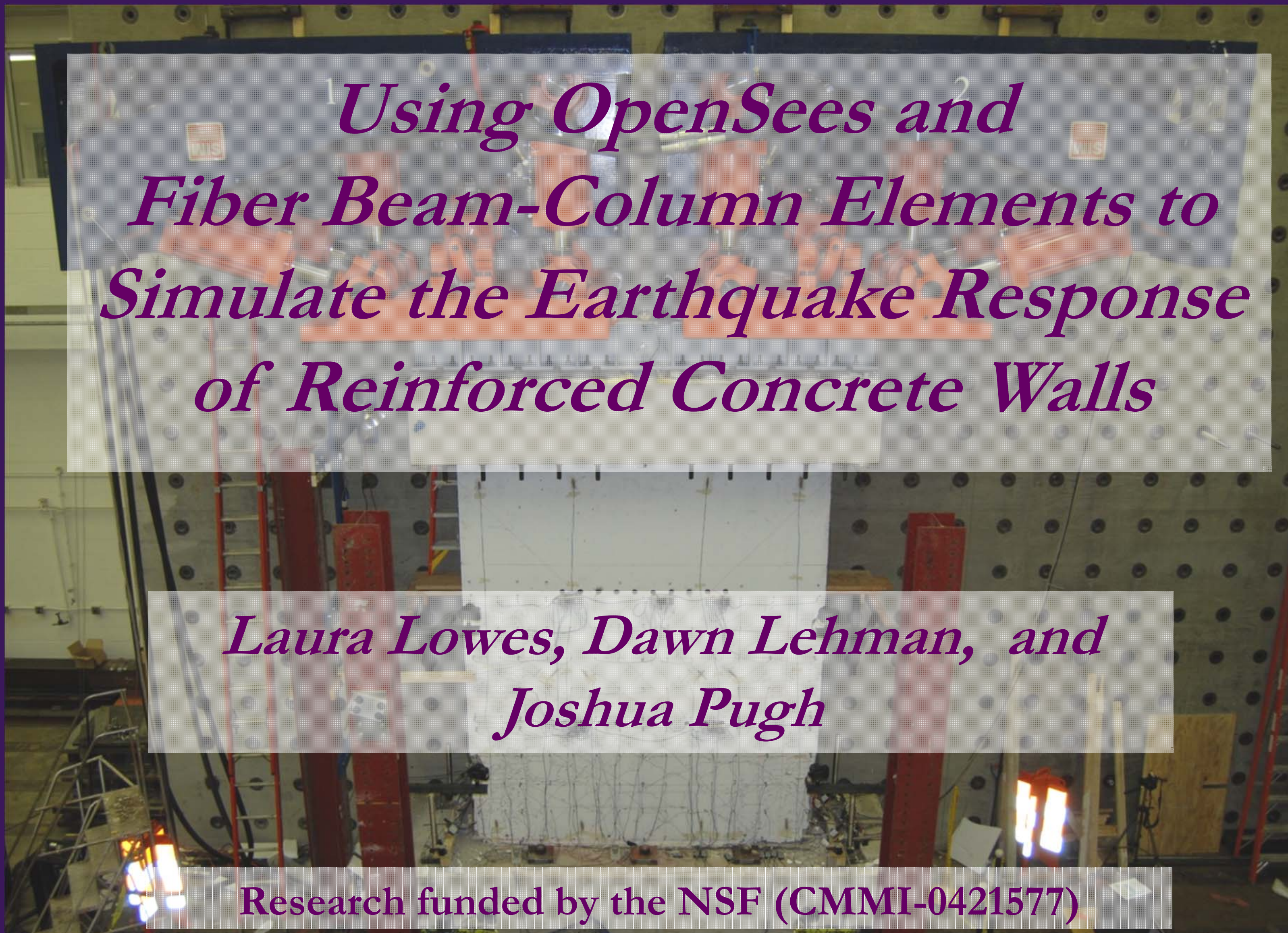


Using OpenSees and Fiber Beam-Column Elements to Simulate the Earthquake Response of Reinforced Concrete Walls

Laura Lowes, Dawn Lehman, and Joshua Pugh

Research funded by the NSF (CMMI-0421577)

Research Objective

- Develop recommendations for simulating the earthquake response of slender RC walls to
  - Enable research investigating both the earthquake performance and seismic design of walled buildings
  - Enable performance-based seismic design of walled buildings in practice

Photo courtesy of MKA Seattle

Why use distributed-plasticity beam-column elements?

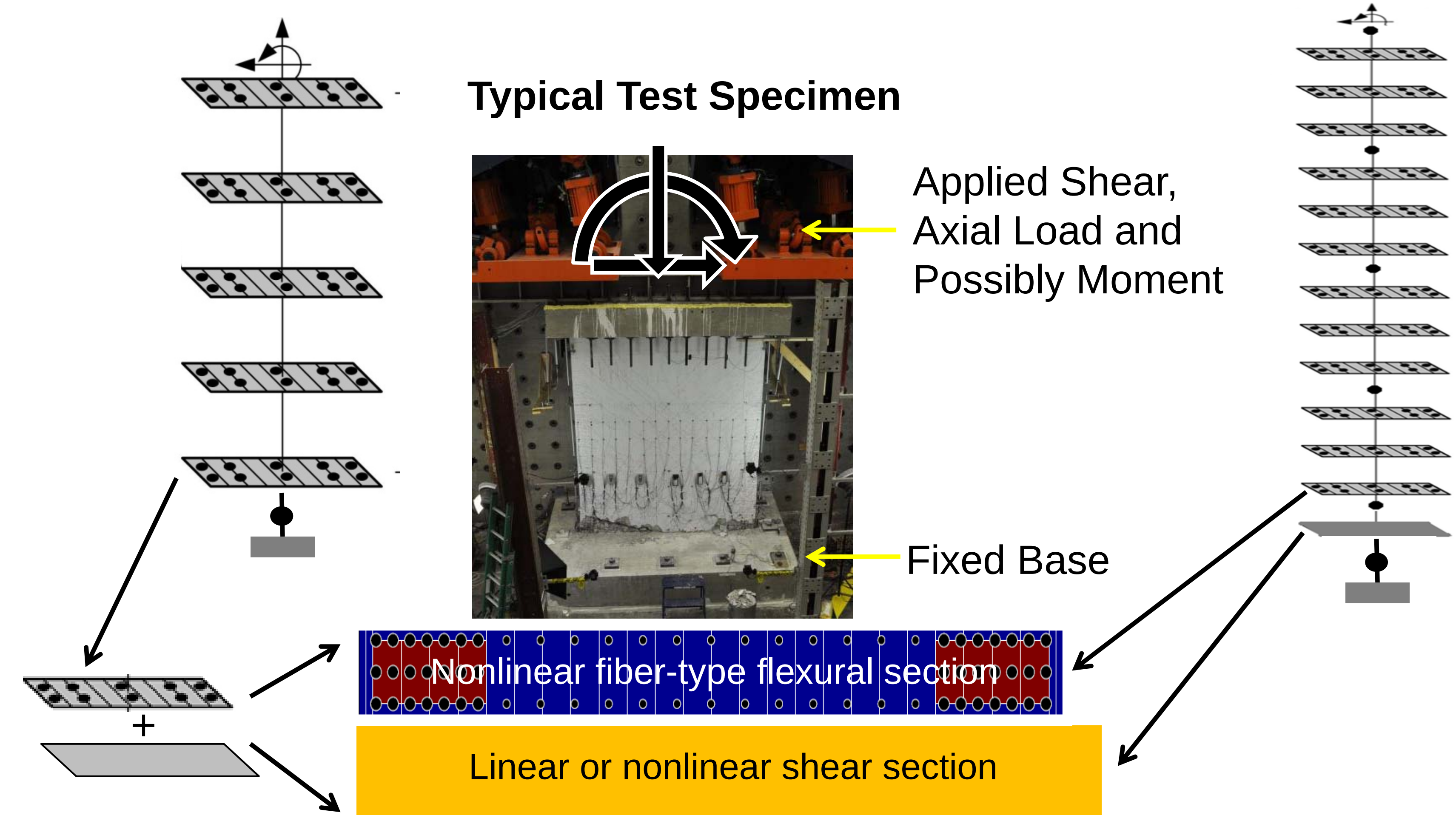
- Lumped-plasticity / plastic-hinge models
  - Don't know where inelastic action will occur in a multi-story building
- Fiber-shell models
  - Probably the preferred approach with respect to modeling behavior
    - Enables simulation of inelastic flexure and shear response
    - Enables accurate simulation of vertical strain distribution along wall length (plane sections don't remain plane),
    - **but** …
  - Computational demands for multi-story, multi-wall building subjected to multiple ground motions are quite large
  - 2D concrete continuum models not as numerically robust as 1D models
- Distributed-plasticity beam-column elements
  - Excellent results for slender walls that respond primarily in flexure

Fiber-Type Beam-Column Elements

- **Force-Based Element:**
  - Assume linear moment distribution, constant shear, and constant axial load (along the length of the element).
  - Intra-element solution to determine section strains and curvatures that satisfy compatibility req’ts.
  - Use one element per story; each element has ~5 sections.
- **Displacement-Based Element**
  - Assume linear curvature distribution and constant axial strain (along the length of the element).
  - No intra-element solution req’d
  - Use multiple elements per story; each element can have 3 sections

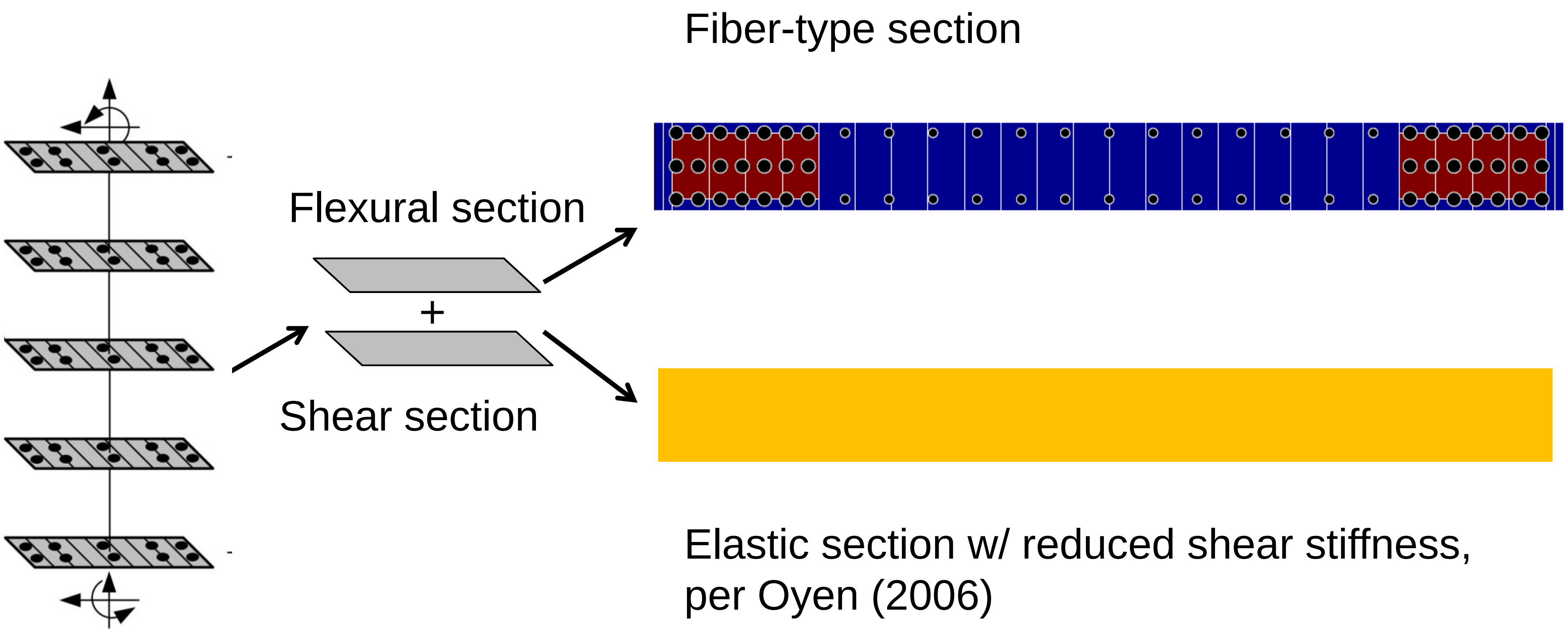
Fiber-Type Beam-Column Elements

- **Force-Based Element:**
- **Displacement-Based Element**

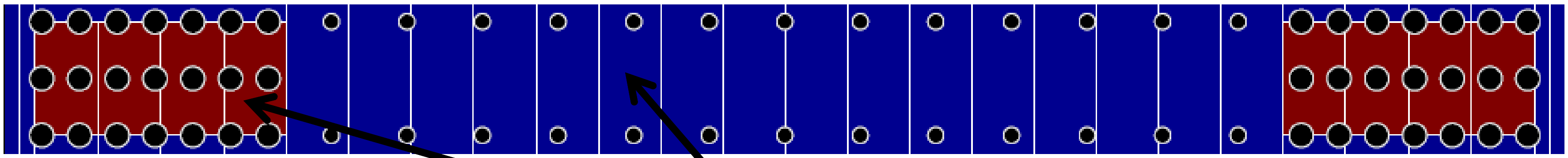


Force-Based Fiber-Type Beam-Column Element in OpenSees

- **Assume:** linear moment distribution, constant axial load -> solve for section strain and curvature to satisfy compatibility req'ts.



