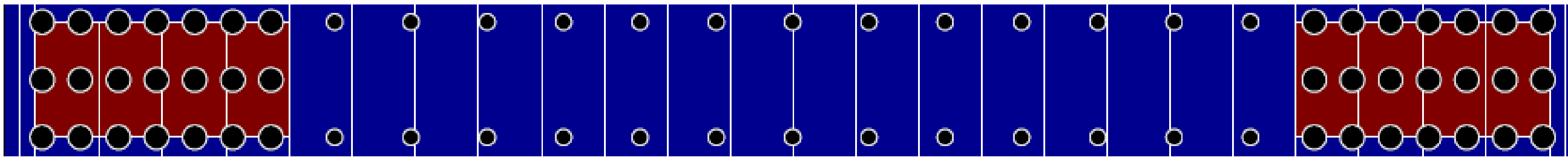
  - Confined fibers:

    K, ε_0, ε_{20} per Saatcioglu and Razvi (1992)



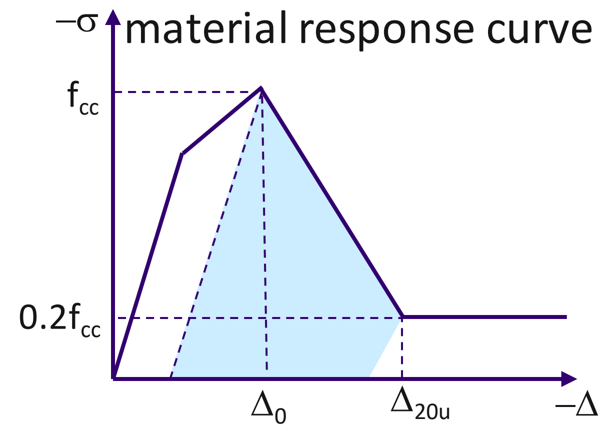
- Tension:
  - Elastic stiffness: $E_t = E_c = 57000\sqrt{f_c}\ psi$
  - Strength per Wong and Vecchio (2006): $f_t = 4\sqrt{f_c}\ psi$
  - Post-peak stiffness per Yassin (1994): $E_{ts} = 0.05E_t$

Regularized Concrete Model

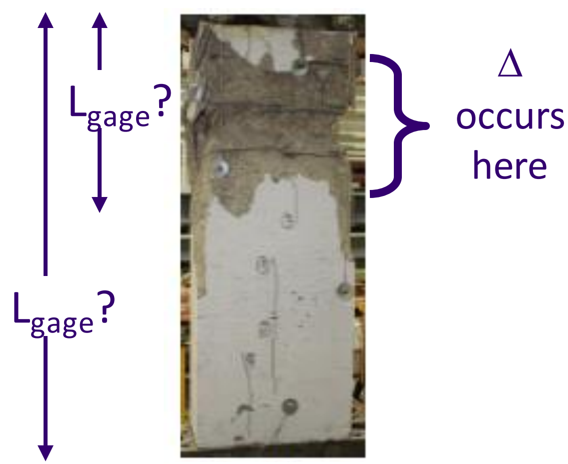


- Regularize material response:
  - Stress vs. deformation (not strain) considered to be the fundamental material property.
  - Testing to demonstrate this by Jansen and Shah (1997) and Nakamura and Higai (2001)
  - Regularization of material response for beam-column elements proposed by Coleman and Spacone (2001)

σ vs Δ is fundamental material response curve

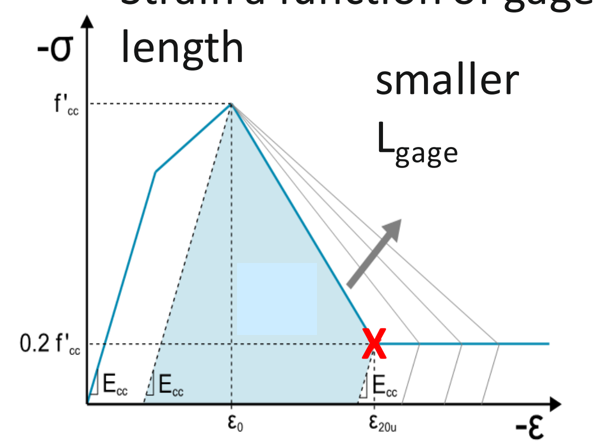


(image from Dragovich)



