Steel Diaphragm Innovation Initiative

Project Update for BSSC PUC

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COLD-FORMED STEEL RESEARCH CONSORTIUM

Steel Diaphragm Innovation Initiative (SDII)

- *Origin*: SDII was born, in part, out of the limitations in knowledge that came to light in developing alternative diaphragm design provisions (R_s) for steel deck diaphragms in the last seismic code cycle
- *Objective*: Advance the seismic performance of steel floor and roof diaphragms utilized in steel buildings through:
  - better understanding of diaphragm-structure interaction,
  - new design approaches, and
  - new three-dimensional modeling tools that provided enhanced capabilities to designers utilizing steel diaphragms in their building systems.
- *Scope*: SDII primarily focuses on the seismic design of diaphragms commonly used in steel mid-rise buildings, but considers innovation for all systems employing steel floor and roof diaphragms.

SDII Team and Partners:

- Management:
  COLD-FORMED STEEL RESEARCH CONSORTIUM
- Industry Sponsors:
  American Iron and Steel Institute; AISC (American Institute of Steel Construction, Founded 1921); Steel Deck Institute SDI; SJI Steel Joist Institute; MBMA Metal Building Manufacturers Association
- Government Sponsors:
  NSF
- Researchers:
  Johns Hopkins Whiting School of Engineering; Virginia Tech; Northeastern; WALTER P MOORE

SDII Case and Research Plan

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- Case Statement
- Research Overview
- Detailed Tasks
  - Innovation and Practice
  - Experiments
  - Modeling
- Funding Plan
- Glossary of terms


Appendix C: Steel Diaphragm Innovation Initiative Case and Plan

SDII

(Steel Diaphragm Innovation Initiative)

Case and Research Plan
version 3.0
(SDII year 2 update)
15 June 2016

Innovation and Practice

Experiments

Modeling

COLD-FORMED STEEL RESEARCH CONSORTIUM

Currently (April 2018) in year 3 of the 5 year plan

Innovation and Practice	Experiments	Modeling

Innovation and Practice

- Building and Diaphragm Archetypes
- Evaluation of Existing Design Methods
- Evaluation of Existing Steel Diaphragm Technologies
  - Gap Analyses: Seismic and Non-seismic performance
- Candidate Design Methods
  - Methods proposed by others
  - Methods proposed by SDII
- Candidate Technologies
  - Revised profiles, material, manufacture, fuses…
- Seismic Standards Work

Experiments

- Existing Tests
- Test Technologies
- Connector Tests
- Interface Tests
- Diaphragm Tests
- Building Bay Tests
- Full Building Tests *
- Test Database
- Test Standards

Modeling

- Conventional Design Models
- Modeling for Experimental Program
- Diaphragm Models
- Whole Building Models
  - Reduced Order
  - OpenSees/Frame Modeling
- Next-generation Models
- Non-Structural Models
- Optimization Models

* SDII industry funding and NSF funding do not full building tests, proposals pending, and collaborating with Fleischman et al. NSF Project

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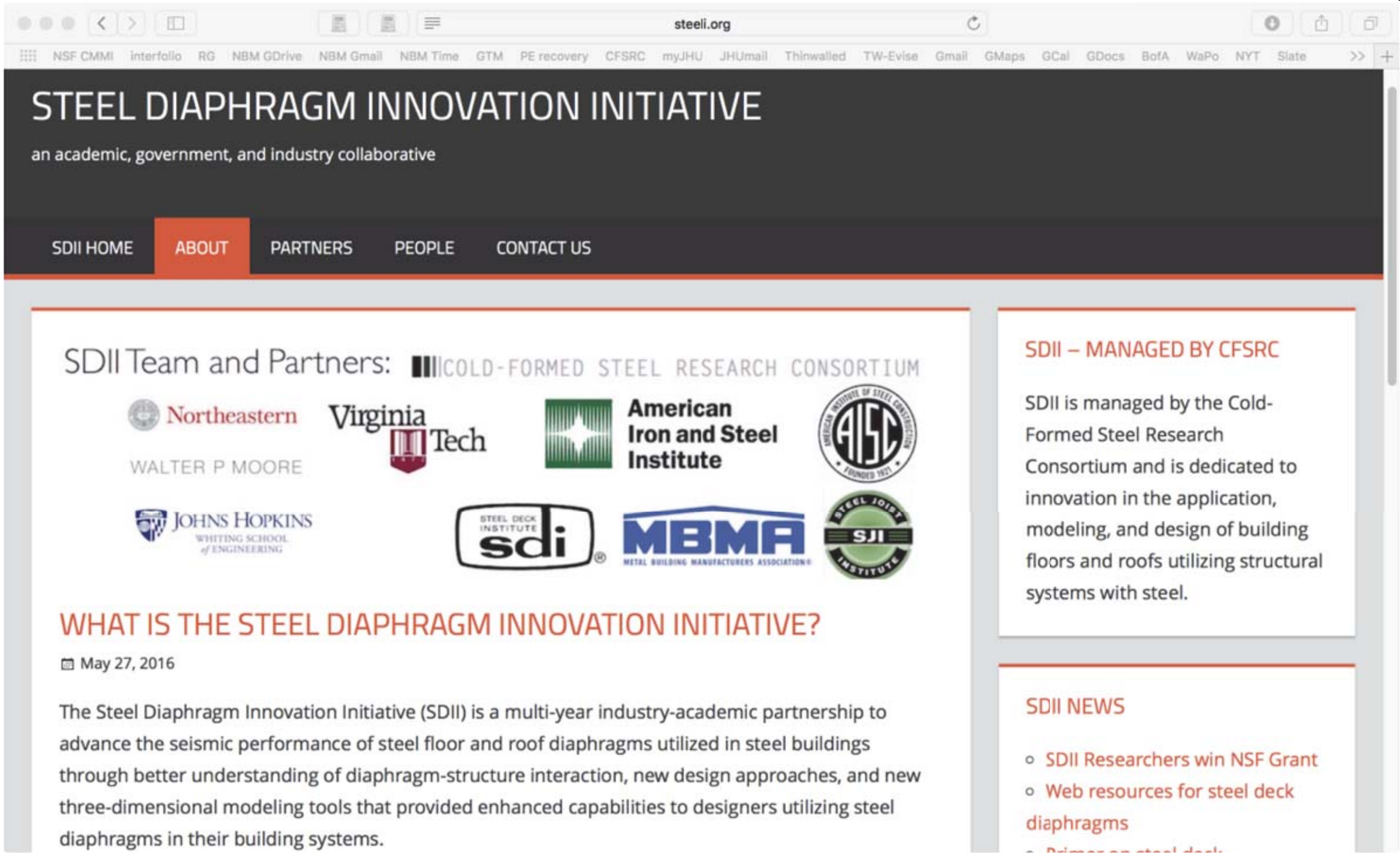
Learn more about the whole effort: steeli.org



