UNIVERSITY OF ILLINOIS Urbana-Champaign
CIVIL AND ENVIRONMENTAL ENGINEERING

NASCC
THE STEEL CONFERENCE
Nashville, Tennessee
April 2–5, 2008

New Developments in Earthquake Engineering of Steel and Composite Structures

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North American Steel Construction Conference

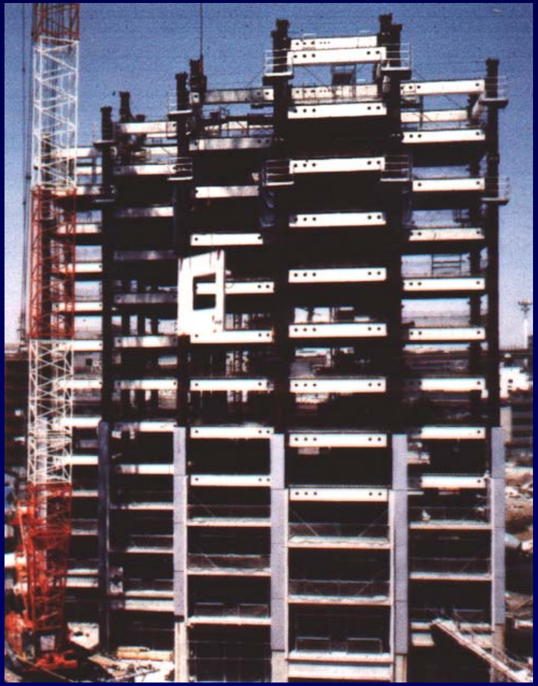
April 3, 2008

Composite Beam-Column Behavior

Composite Columns

- Steel reinforced concrete (SRCs, encased composite columns)

- Concrete-filled tubes (CFTs, filled composite columns)



From R. Kanno,
Nippon Steel Corporation

Acknowledgements: Composite Systems

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  American Institute of Steel Construction
  University of Illinois at Urbana-Champaign
  University of Minnesota
  Georgia Institute of Technology
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  LeJeune Steel Co.
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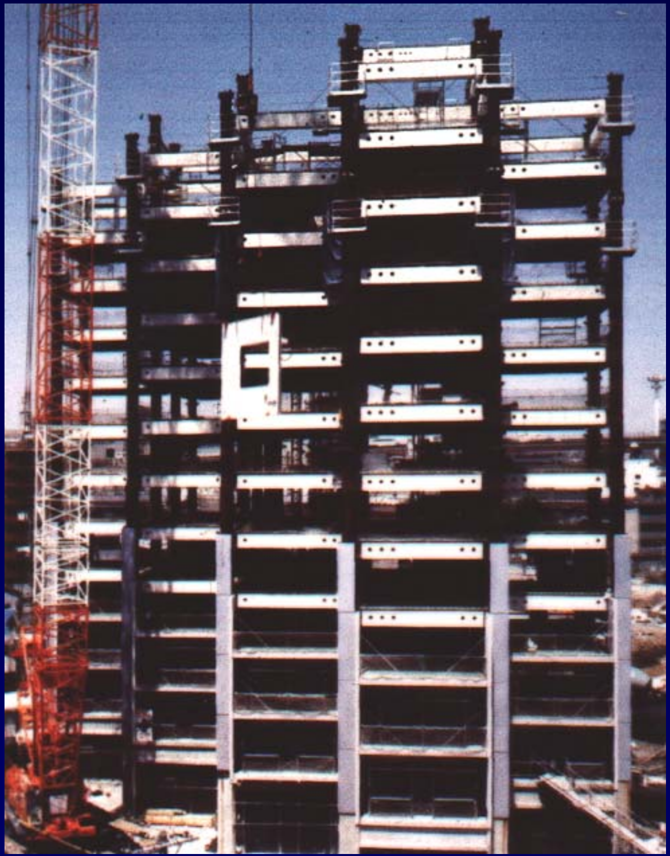
  - **Roberto Leon, Tiziano Perea,** Georgia Tech
- Distributed Plasticity Fiber Model:
  - **Mark Denavit**
  - **Cenk Tort**
  - Paul H. Schiller
  - Alexander O. Molodan
- Concentrated Plasticity Macro Model:
  - **Brett C. Gourley**
  - Matthew C. Olson
- Prototype CFT Building Designs:
  - Jose Zamudio
  - Seokkwon Jang
- Performance-Based Design:
  - Steven Gartner
- Composite Connections:
  - **Luis Pallares**



From R. Kanno, Nippon Steel Corporation

AISC 2005 Provisions for Composite Columns

New Limitations

- *Steel area = 0.01 A_g min*
- *Rectangular HSS:*
  - *$b/t \leq 2.26\ [E/F_y]^{0.5} = 54.4$ for 50 ksi*
- *Round HSS:*
  - *$D/t \leq 0.15\ E/F_y = 87$ for 50 ksi*

AISC 2005 Provisions for Composite Columns

I2.1.2 Filled Composite Columns New Strength Model w/ Slenderness

- For $P_e \geq 0.44\ P_o$:
  $P_n = P_o\ [\ 0.658^{P_o/P_e}]$

- For $P_e < 0.44\ P_o$:
  $P_n = 0.877\ P_e$

- $P_o = A_s\ F_y + A_{sr}\ F_{yr} + C_2\ f'_c\ A_c$
- C_2 = 0.85 SRC, RCFT, 0.95 CCFT (confinement)
- $P_e = \pi^2\ (EI_{eff})\ /\ (KL)^2$
- $(EI_{eff}) = E_sI_s + E_{yr}I_{yr} + C_3E_cI_c$
- $C_3 = 0.1 + 2(A_c/A_g) \leq 0.3$ (SRC)
  $= 0.6 + 2(A_c/A_g) \leq 0.9$ (CFT)

AISC 2005 Provisions for Composite Columns

- *Typically use Plastic Stress Distribution Method*
  - *Plastic Strength Equations*
    - *Example CD Disk w/ AISC Manual*
- *For axial compression:*
  - *Square, rectangular, round HSS are in tables in AISC Manual for CFTs*
  - *Tabulated versus KL (effective length)*
  - $f'_c = 4, 5$ *ksi concrete*

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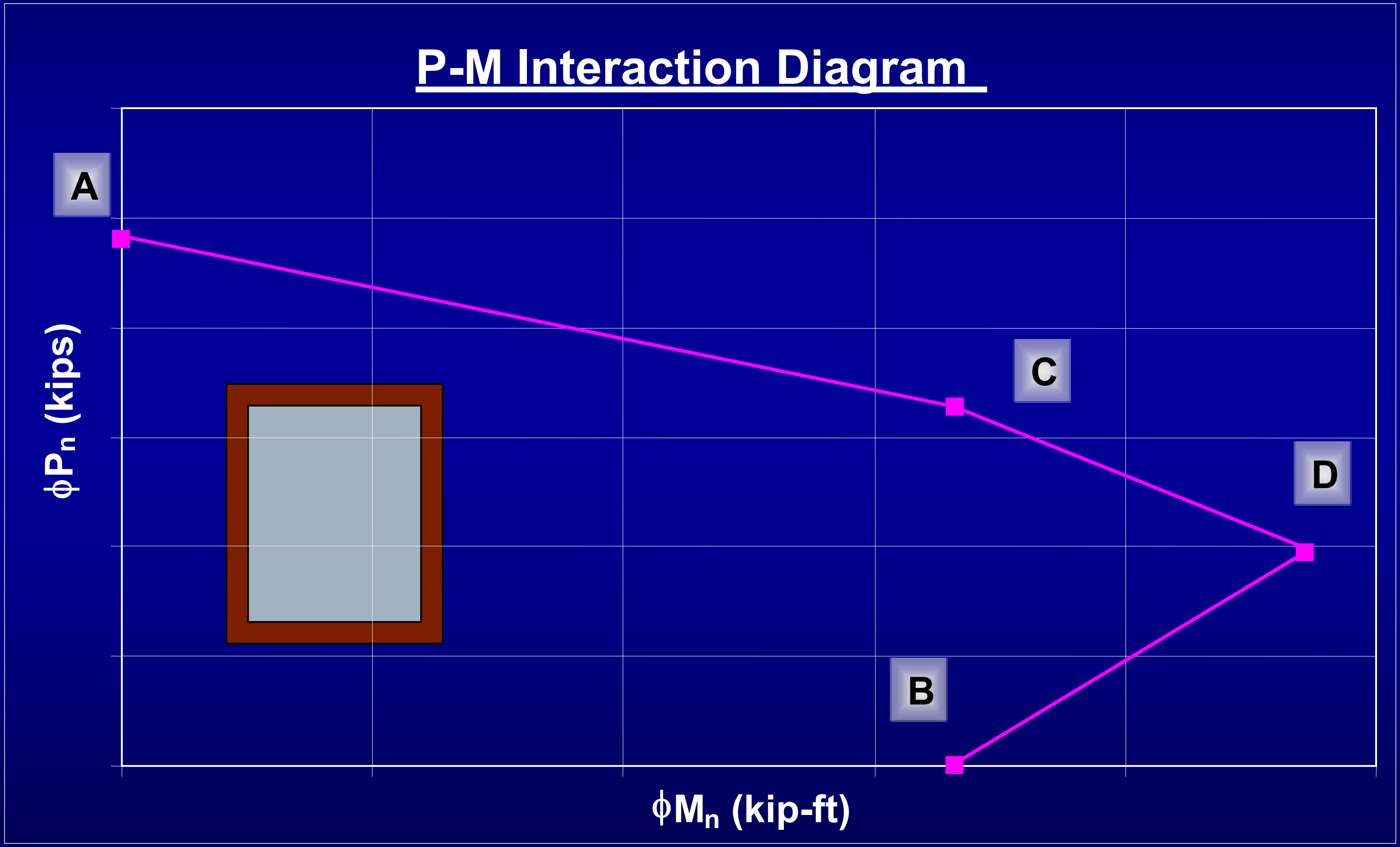
AISC 2005 Provisions for Composite Columns



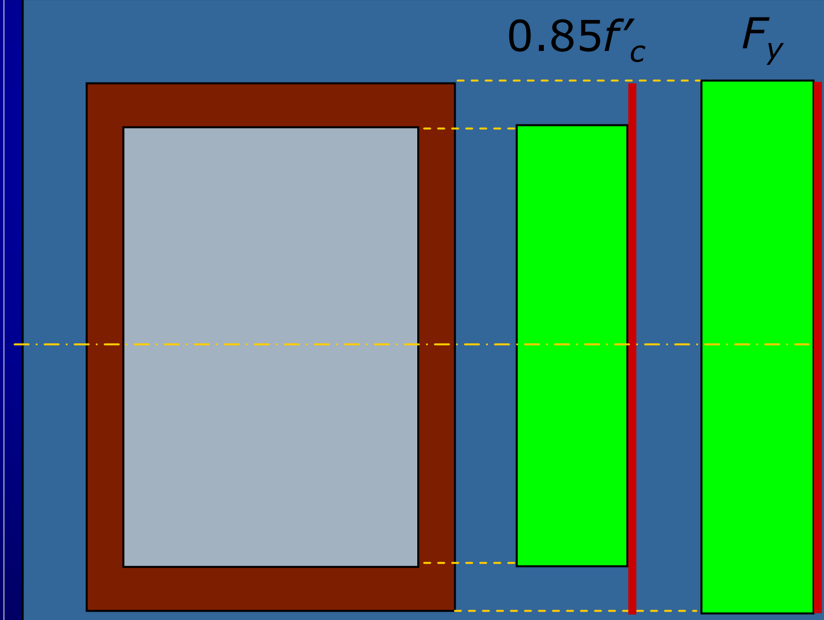
Axial force-bending moment interaction diagram

Slides from L. Griffis, Walter P. Moore & Assoc.