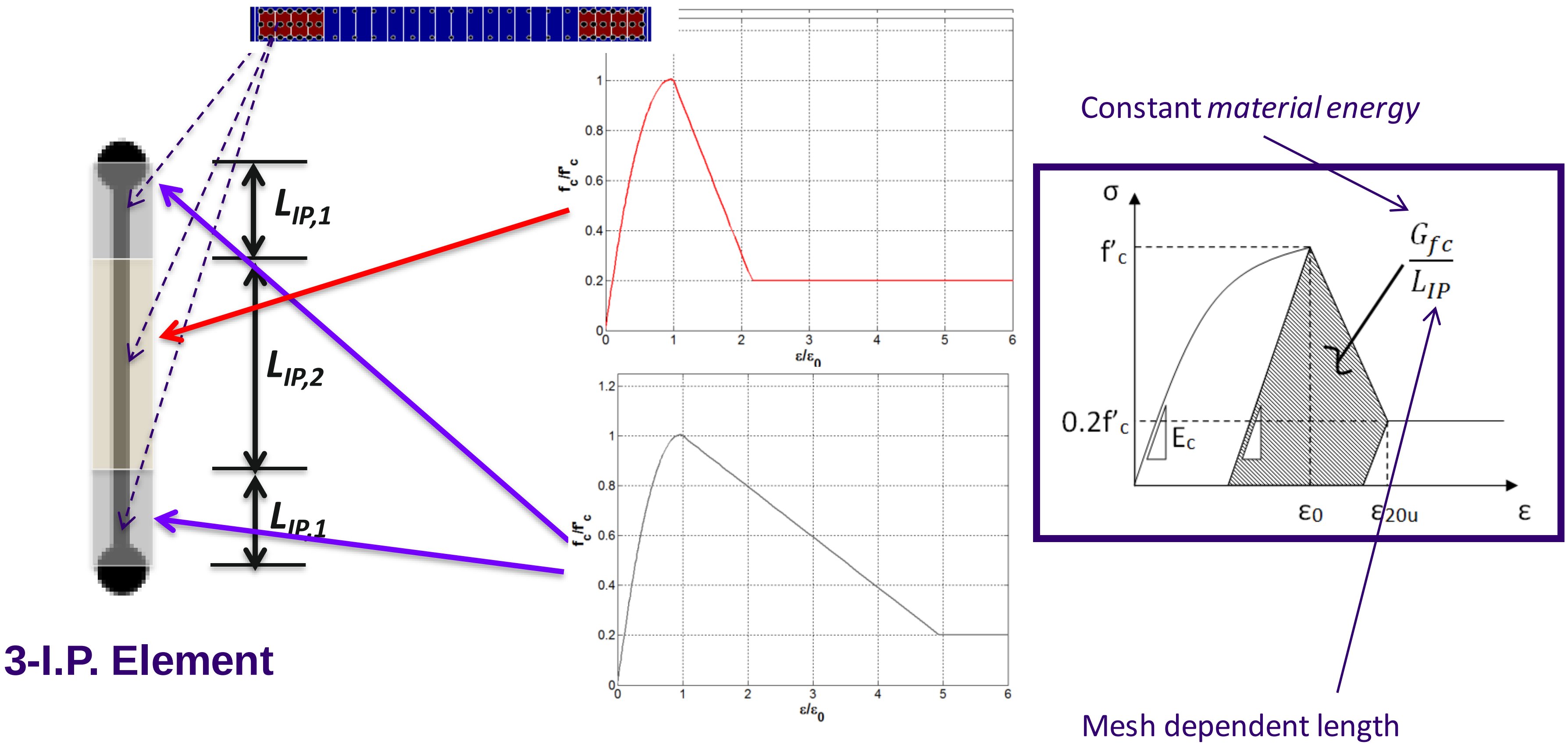
$$\varepsilon = \frac{\Delta}{L_{gage}}$$

