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Influence Of Slab Openings On The Punching Shear Behaviour Of Reinforced Concrete Slabs Supported On L-shaped Columns

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Punching Shear of Concrete Slabs: Insights from New Materials, Tests, and Analysis, Part 1 of 2
Tuesday, April 4, 2023, 8:30-10:30am
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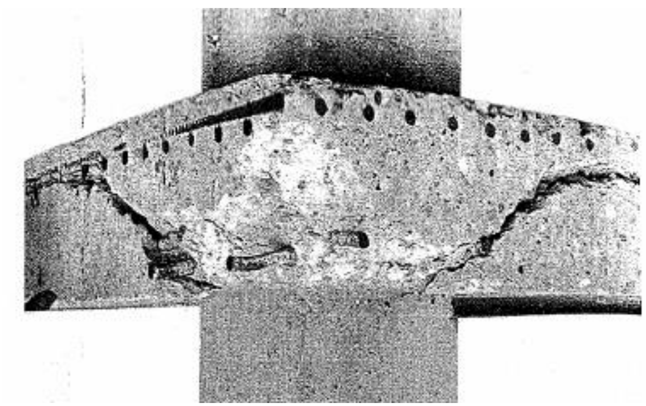
Outline

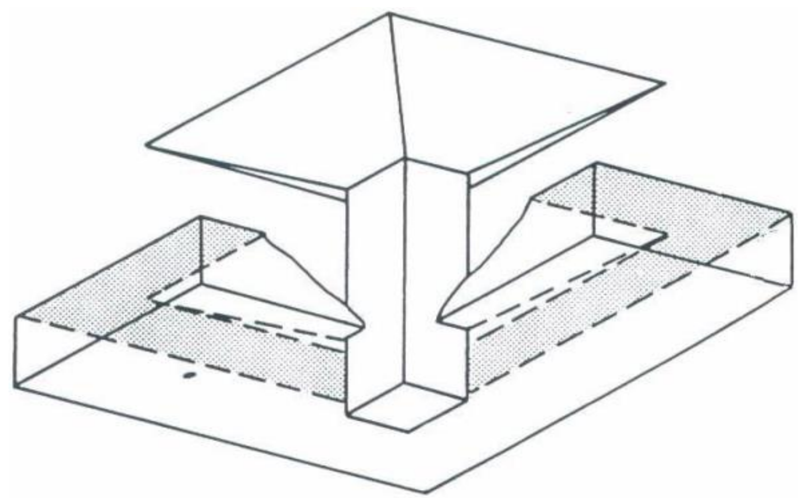
1. Introduction
2. Study Overview
3. FEM Calibration
4. Results – Aligned Column Study
5. Conclusions

What is Punching Shear?

- Brittle failure mode of reinforced concrete slabs
- Can cause progressive collapse
- Occurs due to inclined cracks extending into compression zone



Inclined cracks after punching failure [1]



Punching shear failure surface [1]

Advantages of Finite Element Analysis

- Experimental database of slab-column connections with different geometries limited
- Nonlinear finite element analysis (NLFEA) can be used to supplement database
  - Allows for cost-effective analysis of parameters
  - Can provide insight into structural behaviour

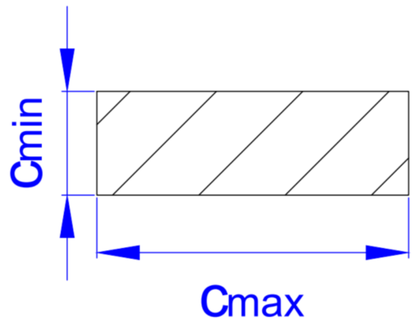
Careful calibration of model parameters required!

Research Significance

- Provisions for special-shaped slab-column connections (SS-SCCs) included in worldwide codes [2, 3, 4]
  - Extremely limited experimental database [5, 6, 7]
- ACI 318-19 [2] definition of β leads to higher nominal shear capacities around special-shaped columns compared to rectangular columns
- No limit on diagonal portion of critical perimeter

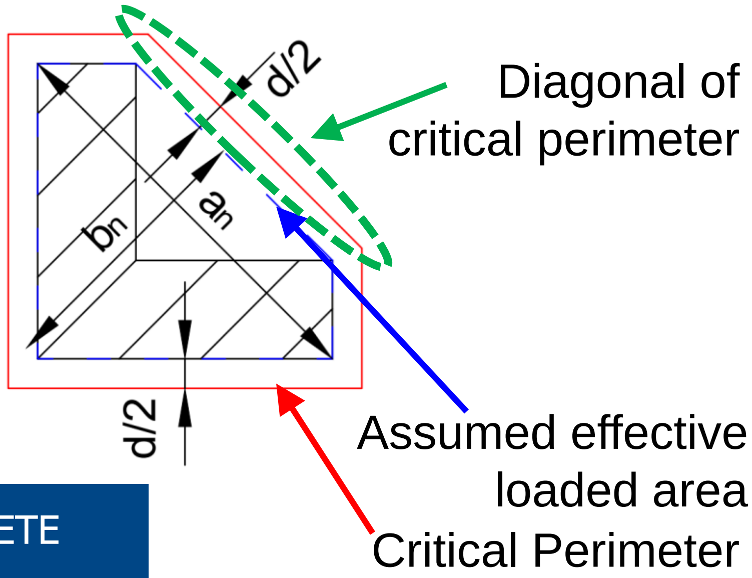
Rectangular:

$$\beta = c_{max}/c_{min}$$



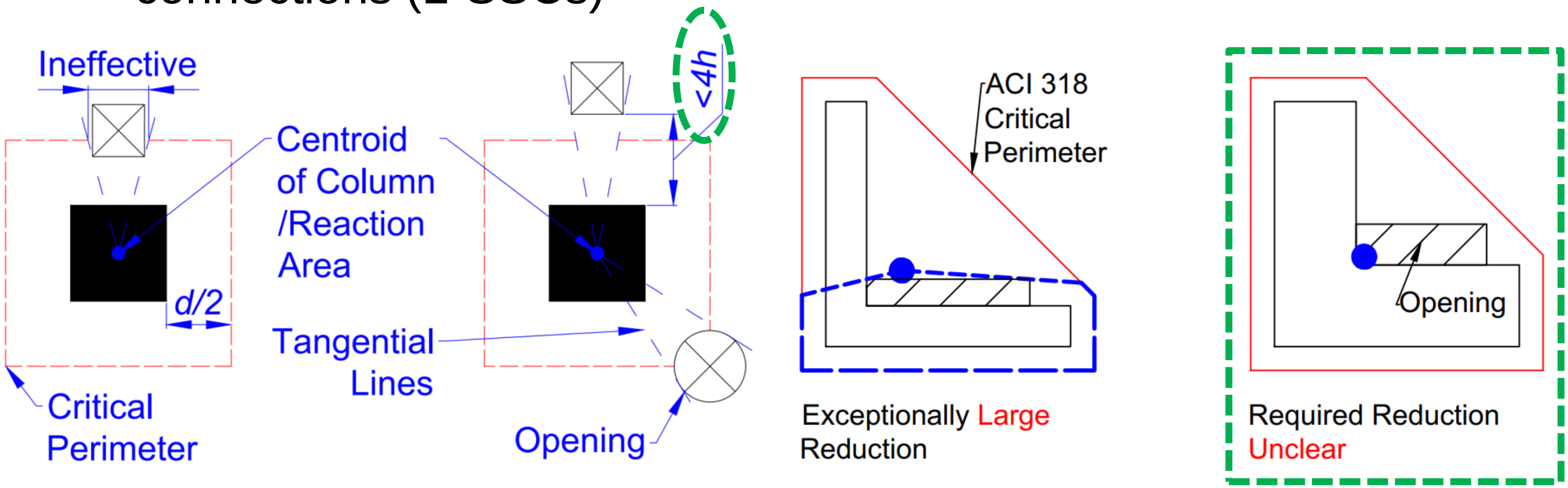
L shape:

$$\beta = a_n/b_n$$



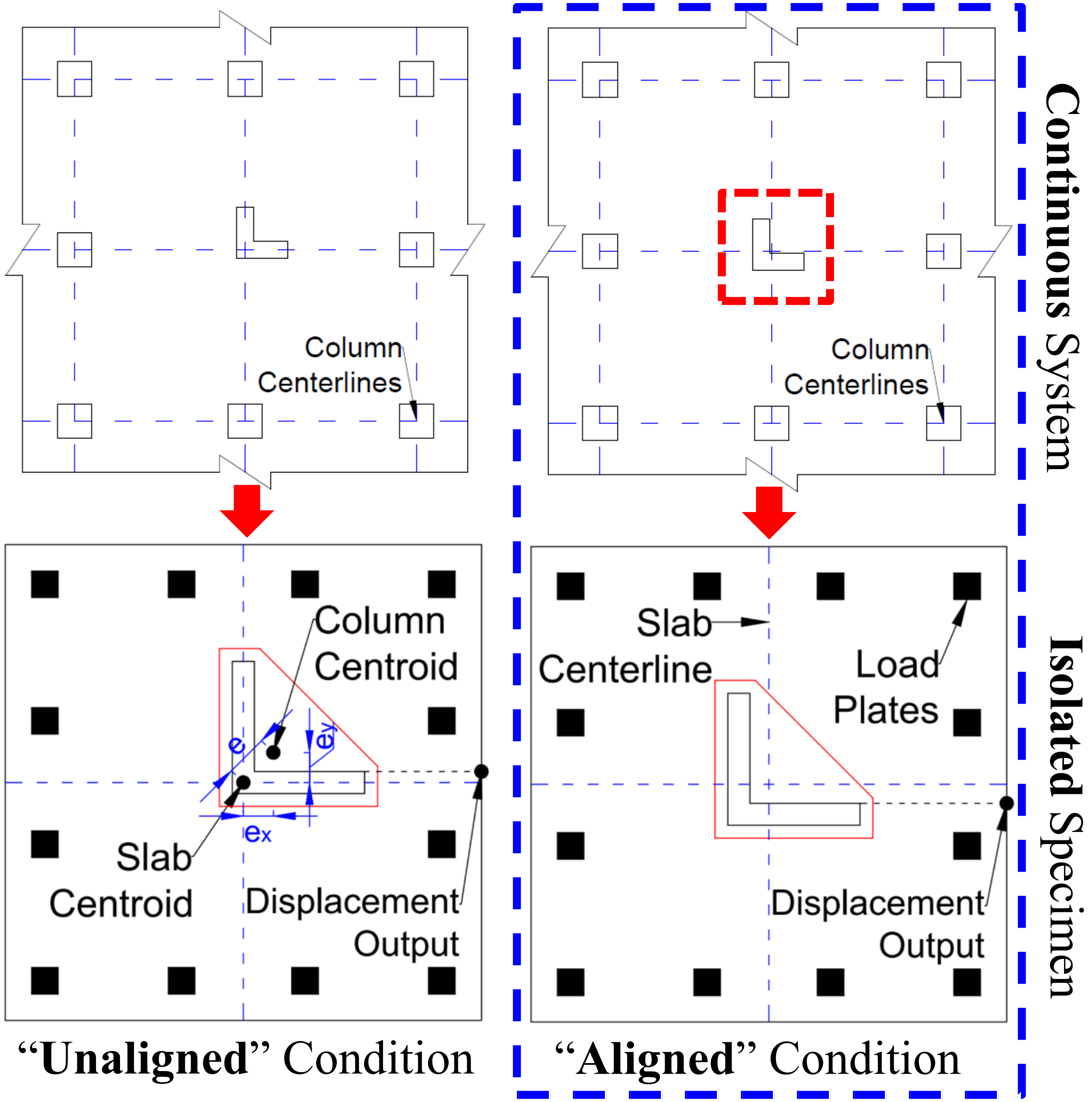
Research Significance

- Opening provisions in ACI 318 are largely unchanged since 1971
- Neglect portion of critical perimeter bounded by tangential lines from column centroid
  - Can result in large reductions for openings between flanges of SS-SCCs, or unclear reductions for L-shaped slab-column connections (L-SSCs)



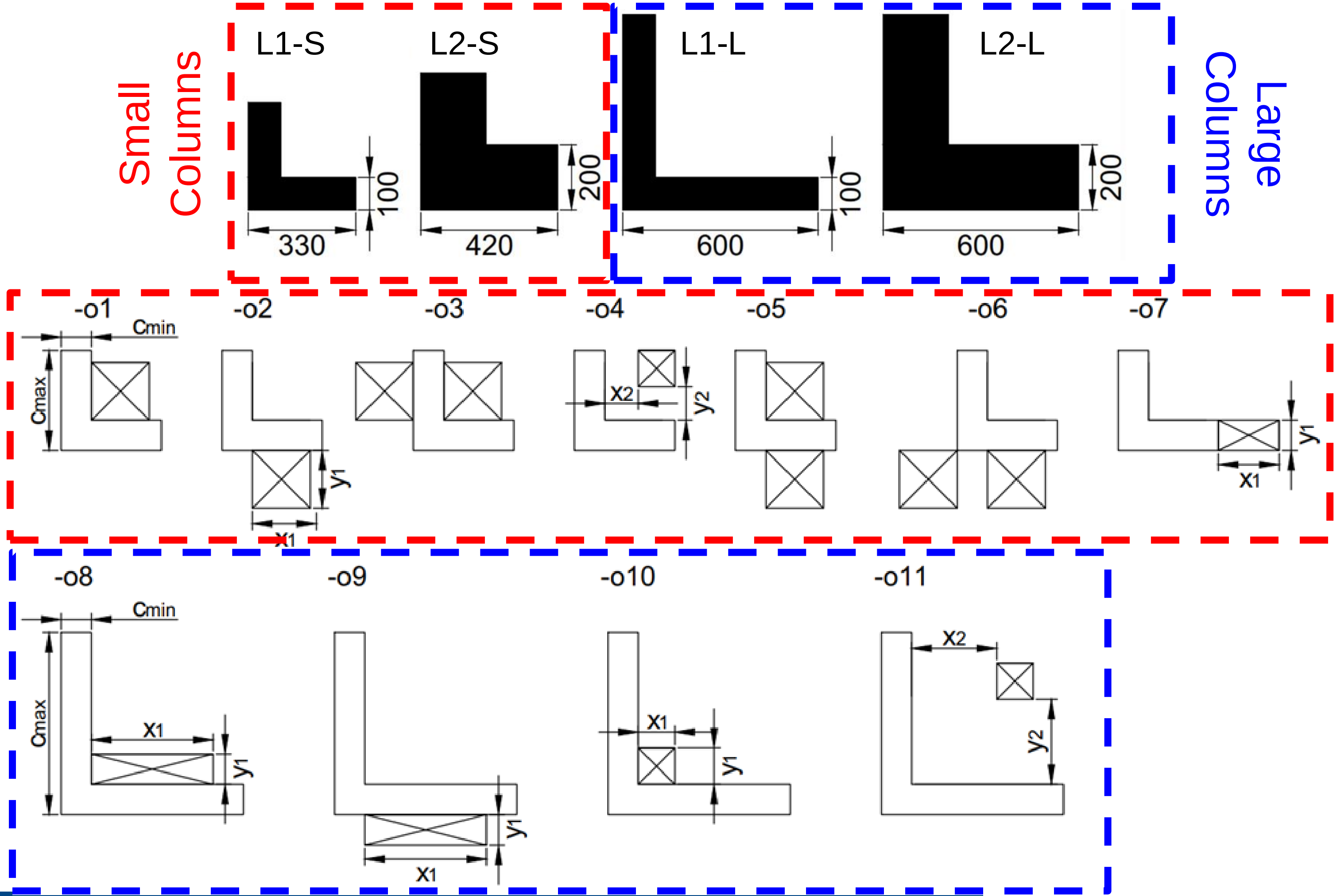
Column Location

- Column and slab centroids aligned in analyzed isolated specimens
- Small eccentricities exist for mesh uniformity (minor impact on results)