Fiber Section:
Concrete 02 model used for concrete

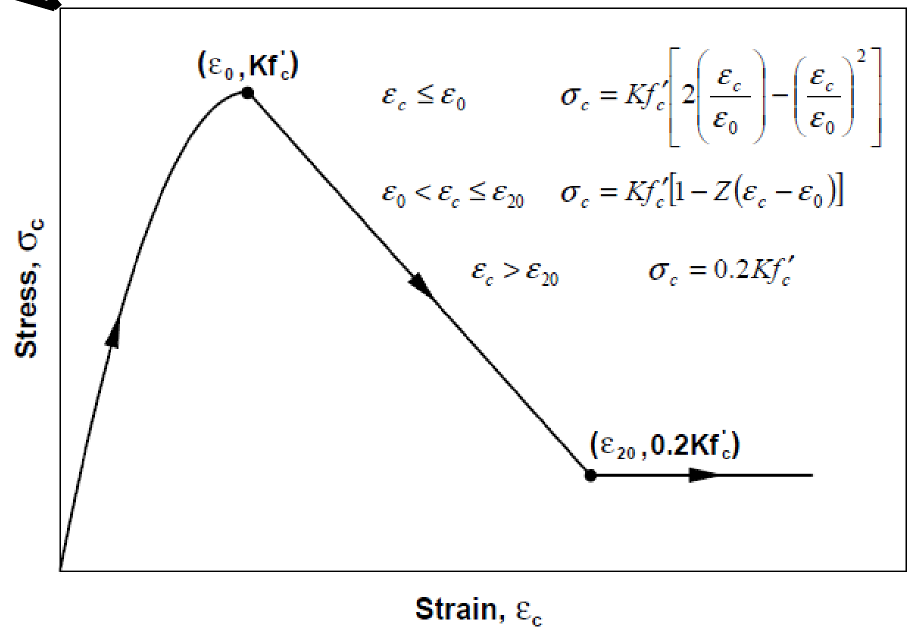


Unconfined Fibers:

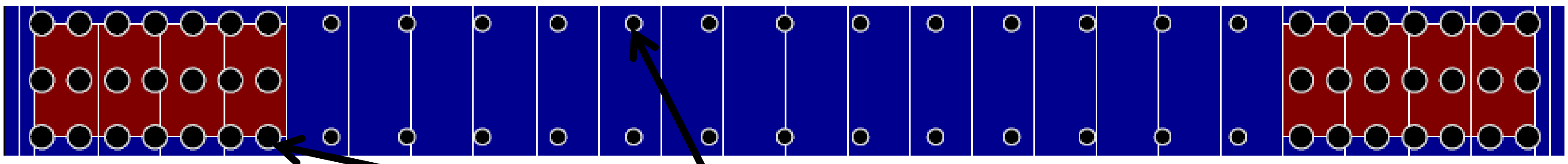
$$\varepsilon_0 = \frac{2f_c'}{57000\sqrt{f_c'}} \qquad \varepsilon_{20} = 0.008$$

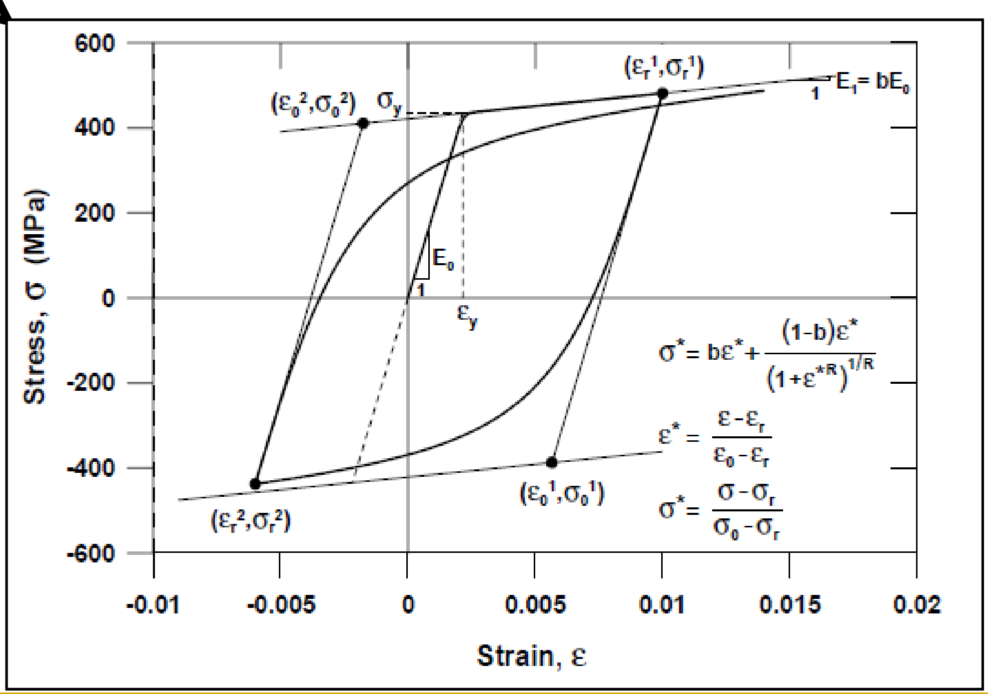
Confined Fibers:

$$\left.\begin{array}{c} K \\ \varepsilon_0 \\ \varepsilon_{20} \end{array}\right\}$$ ***Saatcioglu & Razvi (1992)***



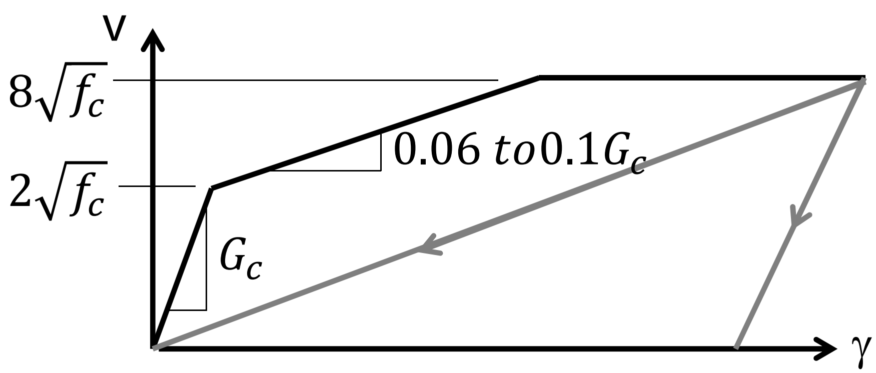
Fiber Section:
Steel 02 used for reinforcing steel





Shear Section

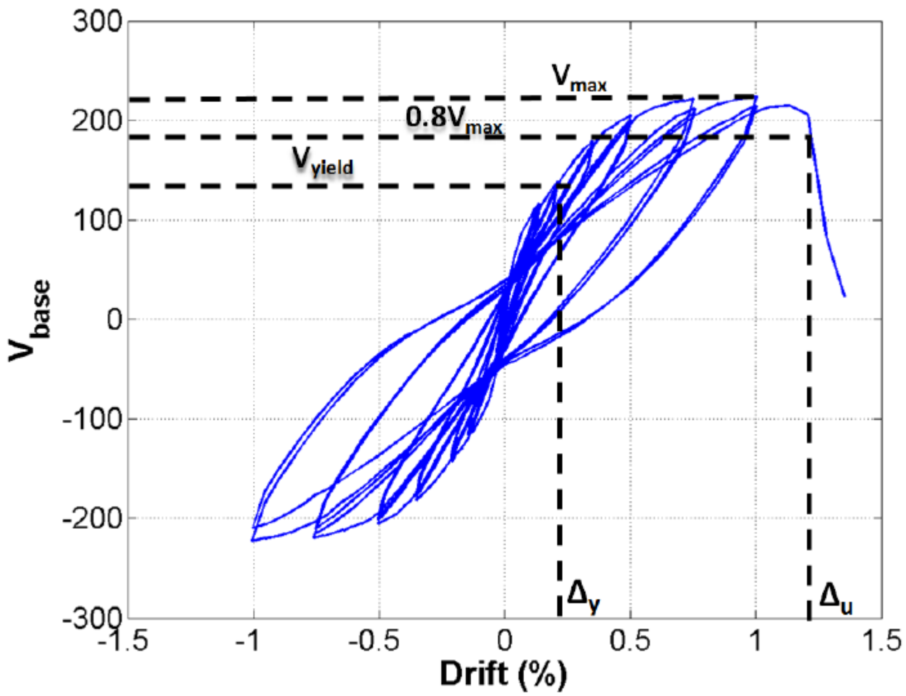
- Elastic models
  - Gross section stiffness: $V = GA_{cv}\gamma \approx 0.4E_cA_{cv}\gamma$
  - Reduced section stiffness:
    - Oyen (2006) using experimental data set of planar walls: $V = 0.1GA_{cv}\gamma \approx 0.04E_cA_{cv}\gamma$
- Nonlinear models
  - Very limited previous research
  - Envelope from planar wall data (Oyen 2006)



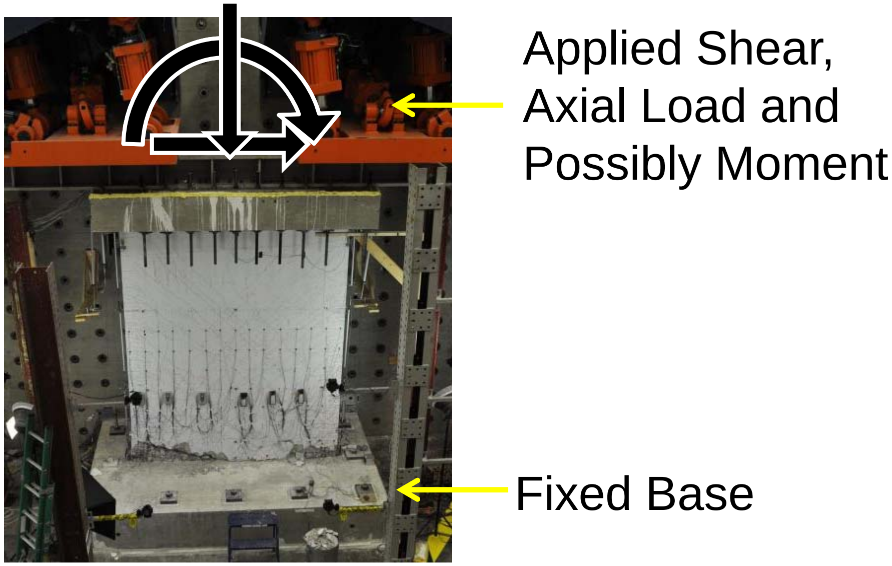
Experimental Data Used for Model Evaluation, Calibration & Validation

- 19 rectangular, 3 barbell, 6 c-shape, 4 t-shaped specimens from 10 test programs
- All walls are slender with $(M/V)/l_w > 2$
- All walls exhibit flexural failure mechanisms
  - Crushing of boundary-element concrete, buckling and/or rupture of long. reinforcement
  - Walls exhibiting web crushing (barbell walls) not included
- All wall have scale = t_w/12 in. > 1/3
- Axial load ratios: $0.01f_cA_g$ - $0.16f_cA_g$
- Shear stress demands: $1.0\sqrt{f_c}A_{cv} - 6.0\sqrt{f_c}A_{cv}$ psi

