Recommendations for Durability and Seismic Design of an External Socket Connection in Steel Bridge Substructures

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PhD Final Oral Examination

Committee:
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NC STATE UNIVERSITY

Acknowledgements

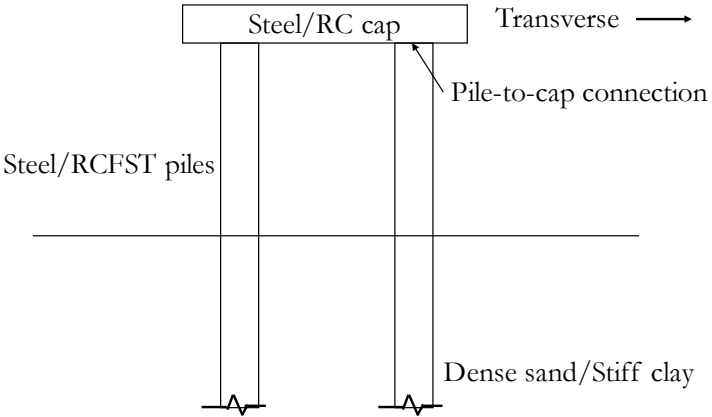
- Alaska Department of Transportation and Public Facilities
- NCSU Department of Civil, Construction, and Environmental Engineering
- Constructed Facilities Laboratory
- Committee Members
- CCEE Graduate and Undergraduate Students

Steel piles/columns supported structures

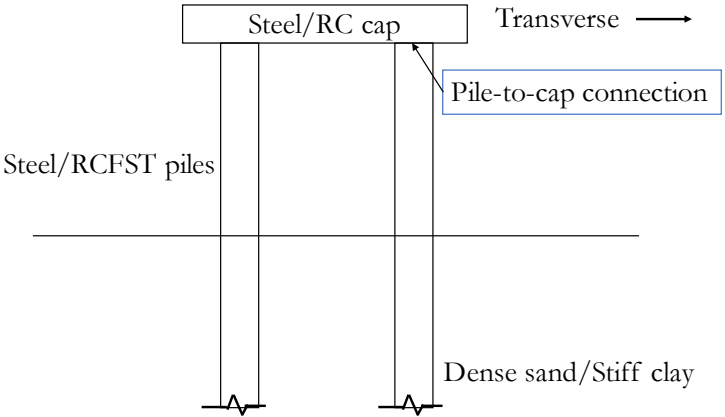
Bridges in Alaska

Source: Alaska Department of Transportation and Public Facilities

A typical bridge pier

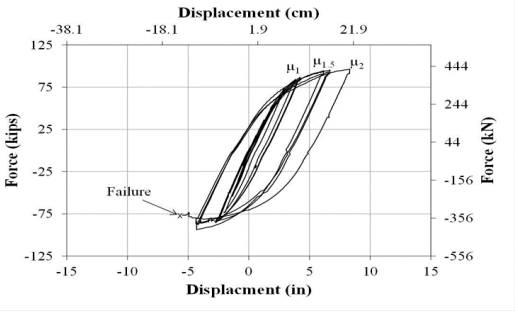


A typical bridge pier



Problem with directly welded connection

Brittle Failure



Hysteresis

Fulmer (2010)

Solution: The Grouted Shear Stud (GSS) Connection

Constituents of the GSS connection

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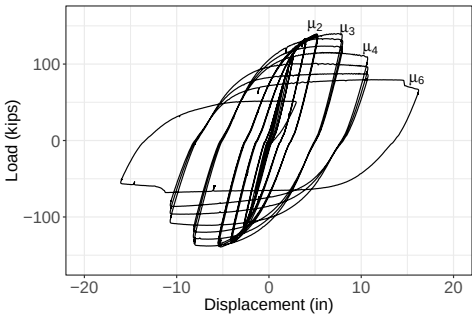
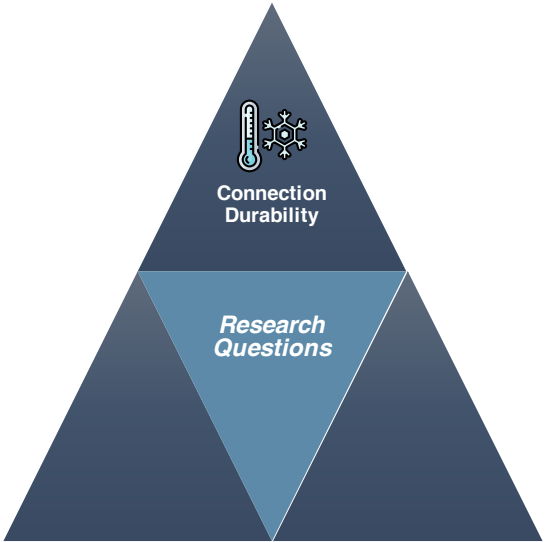


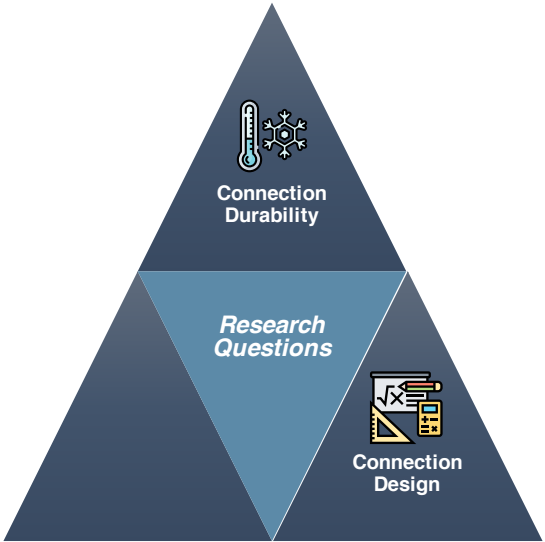
Solution: The Grouted Shear Stud (GSS) Connection

Solution: The Grouted Shear Stud (GSS) Connection

Large ductility capacity and desirable failure mode.


Research
Questions


Connection
Durability
Research
Questions


Connection
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Connection
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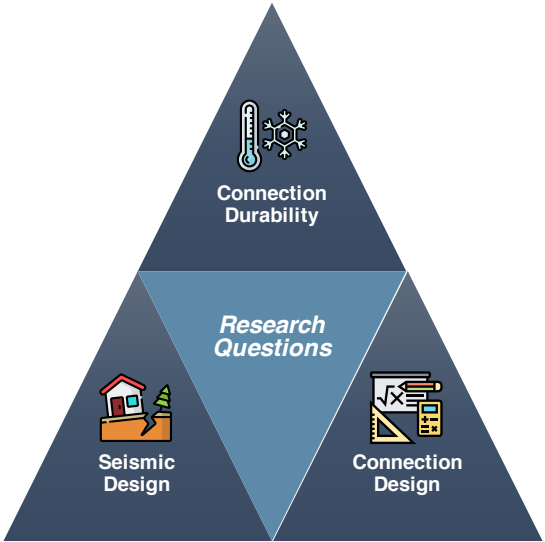
Connection
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Research
Questions
Seismic
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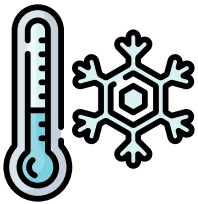
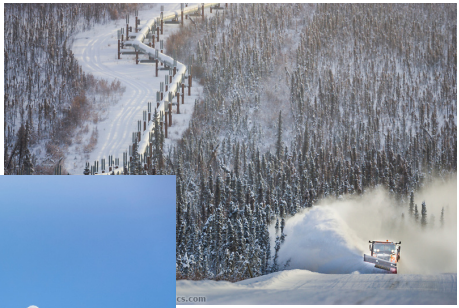
Connection
Design

Durability



What do I mean by durability



Alaska in winter

Source: alaskaphotographics.com

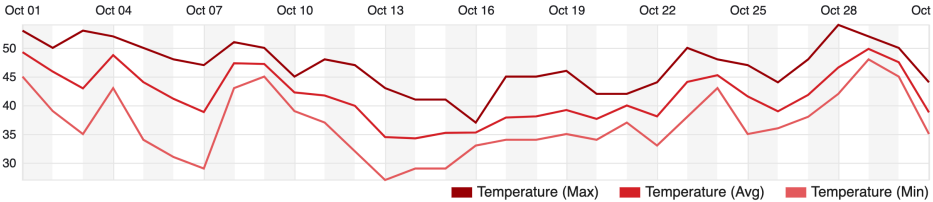
What do I mean by durability

Alaska in summer

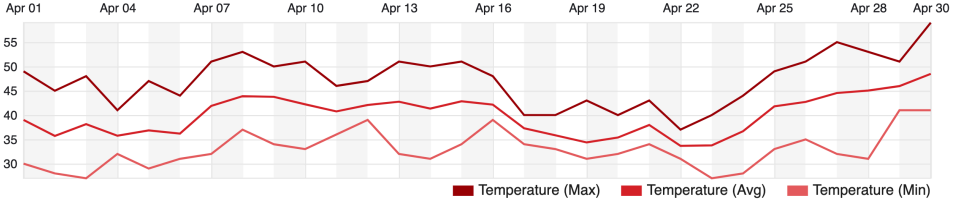
Source: alaskaphotographics.com

What do I mean by durability

October



April



Temperature cycles during transition periods in Anchorage, Alaska.

Source: wunderground.com

What do I mean by durability

Examples of Freeze and Thaw Damage in Concrete

What do I mean by durability

Freeze and Thaw Damage in Grout

Definition: The ability of the GSS connection to serve its primary function under exposure to cold-climates.

Definition: The ability of the GSS connection to serve its primary function under exposure to cold-climates.

Objective: To ascertain if the GSS connection is durable

Breaking the problem down to...