Innovation and Practice	Experiments	Modeling

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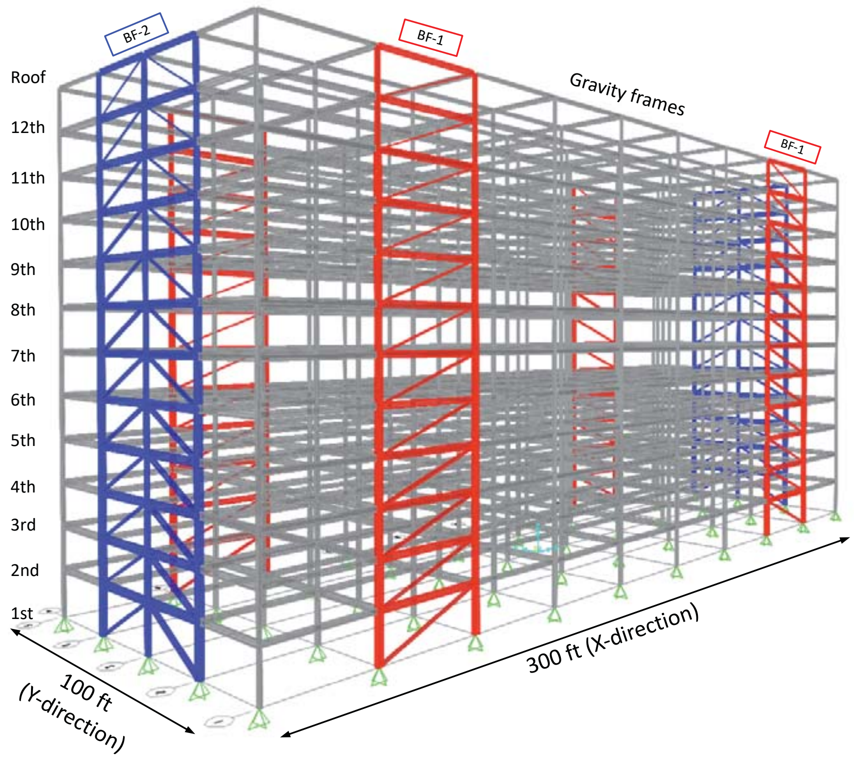
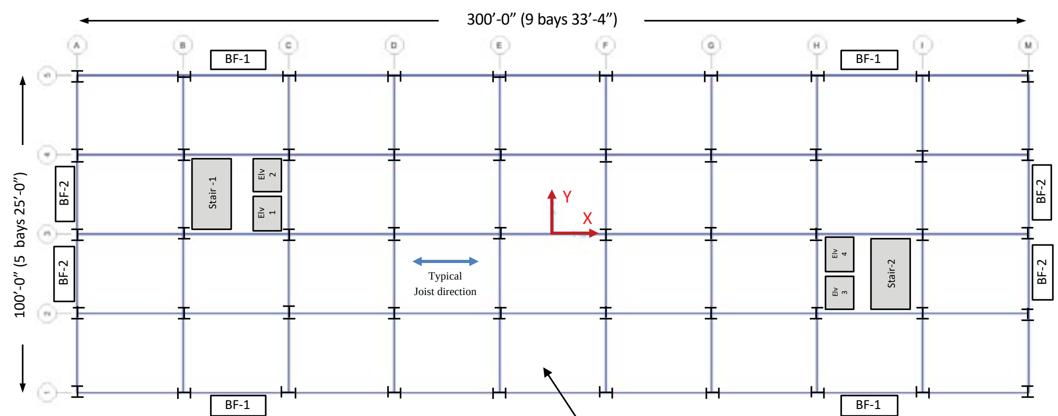
SDII Building Archetypes



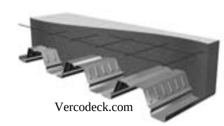
Typical plan



Building Dimensions

Width (E-W)	100.00	(ft)
Length (N-S)	300.00	(ft)
H (First story)	14.00	(ft)
H (Typical story)	12.50	(ft)
Bay size X	33.33	(ft)
Bay size Y	25.00	(ft)
Parapet	3.00	(ft)
Number of Stories	12	(1, 4, 8,12)
H (total height)	151.5	(ft)

Typical floors:
6.25" total slab deck,
Light weight concrete,
2 Hours fire rating



Roof:
Bare Steel deck

- Series of designs, high seismic, high diaphragm utilization
- 1, 4, 8, and 12 stories; NWC and LWC Floors, BRB vLFRS
- Diaphragm design: Traditional, Alt. R_s=1, Alt. R_s=3

Diagrammatic demands (ASCE7-16 and ASCE7-16 Alt. R_s=1, 3)

ASCE7-16 Standard

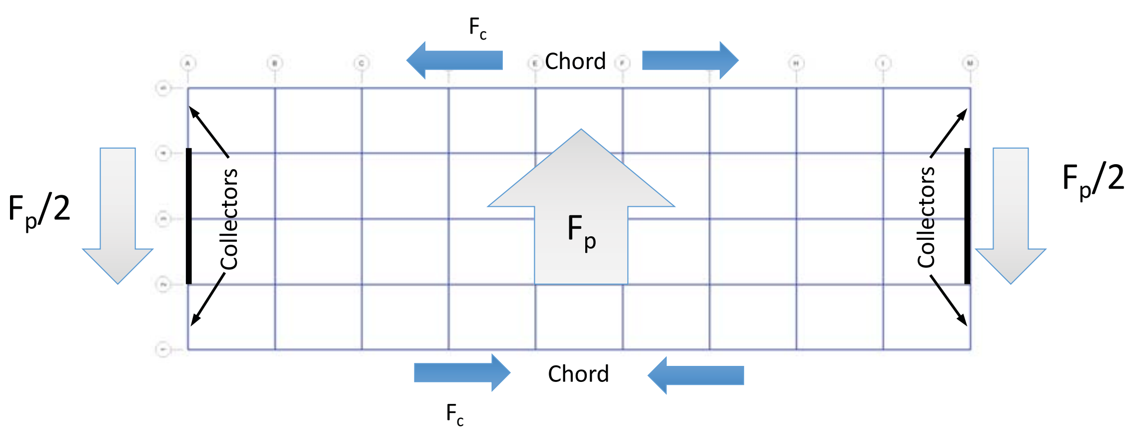
Level	F_i(k)	W_i (k)	F_P (k)	$F_{P\text{-}min}$ (k)	$F_{P\text{-}max}$ (k)	**F_P (k) design**
Roof	145	1271	145	262	524	**262**
12th	252	2545	264	524	1049	**524**
11th	215	2545	245	524	1049	**524**
10th	181	2545	227	524	1049	**524**
9th	149	2545	209	524	1049	**524**
8th	120	2545	193	524	1049	**524**
7th	94	2545	178	524	1049	**524**
6th	70	2545	163	524	1049	**524**
5th	49	2545	150	524	1049	**524**
4th	31	2545	137	524	1049	**524**
3rd	16	2545	126	524	1049	**524**
2nd	6	2545	115	524	1049	**524**

ASCE7 Alt. R_s=3

F_P (k) design
262
524
524
524
524
524
524
524
524
524
524
524

ASCE7 Alt. R_s=1

F_P (k) design
419
839
839
851
873
895
916
938
959
981
1003
1024



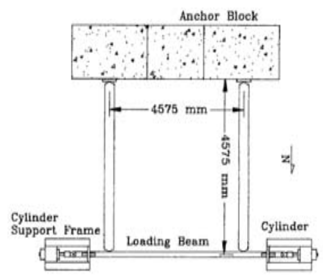
Nonlinear building models using existing data to model key nonlinearities now underway

Cantilever Diaphragm Test Database

Overview

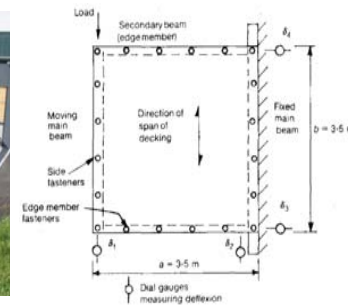
Testing Program	# of Specimens
Cornell University, 1950s-1960s	40
S. B. Barnes and Associates, 1950s -1960s	38
West Virginia University, 1960s-70s	246
Development Lab of Inland Ryserson Co.	1
University of Salford, Manchester 1970s-80s	5
ABK, a Joint Venture, California 1980s	3
Iowa State University, 1980s	32
Virginia Tech, 1990s - 2000s	67
Technical Research laboratory in Kobe, Japan, 1990s	6
Nucor – Vulcraft/Verco Group, 1990s-2000s	120
University of Montreal, McGill University, Canada, 2000s	82
Tongji University, China, 2000s	6
Hilti Corporation, Liechtenstein, 2000s-2010s	92
Tokyo Institute of Technology, Japan, 2010s	15
Total:	753

Types of Experimental Studies Included

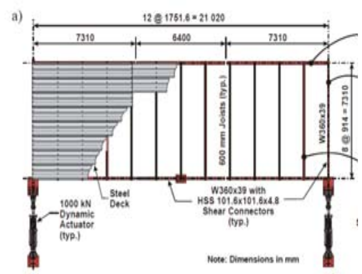


Group from Iowa State in 1980's and 1990's

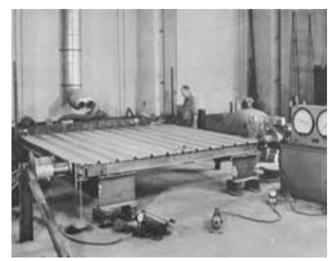
Diaphragm Tests by Industry (e.g. Hilti)



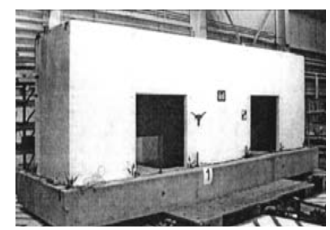
Research from Europe (e.g. Davies and Fisher 1979)