AISC 2005 Provisions for Composite Columns

P-M Interaction Diagram

A



$P_A = A_s F_y + 0.85 f'_c A_c$

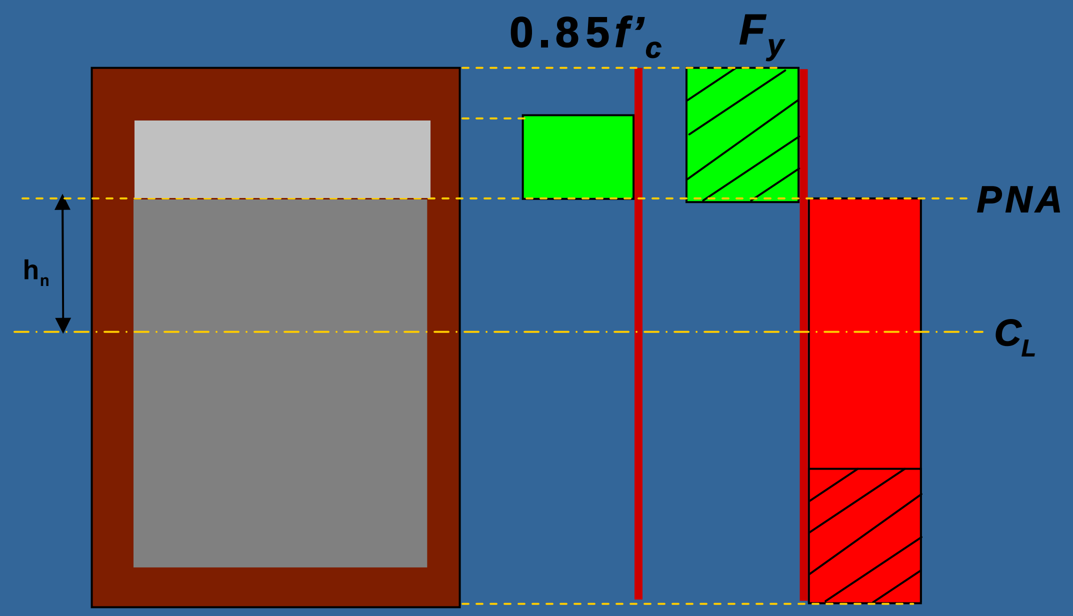
$M_A = 0$

A_s = area of steel shape

$A_c = A_g - A_s$

AISC 2005 Provisions for Composite Columns

P-M Interaction Diagram



$$P_B = 0$$

$$M_B = M_D - Z_{sn}F_y - \tfrac{1}{2}Z_{cn}(0.85f'_c)$$

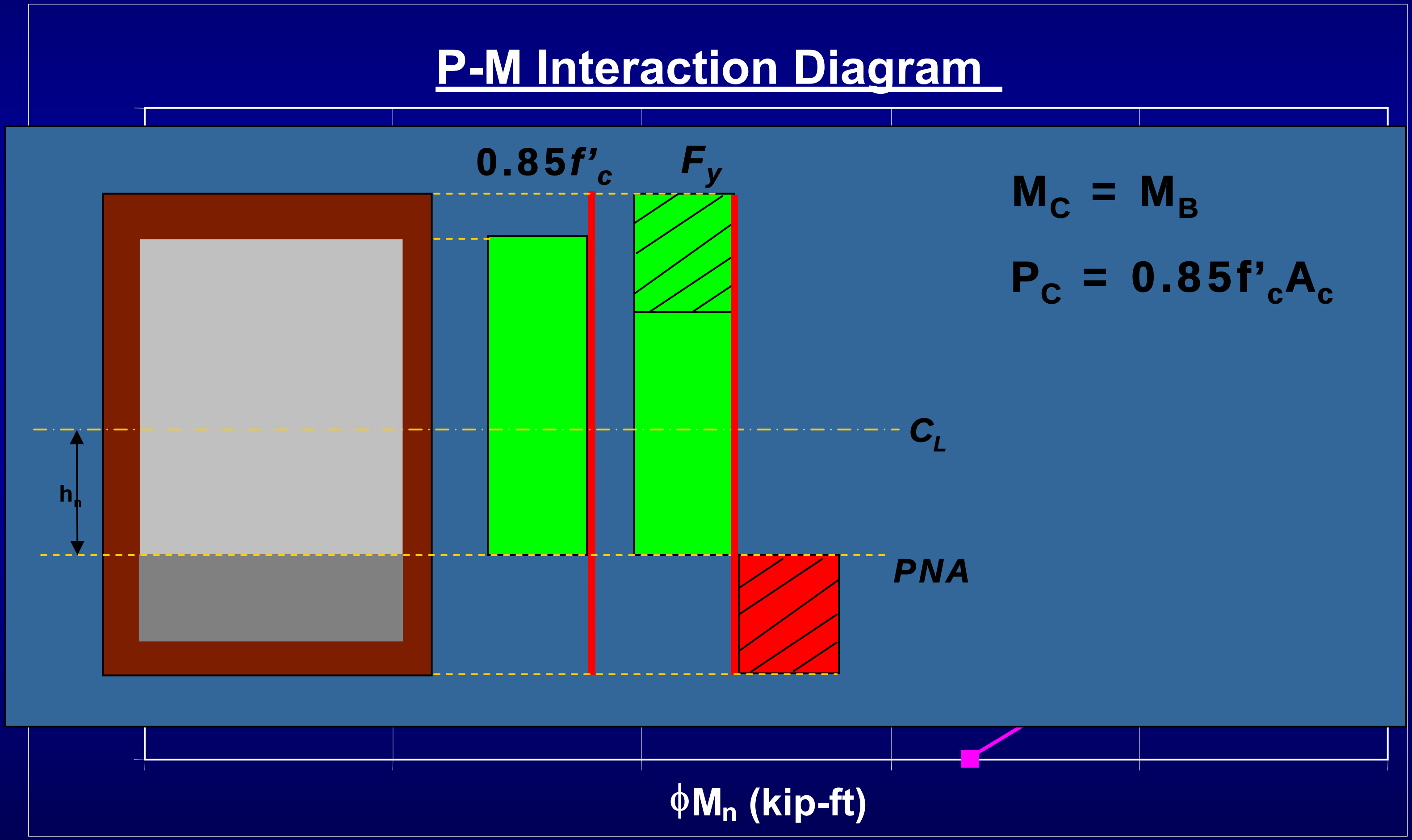
$$Z_{sn} = 2t_w h_n^2$$

$$Z_{cn} = h_1 h_n^2$$

$$h_n = \frac{0.85f'_c A_c}{2\left[0.85f'_c h_1 + 4t_w F_y\right]} \le \frac{h_2}{2}$$

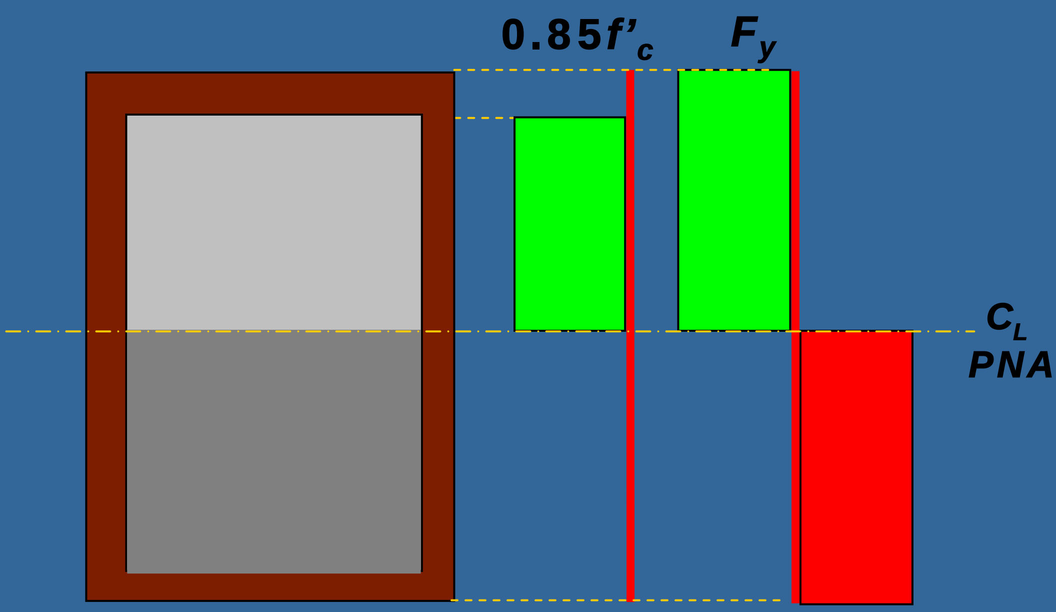
ϕM_n (kip-ft)

AISC 2005 Provisions for Composite Columns



AISC 2005 Provisions for Composite Columns

P-M Interaction Diagram



$$P_D = \frac{0.85 f'_c A_c}{2}$$

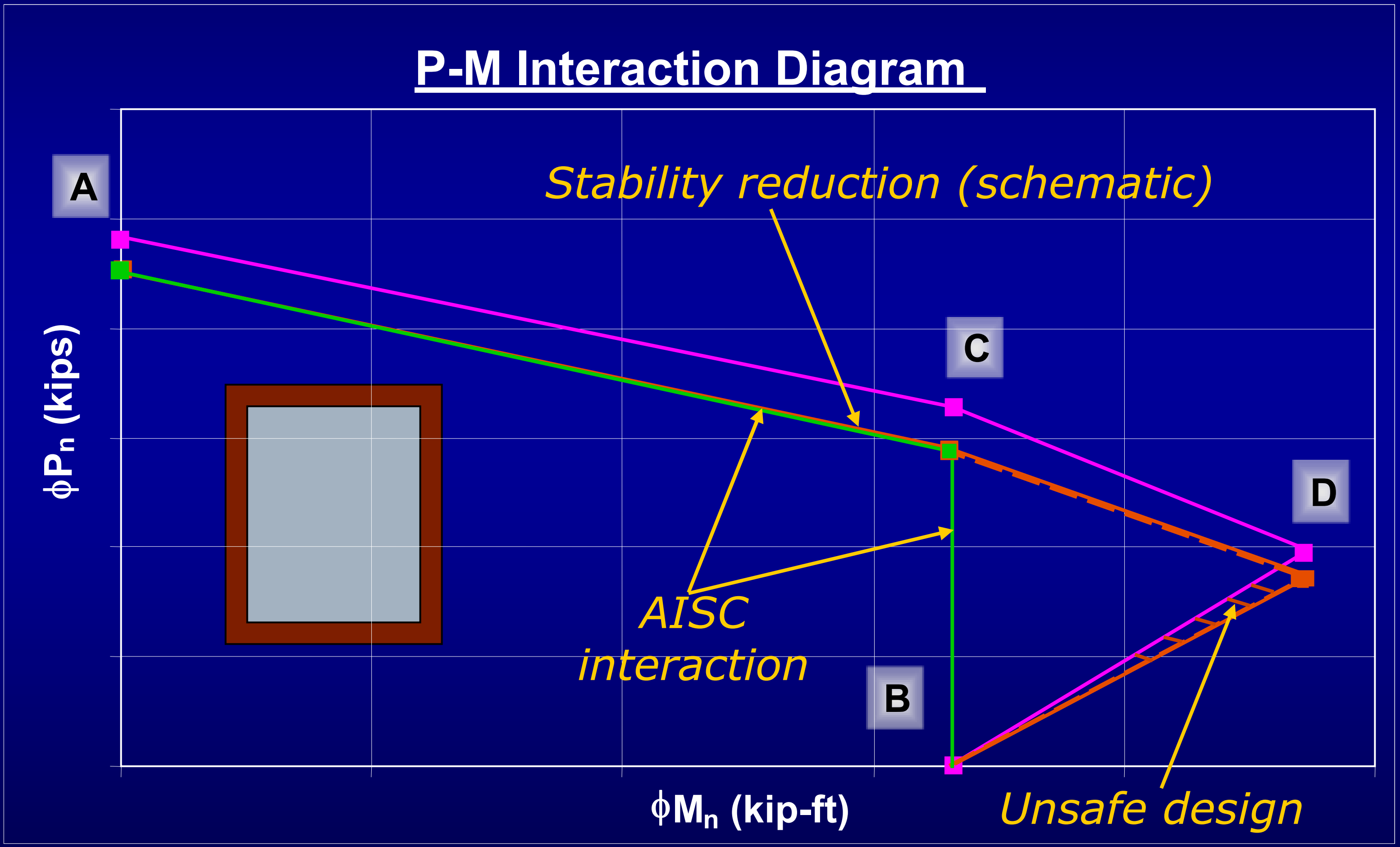
$$M_D = Z_s F_y + \tfrac{1}{2} Z_c (0.85 f'_c)$$

Z_s = full y-axis plastic section modulus of steel shape

$$Z_c = \frac{h_1 h_2^2}{4} - 0.192 r_i^3$$

ϕM_n (kip-ft)

AISC 2005 Provisions for Composite Columns

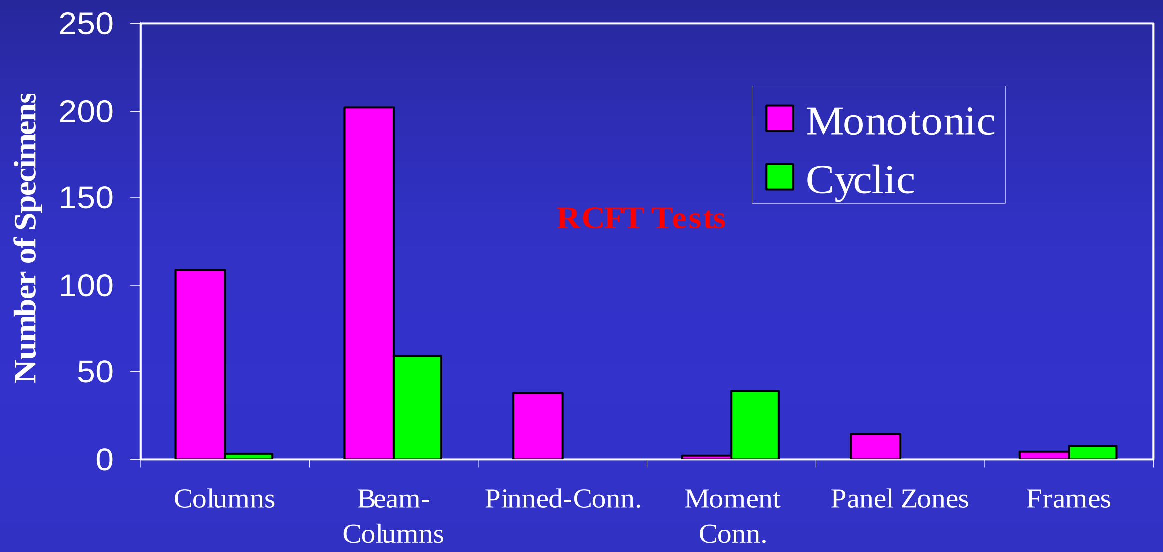


Project Goals

- Facilitate use of composite systems in buildings up to 20 stories and in areas of low, moderate, and high seismicity
- Develop system performance factors (e.g., R, C_d, and Ω_o) for composite braced and unbraced structural systems
- Provide practical guidelines for the analysis and design of composite structures
- Upgrade the computational models available for analyzing complete composite systems and provide detailed documentation to help researchers pursue similar studies

Assessment of Capacity: Database Development for Modeling

- Worldwide test results of RCFT tests were documented:

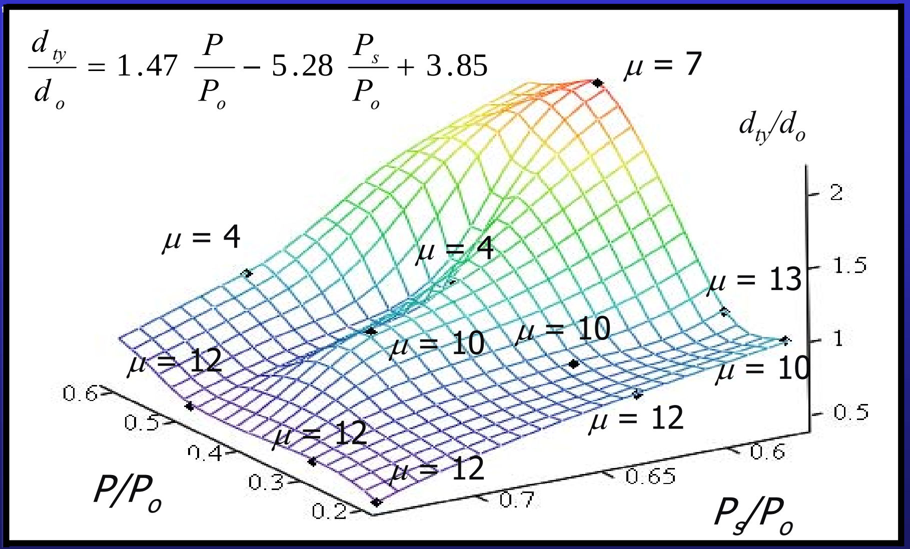


- Each database consists of four sections including:
  - *Test Description:*
  - *Material Properties:*
  - *Geometric Properties:*
  - *Experimental Results:*
    - Failure modes
    - Deformation and load capacities
    - Occurrence of local damage in terms load and deformation levels

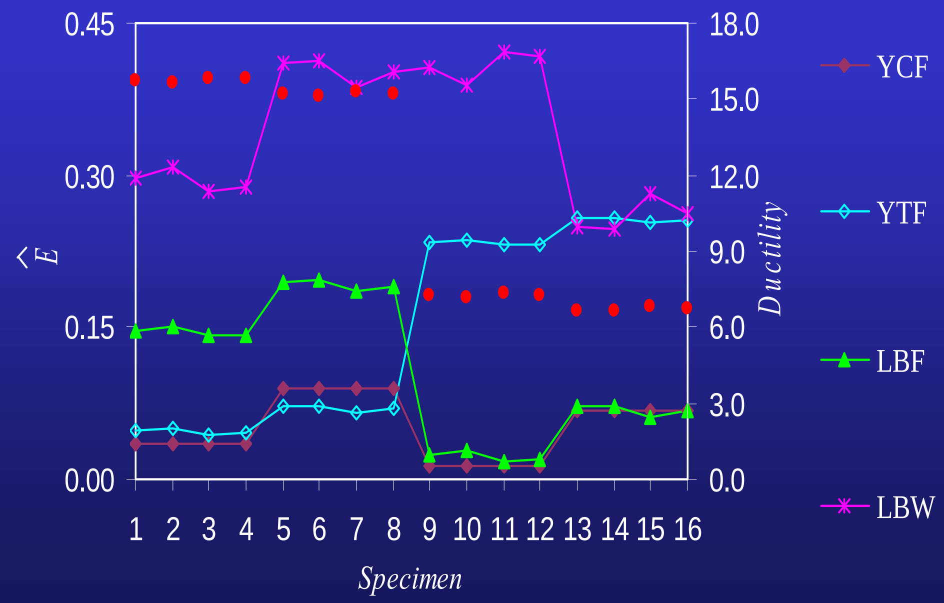
Damage Assessment in RCFT Members and Frames

- Created deformation-based and energy-based damage functions (e.g., concrete crushing, steel yielding, local buckling)
- The damage function values at specific damage levels were correlated to the structural parameters (e.g., f'_c, f_y, D/t, P_c/P_o, P_s/P_o etc.)

