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T.R. Higgins Lecture: SpeedCore and Steel-Concrete Composite Construction – The Best of Both Words

March 17, 2022

Smarter. Stronger. Steel.

AISC Live Webinars

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Course Description

T.R. Higgins Lecture:
SpeedCore and Steel-Concrete Composite Construction – The Best of both Worlds
March 17, 2022

The merits of steel-concrete composite construction have been recognized and leveraged for decades, but they have never been harnessed quite so efficiently as the new SpeedCore system, which consists of composite plate shear walls and composite coupling beams. This system can be used, when needed, in lieu of traditional reinforced concrete core walls/shear walls in commercial, industrial, or nuclear construction. The primary advantages of this composite system stem from the efficient modularization and prefabrication of steel modules, and elimination of rebar cages, formwork, and falsework, resulting in an expedited construction schedule and thus overall increased project economy. In this years T.R. Higgins Lecture, Purdue Universitys Amit Varma will summarize the results of extensive research conducted over more than 12 years, culminating in the development of design specifications, provisions, and guidelines for composite walls and systems for various applications. He'll highlight experimental behavior, numerical modeling, and design of composite walls and the SpeedCore system for wind loading, seismic loading, and fire loading conditions. For wind loading, the presentation will focus on stiffness and strength. For seismic loading, the presentation will focus on the capacity design method and performance evaluation. For fire loading, the presentation will cover both the fire resistance rating (in hours) and strength at elevated temperature.

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Learning Objectives

- Differentiate between steel-plate composite (SC) and SpeedCore systems.
- Summarize minimum requirements for detailing SpeedCore walls and systems.
- Relate the design provisions for SpeedCore systems to experimental behavior and numerical analyses.
- Estimate the fire behavior and resistance of SpeedCore walls.

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SpeedCore and Steel-Concrete Composite Construction –The Best of Both Worlds

Amit H. Varma
Karl H. Kettelhut Professor
Director, Bowen Lab for Large Scale CE Research
Lyles School of Civil Engineering
Purdue University

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Acknowledgments

- American Institute of Steel Construction
- Charles Pankow Foundation
- Steel Institute of New York
- MKA Foundation
- Supreme Group
- Geiger & Peters
- T. R. Higgins Award Jury – 2021
- Mentors and Students (from 1994 – present)

Acknowledgments

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- Soheil Shafaei, Morgan Broberg, Purdue University
- Ata Anvari, Mubashshir Ahmad, Purdue University
- Tom Bradt, Jungil Seo, Purdue University

Outline

1. Introduction to System and Use / History
2. Section Detailing, Limits, Requirements
3. Stiffness, Strength, Deformation Capacity
4. Nonlinear Analysis & Modeling Recommendations
5. Seismic Behavior & Capacity Design
6. Seismic Performance Requirements
7. Fire Performance & Design
8. Current & Future Work

STEEL-CONCRETE COMPOSITE CONSTRUCTION

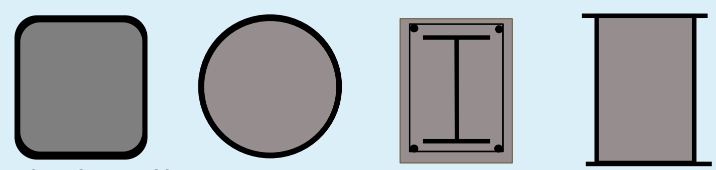
Combines the advantages of both construction materials

- Best of both worlds
- Elegance, lightweight and strength of steel
- Mass, rigidity, and damping of concrete
- Steel formwork and falsework
- Concrete stiffness, stability, and fire resistance

CONVENTIONAL COMPOSITE CONSTRUCTION

Composite Columns of Various Types

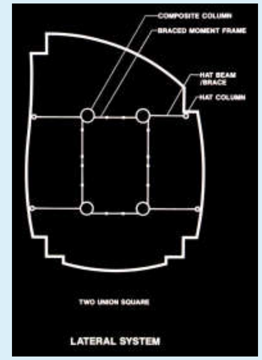
- Concrete filled hollow structural shapes (HSS)
- Steel shapes encased in reinforced concrete (SRC)
- Concrete-filled built-up box sections



Composite Construction

Some prominent examples:

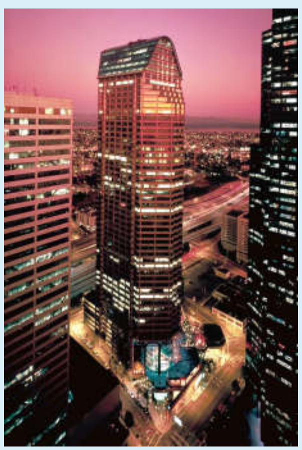
- Columbia Center | Seattle, WA → 1985
- Two Union Square | Seattle, WA → 1989
- Seattle Municipal Tower | WA → 1990
- Many innovative designs around the world



TWO UNION SQUARE, SEATTLE

With symmetrical built-up beams, composite-filled pipe columns with 18,000 psi concrete, and visco-elastic dampened outriggers, one of the most optimized composite steel structures

Courtesy of Magnusson Klemencic Associates



SEATTLE MUNICIPAL TOWER

GATEWAY TOWER

62-story, 140,000-m^2 office building with five levels of parking

Composite columns at the corners

Courtesy of Magnusson Klemencic Associates

Conventional Composite Construction

Inspired decades of research and development

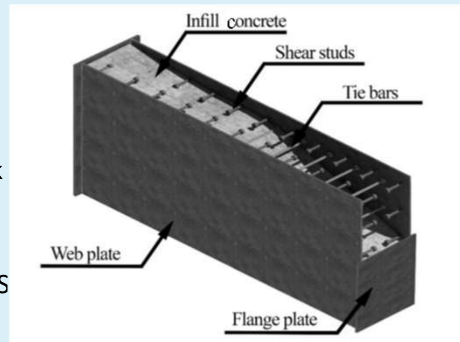
- Circular and square filled composite members and frames
- Seismic behavior and design
- Design of noncompact and slender section members
- Use of high strength materials
- P-M interaction, Shear strength, Fire resistance
- AISC 360 Chapter I, App. 4, AISC 341 Seismic Chapter G

Introducing the New SpeedCore System

Composite Plate Shear Walls – Concrete Filled (C-PSW/CF)

- Steel plates
- Concrete infill
- Tie bars
- Shear studs
- No rebars or formwork

- SHEAR WALLS and / or ELEVATOR CORE WALLS



A New Chapter in Composite Construction

Rainier Square, Seattle

- Client: WRIGHT RUNSTAD & COMPANY
- Architect: nbbj
- Structural & Civil: MAGNUSSON KLEMENCIC ASSOCIATES Structural + Civil Engineers
- GC/GM: LEASE CRUTCHER LEWIS

Courtesy of Magnusson Klemencic Associates

A New Chapter in Composite Construction

Steel Fabricator: SUPREME GROUP

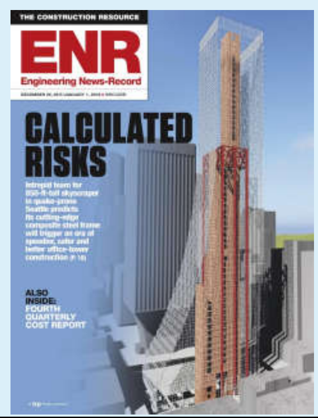
Steel Erector: THE ERECTION CO., INC.

Rebar Fabricator: Farwest Steel Corporation

Concrete Supplier: STONEWAY CONCRETE

100 YEARS 1920-2020 MAGNUSSON KLEMENCIC ASSOCIATES

A New Chapter in Composite Construction



Cover of ENR Magazine

Constructed in 10 months

Eight months savings as compared to conventional RC construction

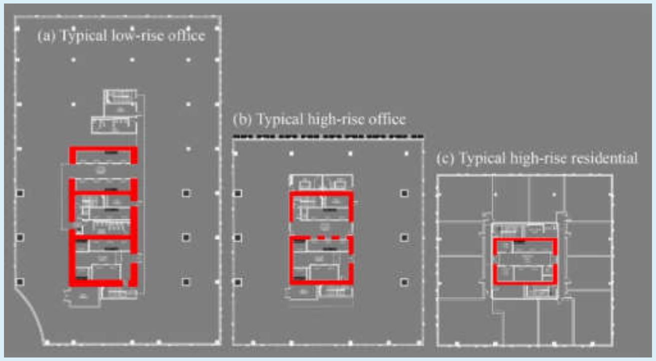
1.4 million square feet

850-feet tall

58-story office + residential

7 levels below-grade parking

Coupled Composite Plate Shear Walls – Core Walls



Courtesy of Magnusson Klemencic Associates

A New Chapter in Composite Construction

200 Park Avenue, San Jose, CA

High seismic region

937,000 rsf

19 stories

Under construction

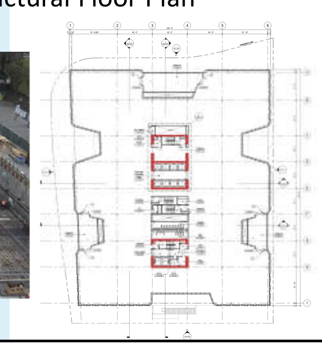
Courtesy of Gensler

A New Chapter in Composite Construction

200 Park Avenue, San Jose, CA

Webcam View – April 5, 2021

Structural Floor Plan



Courtesy of Magnusson Klemencic Associates

Steel-Plate Composite (SC) Walls : Evolution

- Safety-related nuclear facilities
- Various designs AP1000®, US-APWR®, APR+®
- Extensive research, testing, and development
- AISC N690 Nuclear Specification, Appendix N9
- AISC Design Guide 32
- Section detailing, stiffness, strength, local buckling

SC Walls and Designs in Nuclear Structures

Vogtle Unit 3 CA20 Module June 2014 © Georgia Power Company

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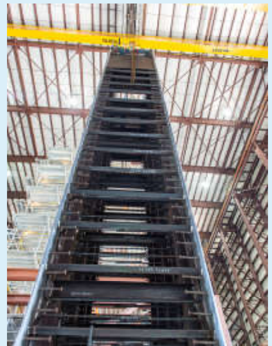
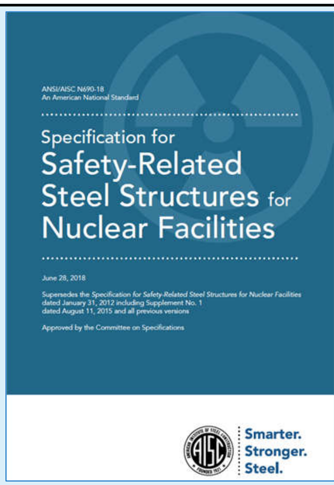
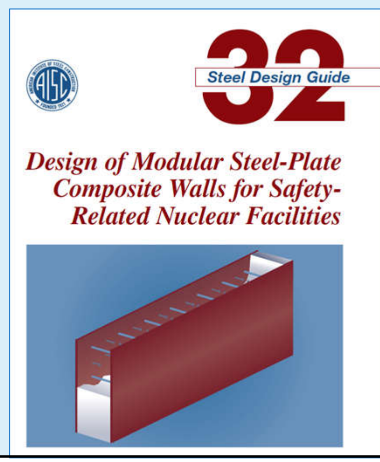


Sub-module inside the Module Assembly Building
May 2015 © Georgia Power Company

Workers placed all six of the third course shield building panels for Unit 3
April 2016 © Georgia Power Company *Accessed From: https://vogtlegallery.georgiapower.com*





Since the modules are so technical, and I end up making the presentation remotely due to the pandemic, I wanted to infuse some humor to keep the audience engaged, but all I could come up with were "inside" jokes!