Work by Tremblay and Rogers in Canada



Larry Luttrell's group at West Virginia



Building Tests (e.g. Cohen et al. 2004)

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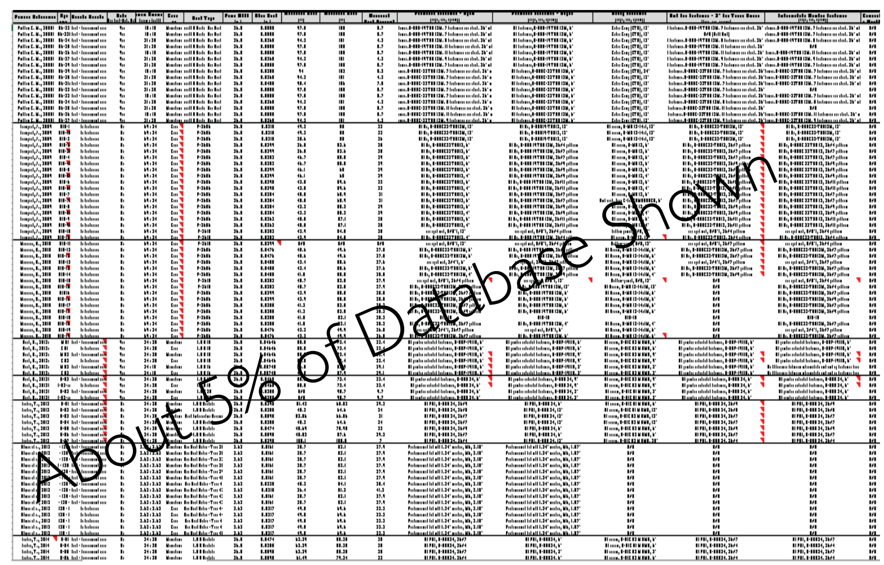
Cantilever Diaphragm Test Database

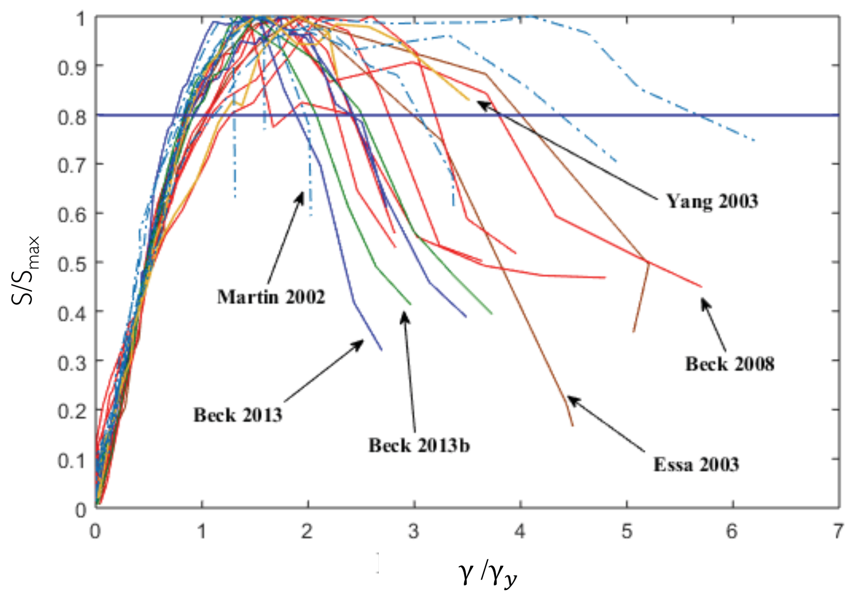
Breakdown of database fields:
Test setup fields (26), test result fields (3), calculated fields (11)

Test Setup Fields	Load Type	Measured deck yield strength
	Load protocol	Measured deck percent elongation
	Setup configuration	Type of structural fastener
	Plan dimensions	Size of structural fastener
	Span dimension	Spacing of structural fastener
	Depth dimension	Type of sidelap fastener
	Deck span direction	Size of sidelap fastener
	Deck span length	Spacing of Sidelap Fastener
	Test frame support member sizes	Endlap location
	Test frame interior support member sizes	Concrete unit weight
	Steel deck profile dimensions	Measured concrete fill thickness
	Steel deck manufacturer	28 day concrete compressive strength
	Steel deck thickness	Type of concrete reinforcement
Test Result Fields	Ultimate shear strength	Shear angle at 80% strength degradation
	Shear stiffness	
Calculated Fields	Predicted structural fastener strength	Strength Factors, R_Ω
	Predicted sidelap fastener strength	Subassemblage Ductility
	Predicted diaphragm strength	System Ductility
	Predicted structural fastener flexibility	Ductility Factor (medium/long period), R_μ
	Predicted sidelap fastener flexibility	Diaphragm Design Force Reduction Factor
	Predicted diaphragm stiffness	(medium and long period), R_s

Available online at:
O'Brien, P., Eatherton, M.R., Easterling, W.S., Schafer, B.W., Hajjar, J.F. (2017) "Steel Deck Diaphragm Test Database v1.0." CFSRC Report R-2017-03, permanent link: jhir.library.jhu.edu/handle/1774.2/40634.



Data provides subassembly ductility



Group with PAF Support Fasteners and Screwed Sidelap Fasteners (Cyclic Testing)

Ductility defined as ratio of displacement at 80% strength degradation to yield displacement

$$\gamma_{ult} = \gamma \ at \ 0.8 \ P_{max}$$

$$\gamma_y = \frac{S_{max}}{G'}$$

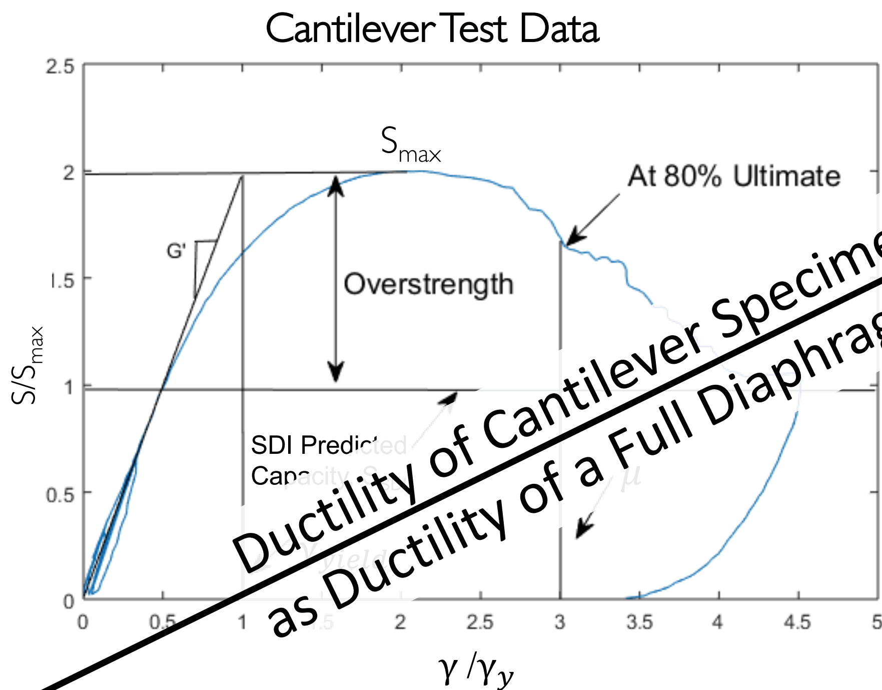
$$\mu_{sub} = \frac{\gamma_{ult}}{\gamma_y}$$

PAF/Screw (21 Specimens)	
Average μ_{sub}	Std. Dev.
2.76	1.02

Data provides insight on ASCE 41 “m” & R_s

Fastener Configuration	Total Specimens	G'_{avg} (kip/in)	S_{max_avg} (kips/ft)	μ_{sub} Avg.	μ_{sub} Std.Dev.	
PAF/Screw	22	47.9	2.03	4.53	3.62	Monotonic No Conc. Fill
Weld/BP	8	20.3	1.27	2.58	0.36	
Weld/Screw	11	49.2	2.05	3.29	1.20	
Weld/Weld	14	68.5	3.00	3.34	1.17	
PAF/Screw	21	45.3	2.52	2.76	1.02	Cyclic No Conc. Fill
Weld/BP	6	12.3	0.66	1.53	0.39	
Weld/Screw	2	17.2	1.09	1.93	0.07	
Weld/Weld	4	21.2	1.55	2.06	0.44	
Welds	14	1490	10.3	5.53	3.08	Cyclic Conc. Fill
Welds and Studs	6	1670	8.09	3.82	0.62	