The GSS connection is durable if

Breaking the problem down to...

The GSS connection is durable if

The cementitious grout is resistant to freeze and thaw damage.

or

Breaking the problem down to...

The GSS connection is durable if

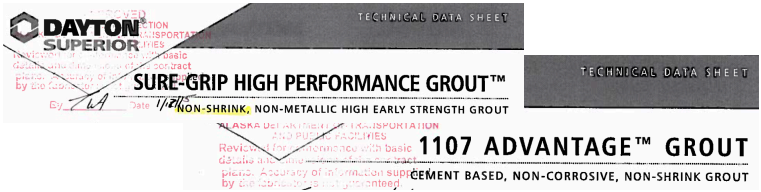
The cementitious grout is resistant to freeze and thaw damage.
or
If grout deterioration does not impact connection performance.

Grout Durability

Grout Durability

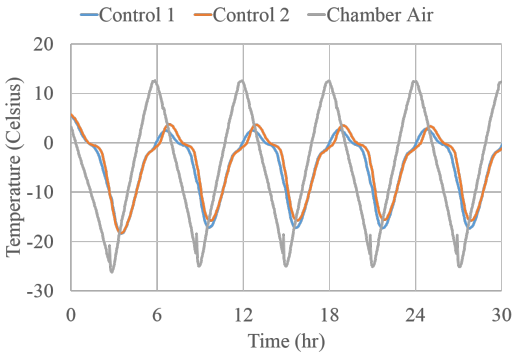
MasterFlow® 928

High-precision mineral-aggregate grout with extended working time



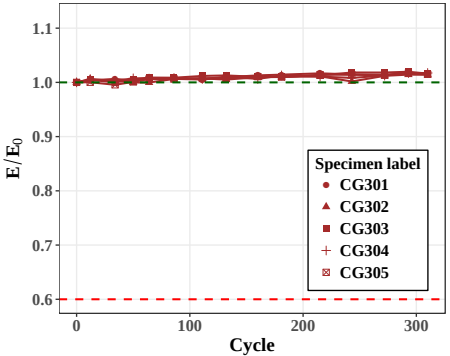
Grout Durability

Elastic modulus measurement

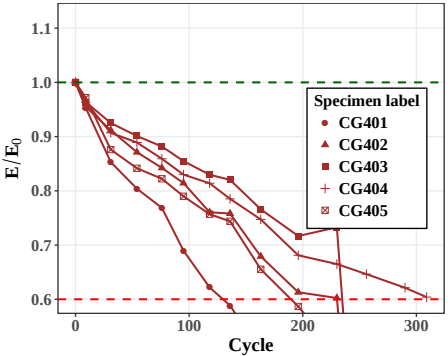


Sample daily temperature profile

Grout Durability



Durability Factor = 100



Durability Factor = 46

Grout Durability

Comparison of freeze-thaw damage among different manufacturers

Grout Durability

Conclusion: Resistance of cementitious grouts to freeze and thaw is highly variable.

Does grout deterioration impact connection performance?

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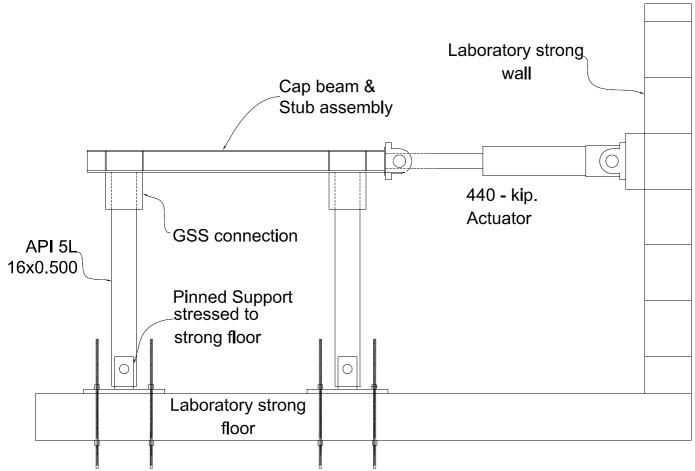
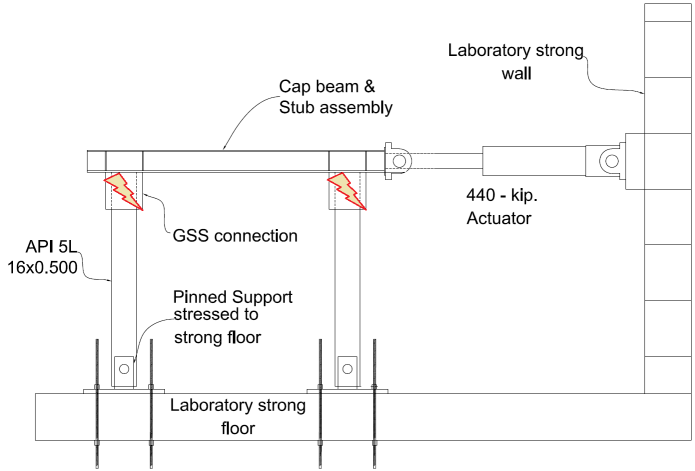


Test 1

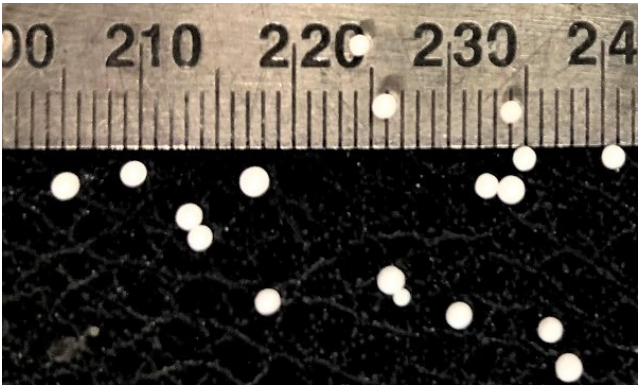
Does grout deterioration impact connection performance?



Test 2

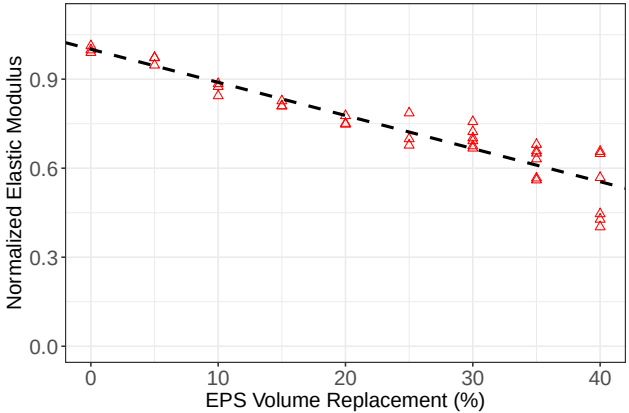
How to simulate grout deterioration?

How to simulate grout deterioration?



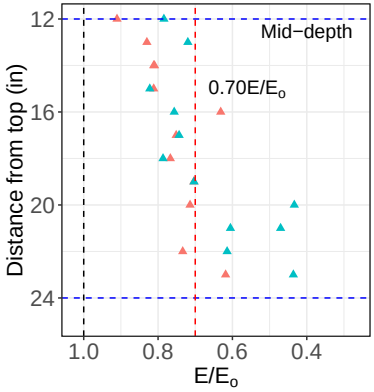
Expanded Polystyrene Beads

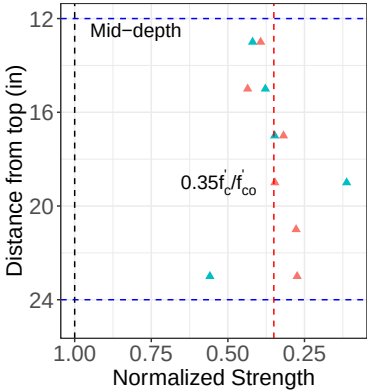
How to simulate grout deterioration?



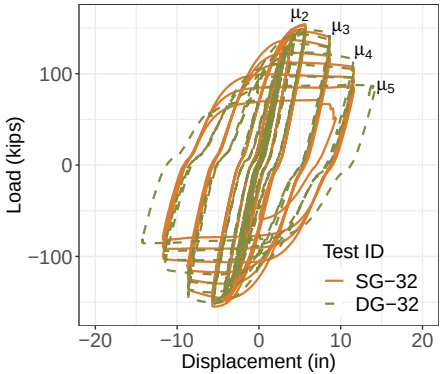
Reduction of elastic modulus with increasing volume fraction of EPS.

How to simulate grout deterioration?



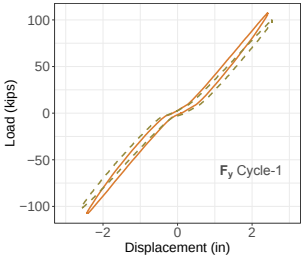


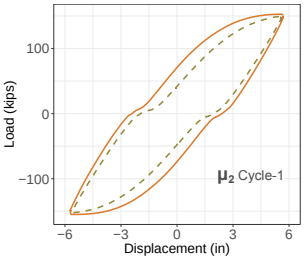
Does grout deterioration impact connection performance?

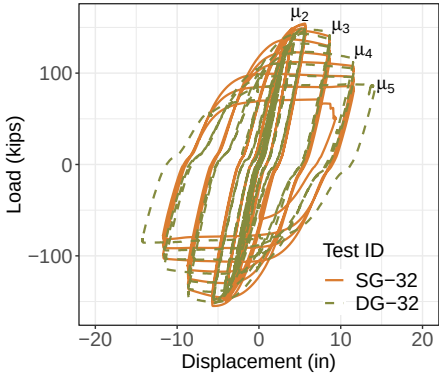


Comparison of global force-displacement hysteresis (Test 1 and Test 2).