Outline

1. Introduction to System and Its Use / History
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6. Seismic Performance Requirements
7. Fire Performance & Design
8. Current & Future Work

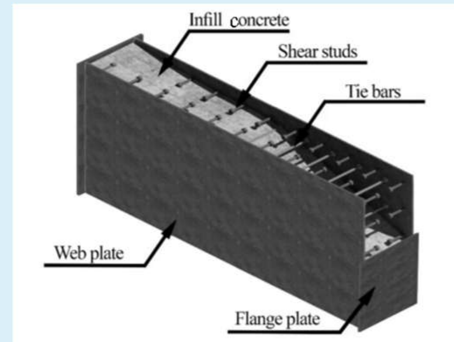
Key Components

Steel plates

Tie bars

Shear studs

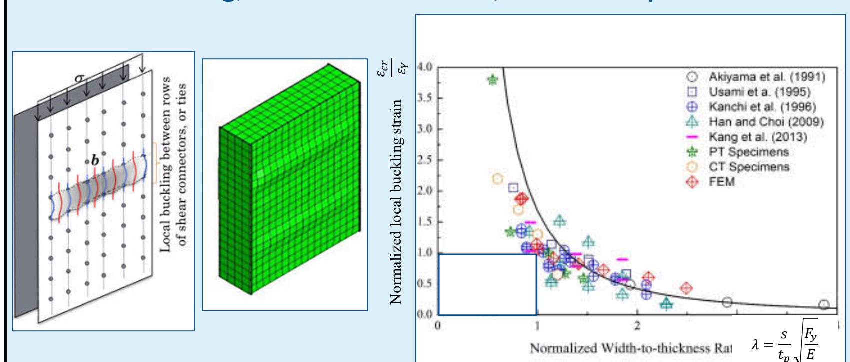
Concrete Infill



Steel Plates

- Reinforcement ratio limits
  - Minimum = 1%   Maximum = 10%
- Two steel plates must be connected to each other using ties
  Ties can consist of bars, steel shapes, or built-up shapes
- Steel plates must be anchored to concrete infill using
  stud anchors or ties or combination of ties and studs

Local buckling, Plate Slenderness, Axial Compression

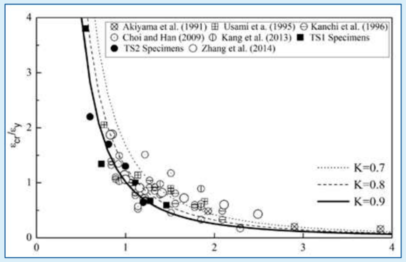


Local Buckling, Plate Slenderness, Axial Compression

Wind: $\frac{b}{t_p} \leq 1.2\sqrt{\frac{E}{F_y}}$

Seismic: $\frac{b}{t_p} \leq 1.05\sqrt{\frac{E_s}{R_y F_y}}$

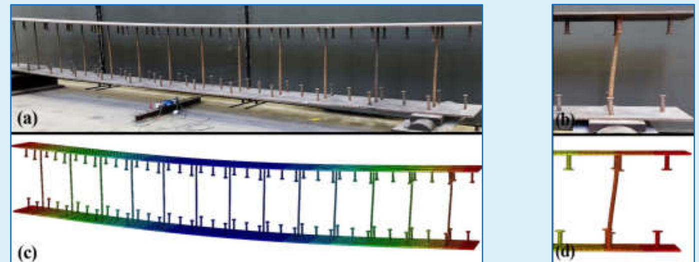
$F_{cr} \geq F_y$



$P_{no} = A_s F_y + 0.85 f'_c A_c$

Tie Bar Size, Spacing, and Stability of Empty Modules

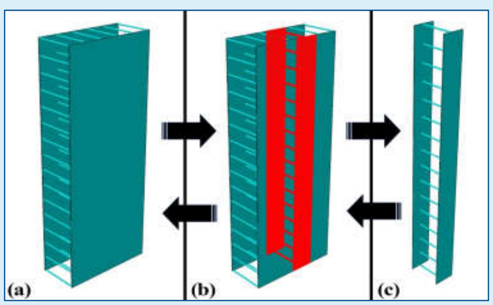
- Empty steel module flexibility governed by effective shear stiffness $(GA)_{eff}$ associated with Vierendeel truss / frame action



$\Delta_{total} = \frac{5 \times wL^4}{384 \times EI_{total}} + \frac{wL^2}{8 \times GA_{eff}}$ dominates

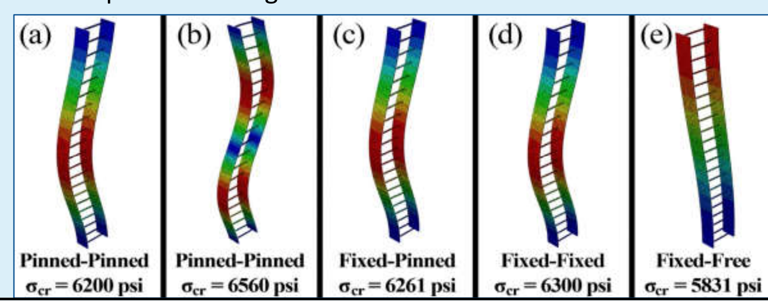
Tie Bar Size, Spacing, and Stability of Empty Modules

- Stability of empty modules during erection, construction and concrete placement → important consideration for design



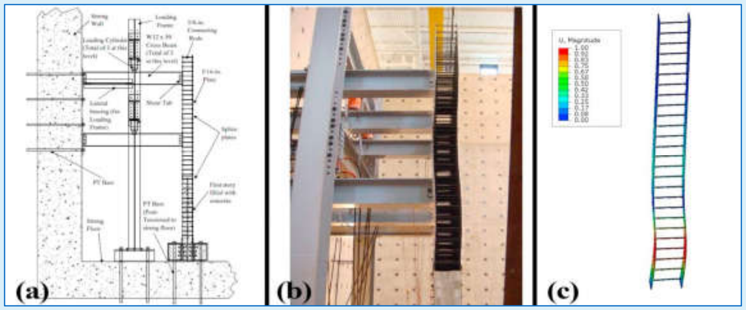
Tie Bar Size, Spacing, and Stability of Empty Modules

- Stability is governed by shear buckling, and P_{cr} is approx. equal to the same effective shear stiffness $(GA)_{eff}$ irrespective of length and end conditions



Tie Bar Size, Spacing, and Stability of Empty Modules

Confirmed by tests, analysis, and mechanics-based models



Tie Bar Size, Spacing, and Stability of Empty Modules

- Minimum $(GA)_{eff}$ of empty module for transportation, erection, and stability during construction, concrete casting
- Refined calculations can be made using theory
- Recommendations for tie bar size

$$\frac{S}{t_p} \le 1.0\sqrt{\frac{E_s}{2\alpha+1}}$$

$$\alpha = 1.7\left[\frac{t_{sc}}{t_p} - 2\right]\left[\frac{t_p}{d_{tie}}\right]^4$$

- α is the ratio of plate flexural stiffness to tie flexural stiffness
- α governs the value of $(GA)_{eff}$, and thus the tie spacing S/t_p requirement
- Still need to meet plate slenderness req.

Tie Bar Size, Spacing, and Stability of Empty Modules

- For example, 24 in. thick wall with ½ in. thick steel plates, and tie diameter of 1 in.
- Value of $\alpha = 4.9$
- $S/t_p < 52$ and required tie spacing = 25 in.
- Plate slenderness requirement = $1.2\sqrt{E/F_y}$
- Max. slenderness = 29, required spacing < 14.5 in.
- Potential designs with tie diameter of 1 in. & spacing of 14 in.

  Or with tie spacing of 24 in. and stud spacing of 12 in.

Recommendations for Stiffness

In-Plane Flexural Stiffness

- Account for concrete cracking corresponding to the required strength level
- Section moment-curvature response → secant stiffness corresponding to 60% of moment capacity
- Extent of concrete cracking, if drift governs or walls are overdesigned

In-plane flexure

$$EI_{eff} = E_s I_s + 0.35 E_c I_c$$

Axial

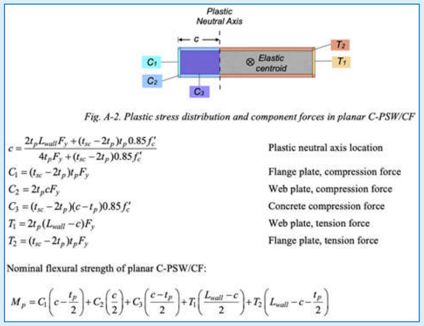
$$EA_{eff} = E_s A_s + 0.45 E_c A_c$$

In-plane shear

$$GA_{v.eff} = G_s A_{s.wall} + G_c A_c$$

Recommendations for Strength

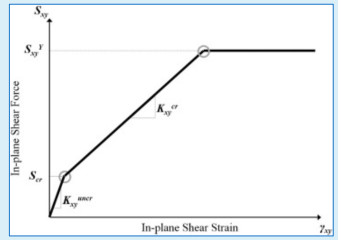
Plastic stress distribution over composite cross-section

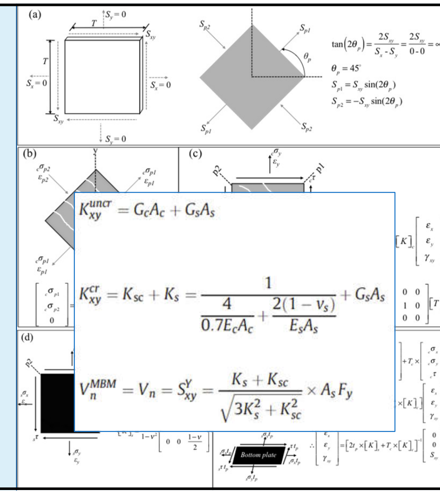


- Steel in compression & tension → f_y
- Compression concrete → $0.85f'_c$
- Equilibrium to calc. plastic neutral axis location, c
- Plastic moment M_p

In-Plane Shear Strength

Mechanics-based theory – orthotropic composite





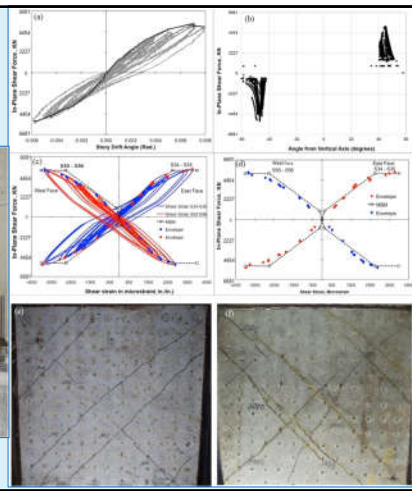
$$K_{xy}^{uncr} = G_c A_c + G_s A_s$$

$$K_{xy}^{cr} = K_{sc} + K_s = \frac{1}{\frac{4}{0.7E_c A_c} + \frac{2(1-\nu_s)}{E_s A_s}} + G_s A_s$$

$$V_n^{MBM} = V_n = S_{xy}^{Y} = \frac{K_s + K_{sc}}{\sqrt{3K_s^2 + K_{sc}^2}} \times A_s F_y$$

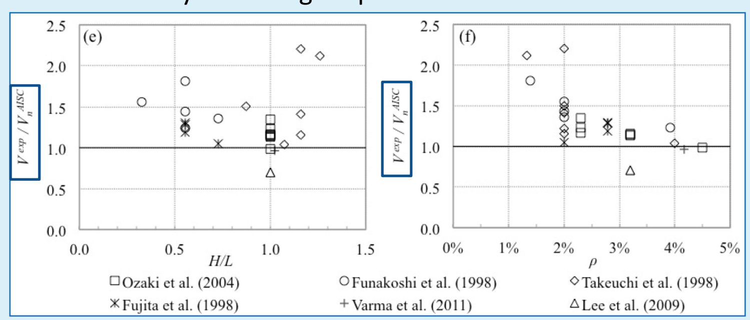
In-Plane Shear Strength

Experimental validation



In-Plane Shear Strength

Tests conducted in US, Japan, S.Korea, China, Europe used to confirm theory and design equations



So… while I was putting together this presentation, I wondered… why the chicken crossed the road… It seems that the chicken behind it was not "social distancing" properly

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EXPERIMENTS

Evaluation of Composite Wall Behavior

Applicable to Seismic or Non-Seismic Behavior
Applicable to Coupled or Uncoupled Systems

Objectives

Experimental Evaluation of Cyclic Lateral Load-Displacement

- Focus on stiffness, strength, and deformation capacity
- Parameters to be considered
  - Axial load level
  - Plate slenderness ratio
  - Tie bar size and spacing
  - Shear connectors

Experimental Method

- Test Matrix
- Test Setup
- Loading Protocol
- Expected Results (stiffness, strength, etc.)
- Experimental Behavior – Along with Various Events
- Comparison and Assessments
- Experimental Findings

Test Matrix

Specimens are planar C-PSW/CF

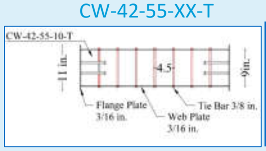
- Length = 36 in.
- Height = 108 in.
- Wall thickness = 9 in.
- Web plate and flange plate thickness = 3/16 in.