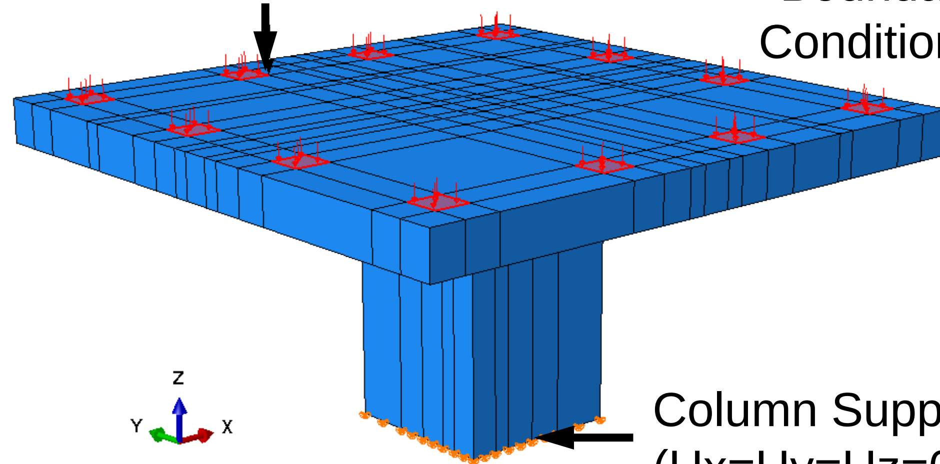
Column Sizes and Opening Layouts

- 4 column sizes and 11 opening layouts investigated



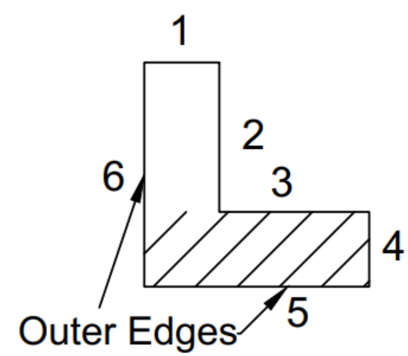
Specimen Naming and Boundary Conditions

- Study parameters:
  - Column size;
  - Slab openings
- Multiple opening locations studied to determine ideal location of openings



L2-S-o1

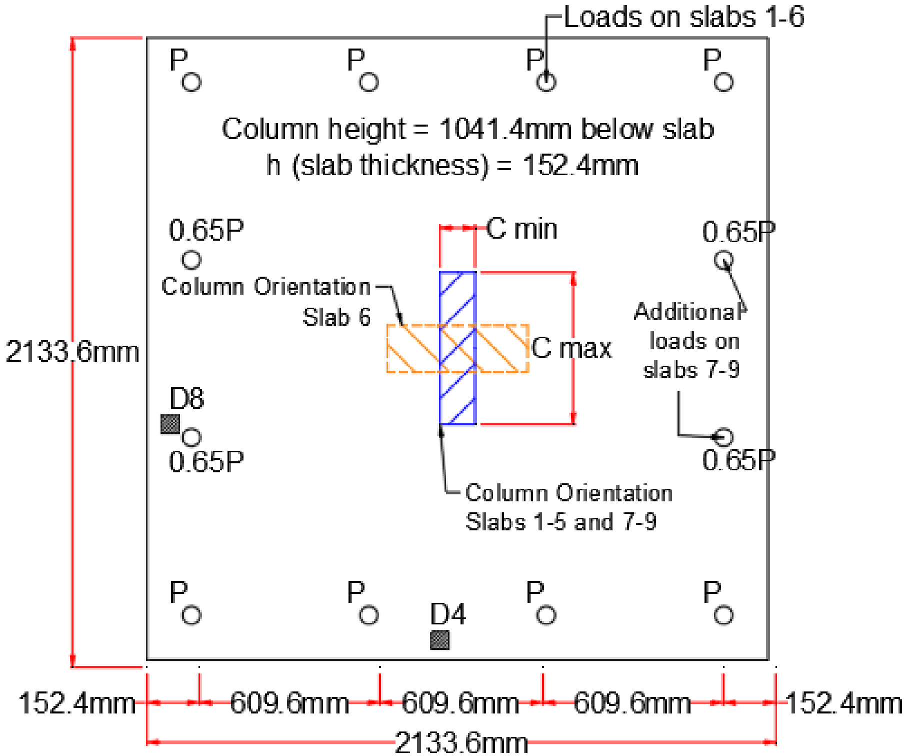
- Opening layout; -0 = No opening
- S: Small Column; L: Large Column
- Column flange thickness: 1=100mm; 2=200mm;
- Column geometry: L: L-shape