First idea for estimating R_s



Calculating R_s using ATC 19 Approach:

$R_s = R_\mu R_\Omega$

$R_\Omega = S_{max} / S_{SDI}$

$$\mu = \frac{\gamma_{ult}}{\gamma_{yield}}$$

$$R_\mu = \sqrt{2\mu - 1} \; or \; \mu$$

Depending on period

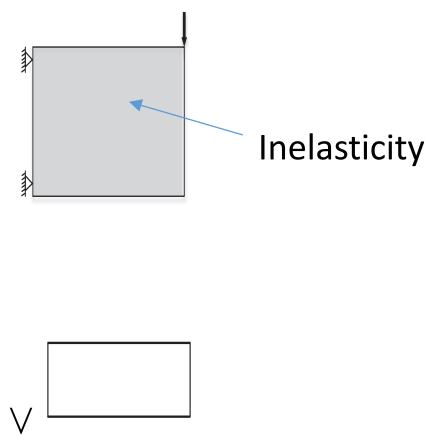
Ductility of Cantilever Specimen Not Same as Ductility of a Full Diaphragm System

Issue: ductility of cantilever test is larger than ductility of a full diaphragm system
Task: develop method to use cantilever test data to calculated system ductility

Source of difference in ductility

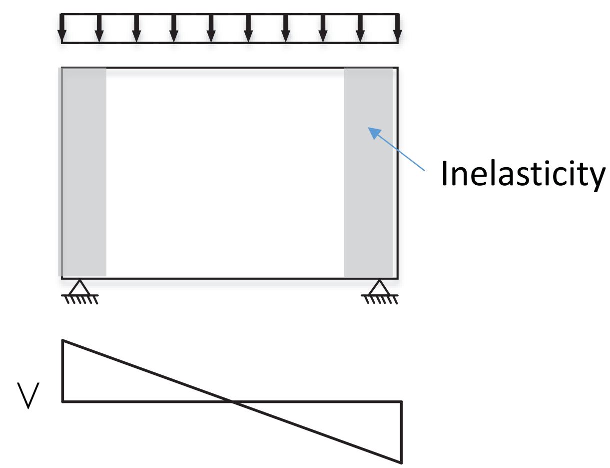
Cantilever specimen – constant shear and distributed inelasticity throughout
Diaphragm system – varying shear and inelasticity will concentrate in end regions

Cantilevered diaphragm test



Shear distribution: Uniform shear

Simply supported diaphragm



Shear distribution: linear variation

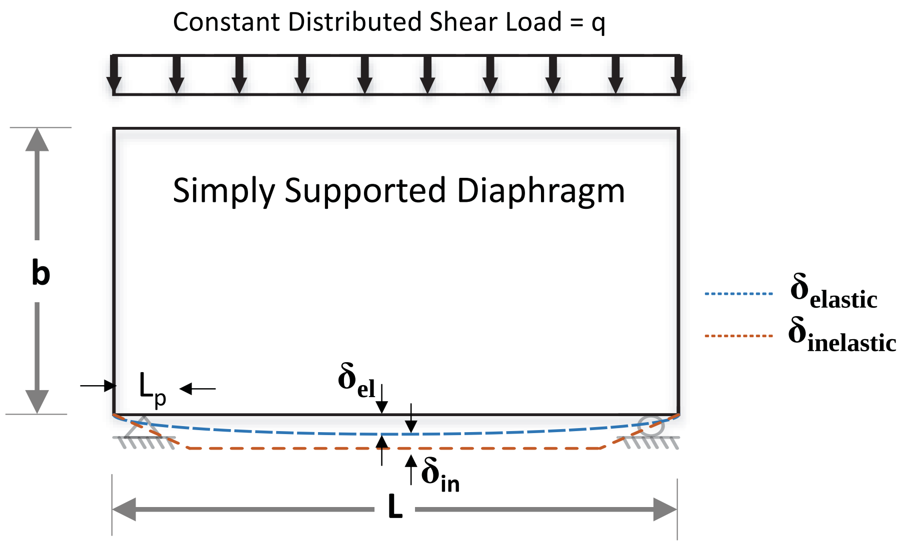
Conclusion: $\mu_{subassembly} > \mu_{system}$

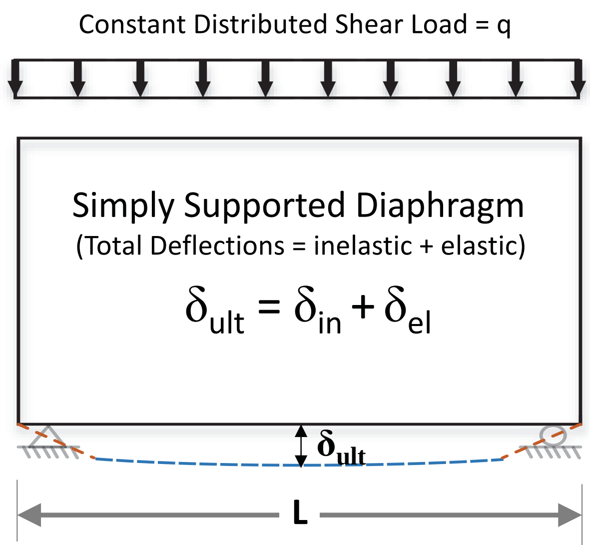
Resolution: estimate elastic and inelastic δ

Deflections and ductility will differ from subassembly to system → $\mu_{subassembly} \neq \mu_{system}$

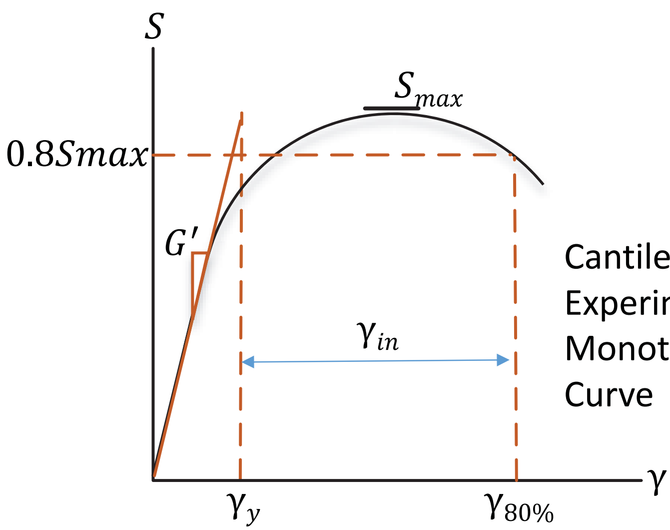
$$\mu_{system} = \frac{\delta_{ult}}{\delta_y} = \frac{\delta_{in} + \delta_{el}}{\delta_{el}}$$

Find δ_{in} and δ_{el}





Resulting Equation for Ductility and R_s



Cantilevered Experimental Monotonic Curve

$$\gamma_y = \frac{S_{max}}{G'}$$

$$\gamma_{in} = \gamma_{80\%} - \gamma_y$$

$$\gamma_{in} = \gamma_y(\mu_{subassembly} - 1)$$

$$\delta_{in} = \gamma_{in} L_p$$

$$\underbrace{\delta_{in} = \gamma_{in} L_p \qquad \delta_{el} = \frac{S_{max} L}{4G'}}$$

$$\delta_{ult} = \delta_{in} + \delta_{el}$$

$$\delta_{ult} = \gamma_{in} L_p + \frac{S_{max} L}{4G'}$$

$$\boxed{\boldsymbol{\mu_{system} = \frac{\delta_{ult}}{\delta_{el}} = 1 + \frac{4\gamma_{in} G'}{S_{max}}\left(\frac{L_p}{L}\right)}}$$

- System ductility depends on L_p/L, not L
- Will need to assume a plastic zone length L_p/L

$$\mathbf{R_{\mu\_system} = \sqrt{2\mu_{system} - 1} \; or \; \mu_{system}}$$

(depending on period)

