FINITE ELEMENT ANALYSIS AND DESIGN OF SHEAR BEHAVIOUR OF RC SLABS SUPPORTED ON WALLS

Graeme J. Milligan

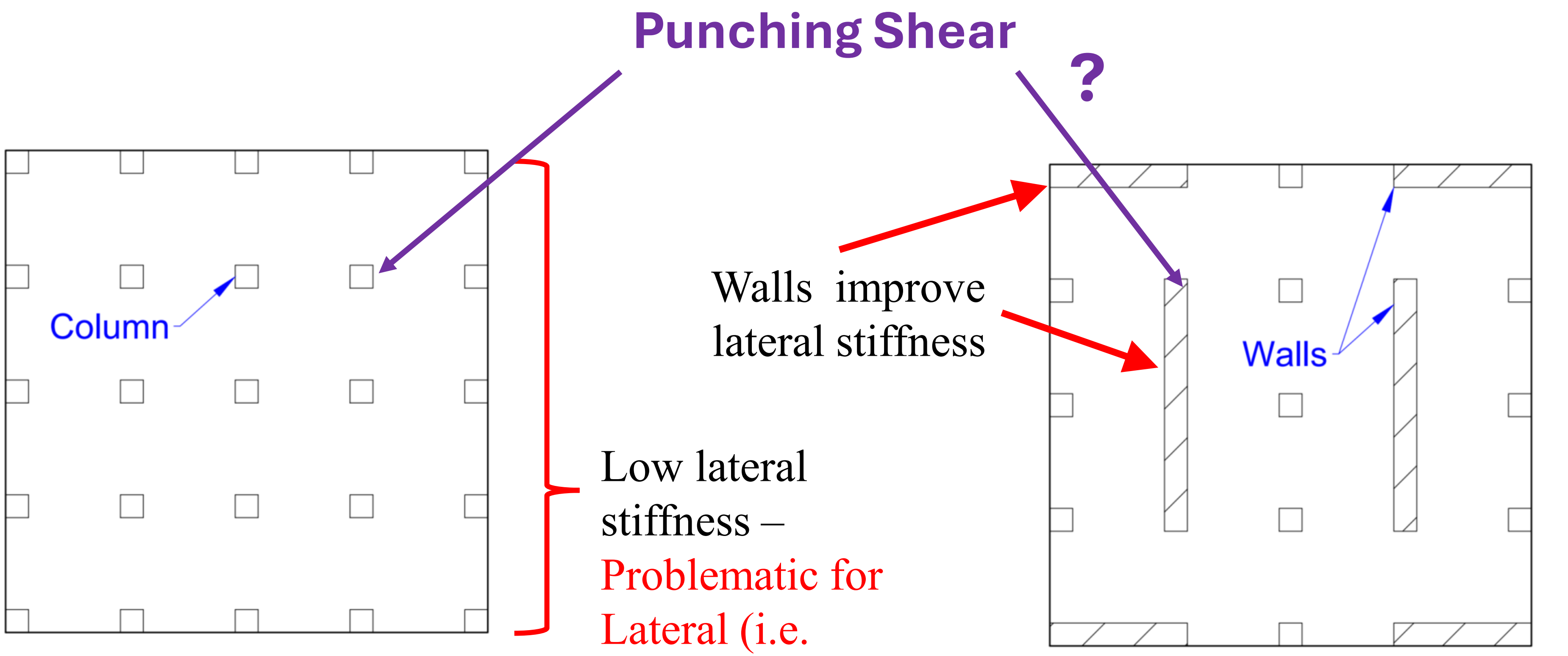
Maria Anna Polak

Cory Zurell

Department of Civil and Environmental Engineering
University of Waterloo

Motivation – Common Flat Slab Configuration

- Due to low lateral stiffness of flat plates **shear walls** typically included to increase stiffness and carry lateral loads



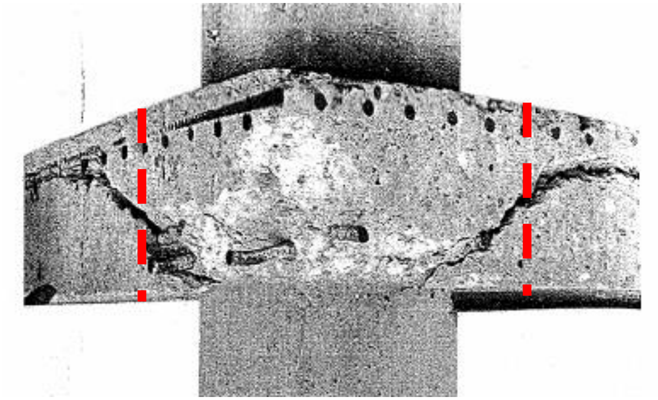
Low lateral stiffness – Problematic for Lateral (i.e. Seismic/Wind Loads

Flat Plate (Slab on Columns Only) – Low Seismicity Regions

Flat Slab Supported on Columns and Walls – Moderate to High Seismicity Regions

What is Punching Shear?

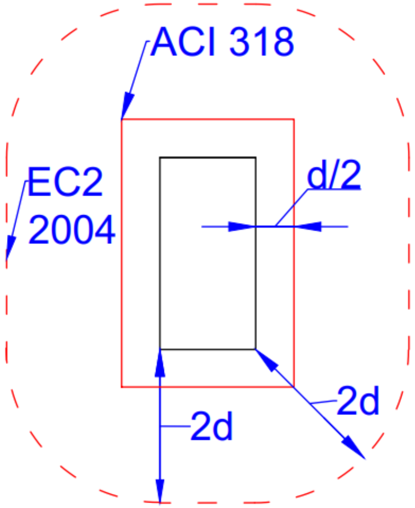
- Brittle failure mode of RC slabs caused by high transverse and in-plane stresses near the column
- Failure occurs when inclined cracks form and extend into the compression zone



Inclined Cracks After Punching Failure (MacGregor and Bartlett, 2000)

Code Provisions

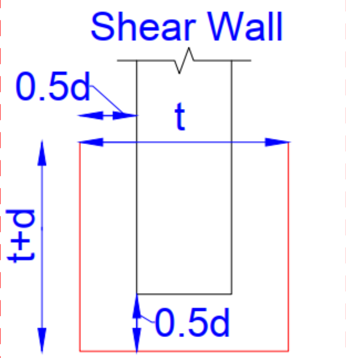
Use the critical perimeter concept (location and capacity vary)



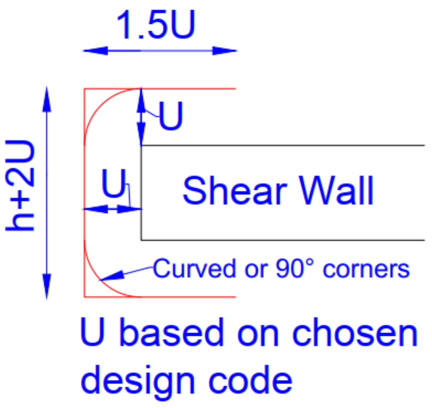
ACI 318-19 and Eurocode 2 (2004)

Critical Perimeters Around Slab-Wall Connections

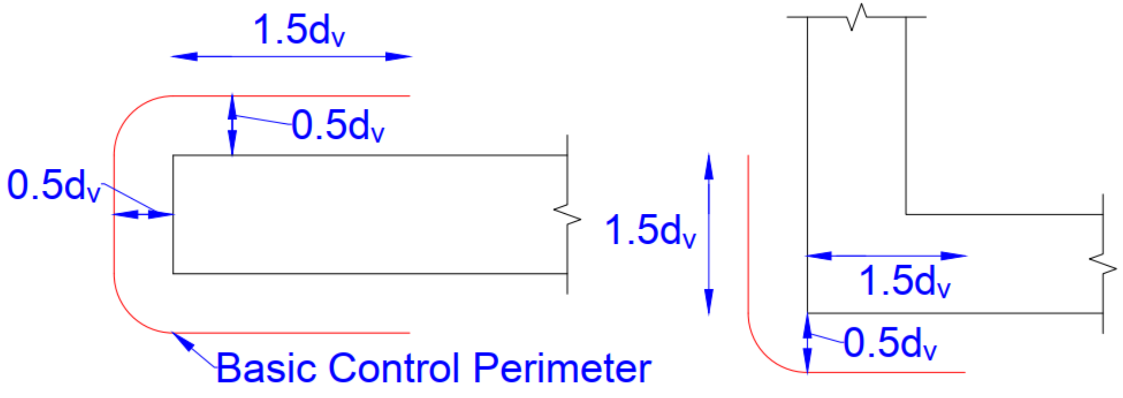
- Numerous critical perimeters recommended in the codes
- Critical perimeter not limited to toe region of the wall in North American codes
- ASCE-ACI 352 recommends Schwaighofer and Collins (1977) method when column aspect ratio ≥ 3
  - $v_c = 0.33\sqrt{f_c'}\ (MPa)$ on assumed critical perimeter



