Behavior and Design of Lightly Reinforced Concrete Walls

Laura N Lowes, *Professor, University of Washington*

Ray Yu, *Design Engineer, Magnusson Klemencic Associates*

Dawn E Lehman, *Professor, University of Washington*

Scott Campbell, *Senior Vice President of Structures and Codes, National Ready Mix Concrete Association*

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  - National Ready Mix Concrete Association (NRMCA)
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  - ACI Com 332E: Residential Concrete – Above Grade Walls
  - ACI Com 380: Plain Concrete

What I hope you learn from today's talk

> There is an opportunity for making reinforced concrete and FRC walls more competitive with other building materials in regions of low to moderate seismicity.

> Limited laboratory testing and high-resolution FEM shows that walls, with much less than the currently required reinforcement, exhibit acceptable behavior.

> FRC with low fiber content can improve performance of lightly reinforced concrete walls.

> Funding should be allocated for laboratory testing to validate FEM results and demonstrate acceptable performance of lightly reinforced concrete walls.

Why investigate lightly reinforced concrete walls?

Insulated Concrete Form Wall

Second + Delaware Apartments

Largest "Passive House" building in the world – entirely concrete construction.
https://www.foxblocks.com/

Tatiana Bilbao House

1. Lightly reinforced concrete walls are used regularly for low-rise construction in regions of low seismicity.

2. Lightly reinforced *insulated concrete form* (ICF) walls have the potential to be highly competitive w/ masonry & wood, as ICF walls meet new building-code requirements for energy efficiency.

3. There are minimal data supporting the current maximum spacing and minimum reinforcement requirements.

Current requirements for wall reinforcement increase the cost of concrete walls and make them less cost competitive.

Lightly reinforced walls are a great building system.

Current Design Requirements: Reinforced Concrete versus Masonry

> ACI 318 Code requirements for RC walls are much more onerous than requirements for concrete masonry walls.

Code Requirements	ACI 318[1]	Masonry
Maximum Spacing	18 inches	48 inches
Minimum ρ_l	0.15%[2]	No. 4 @ 48 in.
Minimum ρ_t	0.25%	No. 4 @ 48 in.

Notes: 1) requirements are provided for construction using No. 4 bar and larger
2) 0.15% corresponds to No. 4 @ 18 in. in a 7.5 in. thick wall

> ACI Code requirements for 18 inch spacing do not appear to be based on data for *walls* subjected to out-of-plane loading.

Research Activities and Objectives

> Research Objectives
  - Investigate the potential for reducing reinforcing requirements for walls in regions of low to moderate seismicity where out-of-plane loading controls design.
  - Investigate the potential of using FRC with low fiber content to improve wall performance.

> Research Activities
  - Use limited existing experiment data to calibrate and validate nonlinear high-resolution continuum-type finite element models of lightly reinforced plain and fiber-reinforced concrete walls subjected to out-of-plane loading.
  - Use validated FEM models to investigate performance of walls with a range of design parameters.

Outline for the Remainder of the Talk

- Behavior of lightly reinforced concrete walls subjected to out-of-plane loading
- Validation of a finite element model
- Application of the FEM to investigate behavior and design of RC walls
- Extension of the FEM for FRC walls
- Application of the extended FEM to investigate behavior and design of FRC walls
- Recommendations for future research

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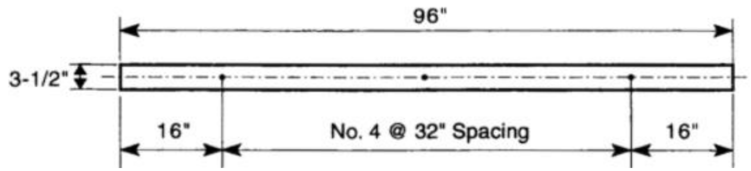
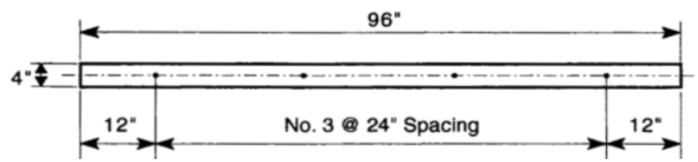
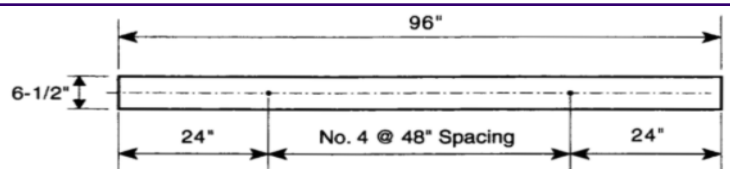
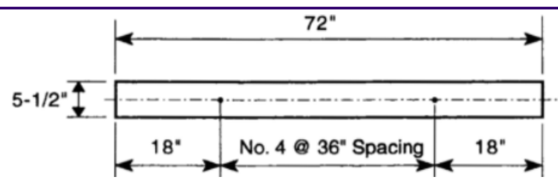
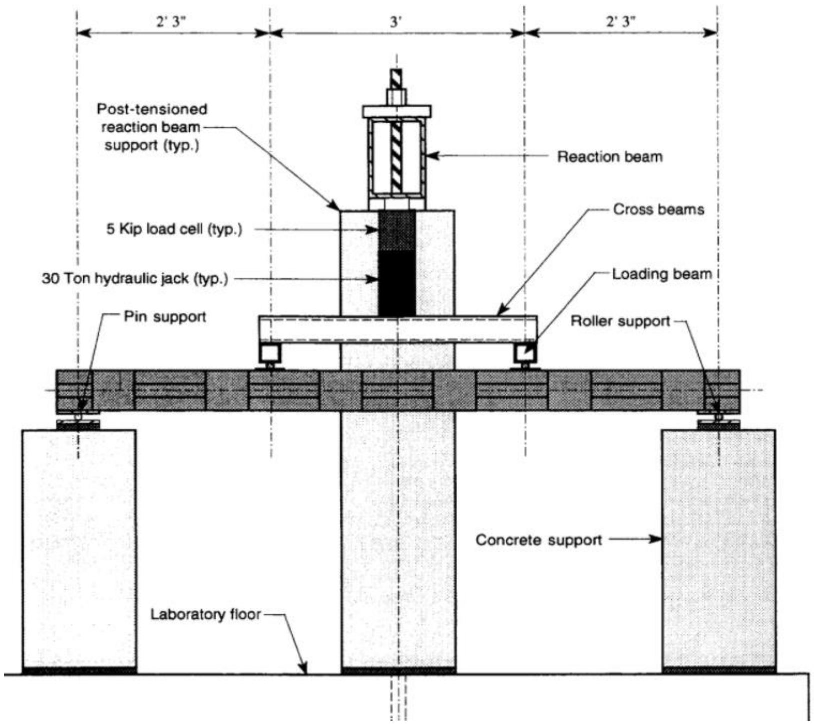
Behavior and Modeling of Lightly Reinforced Concrete Walls Subjected to Out-of-Plane Loading

Behavior of Lightly Reinforced Concrete Walls Subjected to Out-of-Plane Loading: Roller [1996]

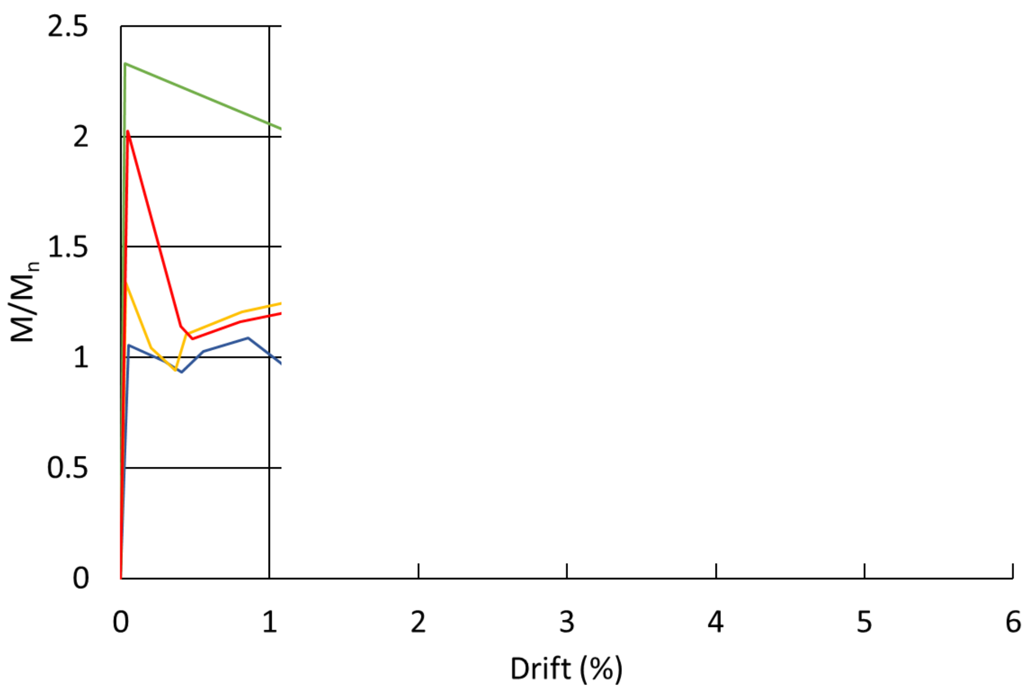
> Experimental data appear to be limited to Roller [1996]

Wall ID	ρ_l (%)	Wall Configuration
R1	0.18	
R2	0.12	
R3	0.06	
R4	0.10	



Results of the Roller [1996] Study

Wall Specimen ID	Wall Thickness (in.)	Bar Size and Spacing	ρ_l (%)	$M_{max} / M_{cr_{ACI}}$	$M_{residual} / M_{n_{ACI}}$	Δ_{max} (%)
R1	3.5	No. 4 @ 32 in.	0.18	0.76	1.09	5.55
R2	4.0	No. 3 @ 24 in.	0.12	0.56	1.38	5.00
R3	6.5	No. 4 @ 48 in.	0.06	0.58	1.66	3.50
R4	5.5	No. 4 @ 36 in.	0.10	0.79	1.35	5.55



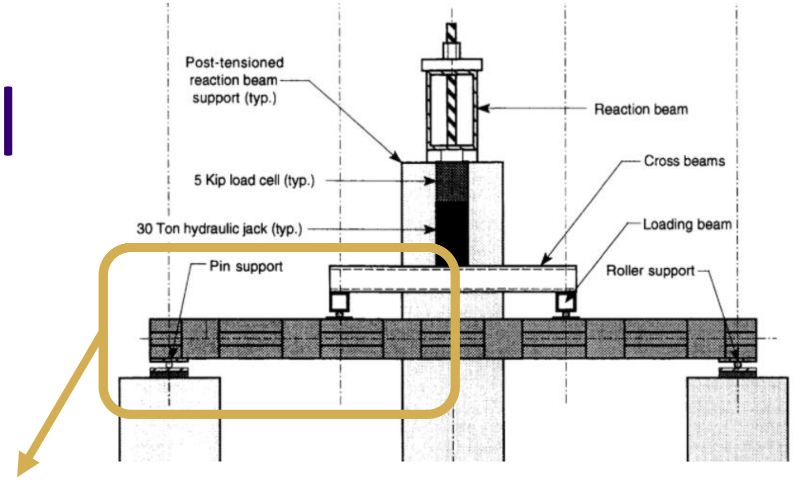
- Maximum strength is determined by cracking not flexural yielding.
- Measured cracking strength is 60% to 80% of ACI-defined cracking strength.
- Relatively stable post-cracking response with strength determined by flexural yielding.
- Post-peak strength is 110% - 170% of M_{n_ACI}.
- Volatility in results likely due to less than ideal test setup, concrete consolidation, and instrumentation.