Quantities Used for Model Evaluation, Calibration & Validation



Typical Test Specimen

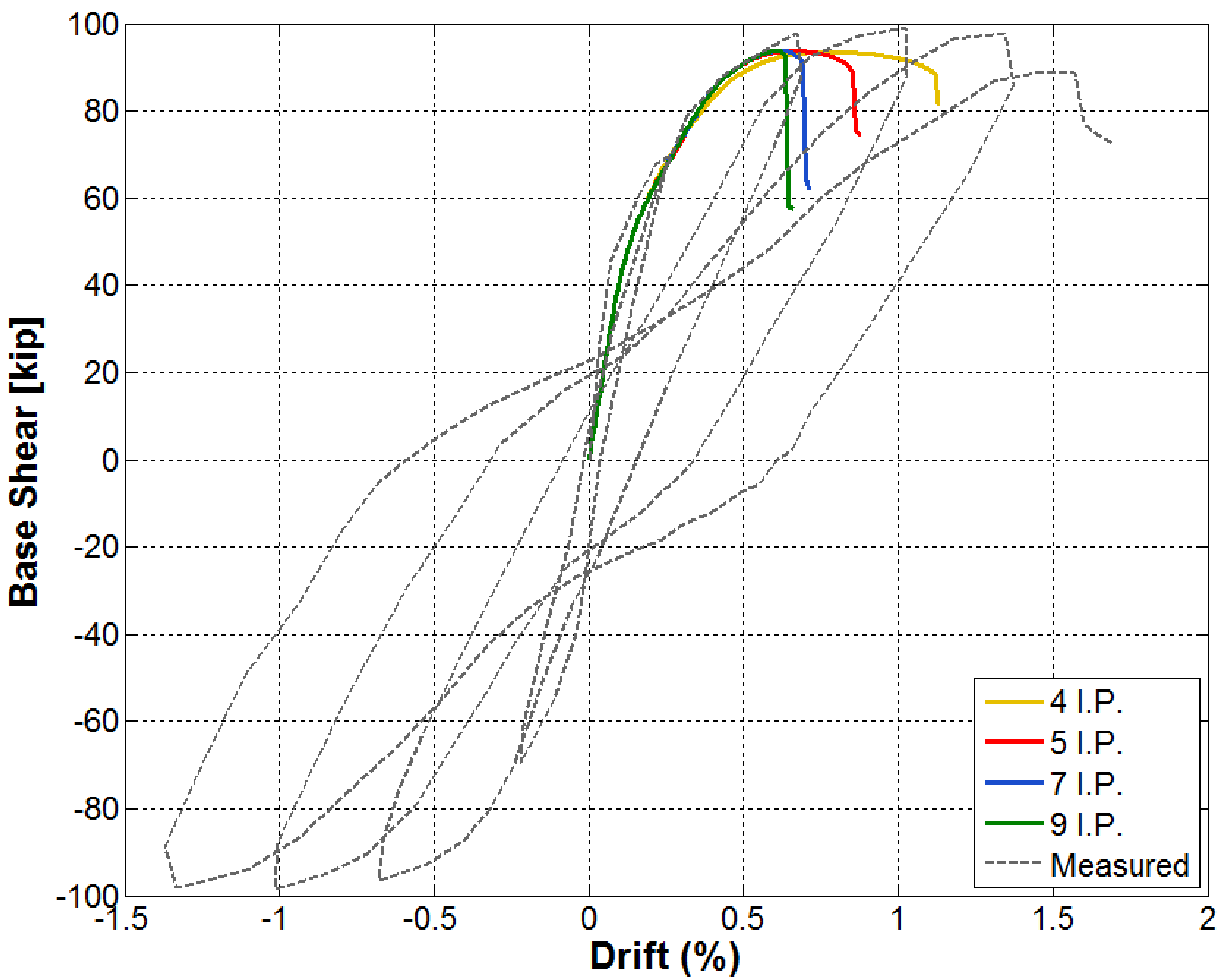


Force-Based Distributed-Plasticity Beam-Column Element:

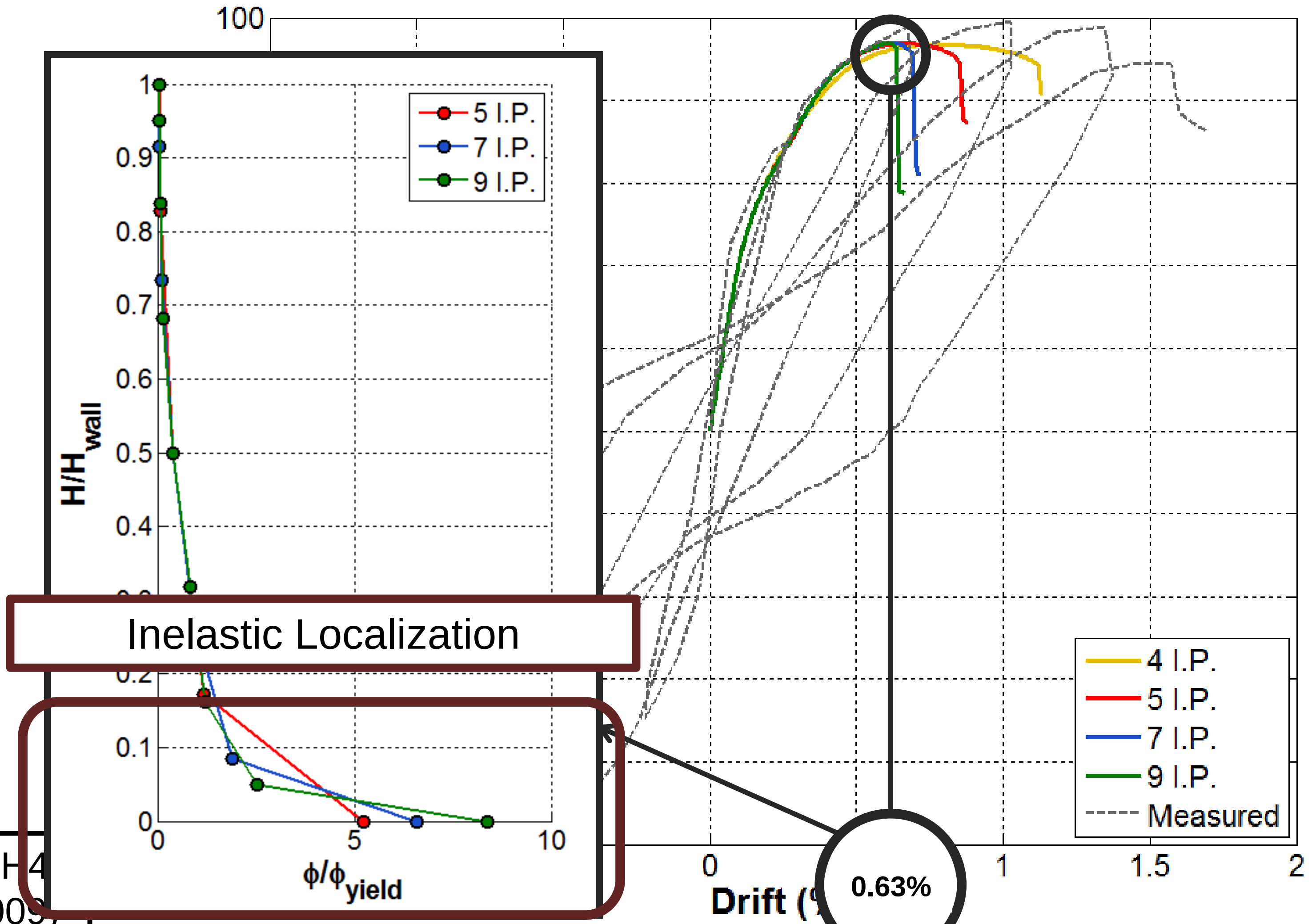
Evaluation, Calibration and Validation

Model Evaluation

No. of I.P.	No. of Spec's	Me
3	23	0.9
5	23	0.9
7	23	0.9

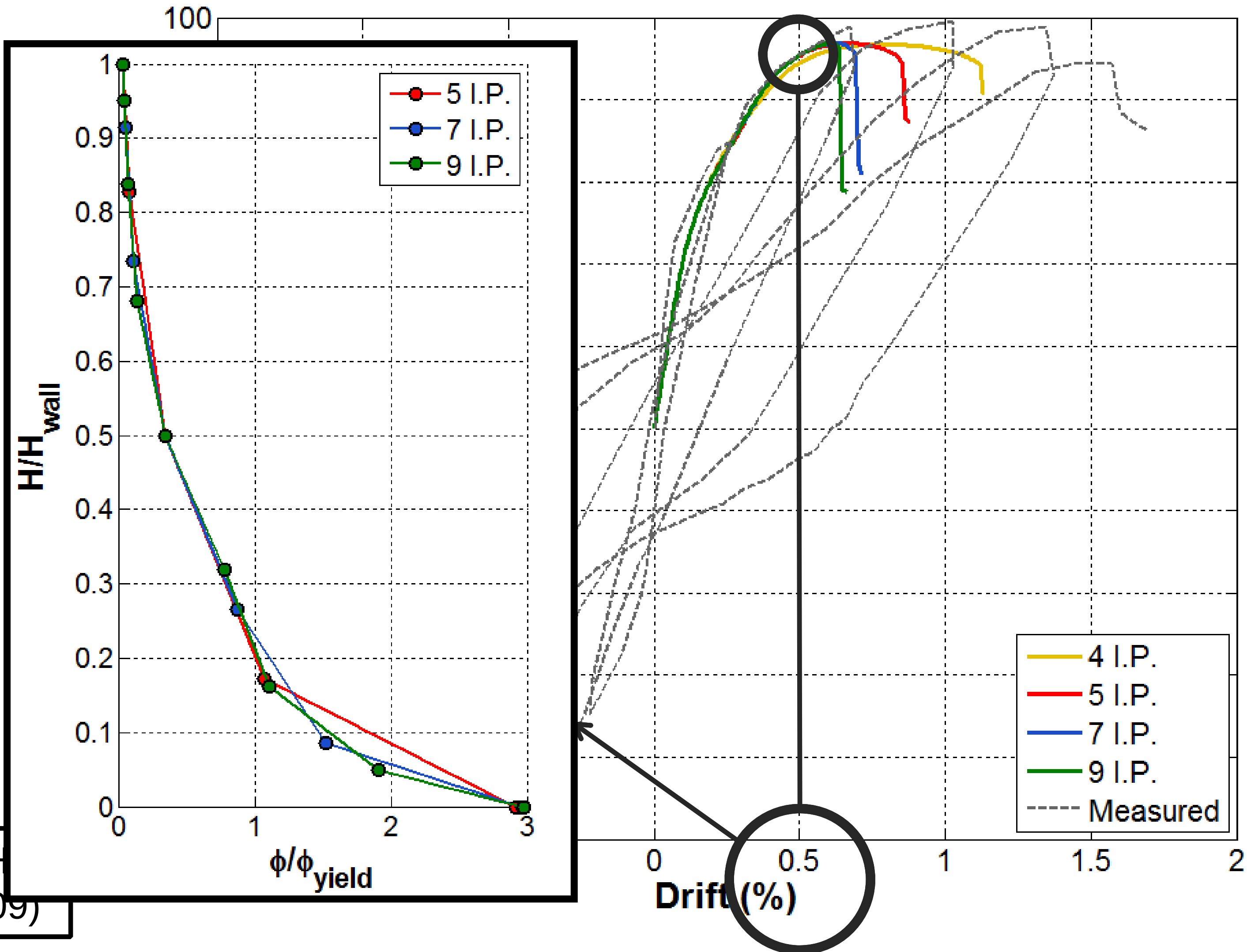


Localization of Damage / Deformation



Specimen WSH4
(Dazio et al. 2009)

No Localization Prior to Strength Loss



Specimen WSH
(Dazio et al. 2009)

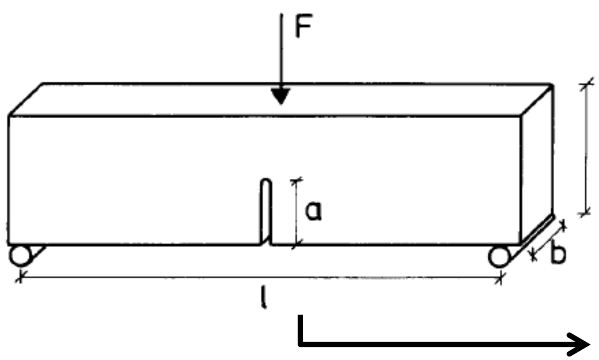
To Achieve Mesh-Objective Results

- Regularize material response using a mesh-dependent length
- Typically done in continuum analysis
- Coleman and Spacone (2001) propose this for beam-column elements;
- To regularize
  - **Concrete:** Use experimental data to define energy under post-peak portion of the stress-deformation curve & convert stress-deformation to stress-strain using integration-point length, L_{IP}
  - **Steel:** Use experimental data to define stress-strain response and adjust post-peak strength strain response based on ratio of laboratory gage length to integration-point length, L_{IP}
- Note that regularization of steel hardening response req'd because deformation localizes to softening section

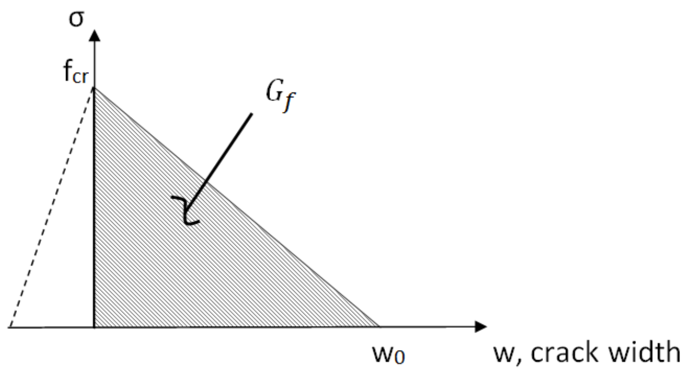
Concrete Tensile Fracture Energy

- Tensile fracture energy, G_f, commonly used to regularize material response for continuum-type finite element analysis
- Several "standard" approaches for defining G_f (e.g., RILEM 50-FMC)
- $G_f \approx$ 75-150 N/m (Wong and Vecchio, 2006)

