Concrete Filled Steel Tubes (CFT) for Bridge Foundations and Substructures

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Acknowledgements

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- Current research funded by California Department of Transportation and Washington Department of Transportation

Presentation

- Brief Overview of CFT
- Overview of Work Done With USArmy Funding
- Summary of CALTRANS Research
- Current Status
- Progress on WSDOT Research
- Initial Recommendations and Discussion

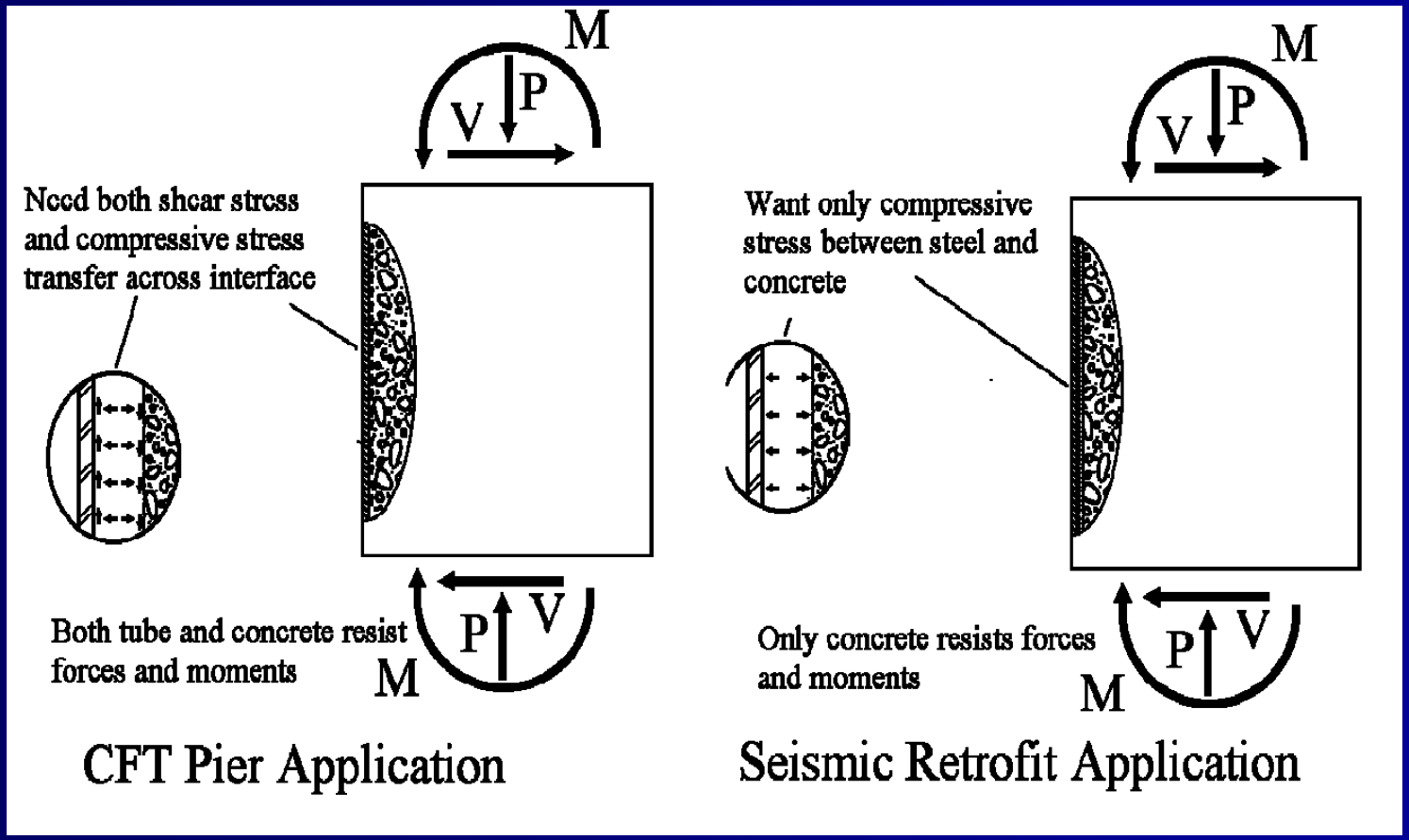
Brief Overview of CFT

CFT Construction: Commonly used in other countries

Advantages

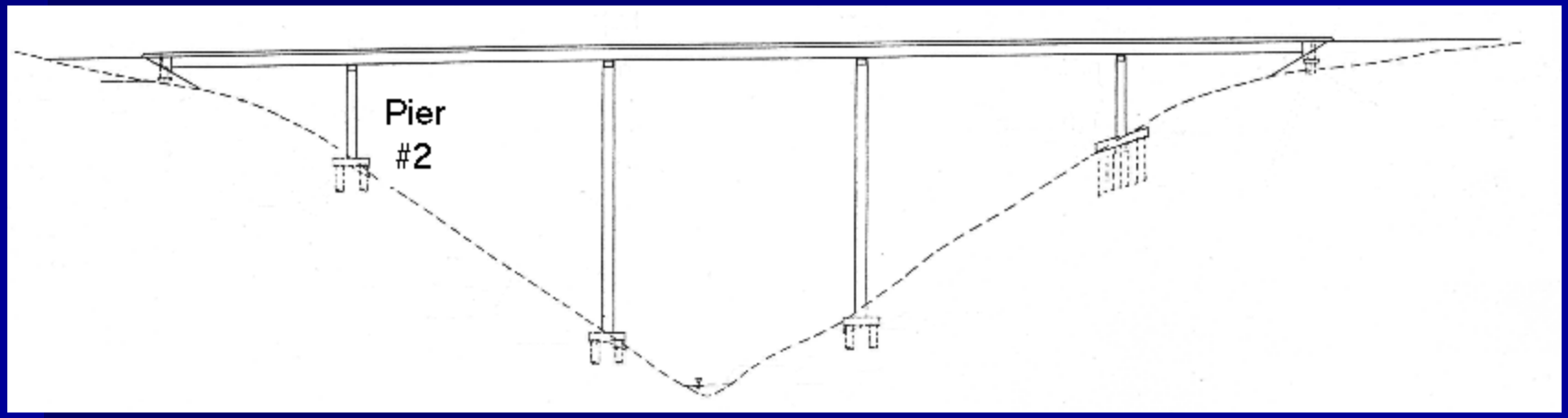
- Large Strength and Stiffness
- Reduced Labor and Rapid Construction ~ no formwork or tying of reinforcing steel
- Concrete fill can be rapidly placed without vibration with low shrinkage self-consolidating concrete
- No reinforcement inside the tube

Goals and Design Requirements for CFT – Composite Design



Cow Creek Bridge

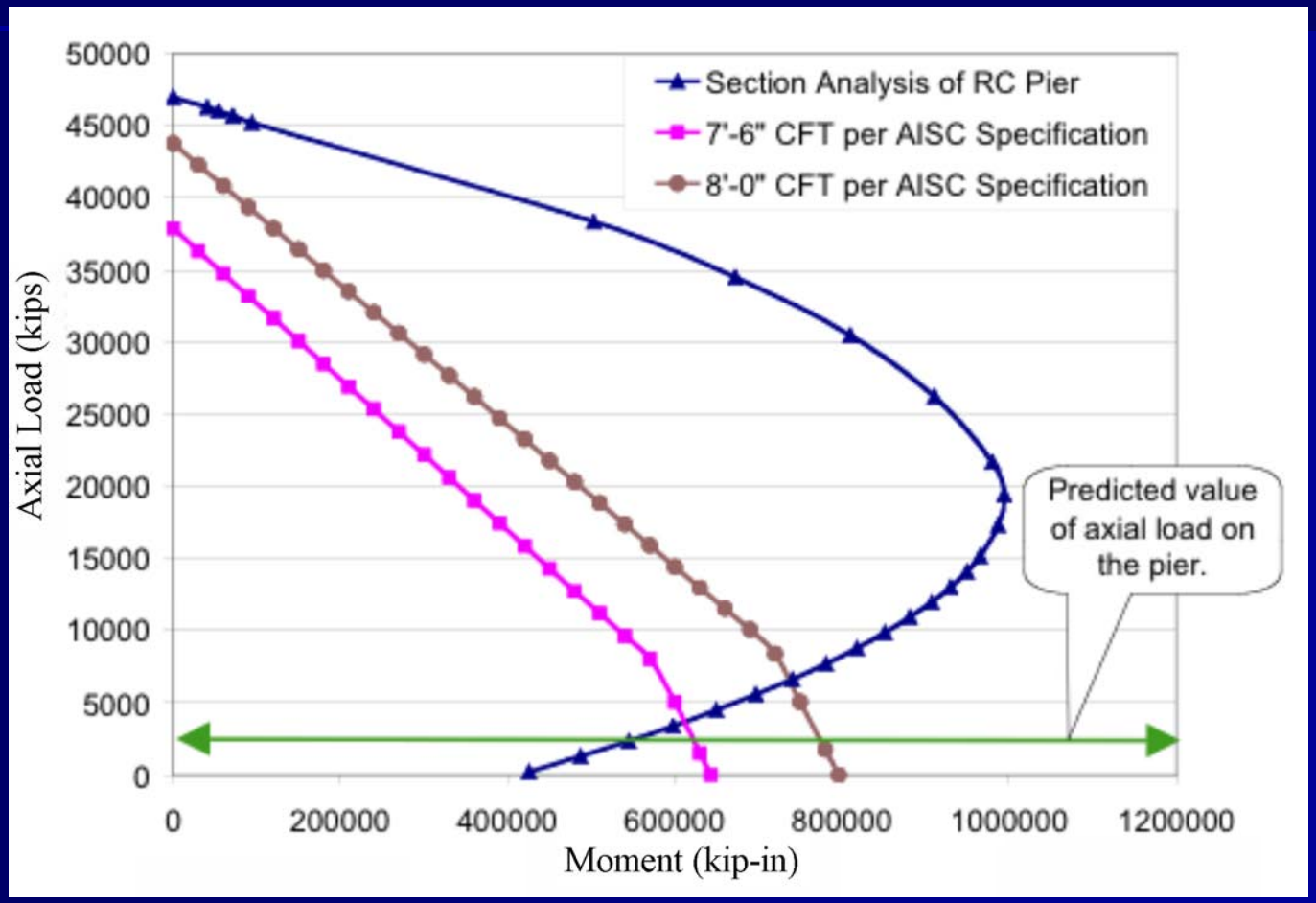
- 865 foot long, steel plate-girder bridge
- Rectangular reinforced concrete columns
- One column at each bridge pier
- Constructed in 1988
- Bridge pier number 2:
  - **7'-0" by 12'-0" dimensions**
  - **60 feet long**



Cow Creek Bridge, Pier #2 M-P Diagram

Comparison of Concrete Filled Tubes With As-built RC Pier

RC Pier is 7'x12'



Overview of Work Done With USArmy Funding

Focused on high strength Vanadium Alloy steels.
Considered yield stresses of 70+ ksi and much more slender tubes than currently used in any specification.

While CFT Showed Promise There Were Severe Limitations

- Connections needed at foundation and pier cap were not known
- Models for predicting the resistance and stiffness were uncertain
- Issue of stress transfer between the steel and concrete not fully defined

Spiral and Straight Seam Tube Welds

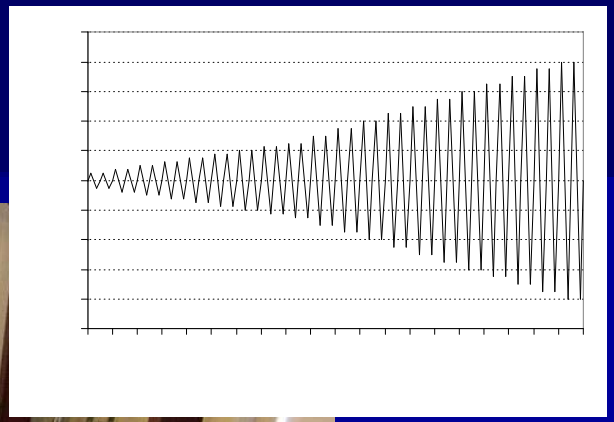
- Spiral welded tubes offer greater versatility and availability with sizes and lengths needed for bridge piers

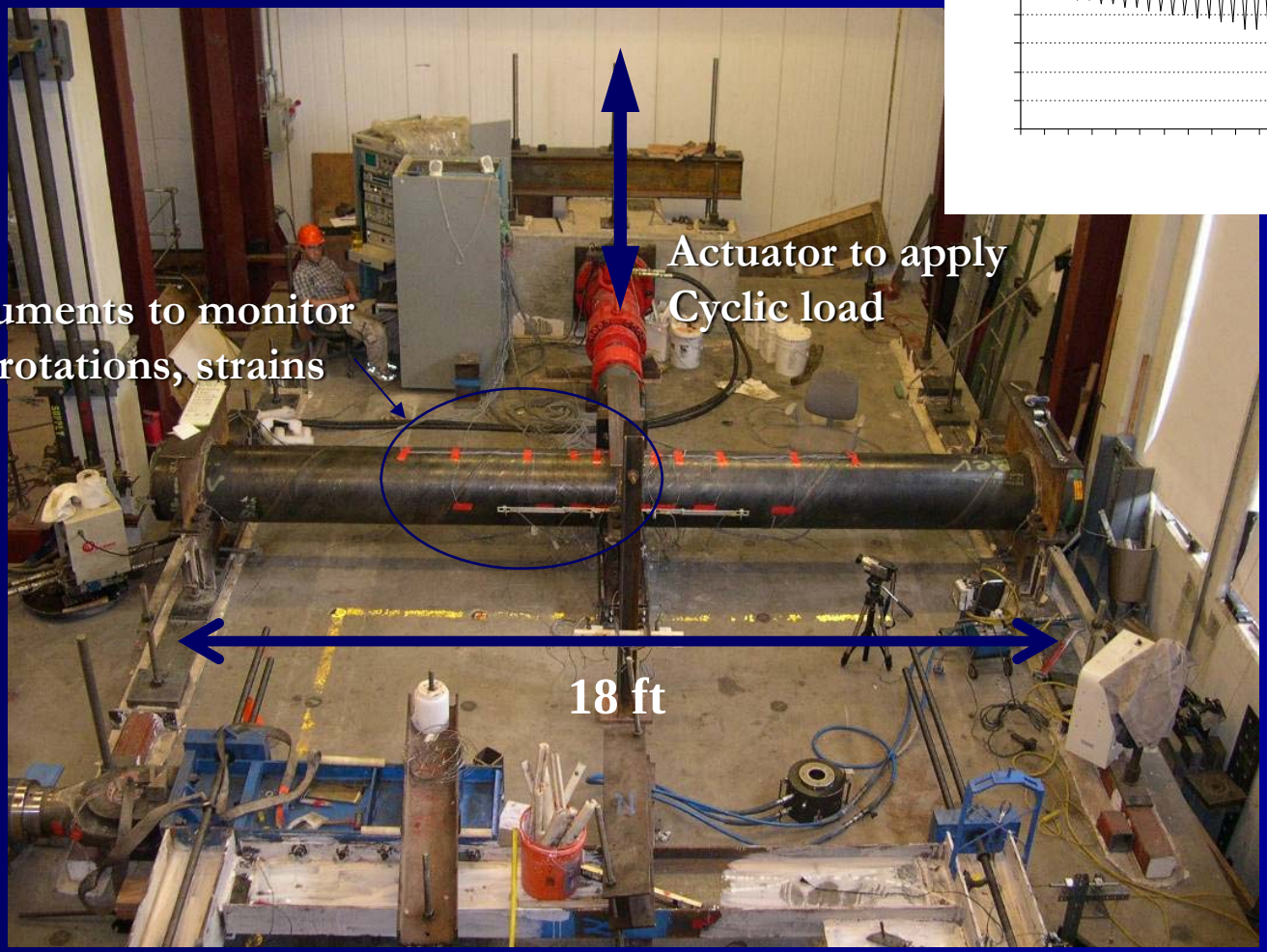
- Spiral welds induce stress on welds that do not occur with straight seem tubes
- Research completed to understand the behavior of these welds under stress

Engineering Properties of CFT

- Investigate engineering properties of CFTs.
  - **Stiffness**
  - **Strength**
  - **Deformability**
  - **Fatigue Resistance**
- Study Parameters
  - **Bond stress**
  - **Weld type and process**
  - **Corrosion**
  - **D/t**