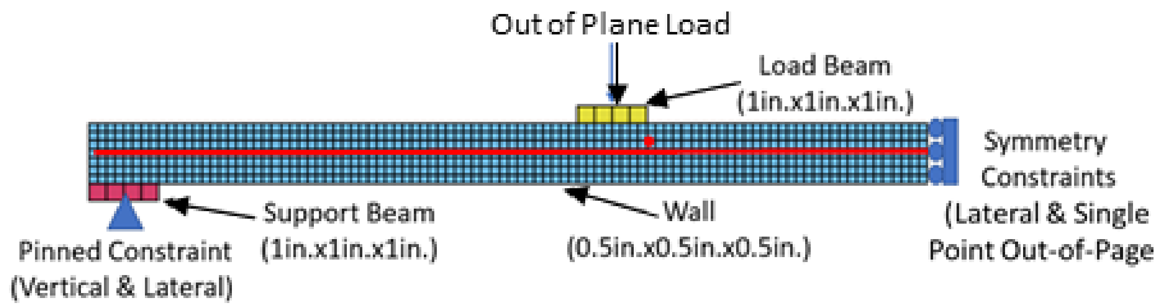
FEM Software

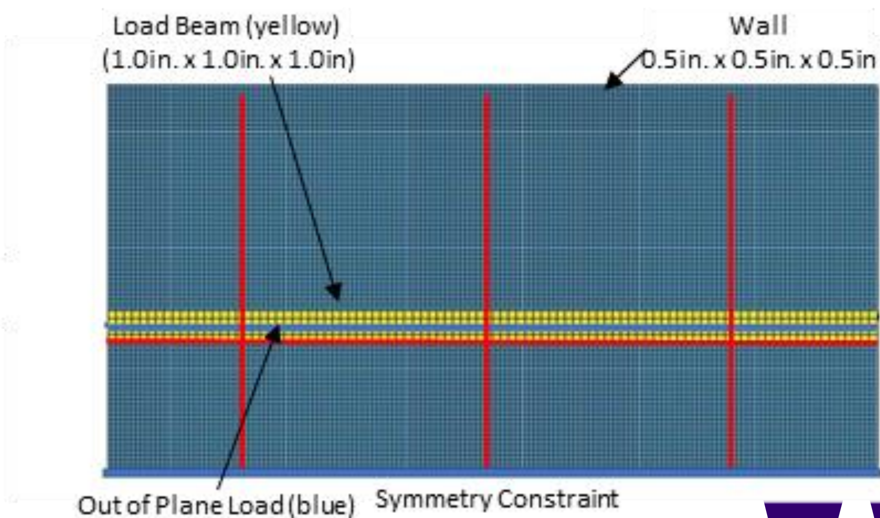
- FEM Software Requirements
  - Material models that enable calibration and representation of controlling *material* behavior, including
    - Peak and post-peak tensile response of plain concrete and FRC
    - Steel yielding
    - Slip due to development of bond forces
    - To a lesser extent: concrete crushing (observed by Roller only at large drifts)
  - Robust solution algorithm
  - Ability to utilize NHERI DesignSafe HPC system
- LS-Dyna chosen for the current study
  - Meets requirements above
  - Professor Lehman's research group is using this software and could provide support for the graduate student working on this project.

Validation of the Model

- Model exploits symmetry of the Roller test setup.
- Concrete elements:
  - Constant strain solid elements w/ hour-glass control.
  - Max dimension of 0.5 in. for all models; 7 to 13 elements through the thickness of the wall for Roller test specimens.
- Reinforcing steel elements:
  - Beam elements to facilitate monitoring stresses.
  - Embedded in concrete elements.
- Bond-slip model
  - Bond-slip model (Mucia-Delso et al. 2011) defines embedment.
  - Concrete and steel elements at same location have different strain values.







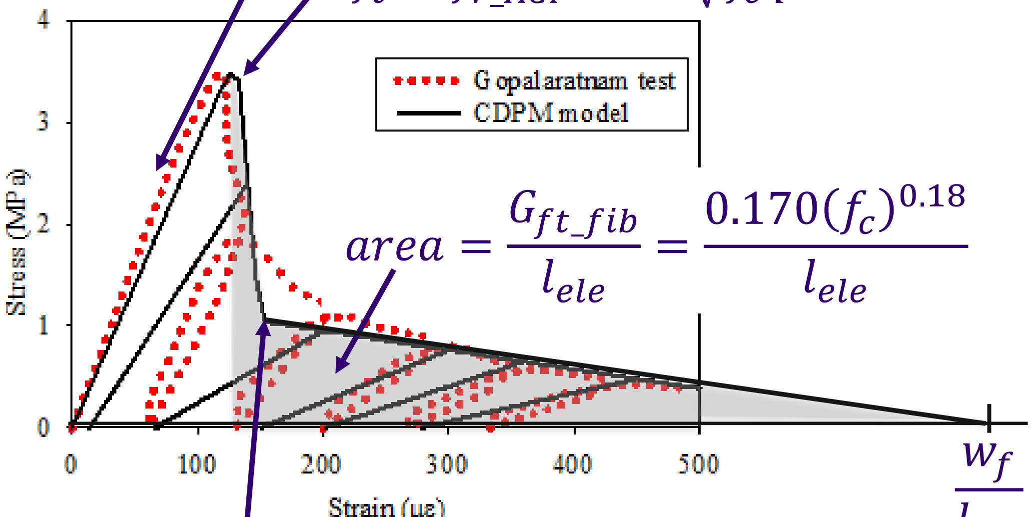
FEM Material Models: Concrete

> Plastic-damage concrete constitutive model developed and implemented by Grassl et al. (2011, 2013 and Grassl and Milan (2006).

Tension

$$E_{c\_ACI} = 57{,}000\sqrt{f_c}\ psi$$

$$f_t = f_{r\_ACI} = 7.5\sqrt{f_c}\ psi$$



$$area = \frac{G_{ft\_fib}}{l_{ele}} = \frac{0.170(f_c)^{0.18}}{l_{ele}}$$

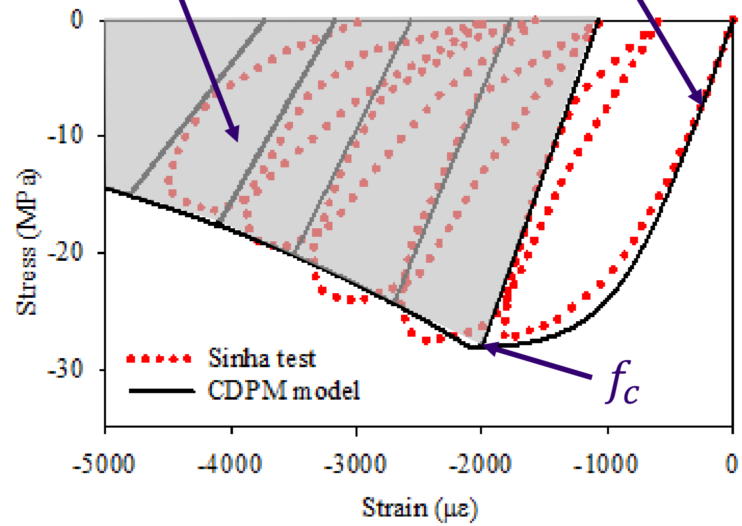
$$\frac{w_f}{l_{ele}}$$

Break point: $\left(0.15\frac{w_f}{l_{ele}}, 0.3f_t\right)$

Compression

$$area = \frac{G_c}{l_{ele}}$$

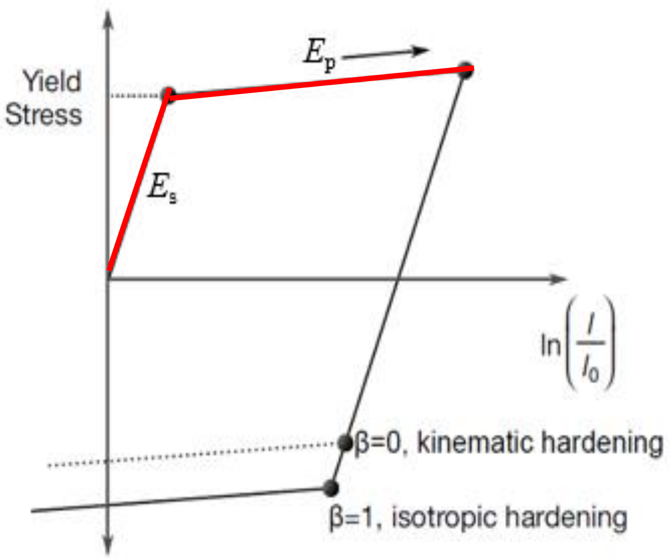
$$E_c = 57{,}000\sqrt{f_c}\ psi$$



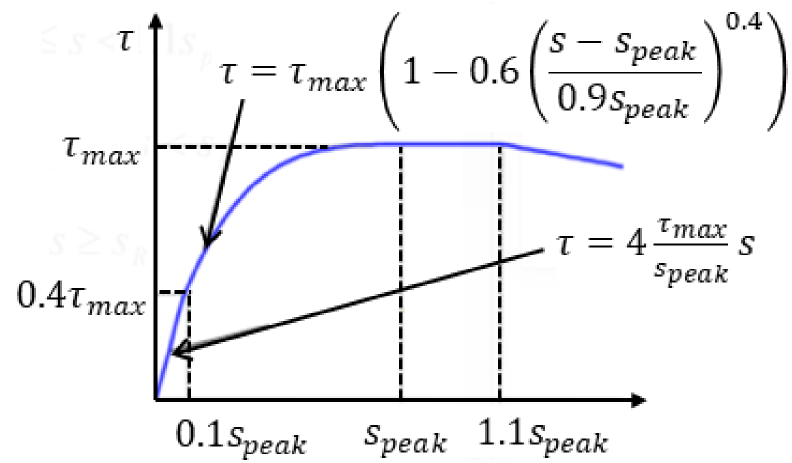
f_c

FEM Material Models: Steel & Bond

- Steel: 1D plasticity with kinematic hardening

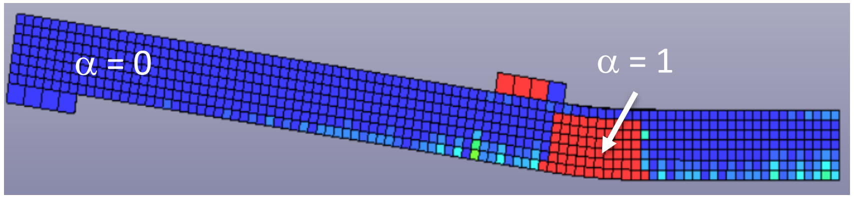


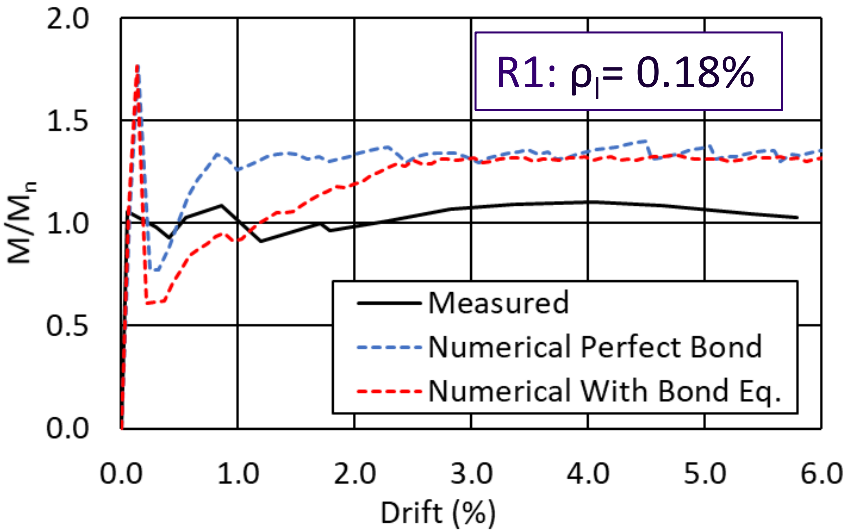
- Bond:
  - stress versus slip model per Murcia-Delso et al. (2011)
  - Stress converted to force via bar surface area.