$\mathbf{R_s = R_\Omega R_{\mu\_system}}$ $\quad$ R_Ω same as test

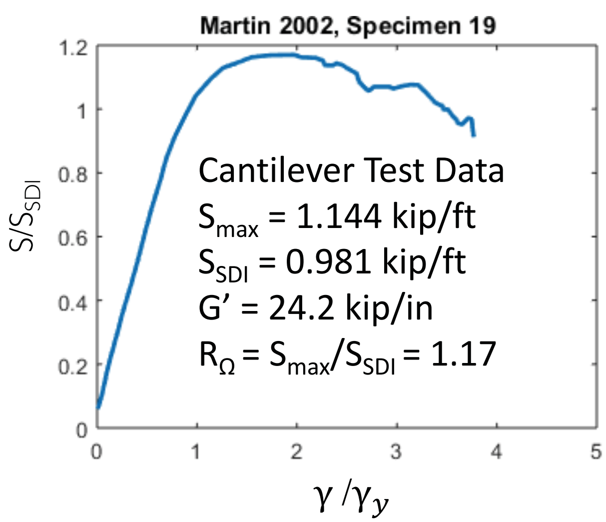
R_s – Example, Mechanical Fasteners Bare Deck Diaphragm (1/2)

$$R_s = R_\mu R_\Omega$$

- 12" fastener spacings
- 20 gauge deck
- Monotonic loading
- 12' span, 20' depth

<u>PAF Structural Fasteners, Screwed Sidelap</u>

Martin 2002, spec. 19



Ductility of subassembly alone:
$\mu_{subassembly} = 3.76$

$$\boldsymbol{\mu_{system} = 1 + \frac{4\gamma_{in}G'}{S_{max}}\left(\frac{L_p}{L}\right)}$$

$$\gamma_{in} = \gamma_y(\mu_{sub} - 1) = 0.01085\, rad$$

Assume plastic zone is 10% of the diaphragm span, Lp/L = 0.10

$$\mu_{system} = 1 + \frac{4(0.01085\, rad)(24.2\,\frac{k}{in})}{1.14\,\frac{k}{ft}\ \ (\frac{1}{12}\frac{ft}{in})}(0.10)$$

$$\mu_{system} = 2.10$$

Ductility of the full diaphragm system

R_s – Example, Mechanical Fasteners Bare Deck Diaphragm (2/2)

$\mathbf{R_s = R_\mu R_\Omega}$

- 12'' fastener spacings
- 20 gauge deck
- Monotonic loading
- 12' span, 20' depth

<u>PAF Structural Fasteners, Screwed Sidelap</u>

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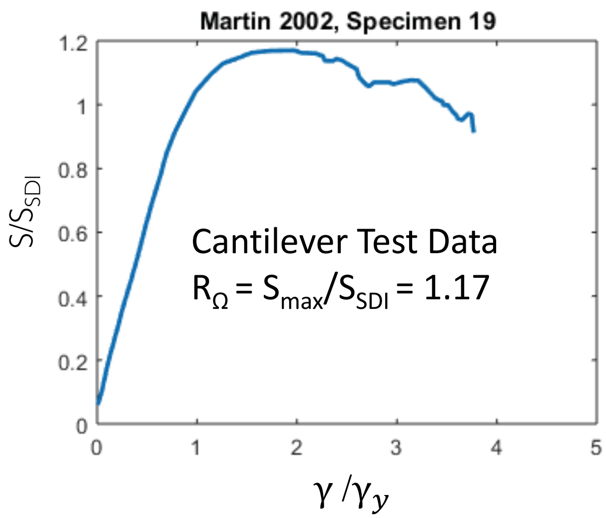


$\mu_{system} = 2.11$

Medium Period

$R_\mu = \sqrt{2\mu_{system} - 1}$

$= \sqrt{2 * 2.10 - 1} =$

1.79

$\mathbf{R_s = R_\mu R_\Omega = 2.09}$

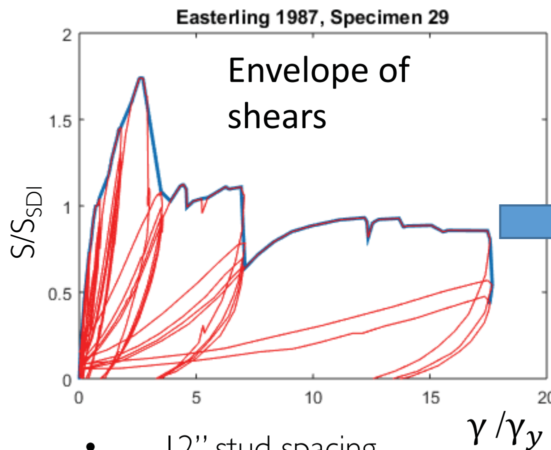
Long Period

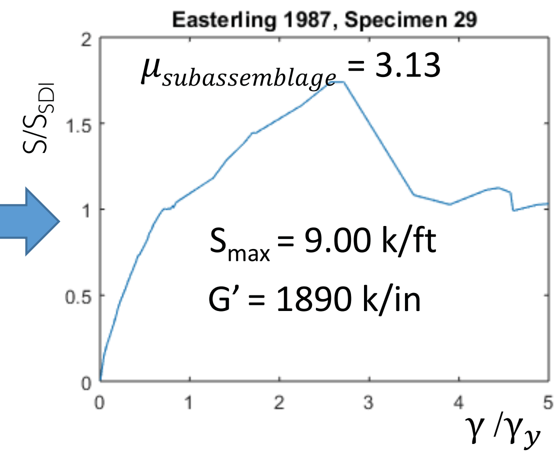
$R_\mu = \mu_{system}$

$= 2.10$

$\mathbf{R_s = R_\mu R_\Omega = 2.46}$

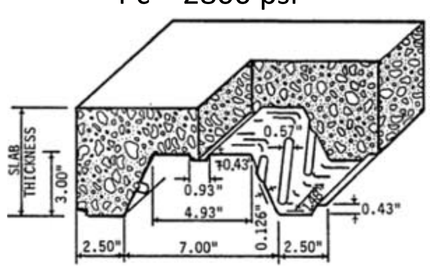
R_s – Example, Concrete Fill (1/2)





Assume plastic zone is 10% of the diaphragm span, Lp/L = 0.10

- 12" stud spacing
- 20 gauge deck
- Cyclic loading
- 12' span, 15' depth
- 5.5" total slab depth
- f'c = 2800 psi



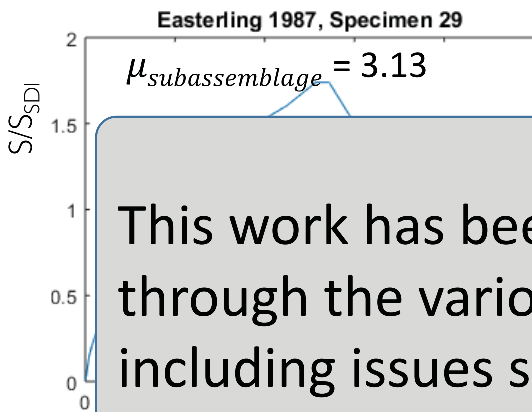
$$\gamma_{in} = \gamma_y(\mu_{sub} - 1) = 0.000846\,rad$$

$$\mu_{system} = 1 + \frac{4(0.000846\,rad)(1890\,\frac{k}{in})}{9.00\,\frac{k}{ft}\;\;(\frac{1}{12}\frac{ft}{in})}(0.10)$$

$$\mu_{system} = 1.85$$

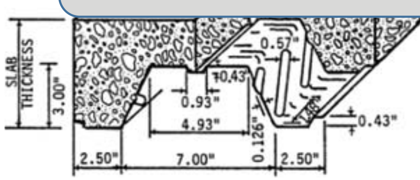
Ductility of the full diaphragm system

R_s – Example, Concrete Fill (2/2)



$R_\Omega = S_{max}/S_{SDI} = 1.74$

This work has been shared with IT9. IT9 still working through the various approaches to determining R_s including issues such as raised here. In addition, SDII building out building archetype models to further explore impact of subassembly ductility vs. system ductility and the impact of this on force reductions in the diaphragm vis-à-vis R_s.