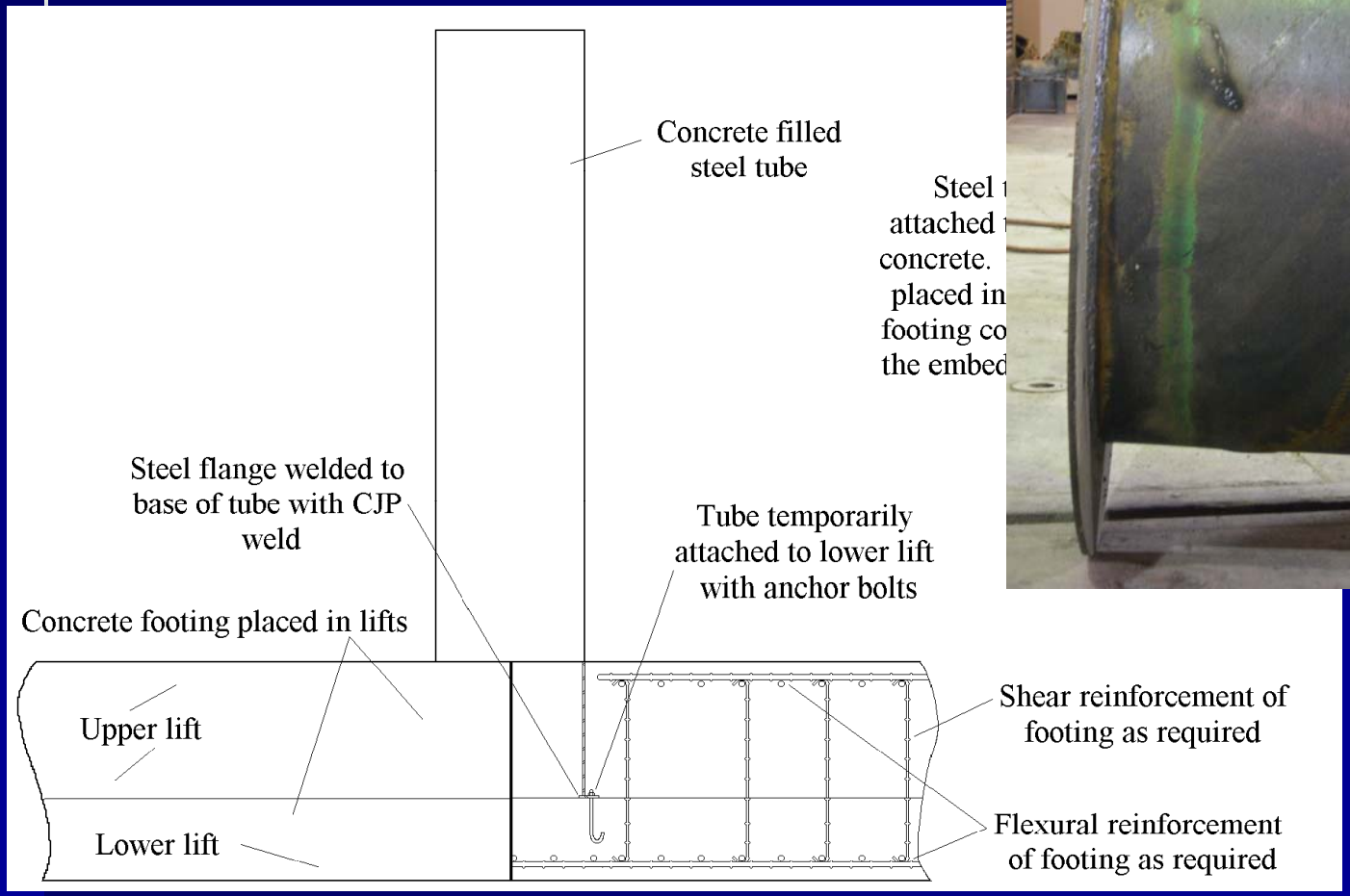
Test configuration





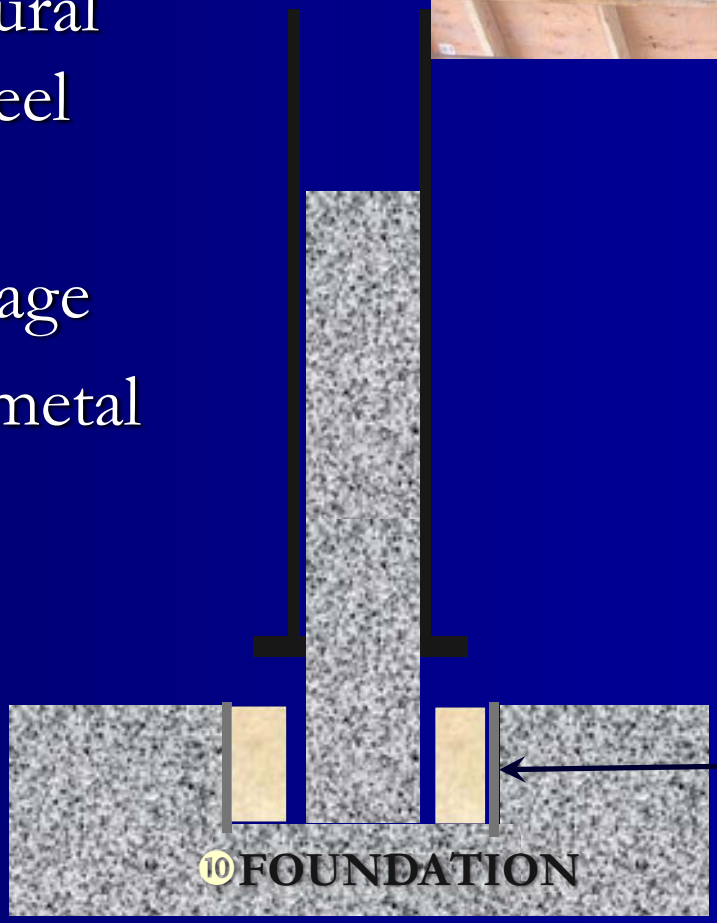
Developed a simple, economical and rapidly constructed connection between CFT column and reinforced concrete foundation or pier cap. Two variations of connection.

Connection Variation 1 – Embedded Connec



Design of Isolated Connection

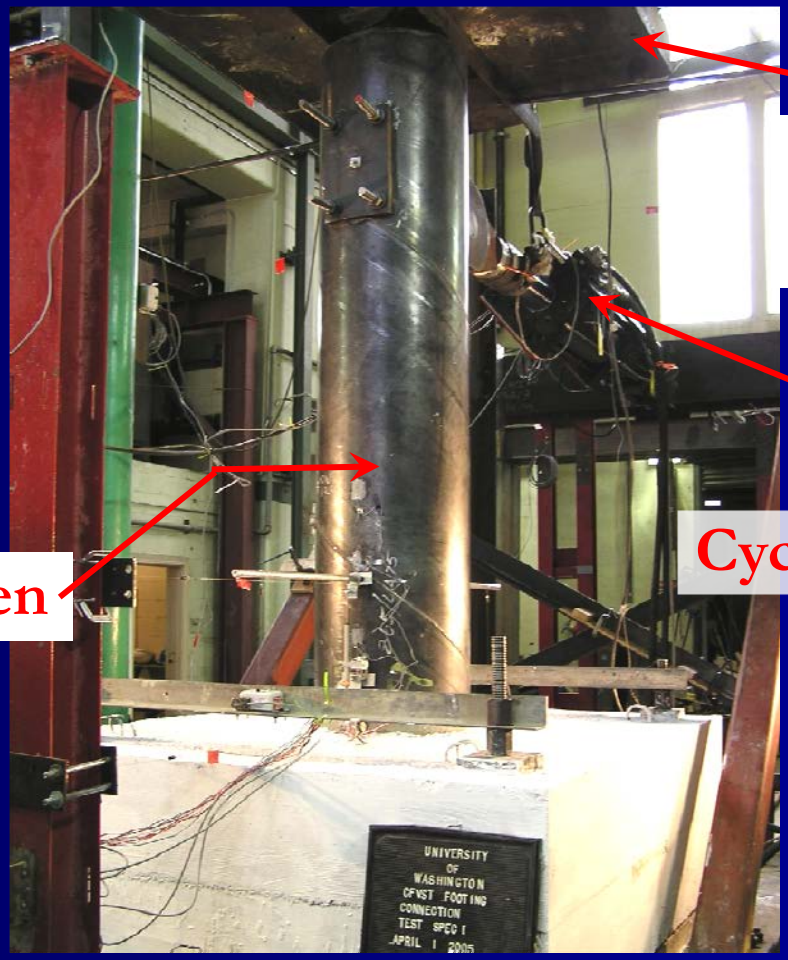
- Isolation of Structural and Reinforcing Steel Trades
- Build foundation cage
- Install corrugated metal pipe
- Cast foundation
- Install and grout tube
- Cast column



CORRUGATED METAL PIPE

Completed full scale tests of this pier and pier connection with both connection variations under siesmi and gravity loading. Very good performance with proper embedment.

Test Configuration for Connection Tests

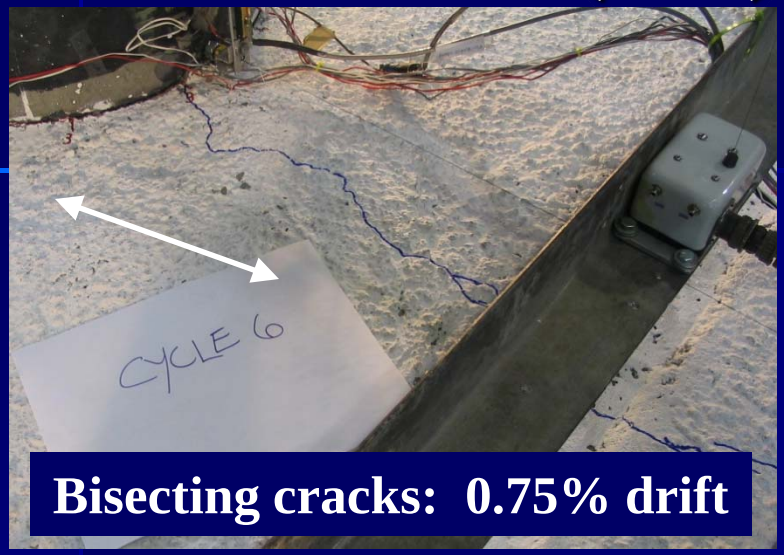


Constant axial load ($10\%P_0$)

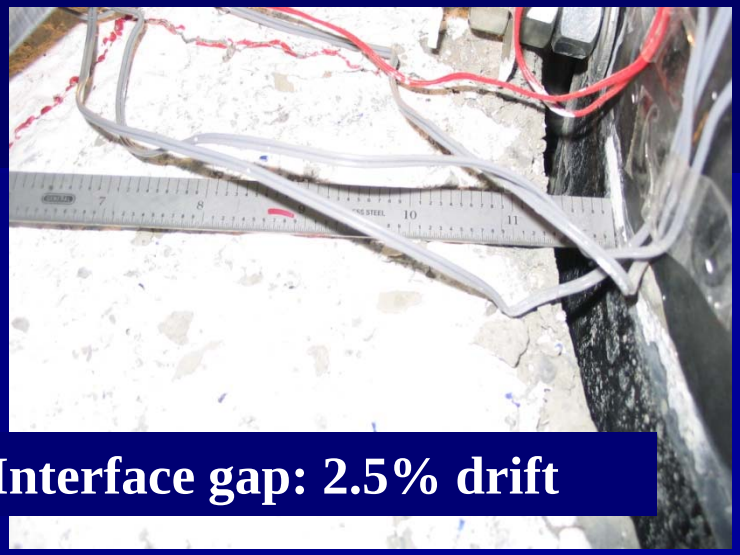
Cyclic Lateral Load

Test Specimen

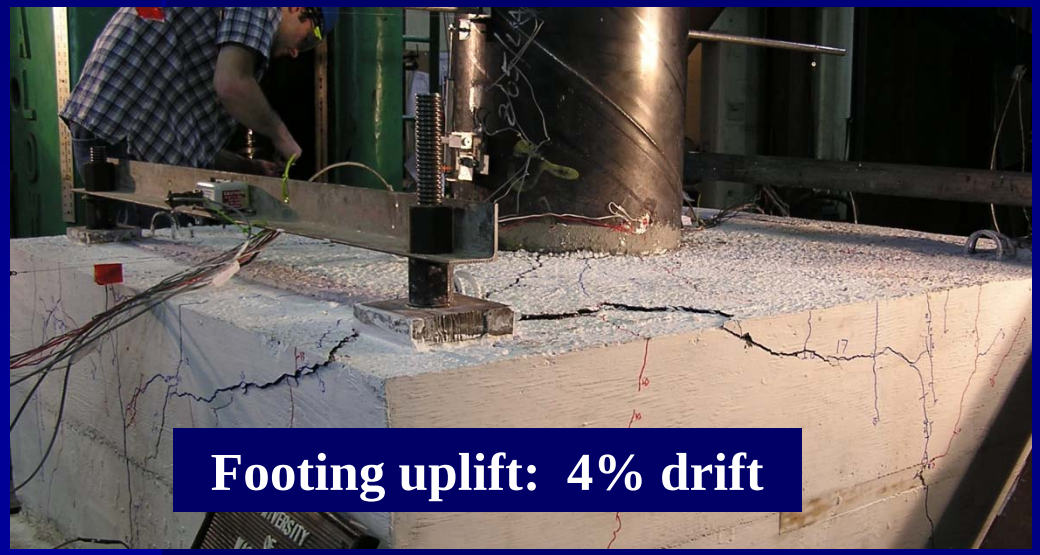
Observed Behavior: Shallow Embedment (.6D)