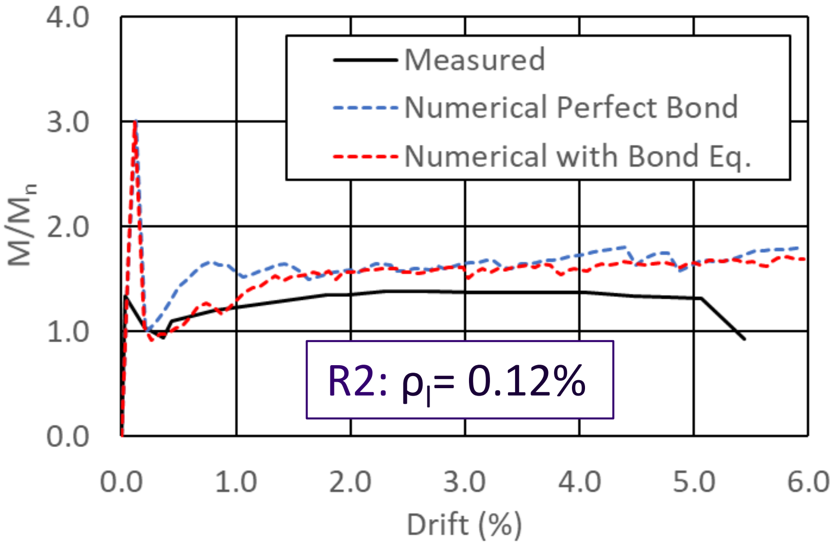


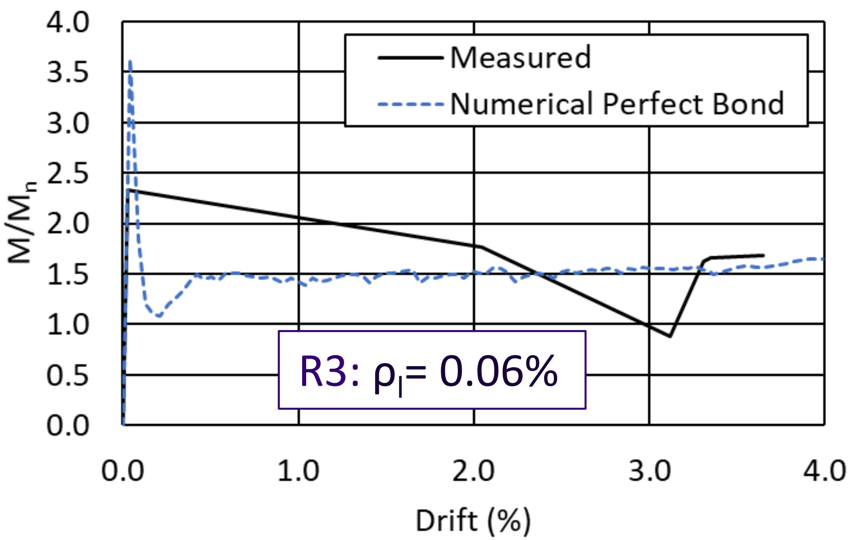
Results: Roller Tests

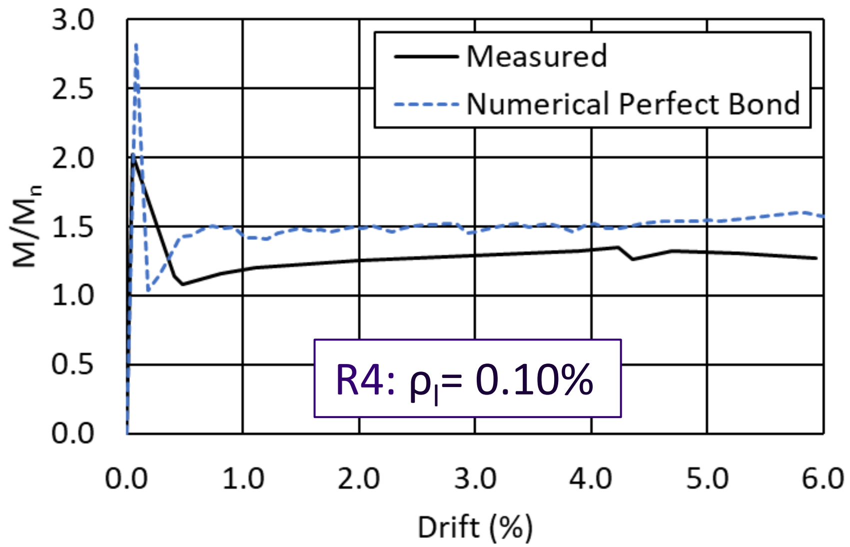
Concrete Damage Parameter, α











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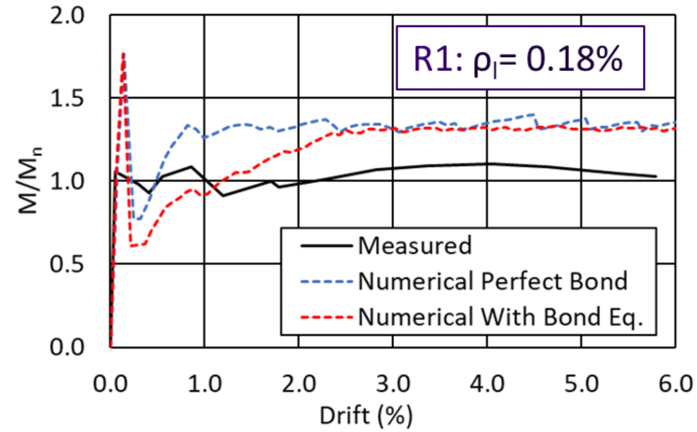

- LS-Dyna model provides good simulation of overall response:
  - elastic response to maximum strength, which is determined by
  -
- LS ... s,
  wh ... sts that
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  -
    - Initial shrinkage cracking of specimens
    - Specimens have a “line of weakness” due to form ties
    - Less than ideal concrete consolidation
  - Additionally
    - Test set up provides less than ideal boundary conditions
    - Potential for load and displacement measurement error

Research team’s conclusion is that LS-Dyna modeling can provide improved understanding of wall behavior and design.

Application of the Model to Investigate Wall Behavior and Design

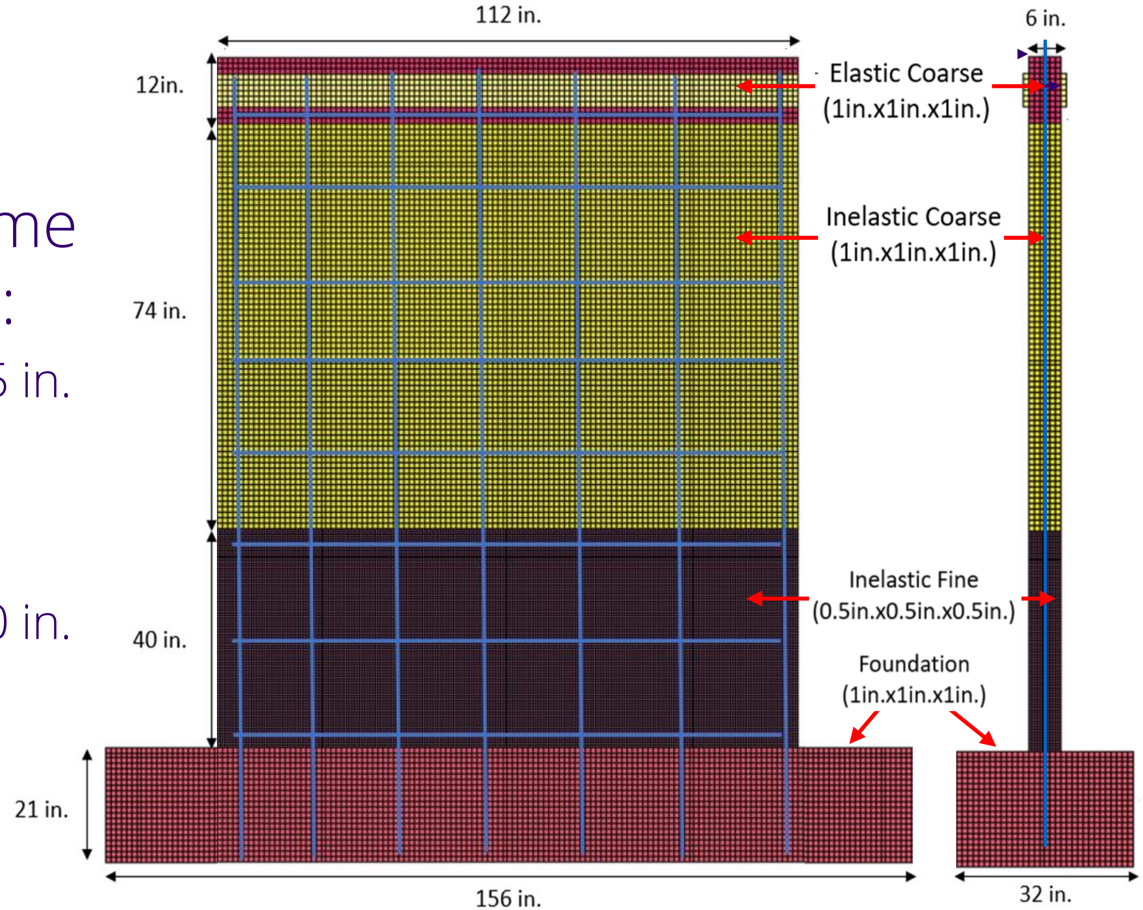
Reference Specimen and Model

> Specimen design and loading:

- One curtain of rebar: No. 4 @ 18 inches, horizontal and vertical
- 120 in. tall by 112 in. wide by 6 in. thick
- f_c' = 4 ksi; f_y = 60 ksi
- Axial load = $0.2 f_c' A_g$

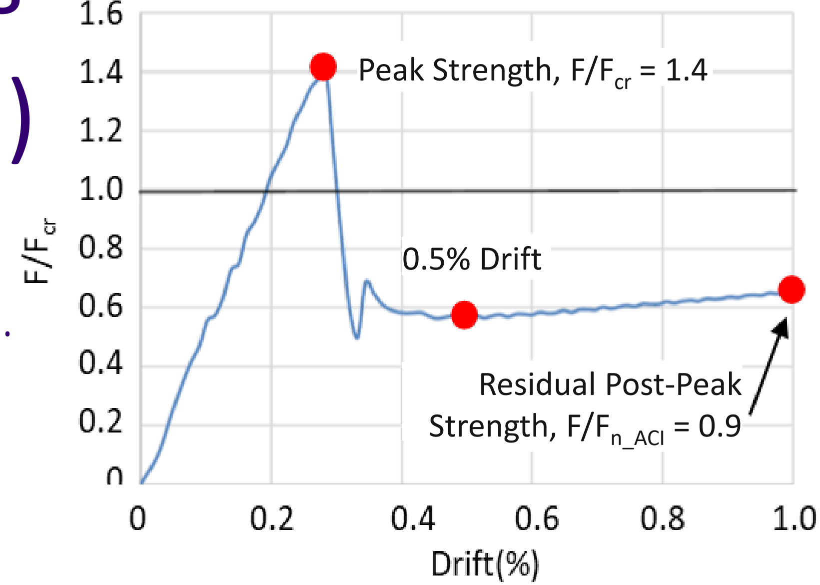
> Model details (note same as for validation study):