Strain a function of gage length

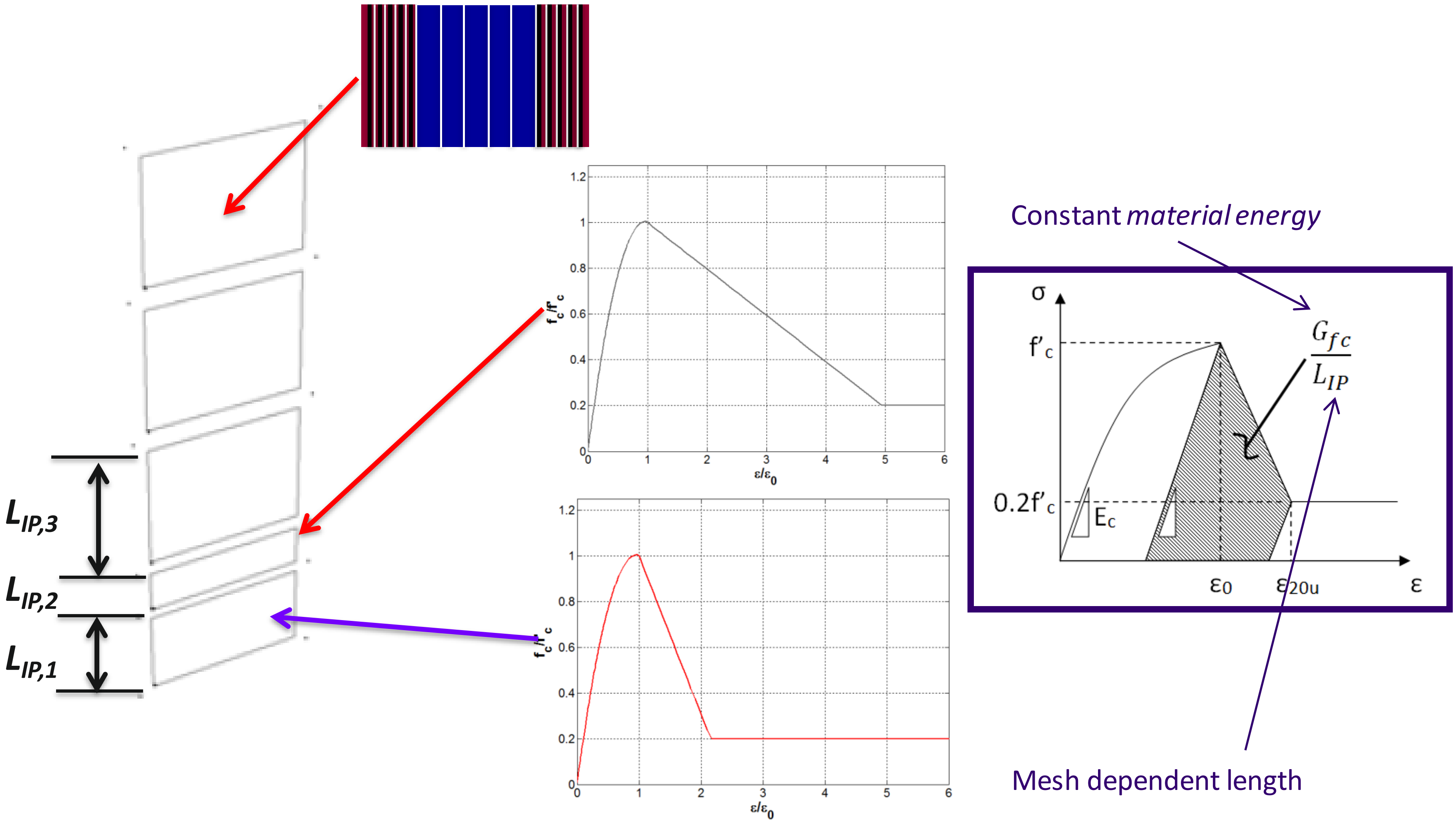


Regularized Concrete Model: Beam-Column Element (OpenSees)