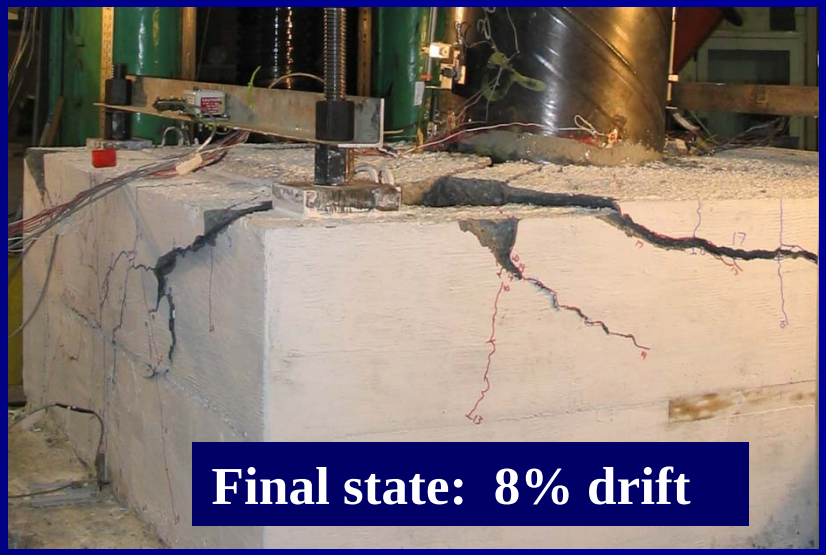
Bisecting cracks: 0.75% drift



Interface gap: 2.5% drift

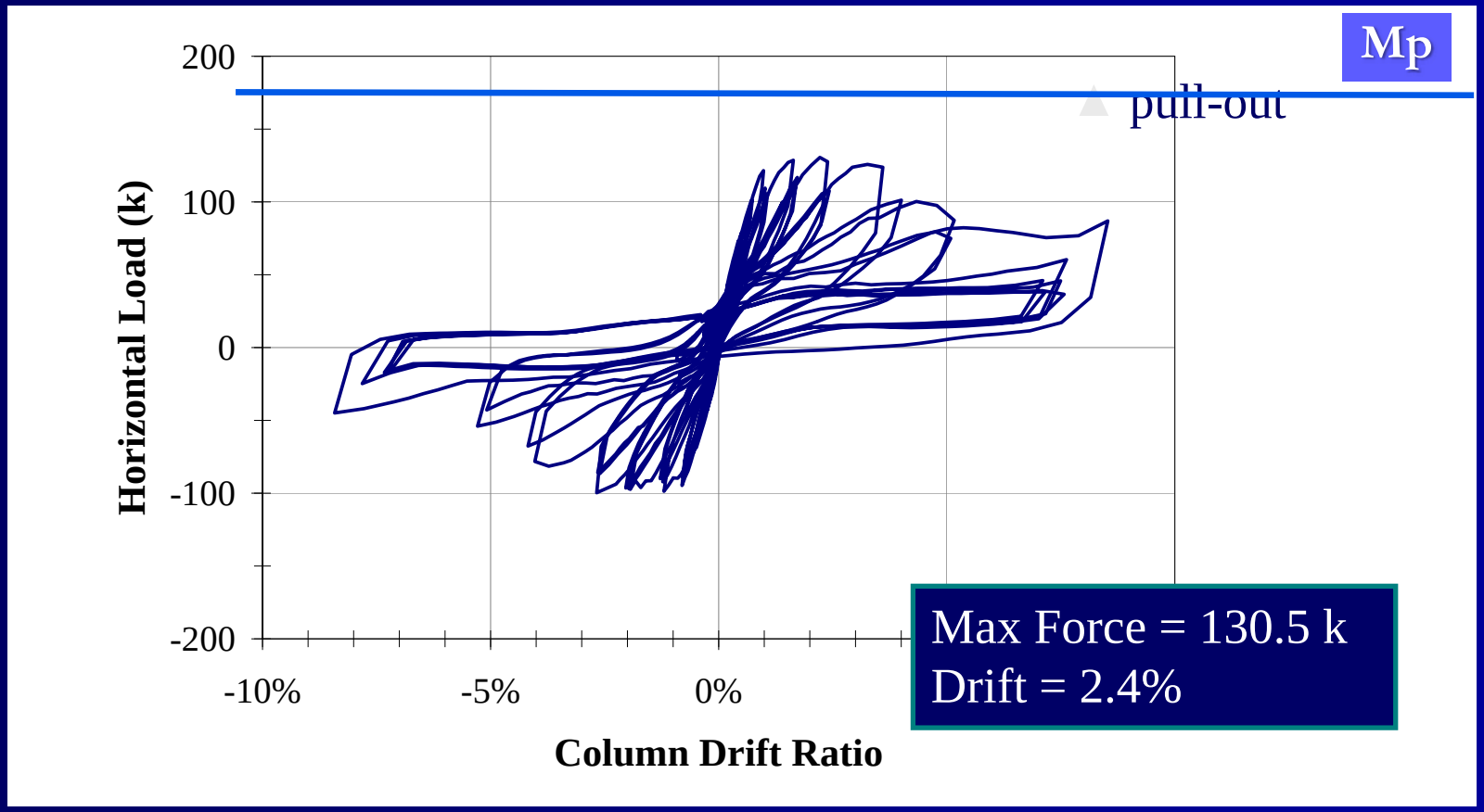


Footing uplift: 4% drift



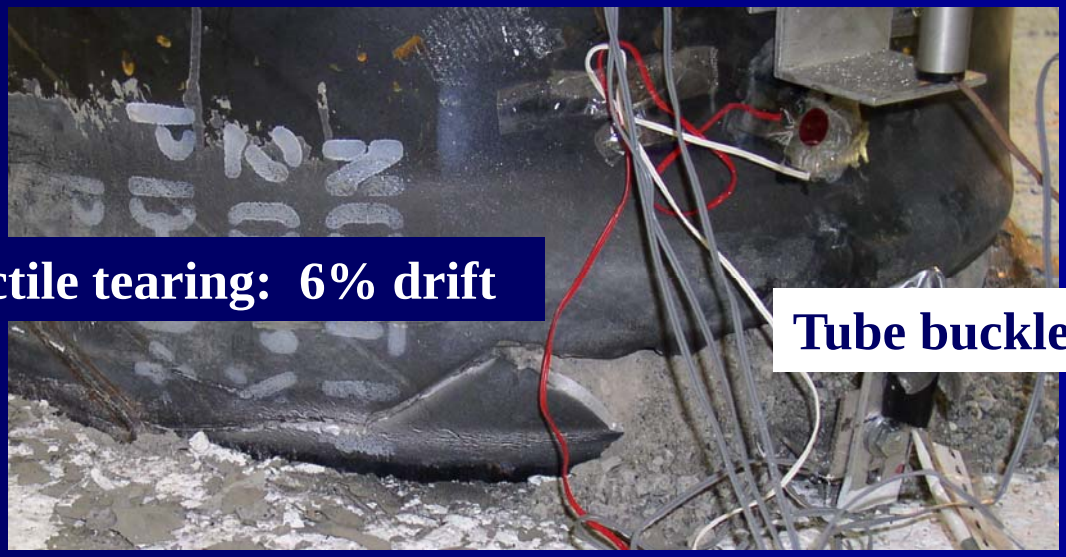
Final state: 8% drift

Response: 0.6D Embedment



Observed Behavior: Deeper Embedment - .9D

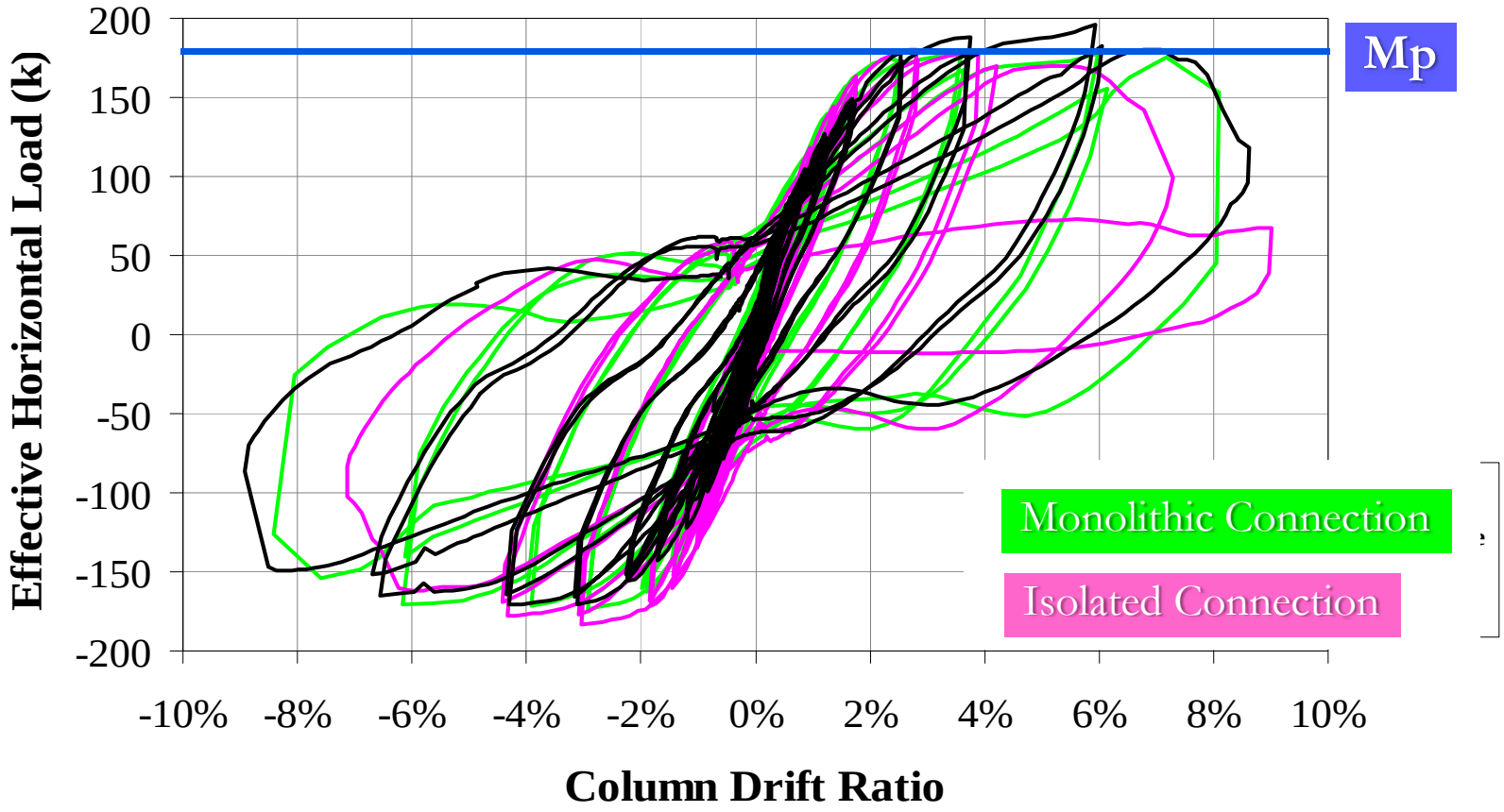
Limited footing damage: 2.5% drift



Ductile tearing: 6% drift

Tube buckles: 4% drift

Isolated vs. Monolithic Connection



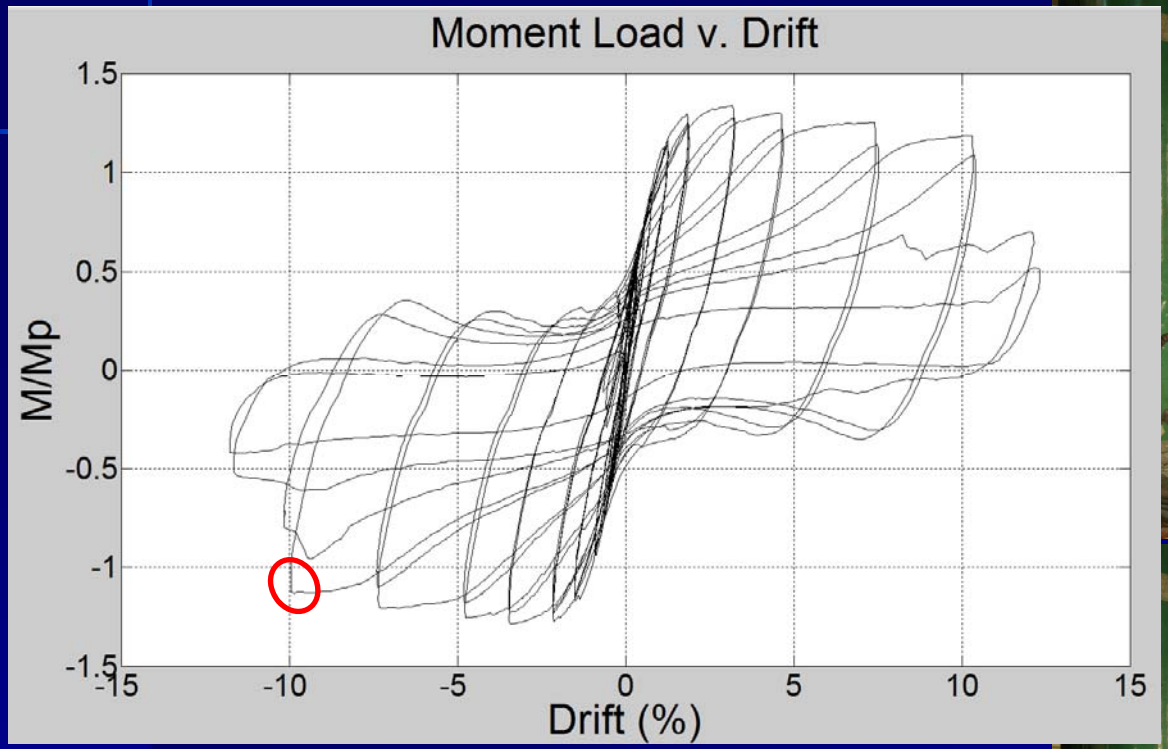
The CFT must be embedded deeply enough to avoid damage to foundation.

Have developed an equation to assure this. Function of strength of concrete and yield stress, diameter, and wall thickness of steel. A key goal of CALTRANS research is refine and verify this equation.

CALTRANS Test Program

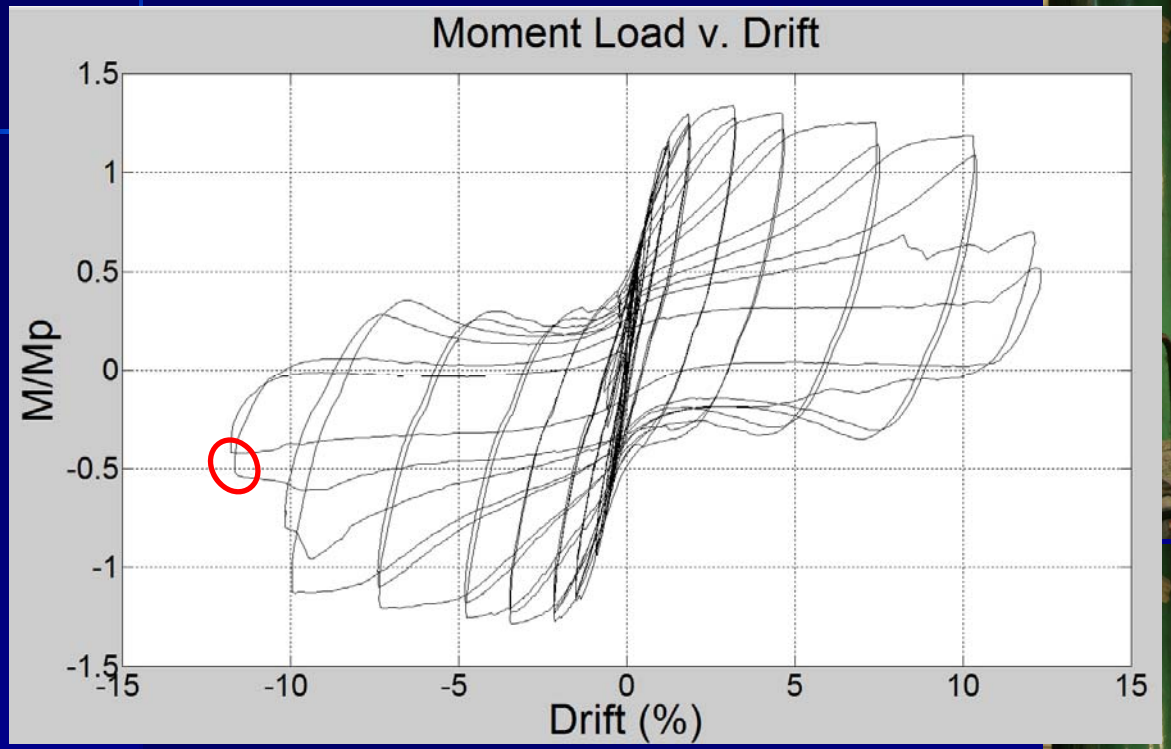
Evaluating piers and pier connections with steel typical of that used in bridge design. Developing design equations. Four tests completed to date – Others in progress

50 KSI –STRAIGHT SEAM WELD TUBE ISOLATED CONNECTION: 10% DRIFT



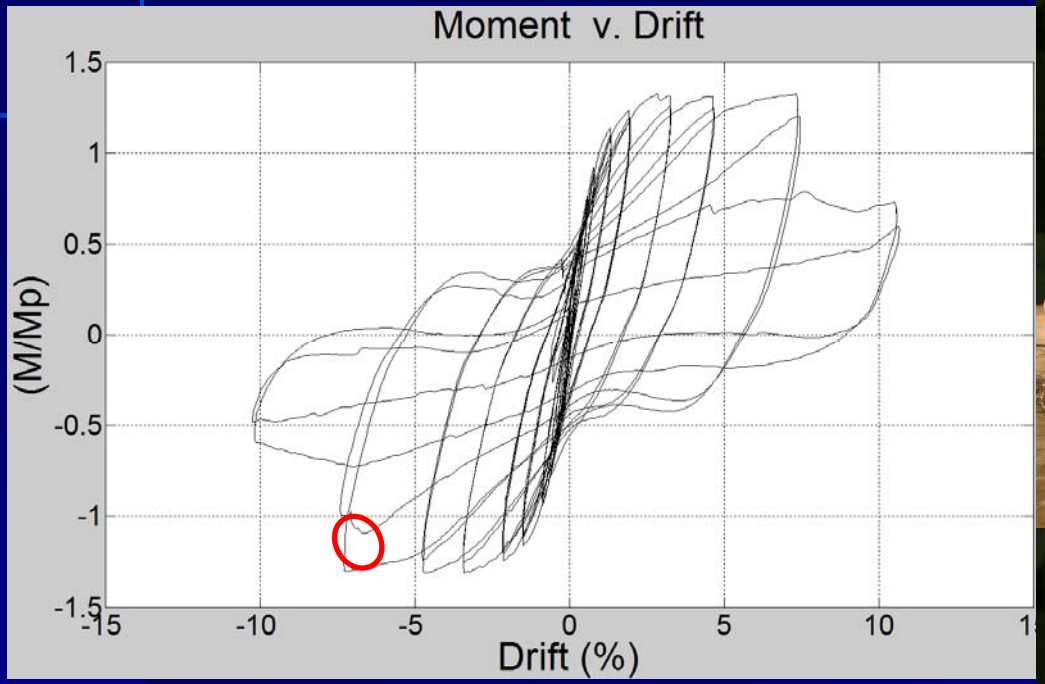
- Moment ≈ 1.18Mp
- 18% of Circumference is Torn

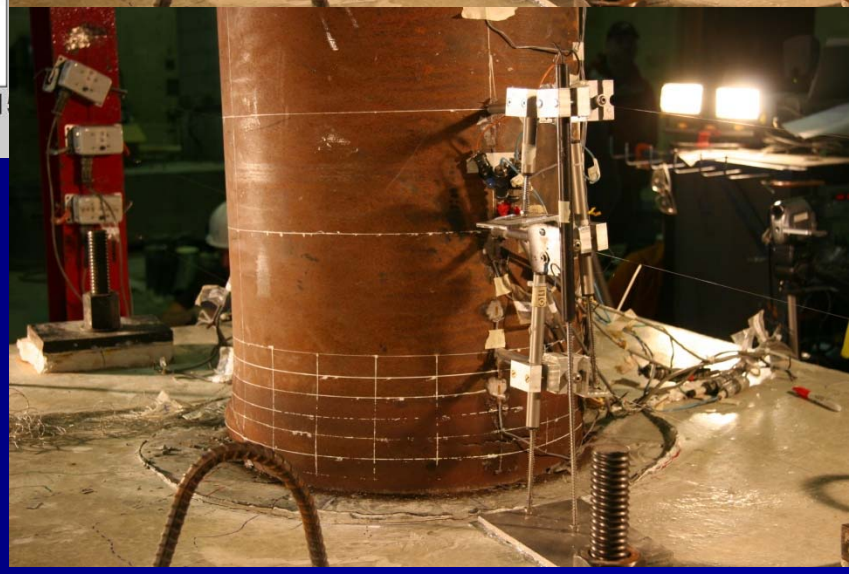
50 KSI –STRAIGHT SEAM WELD TUBE ISOLATED CONNECTION: 12% DRIFT