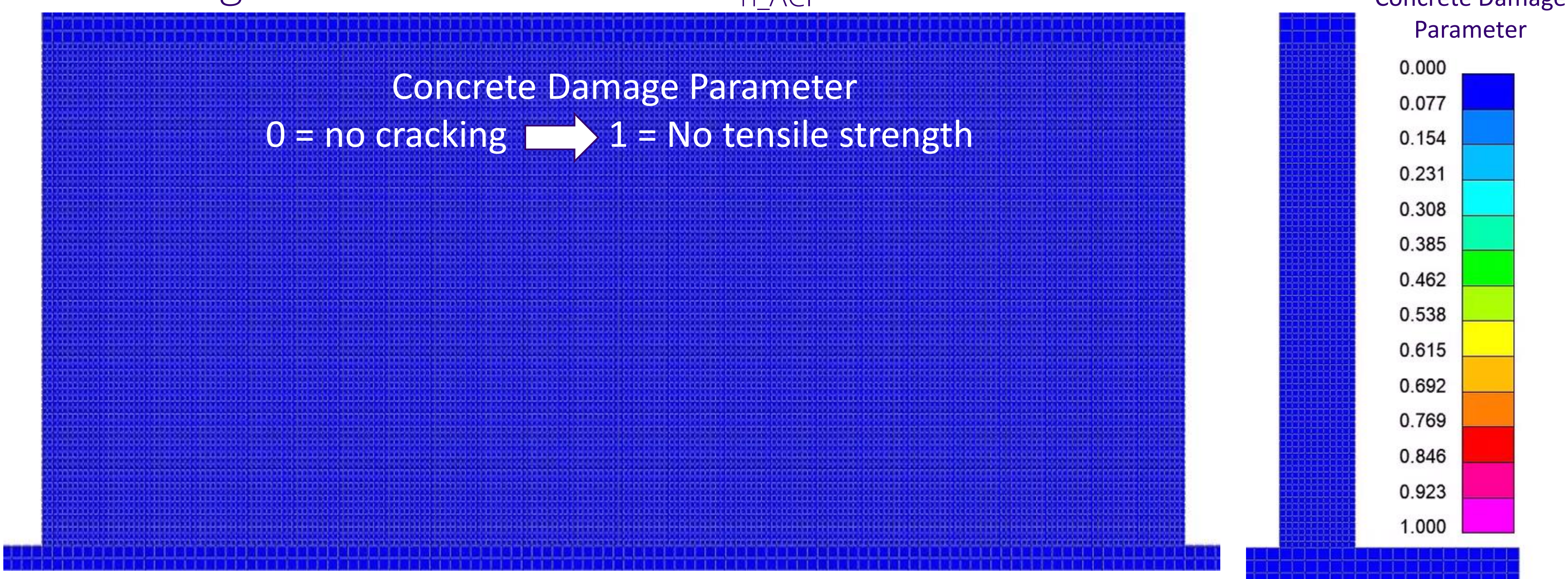
- Concrete elements are 0.5 in. cubes where damage is expected (12 elements through the thickness)
- Concrete elements are 1.0 in. cubes elsewhere
- Bond equation is used to model slip between concrete and steel.



Reference Model Results
No. 4 @ 18 in. (1 curtain)

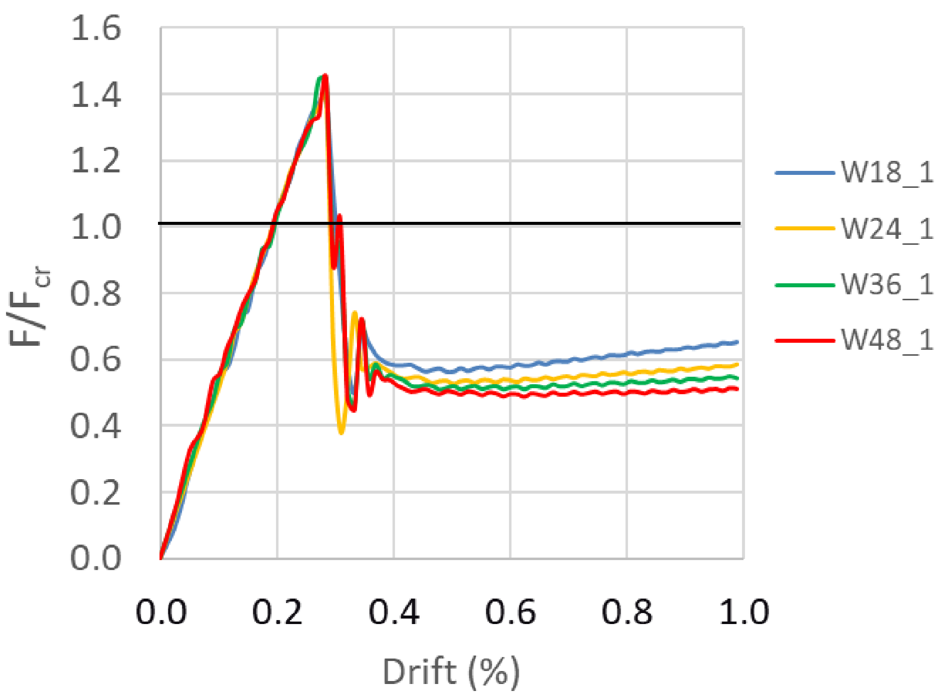
- Onset of strength loss at ~0.3% drift due to cracking at the base of the wall.
- Increased drift demand results in
  - Widening of primary crack
  - Minimal cracking higher in the wall
- Strength at 1% drift is 90% of M_{n_ACI}

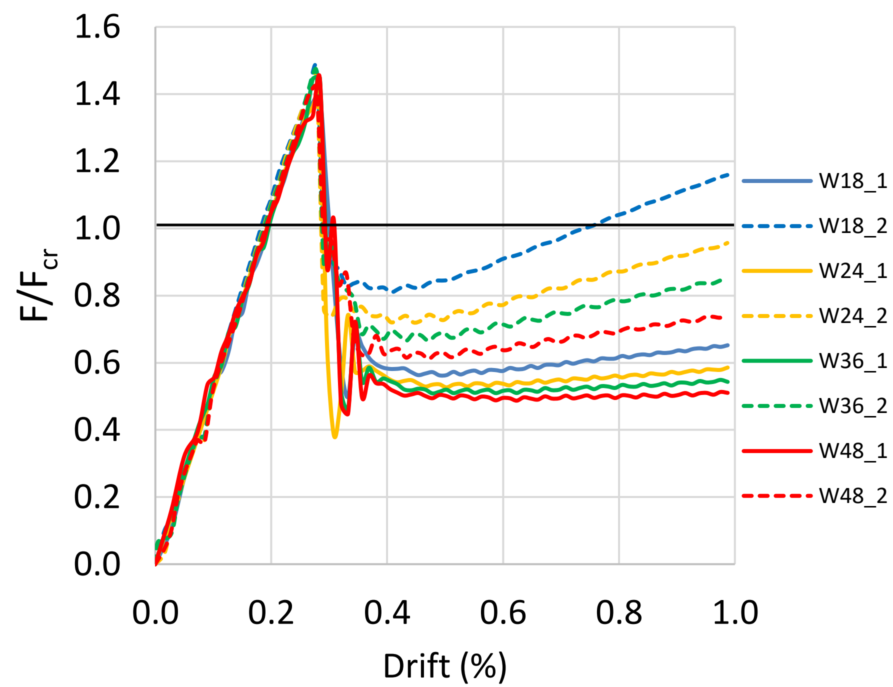




Impact of Steel Spacing & Number of Steel Curtains

> For one curtain of reinforcement, increasing spacing has minimal effect on response.
> Adding a second curtain of steel has a significant effect on strength.



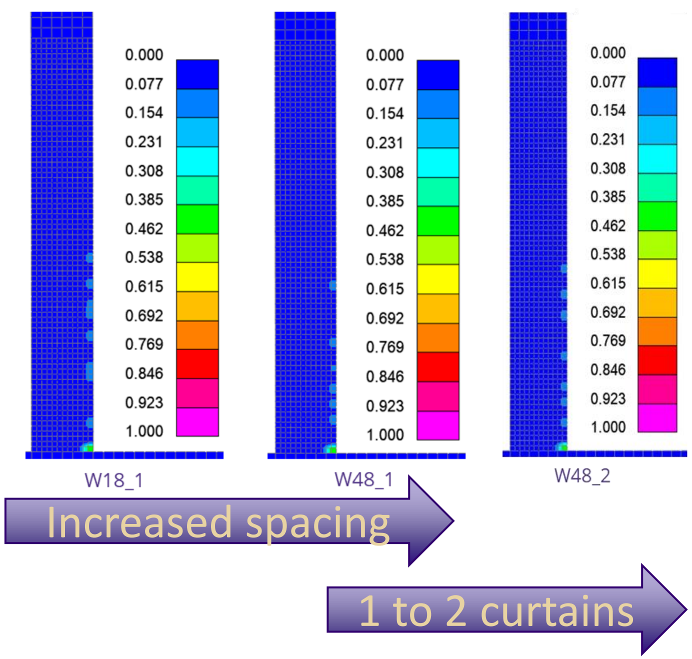


Impact of Steel Spacing & Number of Steel Curtains

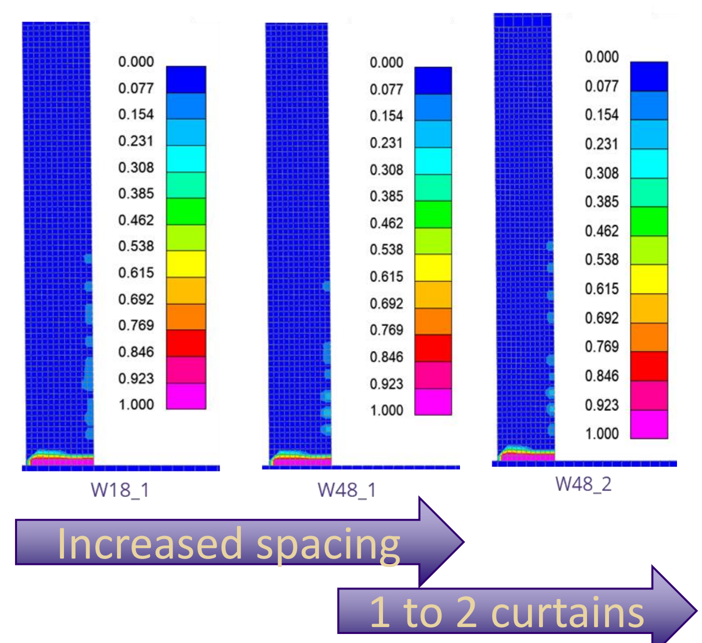
- For one curtain of reinforcement, increasing spacing has minimal effect on response.
- Adding a second curtain of steel has a significant effect on strength.
- **Damage pattern is not effected by either spacing or number of curtains of steel.**