Schwaighofer and Collins (1977)



Coull and Chee (1983)

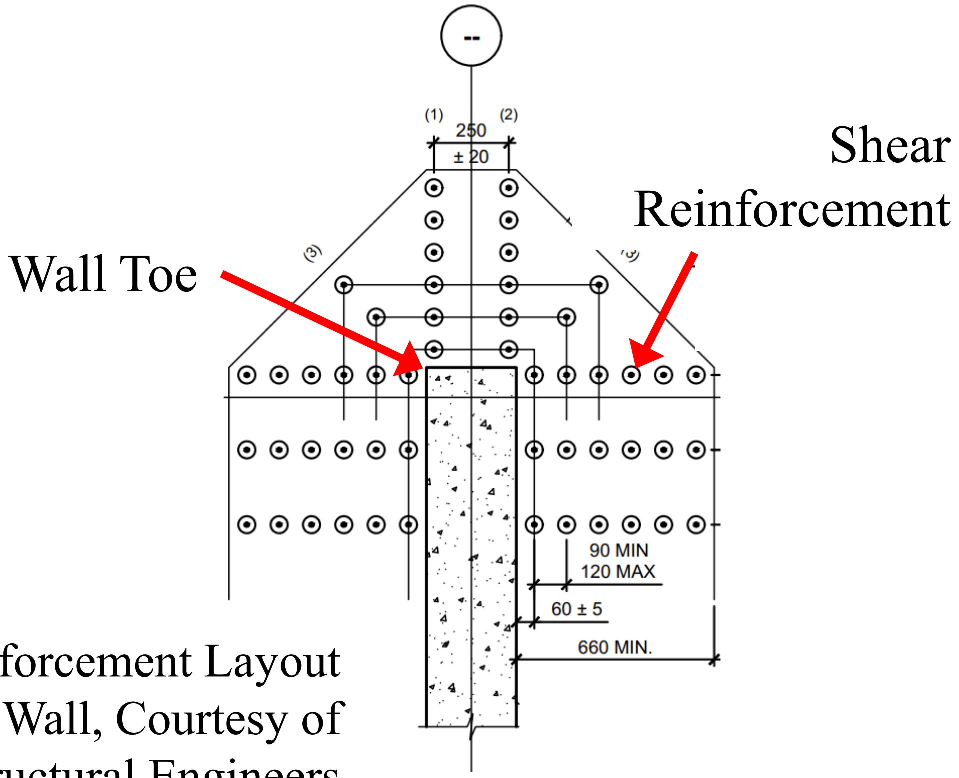


fib Model Code 2010

Current Practice Around End of Walls

- Punching failures around wall toes observed in limited experiments
- Extensive shear reinforcement may be specified around wall toes

- Commercial structural analysis/design software cannot account for punching around wall toes (lack of design provisions even though slab-wall connections are essential)



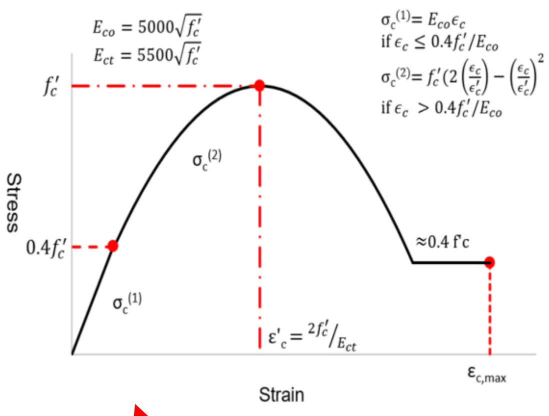
Shear Reinforcement Layout Around End of Wall, Courtesy of Blackwell Structural Engineers

Advantages of Finite Element Analysis

- Limited experimental database of slab-wall connections
- NLFEA can be used to supplement database
  - Allows for cost-effective analysis of parameters
  - Can provide insight into structural behaviour

Careful calibration of model parameters required!

Summary of Calibrated FEM

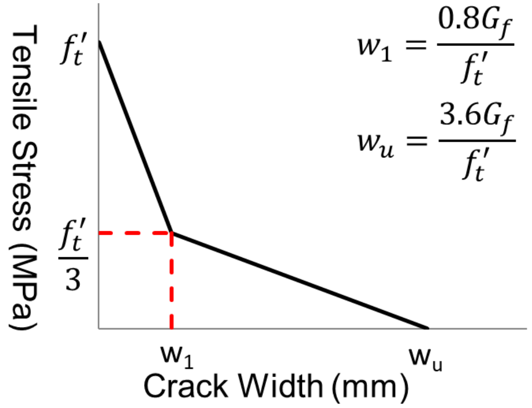


Implemented in ABAQUS using the Concrete Damaged Plasticity (CDP) Model

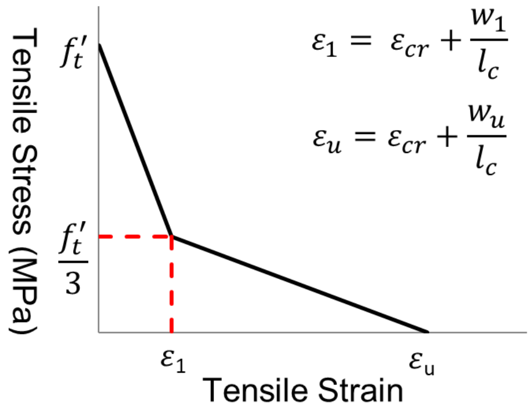
Calibrated based on 7 tests (4 on rectangular columns and 3 on square columns)

Summary of Calibrated FEM

	CDP Model Parameters:
Default Values →	Eccentricity – 0.1, σ_{bo}/σ_{co} – 1.16, K_c – 0.67
	Dilation Angle – 45°
	Uniaxial Compression Model:
	Hognestad Parabola,
	E_c – $5000\sqrt{f_c'}$ (MPa), f_c' – 44.6MPa
	Uniaxial Tensile Model:
	Bi-linear tensile stress-crack width (Petersson, 1981)
	G_f – 93kN/m (Calculated from Model Code 1990)
	Element Details:
	Concrete – C3D8R (20mm), Rebar – T3D2 (20mm)



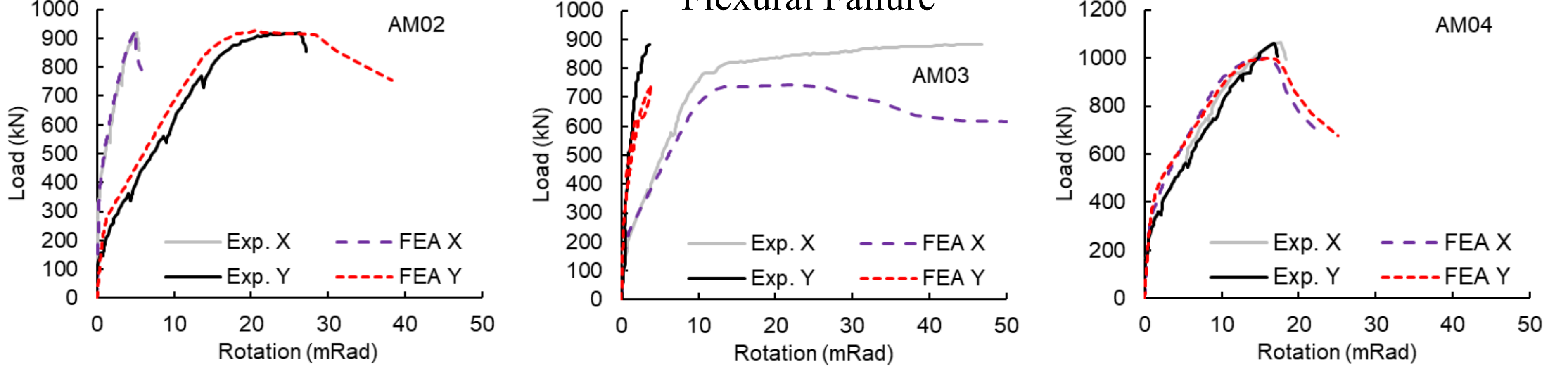
Bi-linear tensile stress crack width relationship (Petersson, 1981)