- Moment ≈ 0.68Mp
- 71% of Circumference is Torn

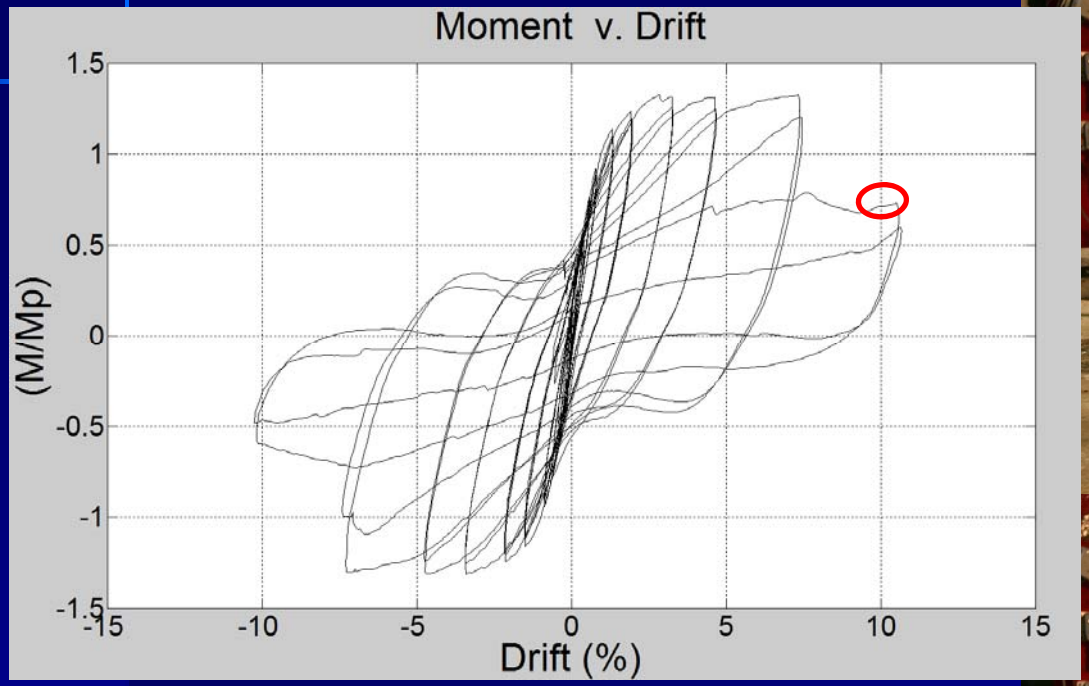
50 KSI – SPIRAL WELDED TUBE ISOLTED CONNECTION 8% DRIFT





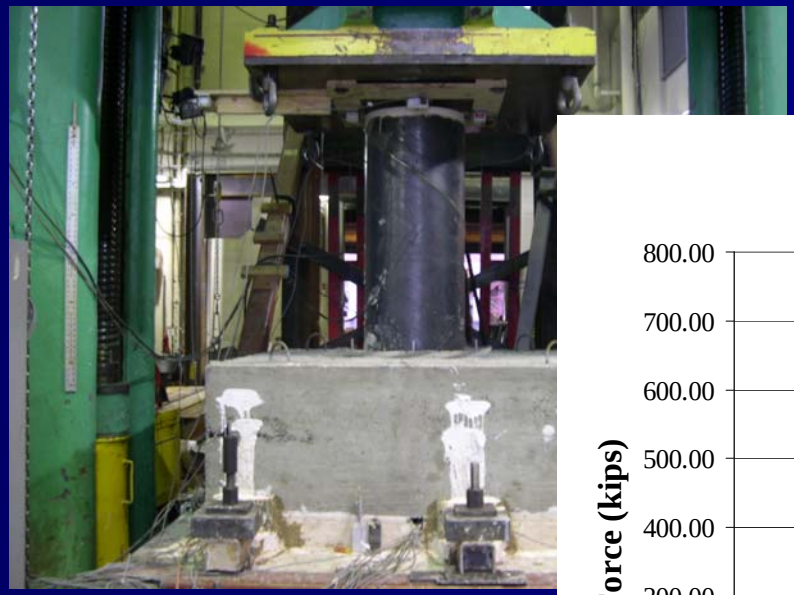
- Moment Demand ≈ 1.3Mp
- Tear Occurs on South Side Approx. 9.5% of Circumference.

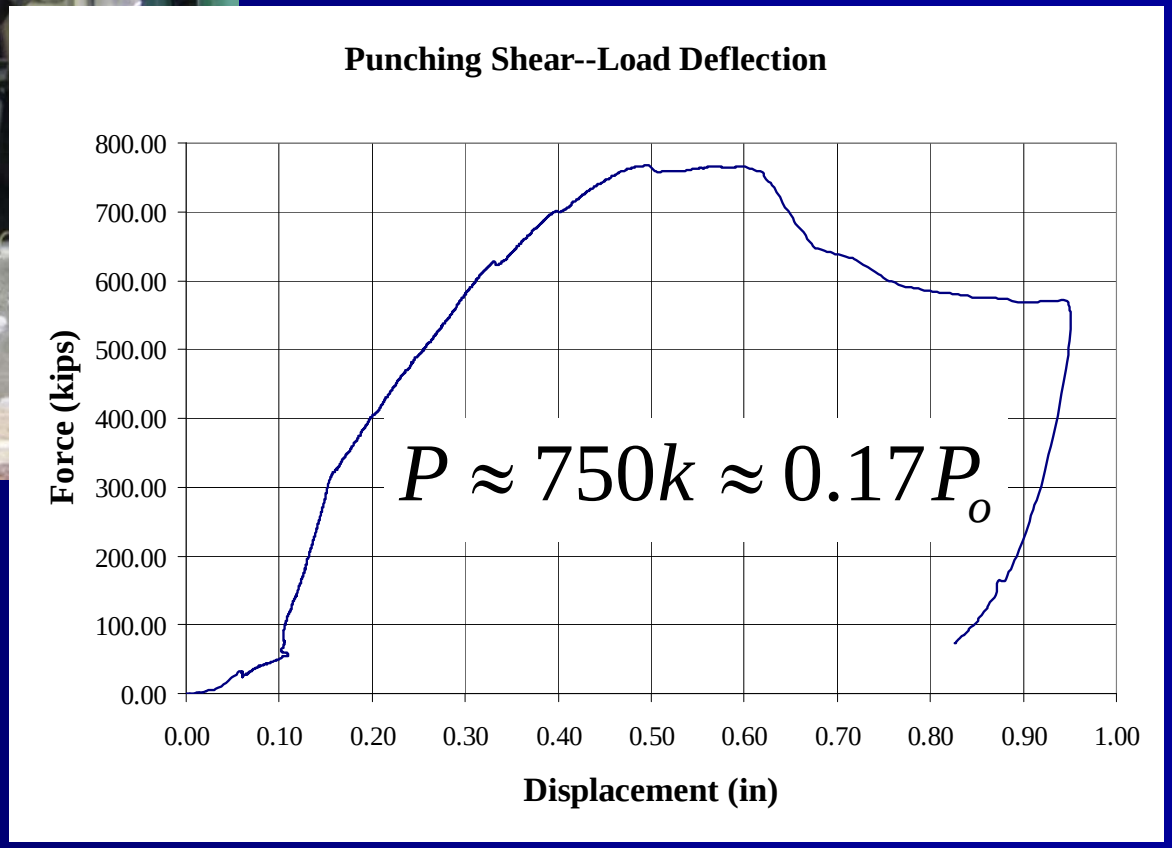
50 KSI – SPIRAL WELDED TUBE ISOLATED CONNECTION 10% DRIFT



- Moment ≈ 0.79 Mp
- ≈ 35% of Circumference Torn on North Side
- ≈ 16% of Circumference Torn on South Side

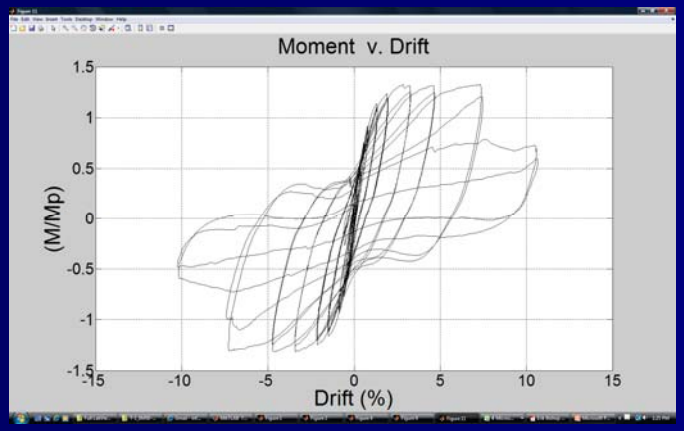
Axial Load Capacity
Punching Through Foundation



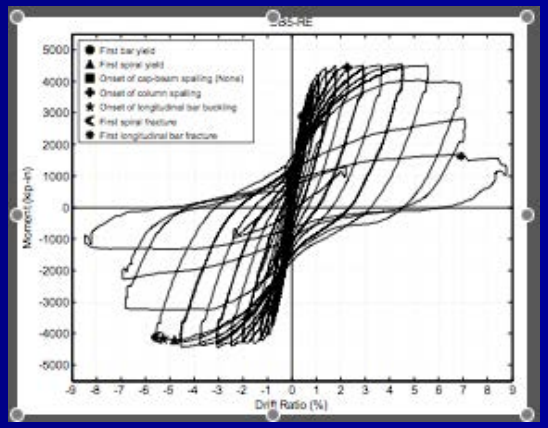


Comparison of CFT and RC Pier Performance – Same diameter, similar aspect ratio

CFT



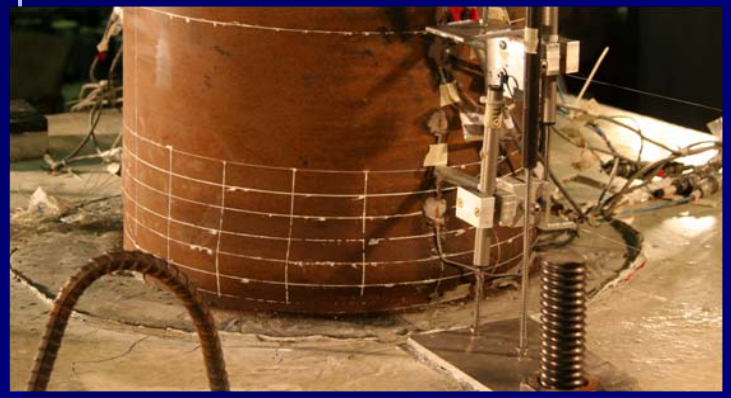
- Well outside allowable AASHTO limits
- Significantly stronger but larger reinforcement ratio
- First significant loss of resistance at 8% drift



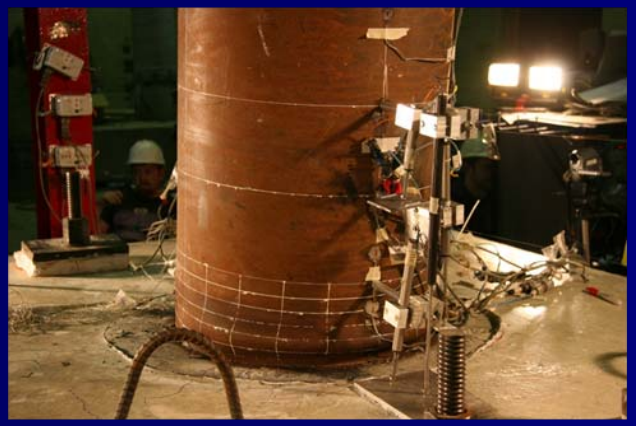
RC Pier

- Note Different Scales
- Satisfies AASHTO seismic
- Significant loss of resistance at 6% drift
- 2.2% total reinforcement (shear + flexure)

Comparison of CFT and RC Pier Performance – Same diamter, similar aspect ratio



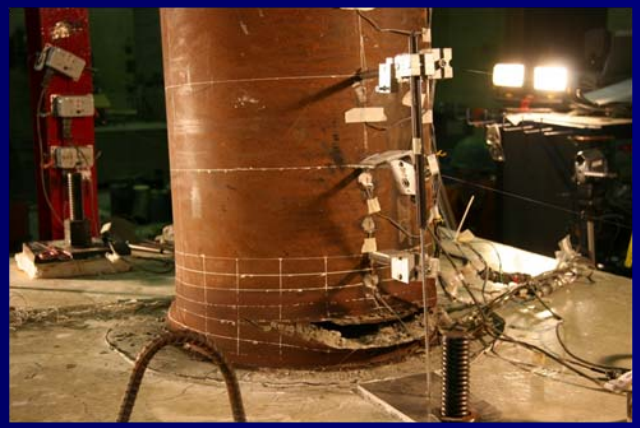
3% Drift



5.5% Drift for RC

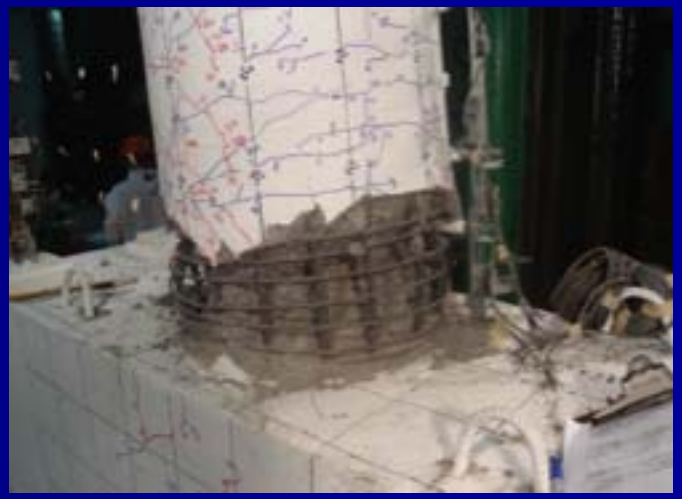
6% Drift for CFT

Comparison of CFT and RC Pier Performance – Same diameter, similar aspect ratio



8.9% Drift RC

10% Drift CFT



CFT: More rapid, cost effective construction

- Concrete fill adds stiffness and restrains buckling of tube
- More strength and stiffness from less material
- Significantly reduced labor requirements
- Better environmental protection -- Concrete placement separated from environmentally sensitive areas -- Longer construction season
- CFT piers and piles can be used in combination with precast concrete caps and framing elements

CFT: More rapid, cost effective construction

- Self-Consolidating concrete reduces construction labor
- Grouted connection permits isolation of construction trades
- Annular ring provides a simple yet effective method to anchor steel tube
- Potential cost savings may be up to 20% relative to traditional reinforced concrete specimen

Initial Conclusions

- CFT offers rapid construction and structural integrity for seismic loading
- Spiral tubes offer numerous advantages of available sizes and geometry - must have matching weld; weld offers supplemental mechanical bond.
- Developed connection offers reduced damage and increased drift relative to RC

Initial Conclusions 2

- Embedment depth is important design parameter for developing foundation and preventing foundation damage
- Lower strength steel tubes achieved higher drift for given D/t ratio
- Failure mechanism is tearing, initial buckling does not reduce capacity.

Initial Conclusions 3

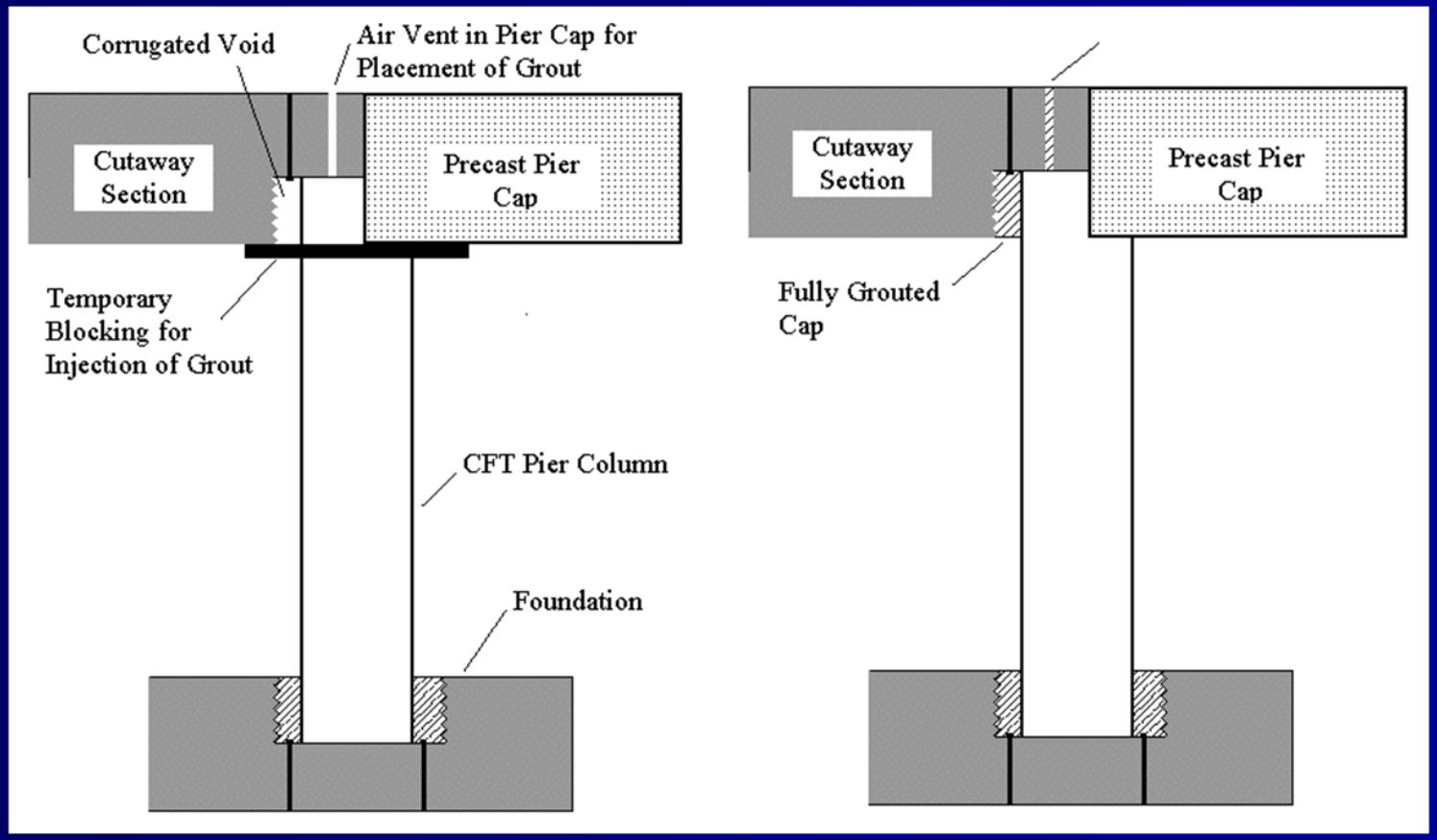
- Isolation construction technique provides excellent performance and reduces required development depth.
- Axial Load Capacity Limited by Foundation Design and Not CFT Capacity

Current Status

Since starting WSDOT research we have made some progress that will benefit both the CALTRANS and WSDOT Research

Research continues with funding by CALTRANS to develop design recommendations for CFT pier and foundation connection. WSDOT funding is directed toward using the resistance of the tube in conjunction with internal reinforcement for deep bridge caissons.