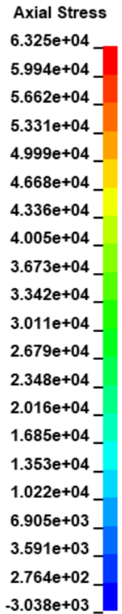
Concrete Damage Parameter

Peak Strength



1% Drift



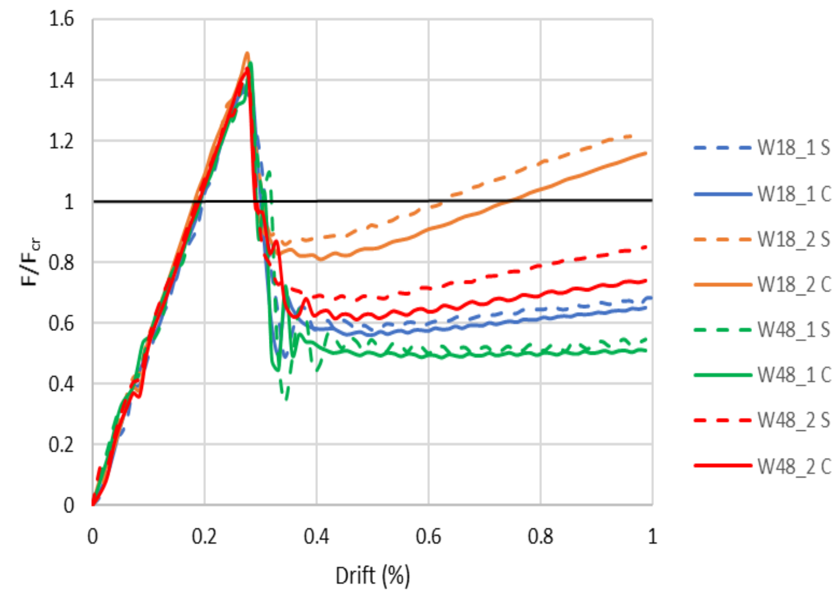


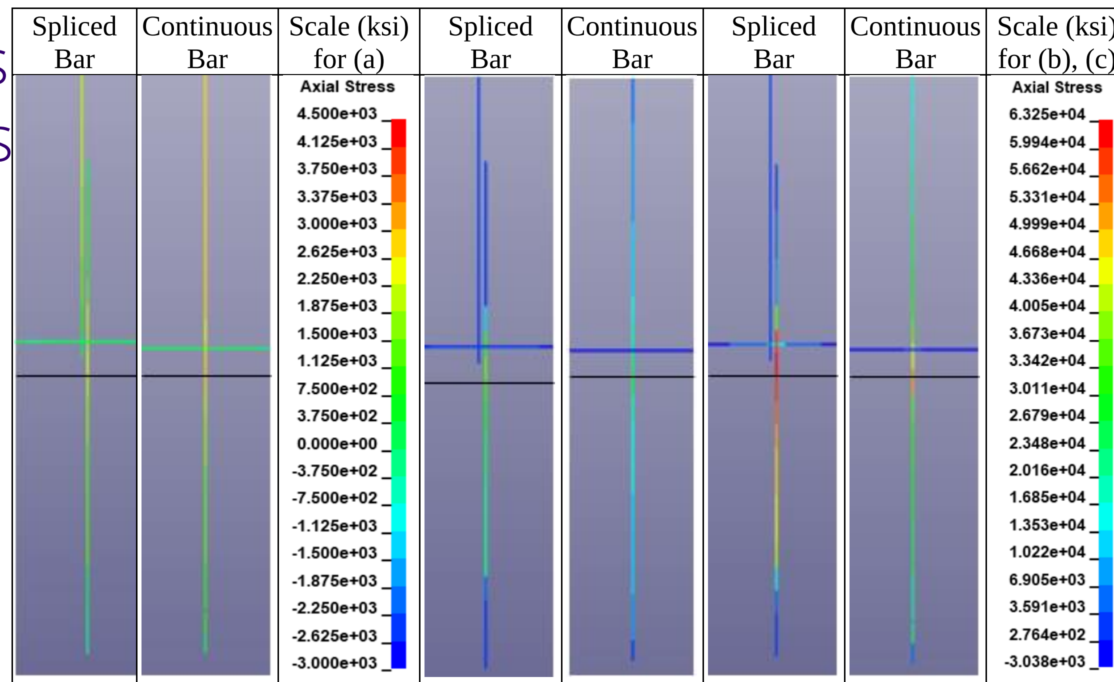
Impact of Splices

plices have small impact n wall response.

Valls with splices are lightly stronger.

> Anchorage stress fields differ for spliced versus continuous rebar.





(a) Bar stresses at maximum strength

(b) Bar stresses at 0.5% drift

(c) Bar stresses at 1.0% drift

Summary for FEM modeling

- Concrete tensile strength determines model peak strength, reinforcing steel does not affect peak strength
- Models do not reach ACI nominal strength, nor does steel yield, at 1% drift
- Models with 2 curtains of steel reinforcement exhibit strain hardening to 1% drift
- Models with 1 curtain of steel reinforcement maintain post-peak strength to 1% drift
- Models see tensile damage at wall-foundation interface with little damage up the height of the wall
- Splices at the base of the wall have limited impact on response.

Summary for RC Walls

- Peak strength is determined by concrete tensile strength.
- Post-peak response:
  - Walls with two curtains of reinforcement exhibit strain hardening to 1% drift
  - Walls with one curtain of steel reinforcement maintain post-peak strength to 1% drift
  - Roller [1996] data show walls with one curtain of steel reinforcement maintain post-peak strength to ~4% drift
  - Walls approach ACI nominal strength at 1% drift.
- Damage
  - Damage is concentrated at wall-foundation interface
  - Minimal damage up the height of the wall
  - Reinforcement configuration has no impact on damage

Application of the Model to Investigate Behavior and Design of FRC Walls

FRC Walls

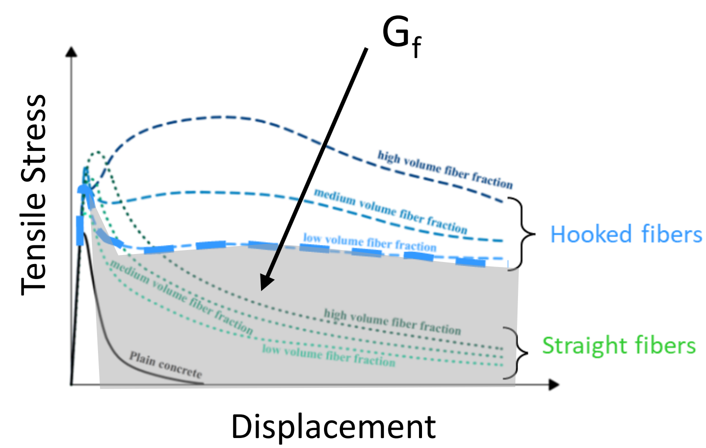
> RC wall strength is determined by concrete tensile strength
  - **FRC has substantially greater tensile strength**

> RC wall damage comprises a single, wide crack at base
  - **FRC provides the potential for distributed, narrow cracks**.

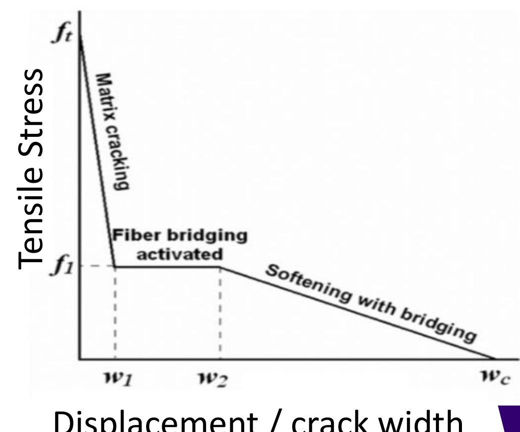
> Use FRC with low volume of hooked steel fibers
  - Steel fiber FRC is much stronger than polymer FRC.
  - Hooked steel fibers increase fracture energy (less rapid strength loss following cracking).
  - Low fiber volume provides some increased strength and toughness without too much impact on workability.

Evaluate Performance of FRC Walls via LS-Dyna Simulations

- Calibrate LS-Dyna concrete tension response model to simulate FRC response in tension
- Marcalikova et al. (2020)
  - Experimental testing to determine fracture energy / toughness, G_{ft}, of FRC with low volumes of hooked steel fiber



- Woo et al. (2014)
  - Proposed a model for post-peak response of FRC



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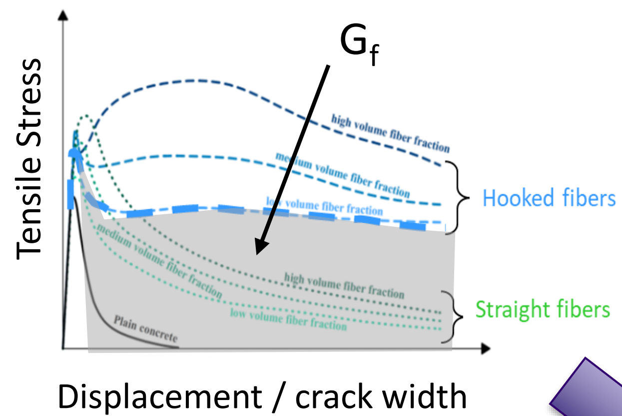

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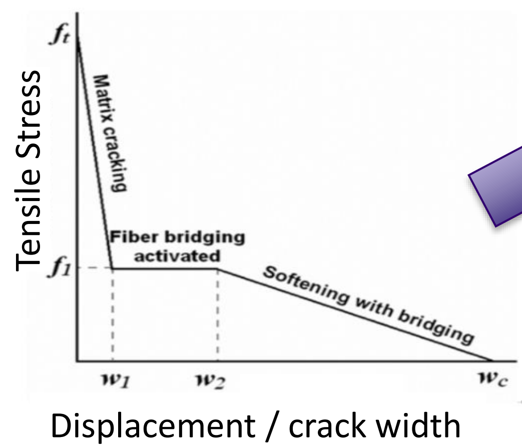
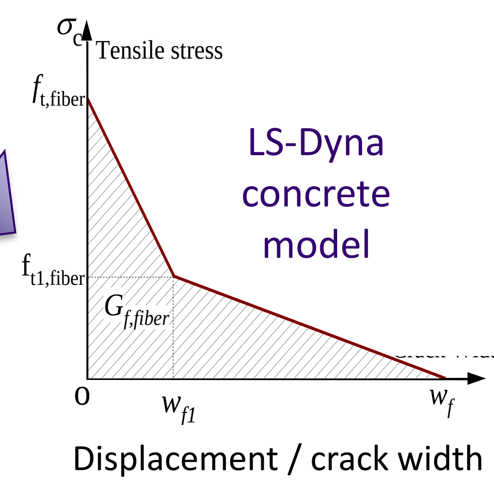
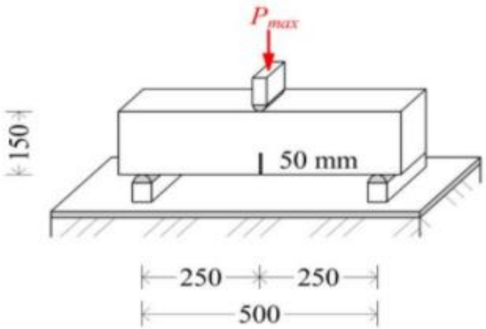
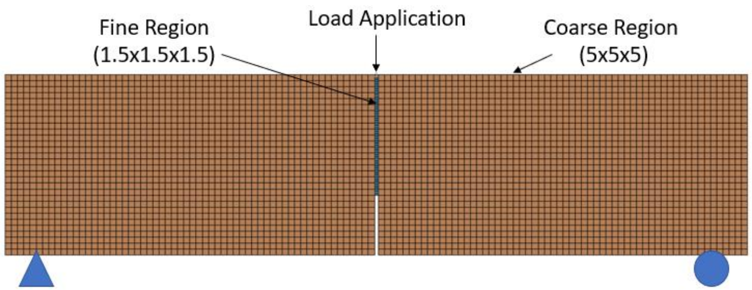


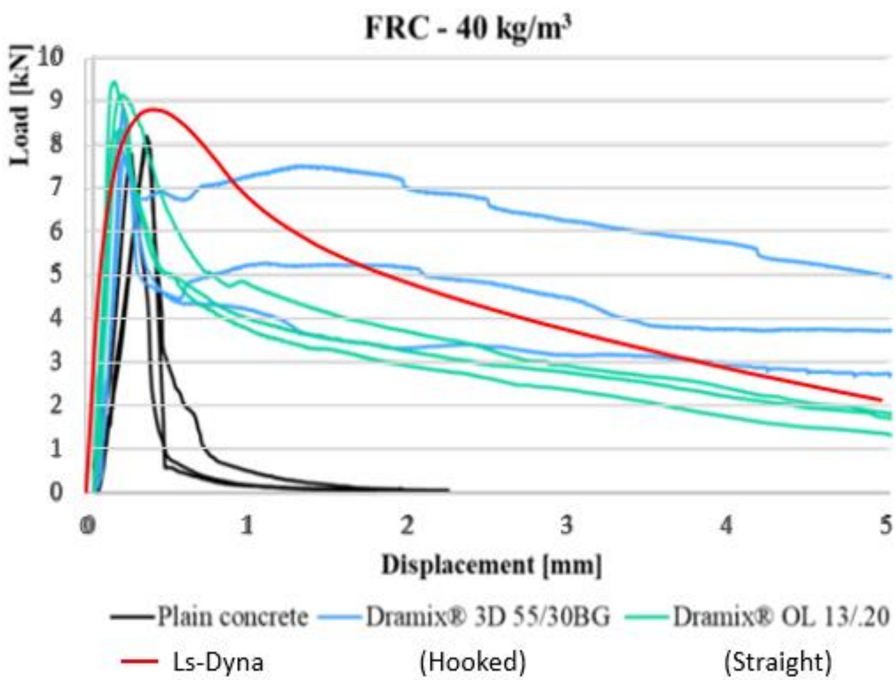


Validation of the FRC Model



Marcalikova et al. (2020)