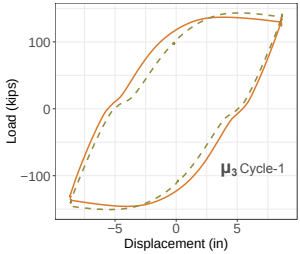
Does grout deterioration impact connection performance?

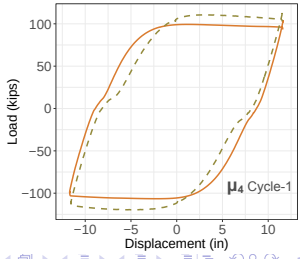






Comparison of global force-displacement hysteresis (Test 1 and Test 2).





Conclusion: Grout deterioration does not significantly alter the structural performance of the GSS connection.

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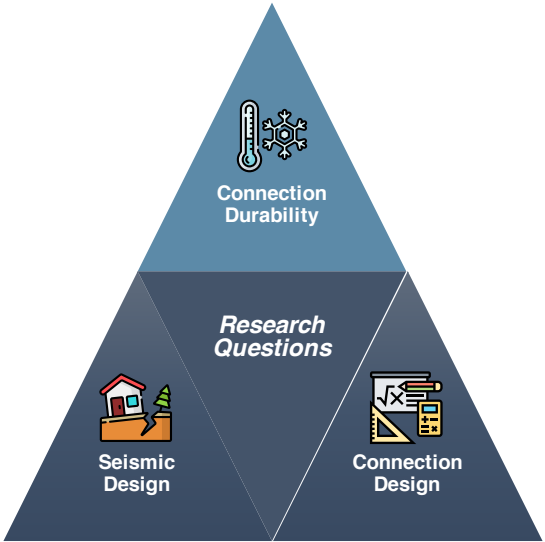
The GSS connection is durable in service.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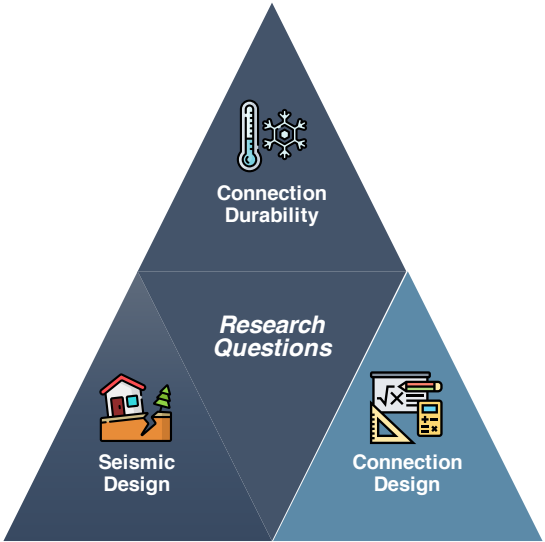
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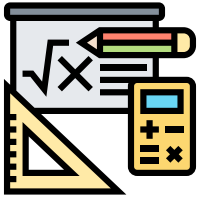
Connection Design

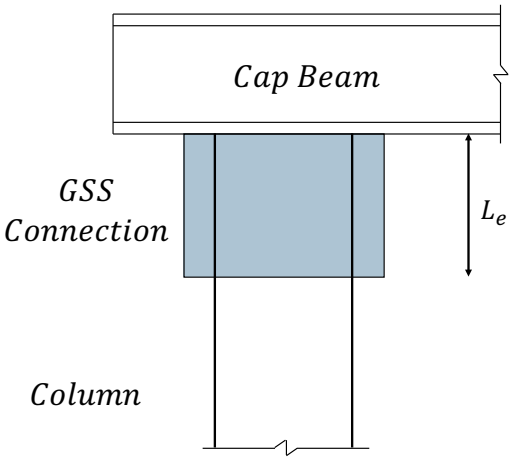


Need to understand the force transfer mechanism first

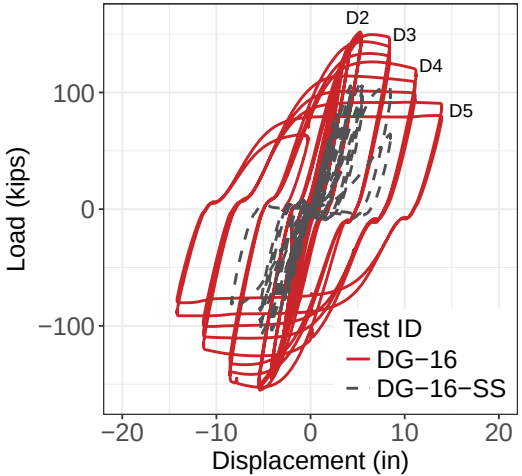
Need to understand the force transfer mechanism first

Test No.	Test ID	Shear Studs	Stud Area	Embedment Length (L_e)	Performance
0	SG-96	96	42.4 in^2	24"	**Adequate**
1	SG-32	32	25.1 in^2	24"	**Adequate**
2	DG-32	32	25.1 in^2	24"	**Adequate**
3	DG-16	16	12.6 in^2	24"	**Adequate**
4	DG-16-SS	16	12.6 in^2	16"	**Inadequate**

Embedment Length (L_e)



Importance of embedment length (L_e)

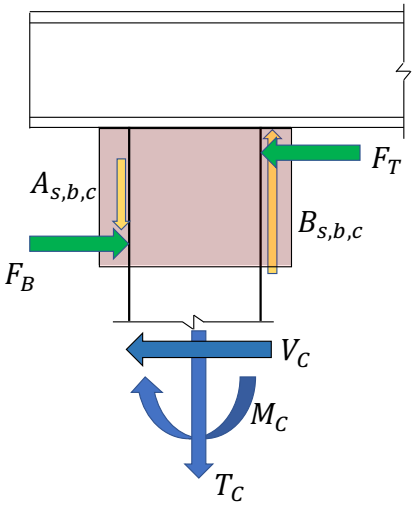


Comparison of global force-displacement hysteresis (Test 3 and Test 4).

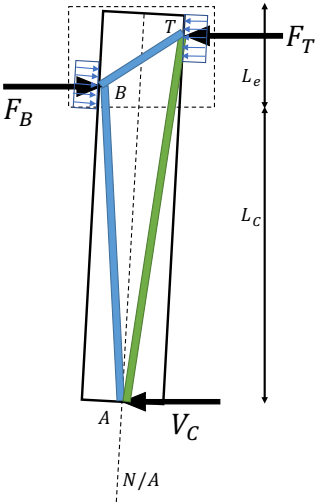
Importance of embedment length (L_e)

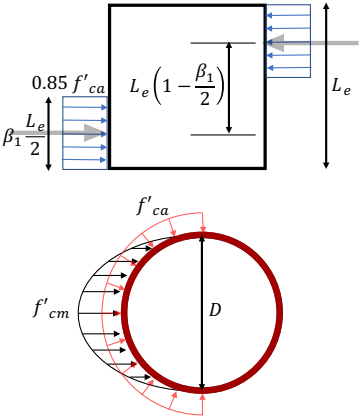
Comparing the behavior of GSS connections with different embedment length.

Force transfer mechanism

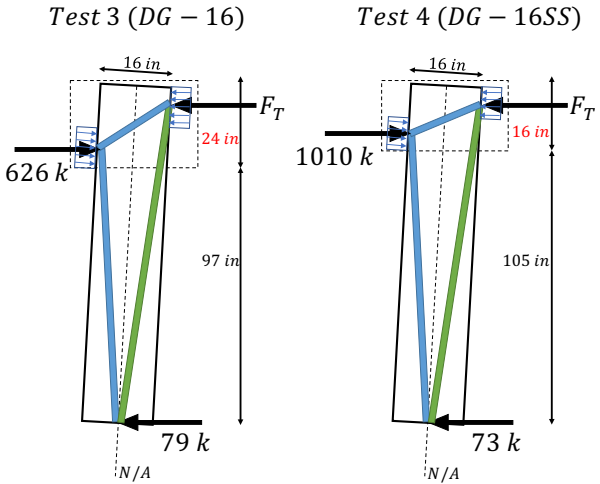


Analytical model





Analytical model



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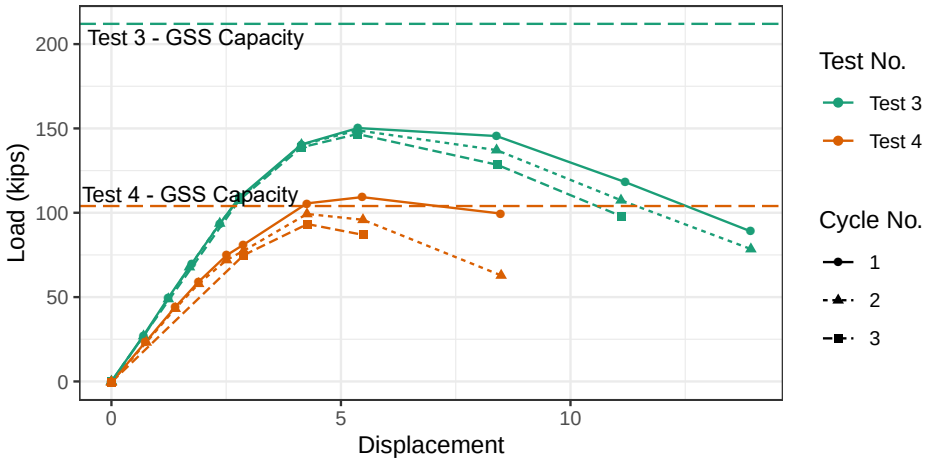