Varied parameters

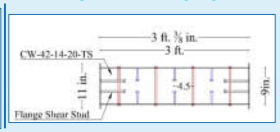
- Axial load level (10 - 30% $A_g f'_c$)
- Plate slenderness ratio (24 – 48)
- Tie bar diameter and spacing ($t_{sc}/2 - t_{sc}$)
- Use of shear studs vs. ties

Test Matrix

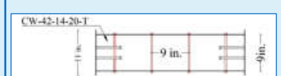
CW-42-55-XX-T



CW-42-14-20-TS

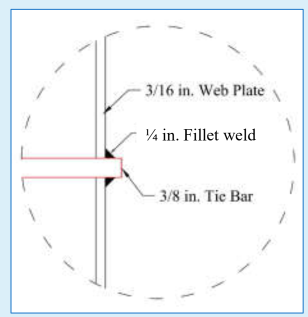


CW-42-14-20-T

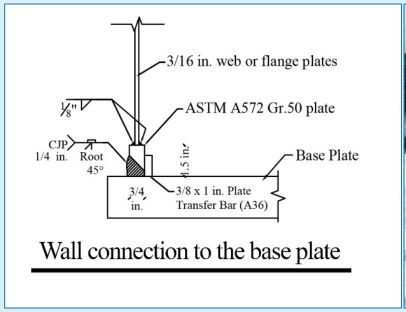


Specimen	General			Web											Flange	
	H, in	L, in	P, $\%A_g f_c'$	t_{sc}, in	t_p, in	ρ	s_{stud}, in	d_{stud}, in	s_{stud}/t_p	s_{tie}, in	d_{tie}, in	s_{tie}/t_p	ρ_t	$t_{p,f}$, in	w_f, in
CW-42-55-10-T	108	36	10	9	3/16	4.2%	-	-	-	4.5	0.375	24.0	0.55%	3/16	11
CW-42-55-20-T	108	36	20	9	3/16	4.2%	-	-	-	4.5	0.375	24.0	0.55%	3/16	11
CW-42-55-30-T	108	36	30	9	3/16	4.2%	-	-	-	4.5	0.375	24.0	0.55%	3/16	11
CW-42-14-20-T	108	36	20	9	3/16	4.2%	-	-	-	9	0.375	48.0	0.14%	3/16	11
CW-42-14-20-TS	108	36	20	9	3/16	4.2%	4.5	0.375	24	9	0.375	48.0	0.14%	3/16	11

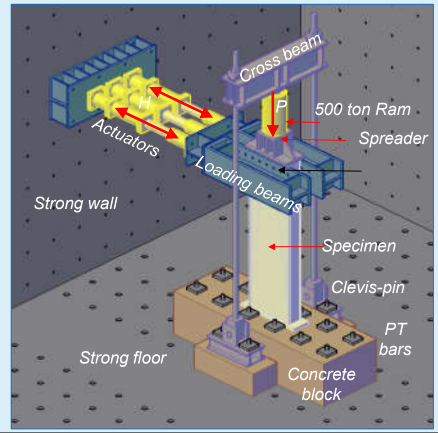
Test Specimens – Tie Bar Weld Details

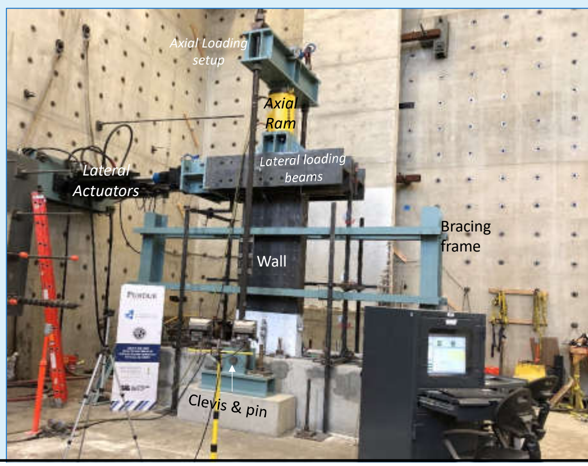


Test Specimens – Base Plate Weld Details



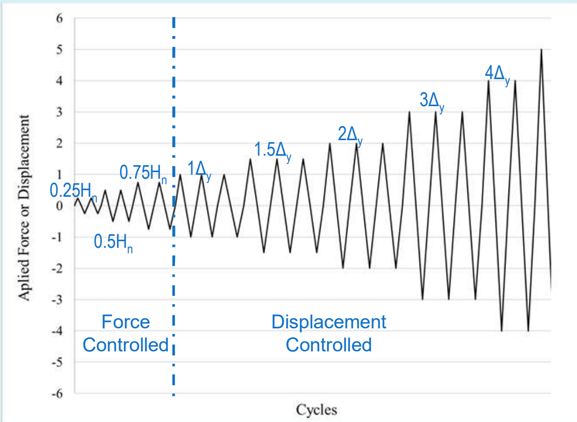
Test Setup



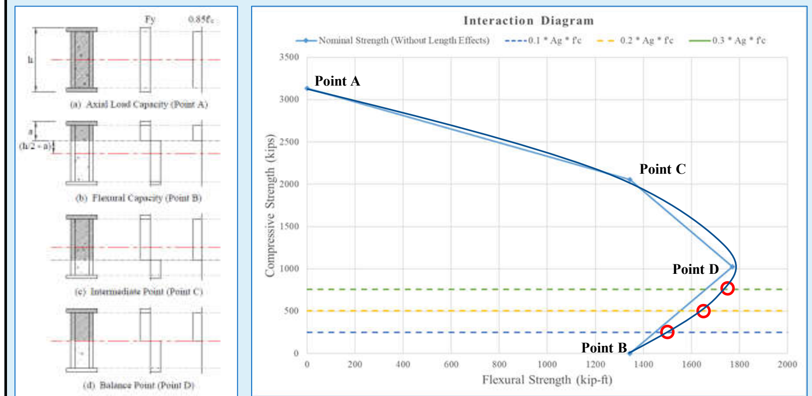


Test Specimens

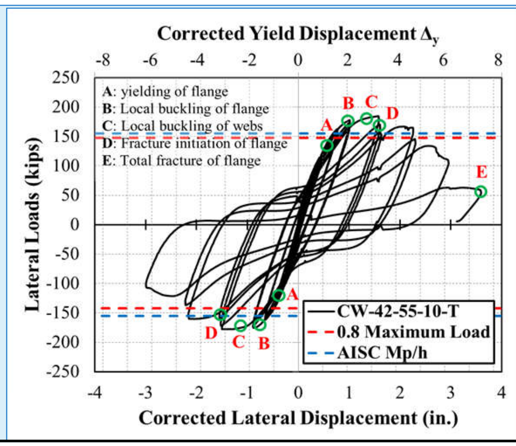
Lateral Cyclic Loading



Expected Stiffness and Strength



Lateral Load-Displacement of CW-42-55-10-T



Photographs of Local Buckling During 2Δy Cycles – Point B

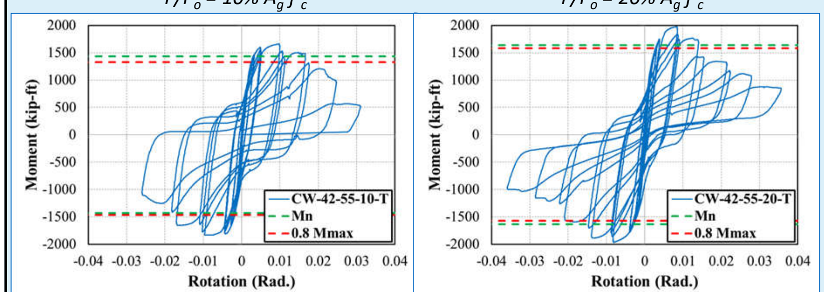
Photographs of Local Buckling During 3Δy Cycles – Point C

Local Buckling & Fracture During 4Δy Cycles – Point D

Fracture Failure During 6Δy Cycles – Point E

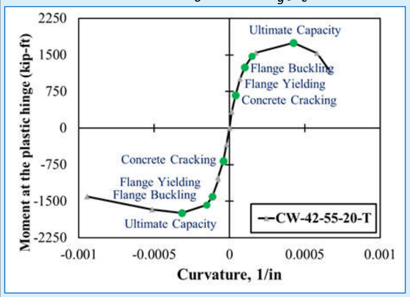
Base Moment – Plastic Hinge Rotation Behavior

$P/P_o = 10\%\ A_g f'_c$ $P/P_o = 20\%\ A_g f'_c$

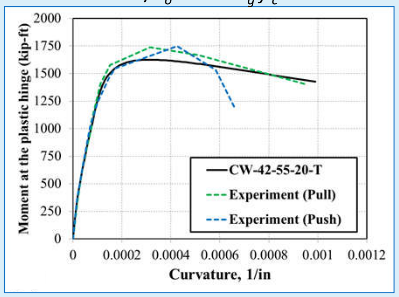


Moment – Curvature Behavior of Plastic Hinge

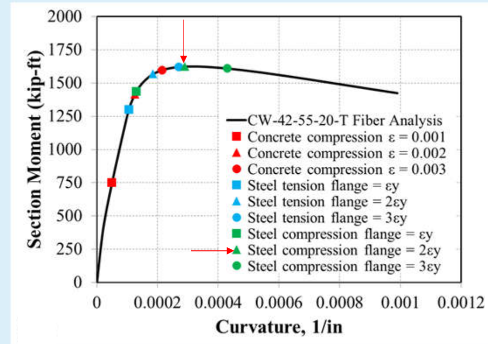
$P/P_o = 20\% \ A_g f'_c$



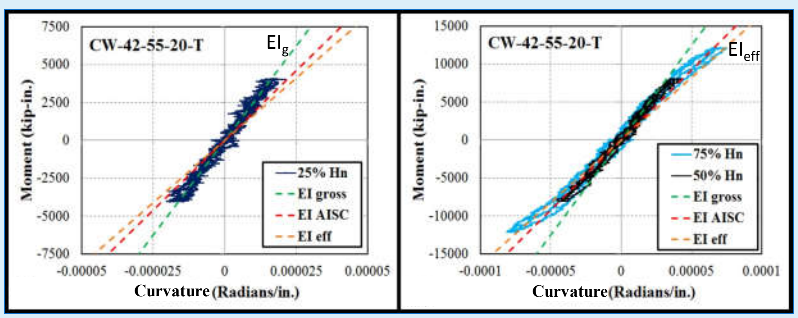
$P/P_o = 20\% \ A_g f'_c$



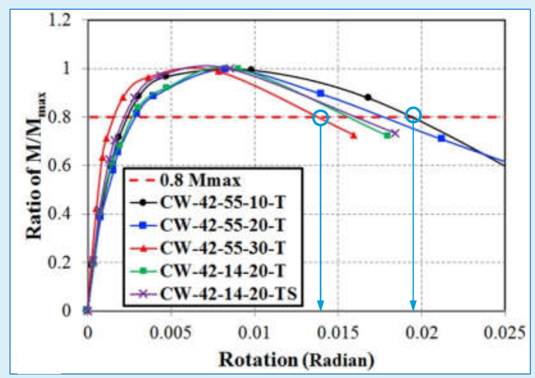
Moment-Curvature Behavior – Fiber Section Analysis



Section Flexural Section Stiffness



Rotation Capacity



Experimental Results

AISC recommended plastic stress distribution and fiber analysis methods can conservatively estimate the flexural capacity of wall specimens.

Increasing the axial load level resulted in increasing the flexural capacity of the planar wall specimens.

The flexural stiffness of the wall specimens (in the elastic range) can be estimated reasonably using EI_{eff} equations

Experimental Results

The plastic rotation capacity of the planar wall specimens (including those subjected to high axial loading) was in the range of 0.015 – 0.02 radians

The moment-curvature responses for the specimens calculated using fiber-based models were comparable to the envelops of the experimentally measured experimental responses.