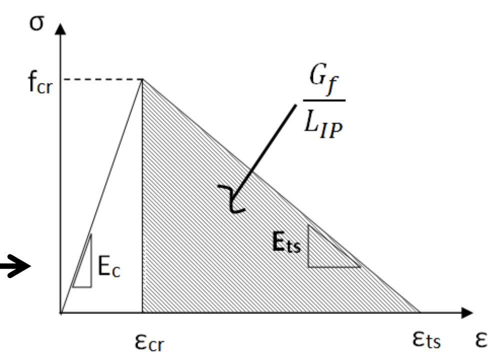
RILEM 50-FMC Lab Test



Laboratory Test Data



σ–ε used in analysis



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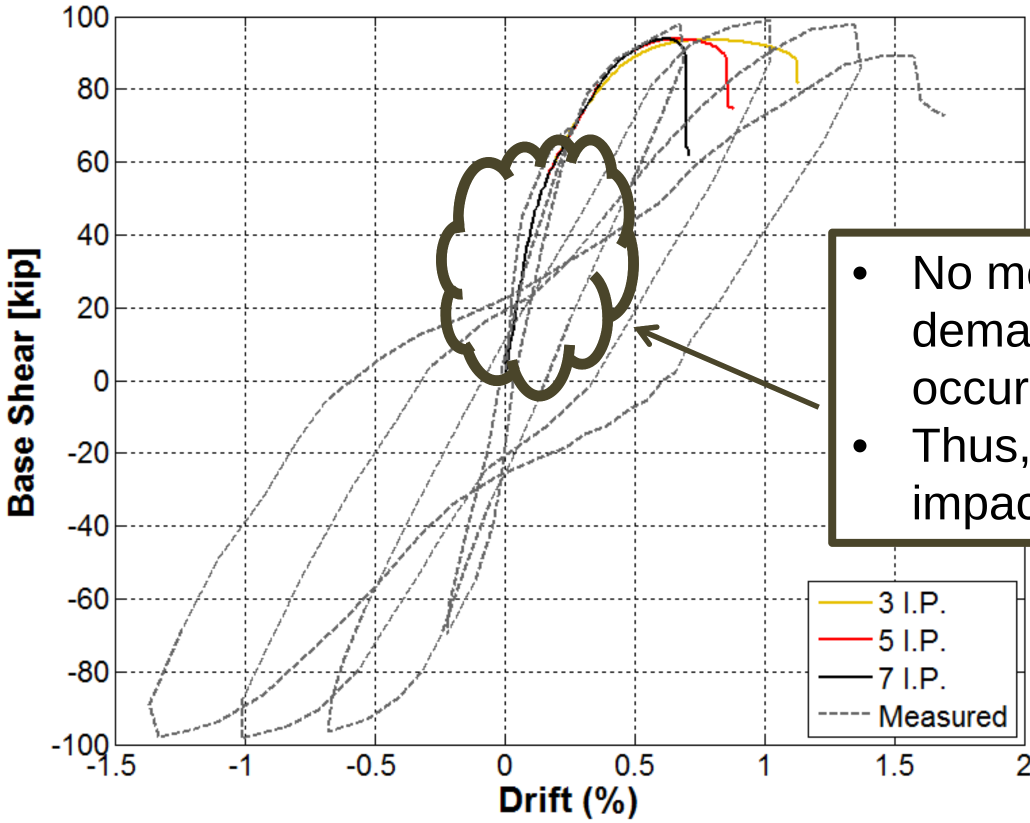
Concrete Material Regularization Using G_f

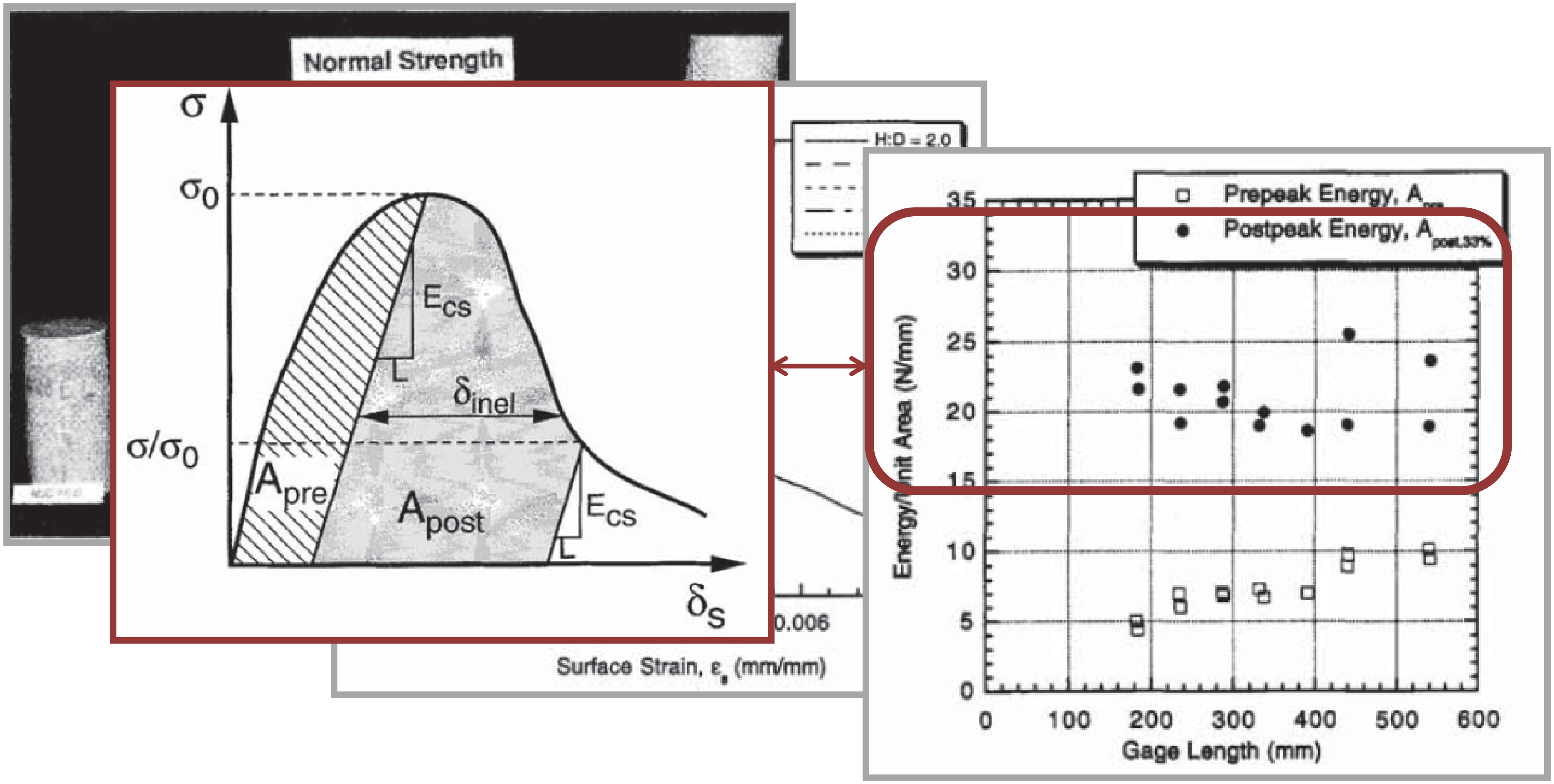
- Has essentially no impact; therefore ignore



- No mesh sensitivity in range of demands in which concrete cracking occurs
- Thus, material regularization has no impact

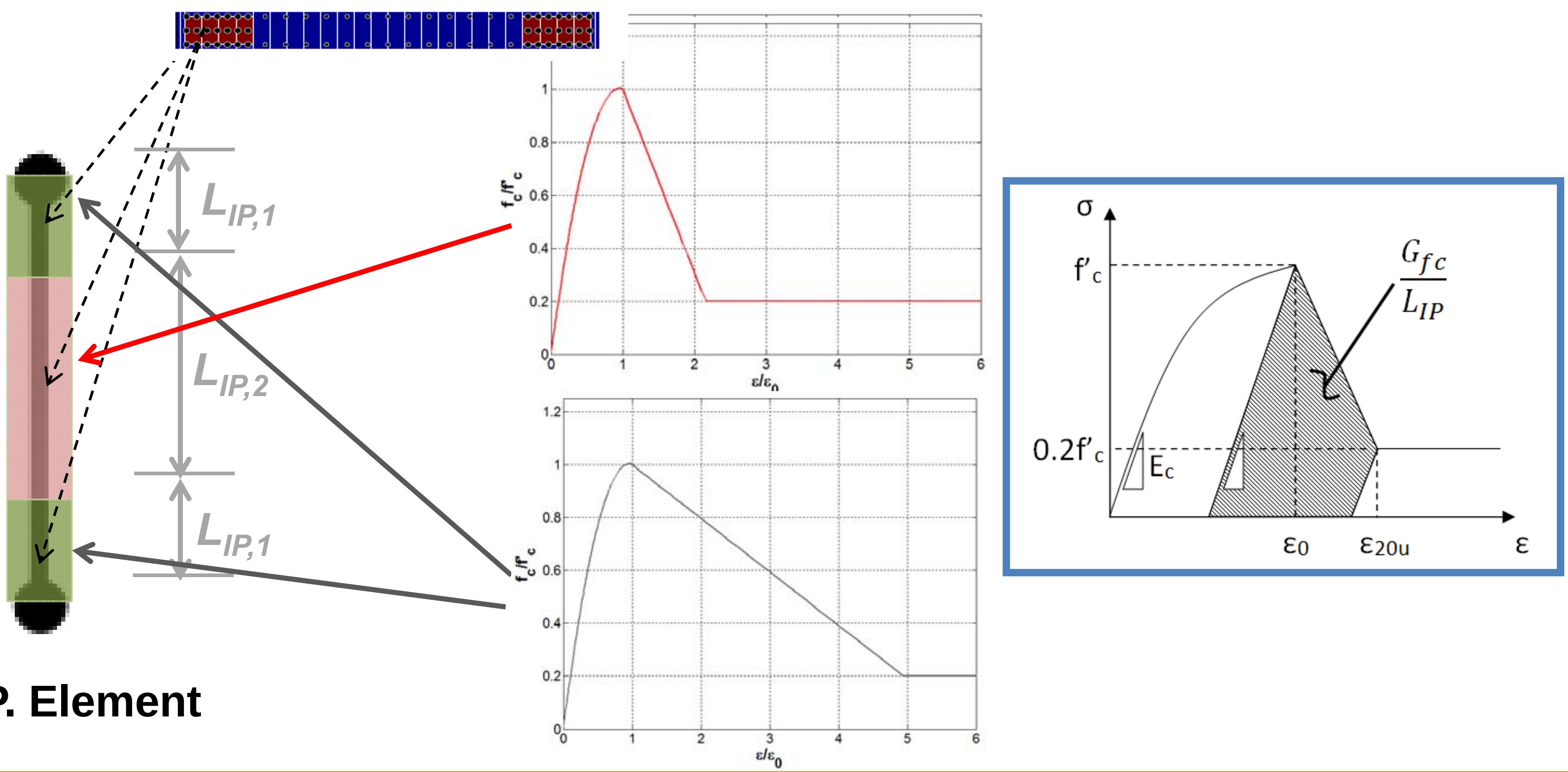
Plain Concrete Crushing Energy

- Jansen and Shah, 1997



Material Regularization: Plain Concrete

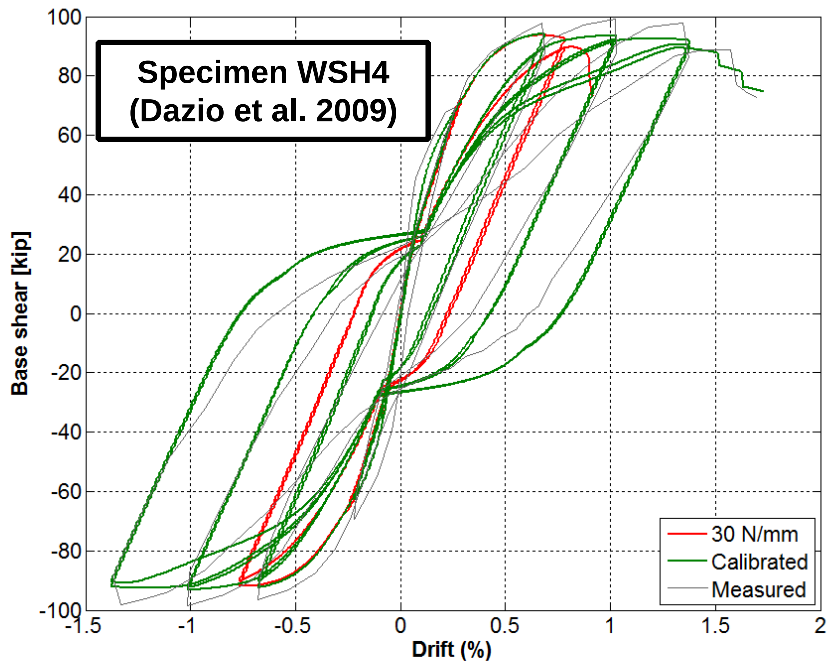
- Crushing energy, G_{fc} = ~20 N/mm per Jansen and Shah (1997)