Analytical model

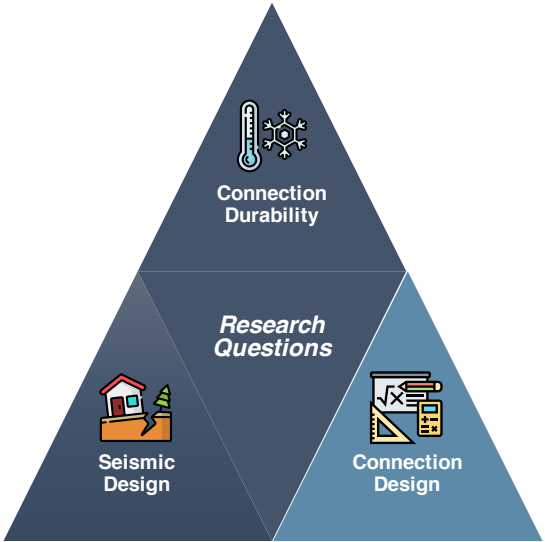
Calculate the maximum column shear force capacity as,

$$V_C \leq \frac{0.85 f'_{ca} \beta_1 D \left(\frac{L_e}{2}\right)}{\left(\frac{1}{2} + \frac{L_c + L_e\left(1 - \frac{\beta_1}{4}\right)}{L_e\left(1 - \frac{\beta_1}{2}\right)}\right)}$$

V_C = Shear force capacity
f'_{ca} = Average grout compressive strength
D = Column diameter
L_e = Embedment length
L_c = Clear cantilever length
L_{tc} = Total cantilever length
β_1 = ACI stress block coefficient

or can be further simplified to,

$$V_C \leq 0.008 f'_{ca} D L_{tc}$$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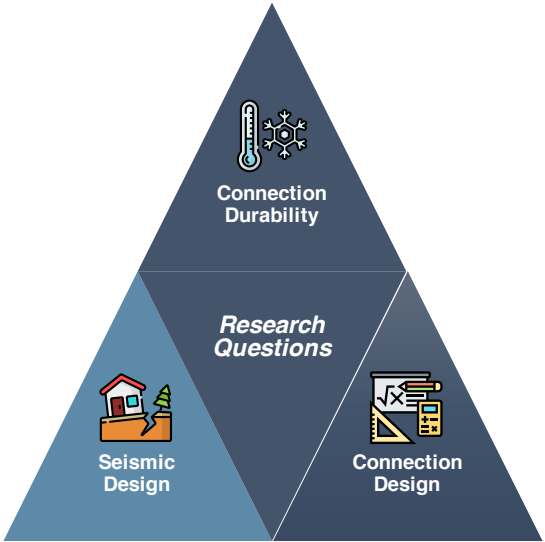
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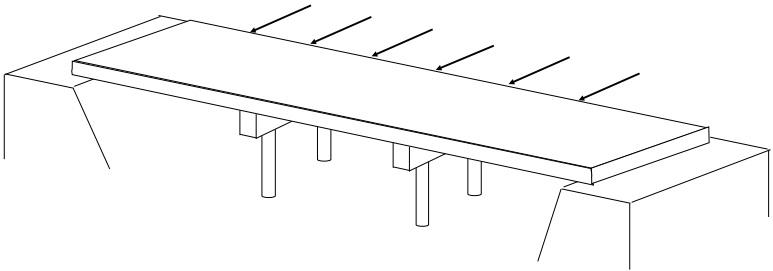
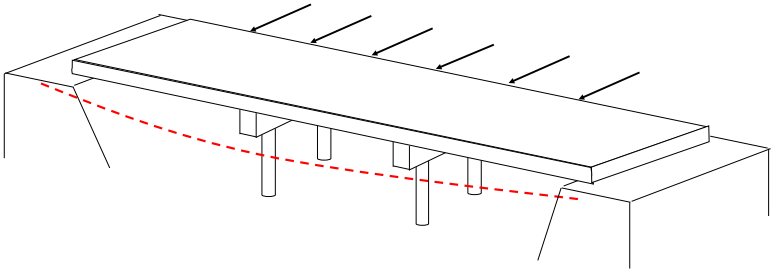
Seismic Design

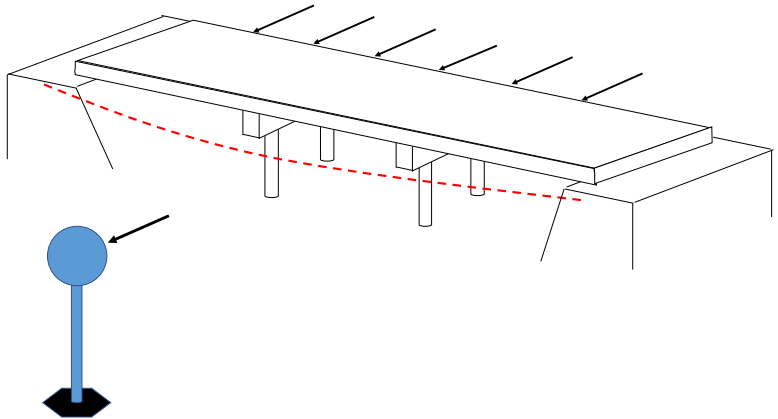
Seismic Design Concept



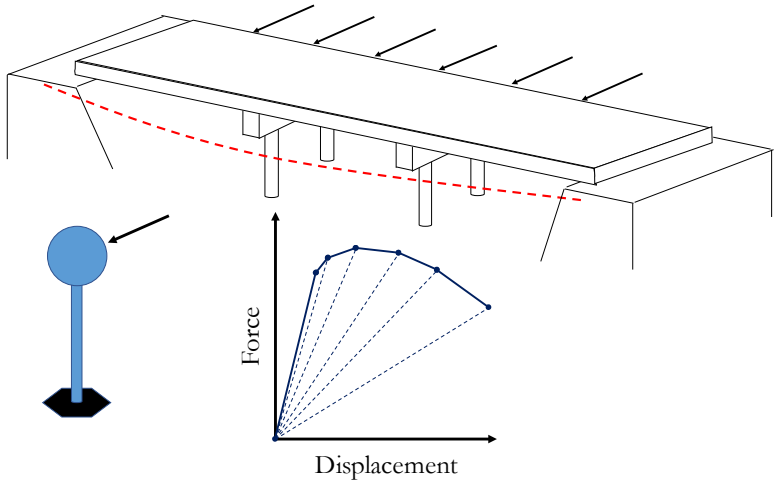
Seismic Design Concept



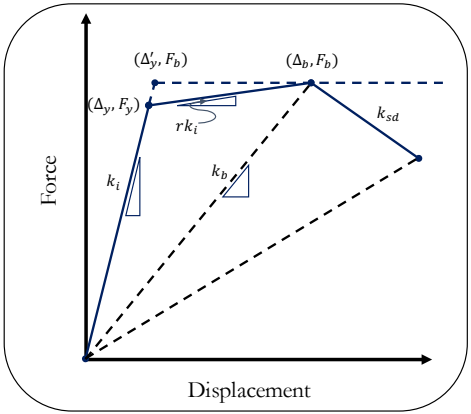
Seismic Design Concept



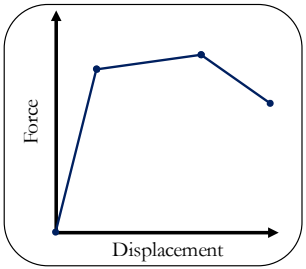
Seismic Design Concept

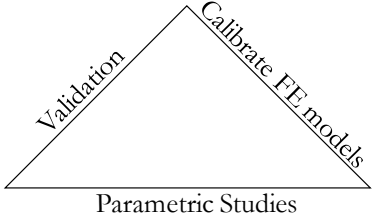


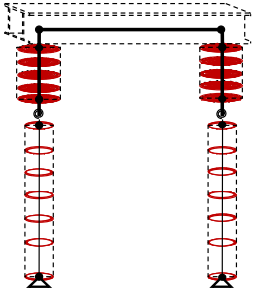
Need a design model to estimate limit state displacements



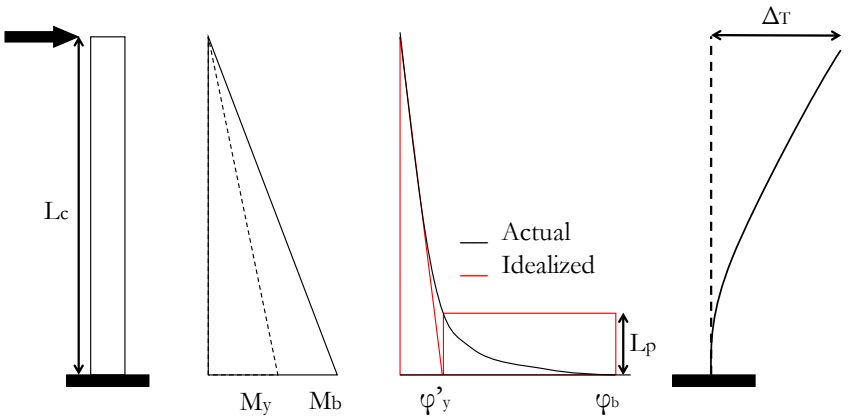
How I approached this problem?