The peak points (M_{max}) on the moment-curvature responses occurred after the compression strain in the steel plates exceeded 2 times the yield strain, which corresponds to concrete compressive strain of about 0.004

Q. What do you call Chewbacca when he has chocolate stuck in his hair
A. Chocolate Chip Wookie!

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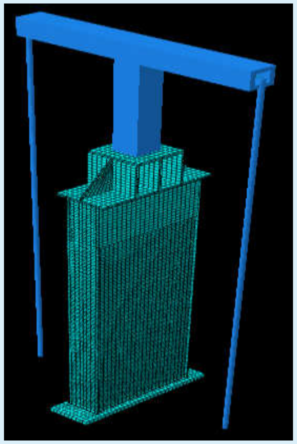
Objectives

- 3D Finite Element Models and Analysis of Planar Walls
- Effective Stress-Strain Relationships for Steel and Concrete
- 2D Finite Element Models and Analysis
- OpenSEES Fiber-Based Models and Analysis

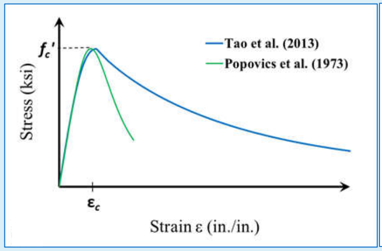
3D Finite Element Models

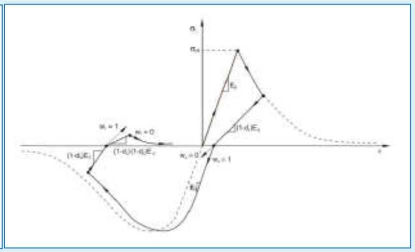
- Individually model
  - Steel faceplates
  - Concrete infill
  - Tie bars
  - Stud anchors
  - Interactions between steel & concrete
  - Entire test setup



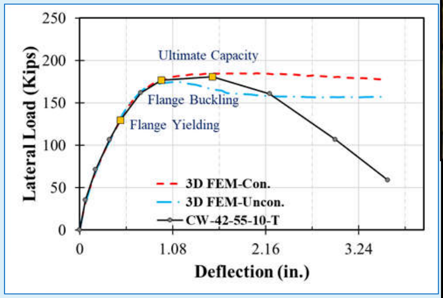
3D Finite Element Models

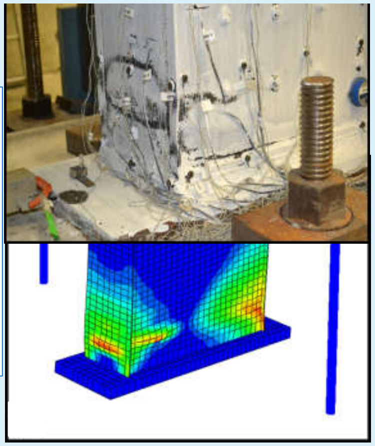
- Steel plasticity, local buckling, fracture
- Concrete compression plasticity, tension cracking
- Tie bar and stud anchor slip capacity & failure



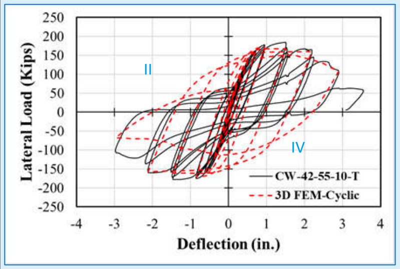


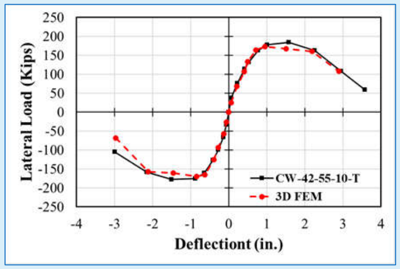
3D Finite Element Models – Monotonic Analysis



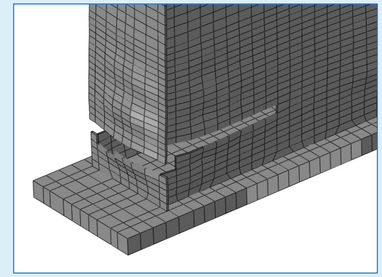


3D Finite Element Models – Cyclic Analysis





3D Finite Element Models – Cyclic Analysis



Effective Stress-Strain Curves

3D Finite Element Models → Complex; Computational resources and time

System Level Analysis → SIMPLER FINITE ELEMENT MODELS

Composite shell elements (2D FEM)

Fiber based elements (2D)

Phenomenological effective stress-strain curves:

- (a) Fundamental behavior and failure mechanisms
- (b) Conservative approach
- (c) Simplicity of their application in numerical models

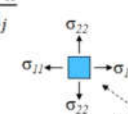
Effective Stress-Strain Curves - Steel

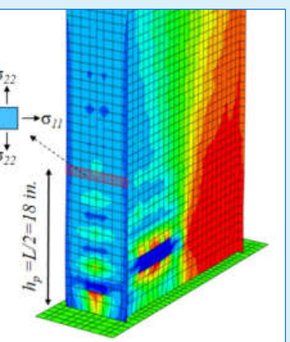
Average stress: $\sigma_{eff} = \frac{\sum A\sigma_{ii}}{\sum A_j}$

Where,
σ_{ii} = Element stress
A_j = Element area

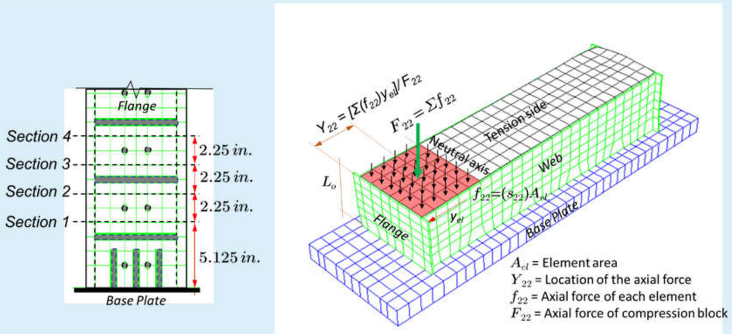
Effective strain: $\varepsilon_{eff} = \frac{\Delta h}{h_p}$

Where, $h_p = \frac{L}{2}$
h_p = Plastic hinge length
L = Length of the wall
Δh = Average of vertical displacements





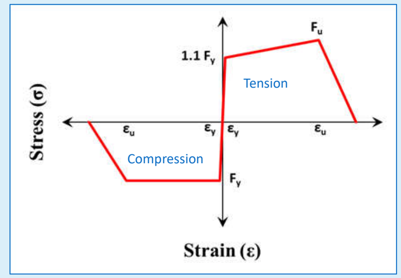
Effective Stress-Strain Curves - Concrete



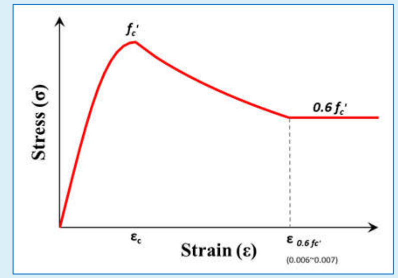
(a) Side view

(b) Compression block calculations

Proposed Effective Stress-Strain Curves

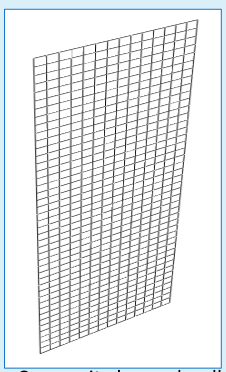


Steel



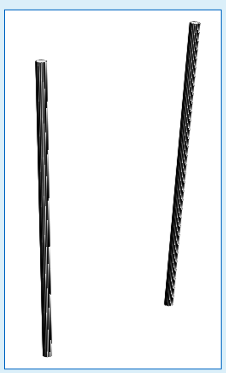
Concrete

2D Finite Element Model



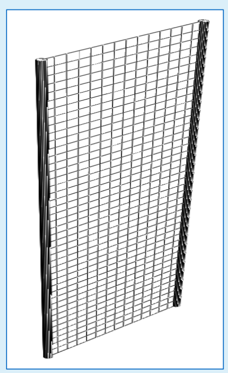
Composite layered wall
(Shell, S4R)

+



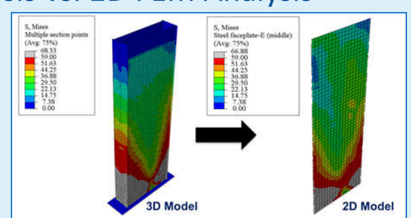
Steel flange plates
(Truss, T3D2)

=

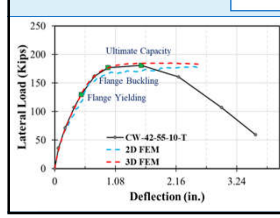


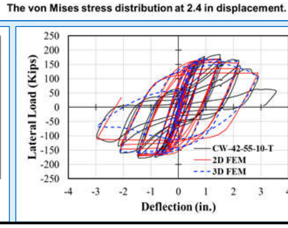
2D Finite Element Model

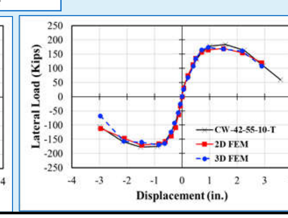
3D FEM Analysis vs. 2D FEM Analysis



The von Mises stress distribution at 2.4 in displacement.

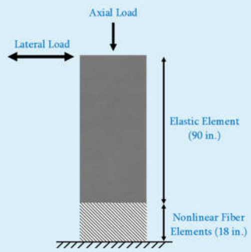


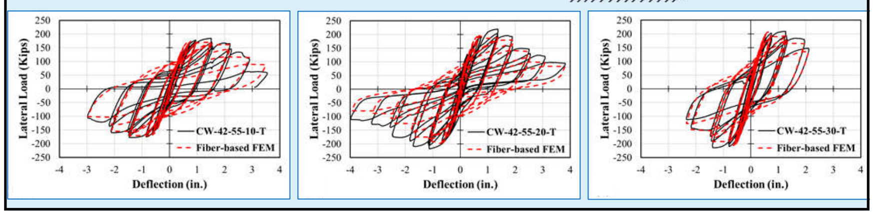




OpenSEES Fiber-Based Models

- Same effective stress-strain curves
- Include hysteretic relationships
- Cyclic fatigue and fracture models





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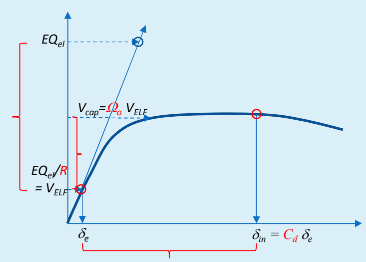
Introduction

- Seismic design can be performed using ASCE 7 Standard and AISC 341 Seismic Provisions
- Performance-based design can also be conducted, but that is project specific, and not discussed here in detail
- Numerical models required for PBD are similar to those presented here

Seismic Design Factors

- *R* – Response modification factor is used to reduce the seismic design forces from elastic level to account for inelastic behavior and ductility of the structure



- Ω_o – Overstrength factor is used to estimate the inherent overstrength in the base shear capacity of system due to redundancies, material., etc.
- C_d – Displacement amplification factor is used to calculate the inelastic story drift from the calculated elastic story drift level

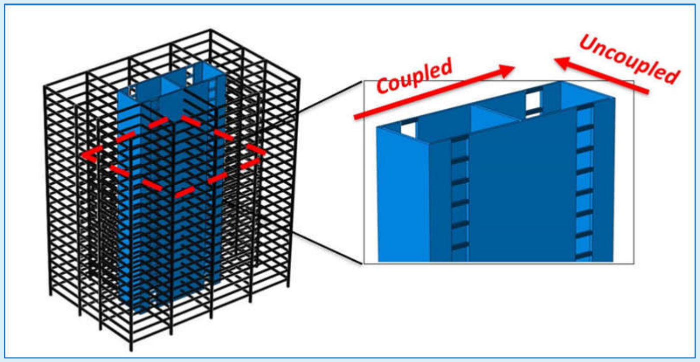
ASCE 7

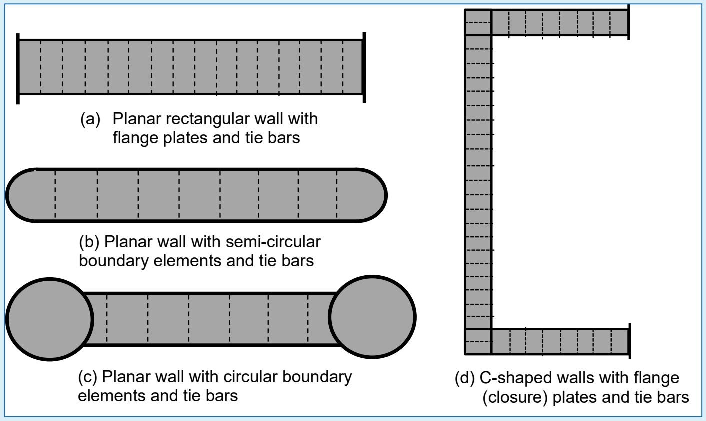
- ASCE 7 provides these seismic design factors for most steel, concrete, and composite systems
- For uncoupled C-PSW/CF system (with only shear walls), ASCE 7 include values of R=6.5, Ω_o = 2.5, and C_d=5.5
- For the coupled C-PSW/CF system (core walls, etc.) ASCE 7 did not include these values
- In ASCE 7, the largest value of R for any system is 8.