$R_\mu = \mu_{system}$
$= 1.85$

$R_s = R_\mu R_\Omega = 2.58$

Summary SDII Seismic Standards Work

- AISC TC9/AISC 341
  - Providing guidance on next Ed. of AISC 341 w.r.t. diaphragms and detailing, presentation at Nov 2017 AISC TC meetings
- AISC TC7/AISC 342 (Steel from ASCE 41)
  - Providing analysis to remediate current ASCE 41 which requires steel deck diaphragms to be designed as elastic, presentation at Nov 2017 AISC TC meetings.
- BSSC IT9/BSSC PUC
  - Provided preliminary inelastic diaphragm design factors and method for correction from subassembly to full diaphragms
  - Developed models that provide insight on R vs Rs and how multiple inelastic systems compete when employed in a mechanical system
  - RWFD work is a companion effort to SDII addressed separately
- AISI S310
  - Provided new proposal for strength of filled deck diaphragms
  - Working with committee to revise current standard for better connections to seismic performance as envisions in AISI S400
- AISI S310/S400
  - Supporting improved clarity on diaphragm provisions for seismic design, working with SDI, other industry partners to provide improved provisions in improved specification home

Innovation and Practice	Experiments	Modeling

• Building and Diaphragm Archetypes
• Evaluation of Existing Design Methods
• Evaluation of Existing Steel Diaphragm Technologies
  • Gap Analyses: Seismic and Non-seismic performance
• Candidate Design Methods
  • Methods proposed by others
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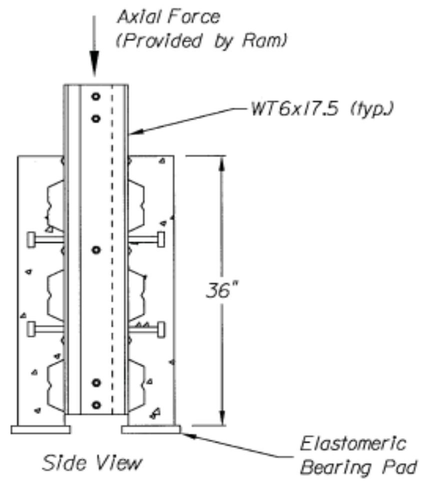
* SDII industry funding and NSF funding do not full building tests, proposals pending, and collaborating with Fleischman et al. NSF Project

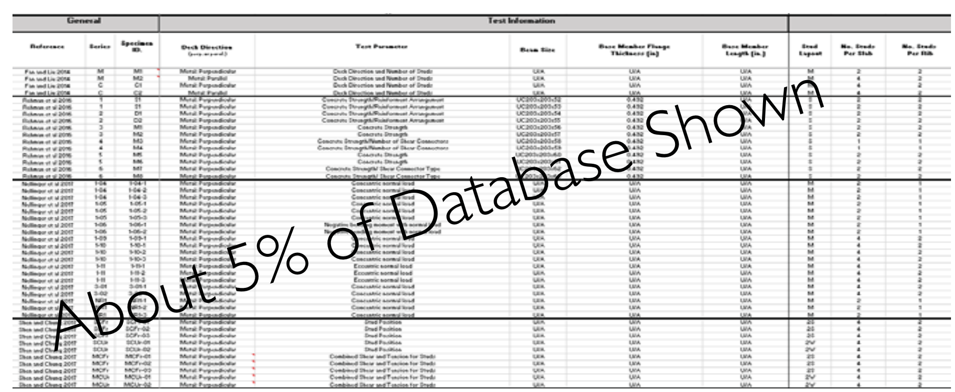
Push-out Test Database Assembled

Overview

- 556 push-out tests of steel deck diaphragm with concrete fill done in 18 research programs
- Database fields (44 fields) include:
  - Test configurations (e.g. test parameter, deck orientation, loading protocol, magnitude of normal force if used, etc.)
  - Geometric properties of studs, base member, and deck (e.g. stud layout, diameter, height, rib width, metal deck type, height, gage, slab thickness, etc.)
  - Material properties (nominal and measured) of concrete, deck, and studs
  - Test results (e.g. peak force per fastener, failure mode, digitized load-slip curves, etc.)
  - Calculated fields (e.g. initial stiffness, ductility, etc.) – based on 123 digitized load-slip curves

Typical push-out test setup



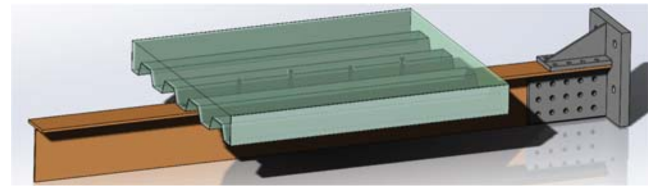


Tested parameters:

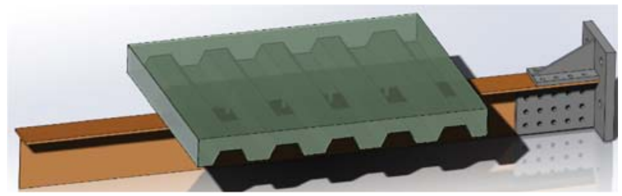
- Stud layout (strong/weak position)
- Stud number and spacing
- Stud properties
- Deck geometry
- Mesh reinforcement
- Concrete properties
- Base member flange thickness
- Normal load

New Cyclic Pushout Tests Coming

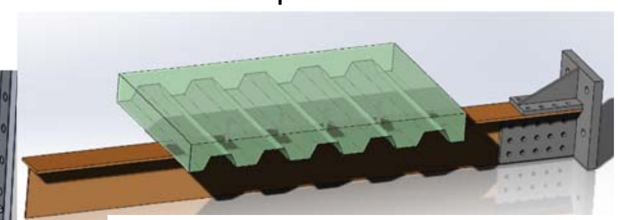
- Cyclic and Monotonic stud behavior compared
- One or Two studs at 12” O.C.
- Strong and weak position behavior investigated
- Parallel, Perpendicular and edge condition Deck specimens
- These tests will inform larger tests in the project