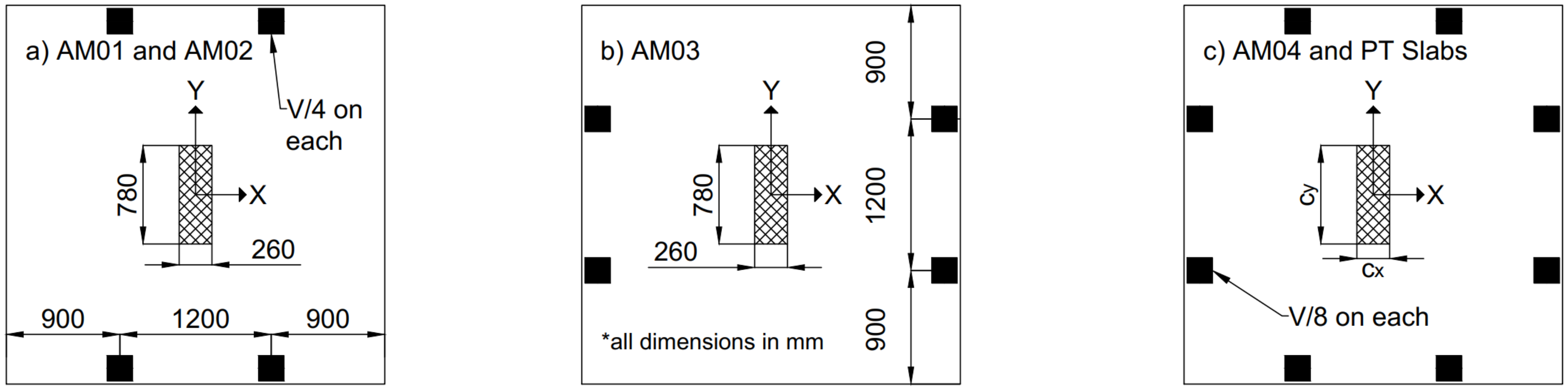


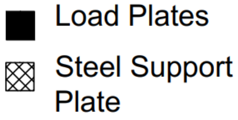
FEM Calibration Results

- Calibrated FEM found to accurately predict behaviour of slabs failing in shear

Flexural Failure







AM04: c_y=780, c_x=260mm
PT Slabs: c_y=c_x=260mm

Sagaseta, J., Tassinari, L., Fernández Ruiz, M., & Muttoni, A. (2014). Punching of Flat Slabs Supported on Rectangular Columns. Engineering Structures, 77, 17-33.

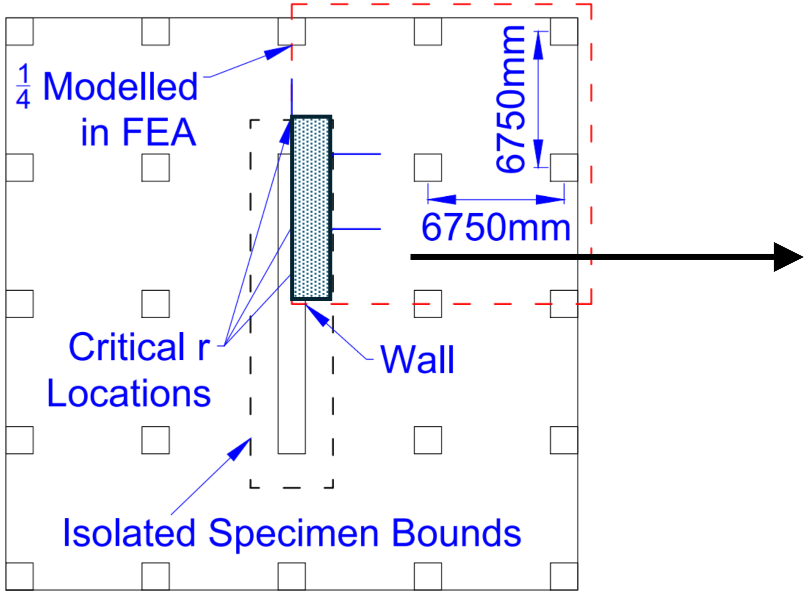
Numerical Studies

- **V study** Concentric vertical load only
  - **3 slab-wall connections** . Large $\beta = c_{max}/c_{min} > 38$
  - different $\kappa = c_{min}/d.$
- **V+M study** Concentric vertical load + uniaxial unbalanced moment
  - **1 slab-wall connection** with a κ = 1.287 is analyzed for two vertical load levels (**40% or 65%** of the concentric capacity from the V study).

	Wall dimensions (mm)		Loading Conditions	
κ (c_{min}/d)	Length (L)	Thickness (c_{min})	V Study	V+M Study
0.792	13660	160	Concentric Load Monotonically Increased to Failure	–
1.287	13760	260		40% or 65% of Concentric Vertical Capacity + Monotonically Increasing Moment
1.980	13900	400		-

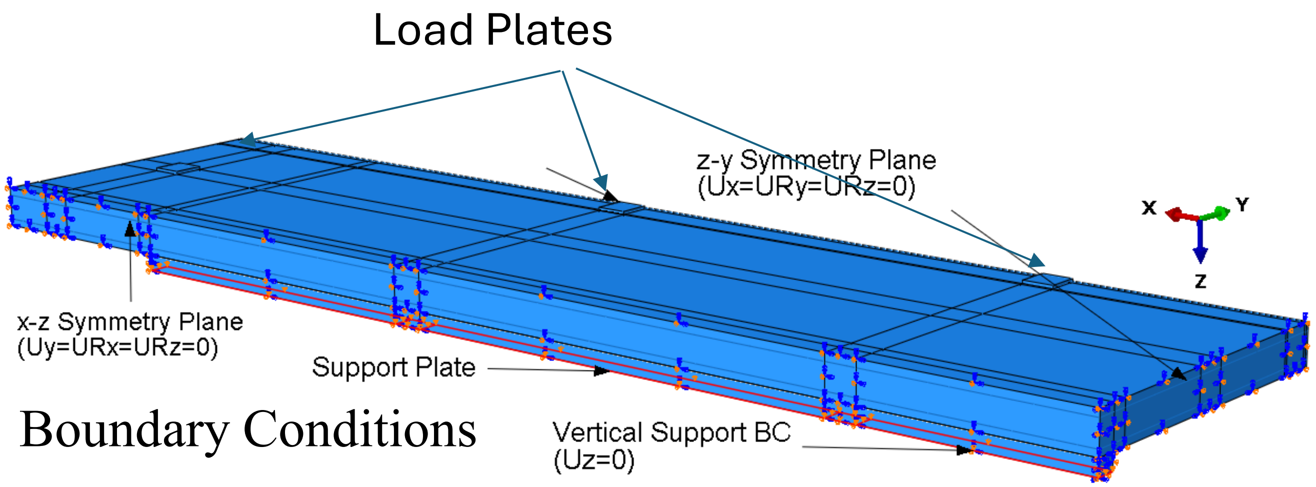
Overview of Isolated Slab-Wall Specimens: V - Study

- Isolated interior slab-wall connections analyzed
  - Required estimation of radius of contraflexure, r, around wall (done with linear elastic FEA)
- Isolated specimens reduce computational demand



Hypothetical Structure (1/4 Modelled in FEA to Determine Isolated Specimen Dimensions)