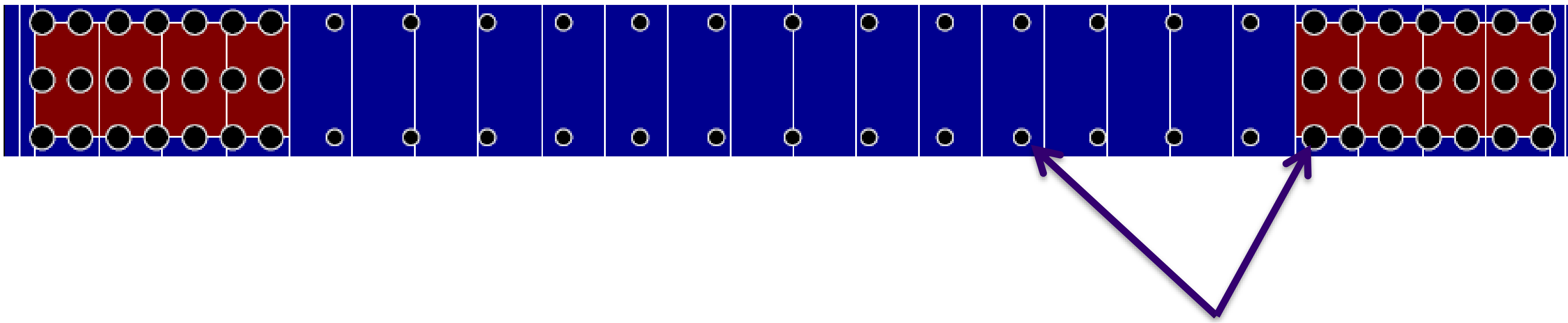
For a given compressive energy, the strain capacity can be determined from the length, LIP



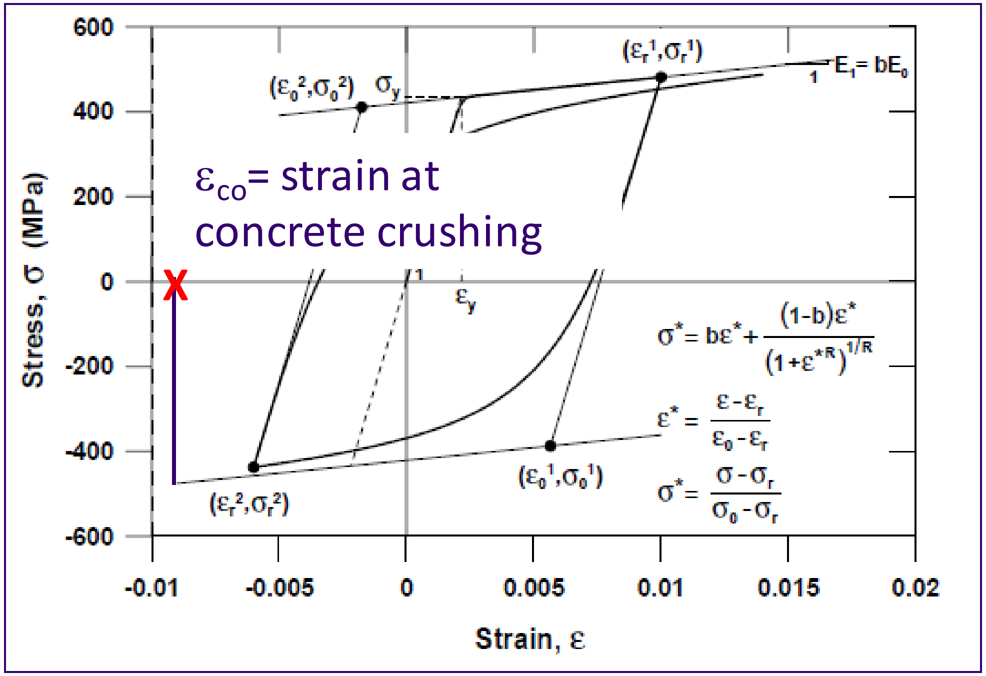
Regularized Concrete Model: Fiber Wall Element (Perform)