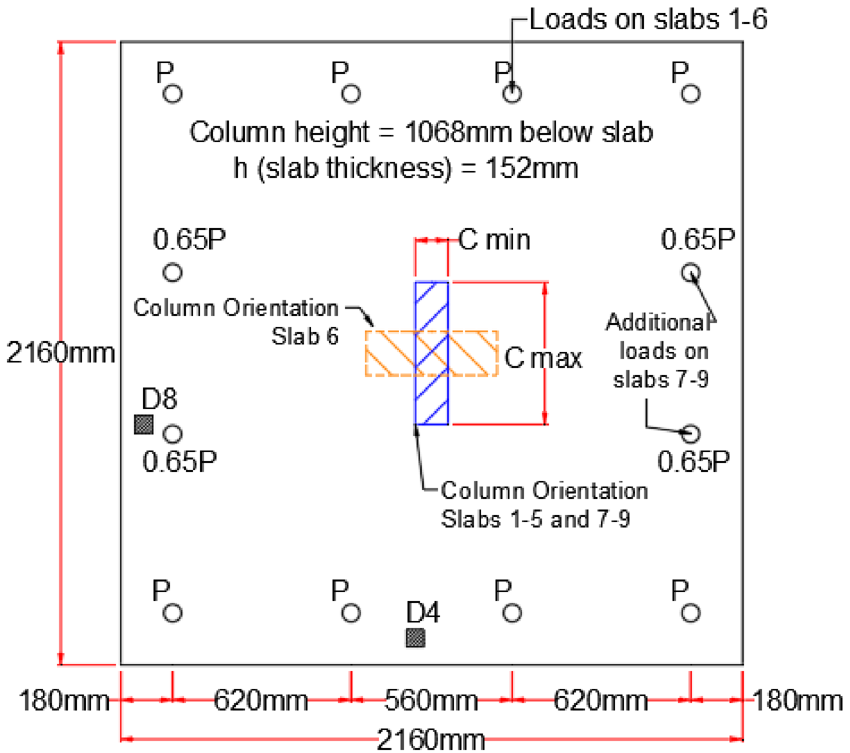
Column flange definition and side numbering

FEM Calibration – Experimental Specimens

- 9 tests by Hawkins et al. [8] to study impact of column rectangularity on punching used for calibration
- Experimental dimensions modified slightly for L-SCCs



Original Slab Dimensions



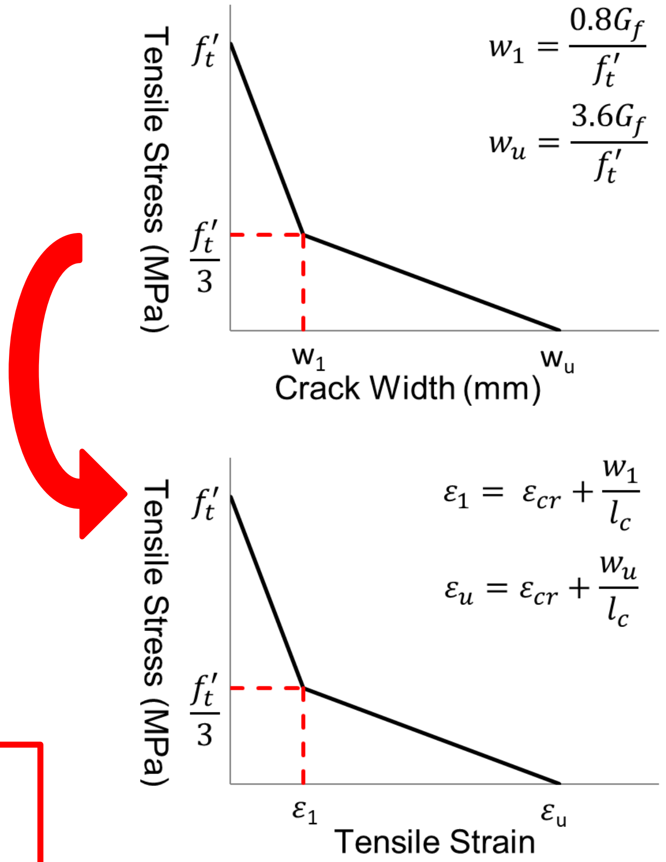
Modified Slab Dimensions

FEM Calibration – CDP Parameters

- 3D, nonlinear finite element analysis implemented in Abaqus/Explicit
- Concrete Damaged Plasticity (CDP) Model used for concrete

Concrete Damaged Plasticity Model Parameters: Dilation Angle – 42°, Eccentricity – 0.1, σ_{bo}/σ_{co} – 1.16, K_c – 0.67
Uniaxial Compression Model: Hognestad Parabola, $E_c - 5000\sqrt{f_c'}$ (MPa), $\nu - 0.2$
Uniaxial Tensile Model: Bi-linear tensile stress-crack width [9], G_f – 0.08N/mm
Element Details: Concrete – C3D8R (20mm), Rebar – T3D2 (20mm)

Average of all 9 slabs



Overview of Assumed Tensile Behaviour for Concrete

FEM Calibration – Comparison to Experiments

- FEM accurately predicts experimental capacities
- Modifications to dimensions have minor change on predictions for Hawkin's et al. [8] slabs

Max underprediction: 15.1% (slab 1)