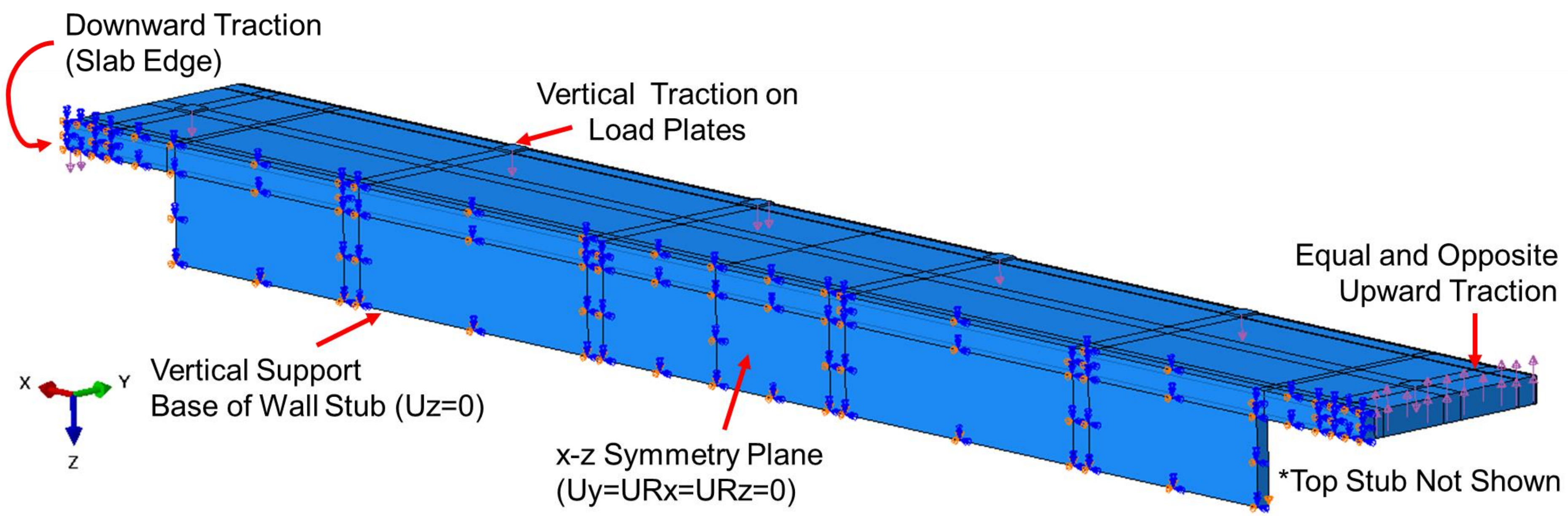
Model



Boundary Conditions

Overview of Concentric Load + Unbalanced Moment: V+ M Study

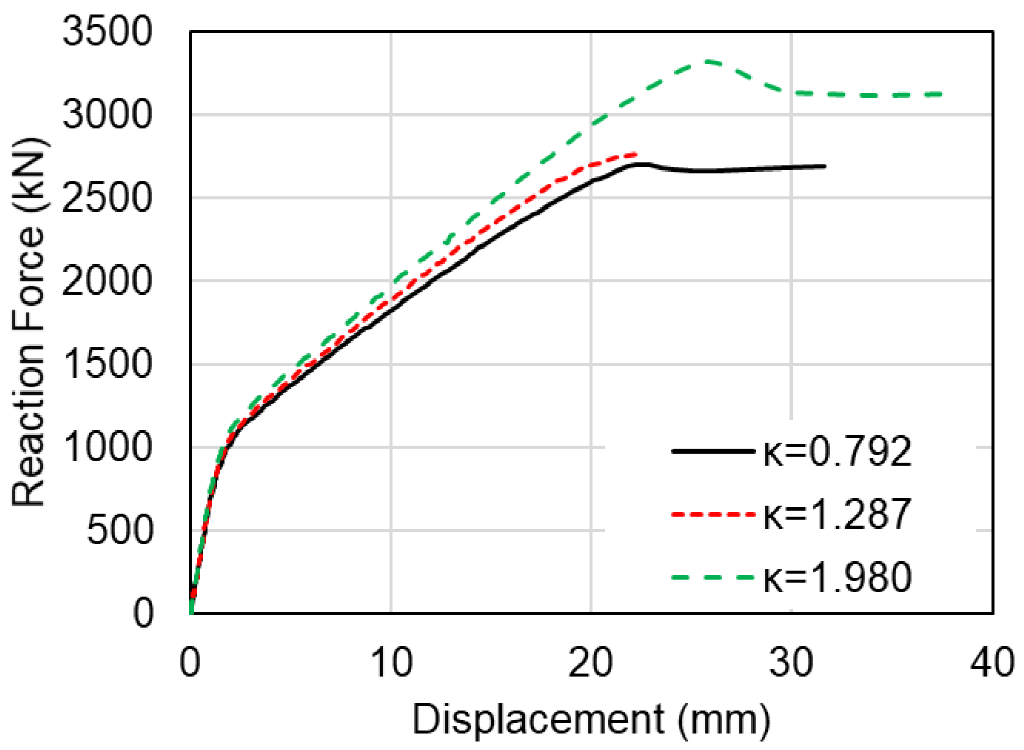
- One SWC subjected to concentric vertical load and unbalanced moment analyzed **κ = 1.287**
- Two different vertical load levels, *V*, considered **40% and 65% of Concentric Load Capacity + Increasing Moment M**