Future Directions: Pier-Cap Connections

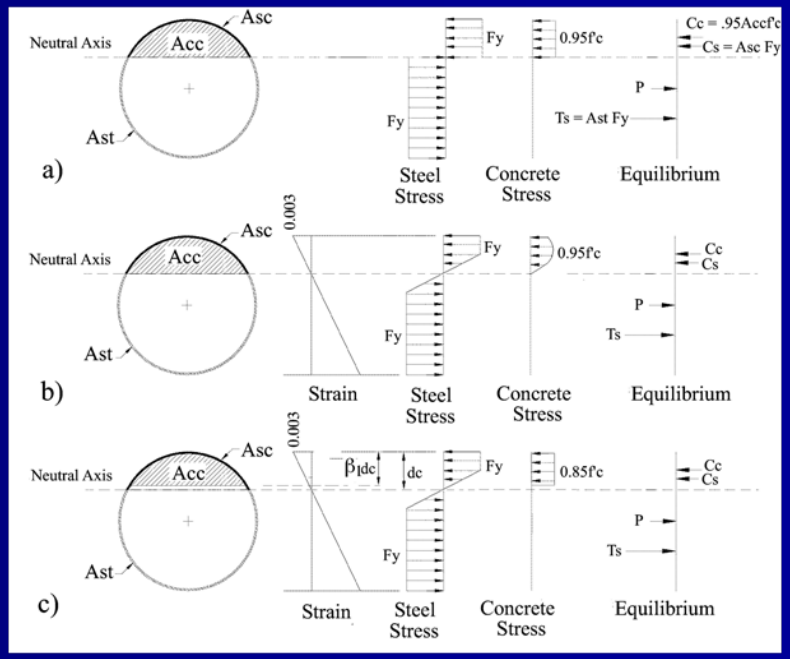


It would be premature to say that CFT bridge piers are completely understood and are ready for widespread application. However, the research has come a long way.

AASHTO LRFD Sections 6.9.5 and 6.12.2 address CFT design methods, and need significant revisions. There are wide variations between AASHTO, ACI and AISC provisions. AASHTO is consistently the most conservative and consistently underestimates the performance of CFT. Should we be considering updating AASHTO LRFD Provisions?

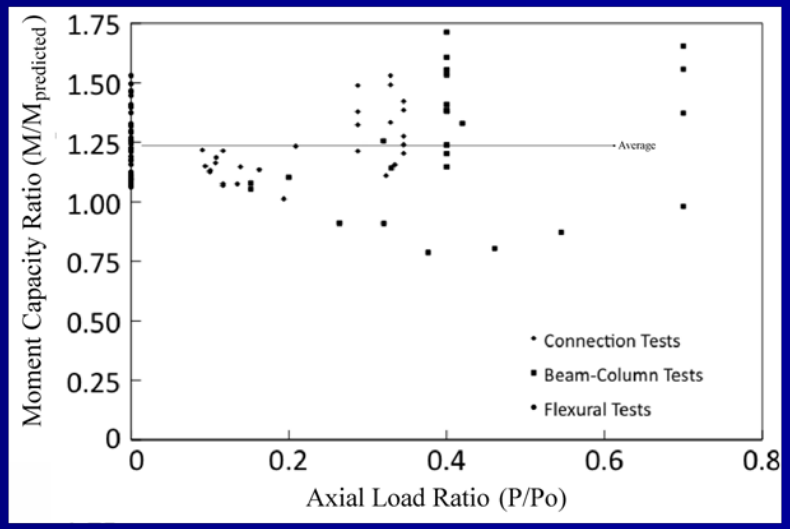
Development of Design Models

- Experimental data from many tests have been obtained
- Different design models have been evaluated and predictions compared to various models



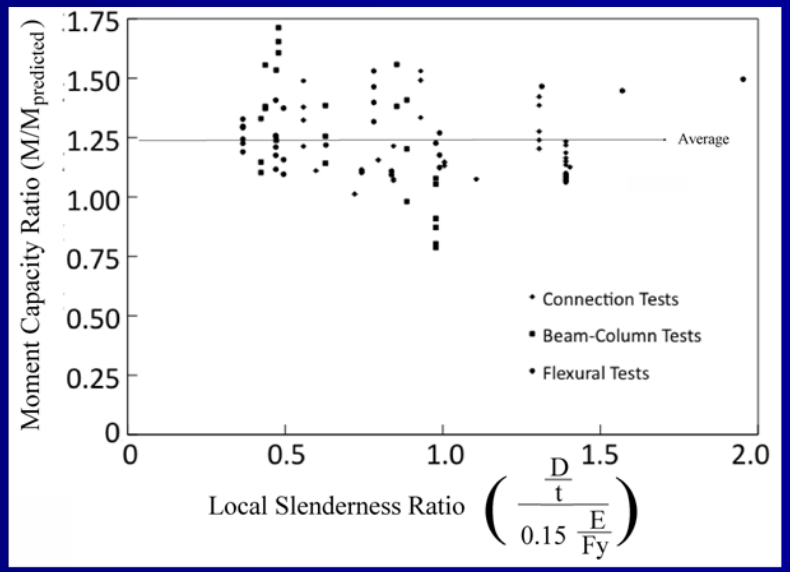
AISC Plastic Stress Distribution Model is Consistent Simpler and More Accurate

- Model conservatively predicts resistance
- Given axial load the model underestimates moment capacity by average of 24%
- Stability must be considered separately
- Specimens with ratios less than 1.0 controlled by stability

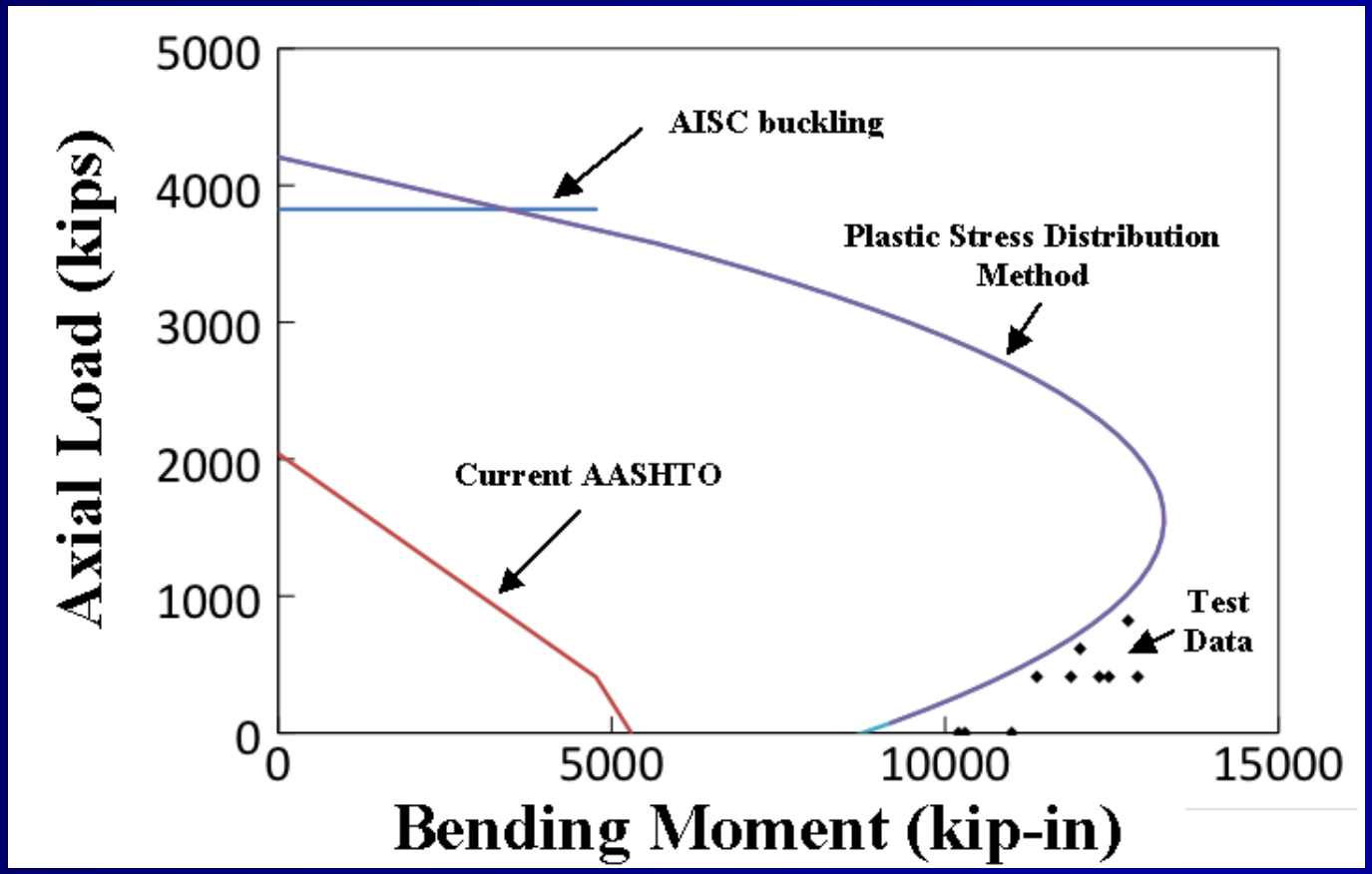


Local and Global Slenderness Must Be Considered

- Since plastic stress distribution is material model, it does not consider local or global slenderness and buckling
- Specimens with ratios less than 1.0 are controlled by buckling



Comparison –

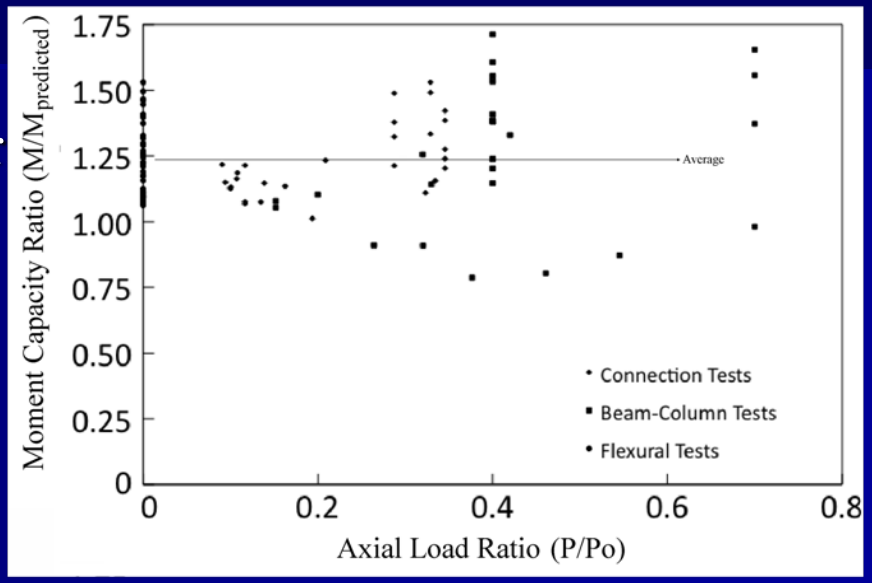

5000
4000
3000
2000
1000
0
Axial Load (kips)
0
5000
10000
15000
Bending Moment (kip-in)
AISC buckling
Plastic Stress Distribution Method
Current AASHTO
Test Data

D/t Slenderness Limits

- AASHTO has more restrictive D/t limits than ACI and AISC
- AISC is most generous
- However, CFT consistently develops full plastic capacity with D/t ratios at AISC limit
- With Grade 50 steel
  - **AISC – 87**
  - **ACI – 68**
  - **AASHTO - 48**

Flexural and Bending Capacity

- AASHTO has much lower resistance limits than ACI and AISC
- AISC is most generous
- Experiments show that CFT members always exceed the capacity predicted by the AISC plastic stress method as long as buckling does not control



- Average CFT resistance is 24% larger than predicted by AISC plastic stress method

Developed Simple Models for Accurately Predicting Resistance

$$r_m = r - \frac{t}{2}$$

$$\theta = \sin^{-1}\left(\frac{y}{r_m}\right)$$

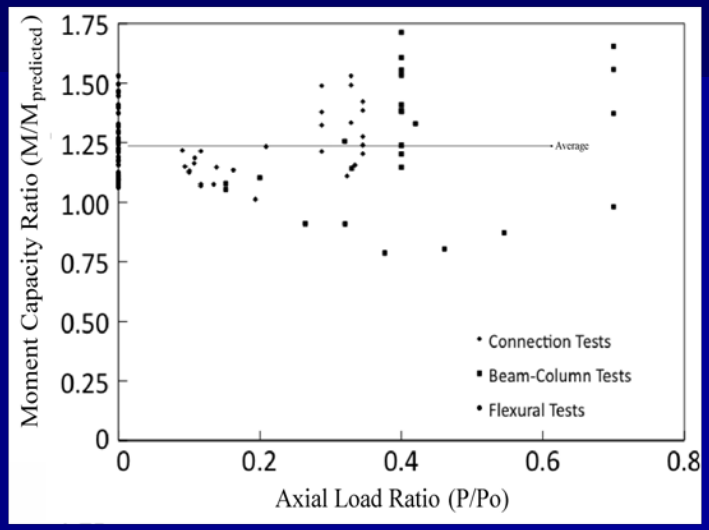
$$c = r_i \cos\theta$$

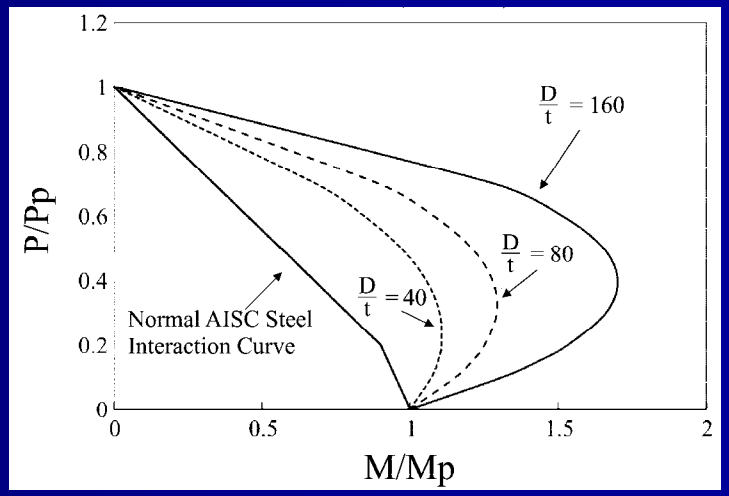
$$P = F_y t r_m \left\{(\pi - 2\theta) - (\pi + 2\theta)\right\} + \frac{0.95 f_c^{'}}{2}\left\{(\pi - 2\theta) r_i^2 - 2yc\right\}$$

$$M = 0.95 f_c^{'} c \left\{\left(r_i^2 - y^2\right) - \frac{c^2}{3}\right\} + 4 F_y t c \frac{r_m^2}{r_i}$$

Equations are accurate and conservative

- Results in Axial Load-Bending Moment interaction curves which are similar to those achieved by ACI provisions
- Ultimate resistance from experiments is 24% larger than predicted by design equations





Developed and Verified Simple and Accurate Models for Stiffness

$$EI_{eff} = E_s I_s + C' E_c I_c$$

$$C' = 0.15 + \frac{P}{P_0} + \frac{A_S}{A_S + A_C} < 0.9$$

- Significantly more accurate than current AISC, ACI and AASHTO Equations

- Verified by comparison to results of 50 past experiments

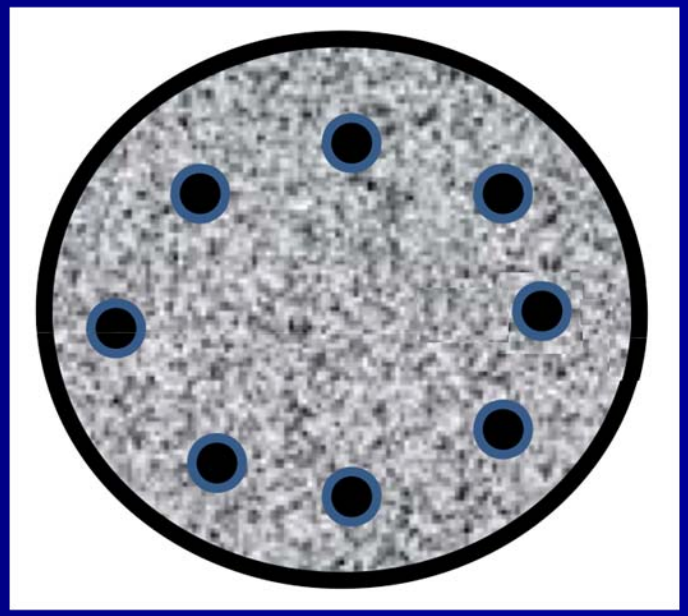
Currently Working with AASHTO T-14 Committee to prepare possible updates to current provisions