Fiber Section: Steel Model

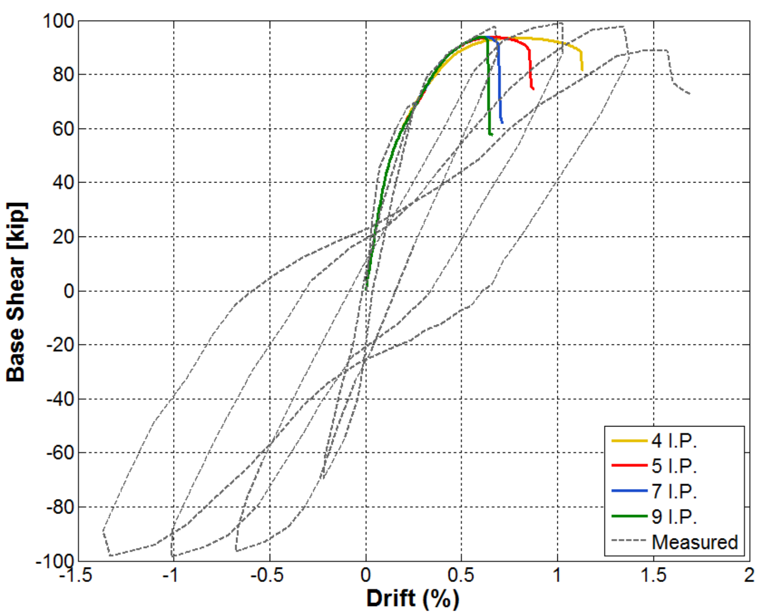


- Menegotto-Pinto-Filippou model (1983)

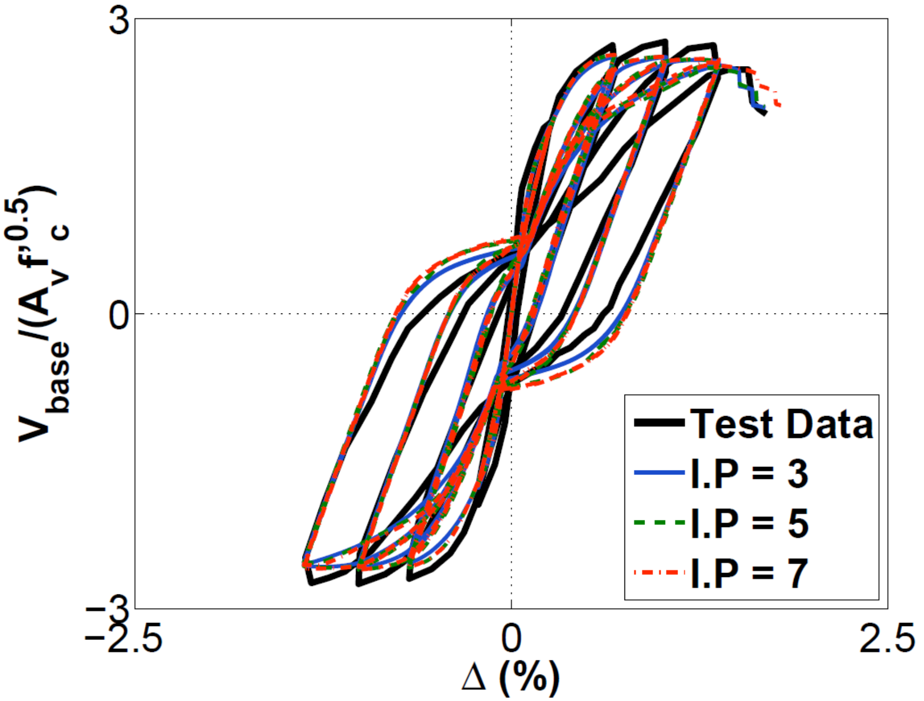


With and Without Regularization

- Without regularization, mesh-dependent results; behavior is more brittle as element length decreases.