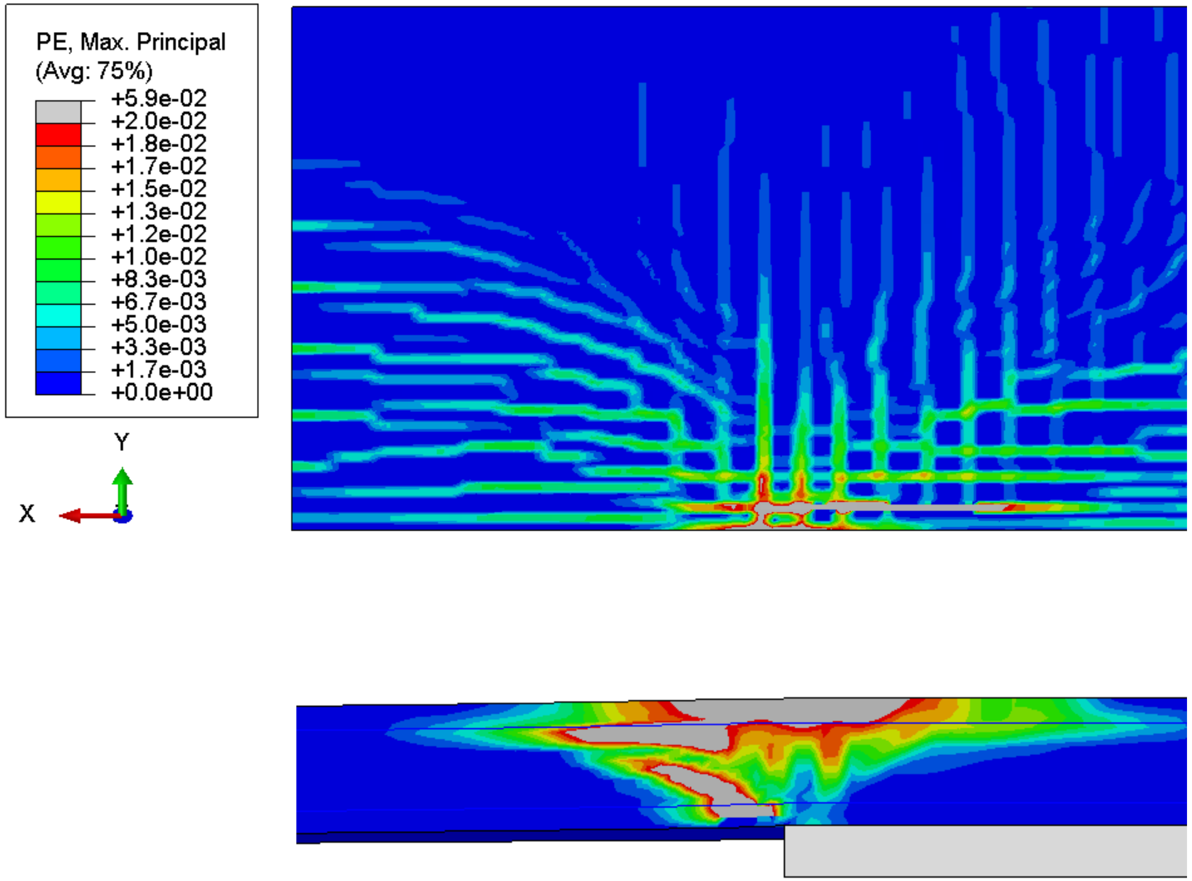
Boundary Conditions in V+M Study

Results - Concentric Load Study - V Study

Force Versus Displacement for
κ=0.792, 1.287,1.980

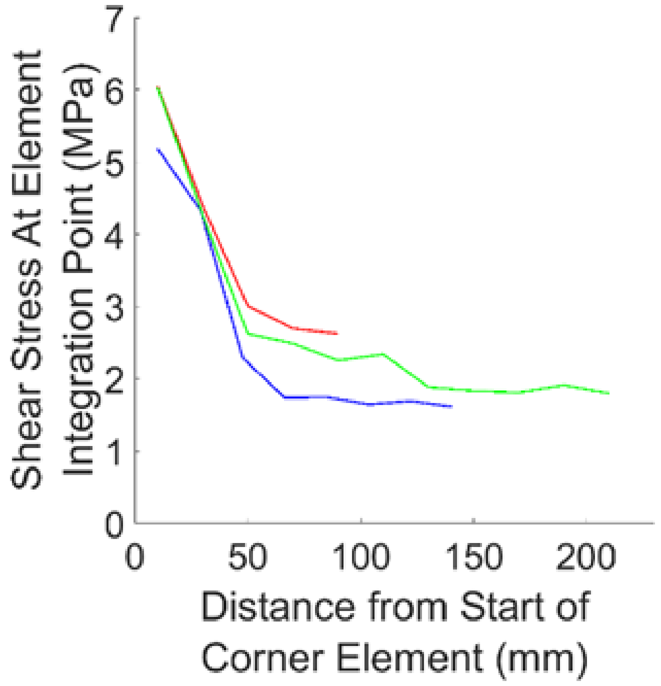


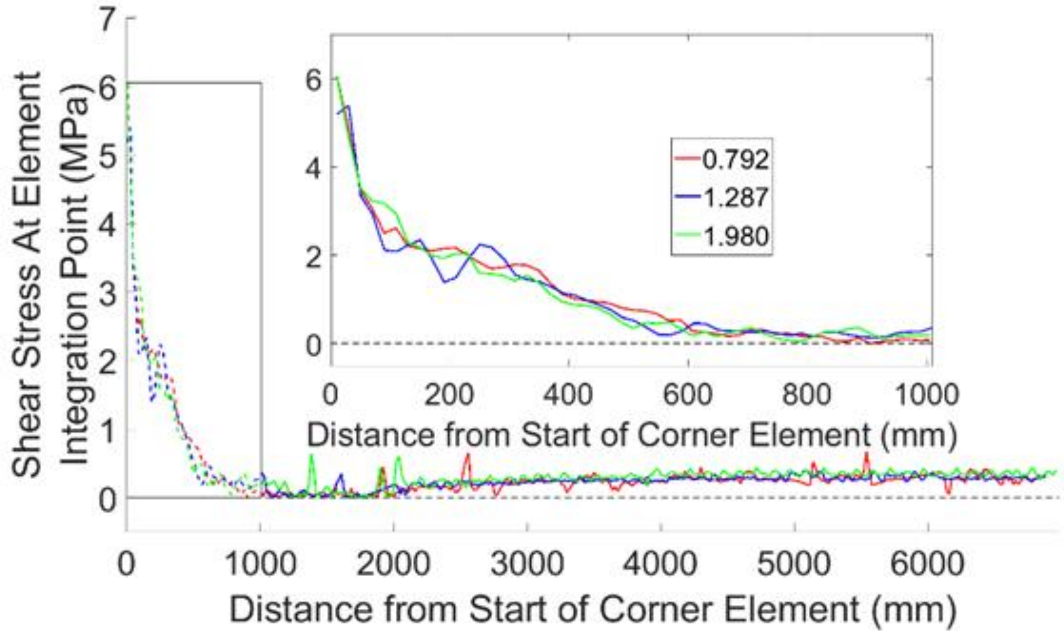
Crack Pattern on Tension Surface and Slab Side,
κ=0.792



Results - Concentric Load Study - V Study

Shear Stress Distribution At Failure Along Wall Perimeter for $\boldsymbol{\kappa}$=0.792, 1.287,1.980