FEMA P-695

- FEMA P-695 is a systematic process to assess the seismic collapse margin of structures designed using a consistent design method and seismic factors (R, Ω_o, C_d)
- Steps include:
  - Consistent design method
  - Archetype structures in different groups
  - Nonlinear models able to model failure modes
  - Scaled suite of ground motions
  - Incremental dynamic analyses
  - Statistical evaluation of results and collapse margin

SpeedCore Systems – Coupled & Uncoupled





SpeedCore System - Uncoupled

- Seismic design provisions in AISC 341 Section H7 (2016) with updates in 2022
- Section H7.1 – Scope
  - Wall height-to-length ratios greater than or equal to 3
  - Flexure-critical walls
  - Walls have boundary elements or flange plates

Uncoupled SpeedCore – FEMA P-695

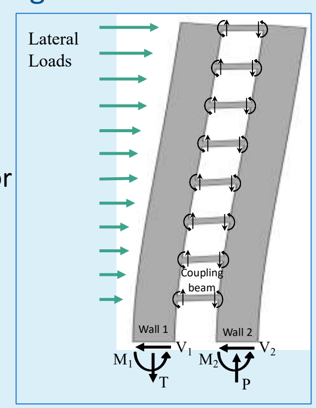
- Comprehensive study was conducted to confirm the seismic design factors (R, Ω_o, C_d) already given in ASCE 7
- Archetype structures included 3, 6, 9 and 12 story structures with planar walls and flange plates.
- Also included archetype structures with C-shaped walls for 15, 18, and 22 story structures
- Nonlinear models (using OpenSEES) and incremental dynamic analyses for 22 sets of FEMA ground motions scaled

Uncoupled SpeedCore – FEMA P-695

- Collapse was defined conservatively with maximum story drift ratio of 3% although the composite walls had not failed
- All the archetype structure passed the adjusted collapse margin ratio limits set forth in FEMA P-695 for 10% probability of failure at maximum considered earthquake, while assuming uncertainties associated with "good" designs, models, ground motions and analyses

Coupled SpeedCore – Capacity Design

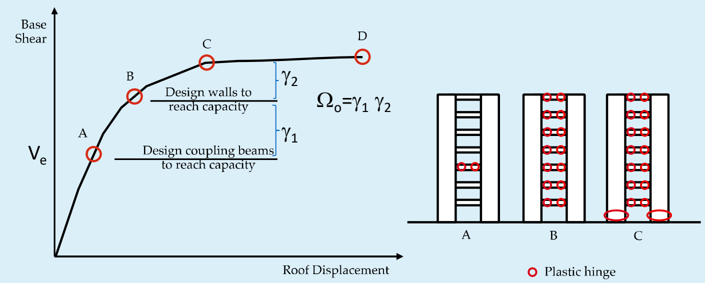
- Target R factor = 8 (highest possible in ASCE 7)
- Additional system level ductility due to coupling
- Potential to spread inelastic behavior along structure height
- Opportunity – to develop capacity design principle and get better system behavior, ductility, and thus higher R factor



Coupled SpeedCore – Capacity Design

- Two potential sources of inelastic deformations
  1. Flexural plastic hinges at ends of coupling beams
  2. Flexural yielding at base of walls
- Preferred inelastic mechanism – form flexural plastic hinges at both ends of coupling beams and at the base of walls
- Strong wall – beam coupling beam design approach followed for sizing of composite members
- Develops extensive plastic hinging in most coupling beams before significant yielding of walls
- Coupling beams can fracture, while walls continue to provide inelastic behavior

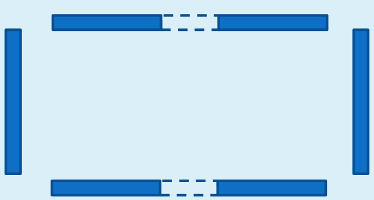
Coupled SpeedCore – Capacity Design



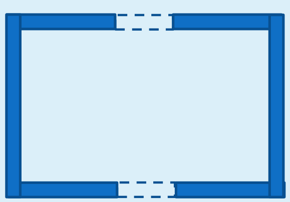
- Coupling beams form plastic hinges and distributed plasticity along structure height
- Walls sized to develop plastic hinges along entire wall height

Coupled SpeedCore – Archetype Structure Design

- 3, 8, and 12 story – Planar coupled walls
- 18, 22 story – C-shaped coupled walls



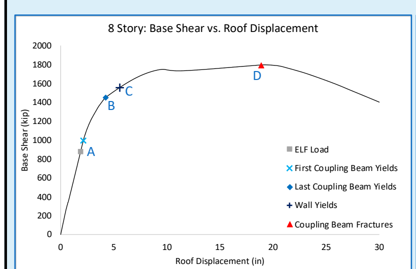
Type 1 – Planar walls
Coupled and uncoupled walls

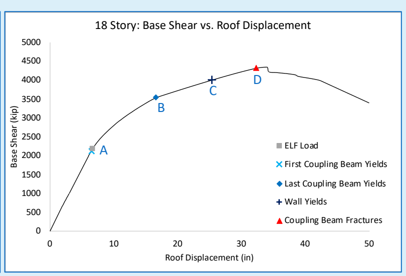


Type 2 – C-shaped walls
Coupled and uncoupled walls

Coupled SpeedCore – Capacity Design

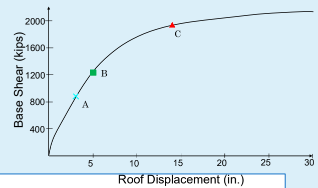
- Typical pushover behavior – OpenSEES Model

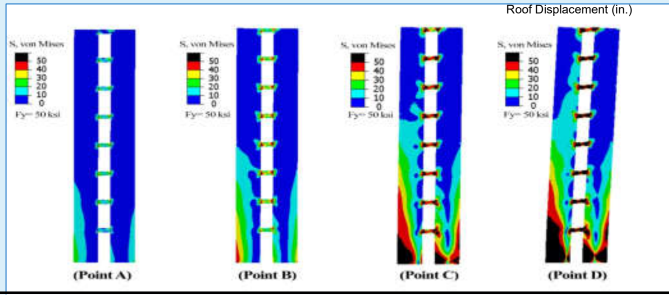




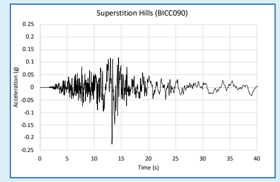
Coupled SpeedCore – Capacity Design

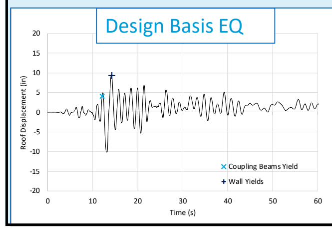
2D Finite Element Model

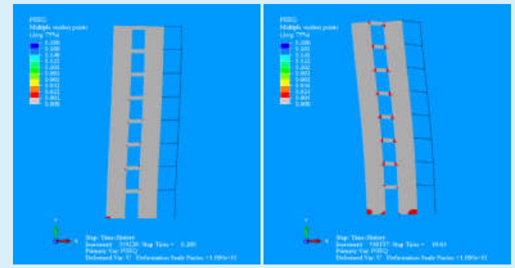




Coupled SpeedCore – Design Basis EQ



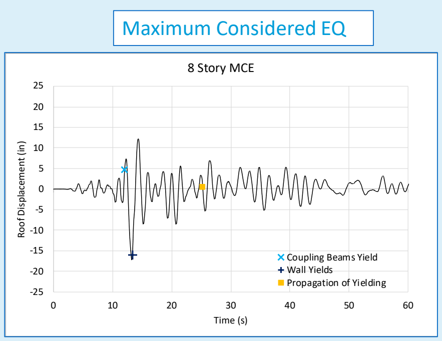


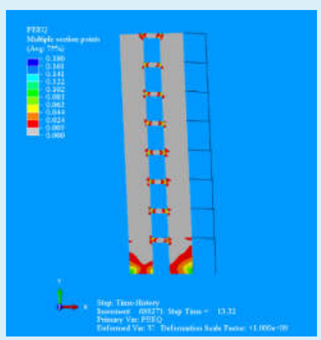


X Coupling beams yield

+ Walls yield

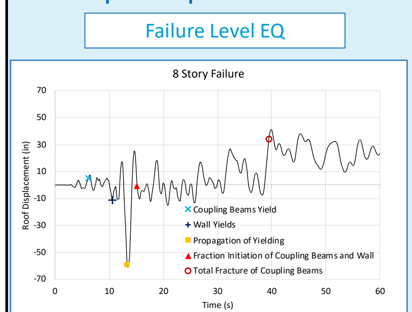
Coupled SpeedCore – Maximum Considered EQ

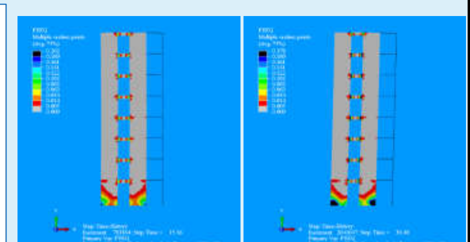




Propagation of yielding

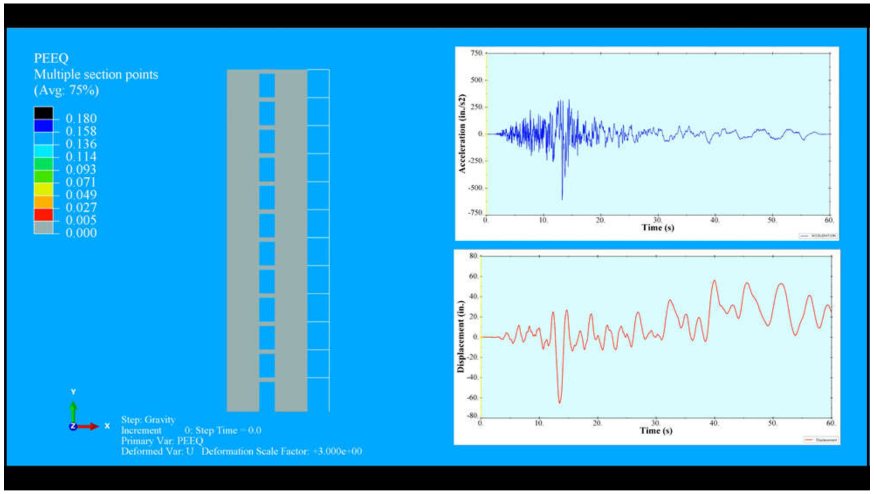
Coupled SpeedCore – Failure Level EQ (Scale Factor 7)





▲ Fracture initiation

○ Total fracture



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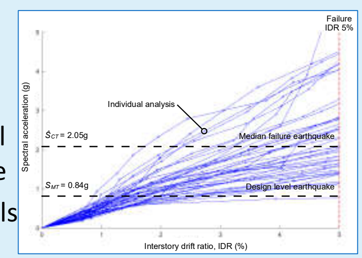
Coupled SpeedCore – FEMA P-695 Results

- Archetype structures designed and detailed according to capacity design and AISC 341-22 – Section H8
- Design provisions included in NEHRP (2020) and ASCE 7-21
- 3, 8, 12 story – planar coupled walls
- 18, 22 story – C-shaped coupled walls
- Nonlinear models developed by two independent teams
- Incremental dynamic analyses for 22 sets of FEMA P-695 ground motions scaled appropriately

Coupled SpeedCore – FEMA P-695 Results

- Failure was conservatively assumed at 5% drift ratio although the walls don't fail
- Collapse margin ratios
- Adjusted collapse margin ratios
- Acceptance criteria for individual and group of archetype structure
- Passes for "good" designs, models, ground motions, analyses
- Confirms the seismic factors R, Ω_o, C_d for the system