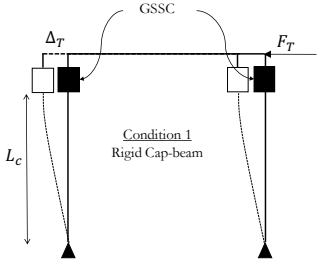


Conventional Plastic Hinge Method



Cantilever Column | Moment Diagram | Curvature Diagram | Deformed Shape

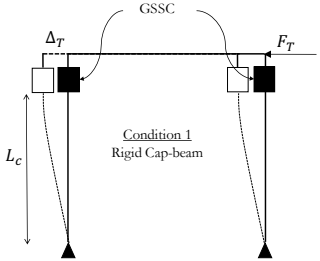
Condition 1



Rigid Cap-beam

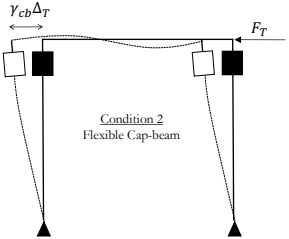
Flexibility Conditions

Condition 1



Rigid Cap-beam

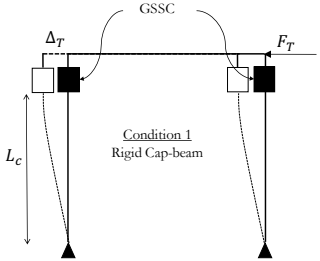
Condition 2



Flexible Cap-beam

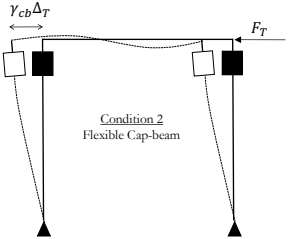
Flexibility Conditions

Condition 1



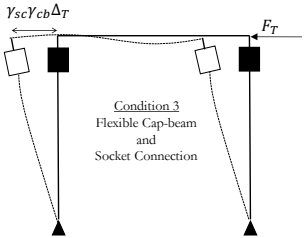
Rigid Cap-beam

Condition 2



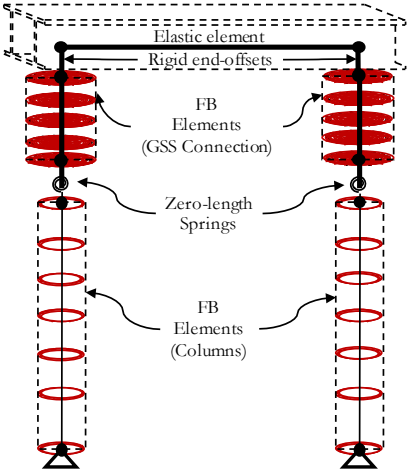
Flexible Cap-beam

Condition 3

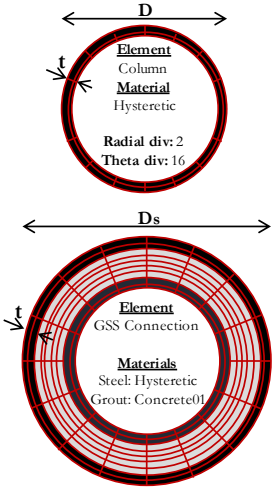


Add Socket Action

Numerical Model Development

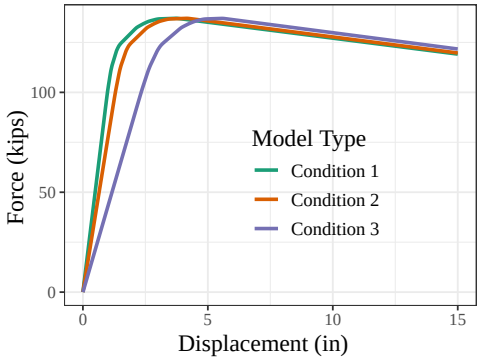


2-D Global model

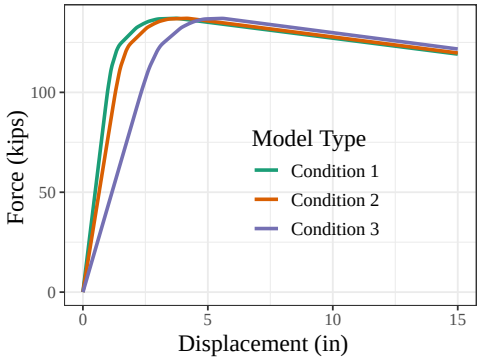


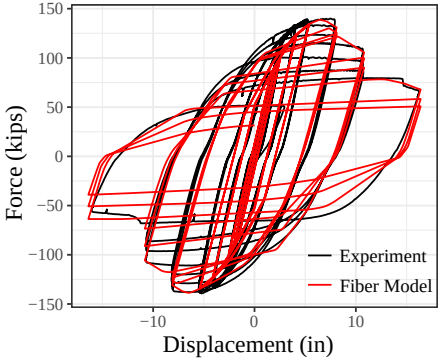
Fiber Sections

Calibrating rotational spring and strength degradation

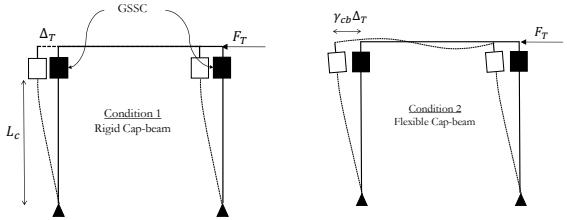


Calibrating rotational spring and strength degradation

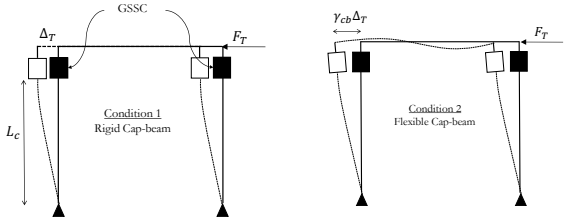




Condition 1 versus Condition 2

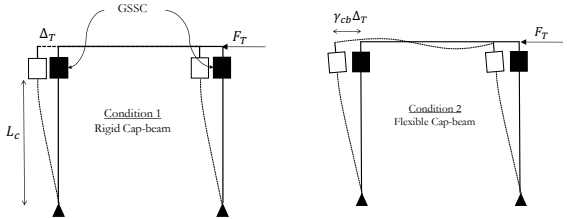


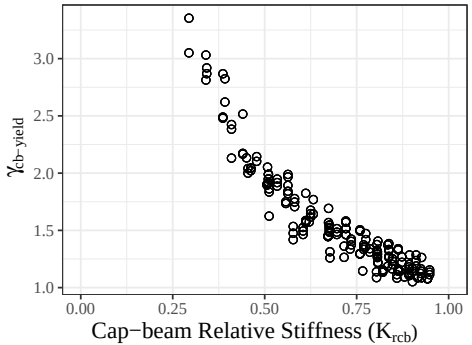
Condition 1 versus Condition 2



Relative stiffness of the cap-beam in each joint is a **significant** variable to estimate system displacement.

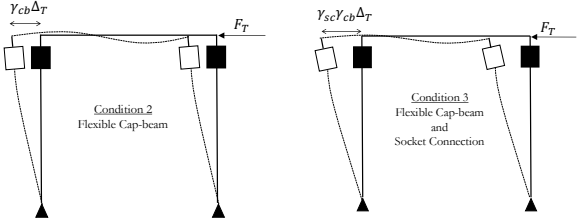
Condition 1 versus Condition 2



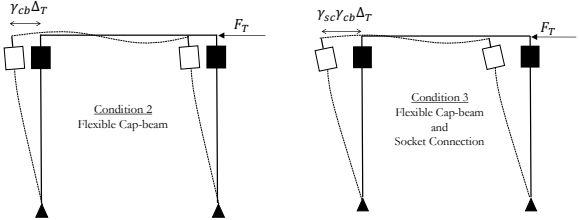


Relative stiffness of the cap-beam in each joint is a **significant** variable to estimate system displacement.

Condition 2 versus Condition 3

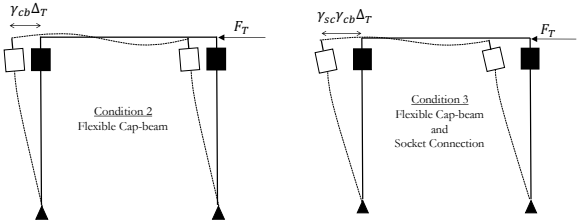


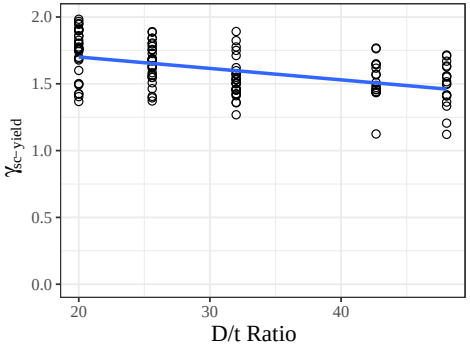
Condition 2 versus Condition 3



Everything else remaining the same, smaller D/t ratio means larger force.