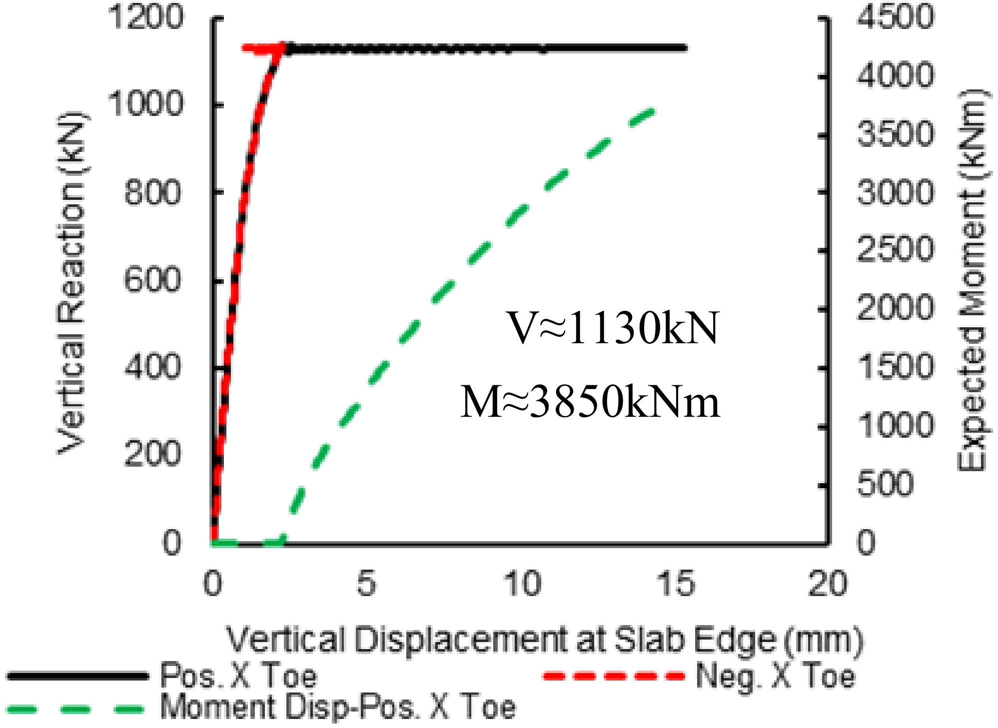
short side of the wall

long side of the wall

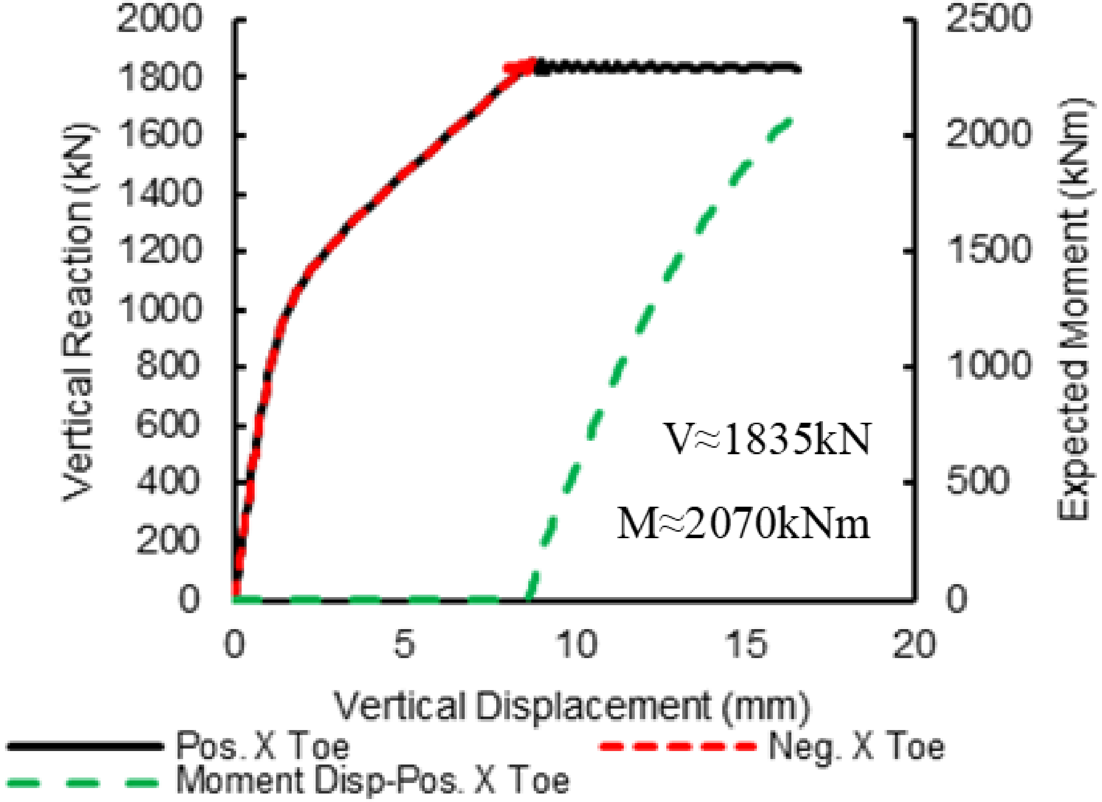
Results – Concentric Load + Unbalanced Moment : V+M Study

Load-Deflection and Moment-Deflection Response for κ=1.287

40% V_{conc}+M



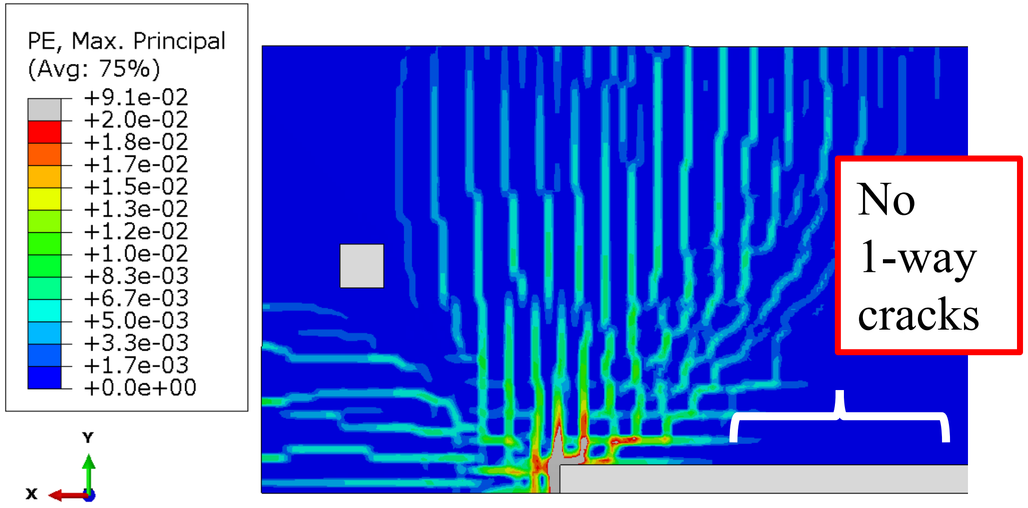
65% V_{conc}+M



ACI CONCRETE CONVENTION

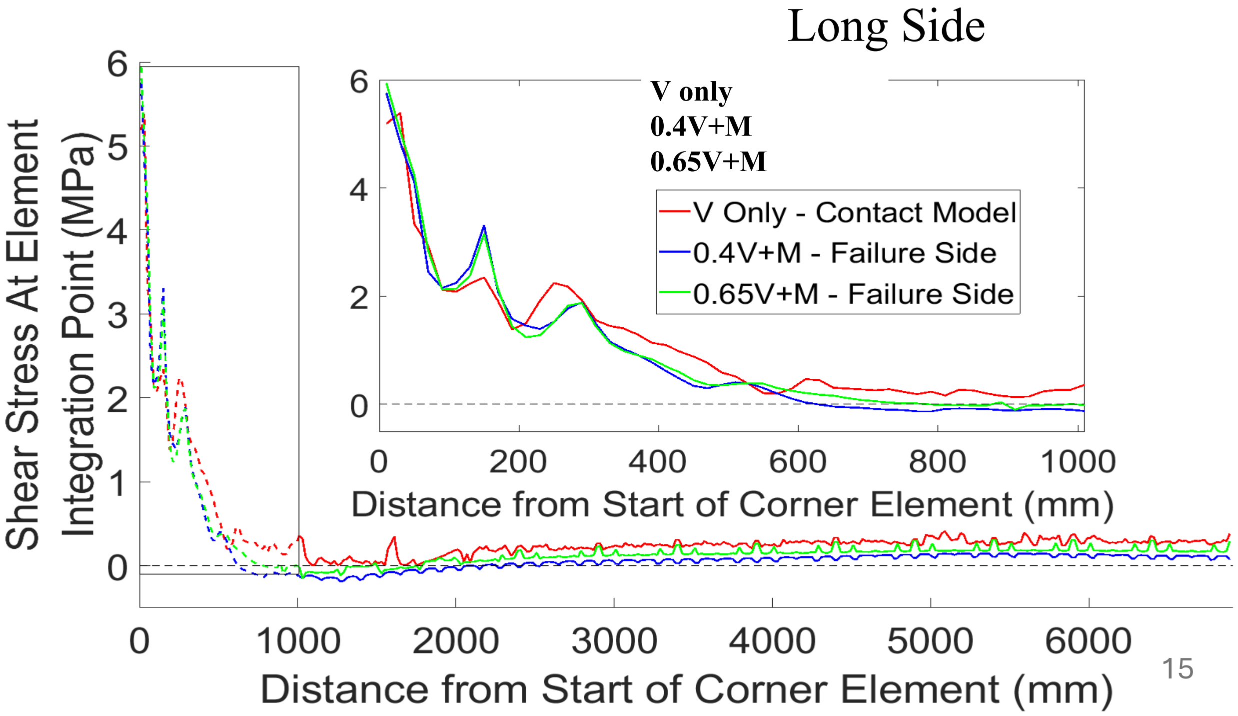
Results – Concentric Load + Unbalanced Moment - V+M study

- Crack pattern and shear distribution similar to vertical load only
- Punching failures occur at similar stress magnitude regardless of loading



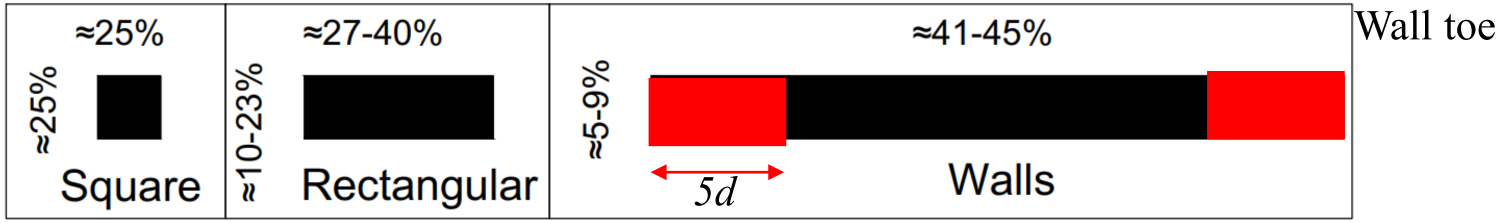
Top: Crack pattern at wall toe where stresses due to V+M are additive

Bottom: Shear Stress Distribution Along Wall Perimeter (same toe)