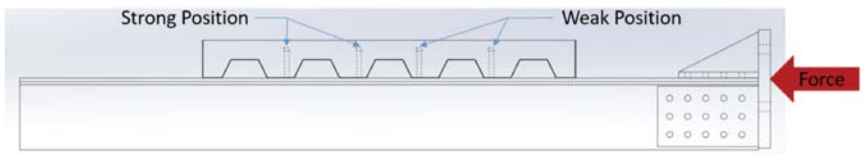
Beam Parallel

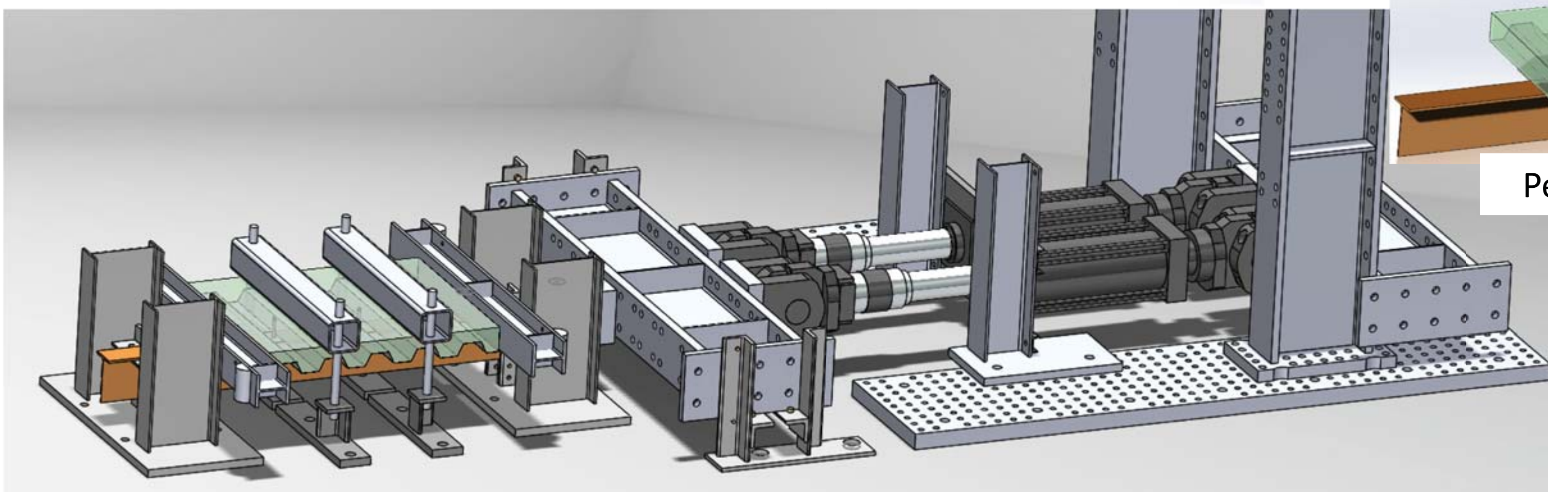


Beam Perpendicular

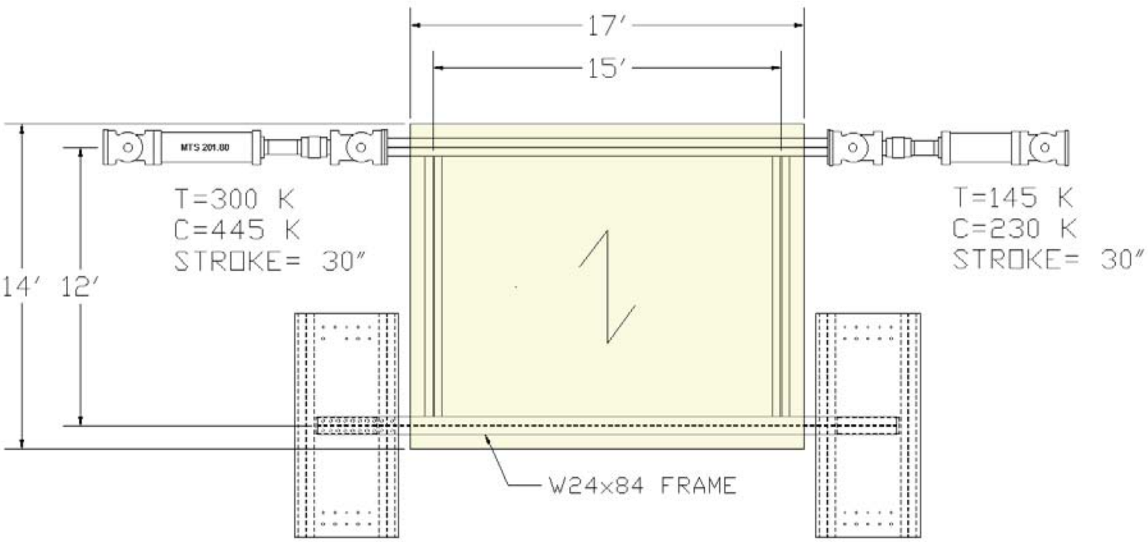


Perpendicular with Edge





Cantilever Diaphragm Tests Underway



Composite Cantilever Diaphragm Tests

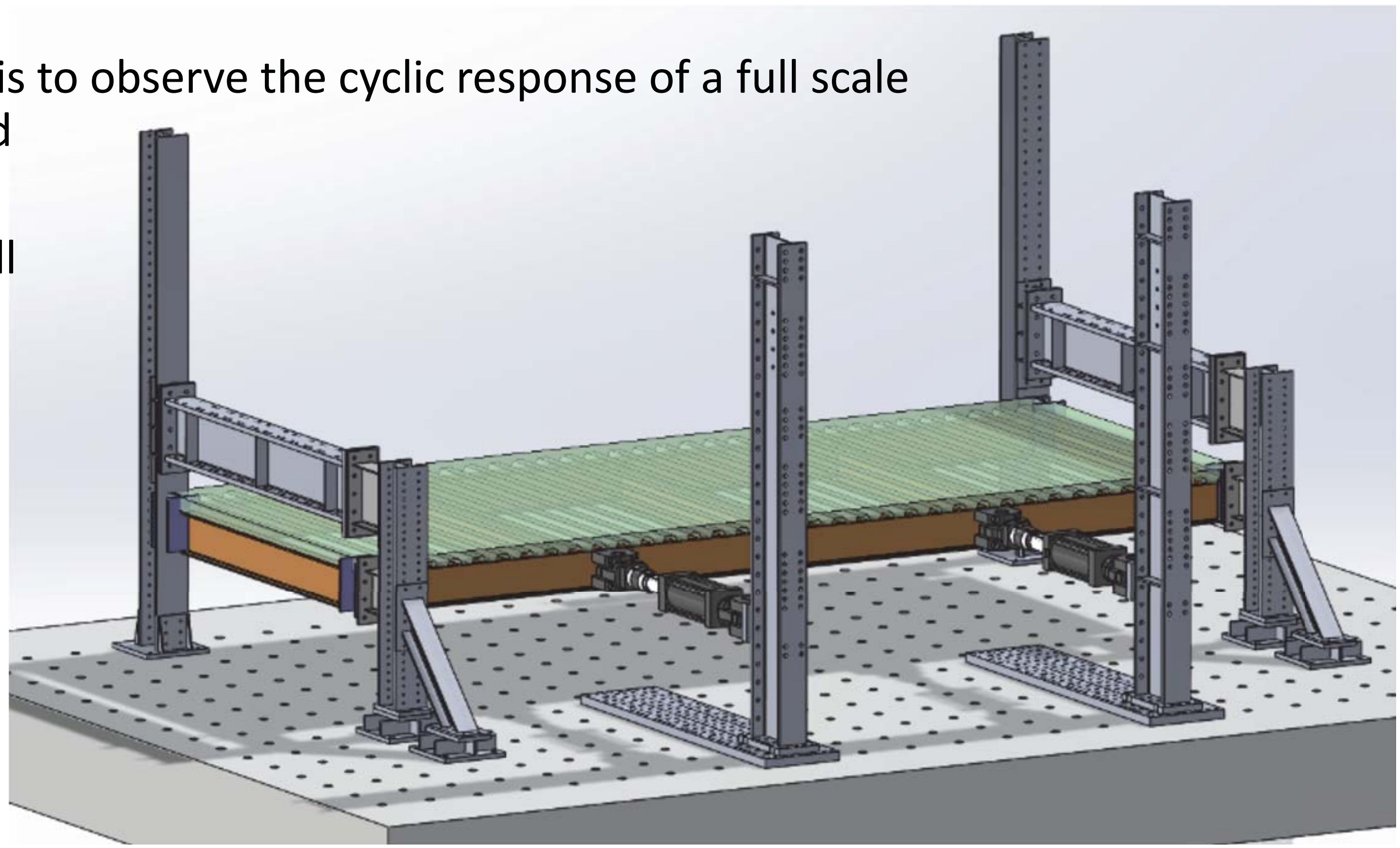
Test Specimen	Steel Deck Depth (in)	Concrete Type	Total Slab Thickness (in)	Concrete Thickness (in)	Objective
3/6.25-4-L-NF-DT	3	Lightweight	6.25	3.25	Typical 2 Hr Fire Rating for LW
3/7.5-4-N-NF-DT	3	Normalweight	7.5	4.50	Typical 2 Hr Fire Rating for NW
2/4-4-N-NF-DT	2	Normalweight	4	2.00	Thin assembly using NW
2/4-4-L-NF-DT	2	Lightweight	4	2.00	Thin assembly using LW
3/6.25-4-L-NF-P	3	Lightweight	6.25	3.25	Fail Studs with LW
3/7.5-4-N-NF-P	3	Normalweight	7.5	4.50	Fail Studs with NW
3/6.25-4-L-F	3	Lightweight	6.25	3.25	Steel Fiber Reinforcement
3/7.5-4-N-F	3	Normalweight	7.5	4.50	Steel Fiber Reinforcement
2/5.25-4-L-F	2	Lightweight	5.25	3.25	Steel Fiber Reinforcement
2/6.5-4-N-F	2	Normalweight	6.5	4.50	Steel Fiber Reinforcement
2/4-4-L-F	2	Lightweight	4	2.00	Steel Fiber Reinforcement
3/5-4-L-F	3	Lightweight	5	2.00	Steel Fiber Reinforcement