Condition 2 versus Condition 3





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Strength Degradation Rate, k_{sd}

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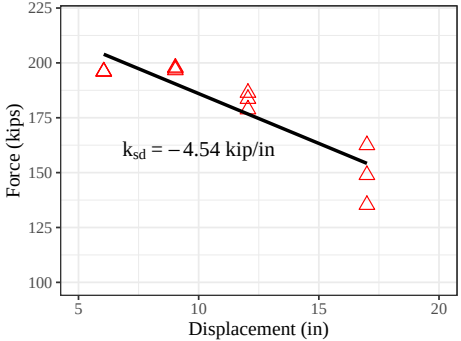
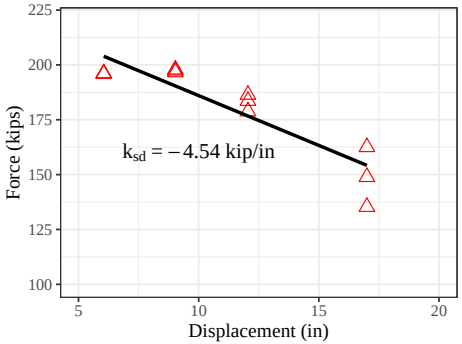
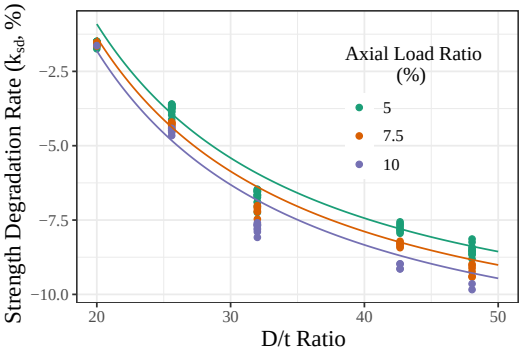
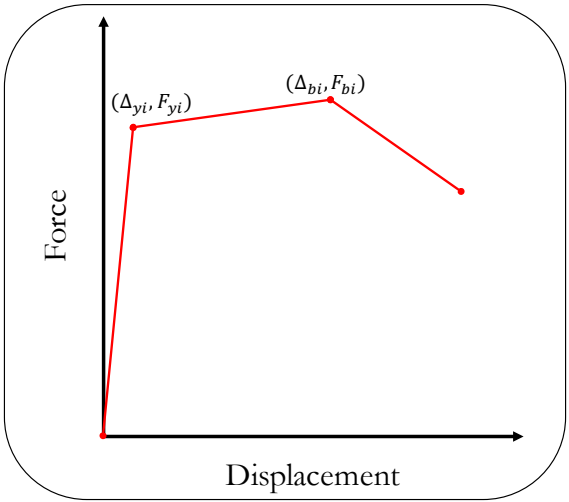


Strength Degradation Rate, k_{sd}

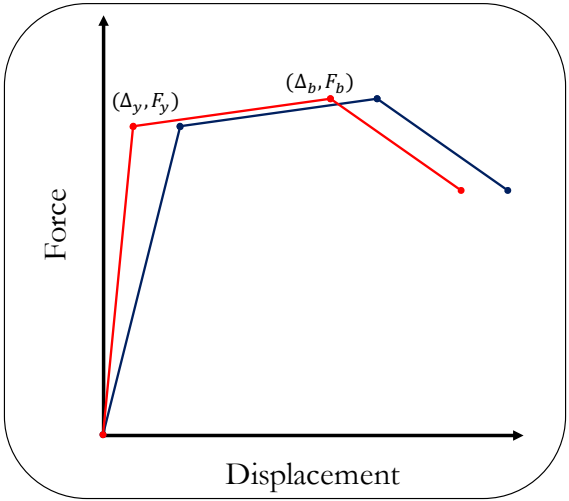




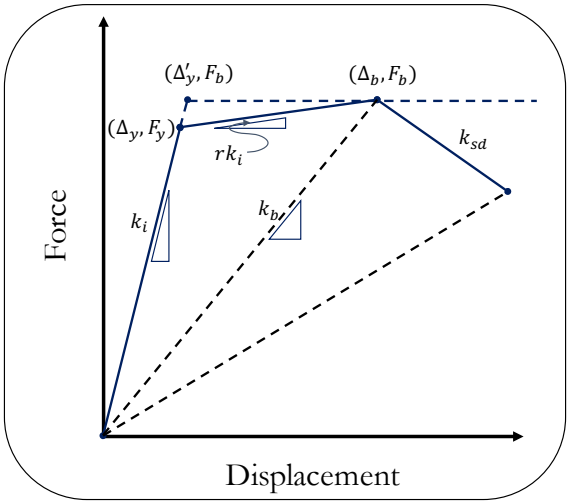
Outcome: Theoretical Capacity Curve



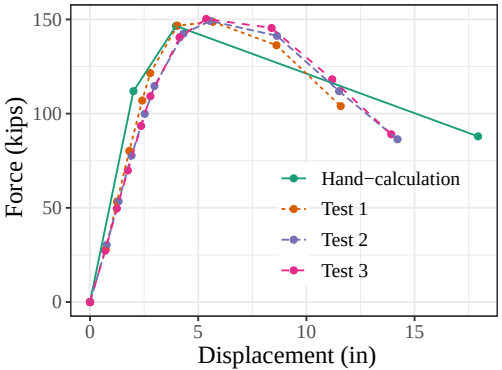
Outcome: Theoretical Capacity Curve



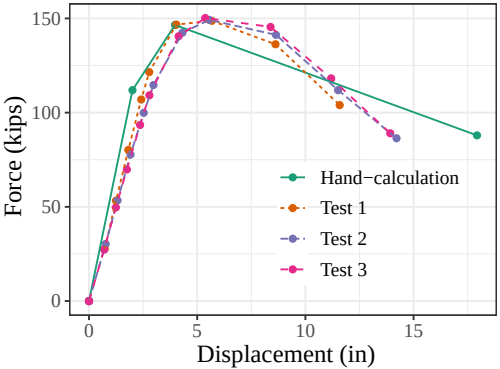
Outcome: Theoretical Capacity Curve

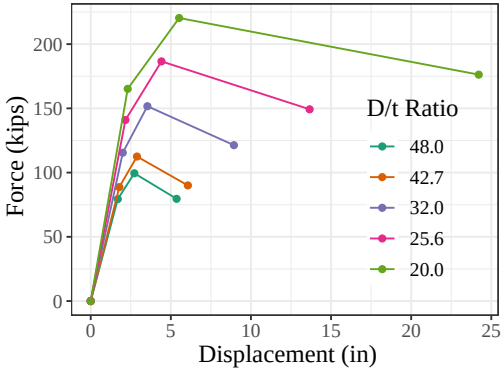


Model in Action



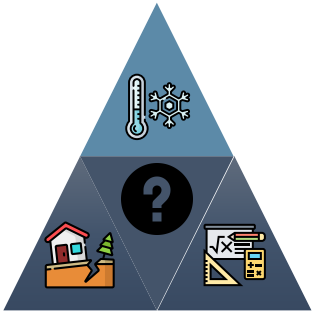
Model in Action





Summary

- The GSS connection is durable in service because grout deterioration is unlikely to impact structural performance.
- The GSS connection can be designed by providing sufficient embedment length to force plastic hinge relocation to the column.
- When estimating limit state displacements, the additional flexibility must be considered. A model is proposed.



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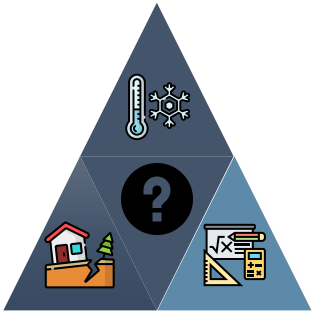

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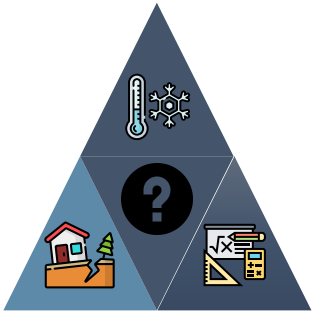

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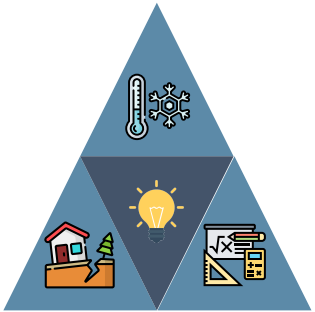
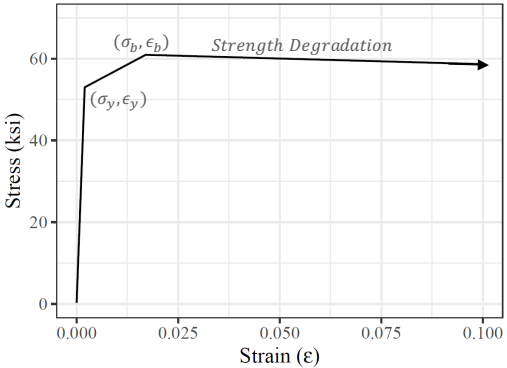
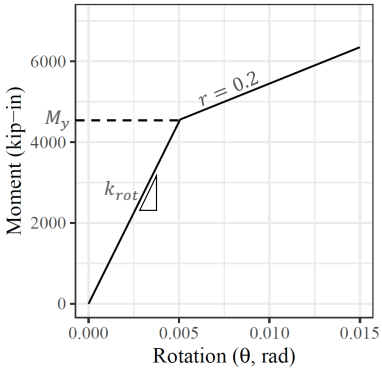