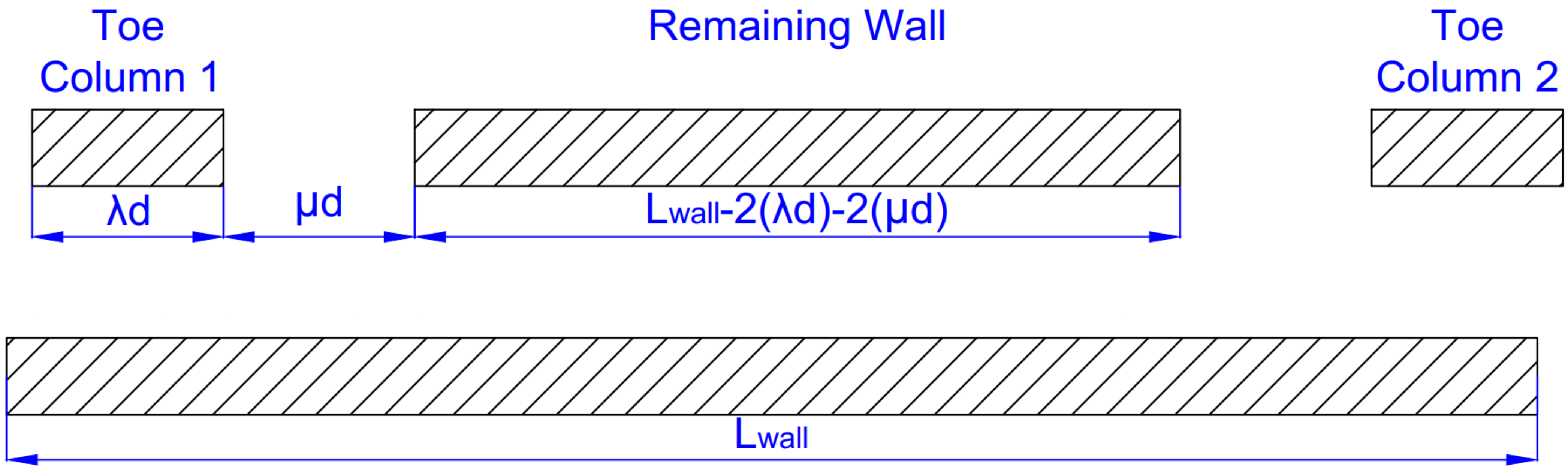
Wall Perimeter Shear Stresses – Concentric Loading - V Study

- As support becomes increasingly elongated more load is transferred along long side
- Approximately 50% of total load transferred through wall toe (region within *5d* of wall end)



Cut-Wall Study – Motivation

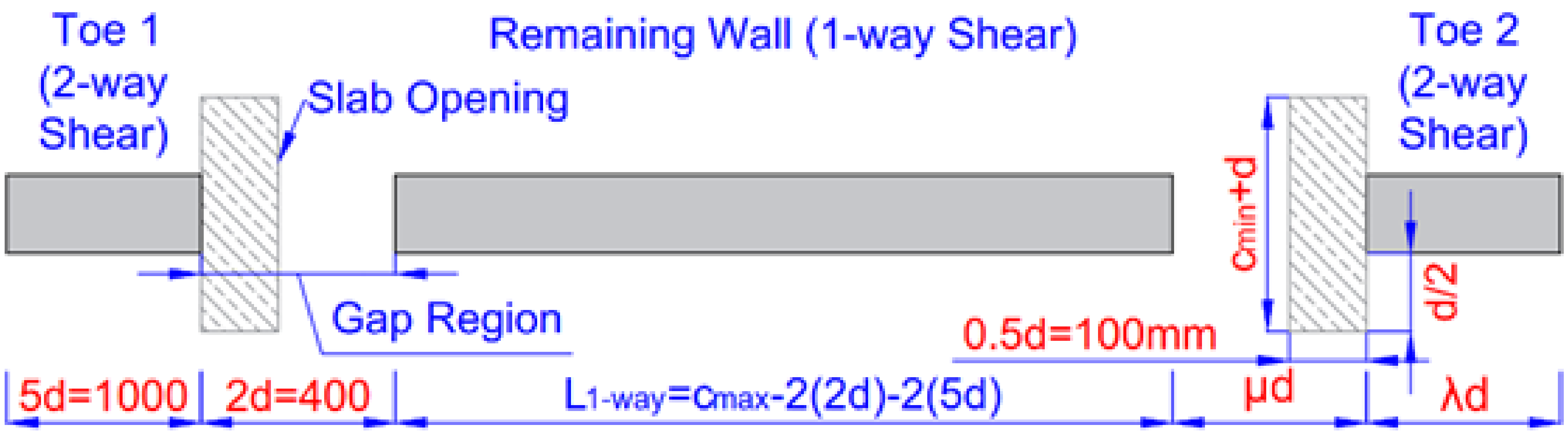
- Current commercial software packages cannot account for punching shear around wall toes
- Designers need a simple model/method to estimate punching capacity
- Use of a cut-wall model could potentially facilitate use of currently available software



Adopted Cut-Wall Model

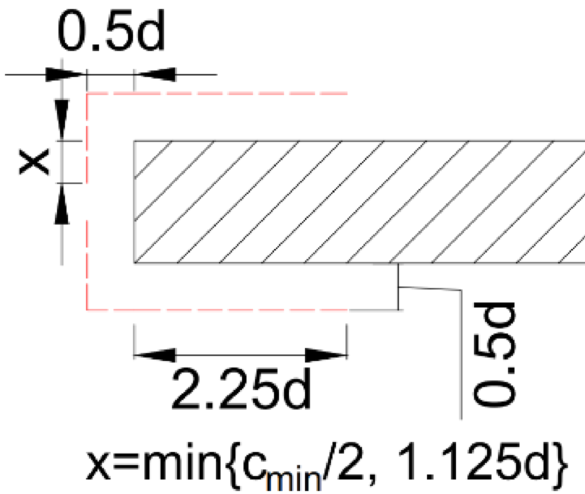
- The **toes length of *5d*** and the **gap of *2d*** best represent the full slab-wall connection.
- The opening to ensure that entire portion of the critical perimeter was removed.
- Proposed design methods neglect stresses in gap region

- Shows that a slab-wall connection can be designed by decomposing into
  - **two-way shear and one-way shear regions.**

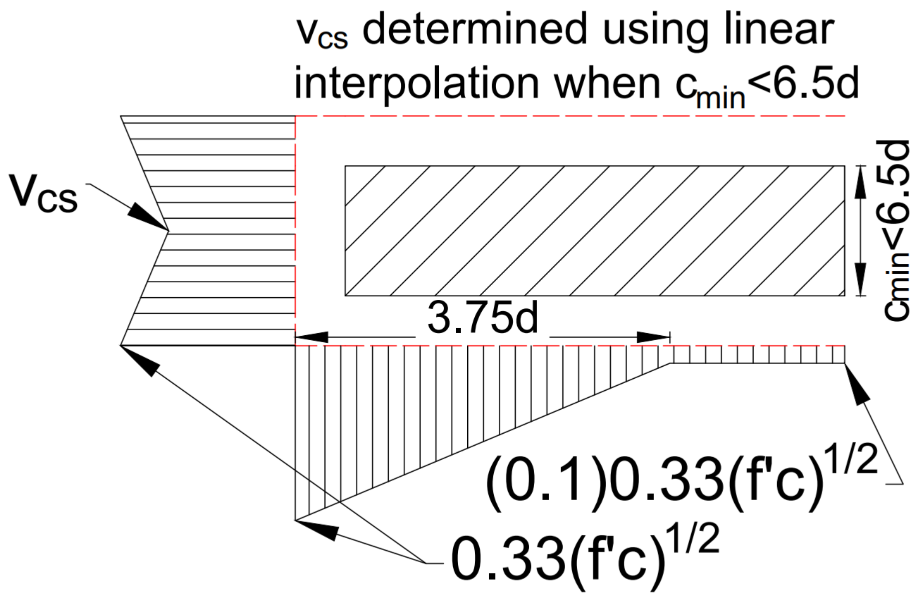


Two-Way Shear Region (Toe) Capacity – Proposed Methods

- Two methods proposed to estimate the punching shear capacity of the toe regions
- **Method 1W → Effective Critical Perimeter**
  - Effective perimeter concentrated at toe end corresponding to wall end
- **Method 2W → Linear Stress Distribution** (nonuniform stress distribution)
  - Same distribution as assumed for the design of rectangular columns
- Maximum stress of $0.33\sqrt{f_c'}$ in both methods (to match ACI 318)