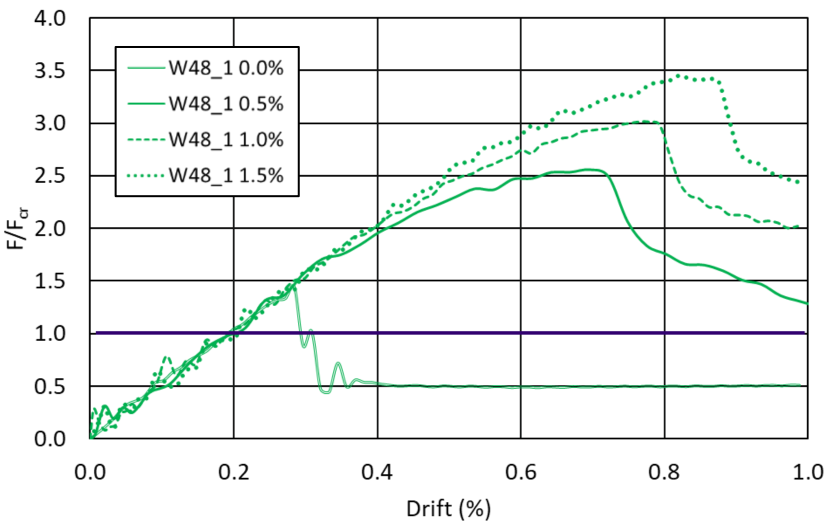


FRC Wall Parameter Study

- Use the same basic model as was used for RC walls
- FRC with
  - Hooked steel fibers
  - Fiber volumes: 0.5%, 1.0%, and 1.5%
- Reinforcement
  - 18 and 48 in. spacings
  - 1 and 2 curtains of steel reinforcement
  - starter bars only

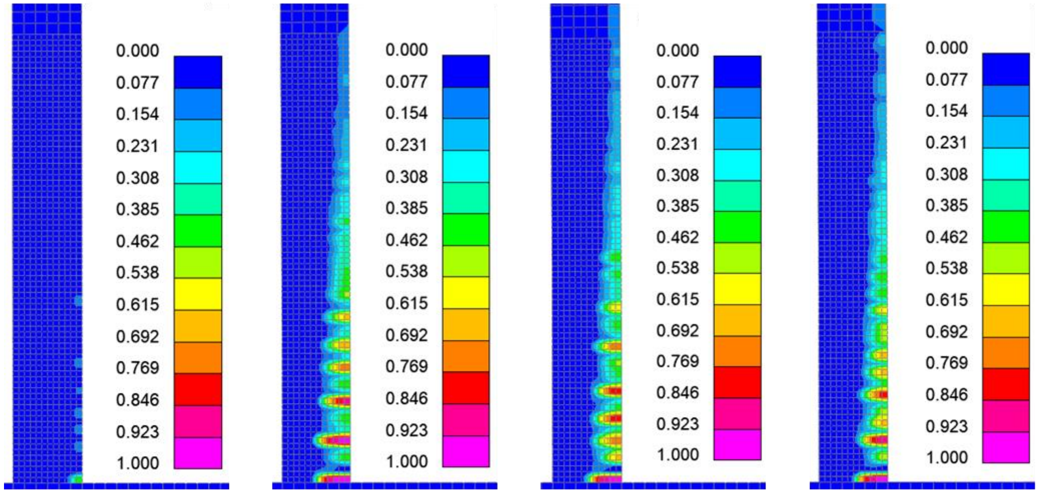
Compare RC and FRC Walls

- One curtain of reinforcement @ 48 in.
- In comparison with plain concrete, FRC wall provides
  - Elastic response to much larger drift and force
  - Less total strength loss and less rapid strength loss
  - Much more distributed cracking



Damage Parameter

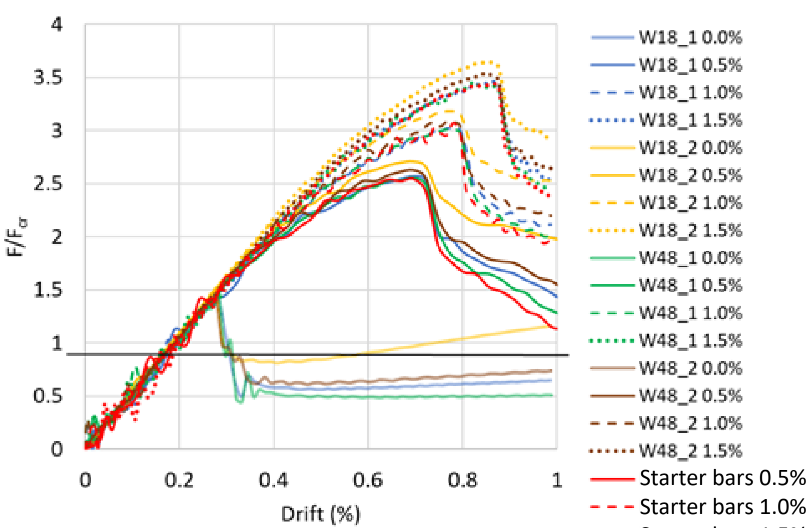
(0 = no cracking; 1.0 = wide cracks and no tensile strength)



0.0% Fiber Content 0.5% Fiber Content 1.0% Fiber Content 1.5% Fiber Content

Compare RC and FRC Walls

- Multiple steel configurations
  - One and two curtains of steel
  - 48 in. and 18 in. spacing as well as starter bars only
- Observations:
  - Two curtains of steel and 18 in. spacing provides greater post-peak strength
  - Maximum strength, drift at onset of strength loss, and post-peak strength increase with increasing fiber content.
  - Starter bars only provides acceptable performance.



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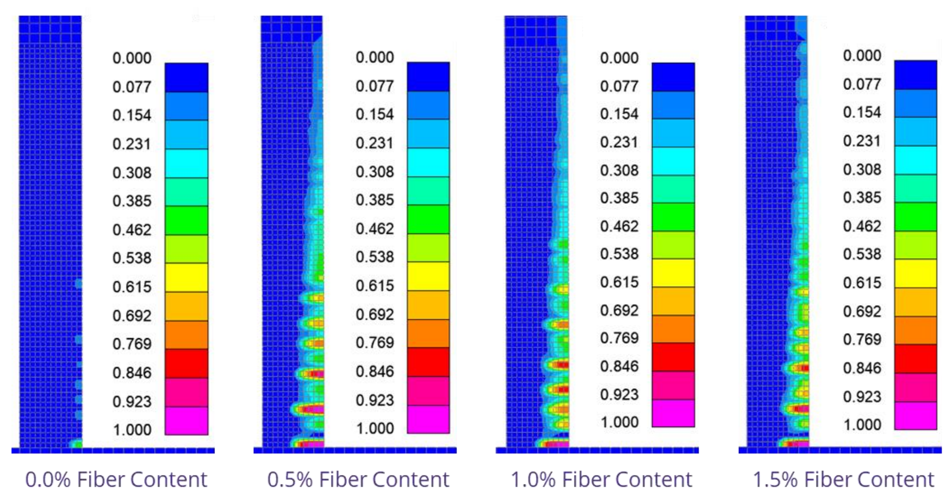

Compare RC and FRC Walls

- Observations:
  - Two curtains of steel and 18 in. spacing provides greater post-peak strength
  - Difference between two curtains @18 in. and one curtain @48 is not big.
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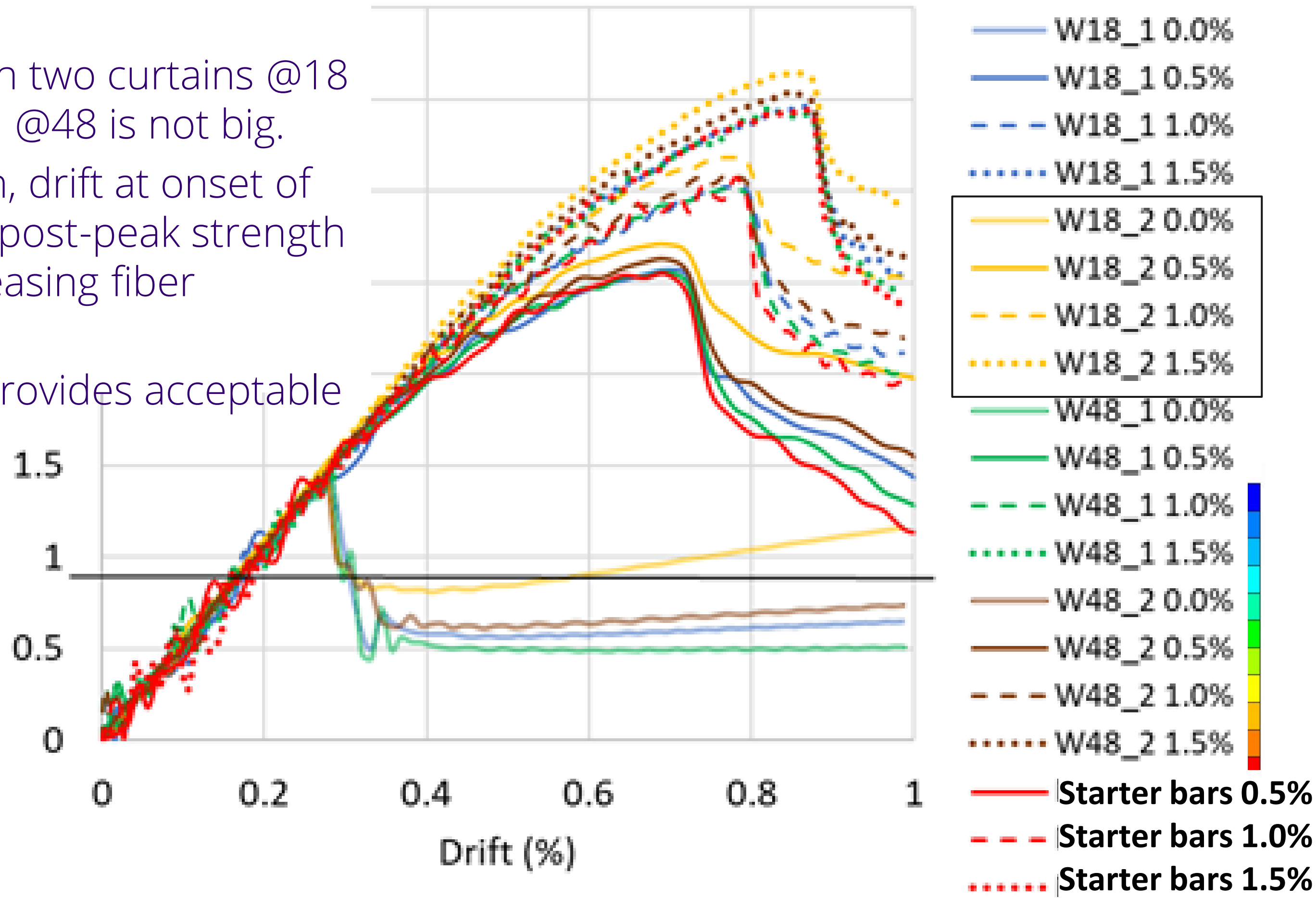