WSDOT study is focused on CFT with rebar inside the tube

WSDOT Study

- Existing literature examined
  - **Many tests on CFT**
  - **But no reliable date on CFT with internal reinforcement**
- Therefore, research based on the experimental results and analytical procedures from CFT and high resolution nonlinear FEM analysis

- Existing literature examined and no reliable data for CFT with internal rebar
- Building recommendations based on the experimental results and analytical procedures from CFT and nonlinear FEM analysis



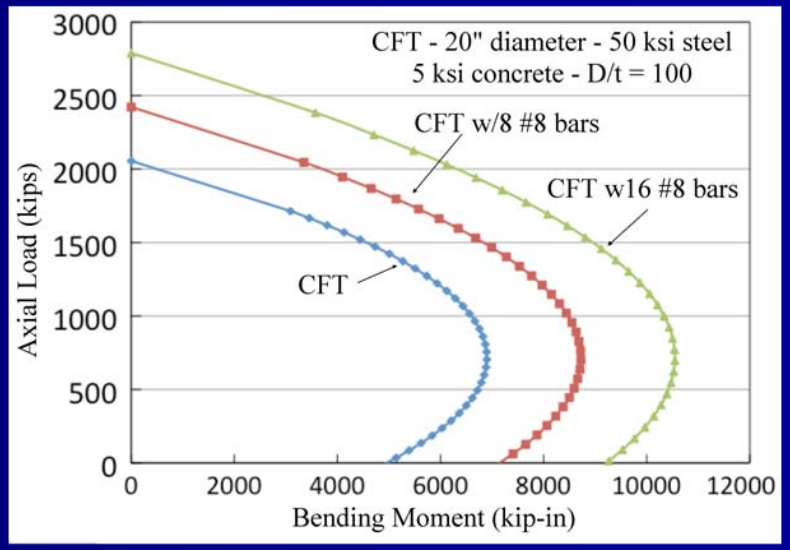
Plastic Stress Distribution Model has been Extended to Include Internal Rebar

Model Development

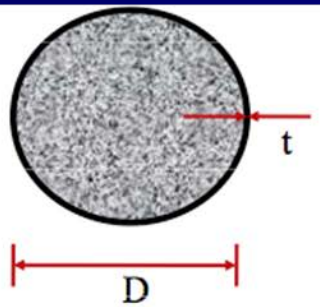
- Same basic procedures but use a tube within a tube to simulate internal reinforcement.
- Closed form equations developed – but not a single equation – allows development of interaction curves as with CFT
- Results verified by nonlinear analyses

Plastic Stress Distribution Comparison

- Shows that the CFT shell dominates the resistance
- Large amount of internal steel needed to develop resistance of CFT

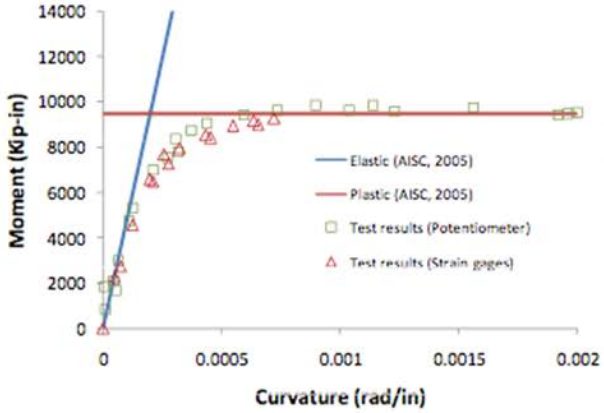


FEM Model was Verified by Comparison to CFT Tests

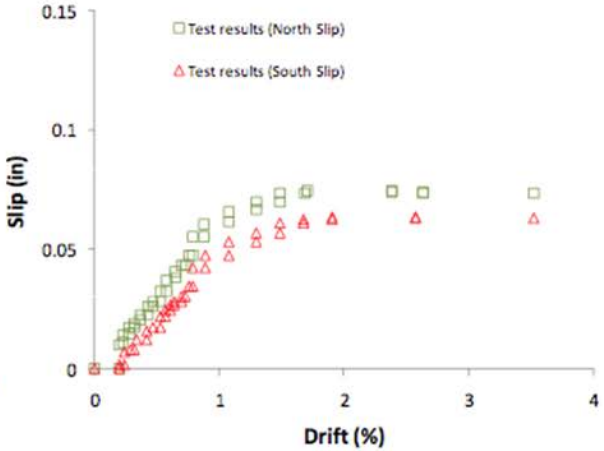


- D=20in; t=0.25in; D/t=80; L=18'
- f_y (for Steel)=75.6ksi; f_u (for Steel)=84.8ksi;
- f_c' (for Concrete)=12.2ksi
- **M_p=9,446.9 Kips-in (From AISC Spec.)**
- **EI_{eff}=52,127,551.4 kips-in² (From AISC Spec.)**

- **Test Results**



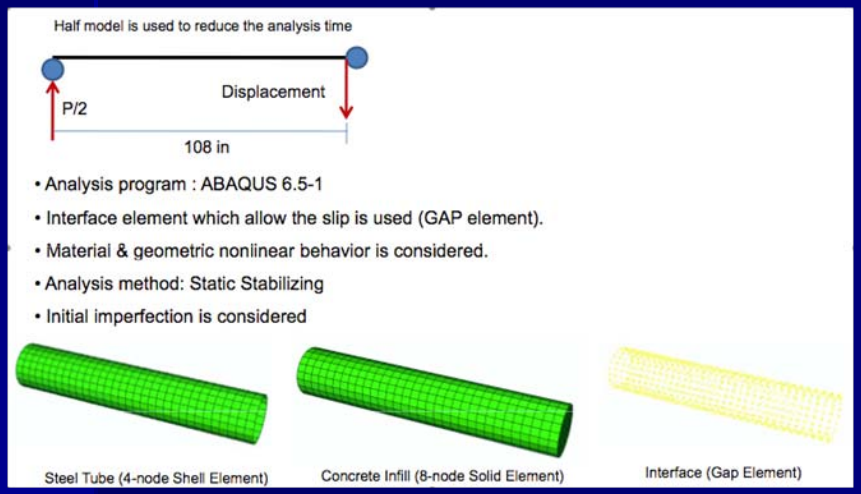
Moment-Curvature relationship



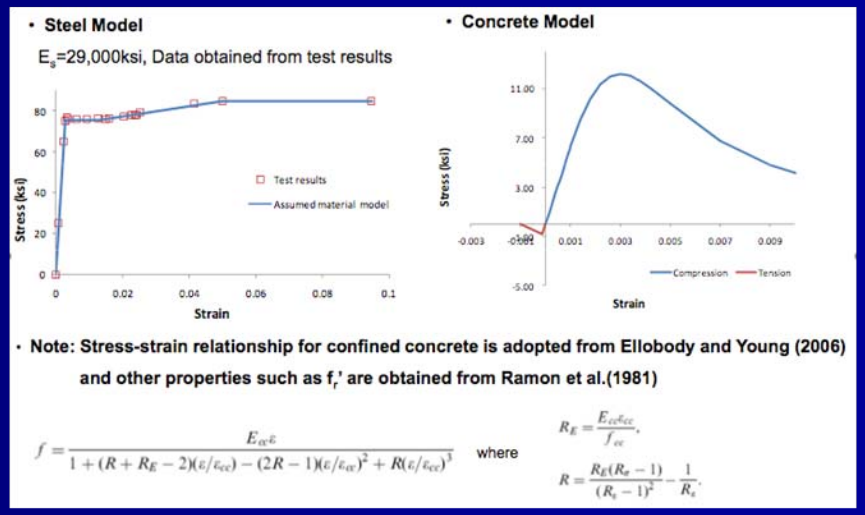
Variation of slip with drift

FEM Model was Verified by Comparison to CFT Tests

Model



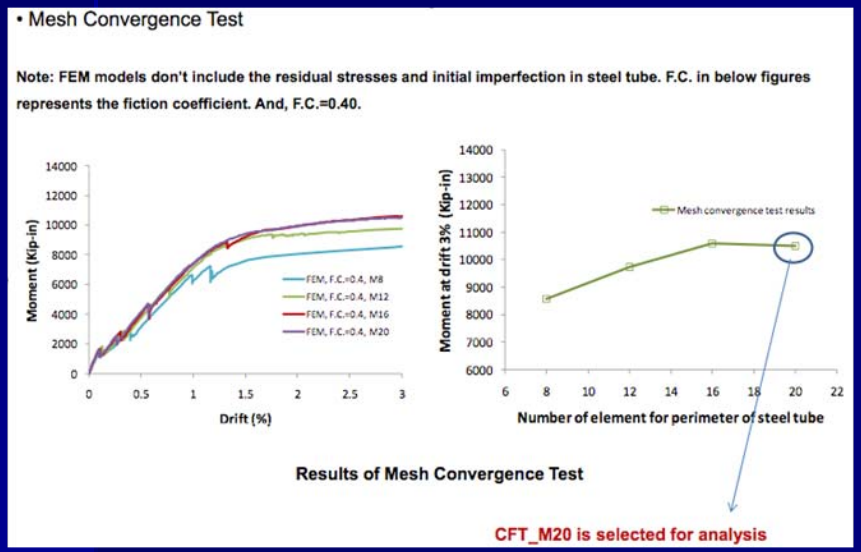
Material Model

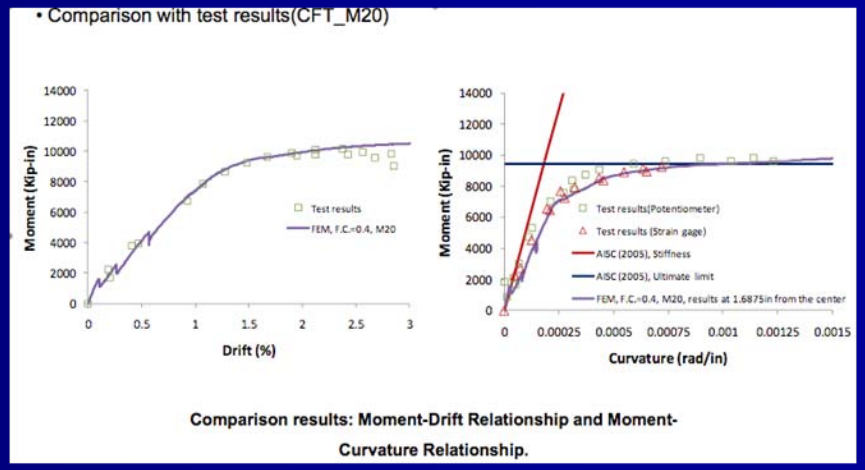


FEM Model was Verified by Comparison to CFT Tests

Convergence and Mesh Refinement

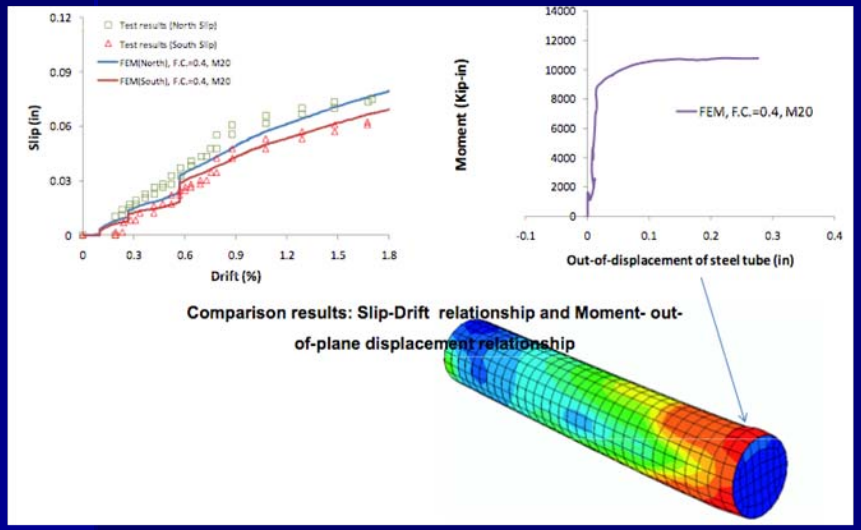
Specific Comparison with Test Results



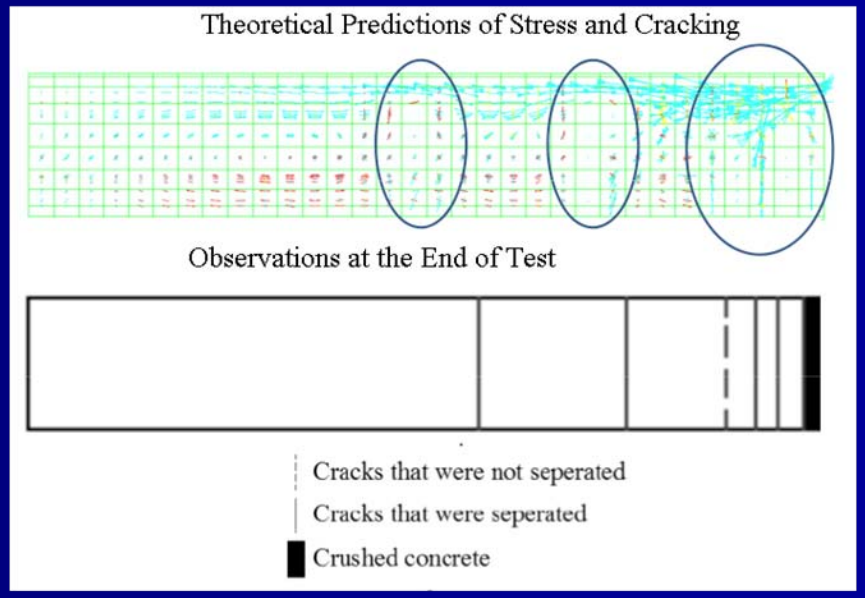


FEM Model was Verified by Comparison to CFT Tests

Comparison of Slip and Friction

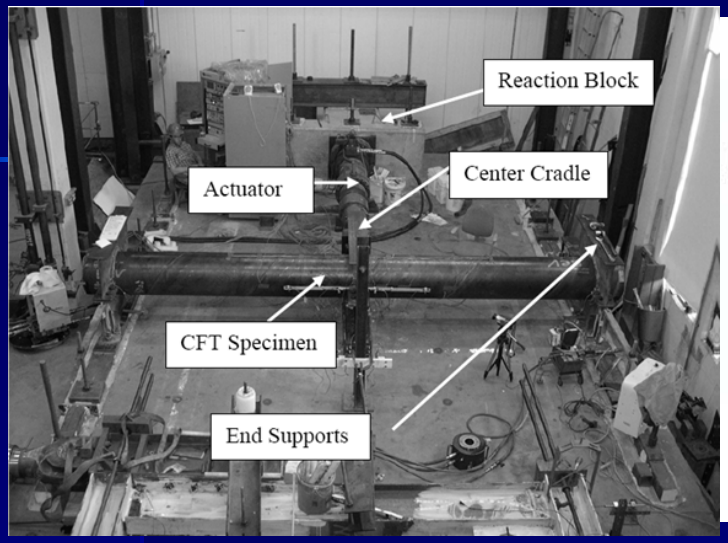


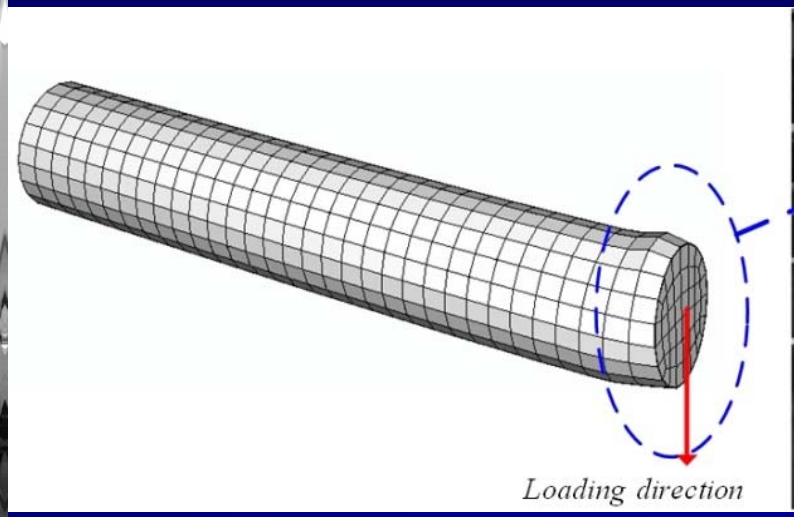
Comparison of Cracking and Crushing



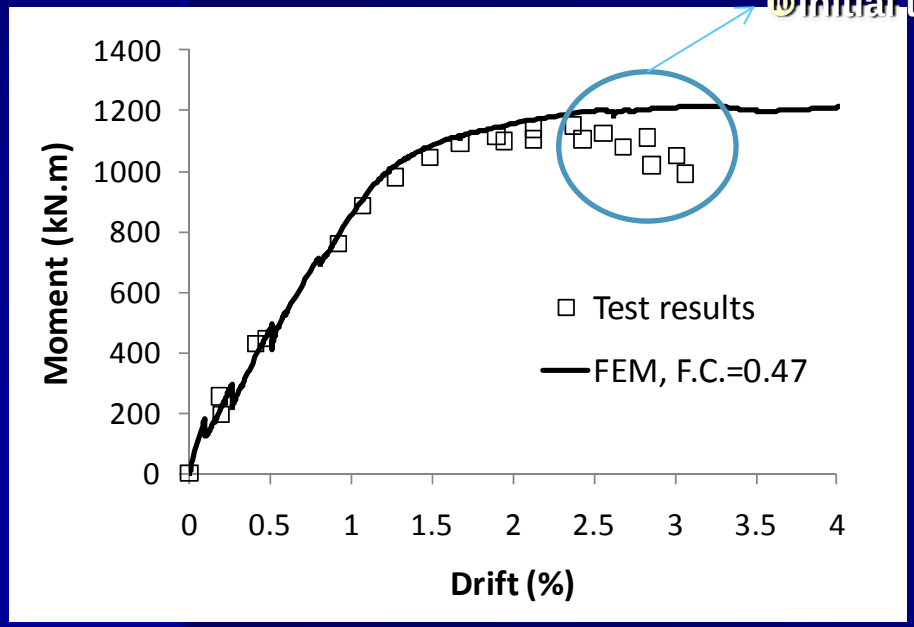
⑩Model, B.C. condition and verification 3/3