Seismic Design Provisions – AISC 341-22 Section H8

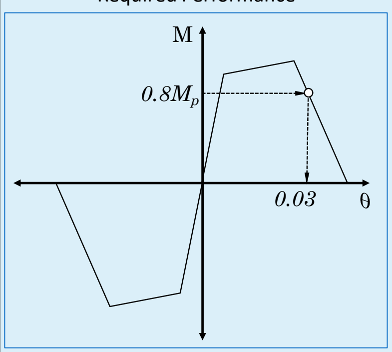
- System level requirements / limitations in addition to those in AISC 360-22 and Section H7 (Uncoupled)
- Wall height-to-length ratio of composite walls greater than or equal to 4, i.e., walls are flexure critical → yielding governs
- Coupling beams are also flexure critical with clear length-to-section depth (L/d) ≥ 3.0 and ≤ 5.0
- Based on archetypes included in FEMA P-695 studies, and desired ductility

Seismic Design Provisions – AISC 341-22 Section H8

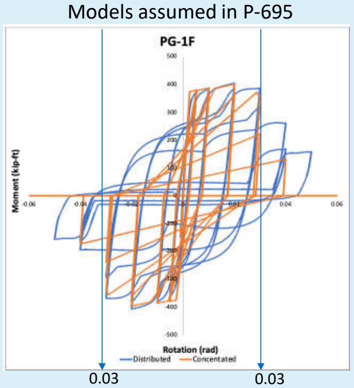
- Slenderness requirements for composite coupling beam and composite wall steel elements
- Coupling beam-to-wall connection requirements
  - Required flexure and shear strength to develop expected plastic strength of coupling beam
  - Chord rotation capacity of 0.03 rad. before strength degrades to 80% of M_p

Coupling Beam-to-Wall Connections

Required Performance



Models assumed in P-695

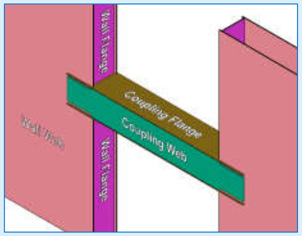


Coupling Beam-to-Wall Connections

- Some tested in the past, but limited testing of flexure critical
- Additional testing ongoing currently
- Composite coupling beam consists of flange plates, web plates and concrete infill
- Different connections between these elements and wall web plates, flange plates and concrete infill
- Various connection types considered, vetted by industry, fabricators, and three final candidates selected
- Three connection types and two L/d ratios of 3 and 5

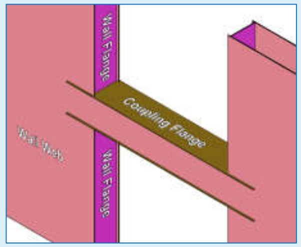
Coupling Beam-to-Wall Connections

Connection Type 1B



- Coupling beam flange plates penetrate into walls
- Coupling beam web plates lapped and welded to walls

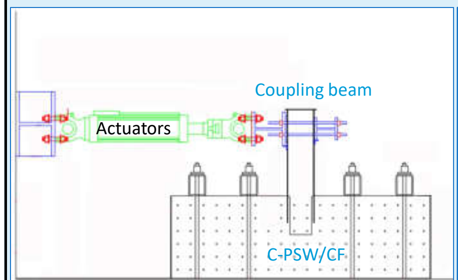
Connection Type 3

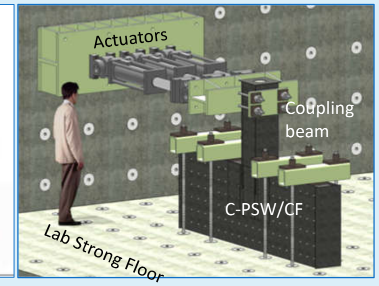


- Coupling beam flange plates penetrate into walls
- Wall web plates continuous with beam web plates

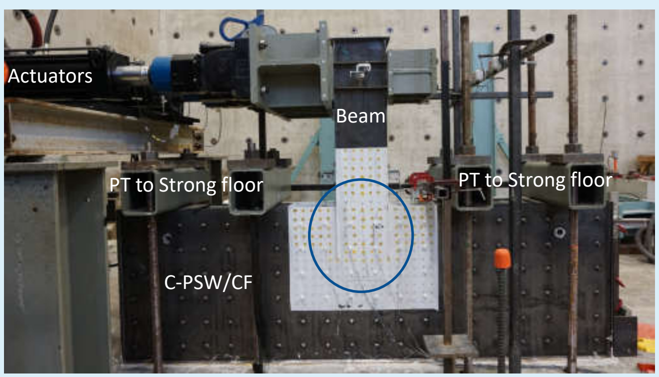
Test Setup and Specimens

Specimens are 1:2 scale

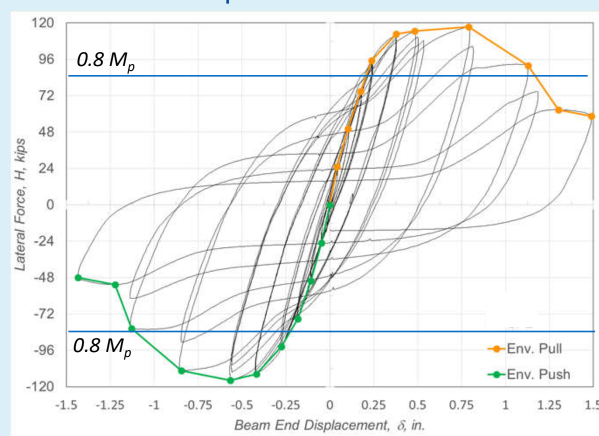




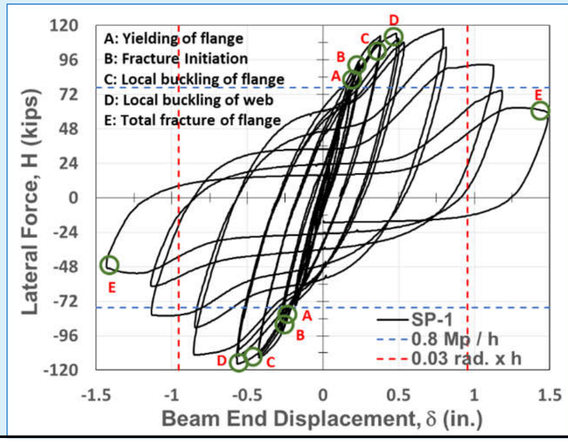
Test Setup



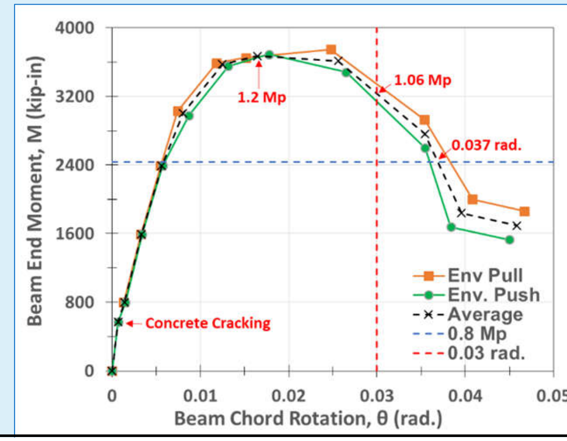
Lateral Force-Displacement Behavior SP-3



Lateral Force – Chord Rotation Behavior SP-3

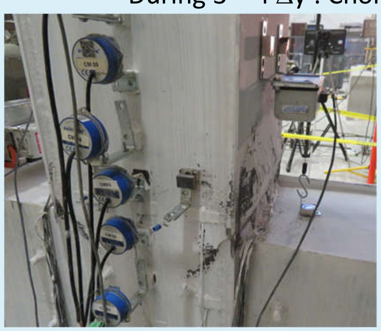


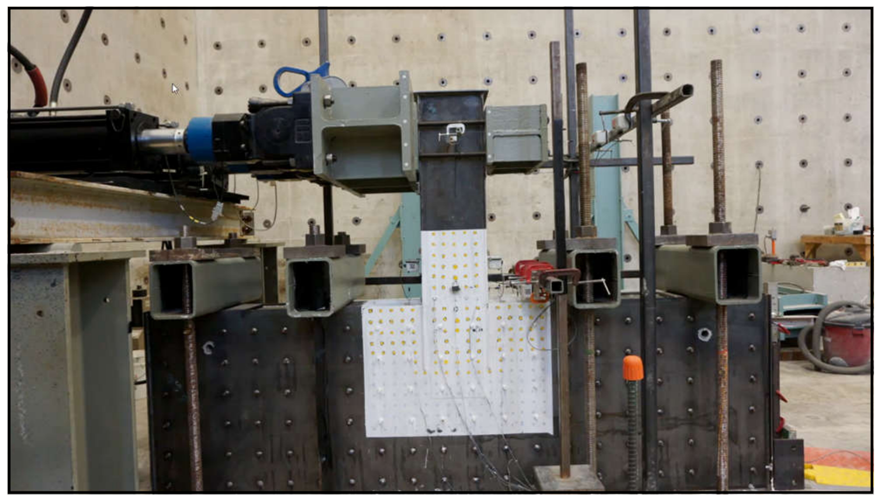
Moment – Chord Rotation Behavior for SP-3



Photographs of Specimen During Testing

During 3 – 4 Δy : Chord rotation of 0.035 rad.





Findings from Seismic Performance Requirements

- Coupling beam-to-wall connections have been tested and confirmed for SpeedCore
- Three connection types have been fully tested successfully for different length-to-depth ratios

Outline

1. Introduction to System and Its Use / History
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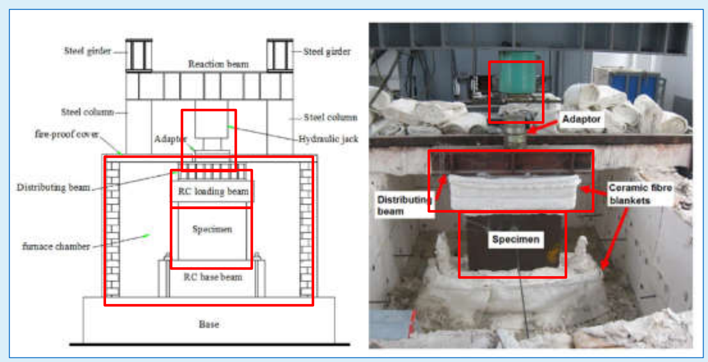
5. Seismic Behavior & Capacity Design
6. Seismic Performance Requirements
7. Fire Performance & Design
8. Current & Future Work

Fire Resistance and Design of C-PSW/CF Walls

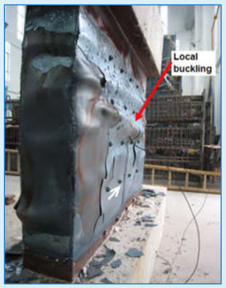
- Focus on unprotected composite walls
- Experimental Behavior - Thermal & Structural
- Uniform and non-uniform heating
- Numerical Models, Benchmarking, Parametric Studies
- Wall axial strength equation as function of temperature
- Fire resistance rating in hours
- Steam vent hole design

Recent Testing in China



Observed Failure Modes

Local Buckling

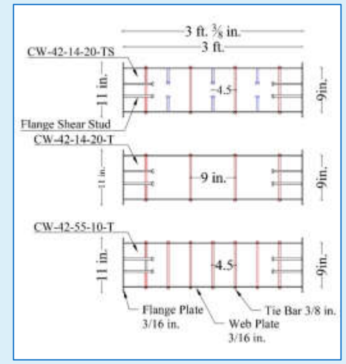


Weld Failure

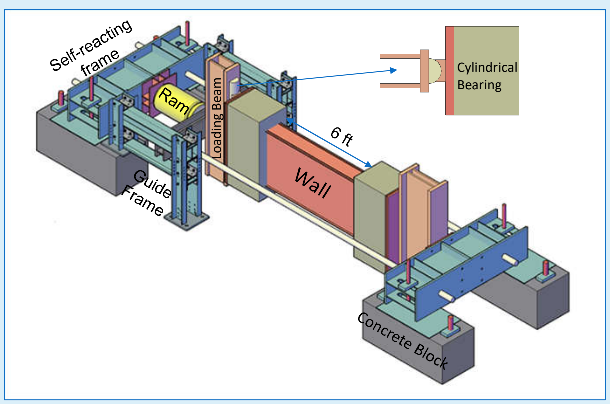
Global Instability

Experimental Investigations

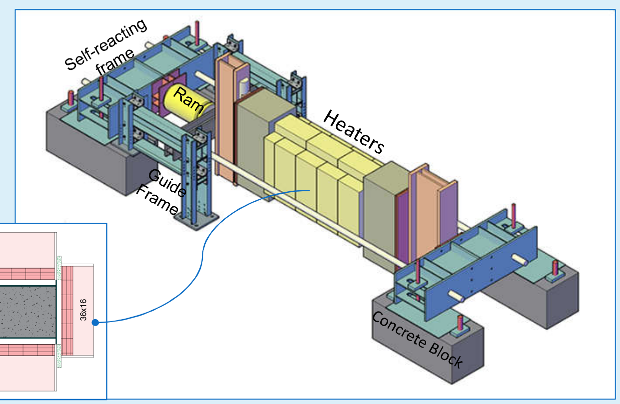
Wall thickness	9 in.
Load ratio	20 -28 %
Plate slenderness	24-48
Fire scenarios	Uniform Non-uniform
Using shear studs between tie bars	