Example: Tension flange yielding occurs pre-peak for thick-walled RCFTs with low axial force



A parametric study was conducted on the equations to estimate the range of probable damage function values

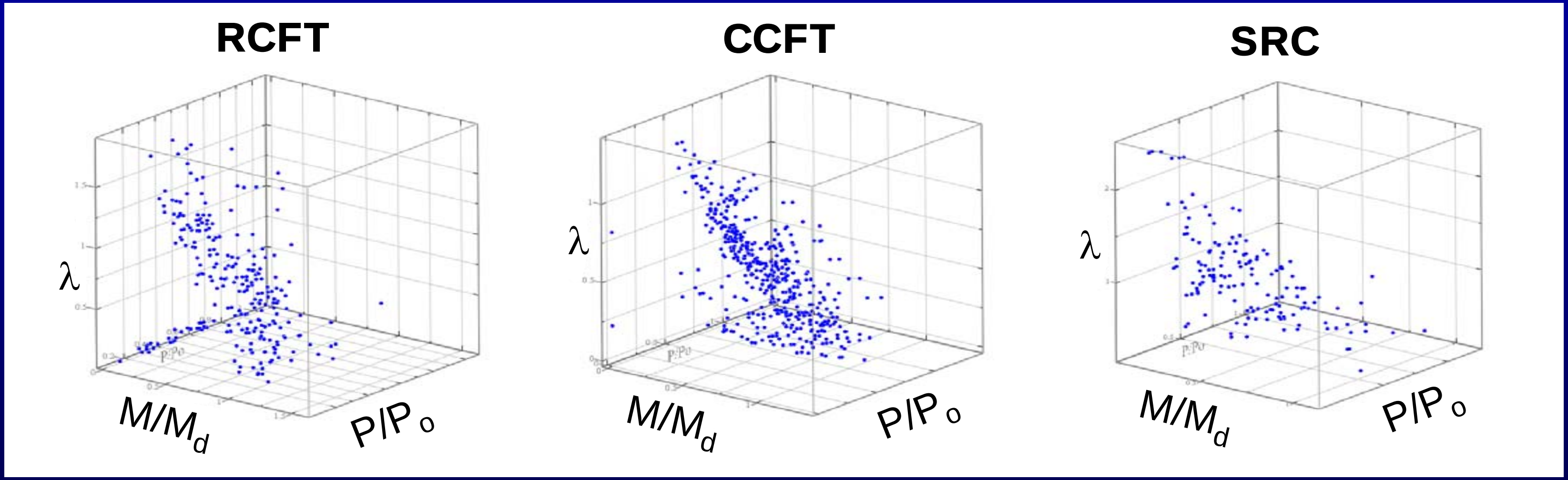


Database Development for Testing

- Work of previous researchers (Leon, Goode, Morino) combined to create a comprehensive worldwide database
- Database used to identify gaps in test data and calibrate computational model

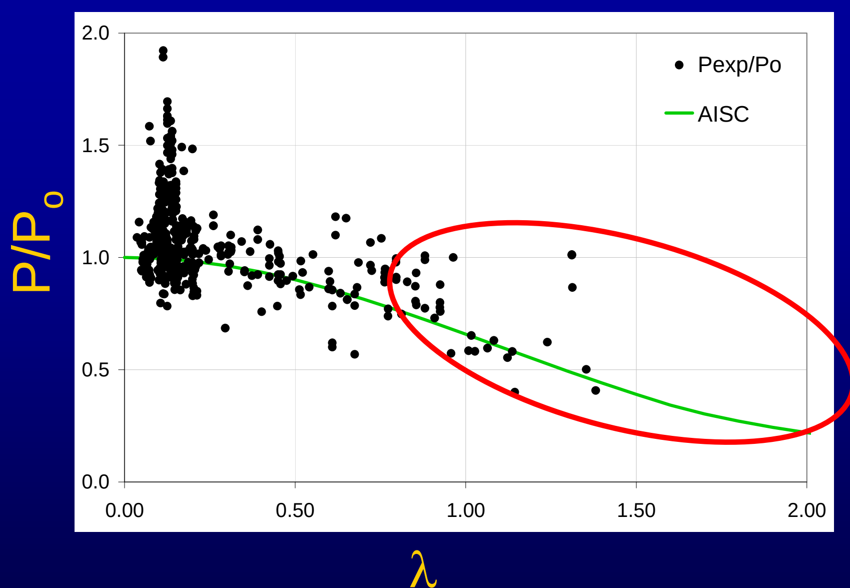
Number of Tests

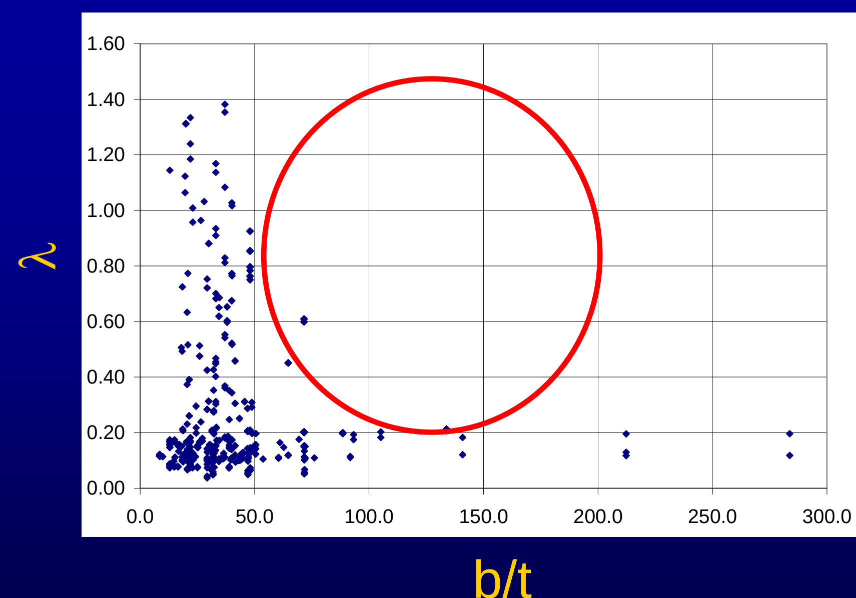
	CCFT	RCFT	SRC
Columns	762	455	119
Beam-Columns	395	189	120



Gaps In Test Data

- Fewer tests for slender members (λ > 1.5)
  - Flexural Buckling
- Fewer tests for slender sections (*b/t* > 50)
  - Local Buckling
- Few with both slender members and sections
- Other gaps in material properties





MAST Facility

From NEES@Minnesota

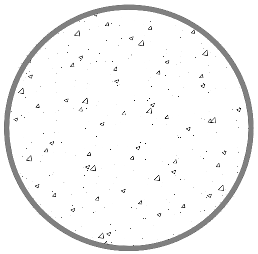
- The MAST facility permits the comprehensive testing of a wide range of composite beam-columns subjected to three dimensional loading at a realistic scale.

Maximum non-concurrent capacities of MAST DOFs

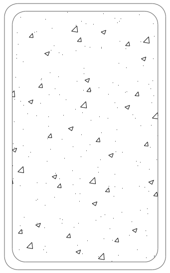
Degree of Freedom	Load	Stroke/ Rotation
X-Translation	±880 kips	±16 in
X-Rotation	±8,910 kip-ft	±7°
Y-Translation	±880 kips	±16 in
Y-Rotation	±8,910 kip-ft	±7°
Z-Translation	±1,320 kips	±20 in
Z-Rotation	±13,200 kip-ft	±10°

CFT Test Series

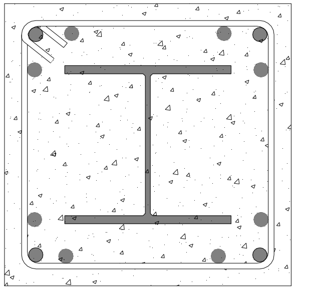
Specimen	D/t	Fy (ksi)	f'c (ksi)	L (ft)	λ	Po (kip)	Pn (kip)	Pd (kip)	Md (k-ft)	Md/Pd (in)
CCFT20x0.25	86	42	5	18.0	1.03	2273	1456	712	691	11.7
				26.0	1.49	2273	897	712	691	11.7
	86	42	12	18.0	1.25	4266	2210	1708	1035	7.3
				26.0	1.81	4266	1141	1708	1035	7.3
CCFT12.75x0.25	55	42	5	18.0	1.56	1101	396	282	240	10.2
				26.0	2.25	1101	190	282	240	10.2
	55	42	12	18.0	1.85	1889	482	676	325	5.8
				26.0	2.68	1889	231	676	325	5.8
CCFT5.563x0.134	45	42	5	18.0	0.88	231	167	53	23	5.2
				26.0	1.27	231	117	53	23	5.2
	45	42	12	18.0	1.03	378	242	126	30	2.8
				26.0	1.49	378	149	126	30	2.8



Specimen	h/t	Fy (ksi)	f'c (ksi)	L (ft)	λ	Po (kip)	Pn (kip)	Pd (kip)	Md (k-ft)	Md/Pd (in)
RCFT20x12x0.3125w	67	46	5	18.0	1.38	2118	952	471	594	15.1
				26.0	2.00	2118	466	471	594	15.1
	67	46	12	18.0	1.61	3438	1158	1131	773	8.2
				26.0	2.33	3438	555	1131	773	8.2
RCFT12x20x0.3125s	67	46	5	18.0	0.89	2118	952	471	875	22.3
				26.0	1.28	2118	466	471	875	22.3
	67	46	12	18.0	1.02	3438	1158	1131	1173	12.4
				26.0	1.47	3438	555	1131	1173	12.4



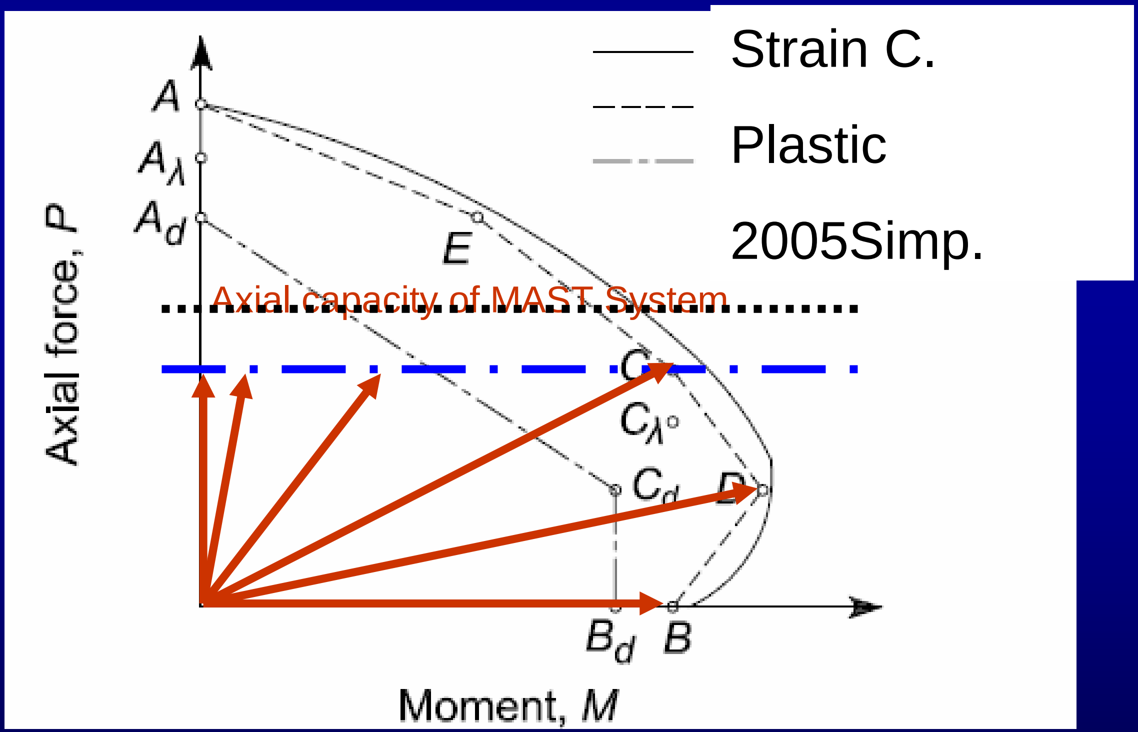
Preliminary SRC Test Series

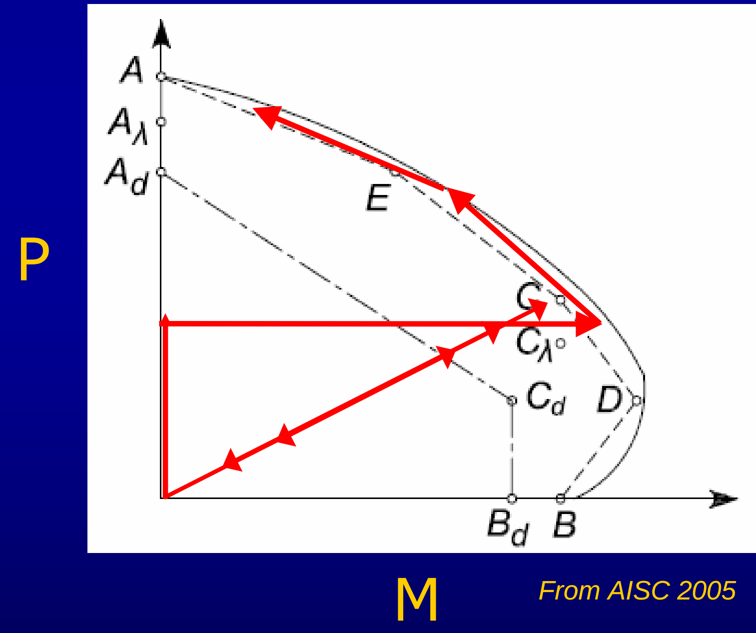


Label	RC Section b (in)	RC Section d (in)	Steel Section	Axis	f'_c (ksi)	F_y (ksi)	Long. Reinf.	Trans. Reinf.	ρ (%)	L (ft)	λ $\sqrt{P_e/P_o}$	L/r
SRC1	24	24	W10x49	Strong	5	50	8#8	#4@12	2.3	14	1.00	23.3
SRC2	24	24	W10x49	Strong	5	50	8#8	#4@12	2.3	20	2.00	33.3
SRC3	16	16	W10x100	Strong	5	50	8#6	#4@12	10.3	14	1.25	35.0
SRC4	16	16	W10x100	Strong	5	50	8#6	#4@12	10.3	20	2.50	50.0
SRC5	16	16	W10x100	Weak	5	50	8#6	#4@6	10.3	14	1.25	35.0
SRC6	16	16	W10x100	Biaxial	5	50	8#6	#4@12	10.3	20	2.50	50.0
SRC7	16	16	W10x100	Strong	8	65	8#6	#4@12	10.3	20	2.50	50.0
SRC8	16	16	W10x100	Strong	12	65	8#6	#4@12	10.3	20	2.50	50.0