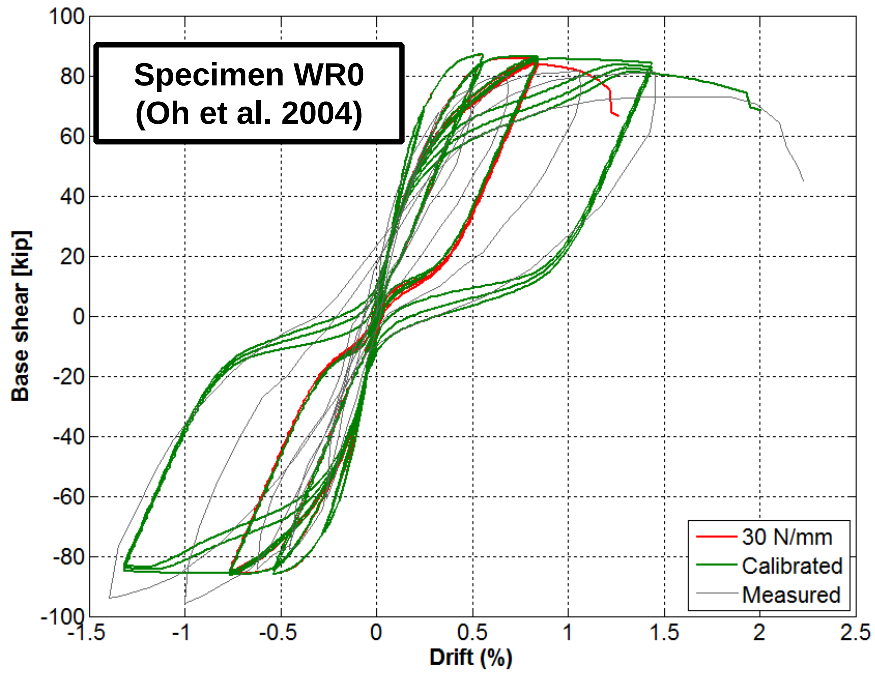


3-I.P. Element

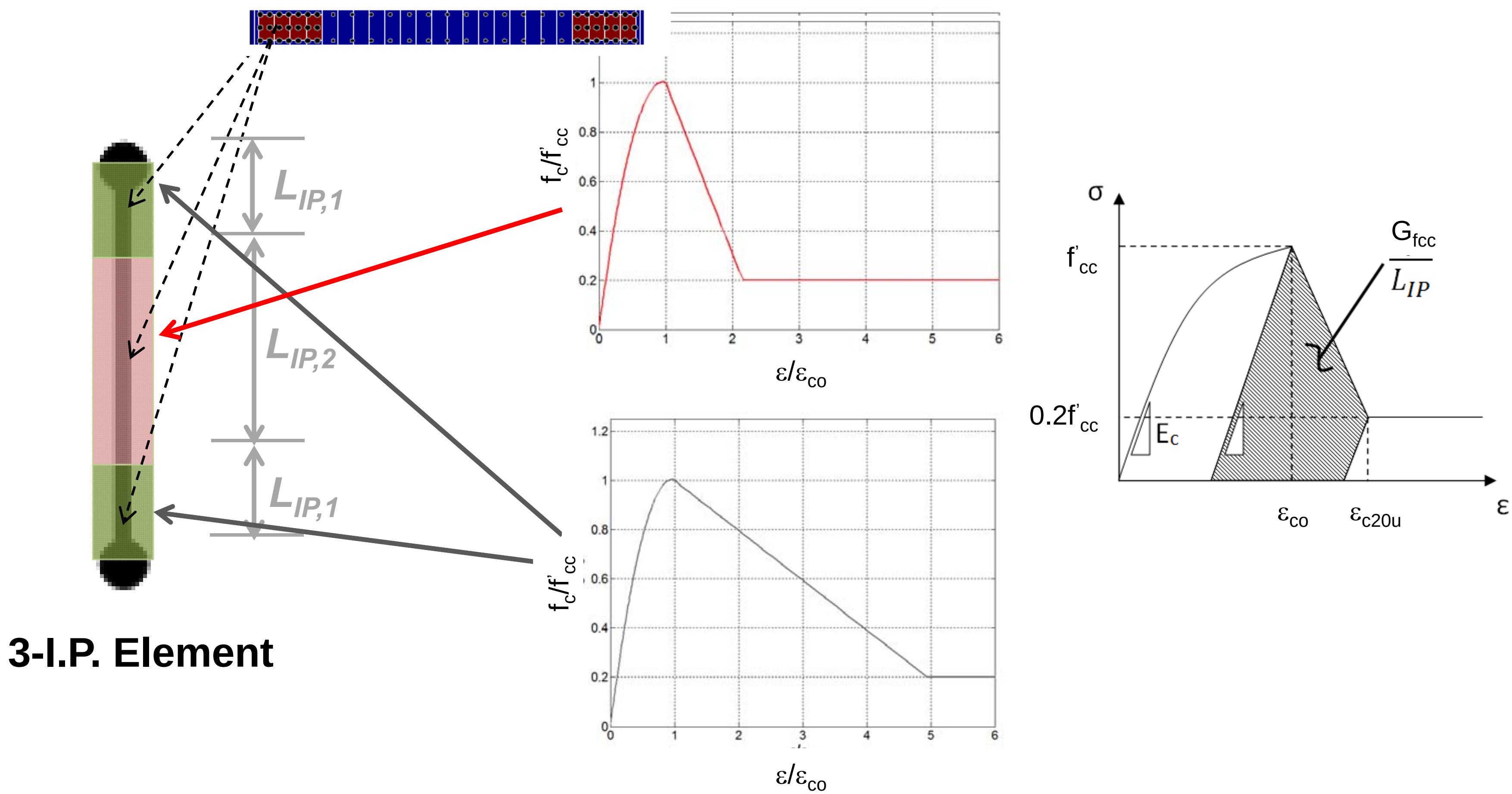
Determine Required G_{fc}

- Use experimental data for two planar walls constructed of unconfined concrete and exhibiting flexural failure due to concrete crushing
- G_{fc} = 60 – 80 N/mm = $2f_c$ with f_c in MPa
- Note that increase in G_{fc} above Jansen and Shah 20 N/mm for plain concrete cylinders is attributed to the presence of longitudinal steel



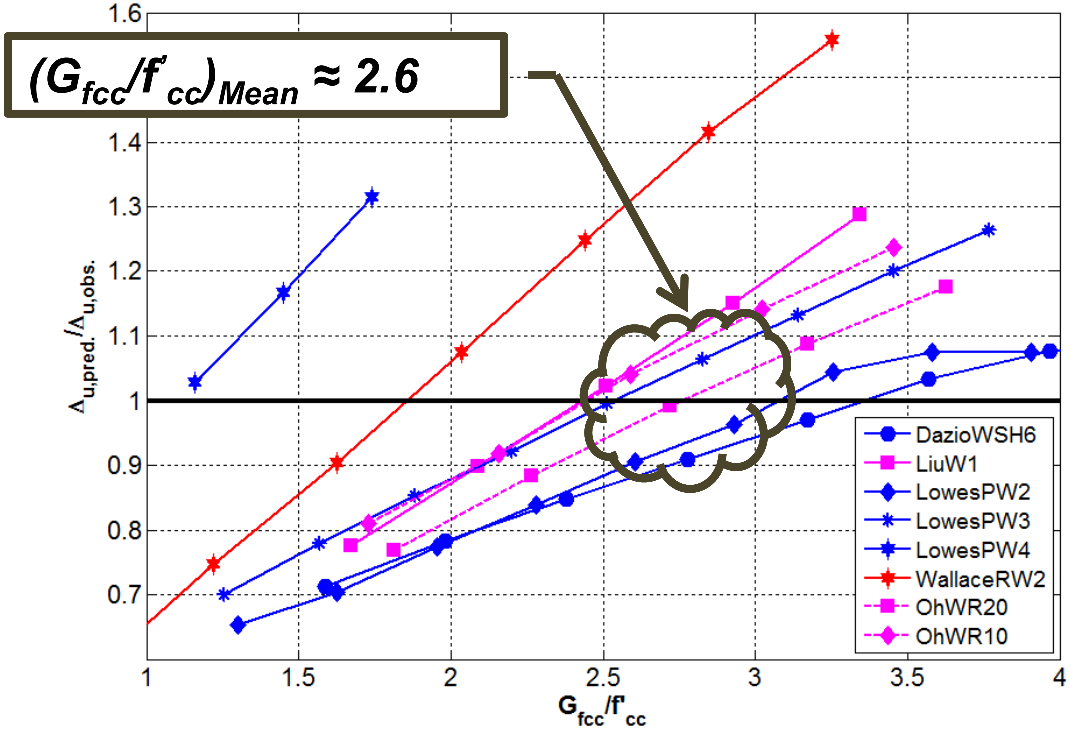


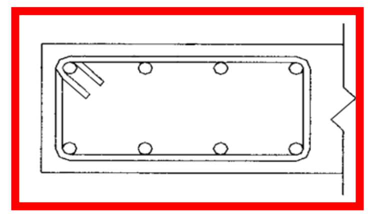
Material Regularization: Conf. Concrete

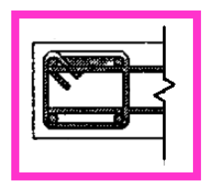


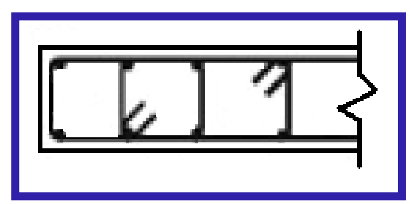
Determine Required G_{fcc}

- Use experimental data for eight planar walls w/ confined concrete exhibiting flexural failure due to concrete crushing
- G_{fcc} appears to be a function of confinement detailing, but insufficient data for model calibration



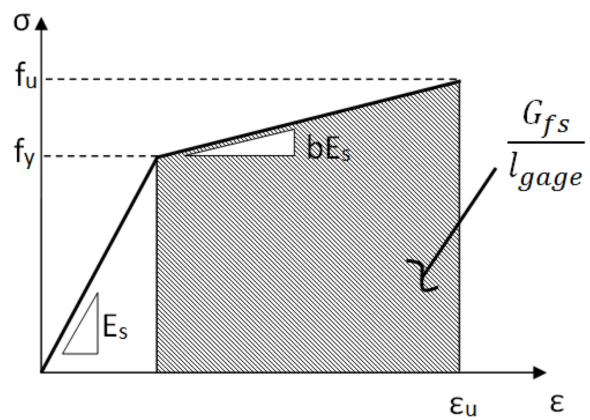




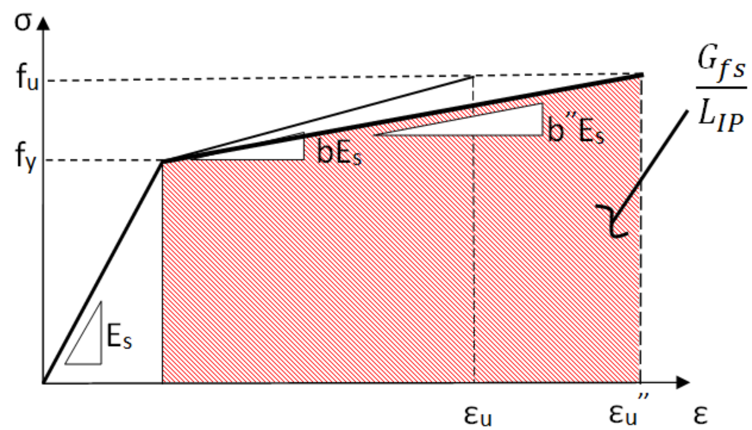


Material Regularization: Steel

- Required despite steel hardening because deformations localize to single softening section
- G_{fs} / l_{gage} determined from material tests
- Regularized steel stress-strain response used in fiber-section model determined by L_{IP}
- Regularization results in adjusted tensile rupture strain; include compressive failure strain equal to strain at which concrete loses 80% of compressive strength