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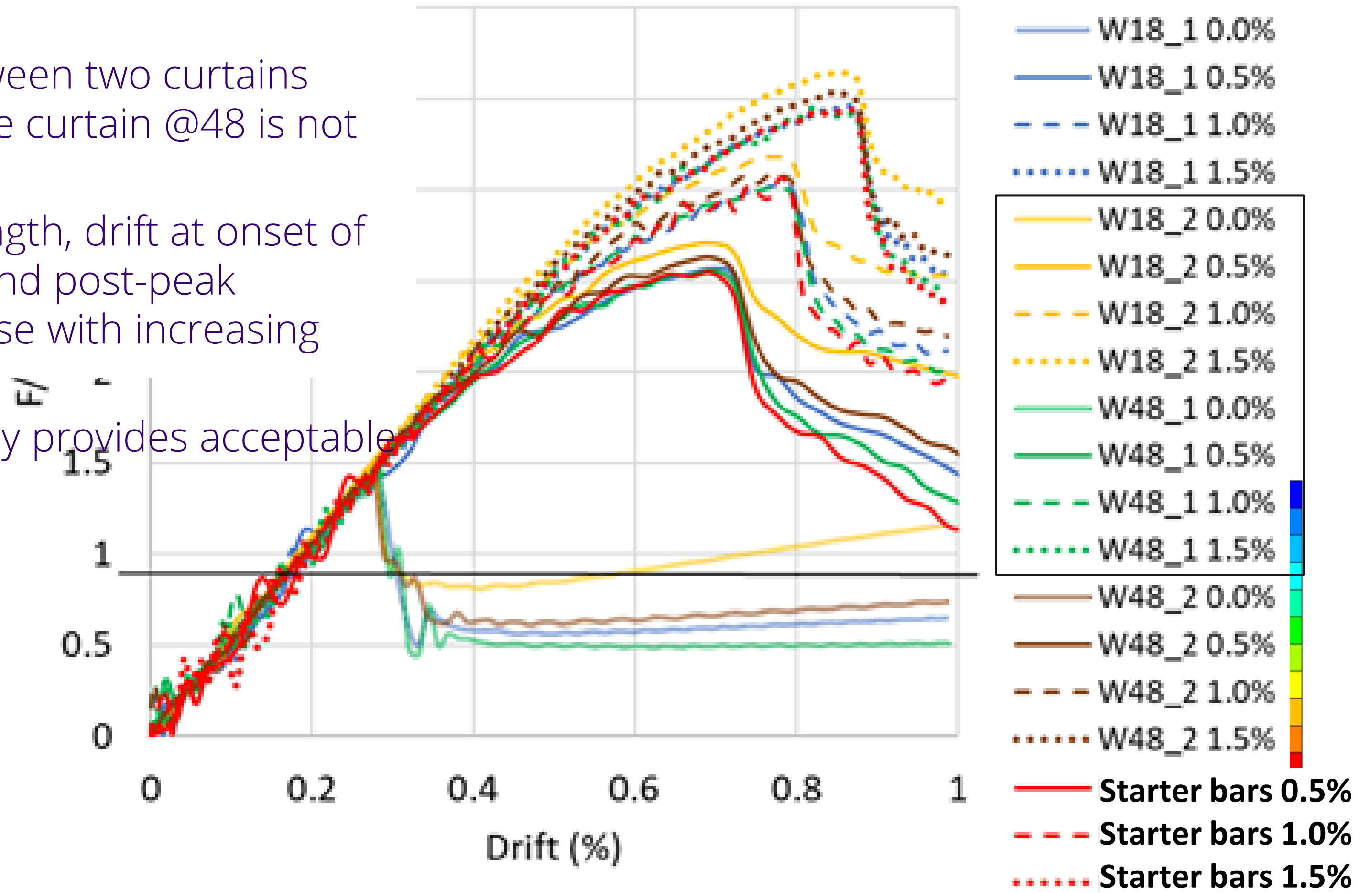
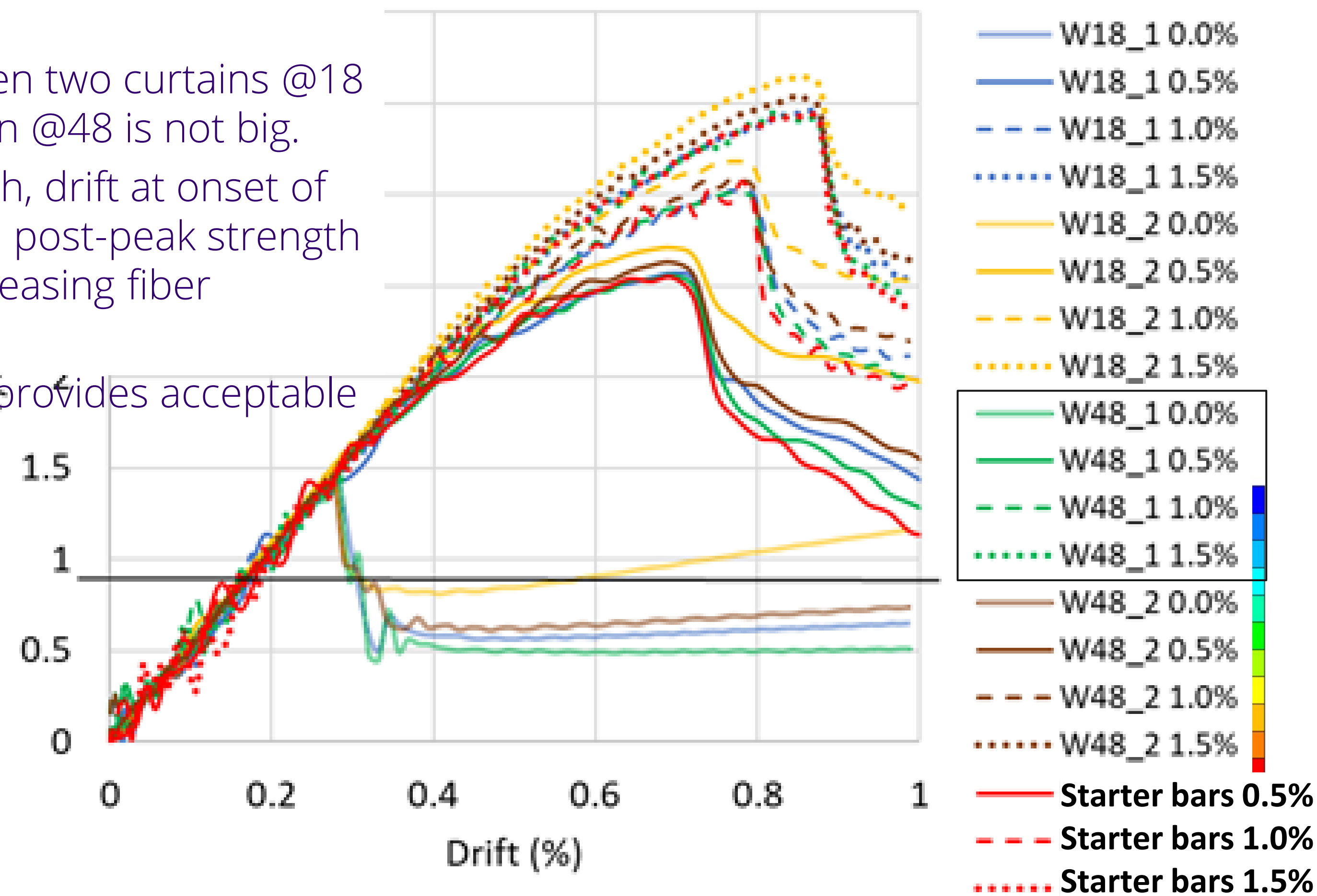


Compare RC and FRC Walls

> Observations:
  - Two curtains of steel and 18 in. spacing provides greater post-peak strength
  - Difference between two curtains @18 in. and one curtain @48 is not big.
  - Maximum strength, drift at onset of strength loss, and post-peak strength increase with increasing fiber content.
  - Starter bars only provides acceptable performance.



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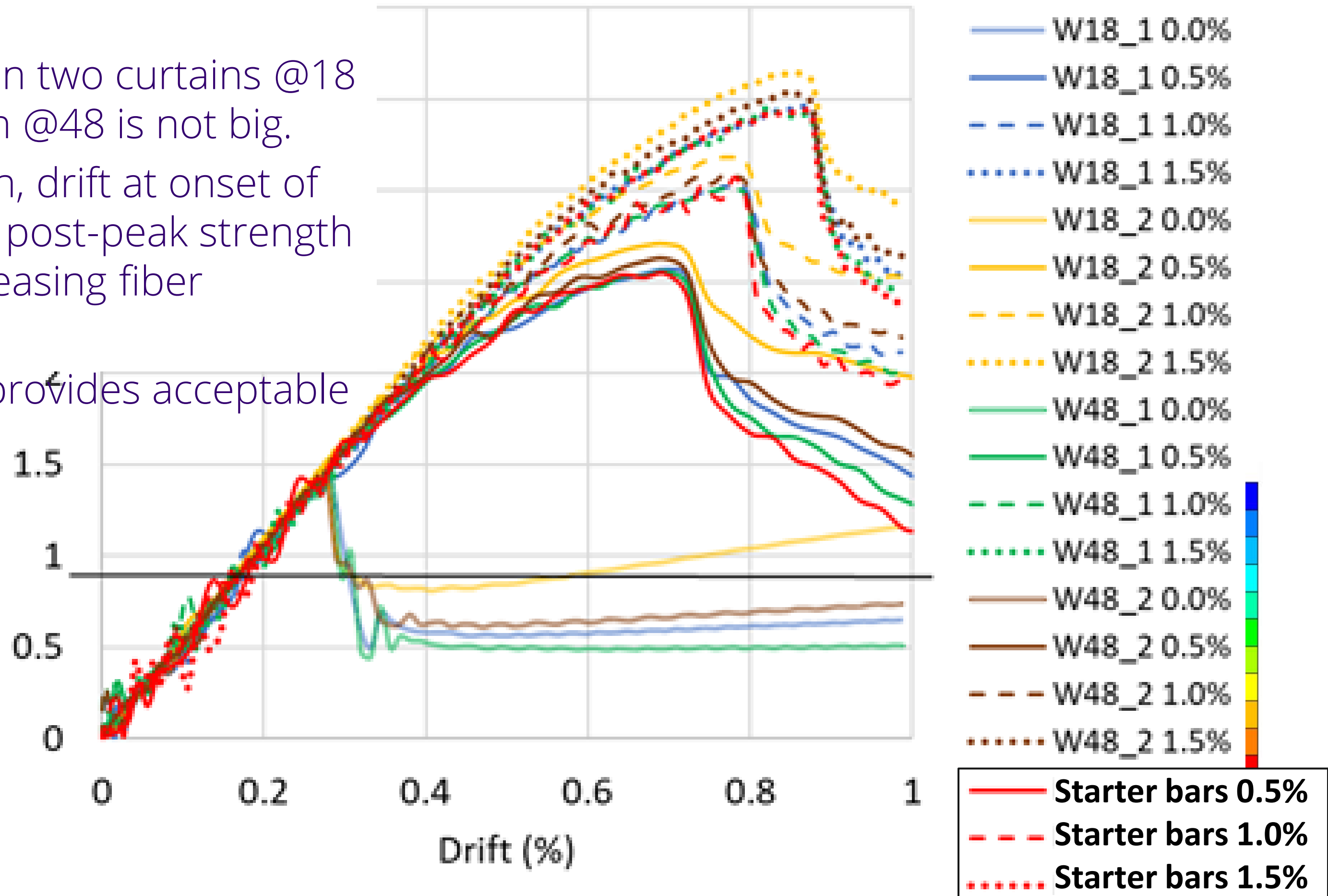
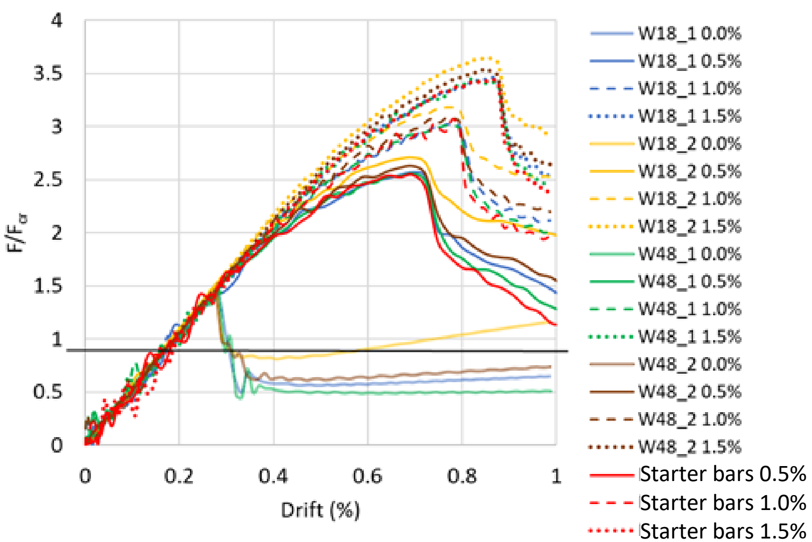


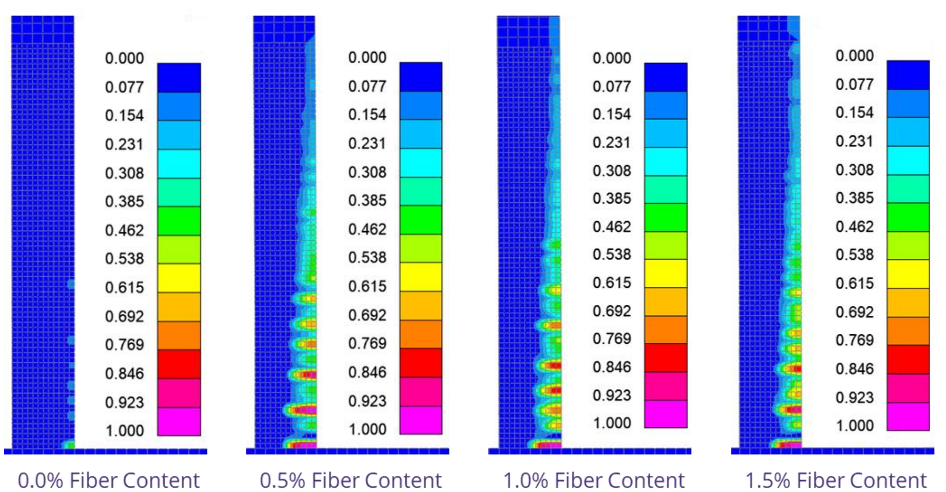
Compare RC and FRC Walls

- Multiple steel configurations
  - One and two curtains of steel
  - 48 in. and 18 in. spacing as well as starter bars only
- Observations:
  - Two curtains of steel and 18 in. spacing provides greater post-peak strength
  - Maximum strength, drift at onset of strength loss, and post-peak strength increase with increasing fiber content.
  - Starter bars only provides acceptable performance.