Load Histories

- Proportional; Non-proportional; Non-symmetric



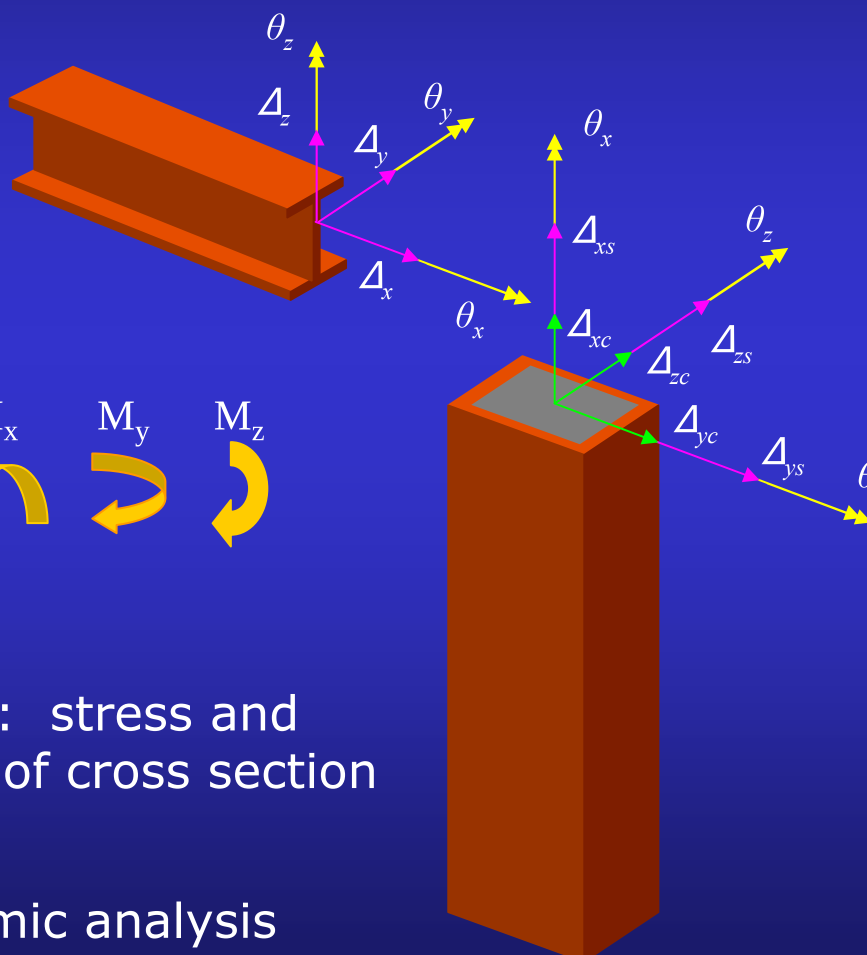


From AISC 2005

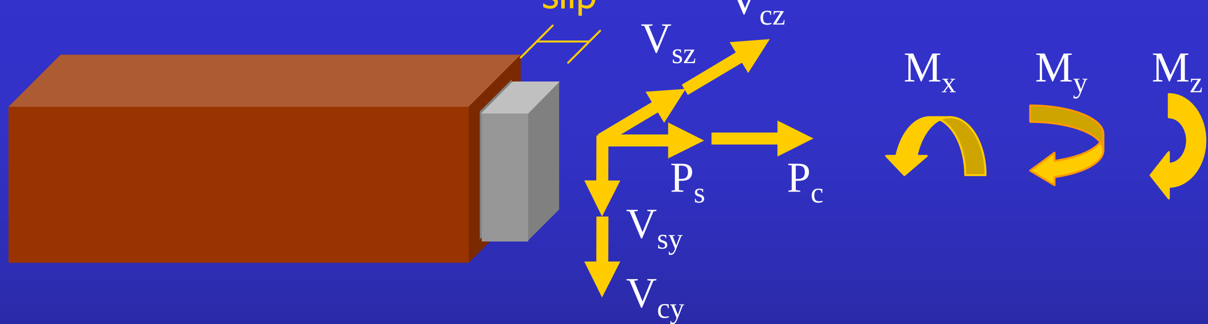
Assessment of Demand: Computational Modeling

A 3D 18 DOF Beam-Column element was formulated:

- Separate translational DOFs for steel tube and concrete core were defined



- Differential displacement allowed in the axial direction



- Distributed plasticity fiber formulation: stress and strain modeled explicitly at each fiber of cross section

- Suitable for static and transient dynamic analysis

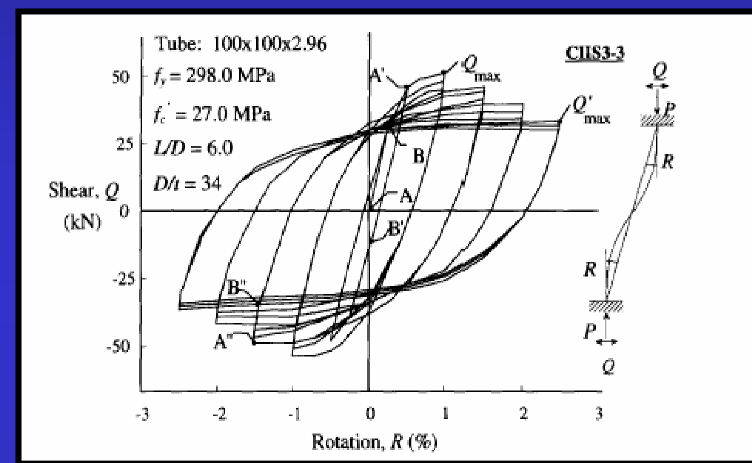
- Implemented in OpenSEES

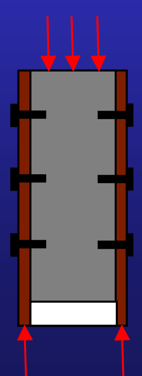
Physical Characteristics of Rectangular CFTs

Cyclic Behavior of RCFT members

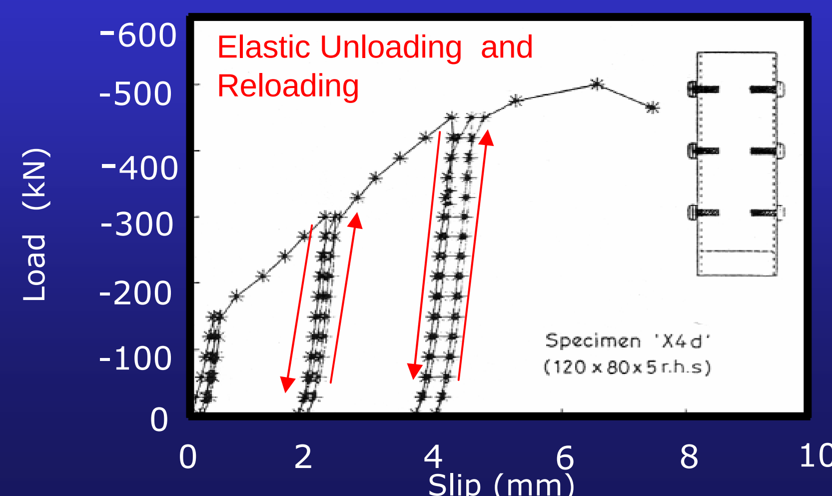
Sakino and Tomii (1981)

- Elastic Unloading — concrete + steel
- Decreasing Elastic Zone — concrete + steel
- Strength Degradation — concrete + steel
- Bauschinger Effect — steel
- Gradual Stiffness Reduction — concrete + steel
- Bounding Stiffness — steel
- Softening — concrete + steel



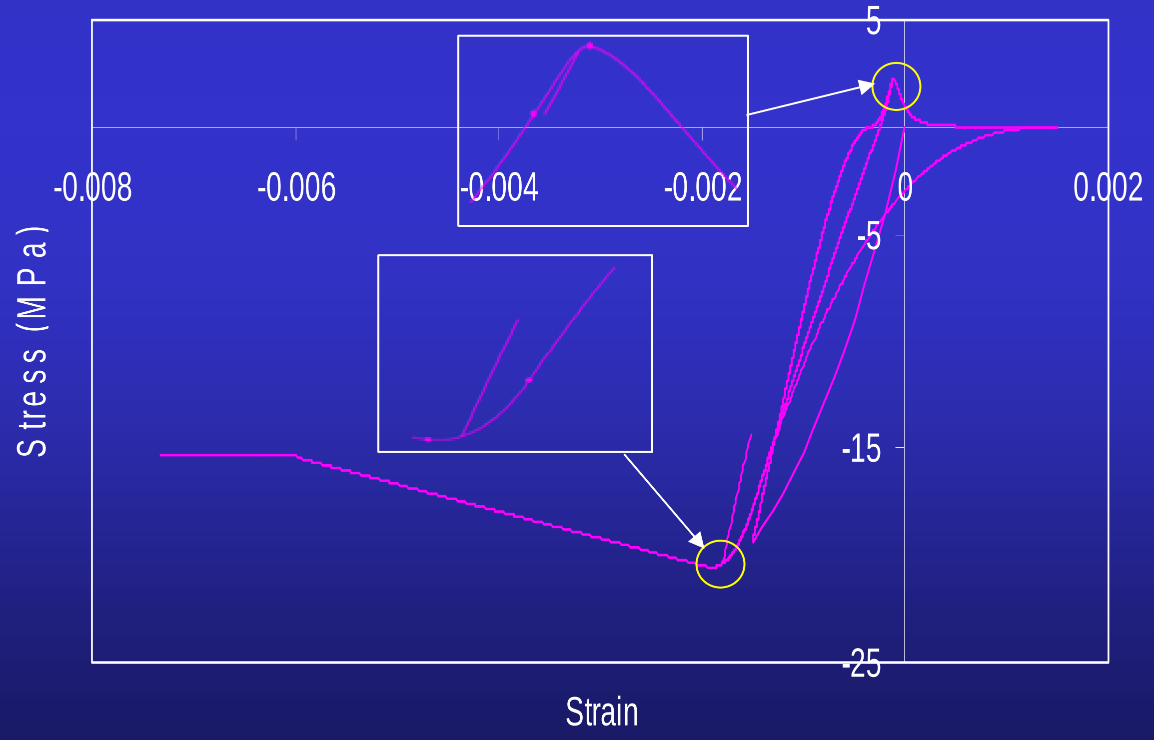


Shakir-Khalil (1993)

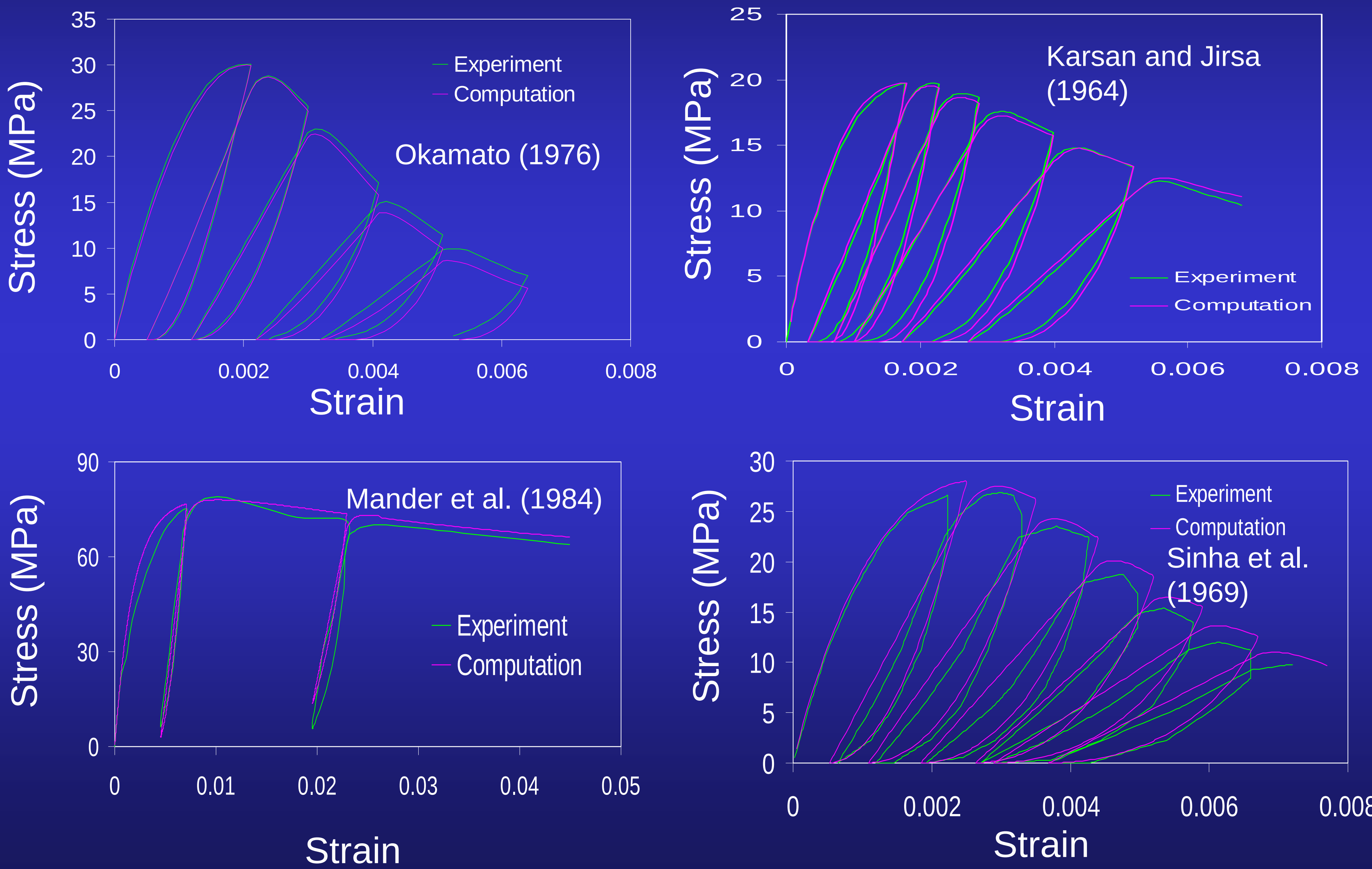


Concrete Constitutive Formulation

- Cyclic constitutive model proposed by Chang and Mander (1994) was adapted and modified extensively to simulate strain vs. stress response of concrete
  - Accounts for confinement implicitly through slope of softening branch
  - Tension stiffening
  - Cycle into tension and back into compression
  - Robust formulation at section iteration level to capture softening