- With regularization, analyses converge to the correct solution.



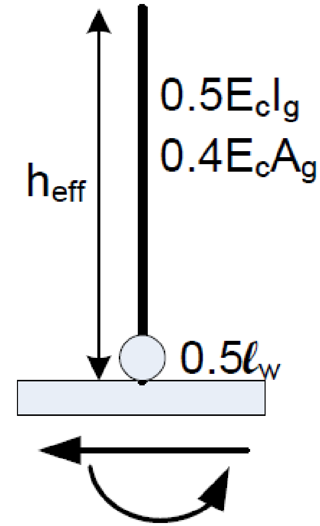
RESULTS: Regularized FBBC Element Model

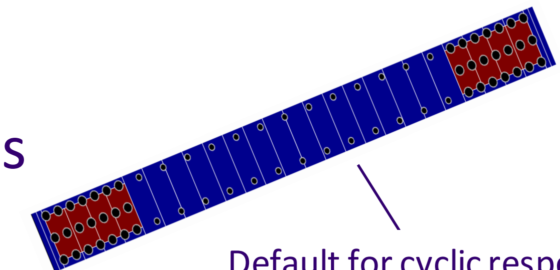
	$\frac{V_{max,sim.}}{V_{max}}$		$\frac{\Delta_{yield,sim.}}{\Delta_{yield}}$		$\frac{\Delta_{u,sim.}}{\Delta_{u}}$	
Failure Mode (3 EL / 7 IP)	**Mean**	**COV**	**Mean**	**COV**	**Mean**	**COV**
Crushing (12 Specimen)	**0.94**	**0.04**	**0.98**	**0.10**	**1.02**	**0.17**
Buckling or Rupture (9 Specimens)	**0.99**	**0.06**	**0.99**	**0.10**	**1.12**	**0.25**
All Flexure	**0.96**	**0.04**	**0.98**	**0.06**	**1.06**	**0.17**
C-Shaped Walls (6 Specimen)	**0.97**	**0.07**	**1.07**	**0.11**	**0.99**	**0.17**

- Similar results for DBBC element model
- Similar results for PERFORM fiber-shell model

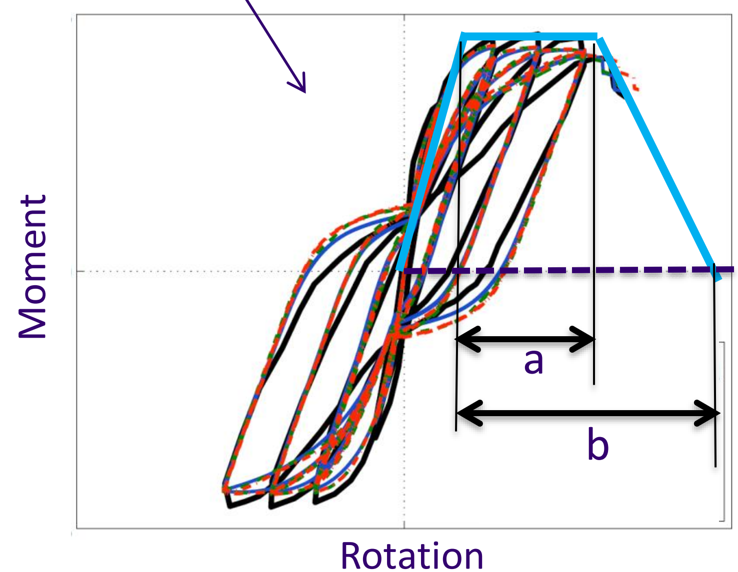
Lumped-Plasticity Model

- $L_p = 0.5l_w$ or other.
- Use reduced effective flexure and shear stiffness values outside of hinge.
- Hinge response defined, in part, by fiber-type section model.
  - Regularized materials required.
  - L_p is regularization length.
  - Use fiber section model to define entire response history or just envelope.