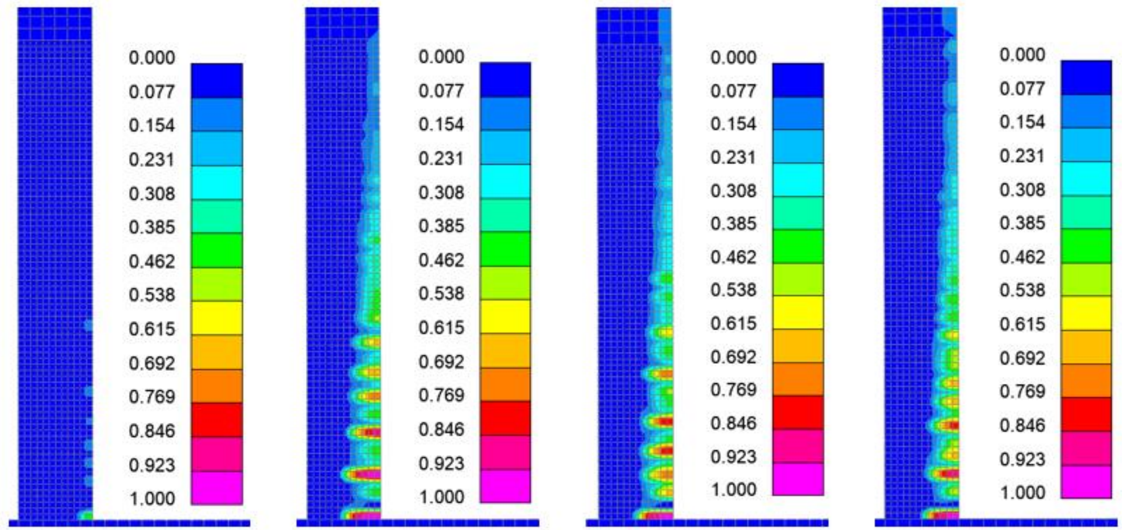
Damage Parameter at Peak Strength

(0 = no cracking; 1.0 = wide cracks and no tensile strength)

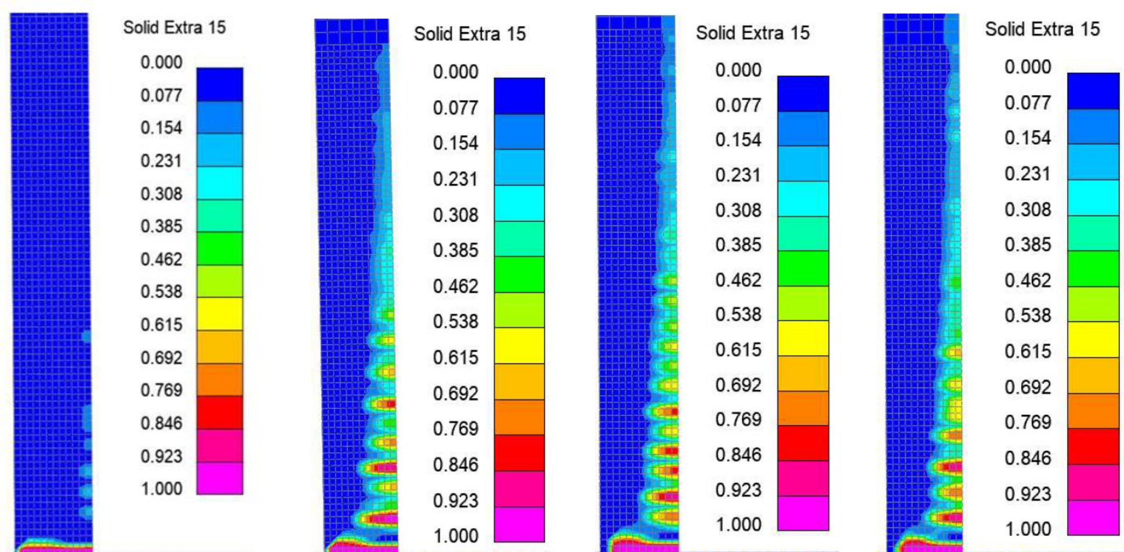


Concrete Damage Parameter: Walls With and Without Fiber

> Peak Strength

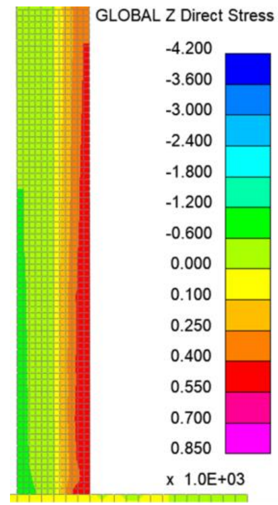


> 1% out of plane drift

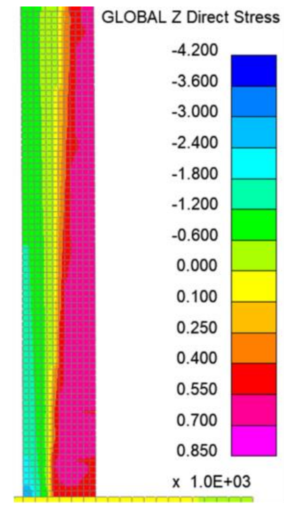


Concrete Vertical Stress Fields: Walls With and Without Fiber

> Peak Strength



W48_1_0.0



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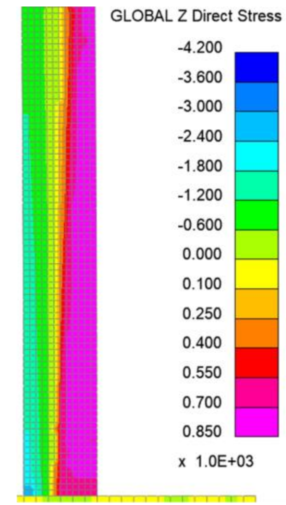

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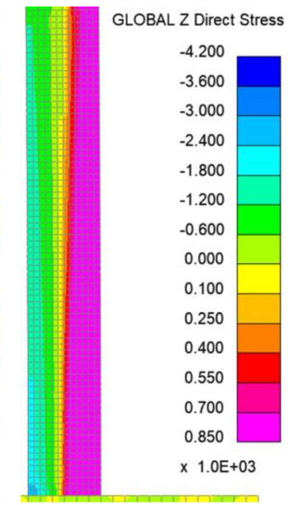
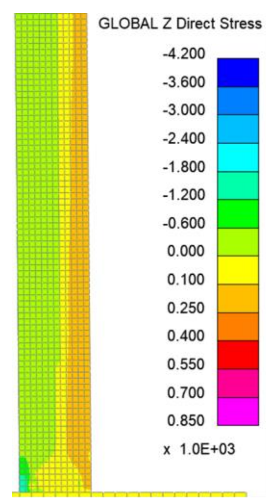


W48_1_1.5

> 1% out of plane drift



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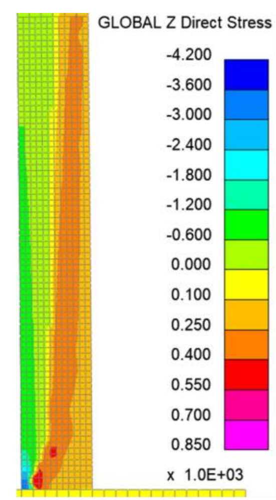

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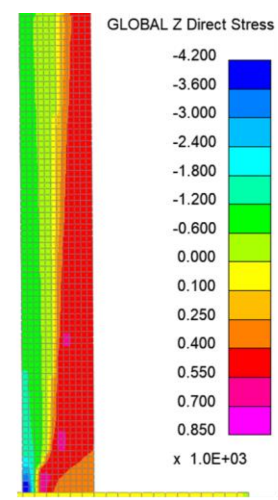
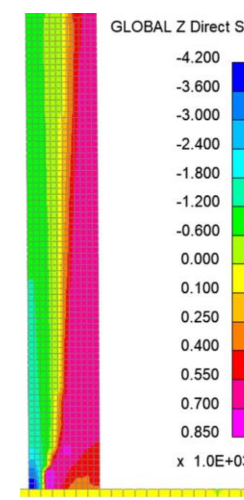


W48_1_1.0



W48_1_1.5

Conclusions

- LS-Dyna modeling can provide acceptably accurate simulation of measured response for lightly reinforced concrete walls.

- Simulation data show that lightly reinforced concrete walls exhibit acceptable performance when constructed with lower reinforcement ratios than required by the ACI Code.

- FRC with low fiber volume offers the potential for substantially increased wall strength and deformation capacity.

- Funding should be allocated for laboratory testing to validate FEM results and demonstrate acceptable performance of lightly reinforced concrete walls.

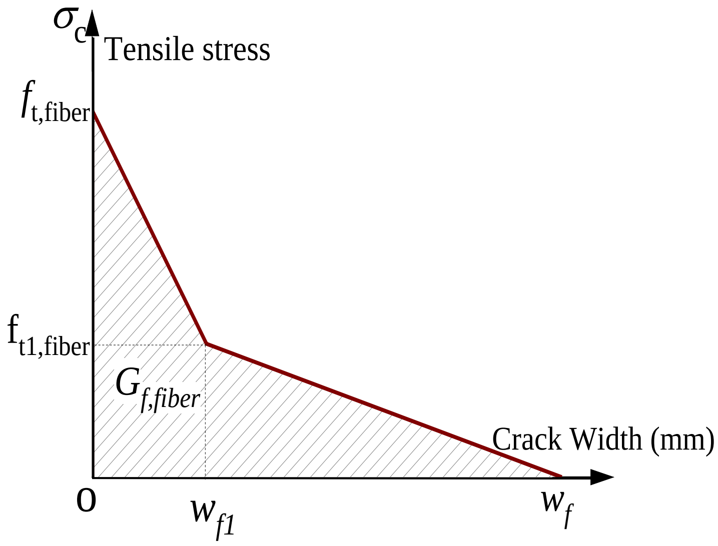
Model Developement

Calibrated from Marcalikova et al. (2020)

- $f_{t,fiber} = 1.65FC + f_{t,RC}$
- $G_{f,fiber} = 20FC + G_{f,RC}$
- FC = Fiber Content (%)

Fitting Woo et al. (2014) curve to CDPM curve

- $f_{t1,fiber} = 0.4f_{t,fiber}$
- $w_{f1} = 0.25$ mm
- w_f =solve via area under curve when area = $G_{f,fiber}$



Impact of Steel Spacing