Max overprediction: 2.0%

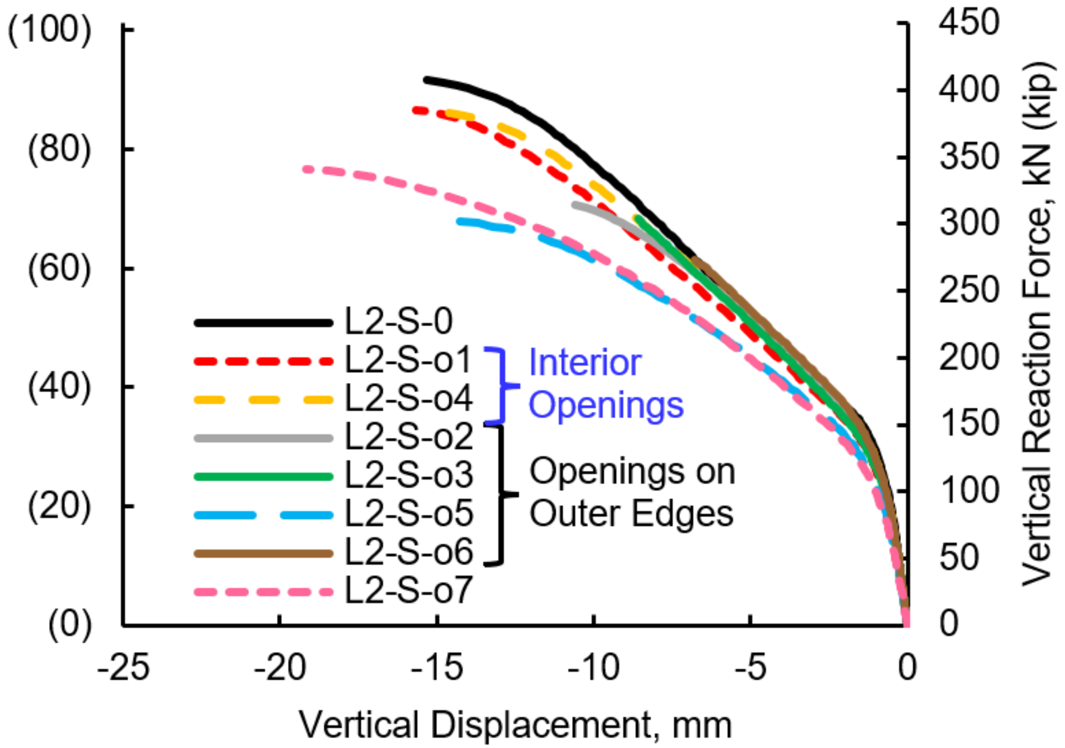
Average Error: -6.7%

Slab	Column Dimensions c_{max} (mm)	c_{min} (mm)	V_{exp} (kN)	$V_{FEA}^{(a)}$ (kN)	$V_{FEA}^{(b)}$ (kN)	% Difference
1	304.8	304.8	383.9	326.0	336.8	3.28
2	203.2	406.2	351.4	331.3	332.2	0.25
3	152.4	457.2	333.2	339.9	351.8	3.48
4	114.3	495.3	330.5	331.8	337.2	1.63
5	152.4	457.2	355.0	325.8	332.6	2.09
6	152.4	457.2	335.8	300.9	308.2	2.43
7	152.4	457.2	319.8	297.7	307.3	3.24
8	114.3	495.3	314.5	292.5	298.4	2.03
9	152.4	304.8	315.4	285.0	287.7	0.94

$V_{FEA}^{(a)}$ – Original Dimensions, $V_{FEA}^{(b)}$ – Modified Dimensions

Predicted Load-Displacement Responses

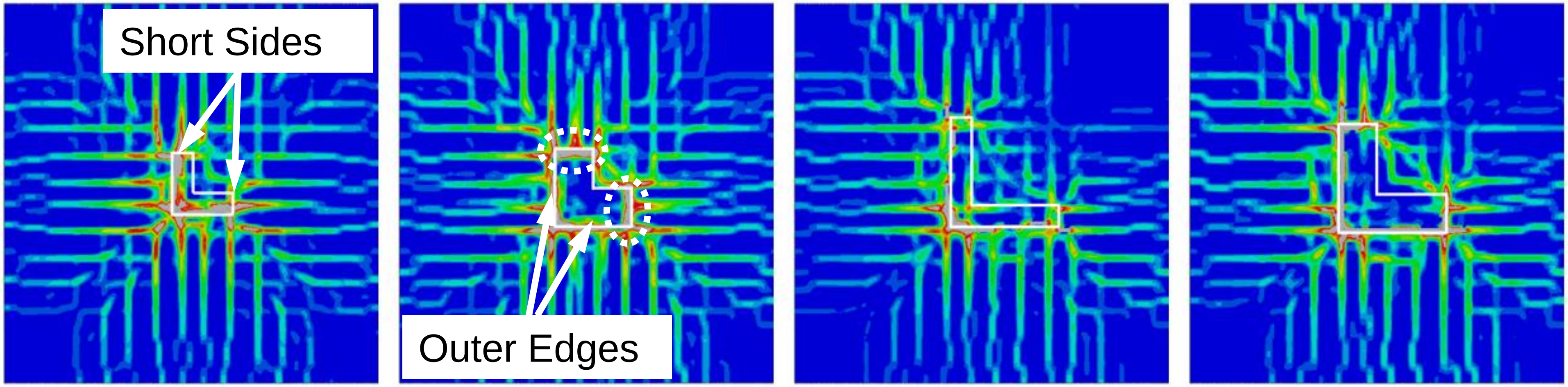
- Openings reduce connection capacity and stiffness
- Impact is dependent on distance from column, and location with respect to column (i.e. where around the column opening is located)



Openings between flanges have minor impact on concentric behaviour of L-shaped connections