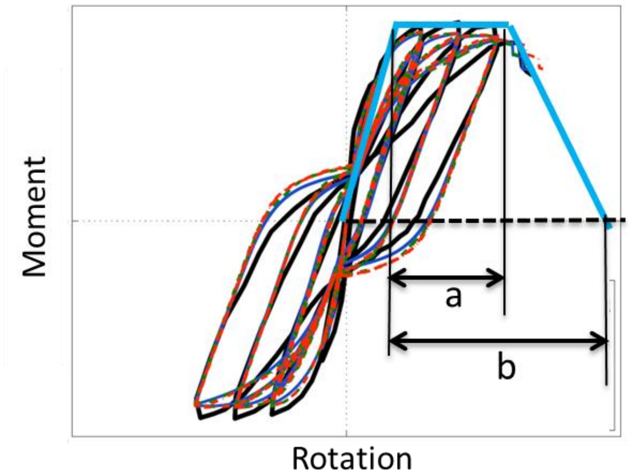


Default for cyclic response and/or envelope

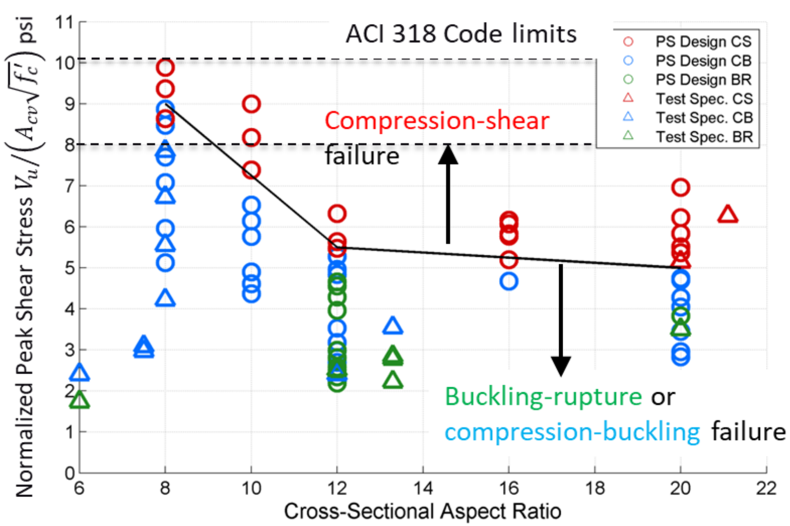


Deformation Capacity - “a”

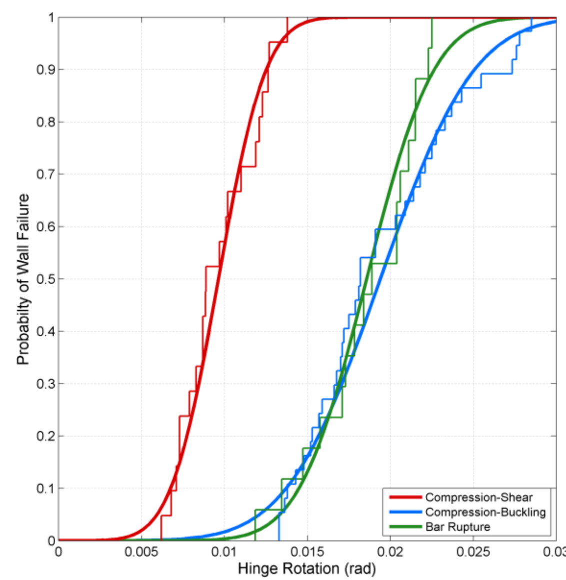
- For “pure” flexure-controlled walls (BR or CB)
  - Fiber section model w/ regularized materials
- For flexure-shear walls
  - Rotation capacities per continuum analysis by Whitman (2015) or per experimental data by Abdulla and Wallace (ACI 369 activity)
- For non-planar walls
  - Rotation capacities per continuum analysis by Ahmed, et al. (in progress) or per experimental data by Abdulla and Wallace (ACI 369 activity)