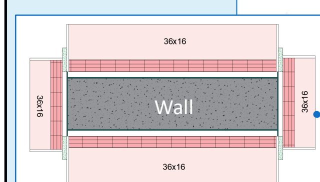


Structural Test Setup



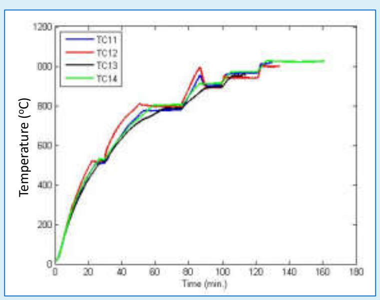
Heating Test Setup

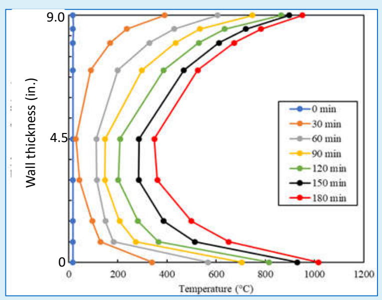




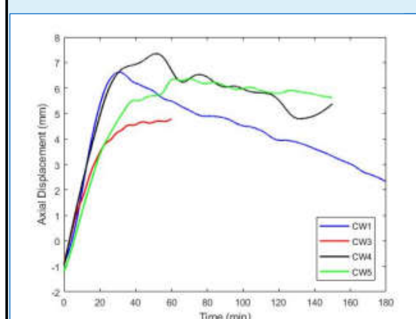
Photograph of Test Setup

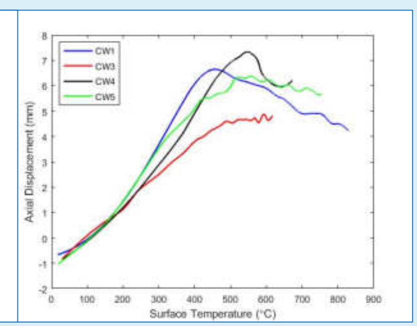
Typical Experimental Results (Thermal)





Typical Experimental Results (Structural)





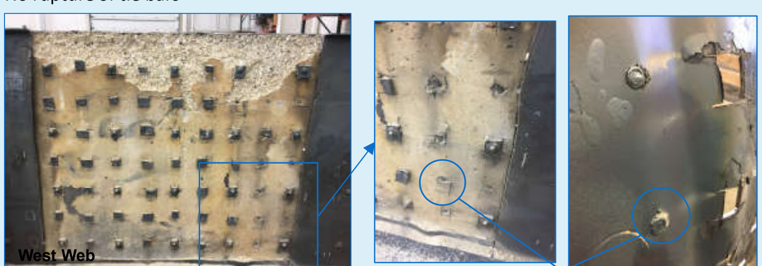
Post-Fire Photographs

Post-Fire Photographs

Post-Fire Photographs

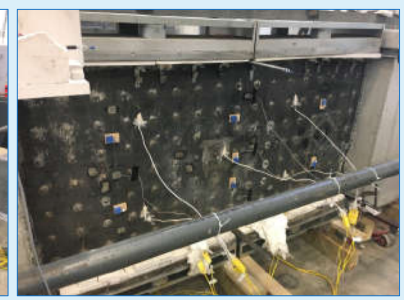
Shear stud weld failure at buckled regions

No rupture of tie bars



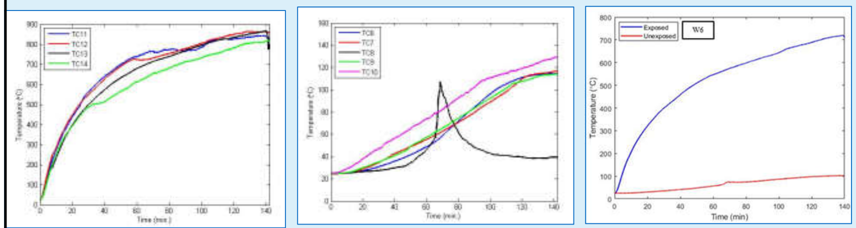
Non-Uniform (Three-Sided) Heating

East Web



West Web

Experimental Results



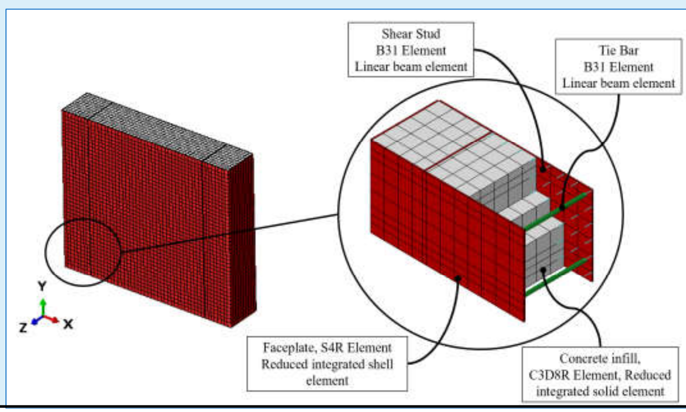
Thermal Insulation Criteria:

- Average surface temperature of unexposed surface < 139°C
- Increase at any one location < 181°C

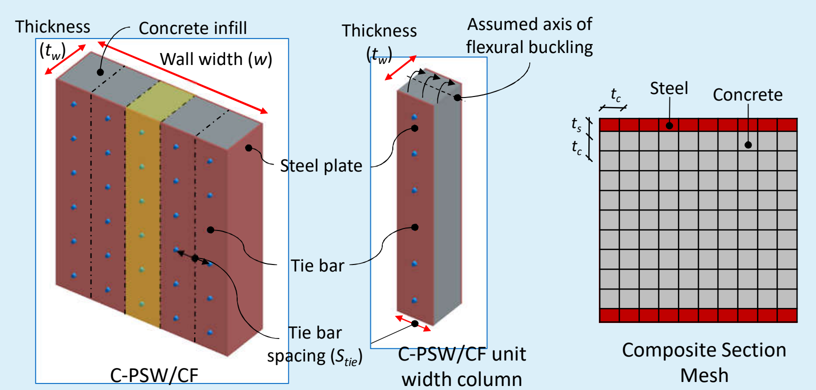
Experimental Findings

- Uniform heating of 9 in. thick walls
  - More than 2 hours of fire resistance
  - Local buckling between ties or ties and shear studs
  - No rupture in tie bars but some failure at stud welds
  - Vent hole spacing and diameter need to be considered
- Non-uniform heating of 9 in. thick walls
  - No failure after 140 minutes (structural or thermal)
  - Out-of-plane (global) bending

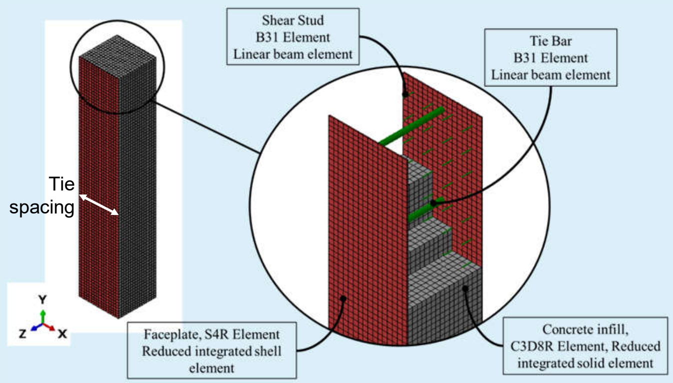
3D Finite Element Models and Benchmarking



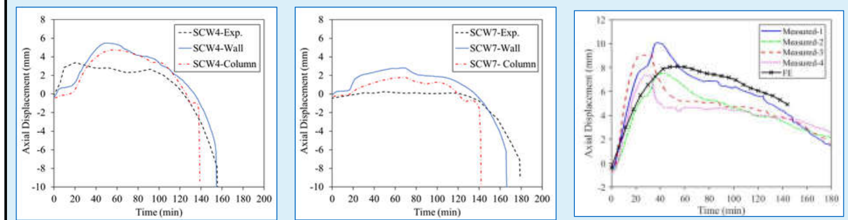
C-PSW/CF Unit Width Column



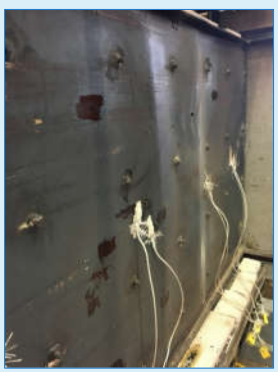
3D Finite Element Models and Benchmarking

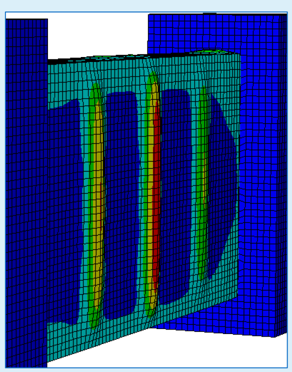


3D Finite Element Models and Benchmarking

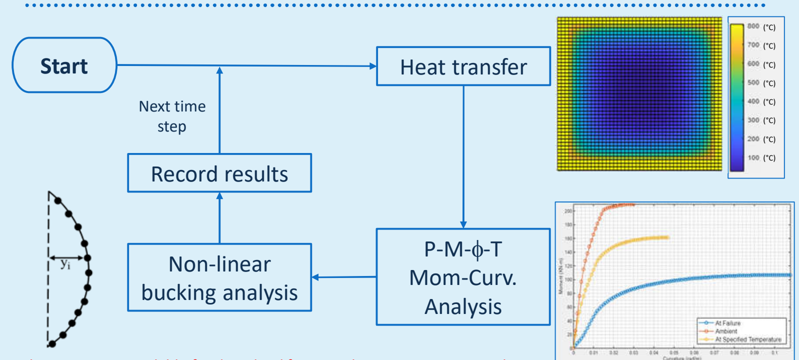


3D Finite Element Models and Benchmarking



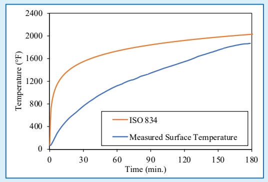


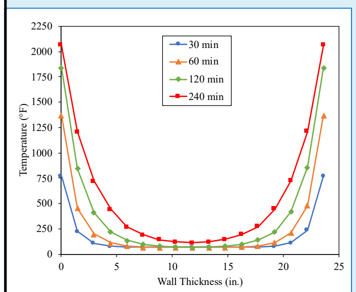
Computer Program for Fire Design of C-PSW/CF

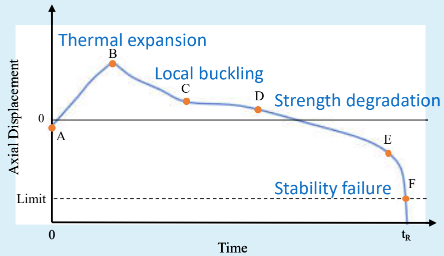


The program is available for download from Purdue University Research Repository (PURR) - https://purr.purdue.edu/publications/3473/

Summary of Behavior
Thermal & Structural







Parametric Studies

- Wall slenderness (H/T = 5 – 20)
- Wall thickness (200 – 600 mm)
- Load ratio (20, 30% $A_c f'_c$)
- Tie bar spacing (S_{tie}/T = 0.5 – 1.0)
- Steel ratio (A_s/A_g = 1.33 – 5.33 %)
- Concrete strength (f'_c = 40, 55 MPa)
- Boundary condition (Pinned, Fixed)