Predicted Crack Patterns – Without Openings

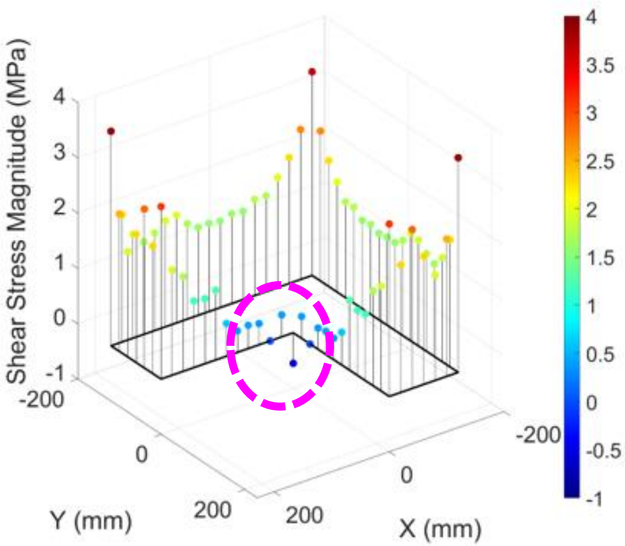
- Substantial cracking on outer edges of connection
  - Significant amount of load transferred along outer edges
  - One-way shear is significant in these areas
- Crack concentrations predicted near short sides of column flanges



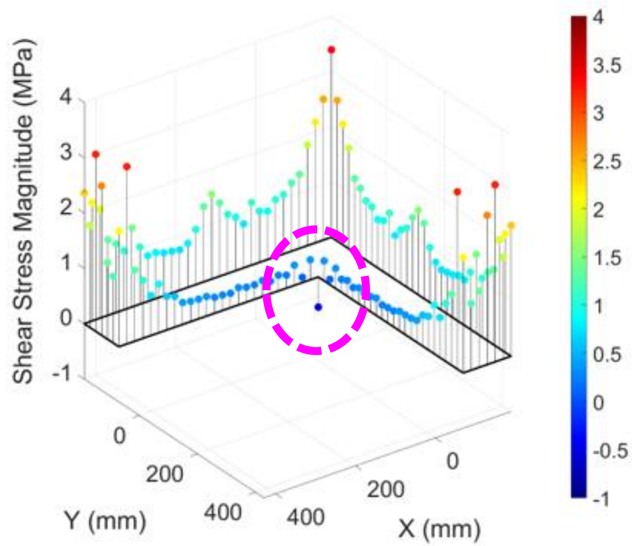
L1-S-0 L2-S-0 L1-L-0 L2-L-0

Column Perimeter Shear Stress Distributions

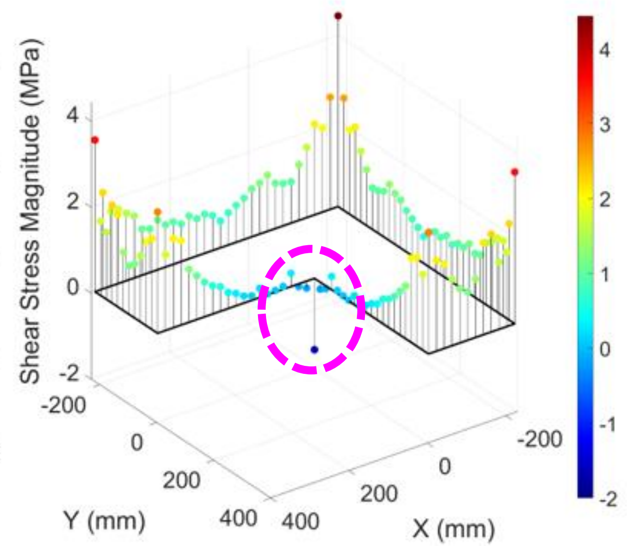
- Column perimeter shear stresses are nonuniform
  - Confirm that all column sides are not equally effective
- Peak shear stresses occur at exterior corners
- Minimum shear stresses near interior corner