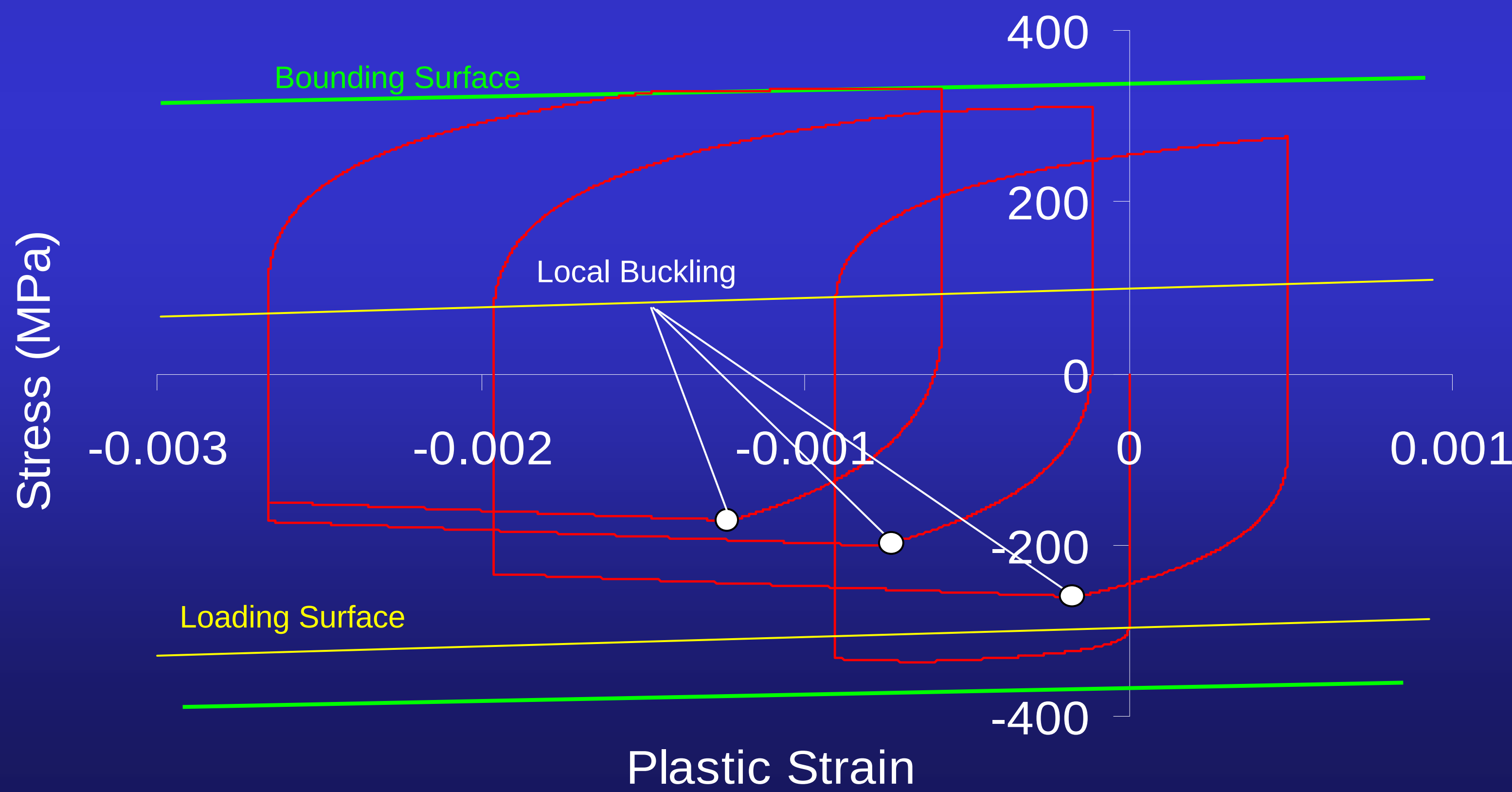


Calibration of Concrete Constitutive Formulation

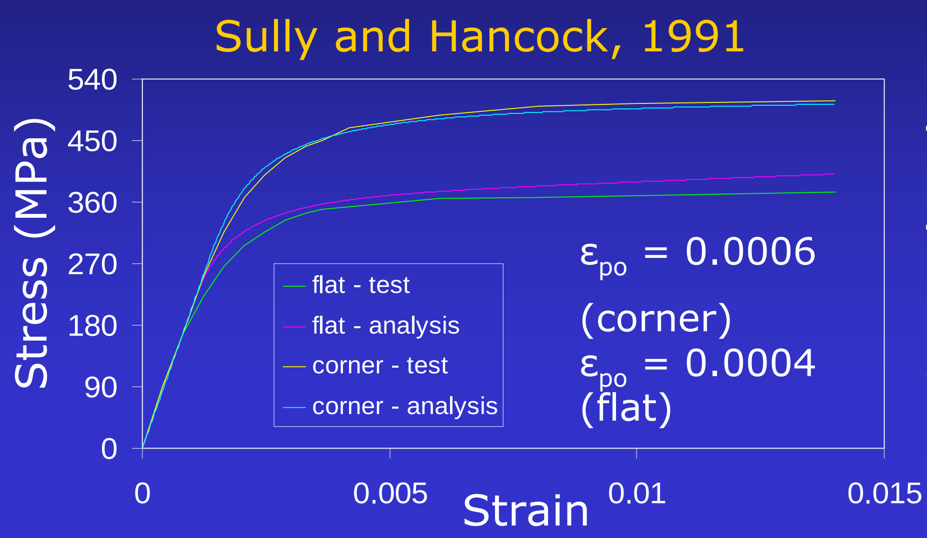


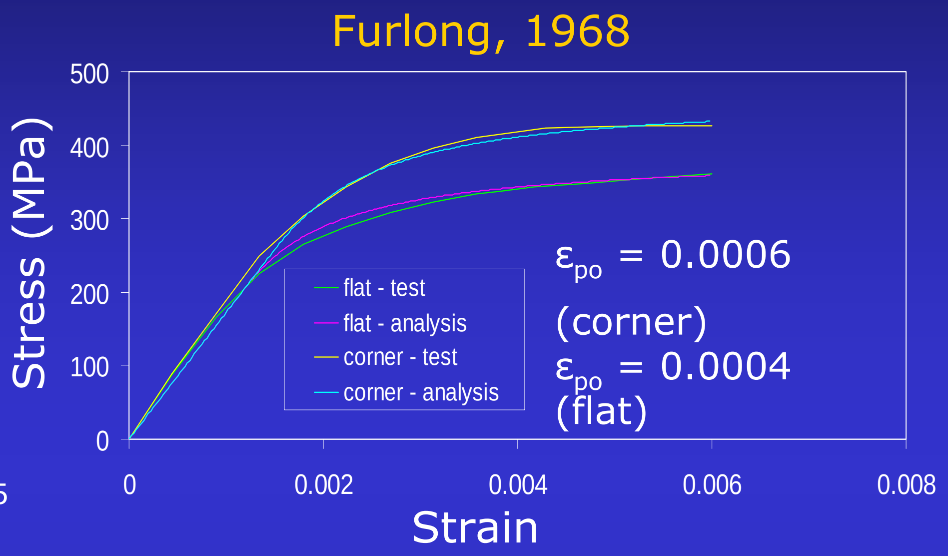
Steel Constitutive Formulation

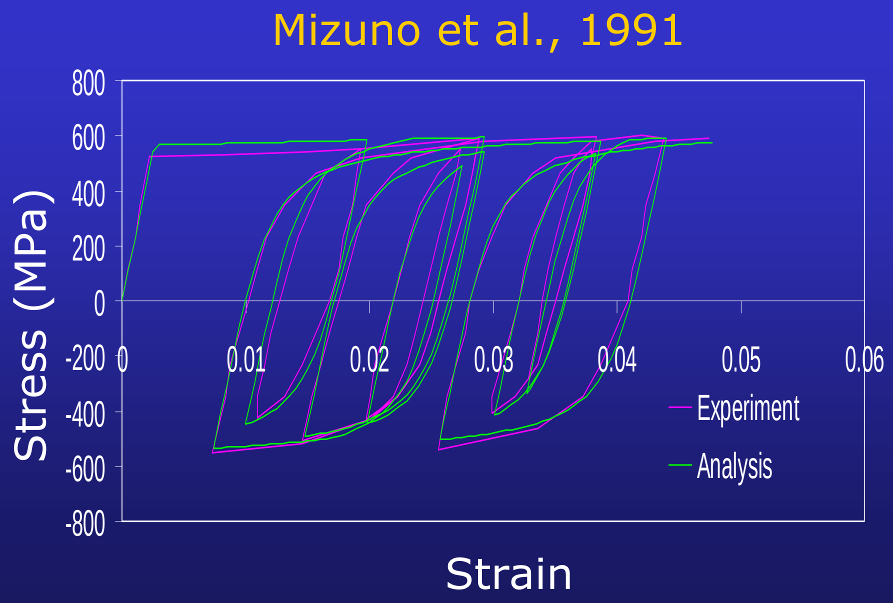
- Cyclic constitutive model proposed by Mizuno at el. (1992) was adapted and modified to simulate strain vs. stress response of cold-formed steel tube
- Uniaxial bounding surface model with local buckling

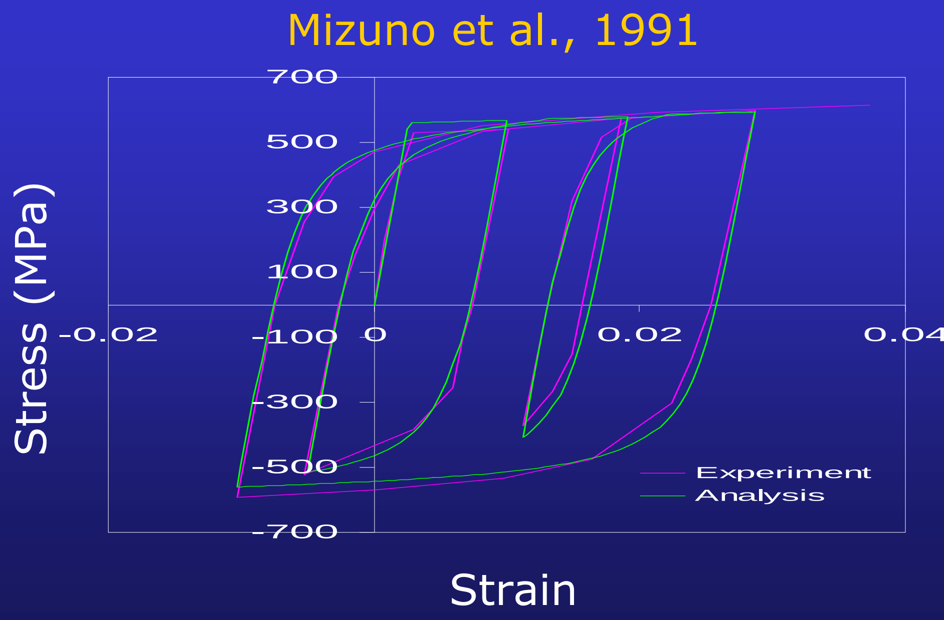


Calibration of Steel Constitutive Formulation









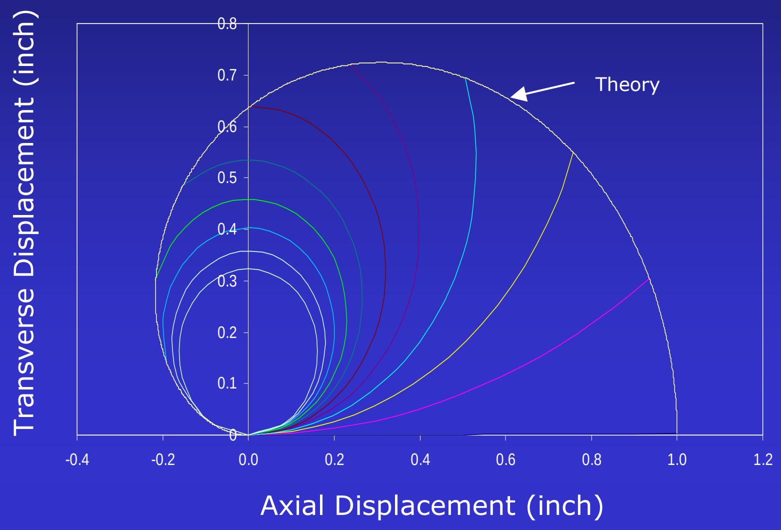
Verification of RCFT Beam-Columns: Geometric Nonlinearity

Cantilever:

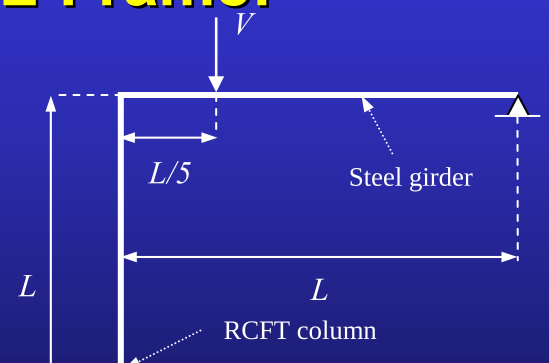
L = 1 inch   A = 1000 inch^2

I = 1 inch^4 E = 1 ksi

3 elements

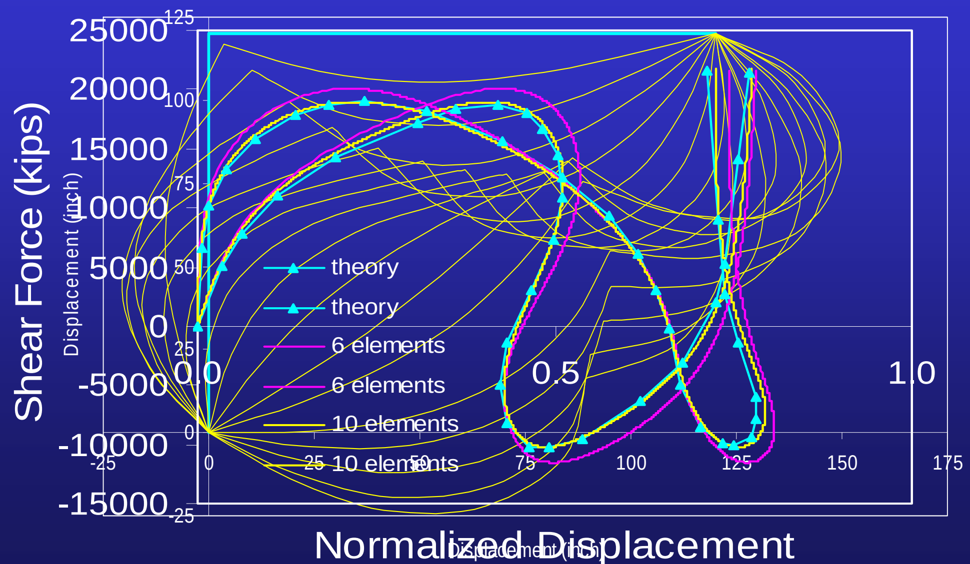


L-Frame:

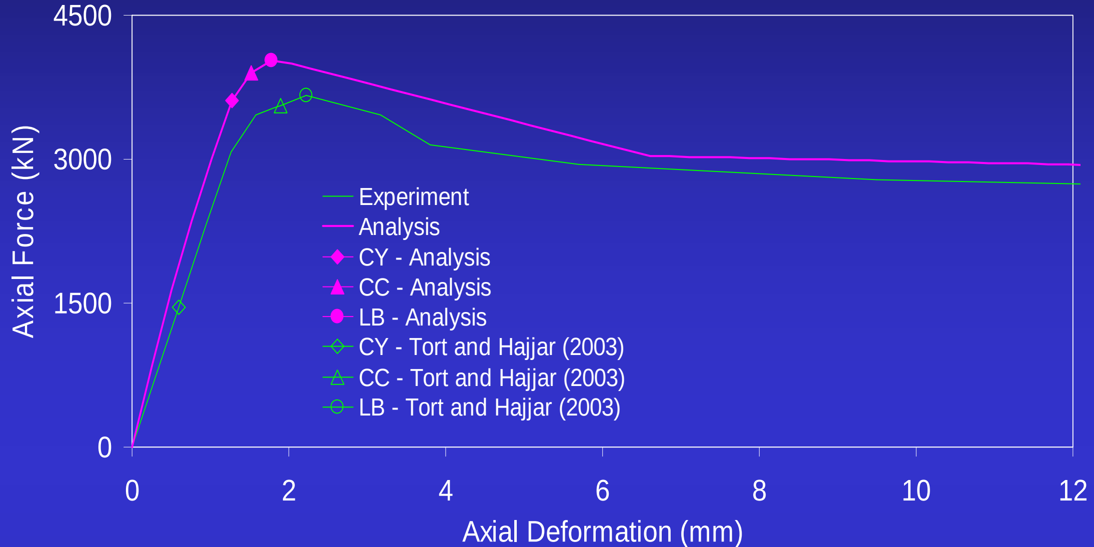


L = 120 inch E = 7.2 x 10^6 ksi

A = 6 inch^2 I = 2 inch^4



Axially Loaded RCFT Columns



Nakahara and Sakino, 1998

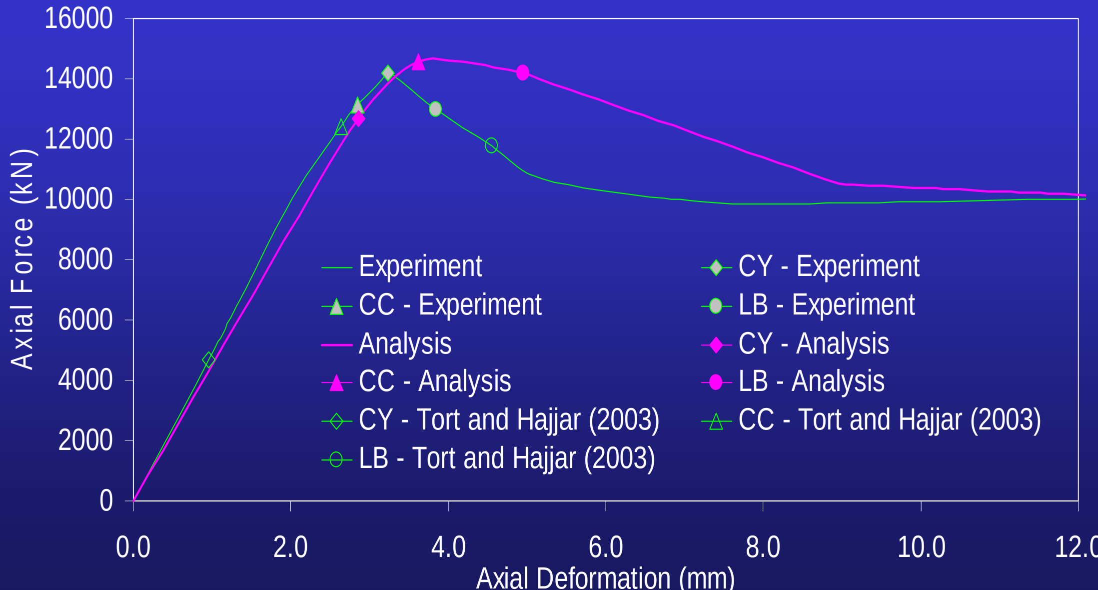
CR4-D-2

$D/t = 73.7$

$f_y = 262.0$ MPa

$f'_c = 25.4$ MPa

$L/D = 3$



Varma, 2000

SC32-80

$D/t = 34.3$

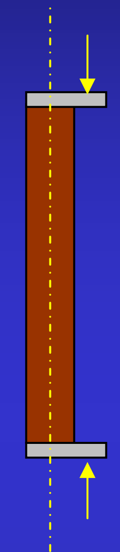
$f_y = 600.0$ MPa

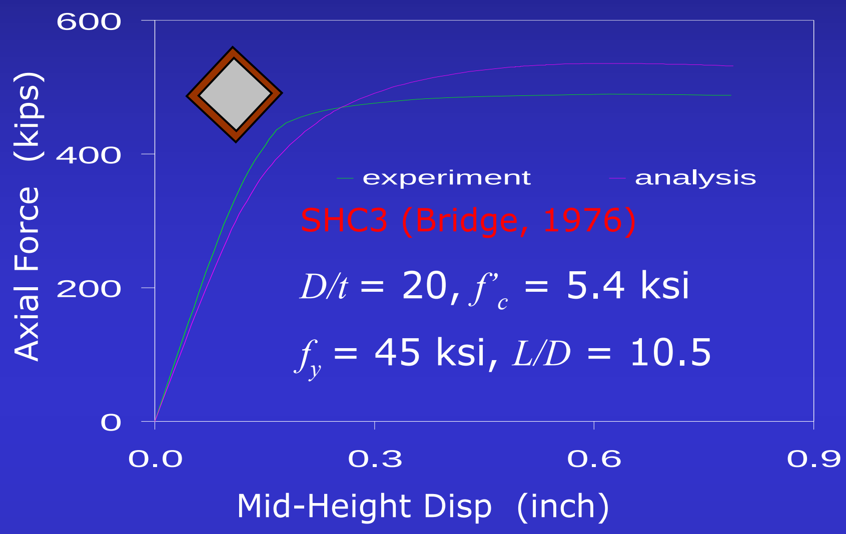
$f_c = 110.6$ MPa

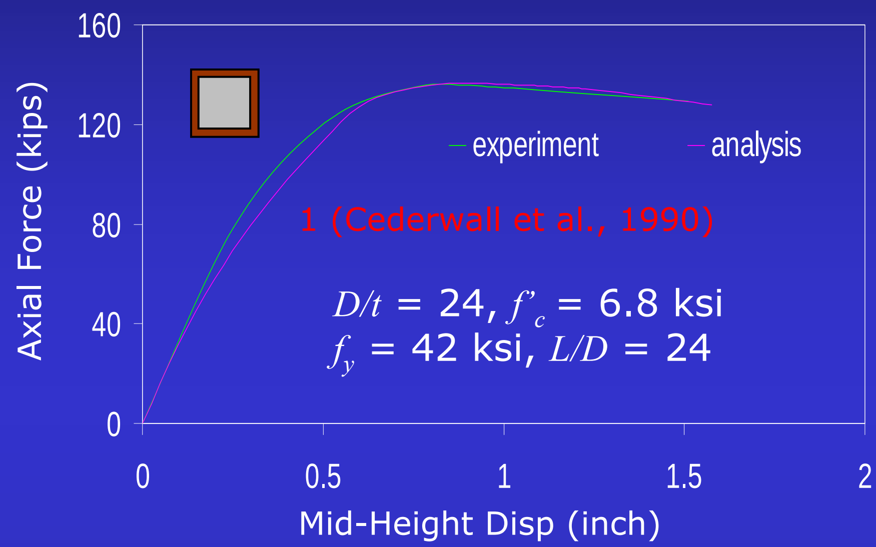
$L/D = 4$

RCFT Beam-Columns

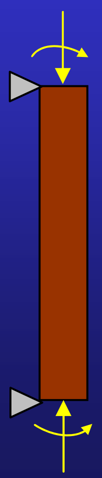
- Proportionally Loaded Columns: 4 elements 3 integration points

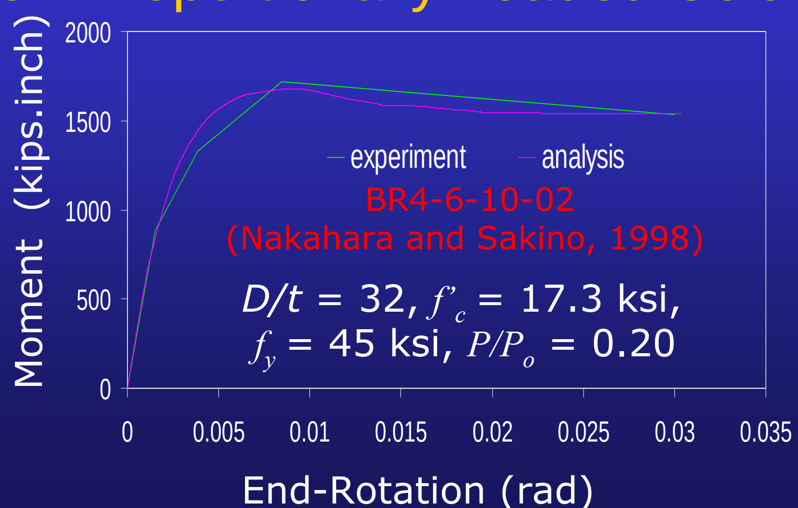


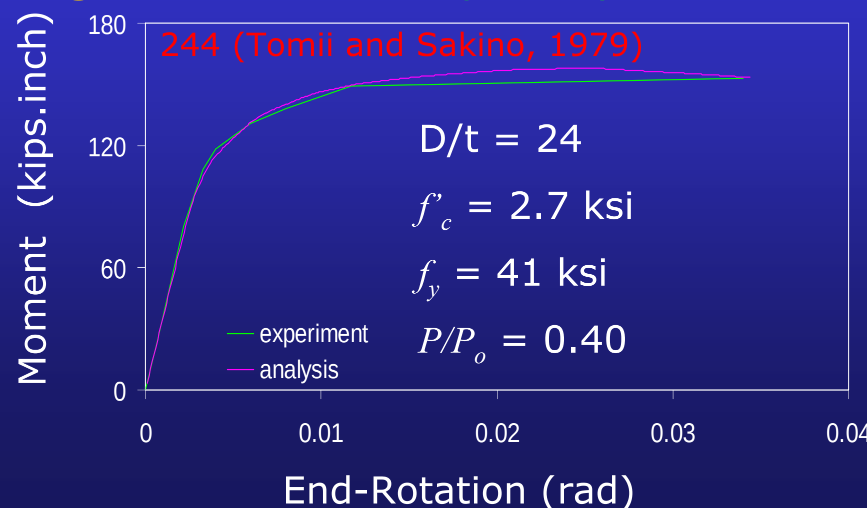




- Non-Proportionally Loaded Columns: 2 elements 3 integration points



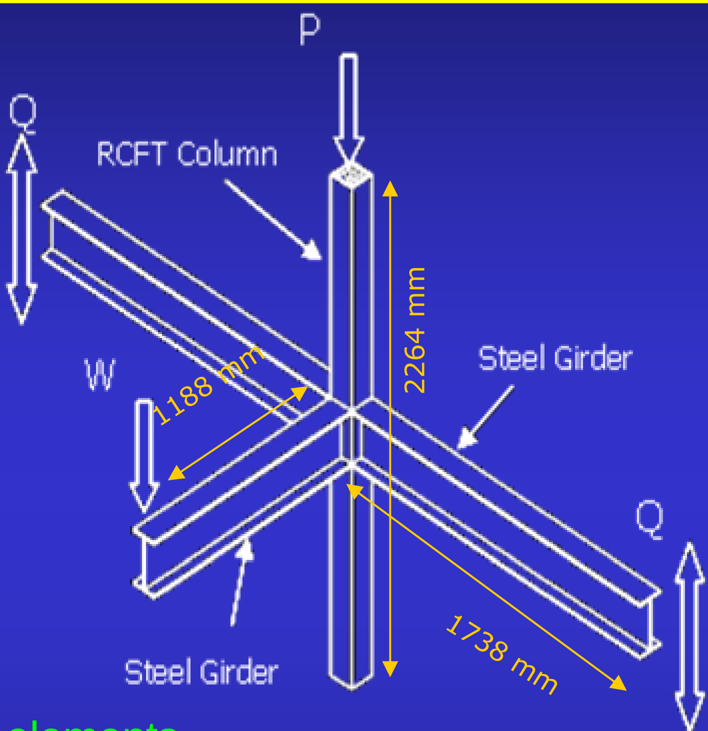


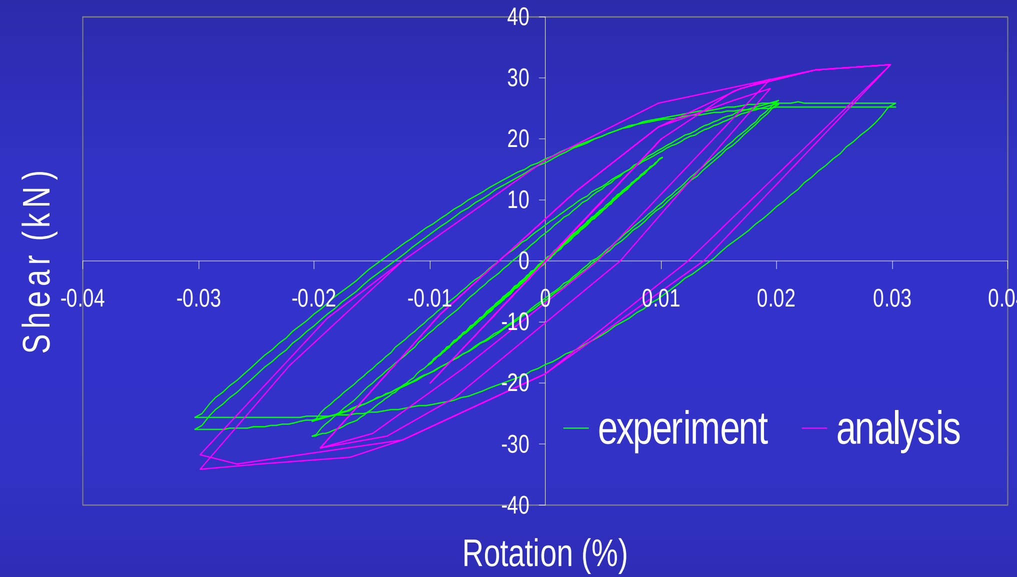


Three-Dimensional Verification of RCFT Response

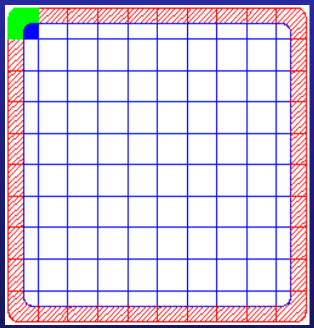
Morino et al., 1993 – 3D Subassemblage

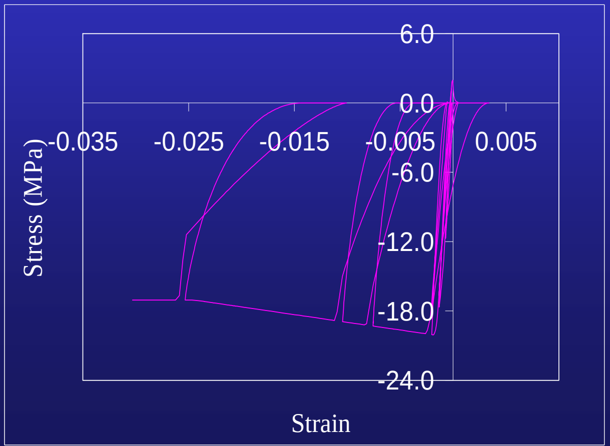
$f'_c = 20$ MPa $f_y = 395$ MPa $D/t = 21.8$ $L/D = 9$