Results from Parametric Studies

- Wall slenderness ratio, wall thickness, load ratio and type of boundary conditions significantly affect the failure time
- Walls with slenderness higher than 10 fail due to global buckling
- The middle region of concrete infill takes longer to heat up in thicker walls, resulting in higher fire resistance
- Limiting the steel plate slenderness ratio can marginally improve the fire resistance of walls

Results from Parametric Studies

- Non-uniform (one-sided) heating results in thermal bowing, second-order moments, and eccentric moments in the walls
- Walls with height / thickness ratios greater than 20, and subjected to one-sided heating, need fire protection on the exposed surfaces
- Typical wall height / thickness ratios are within 5 – 10
- Typical SpeedCore wall designs do not need fire protection

Proposed Equations for Wall Strength

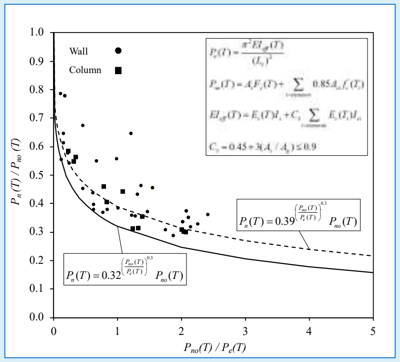
Lower Bound

$$P_n(T) = \left[0.32^{\left(\frac{P_{no}(T)}{P_e(T)}\right)^{0.3}}\right] P_{no}(T)$$

$$P_e(T) = \frac{\pi^2 EI_{eff}(T)}{(L_c)^2}$$

$$P_{no}(T) = A_s F_y(T) + \sum_{i=elements} 0.85 A_{ci} f_c^{'}(T_i)$$

$$EI_{eff}(T) = E_s(T) I_s + C_3 \sum_{i=elements} E_c(T_i) I_{ci}$$



Fire Resistance Rating

Using results from parametric studies, and strength equation

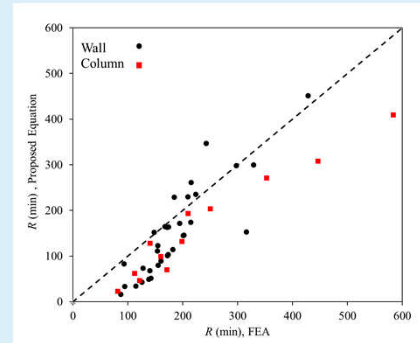
$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{\left(0.24 - \frac{H/t_w}{230}\right)} + 15\right]\left(\frac{1.9 t_w}{200} - 1\right)$$

R = Fire resistance rating in hours

P_u/P_n = utility ratio at ambient

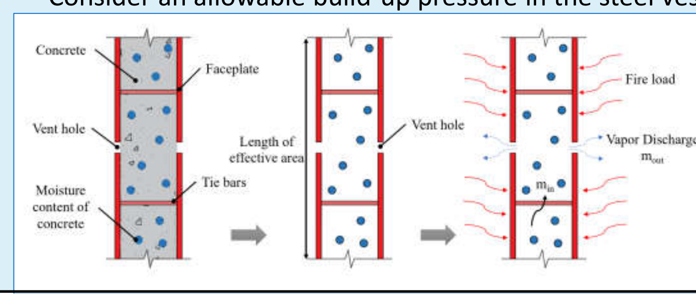
H/t_w = wall slenderness

t_w = wall thickness in mm.



Vent Hole Design

- Calculate vapor generation rate using concrete moisture content and calculated thermal gradients
- Consider an allowable build-up pressure in the steel vessel



Vent Hole Design

- Based on relief pressure valve design
- Input – vent hole spacing, vapor generation rate, allowable pressure
- Output – vent hole size based on effective area

- In most cases, 12 ft spacing, 1 in. diameter holes are adequate

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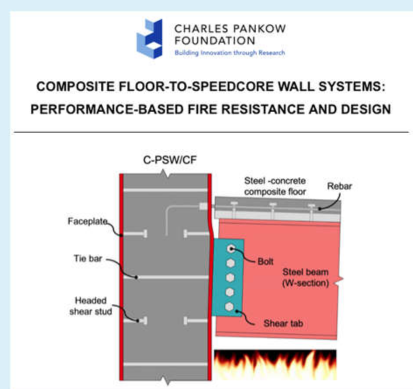
Ongoing AISC – CPF Project

- Testing of C-PSW/CF with structural shapes (wide-flange, channel sections) as boundary elements
- Testing of different types of wall-to-foundation connections (for seismic and for wind loading)
- Testing of bolted splice connection for non-seismic applications
- Testing of SC-to-RC wall splice connections for various applications
- Testing of additional steel beam-to-composite wall connections

Current & Future Work



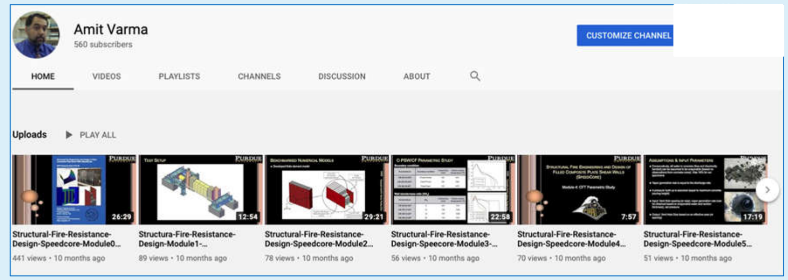
New research project

Started Jan. 2021

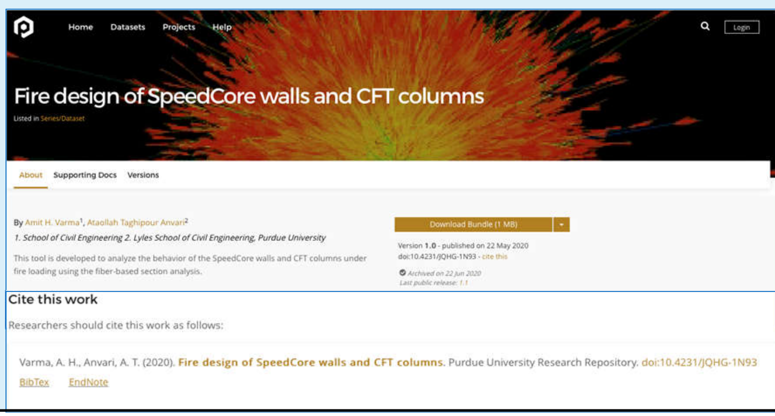
Upcoming Publications

- Upcoming AISC 360, AISC 341, and ASCE 7.
- Design Guide 37 for SpeedCore Systems – design for wind, seismic, and fire loading
- Co-authors: Soheil Shafaei, Morgan Broberg, Ata Anvari
  - Chapter 2 – Wind Design – Three full design examples for uncoupled and coupled systems, Mathcad sheets (download)
  - Chapter 3 – Seismic Design – Two design examples for uncoupled systems, Mathcad sheets (download)
  - Chapter 4 – Seismic Design – Two design examples for coupled systems, Mathcad sheets (download)
  - Chapter 6 – Fire Design – Design example and program

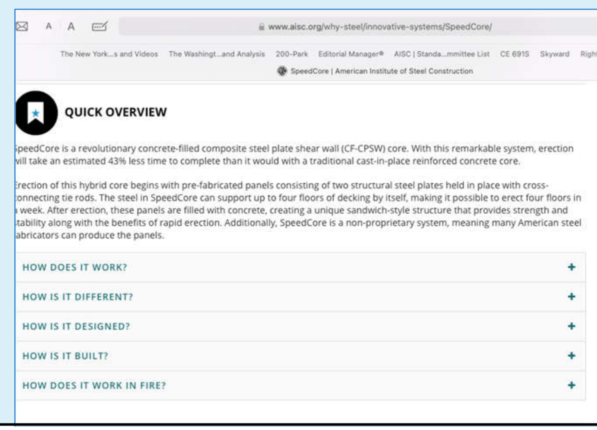
Available Resources



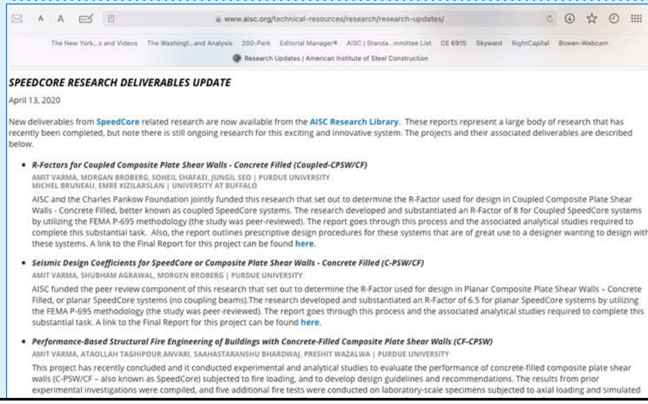
Available Resources



Available Resources



Available Resources


www.aisc.org/technical-resources/research/research-updates/

Research Updates | American Institute of Steel Construction

SPEEDCORE RESEARCH DELIVERABLES UPDATE

April 13, 2020

New deliverables from SpeedCore related research are now available from the AISC Research Library. These reports represent a large body of research that has recently been completed, but note there is still ongoing research for this exciting and innovative system. The projects and their associated deliverables are described below.

- ***R-Factors for Coupled Composite Plate Shear Walls - Concrete Filled (Coupled-CPSW/CF)***
  AMIT VARMA, MORGAN BROBERG, SOHEIL SHAFAEI, JUNGIL SEO | PURDUE UNIVERSITY
  MICHEL BRUNEAU, EMRE KIZILARSLAN | UNIVERSITY AT BUFFALO
  AISC and the Charles Pankow Foundation jointly funded this research that set out to determine the R-Factor used for design in Coupled Composite Plate Shear Walls - Concrete Filled, better known as coupled SpeedCore systems. The research developed and substantiated an R-Factor of 8 for Coupled SpeedCore systems by utilizing the FEMA P-695 methodology (the study was peer-reviewed). The report goes through this process and the associated analytical studies required to complete this substantial task. Also, the report outlines prescriptive design procedures for these systems that are of great use to a designer wanting to design with these systems. A link to the Final Report for this project can be found here.
- ***Seismic Design Coefficients for SpeedCore or Composite Plate Shear Walls - Concrete Filled (C-PSW/CF)***
  AMIT VARMA, SHUBHAM AGRAWAL, MORGEN BROBERG | PURDUE UNIVERSITY
  AISC funded the peer review component of this research that set out to determine the R-Factor used for design in Planar Composite Plate Shear Walls – Concrete Filled, or planar SpeedCore systems (no coupling beams).The research developed and substantiated an R-Factor of 6.5 for planar SpeedCore systems by utilizing the FEMA P-695 methodology (the study was peer-reviewed). The report goes through this process and the associated analytical studies required to complete this substantial task. A link to the Final Report for this project can be found here.
- ***Performance-Based Structural Fire Engineering of Buildings with Concrete-Filled Composite Plate Shear Walls (CF-CPSW)***
  AMIT VARMA, ATAOLLAH TAGHIPOUR ANVARI, SAAHASTARANSHU BHARDWAJ, PRESHIT WAZALWA | PURDUE UNIVERSITY
  This project has recently concluded and it conducted experimental and analytical studies to evaluate the performance of concrete-filled composite plate shear walls (C-PSW/CF – also known as SpeedCore) subjected to fire loading, and to develop design guidelines and recommendations. The results from prior experimental investigations were compiled, and five additional fire tests were conducted on laboratory-scale specimens subjected to axial loading and simulated

PURDUE UNIVERSITY | Lyles School of Civil Engineering

Questions?

Discussion !

Questions

CEU / PDH Certificates

For those participating at their own connection…

- Reporting attendance is not necessary.
- Certificates will be issued based on AISC's attendance record.
- You will be receiving certificates via email from registration@aisc.org.

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CEU / PDH Certificates

For those participating at one connection with a group…

- Main registrant will report attendance via an online form. (The link will be provided in an email from registration@aisc.org.)
    - Username: Same as AISC website username.
    - Password: Same as AISC website password.
- Once attendance has been reported, each group member will be receiving certificates via email from registration@aisc.org.

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AISC | Thank you

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