Response from lab data



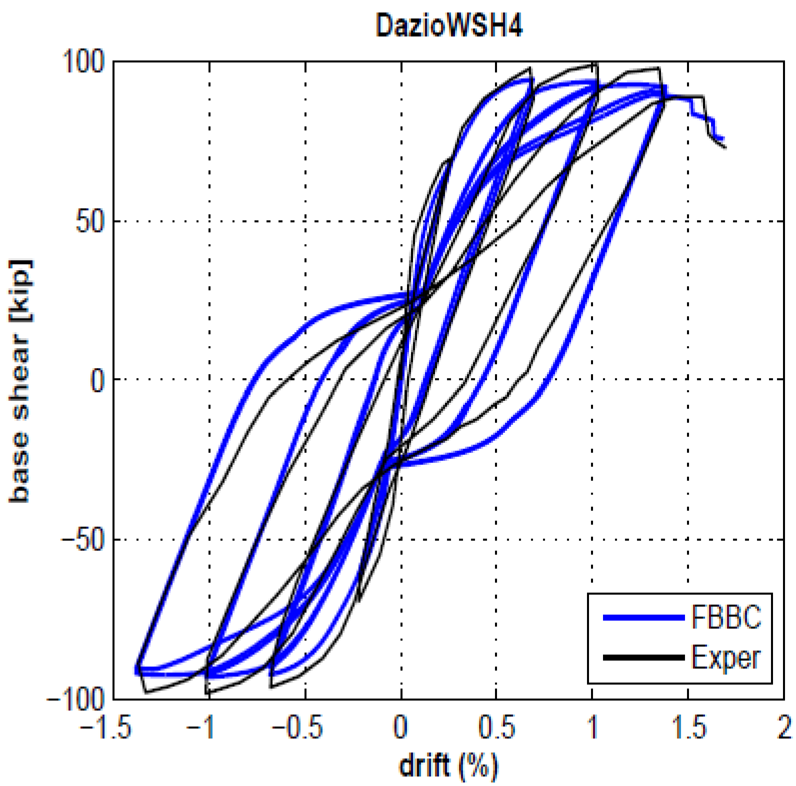
Regularized response model

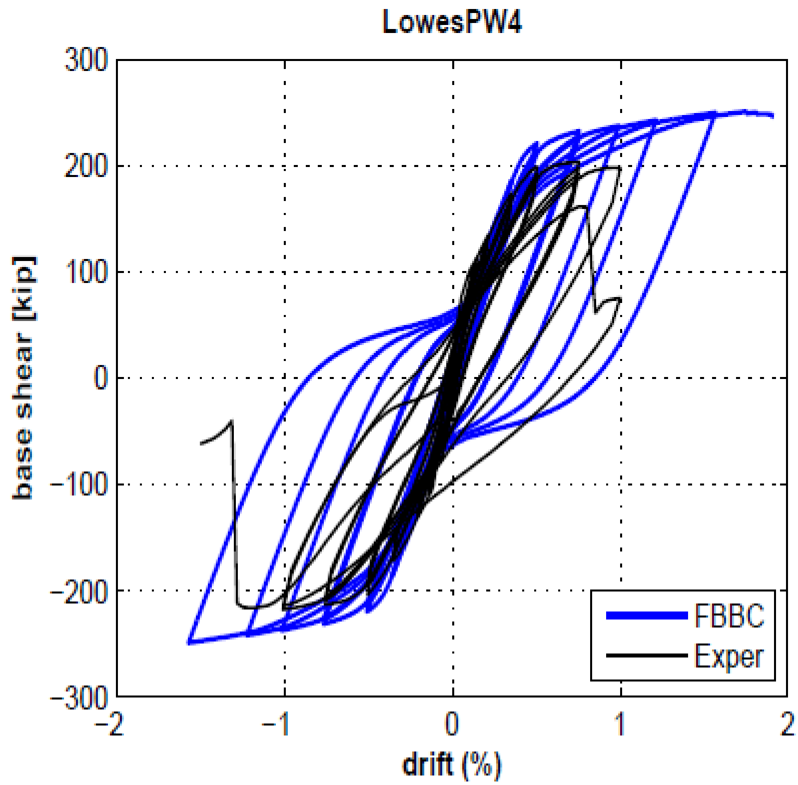
FBBC: Regularized Results for Planar Walls

	$\frac{V_{max,sim.}}{V_{max}}$		$\frac{\Delta_{yield,sim.}}{\Delta_{yield}}$		$\frac{\Delta_{u,sim.}}{\Delta_{u}}$	
Failure Mode	**Mean**	**COV**	**Mean**	**COV**	**Mean**	**COV**
Crushing (9 specimens)	**0.93**	**0.04**	**0.83**	**0.26**	**0.96**	**0.15**
Rupture/Buckling (6 specimens)	**0.95**	**0.05**	**1.01**	**0.33**	**1.12**	**0.21**
Rupture (2 specimens)	**0.98**	**0.03**	**0.94**	**0.02**	**1.08**	**0.04**
Out of Plane (2 specimens)	**0.98**	**0.03**	**0.94**	**0.28**	**1.31**	**0.08**
All Flexure	**0.95**	**0.07**	**0.90**	**0.28**	**1.06**	**0.22**

Regularized Results: Planar Walls

- Good results: WSH4 Dazio et al.
- Not so good results: PW4 Lowes et al.





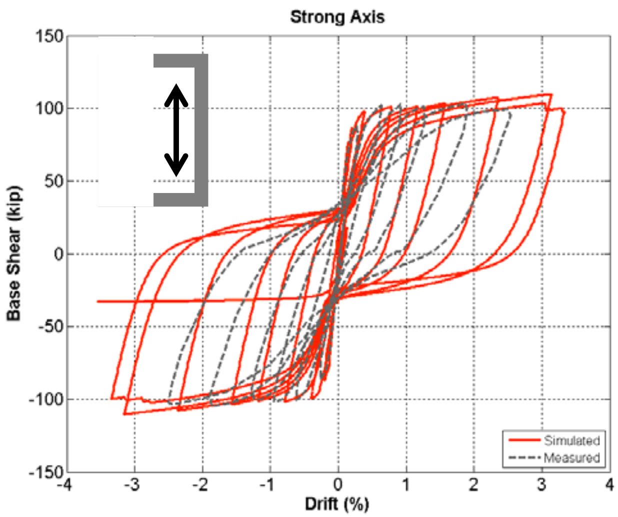
Regularized Results: C-Shaped Walls

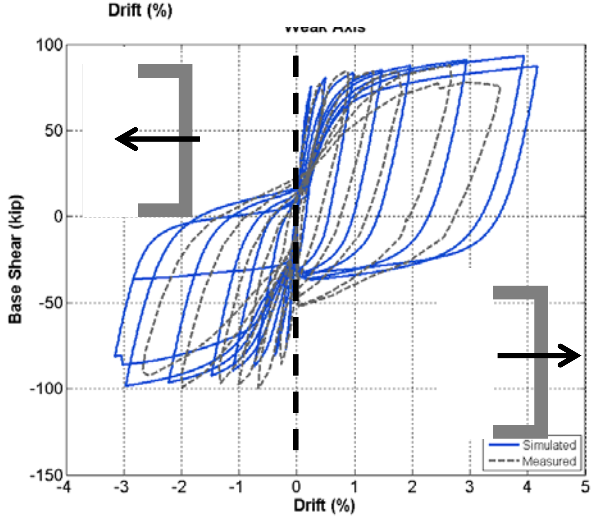
- Apply regularization method calibrated for planar walls to C-shaped walls:

Specimen	Loading	$\frac{V_{max,sim.}}{V_{max}}$	$\frac{\Delta_{yield,sim.}}{\Delta_{yield}}$	$\frac{\Delta_{u,sim.}}{\Delta_{u}}$
UW1 (Lowes et al.)	Strong Axis	1.01	1.13	1.20
W1 (Ile and Reynouard)	Strong Axis	0.90	0.85	1.00
W2 (Ile and Reynouard)	Weak Axis	0.94	0.87	0.77
W3 (Ile and Reynouard)	Bi-Directional	0.93	1.10	0.70
TUA (Beyer at al.)	Bi-Directional	1.06	0.90	1.04
TUB (Beyer et al.)	Bi-Directional	1.08	1.15	1.06
Mean (COV)		0.99 (0.08)	1.00 (0.14)	0.96 (0.20)

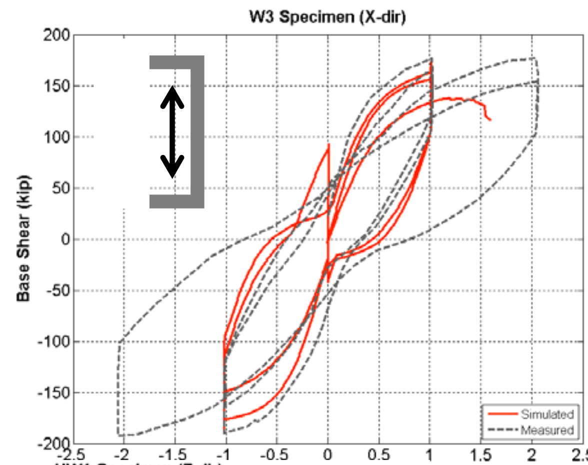
Regularized Results: C-Shaped Walls

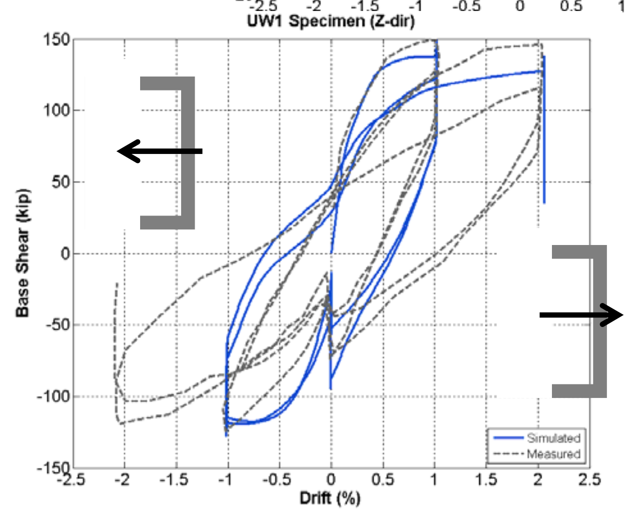
- Good: TUA Beyer et al.





- Not so good: W3 Ile and Reynouard





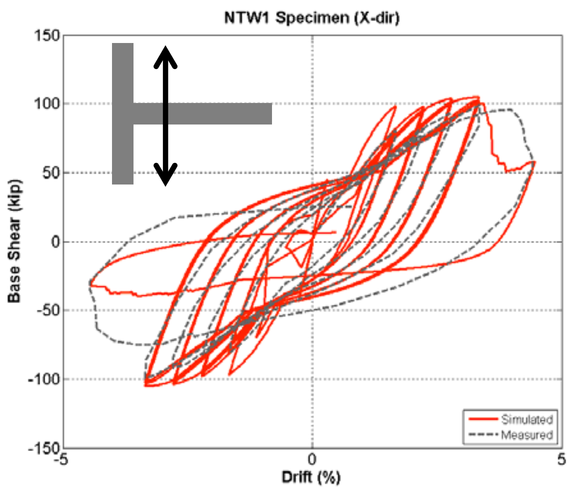
Regularized Results: T-Shaped Walls

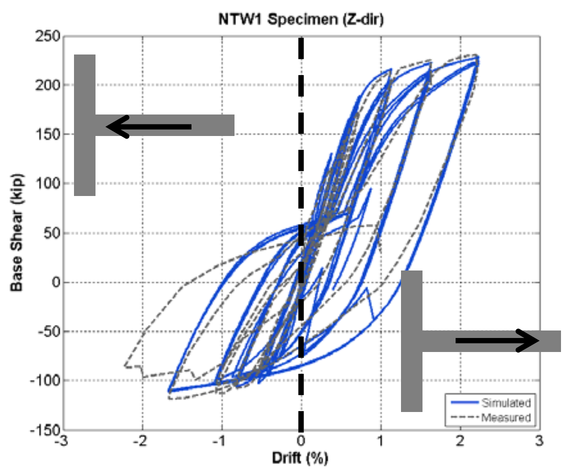
- Apply regularization method calibrated for planar walls to T-shaped walls:

Specimen	Loading	$\frac{V_{max,sim.}}{V_{max}}$	$\frac{\Delta_{yield,sim.}}{\Delta_{yield}}$	$\frac{\Delta_{u,sim.}}{\Delta_{u}}$
TW1 (Thomsen and Wallace)	**Uni-directional**	**1.25**	**2.4**	**0.42**
TW2 (Thomsen and Wallace)	**Uni-directional**	**1.00**	**1.6**	**0.45**
NTW1 (Brueggen et al.)	**Bi-Directional**	**1.00**	**1.14**	**0.86**
NTW2 (Brueggen et al.)	**Bi-Directional**	**0.95**	**1.05**	**0.82**
Mean/COV		**1.05/0.13**	**1.55/0.40**	**0.64/0.37**

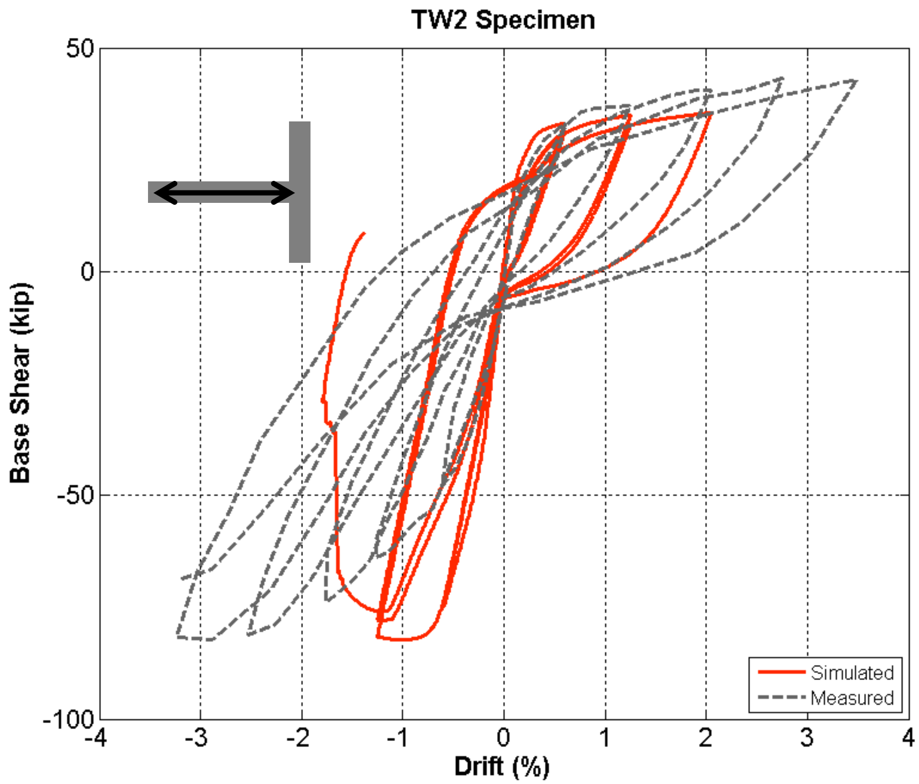
Regularized Results: T-Shaped Walls

- Good: NTW1 Brueggen et al.