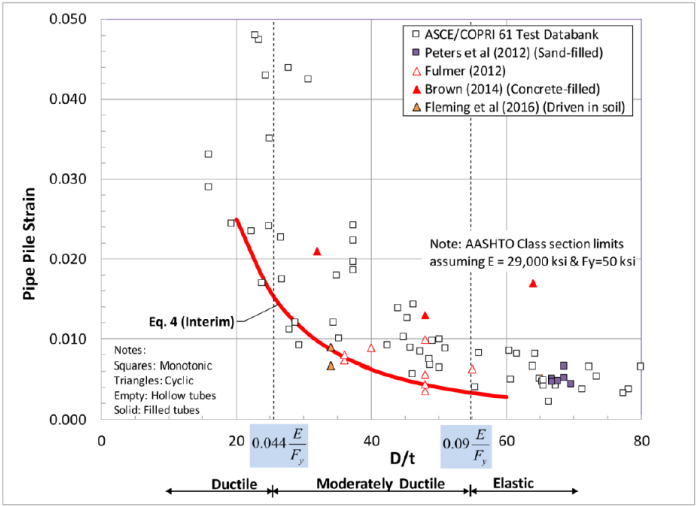
Backup Slides

Uniaxial models that were used



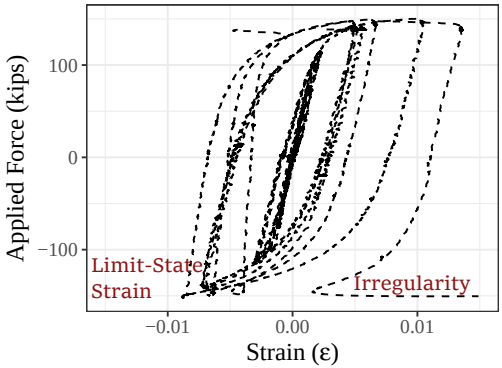


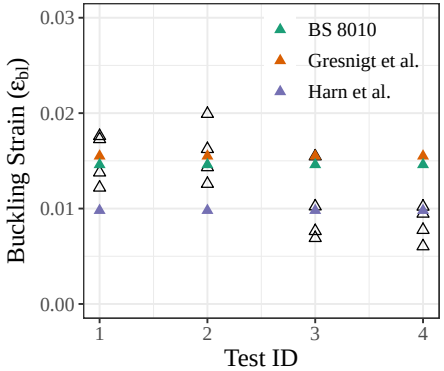
Identifying local buckling limit state

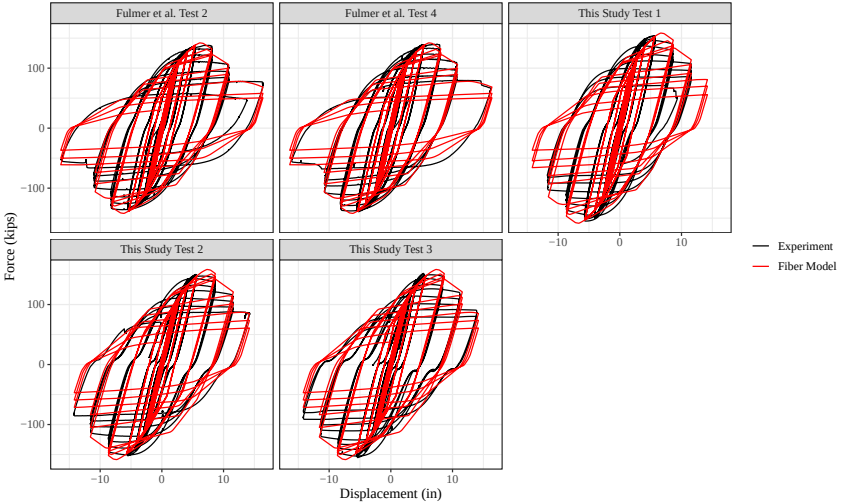


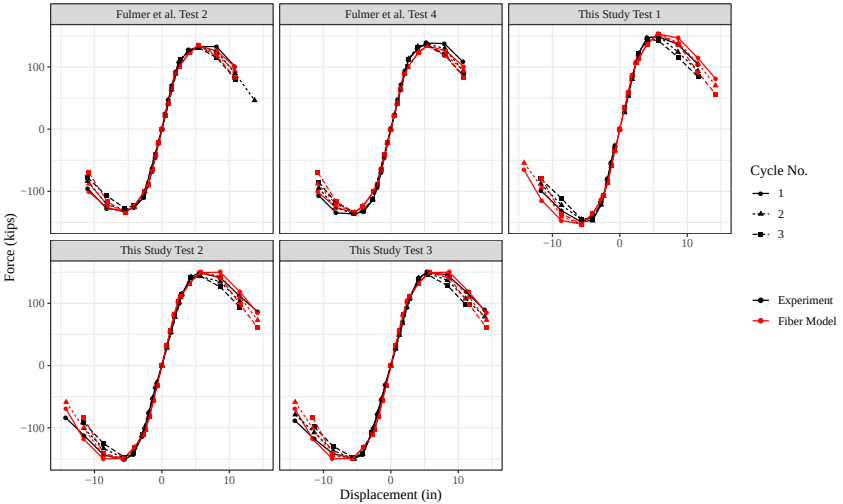
Harn et al. (2019)

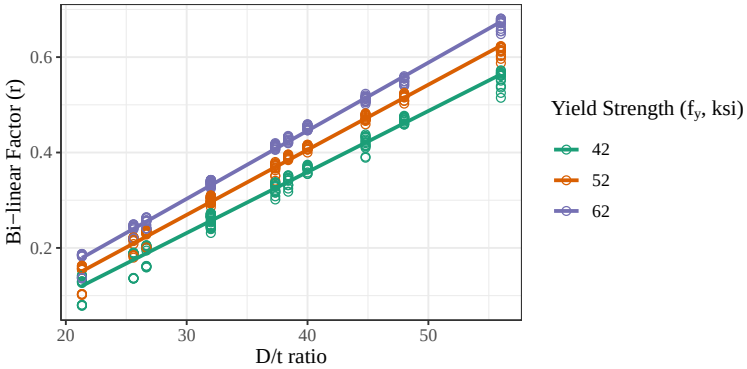
Identifying local buckling limit state

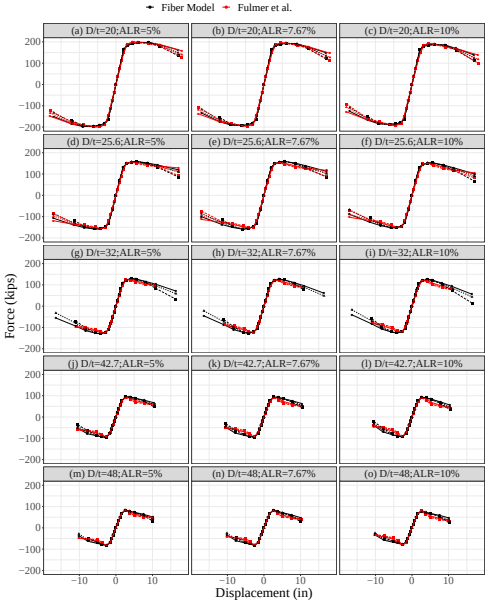


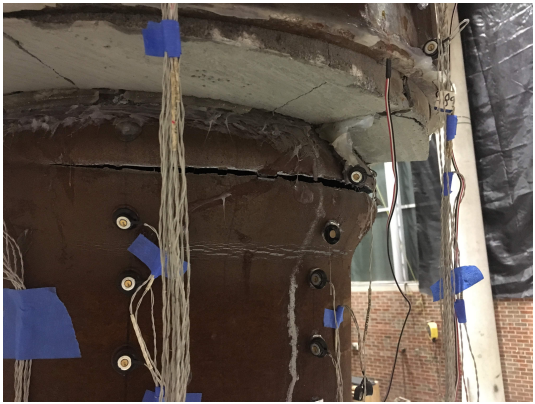


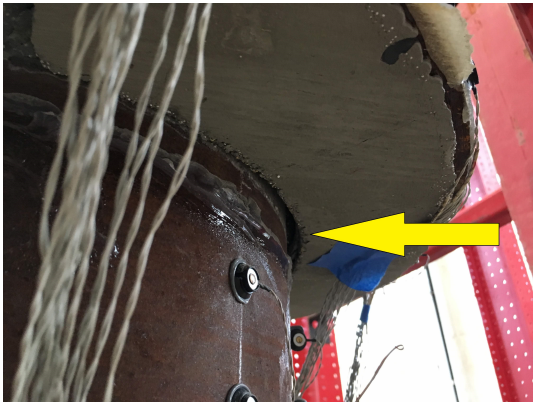

Fulmer et al. Test 2
Fulmer et al. Test 4
This Study Test 1
This Study Test 2
This Study Test 3
Force (kips)
100
0
−100
−10
0
10
Displacement (in)
Experiment
Fiber Model

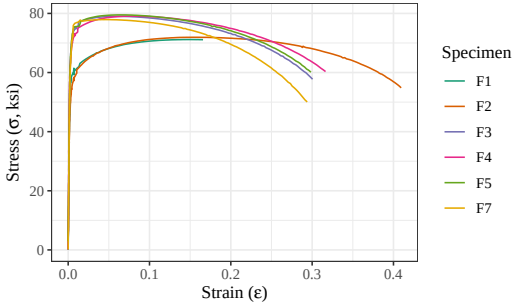

Fulmer et al. Test 2
Fulmer et al. Test 4
This Study Test 1
This Study Test 2
This Study Test 3
Force (kips)
Displacement (in)
100
0
−100
−10
0
10
Cycle No.
1
2
3
Experiment
Fiber Model

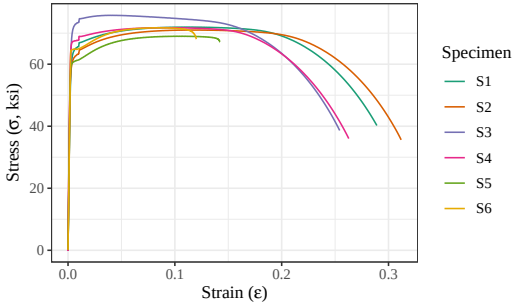

Bi−linear Factor (r)
0.2
0.4
0.6
20
30
40
50
D/t ratio
Yield Strength (f_y, ksi)
42
52
62

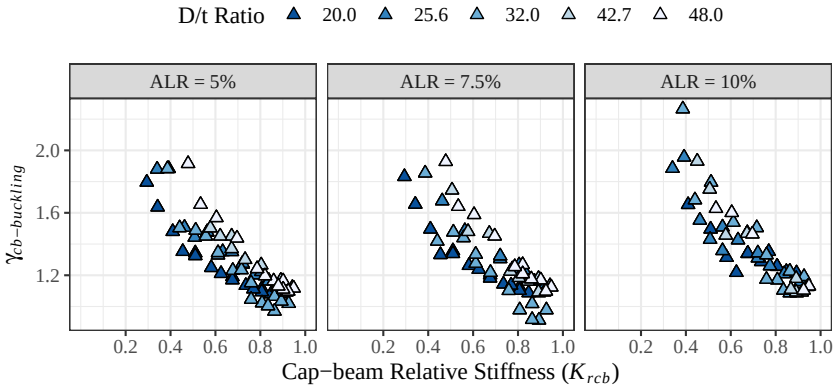

Fiber Model
Fulmer et al.
(a) D/t=20;ALR=5%
(b) D/t=20;ALR=7.67%
(c) D/t=20;ALR=10%
(d) D/t=25.6;ALR=5%
(e) D/t=25.6;ALR=7.67%
(f) D/t=25.6;ALR=10%
(g) D/t=32;ALR=5%
(h) D/t=32;ALR=7.67%
(i) D/t=32;ALR=10%
(j) D/t=42.7;ALR=5%
(k) D/t=42.7;ALR=7.67%
(l) D/t=42.7;ALR=10%
(m) D/t=48;ALR=5%
(n) D/t=48;ALR=7.67%
(o) D/t=48;ALR=10%
Force (kips)
200
100
0
−100
−200
−10
0
10
Displacement (in)