Failure Mode as a function of shear demand and cross-sectional aspect ratio



Rotation capacity as a function of failure mode



Modeling Rec's & Deformation Capacities

		Rotational Hinge	Fiber Hinge	Fiber-Type Line Element	Fiber-Type Planar Element	Continuum Model
Planar Walls w/ moderate shear and/or low CSAR	Interstory Drift (%)	2.0 (0.3)	OPTIONAL - use drift and rotation limits to verify model			
	Hinge Rotation (rad)	0.016 (0.3)				
	Concrete Strain		$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = hinge length (fiber hinge), section integration length (FT line ele.), element height (FT planar ele., continuum ele.)			
Planar Walls w/ high shear and/or high CSAR	Interstory Drift (%)	1.2 (0.16)	Model defines stiffness and strength; drift / rotation limits define onset of strength loss			OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)	0.009 (0.15)				
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = element height
Symmetric Flanged Walls w/ flanges in T/C	Interstory Drift (%)	**Future Work**				OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)					
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = element height
Asymmetric Flanged Walls; Symmetric Flanged Walls w/ wall toes in T/C	Interstory Drift (%)	**Future Work**				OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)					
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = element height

Modeling Rec's & Deformation Capacities

		Rotational Hinge	Fiber Hinge	Fiber-Type Line Element	Fiber-Type Planar Element	Continuum Model
Planar Walls w/ moderate shear and/or low CSAR	Interstory Drift (%)	2.0 (0.3)	OPTIONAL - use drift and rotation limits to verify model			
	Hinge Rotation (rad)	0.016 (0.3)				
	Concrete Strain		$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = hinge length (fiber hinge), section integration length (FT line ele.), element height (FT planar ele., continuum ele.)			

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		Rotational Hinge	Fiber Hinge	Fiber-Type Line Element	Fiber-Type Planar Element	Continuum Model
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	Concrete Strain		$\frac{G_{fc}}{0.6f_{cc}L} - \frac{0.8f_p}{E_0} + \varepsilon_{0c}$ with L = hinge length (fiber hinge), section integration length (FT line ele.), element height (FT planar ele., continuum ele.)			
Planar Walls w/ high shear and/or high CSAR	Interstory Drift (%)	1.2 (0.16)	Model defines stiffness and strength; drift / rotation limits define onset of strength loss			OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)	0.009 (0.15)				
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6f_{cc}L} - \frac{0.8f_p}{E_0} + \varepsilon_{0c}$ with L = element height

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		Rotational Hinge	Fiber Hinge	Fiber-Type Line Element	Fiber-Type Planar Element	Continuum Model
Planar Walls w/ moderate shear and/or low CSAR	Interstory Drift (%)	2.0 (0.3)	OPTIONAL - use drift and rotation limits to verify model			
	Hinge Rotation (rad)	0.016 (0.3)				
	Concrete Strain		$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = hinge length (fiber hinge), section integration length (FT line ele.), element height (FT planar ele., continuum ele.)			
Planar Walls w/ high shear and/or high CSAR	Interstory Drift (%)	1.2 (0.16)	Model defines stiffness and strength; drift / rotation limits define onset of strength loss			OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)	0.009 (0.15)				
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = element height
Symmetric Flanged Walls w/ flanges in T/C	Interstory Drift (%)	← **Future Work** →				OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)					
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = element height
Asymmetric Flanged Walls; Symmetric Flanged Walls w/ wall toes in T/C	Interstory Drift (%)	← **Future Work** →				OPTIONAL - use drift and rotation to verify model
	Hinge Rotation (rad)					
	Concrete Strain	NA	NA	NA	NA	$\frac{G_{fc}}{0.6 f_{cc} L} - \frac{0.8 f_p}{E_0} + \varepsilon_{0c}$ with L = element height