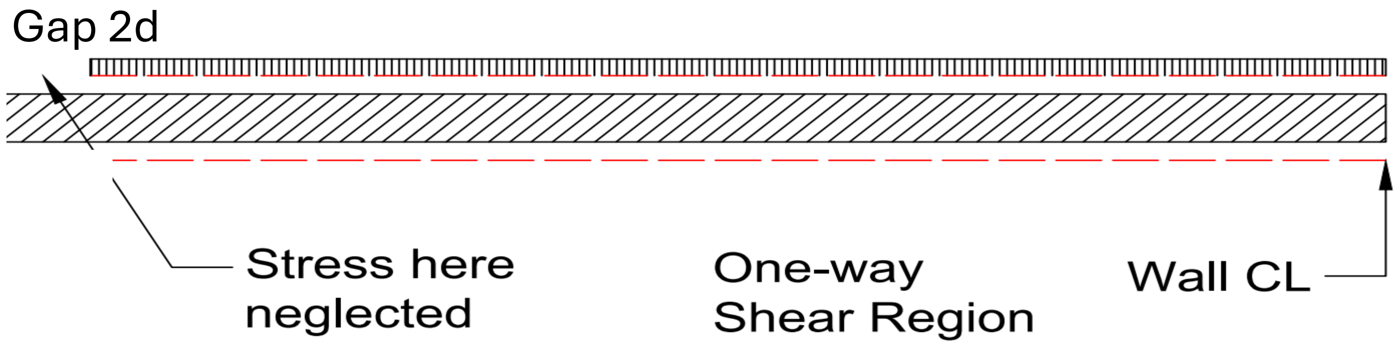
Method 1W (Effective Critical Perimeter)



Method 2W (Linear Stress Distribution)

One-Way Shear Capacity – Proposed Method

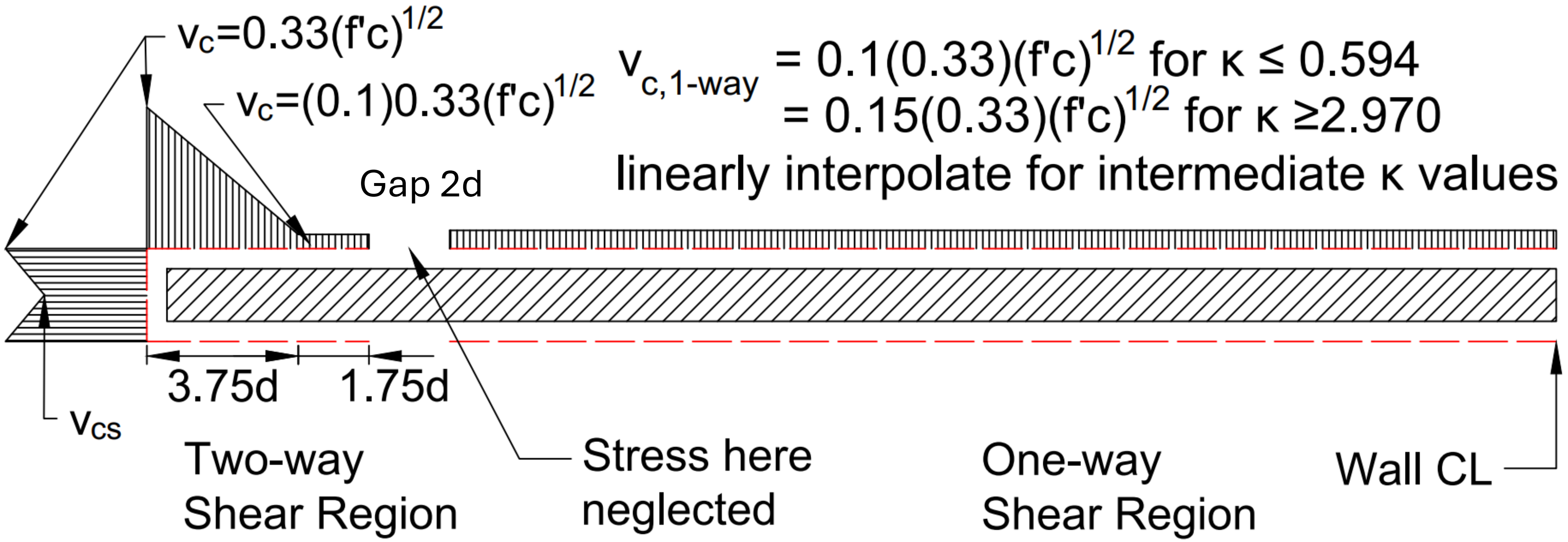
- Uniform distribution used to predict capacity of one-way shear region
- Design equations are presented in terms of **shear force, V**
  - Due to fact that SWC is decomposed into multiple regions



- $V_{1-way} = v_{c,1-way}(2L_{1,way})d$
  - $L_{1,way}$: length of one-way shear region ($c_{max} - 2(2d) - 2(5d)$)
  - $v_{c,1-way}$:
    - $0.1(0.33)\sqrt{f'_c} \rightarrow \kappa = 0.594$
    - $0.15(0.33)\sqrt{f'_c} \rightarrow \kappa = 2.970$
    - Linearly interpolate between these values

Design Methods Summary

- Design method applies to supports where $c_{max} \geq 14d$ (this limit is based on cut-wall model results)
- SWC decomposed into toe region (2-way shear) and remaining wall (one-way shear)
- Nonuniform distribution used to predict capacity of toe region



Summary of Proposed Design Method for SWCs – ½ Wall Shown

Predicted Capacities of Toe Two-Way Shear Regions

	Predicted Toe Load Capacity (kN)				V_{calc}/V_{FEA}		
κ	FEA (Full Wall)	ACI 318	Method 1W	Method 2W	ACI 318	Method 1W	Method 2W
0.792	1421	**1213**	1312	1093	0.85	0.92	0.77
1.287	1415	**1278**	1401	1160	0.90	0.99	0.82
1.980	1641	**1370**	1525	1245	0.83	0.93	0.76
				Avg.	0.86	0.95	0.78

ACI capacity based on aspect ratio of full slab-wall connections.

ACI capacity based on toe aspect ratio is overpredicted by 30%.

The cut-wall method cannot be directly used in commercial slab analysis programs, which would take the toe dimensions to calculate the predictions.

Predicted One-Way Shear Region Capacities

	Predicted One-Way Region Capacity (kN)			V_{calc}/V_{FEA}	
κ	FEA	ACI	Proposed	ACI	Proposed
0.792	1279	**5464**	1005	4.3	0.8
1.287	1349	**5588**	1115	4.1	0.8
1.980	1675	**5763**	1273	3.4	0.8
			Avg.	3.9	0.8

Predicted Punching Capacities for Interior Slab-wall Connections

	Wall Parameters			Predicted Punching Shear Capacity (kN)			
κ, c_{min}/d	Thickness, c_{min} (mm)	Length, c_{max} (mm)	Aspect Ratio, β	V_{FEA}, Full Wall	V_{FEA}, Cut Wall	V_{ACI}	**$V_{proposed}$**
0.792	160	13660	85.4	2700	2676	6677	**2097**
1.287	260	13760	52.9	2764	2765	6866	**2275**
1.782	360	13860	38.5	3149	3157	7056	**2450**

Conclusions – Finite Element Studies

- **ACI 318-19 result in unconservative** estimates of punching capacity of slab wall connections, compared to the FEA.

- The assumption of a uniform shear stress along the entire critical perimeter is incorrect.
- The shear stresses concentrate along the short side of the wall and near the wall corner along the long side.
- Punching shear failures of slab-wall connections can occur before one-way shear failures, but the predicted capacities are much higher than those expected in a typical structure.

  - **Punching shear failures are unlikely in the absence of extremely large, concentrated loads or significant slab openings in the vicinity of the wall toe.**

Conclusions – Design Methods

- 40-50% of the total gravity load is transferred through the toe regions.
- **a two-way** shear region near the wall toes and a **one-way** shear region, considered separately
- Two possible methods for two-way shear regions:
  - **Method 1W – effective critical perimeter and a constant nominal shear stress**
  - **Method 2W - nonuniform shear stress n along the critical perimeter.**
- The **one way shear region- a constant shear stress, which is dependent on κ** ($\kappa = c_{min}/d$).

- The proposed design methodology provides reasonable and conservative capacities of the slab-wall connections.

Acknowledgements

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