- Not so good: Thomsen and Wallace
- Data show plane sections do not remain plane, so strain distribution is not correctly simulated

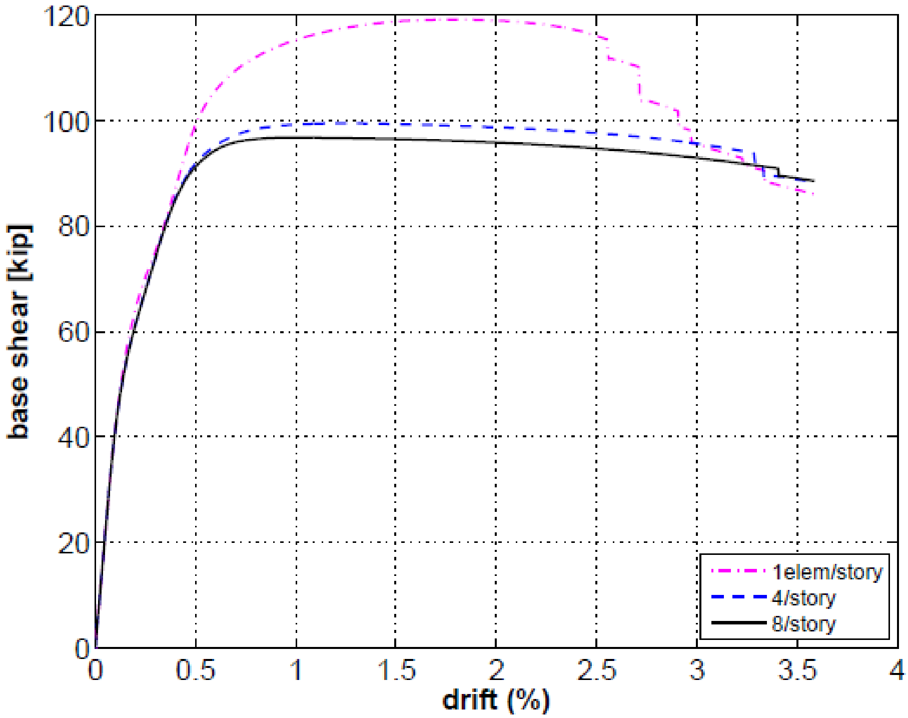


Displacement-Based Distributed-Plasticity Beam-Column Element:

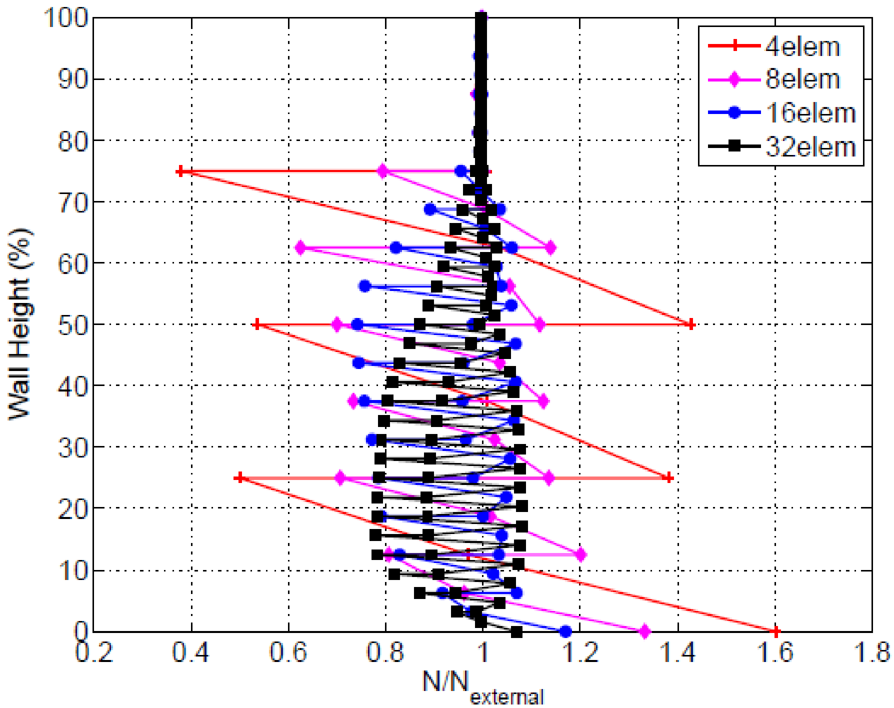
Evaluation, Calibration and Validation

Model Evaluation: Mesh Refinement Study

- Load-displacement response



- Axial load at the section (formulation assumes constant axial strain not force)



Impact of Axial Load Variation

- Soften section (i.e. critical section) is located above the base of the wall and is not the section with highest flexural demand
  - Fiber section at the base of the wall has an axial load that is larger than the applied axial load; this results in increased flexural strength and reduced curvature ductility.
  - Fiber section above the base of the wall has an axial load that is smaller than the applied axial load; this results in reduced flexural strength and increased curvature ductility.
- Accurate simulation of drift capacity requires modification of concrete crushing energies to account for error in section axial load
  - Unconfined: $G_{fc\_DBBE} = \alpha G_{fc\_FBBE} = 0.28 G_{fc\_FBBE} = 0.56 f_c$ with f_c in MPa
  - Confined: $G_{fcc\_DBBE} = \alpha G_{fcc\_FBBE} = 0.28 G_{fcc\_FBBE} = 0.73 f_{cc}$ with f_{cc} in MPa

Conclusions

- FBBC & DBBC
  - Strength and stiffness are accurately and precisely simulated without material regularization
  - DBBC element requires large number of element & sections to reduce variability in axial load and the impact of this on stiffness and strength
  - FBBC element requires one element with five sections per story
- For compression-controlled RC elements
  - Accurate simulation of drift capacity requires regularization of concrete and steel material response
- For planar and some non-planar walls
  - Proposed regularization method and unconfined / confined concrete crushing energies determined from laboratory tests of planar walls results in accurate and precise simulation of drift capacity.
- For some non-planar walls
  - Assumption of plane sections remain plane is inadequate and line-element models cannot provide accurate simulation of response.

Future Work

- Determine limits for application of line-elements to simulate wall response:
  - When does "plane sections remain plane" assumption result in unacceptable error.
- Improved simulation of shear response decoupled from flexural response.

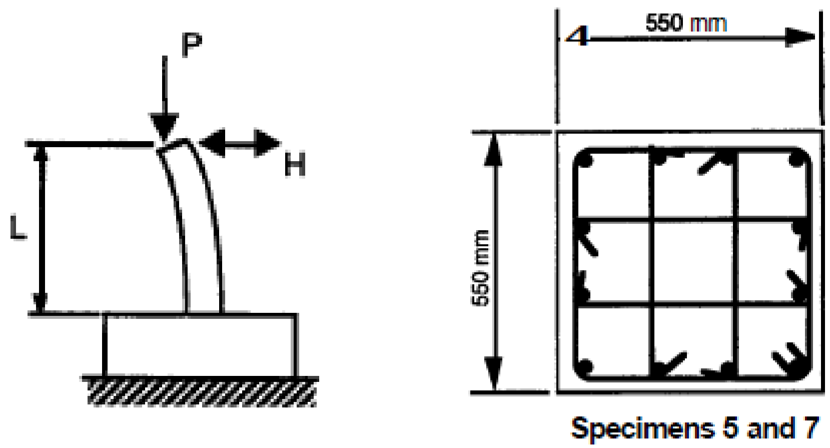
A Final Note:

Application to Simulation of RC Column Response

Simulation of RC Column Response

- Regularization allows simulation of **softening** RC component response
- Not critical if critical section exhibits minimal softening prior to failure

- **Tanaka and Park (1990)**

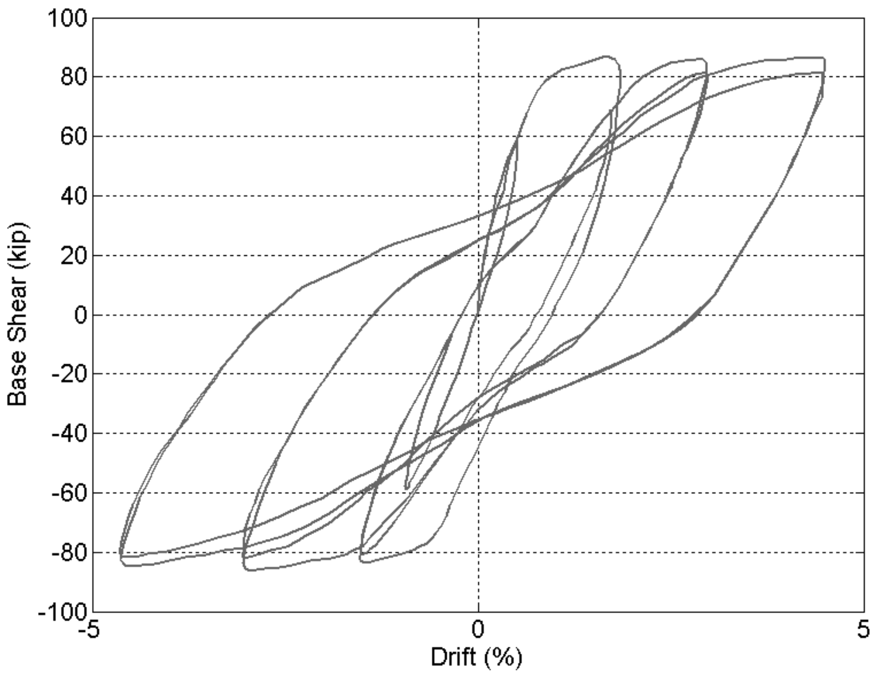


Specimen	ρl_{ong}	Axial Load Ratio
5	1.25%	$0.1f'_cA_g$
7	1.25%	$0.3f'_cA_g$

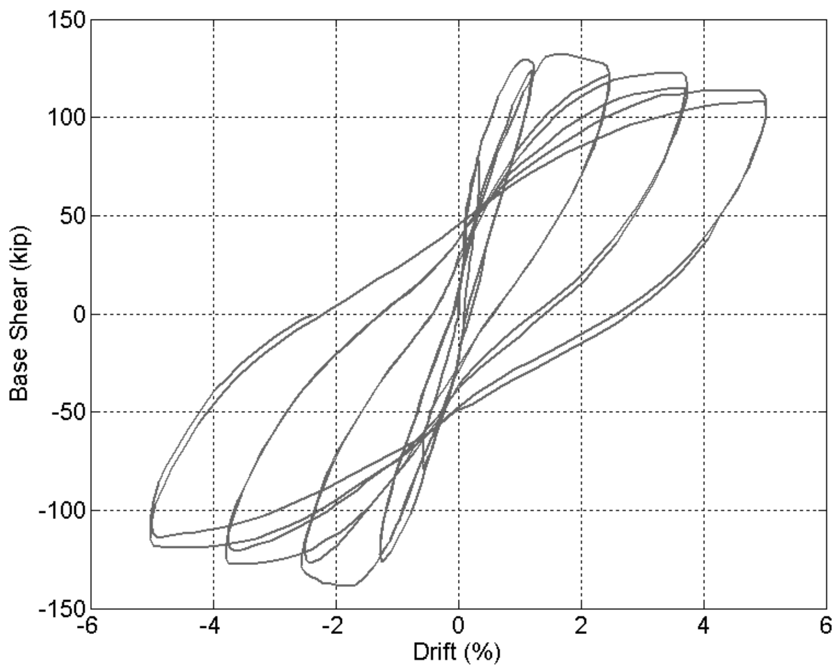
Simulation of RC Column Response

- Low axial load: N = 0.1fcAg
- Failure due to bar buckling & rupture

- High axial load: N = 0.3fcAg
- Failure due to concrete crushing



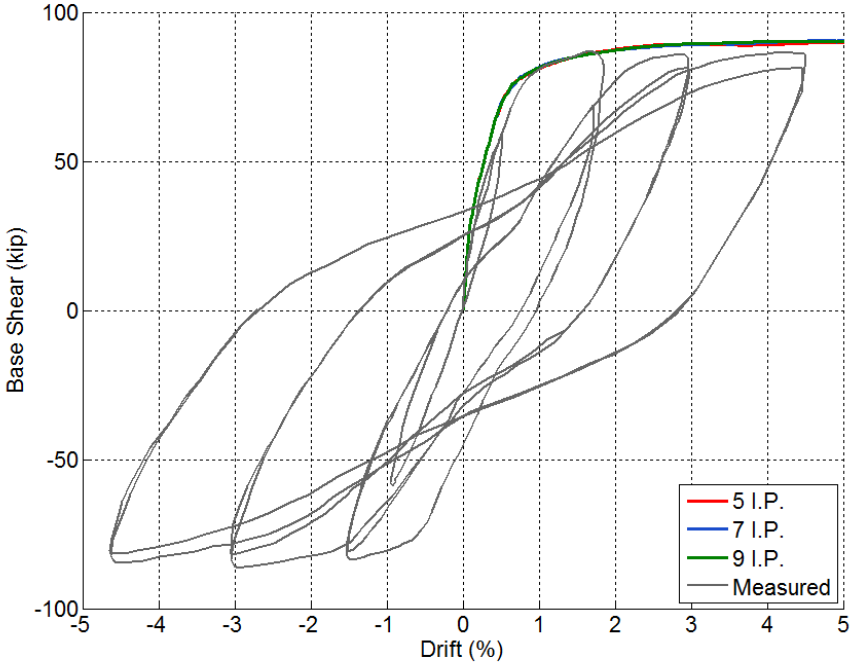
Specimen 5 (Tanaka and Park, 1990)