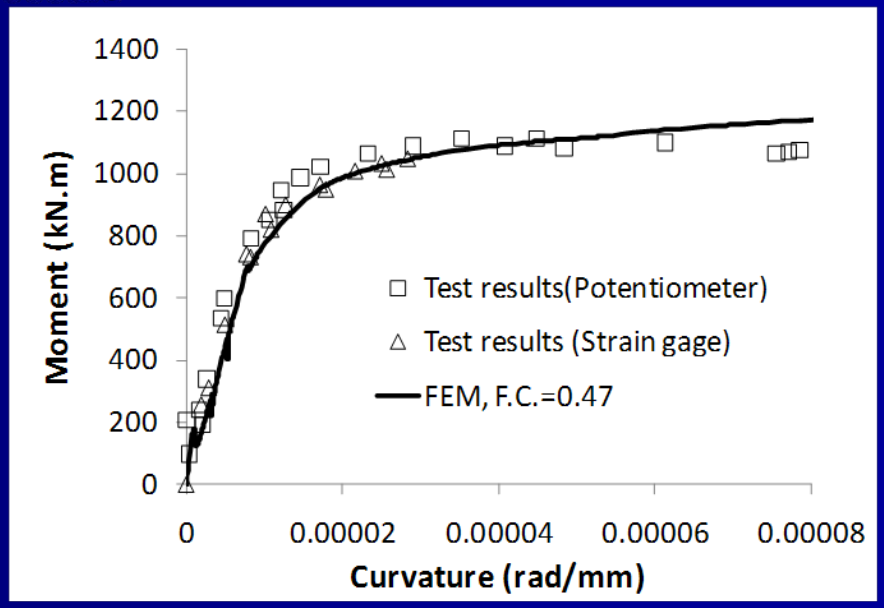
- **Comparison with experimental work (It is noted that the specimen has no reinforcement)**





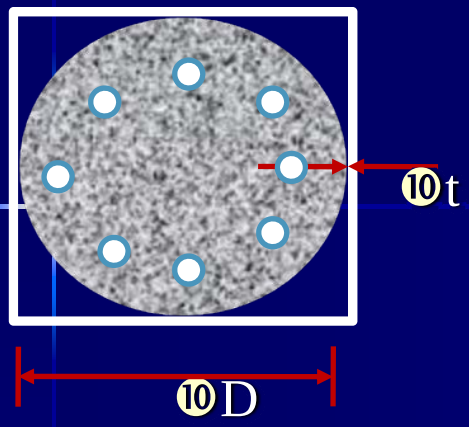
⑩Initial tear occurs





After this comparison we feel pretty confident of the reliability of FEM analysis

⑩ Variables for parametric study 1/3



- D=20in; t=0.25, 0.1875, and 0.125 in; D/t=80; L=18'
- f_y (for Steel)=70ksi
- f_y (for rebar)=60ksi
- f_c' (for Concrete)=10ksi
- Distance from outside of concrete infill to rebar is 2 in

Model	D (in)	t (in)	D/t	f_y (ksi)	f_c'(ksi)	f_y/f_c'	F.C.	ϱ (%)
RM1	20	0.25	80	70	10	7	0.47	0.5
RM2	20	0.25	80	70	10	7	0.47	1
RM3	20	0.25	80	70	10	7	0.47	1.5
RM4	20	0.25	80	70	10	7	0.47	2

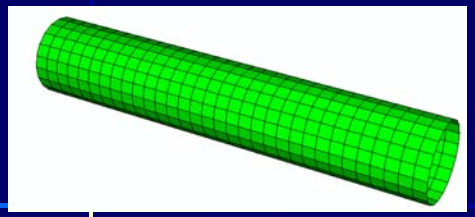
⑩ Variables for parametric study 2/3

Model	D (in)	t (in)	D/t	f_y (ksi)	f_c'(ksi)	f_y/f_c'	F.C.	ϱ (%)
RM5	20	0.1875	107	70	10	7	0.47	0.5
RM6	20	0.1875	107	70	10	7	0.47	1
RM7	20	0.1875	107	70	10	7	0.47	1.5
RM8	20	0.1875	107	70	10	7	0.47	2
RM9	20	0.125	160	70	10	7	0.47	0.5
RM10	20	0.125	160	70	10	7	0.47	1
RM11	20	0.125	160	70	10	7	0.47	1.5
RM12	20	0.125	160	70	10	7	0.47	2

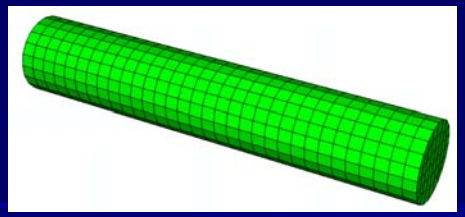
⑩ Variables for parametric study 3/3

Model	D (in)	t (in)	D/t	f_y (ksi)	f_c'(ksi)	f_y/f_c'	F.C.	ϱ (%)
B1	20	0	∞	70	10	7	0.47	0.5
B2	20	0	∞	70	10	7	0.47	1
B3	20	0	∞	70	10	7	0.47	1.5
B4	20	0	∞	70	10	7	0.47	2

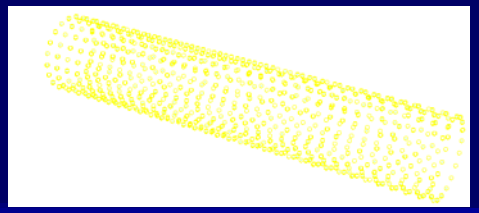
⑩Model, B.C. condition and verification 1/3



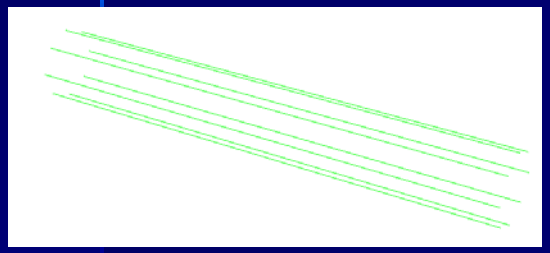
• Steel Tube (Shell element)



• Concrete infill(Solid element)

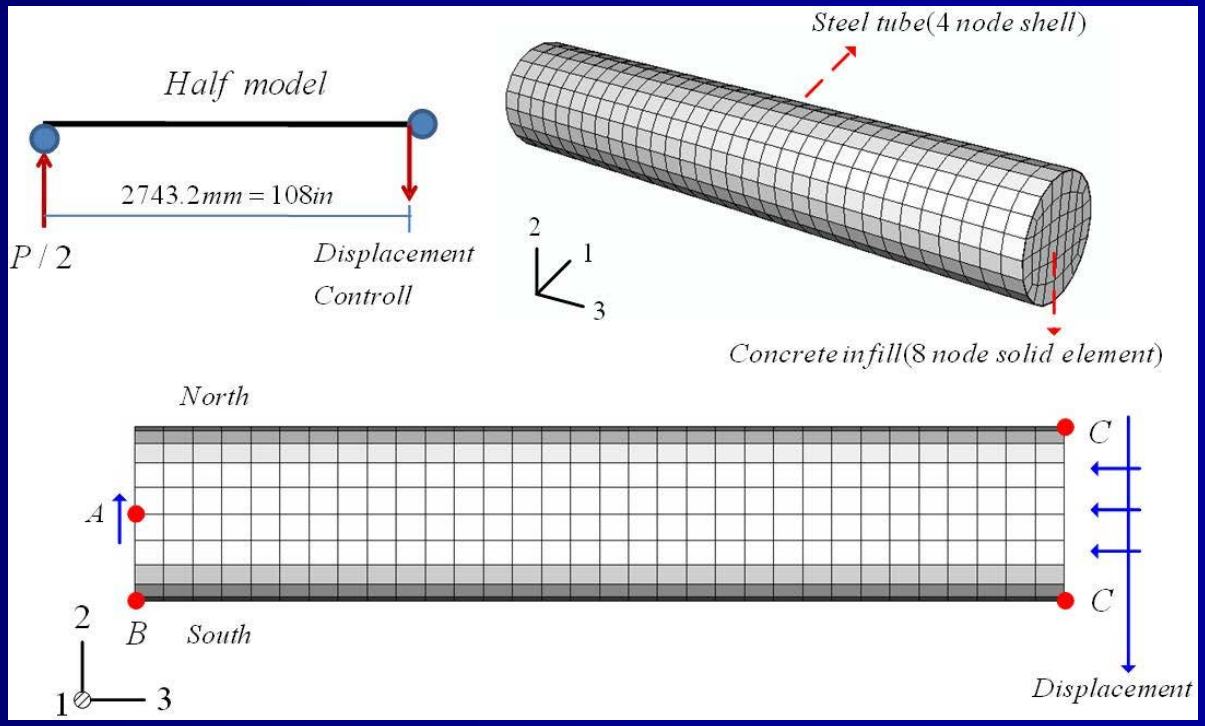


• Interface (Gap element)



• Rebar (Truss element)

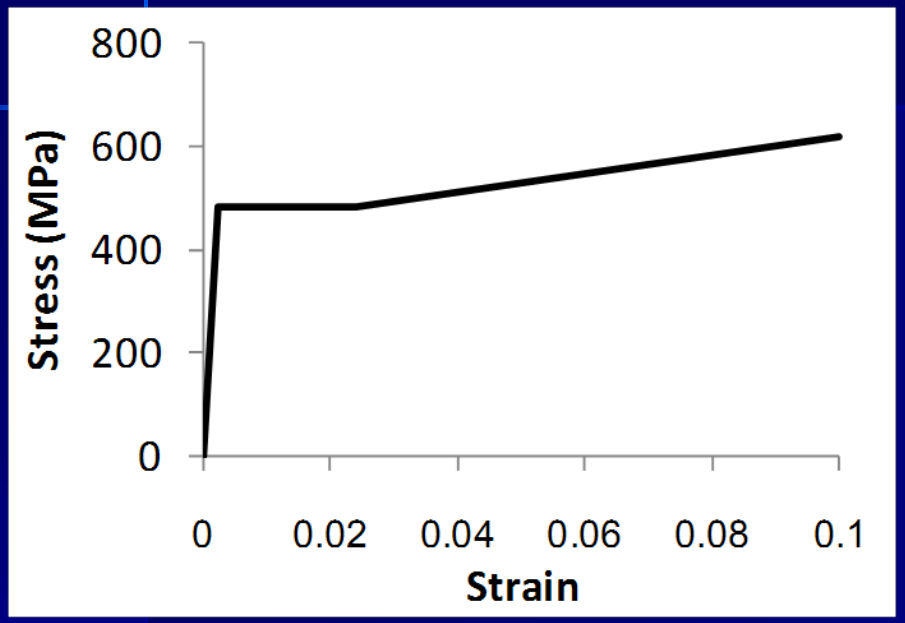
• fy=413.4Mpa(=60ksi)



• Typical mesh and B.C. condition

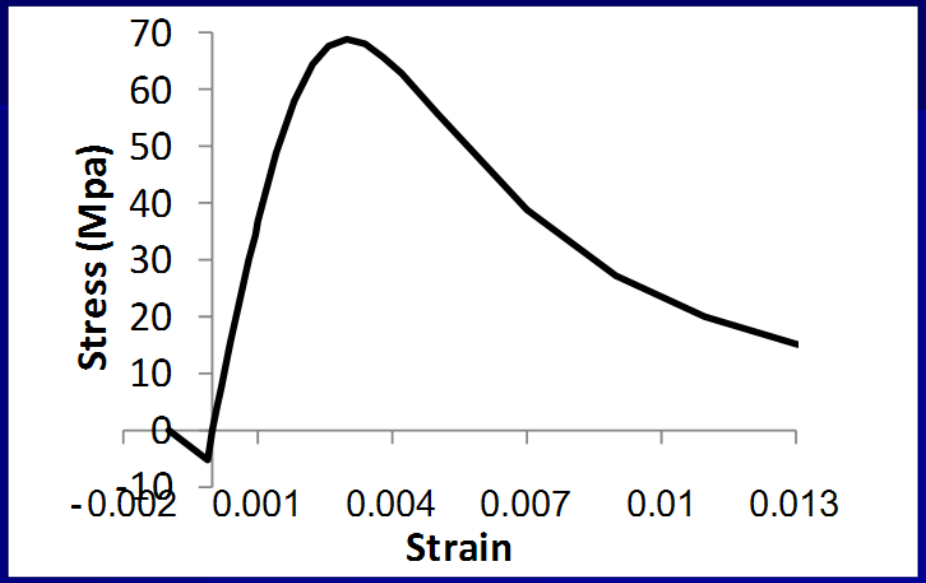
⑩Model, B.C. condition and verification 2/3

- **Steel Model for tube**



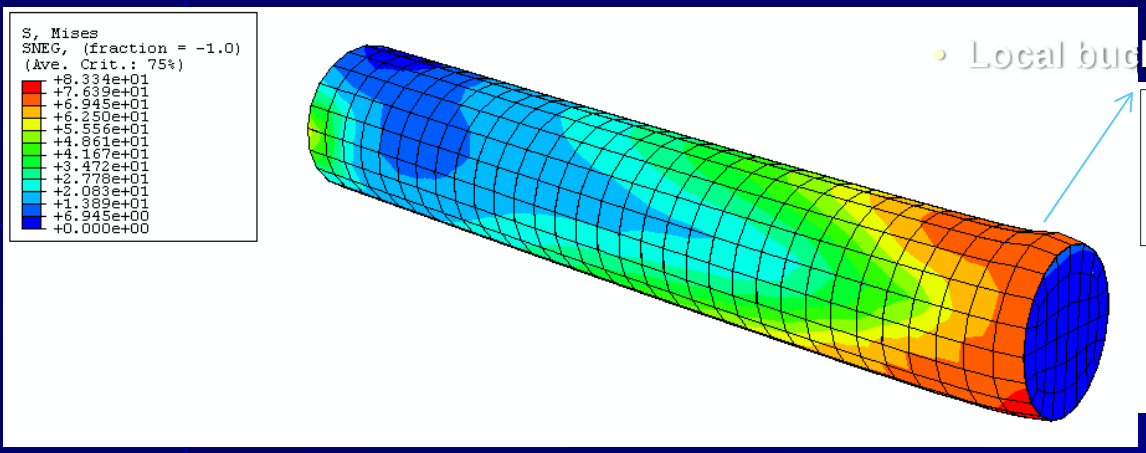
- **70 ksi steel: fy=482.3Mpa(=70ksi)**
- **fu=620.1Mpa(=90ksi)**

- **Concrete Model**

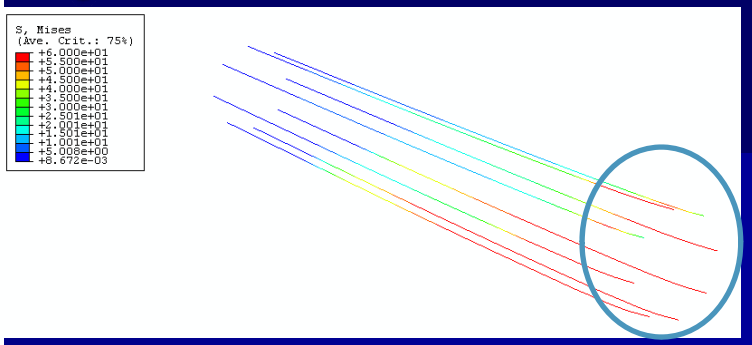


- **Tensile stress reaches zero when tensile strain is equal to 0.001**
- **fc'=68.9Mpa=10ksi**