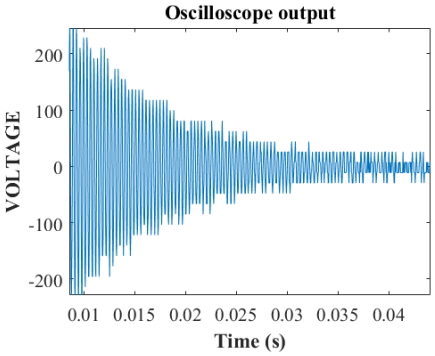


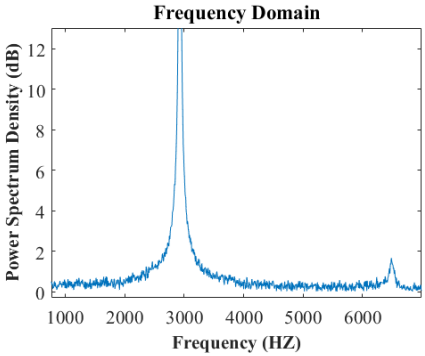


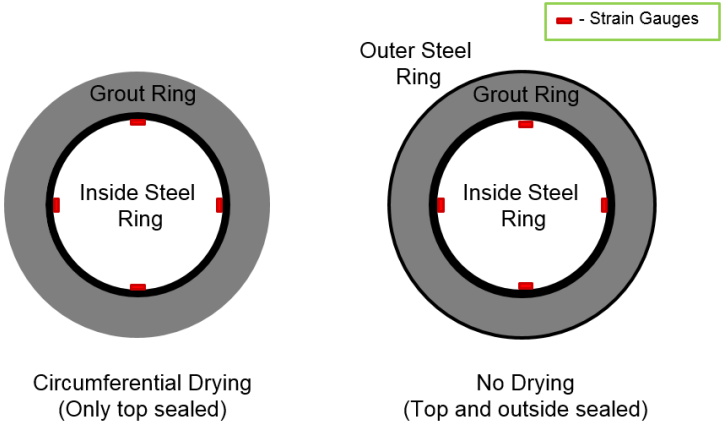

Stress (σ, ksi)
Strain (ε)
0
20
40
60
80
0.0
0.1
0.2
0.3
0.4
Specimen
F1
F2
F3
F4
F5
F7

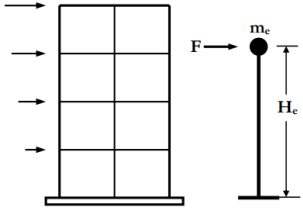

Stress (σ, ksi)
Strain (ε)
0
20
40
60
0.0
0.1
0.2
0.3
Specimen
S1
S2
S3
S4
S5
S6


D/t Ratio
20.0
25.6
32.0
42.7
48.0
ALR = 5%
ALR = 7.5%
ALR = 10%
$\gamma_{cb-buckling}$
2.0
1.6
1.2
0.2
0.4
0.6
0.8
1.0
Cap−beam Relative Stiffness (K_{rcb})

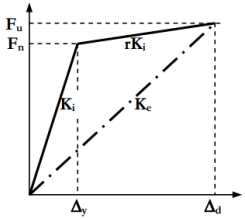

Oscilloscope output
VOLTAGE
200
100
0
-100
-200
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Time (s)


Frequency Domain
Power Spectrum Density (dB)
12
10
8
6
4
2
0
1000
2000
3000
4000
5000
6000
Frequency (HZ)

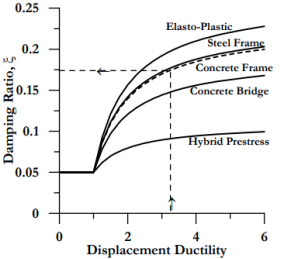

- Strain Gauges
Outer Steel Ring
Grout Ring
Inside Steel Ring
Grout Ring
Inside Steel Ring
Circumferential Drying
(Only top sealed)
No Drying
(Top and outside sealed)



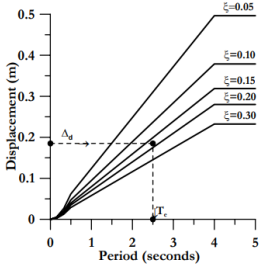
(a) SDOF Simulation



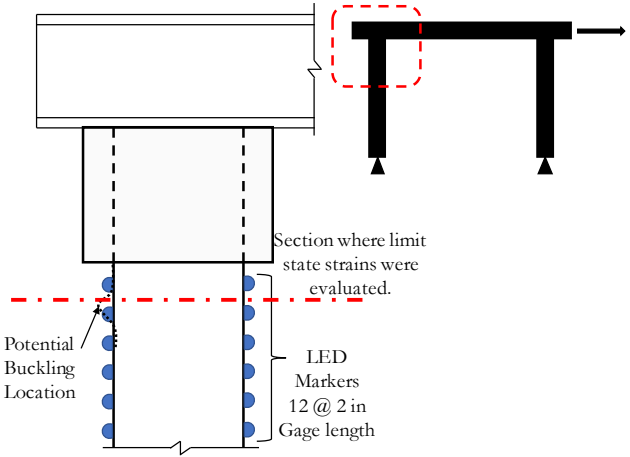
(b) Effective Stiffness K_e

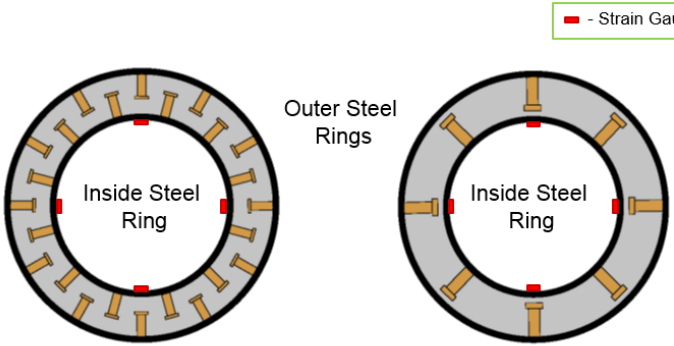


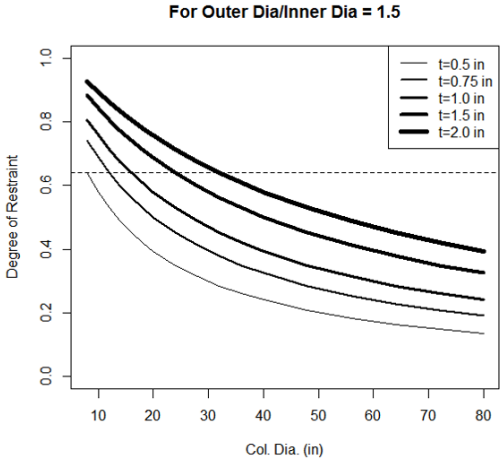
(c) Equivalent damping vs. ductility

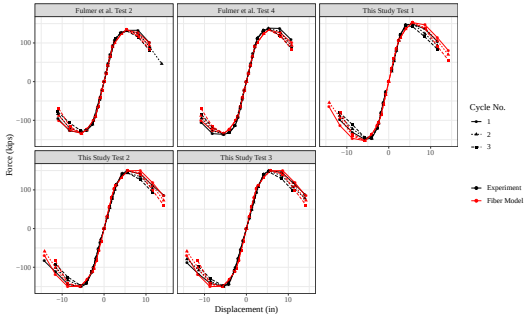


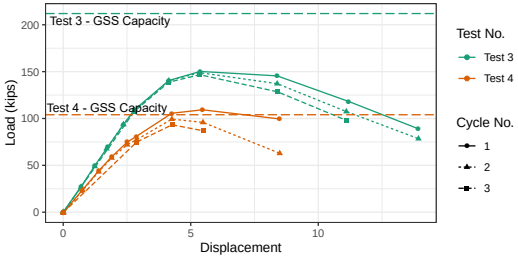
(d) Design Displacement Spectra


Section where limit
state strains were
evaluated.
Potential
Buckling
Location
LED
Markers
12 @ 2 in
Gage length


- Strain Gauges
Outer Steel Rings
Inside Steel Ring
Inside Steel Ring
¾ inch dia. studs (24 Nos.)
1 inch dia. studs (8 Nos.)


For Outer Dia/Inner Dia = 1.5
t=0.5 in
t=0.75 in
t=1.0 in
t=1.5 in
t=2.0 in
Degree of Restraint
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
80
Col. Dia. (in)


Fulmer et al. Test 2
Fulmer et al. Test 4
This Study Test 1
This Study Test 2
This Study Test 3
Force (kips)
Displacement (in)
Cycle No.
1
2
3
Experiment
Fiber Model


Test 3 - GSS Capacity
Test 4 - GSS Capacity
Load (kips)
200
150
100
50
0
0
5
10
Displacement
Test No.
Test 3
Test 4
Cycle No.
1
2
3

Frame Title

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