L1-S-0



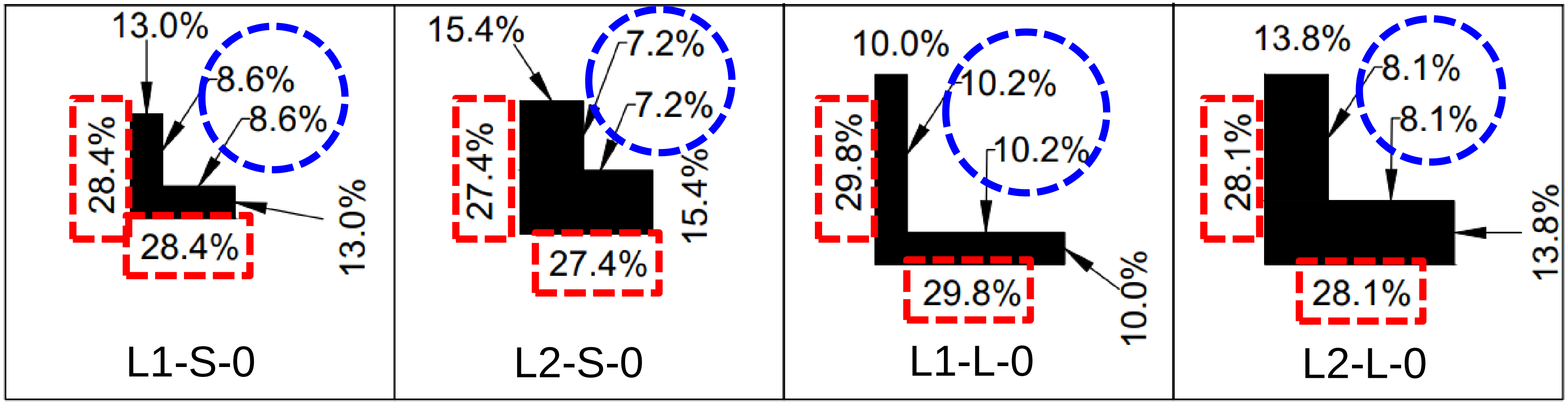
L1-L-0



L2-L-0

Column Perimeter Shear Force Distribution

- Outer edges of L transfer majority of load
- Region between column flanges is relatively ineffective
  - Hence why openings between the column flanges have minimal impact



Results correspond to specimens without openings

Comparison of FEA and ACI Predictions

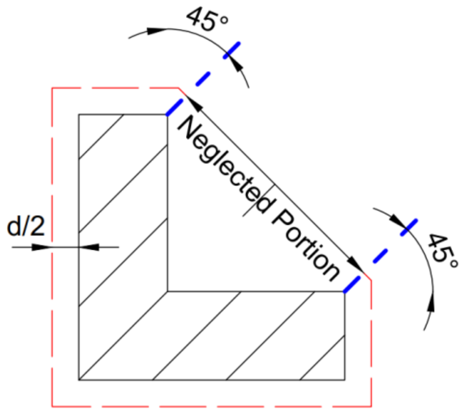
- ACI provisions (318-19 and 421.1R-20) overpredict influence of openings between the column flanges
- 318-19 [2] concentric provisions overpredict capacity of L1-L and L2-L specimens
- 421.1R-20 [9] can be used to conservatively predict concentric punching capacity

ID	$\frac{V_{ACI}}{V_{FEA}}$	$\frac{V_{421}}{V_{FEA}}$	Opening Impact FEA	Opening Impact 318	Opening Impact 421.1R-20
L2-S-0	1.04	1.03	-	-	-
L2-S-o1	0.89	0.74	-5.4	-19.1	-31.4
L2-S-o2	1.18	1.02	-22.9	-13.0	-23.2
L2-S-o3	0.95	0.76	-25.5	-32.1	-44.9
L2-S-o4	1.03	0.99	-6.0	-7.3	-9.6
L2-S-o5	0.95	0.76	-25.8	-32.1	-44.9
L2-S-o6	1.17	0.87	-33.1	-24.8	-43.6
L2-S-o7	1.09	0.93	-16.3	-12.4	-24.0

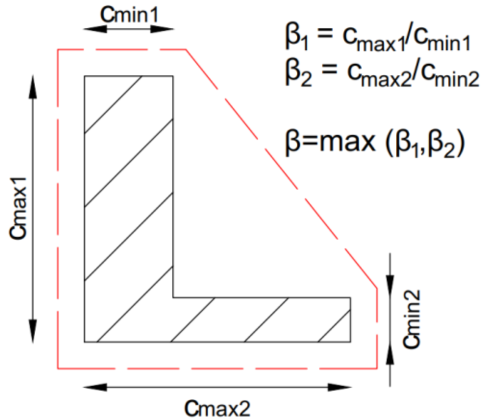
ID	$\left(\frac{V_{ACI}}{V_{FEA}}\right)_{avg}$	$\left(\frac{V_{421}}{V_{FEA}}\right)_{avg}$
L1-S	1.07	0.84
L2-S	1.04	0.89
L1-L	1.35	1.07
L2-L	1.20	1.06

Proposed Modifications to ACI 318

- While ACI 421.1R-20 method is accurate, it is not suitable for preliminary design
- Use of two modifications to concentric provisions investigated
- Neglecting diagonal portion of critical perimeter results in typically conservative punching capacity estimates



Modification 1: Neglecting Diagonal Portion of Critical Perimeter



Modification 2: Redefining β as Maximum of all Column Flanges

ID	$\left(\frac{V_{mod1}}{V_{FEA}}\right)_{avg}$	$\left(\frac{V_{mod2}}{V_{FEA}}\right)_{avg}$
L1-S	0.79	0.88
L2-S	0.91	1.04
L1-L	0.96	0.95
L2-L	0.95	1.07

Conclusions

- Openings reduce connection capacity and stiffness
- Openings between column flanges of L-shaped slab-column connections (L-SCCs) have a minor impact on concentric behaviour
- Majority of force is transferred along outer edges of L-SCCs
  - Significant amount of load is transferred via one-way shear in these areas
- Region between column flanges is relatively ineffective for L-SCCs

Conclusions

- ACI 318-19 provisions are inaccurate for L-SCCs
  - Capacity of L1-L and L2-L specimens significantly overpredicted
  - Influence of openings between column flanges overpredicted (or unclear in some cases)
- Concentric capacity of L-SCCs can be estimated using concentric provisions if diagonal portion of critical perimeter neglected
- ACI 421.1R-20 can be used to estimate concentric punching capacity of L-SCCs

Acknowledgements

- Thank you to those who have supported this research
  - Natural Sciences and Engineering Research Council of Canada (NSERC)
  - Government of Ontario
  - University of Waterloo

NSERC
CRSNG

Ontario

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Questions?