⑩Analysis results 1/4

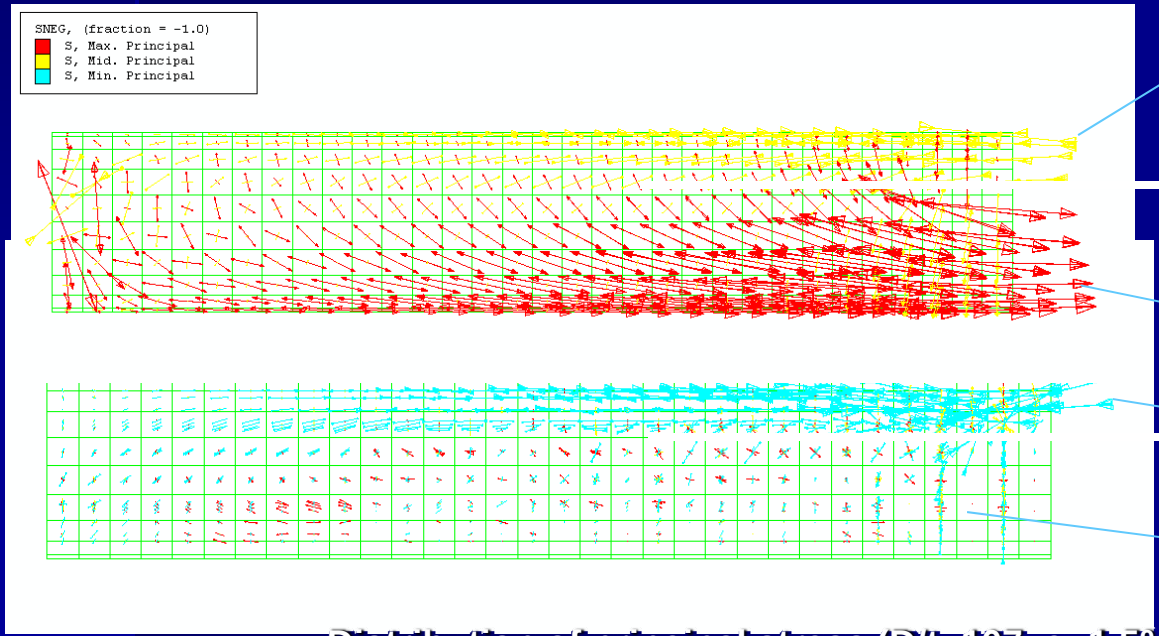


- Local buckling occurs



- yielding of rebar

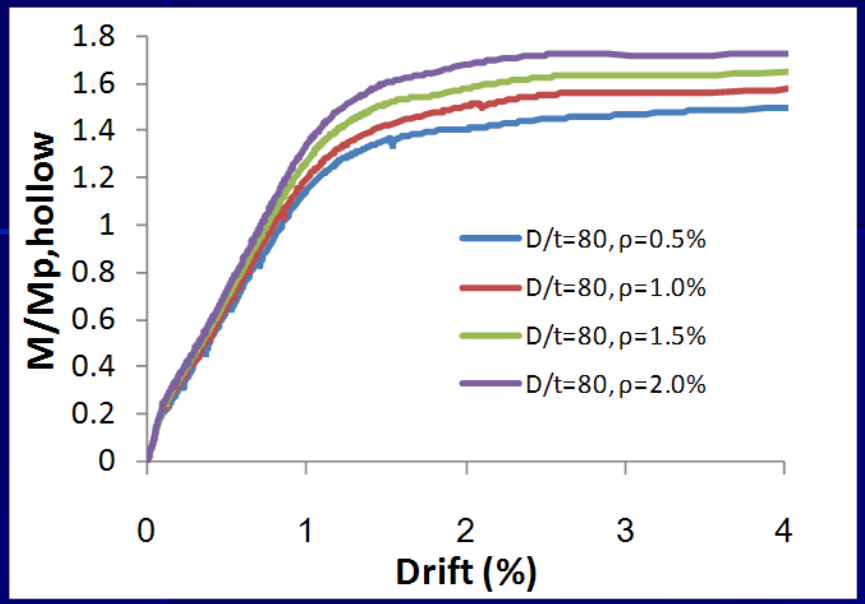
- Deformed shape and stress distribution (D/t=107, ρ=1.5%)

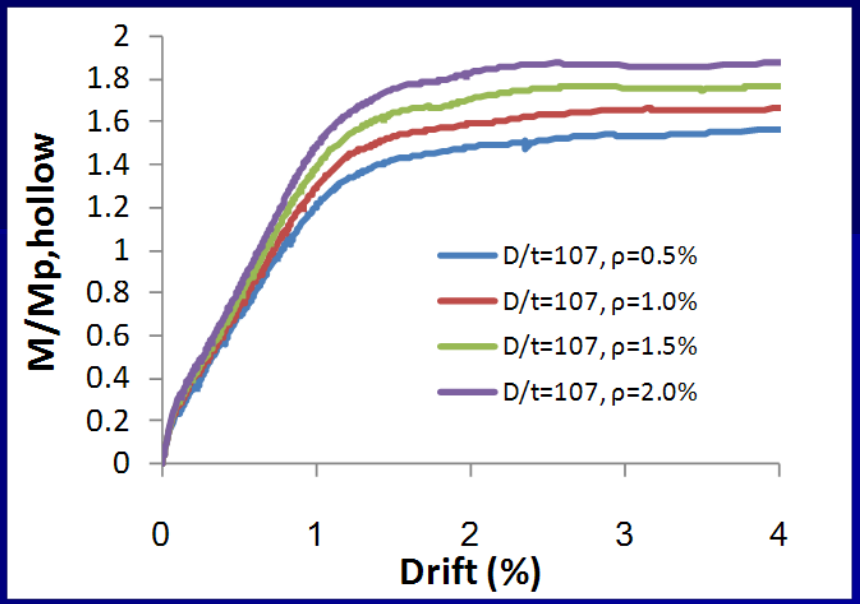


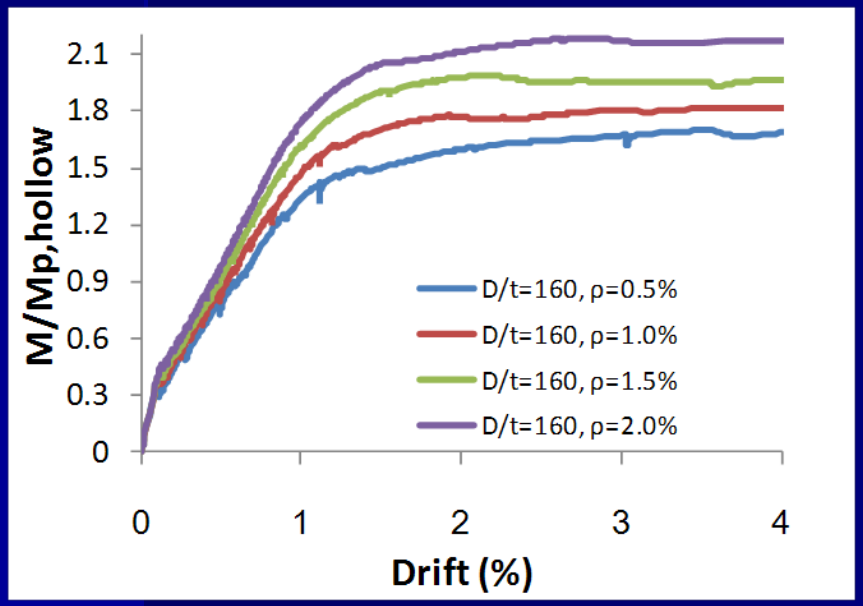
- Compression
- Zero stress line
- Tension
- Compression
- Zero stress line
- Crack occurs

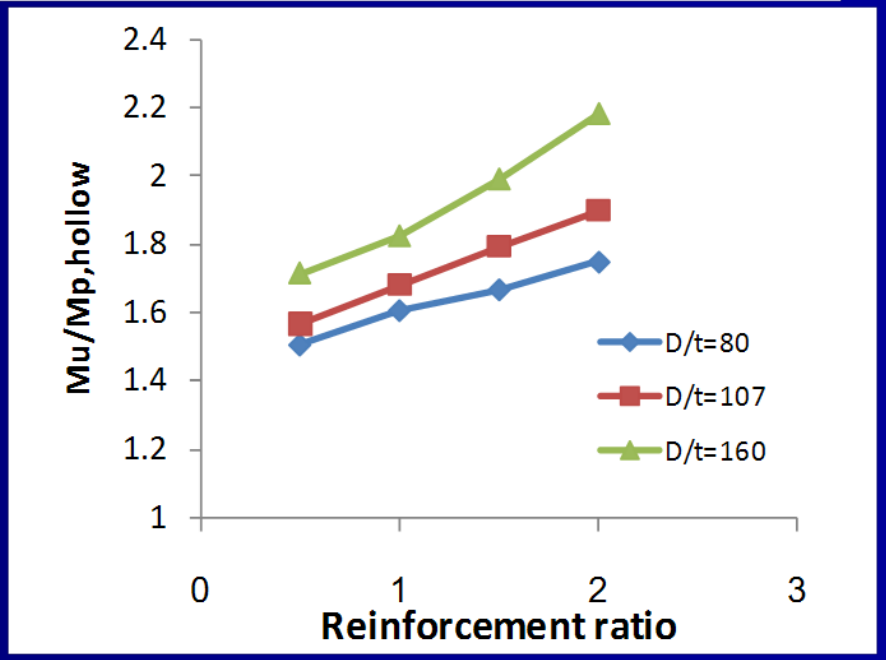
- Distribution of principal stress (D/t=107, ρ=1.5%)

⑩Analysis results 2/4

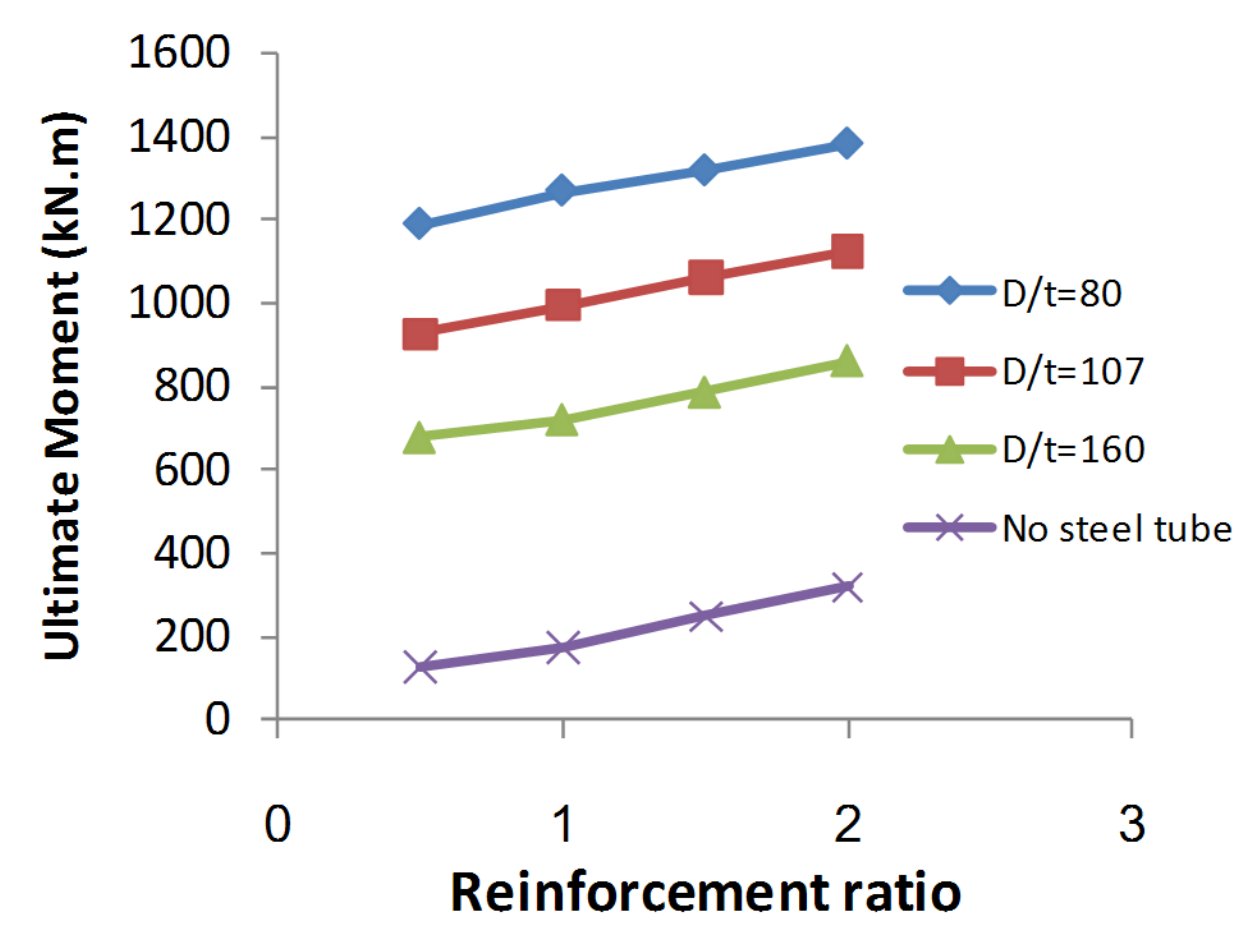




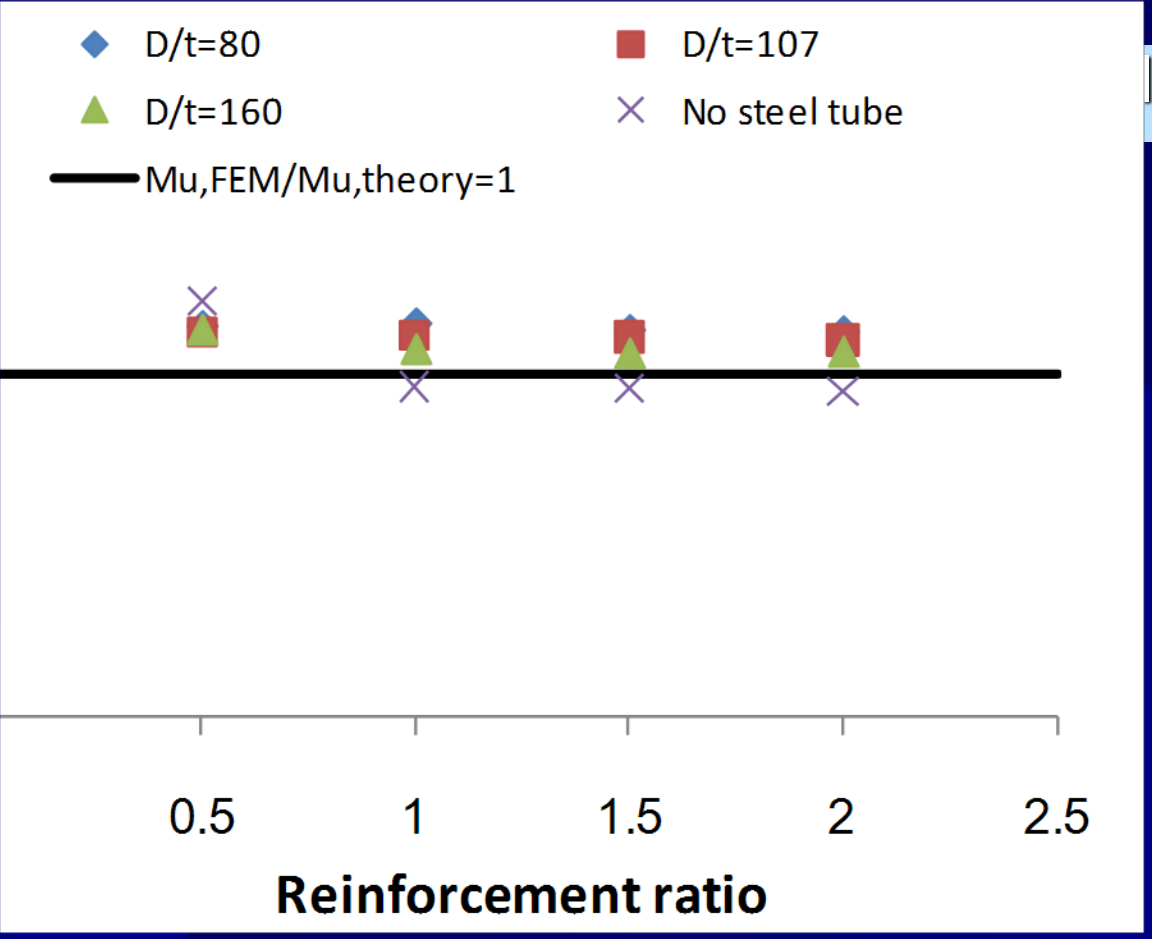




⑩Analysis results 3/4



lts 4/4


D/t=80
D/t=107
D/t=160
No steel tube
Mu,FEM/Mu,theory=1
0.5
1
1.5
2
2.5
Reinforcement ratio

Comparison of FEM and Plastic Stress Distribution Predictions

- Conservatism predicted by the FEM analysis with the plastic distribution method is comparable to that obtained for CFT experiments

D/t & ρ	M_{FEM} (k-in)	M_{PS} (k-in)	M_{FEM}/M_{PS}
80, 0.5%	10511	9237	1.14
80, 1.0%	11221	9794	1.15
80, 1.5%	11652	10344	1.13
80, 2.0%	12223	10887	1.12
106.7, 0.5%	8202	7307	1.12
106.7, 1.0%	8799	7896	1.11
106.7, 1.5%	9389	8475	1.11
106.7, 2.0%	9950	9046	1.10
160, 0.5%	5986	5288	1.13
160, 1.0%	6366	5918	1.08
160, 1.5%	6948	6534	1.06
160, 2.0%	7619	7137	1.07

Discussion?

- Made pretty good progress thus far but more work is needed
- Appears to be huge benefit in including the tube in caisson calculation. Analysis supports this benefit but no experimental results are available. A limited series of experiments would be beneficial and cost effective

- Stress-Strain, curvature or other analytical models are needed. The behavior of these CFT elements are different than typical RC element. The form of these models may be different.

THANK YOU