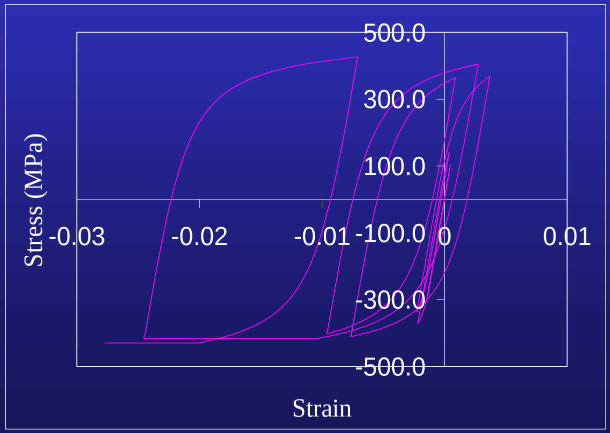




3 elements
4 integration points







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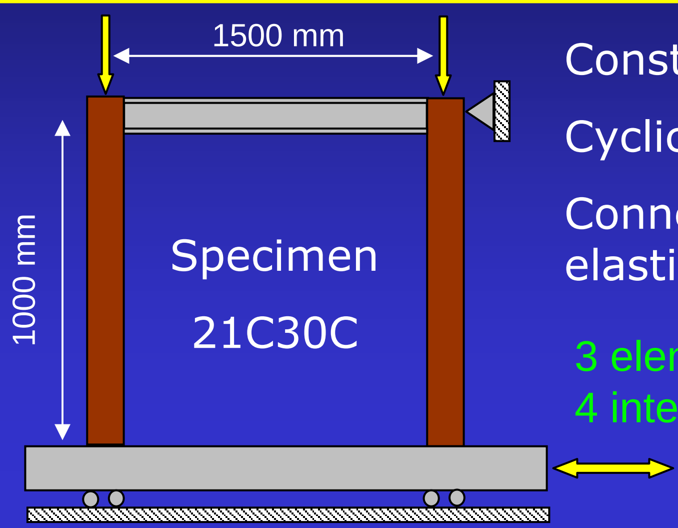
RCFT Frame Response