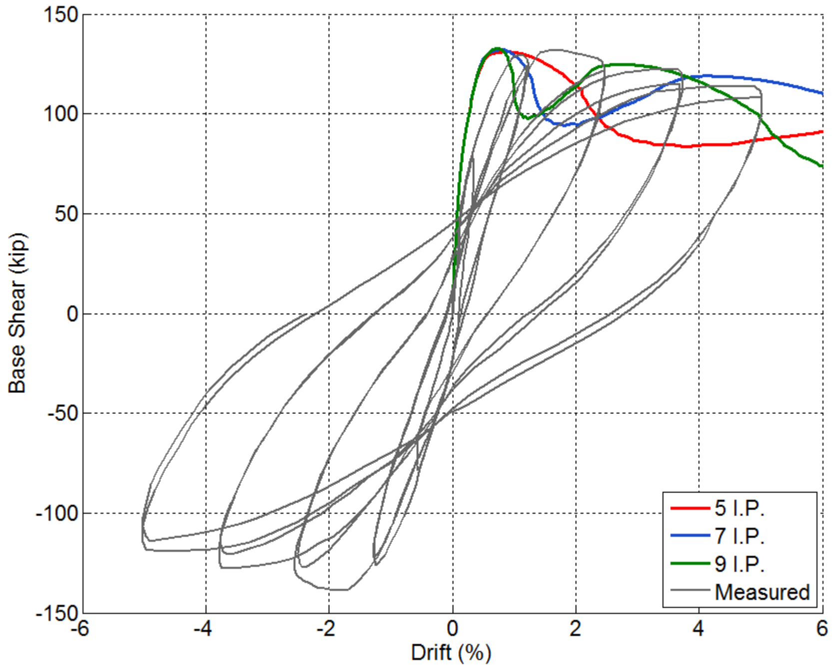
Specimen 7 (Tanaka and Park, 1990)

No regularization

- Low axial load:
  N = 0.1fcAg
- High axial load:
  N = 0.3fcAg



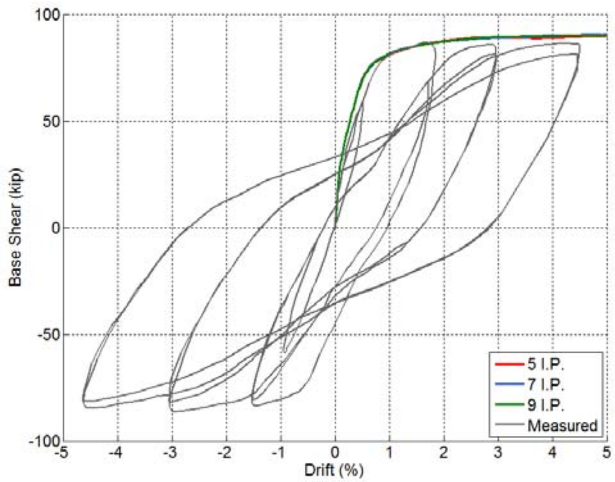
Specimen 5 (Tanaka and Park, 1990)



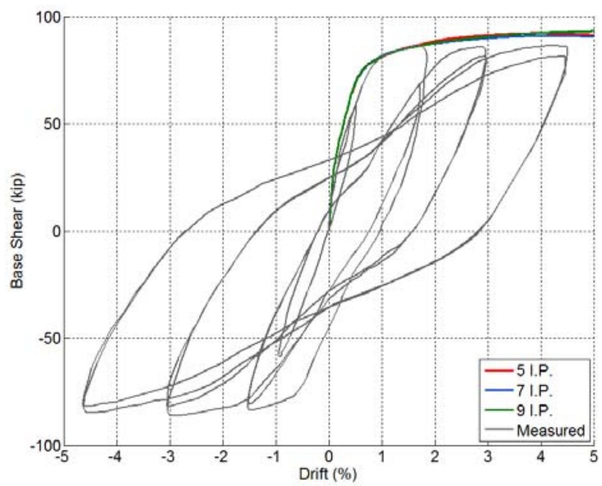
Specimen 7 (Tanaka and Park, 1990)

Regularization: Low Axial Load

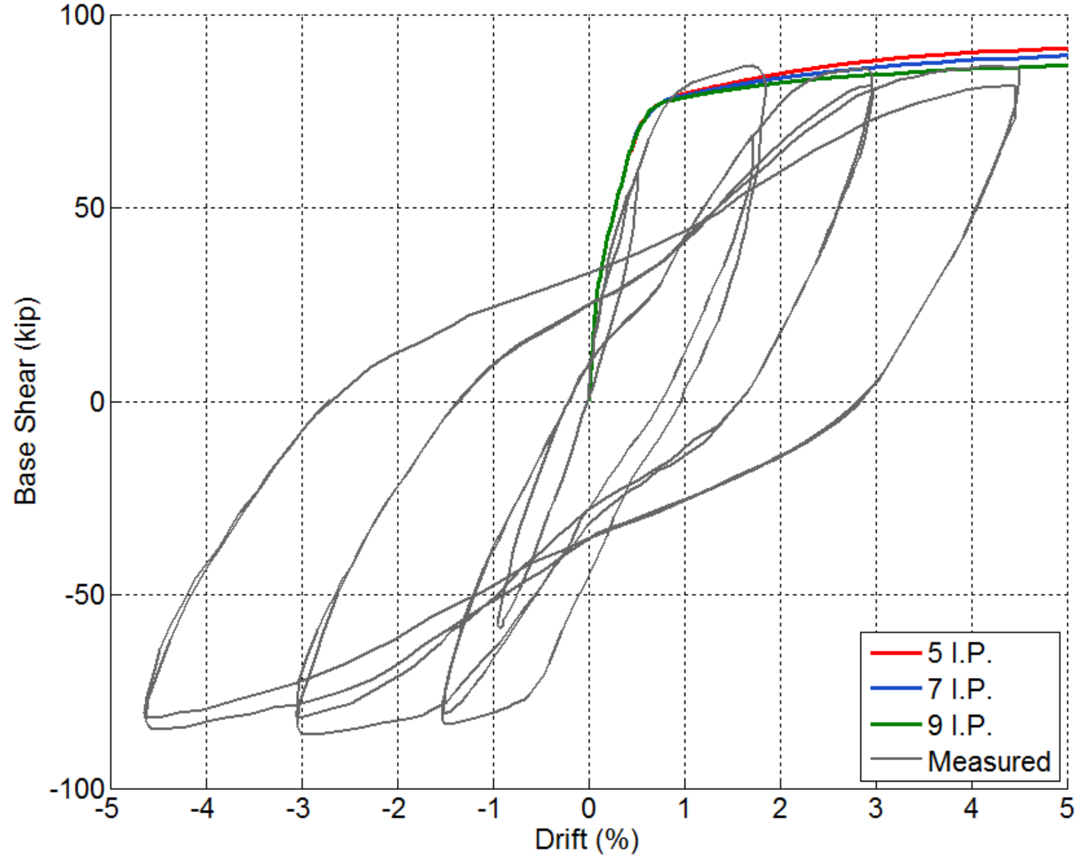
- **w/o Regularized Concrete**



- **w/ Regularized Concrete**



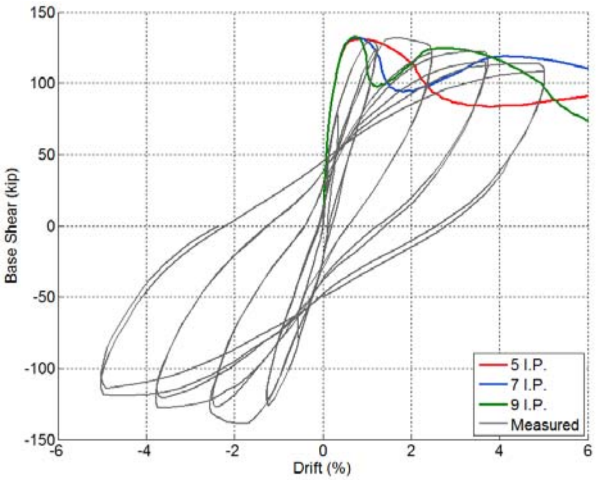
- **w/Regularized Concrete and Steel**



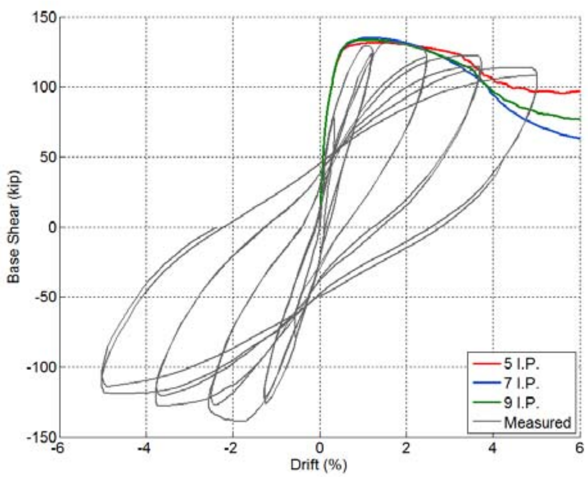
Column S5 (Tanaka and Park, 1990)

Regularization: High Axial Load

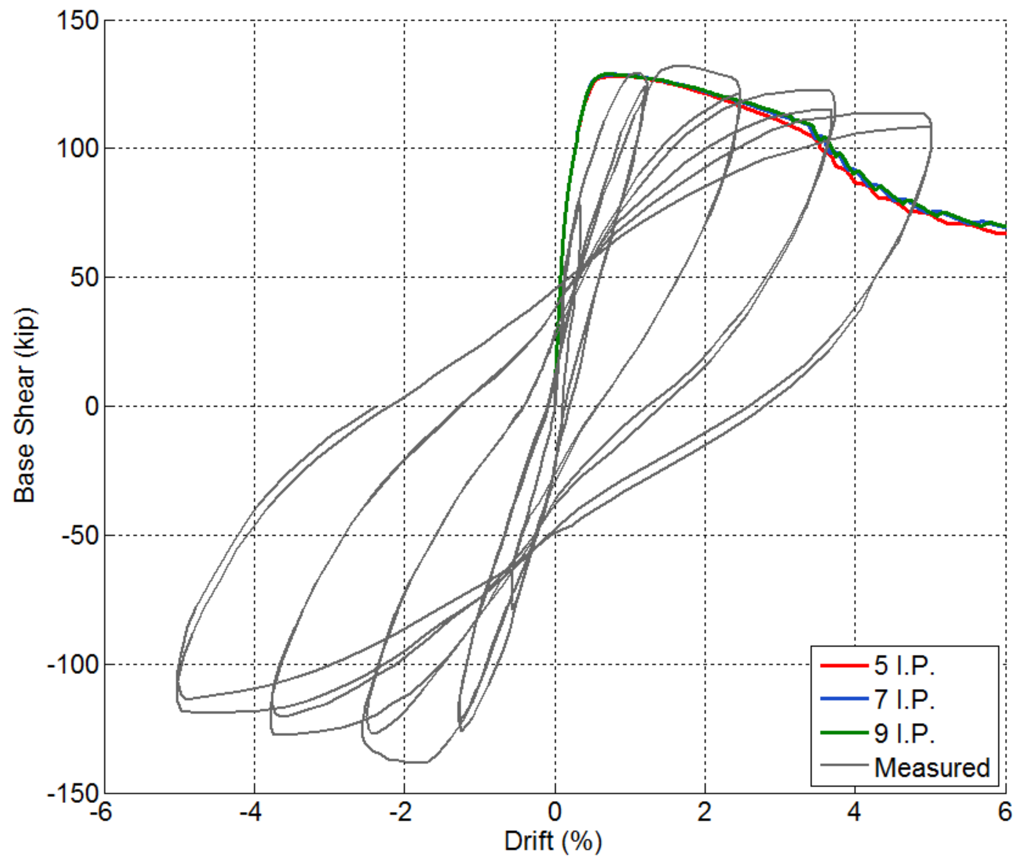
- **w/o Regularized Concrete**



- **w/ Regularized Concrete**



- **w/Regularized Concrete and Steel**



Column S7 (Tanaka and Park, 1990)

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