Constant Axial Load

Cyclic Shear Force

Connections remain elastic

3 elements
4 integration points

Kawaguchi, 2000

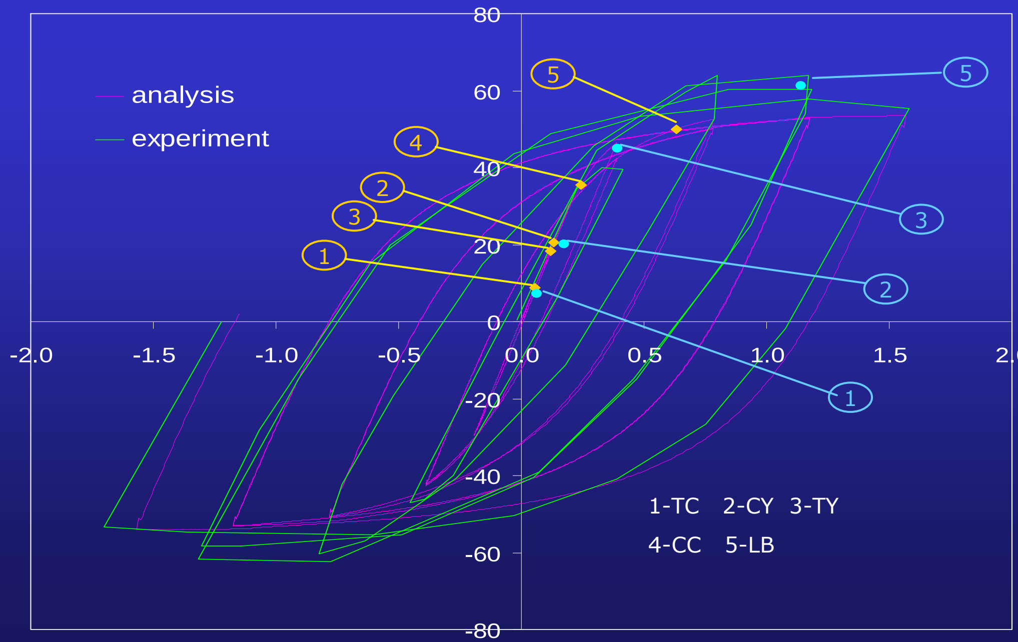
D/t = 21.6

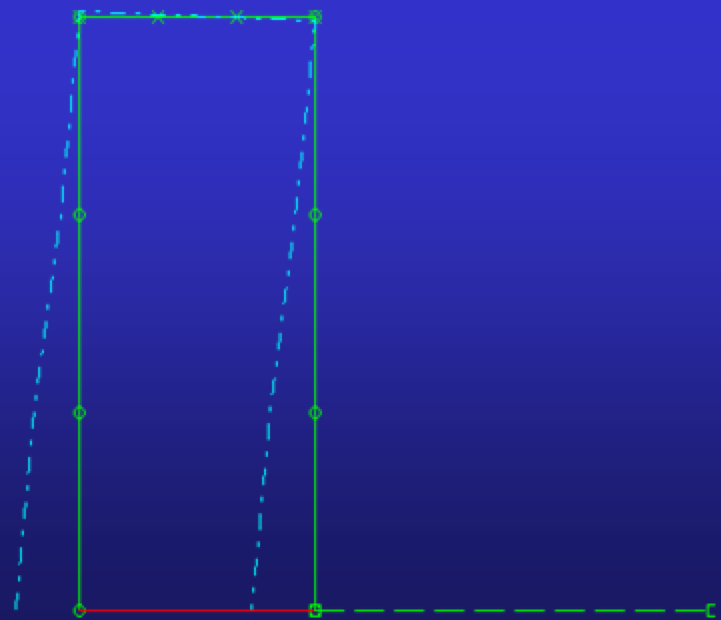
f'_c = 17.9 MPa

f_y = 404 MPa

L/D = 8

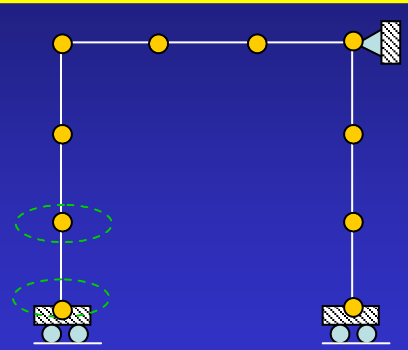
P/P_o = 0.30

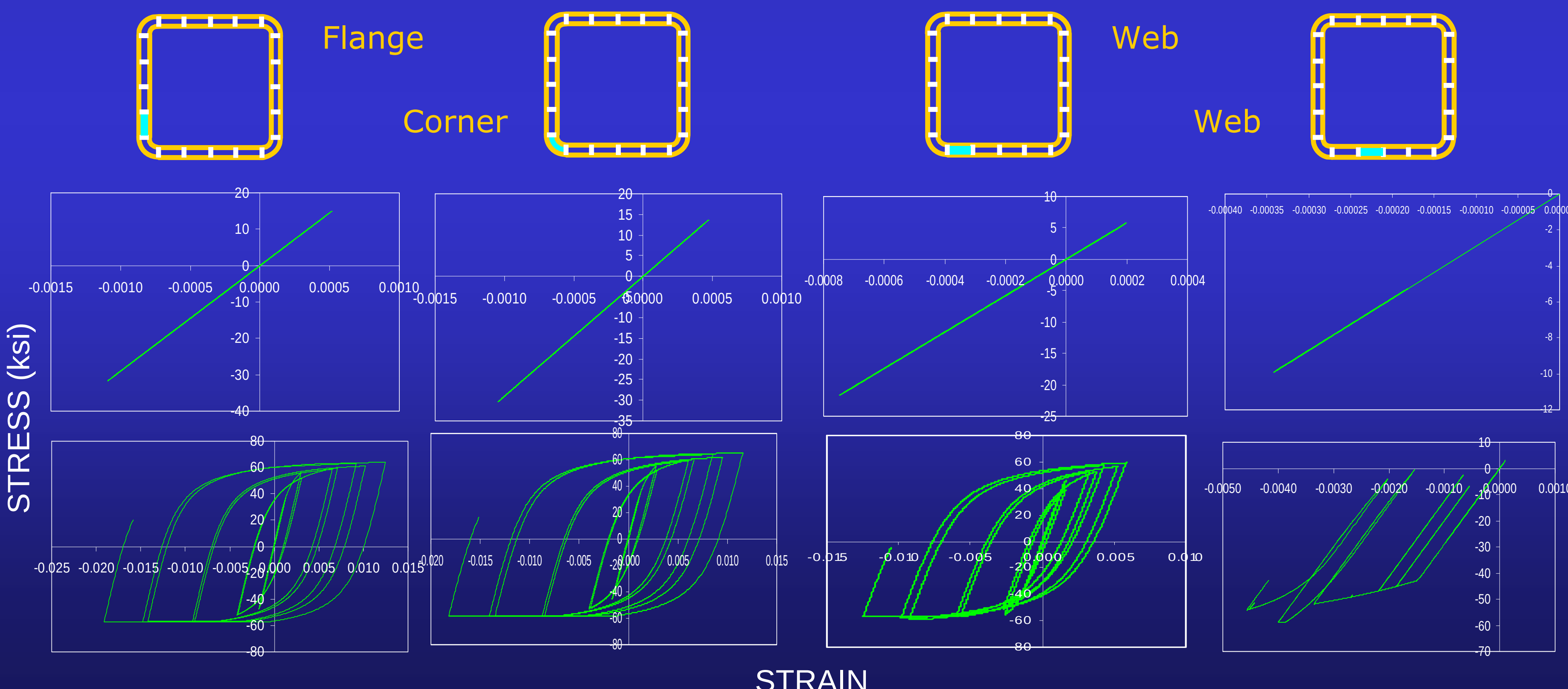




RCFT Frame Response: Steel Stress-Strain Curves

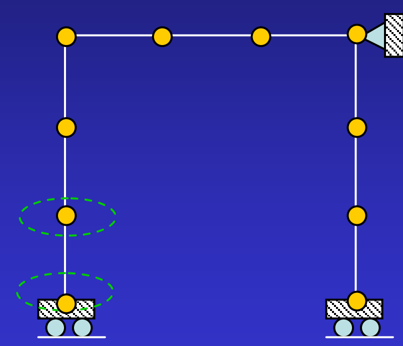
Steel
Stress-Strain
Curves

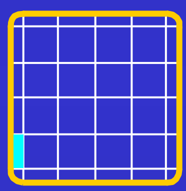




RCFT Frame Response: Concrete Stress-Strain Curves

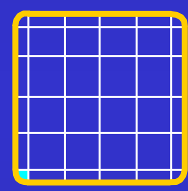
Concrete Stress-Strain Curves

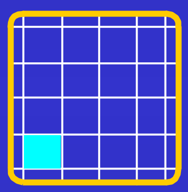




Flange

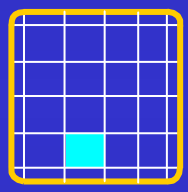
Corner

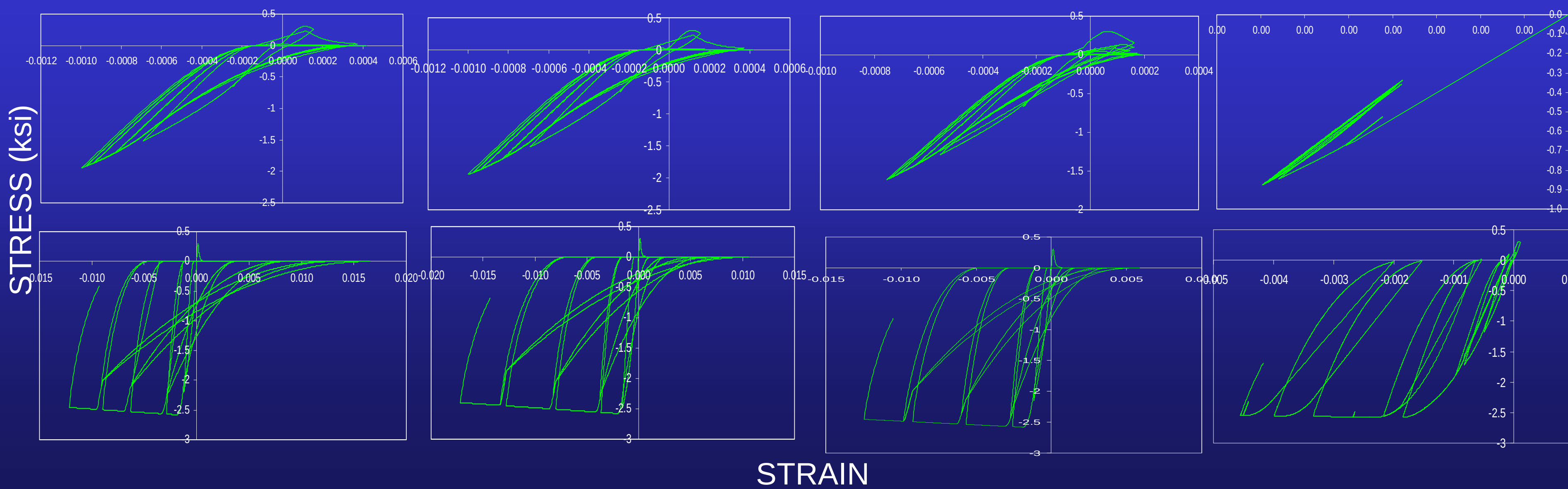




Web

Web

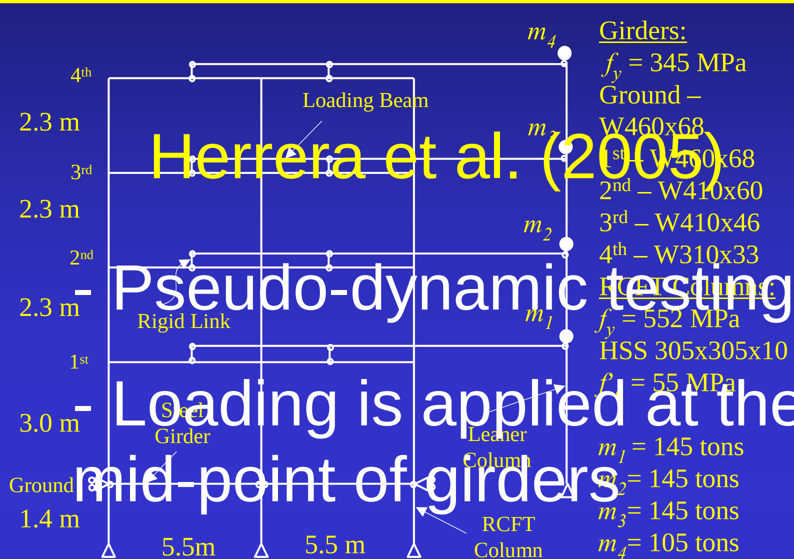


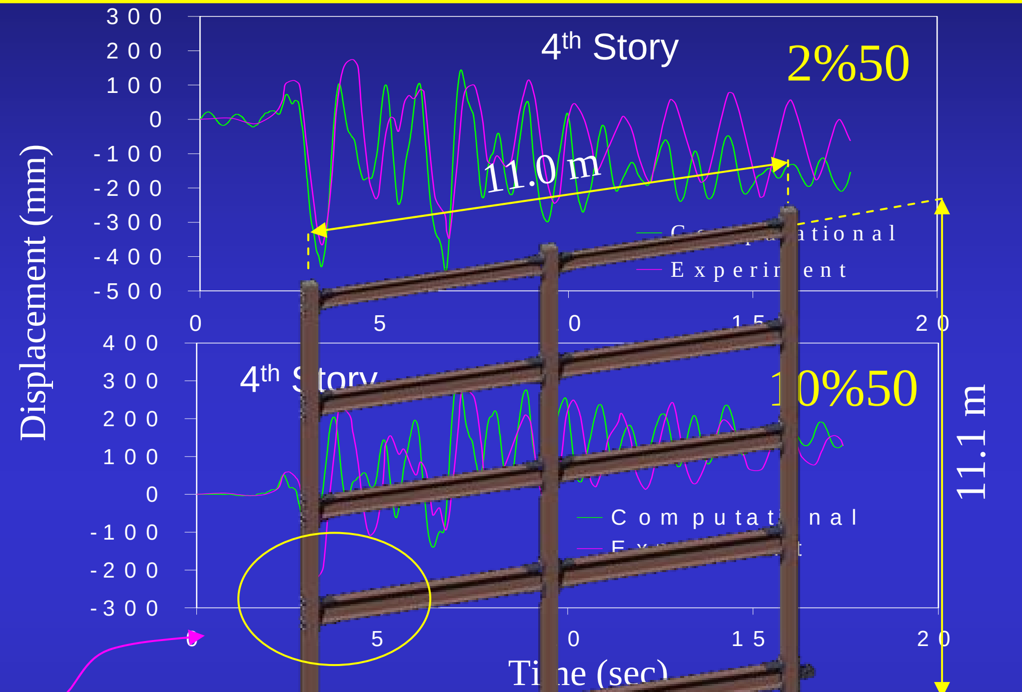


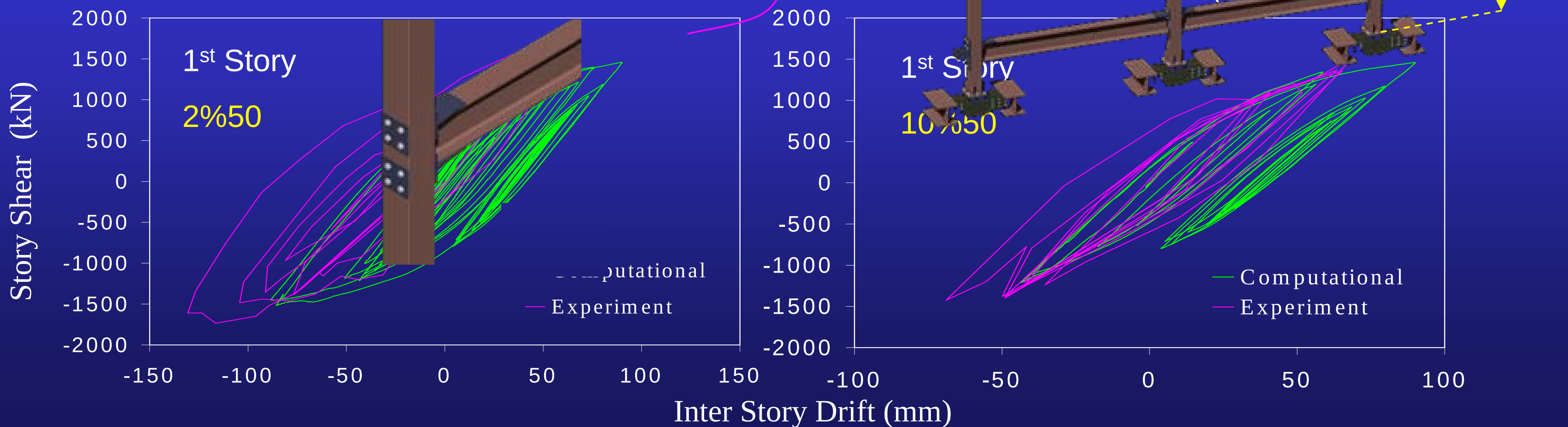
RCFT Frame Response: Pseudo-Dynamic Experiment

Herrera et al. (2005)

- Pseudo-dynamic testing
- Loading is applied at the mid-point of girders
- High strength materials







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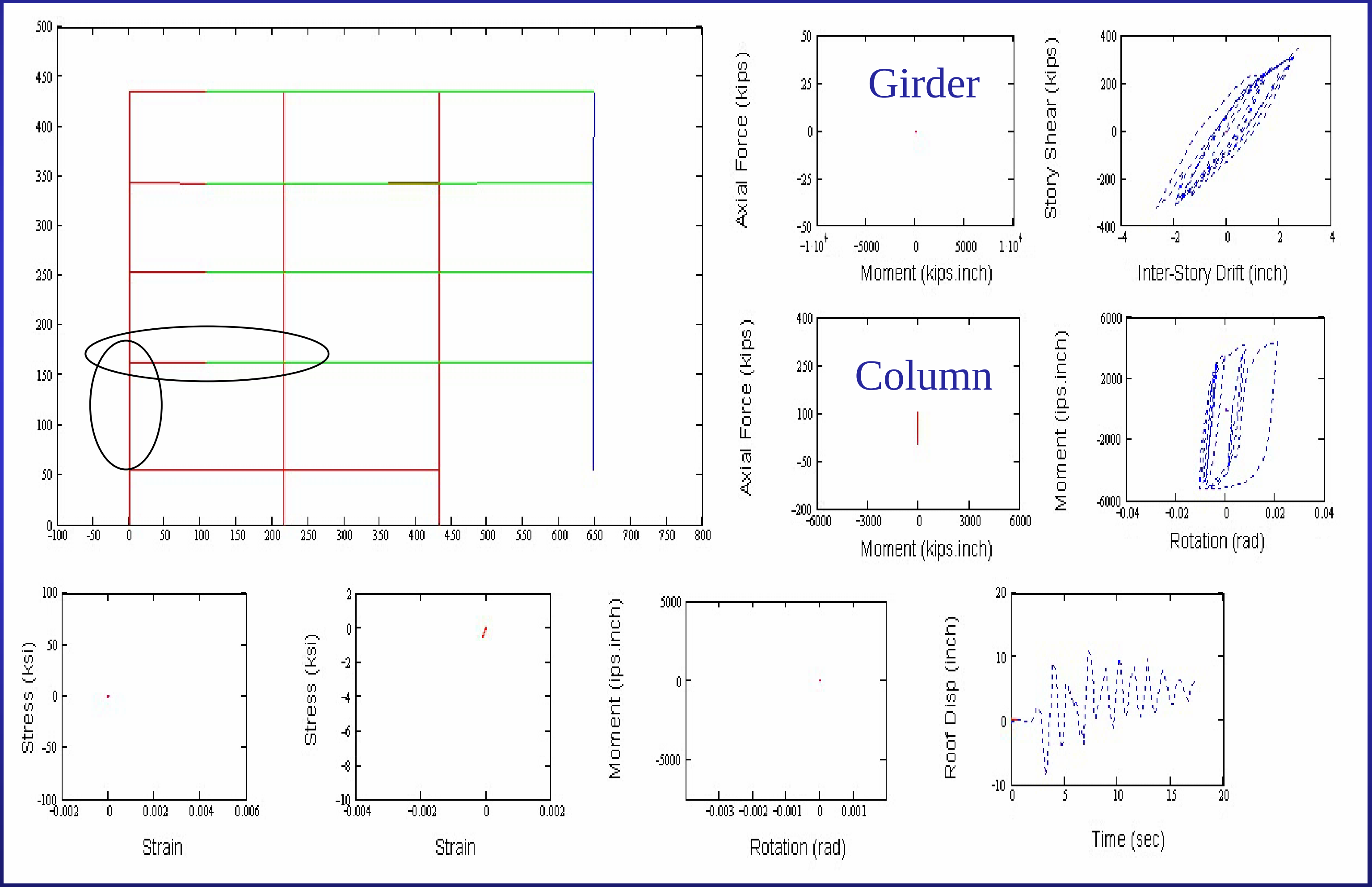
Computational Modeling of RCFTs

070612 Herarra Frame Movie.mpg

1st Story Column and Girder P-M Interaction



1st Story Shear vs. Drift

1st Story Girder Moment vs. Rotation

4th Story Displacement vs. Time

1st Story Column Steel Tube Stress vs. Strain

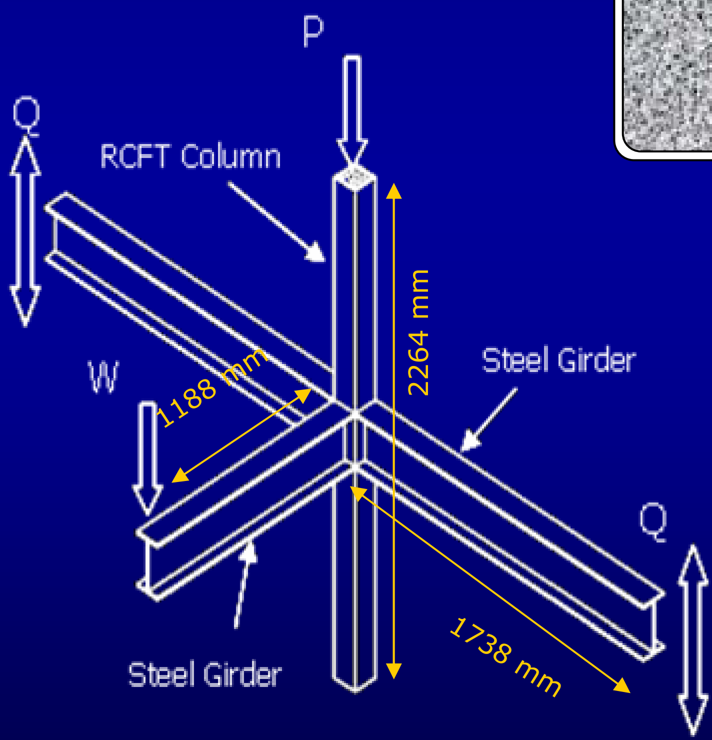
1st Story Column Concrete Core Stress vs. Strain

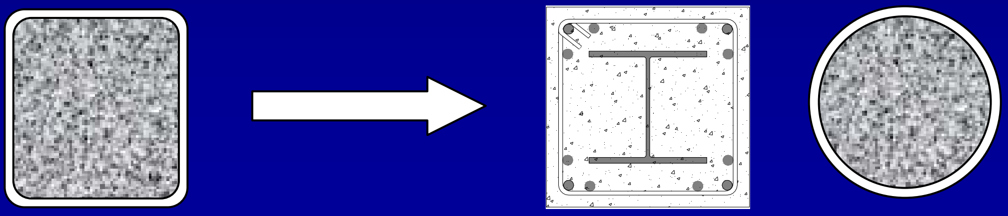
1st Story Column Moment vs. Rotation

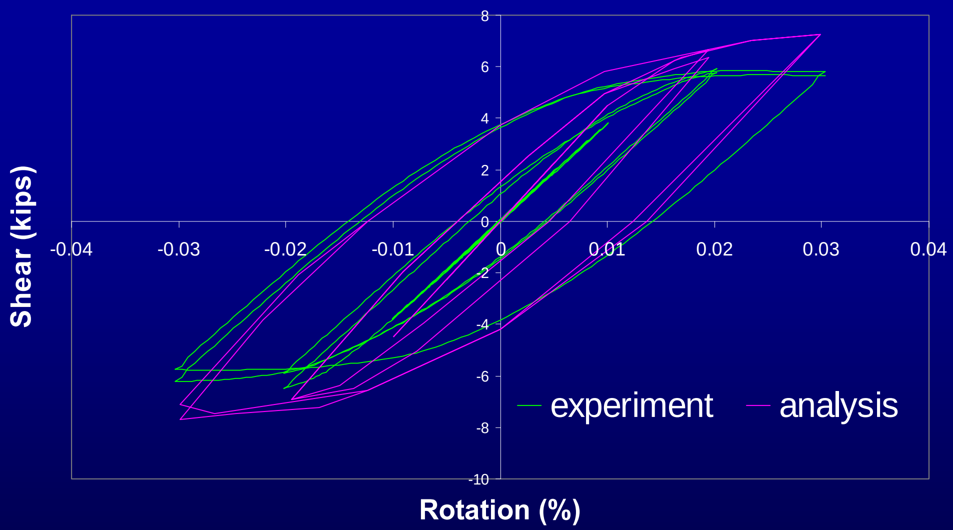
10% in 50 year Northridge ground motion

Computational Model

- Extending now to circular CFTs and SRCs







Upcoming: Parametric Studies

- Parametric studies will be performed to document the performance limit states of composite systems, leading to the development of new recommendations for non-seismic and seismic design of composite beam-columns.

Upcoming: Equivalent Stiffness for AISC

- A simplified, mechanistically based equation for the prediction of the equivalent stiffness, EI_{eq}, of composite beam-columns will be developed.
- Equations similar to the current ones for buckling of composite sections in the 2005 AISC Specification will be derived.

$$EI_{eff} = E_s\, I_s + 0.5\, E_s\, I_{sr} + C_1\, E_c\, I_c$$

where C_1 is a simple parameter based on the reinforcement ratio.

Upcoming: System Performance Factors

- Rational system performance factors (e.g., R, C_d, and Ω_o) will be developed.
- Currently, they are based on a perceived equivalence to either concrete or steel systems.

Seismic-Force-Resisting Systems	R	Ω_o	C_d
Composite eccentrically braced frames	8	2 ½	4
Composite concentrically braced frames	5	2	4 ½
Ordinary composite braced frames	3	2	3
Special composite moment frames	8	3	5 ½
Intermediate composite moment frame	5	3	4 ½
Ordinary composite moment frame	3	3	2 ½

FEMA 450-1/2003 Edition