Note: All calculations were based on fc’ = 4000 psi and Gage 18 Deck
Test Specimen Notation: Deck Depth/Total Slab Thickness – fc’ in ksi – Lightweight (L) or Normalweight (N) – Fibers (F) or No Fibers (NF) – Diagonal Tension Cracking (DT) or Perimeter Fastener Failure (P)
Example: 3VLI18 Deck, 6.25” Composite Slab, 4000 psi Lightweight concrete without fibers and an expected perimeter fastener failure mode = 3/6.25-4-L-NF-SF

- Motivation:
  - Expand database with specimens reflecting modern construction practices
  - Tests with fiber reinforced concrete support FRC in diaphragms
- Supporting tests:
  - Push-out tests
  - Concrete cylinder testing
  - Tensile coupon tests of steel deck

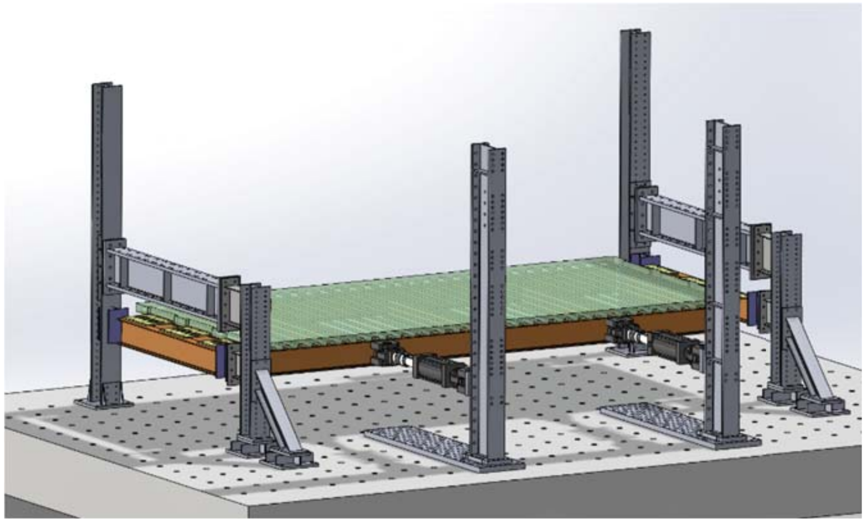
Full-Scale Beam-Style Test Coming

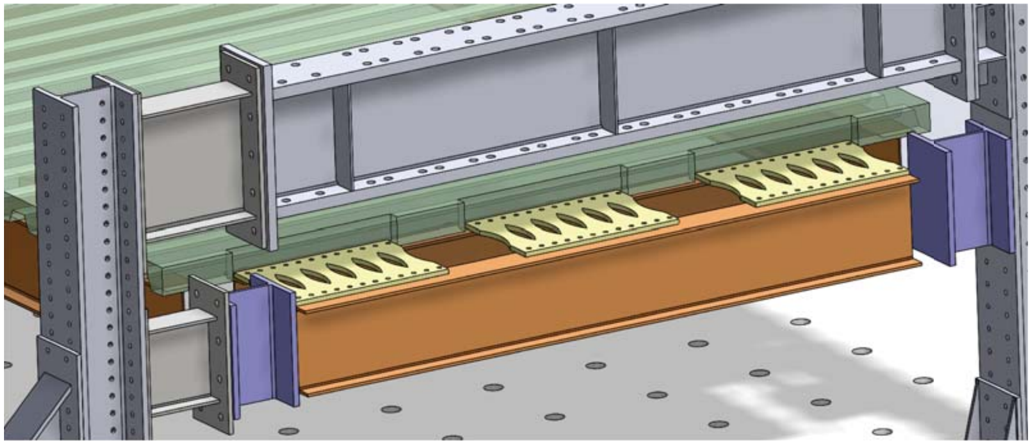
- This specimen is supported at outside corners and loaded laterally at third-points
- The purpose of this test is to observe the cyclic response of a full scale composite structure, and to identify critical areas.
- This test is cyclic, and will investigate the response of concrete strain in critical areas and cyclic shear stud behavior on chords and collectors.

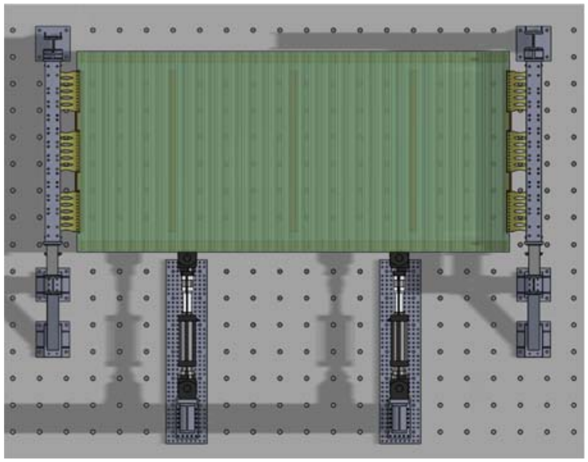


Integration of Fuses

- A second part of this experimental effort is to identify areas where energy-dissipating fuses can be attached to the system to minimize damage to primary components.







Test With Energy-Dissipating Fuses

Innovation and Practice	Experiments	Modeling

Innovation and Practice

- Building and Diaphragm Archetypes
- Evaluation of Existing Design Methods
- Evaluation of Existing Steel Diaphragm Technologies
  - Gap Analyses: Seismic and Non-seismic performance
- Candidate Design Methods
  - Methods proposed by others
  - Methods proposed by SDII
- Candidate Technologies
  - Revised profiles, material, manufacture, fuses…
- Seismic Standards Work

Experiments

- Existing Tests
- Test Technologies
- Connector Tests
- Interface Tests
- Diaphragm Tests
- Building Bay Tests
- Full Building Tests *
- Test Database
- Test Standards

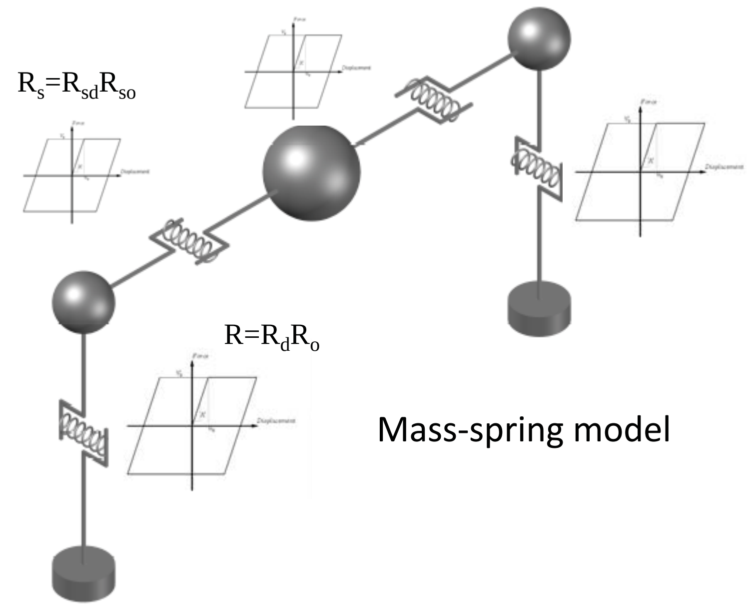
Modeling

- Conventional Design Models
- Modeling for Experimental Program
- Diaphragm Models
- Whole Building Models
  - **Reduced Order**
  - OpenSees/Frame Modeling
- Next-generation Models
- Non-Structural Models
- Optimization Models

* SDII industry funding and NSF funding do not full building tests, proposals pending, and collaborating with Fleischman et al. NSF Project

SDII Mass-Spring Models

- Simplified mass-spring models from 1 to 12 stories studied to explore R vs R_s or vLFRS vs hLFRS issues.
- Large parameter variation across *m*, *K* , *T*, yielding of both vertical and horizontal systems
- Inelastic time history analysis across P695 EQ suite
- Allows for broad discussion on the impact of ductility in the walls, floors, or both on the force levels and drift demands expected in the system given R and R_s.



R_d based on ASCE 7 Steel Systems and (Ω_o~=R_o)

System	R	Ω_0	R_d
Elastic	1	1	1.00
Steel	3	3	1.00
OMF	3.5	3	1.17
IMF	4.5	3	1.50
OCBF	3.25	2	1.63
SMF	8	3	2.67
SCBF	6	2	3.00
BRB	8	2.5	3.20
EBF	8	2	4.00

R_{sd} based on ASCE 7-16 Floor Systems

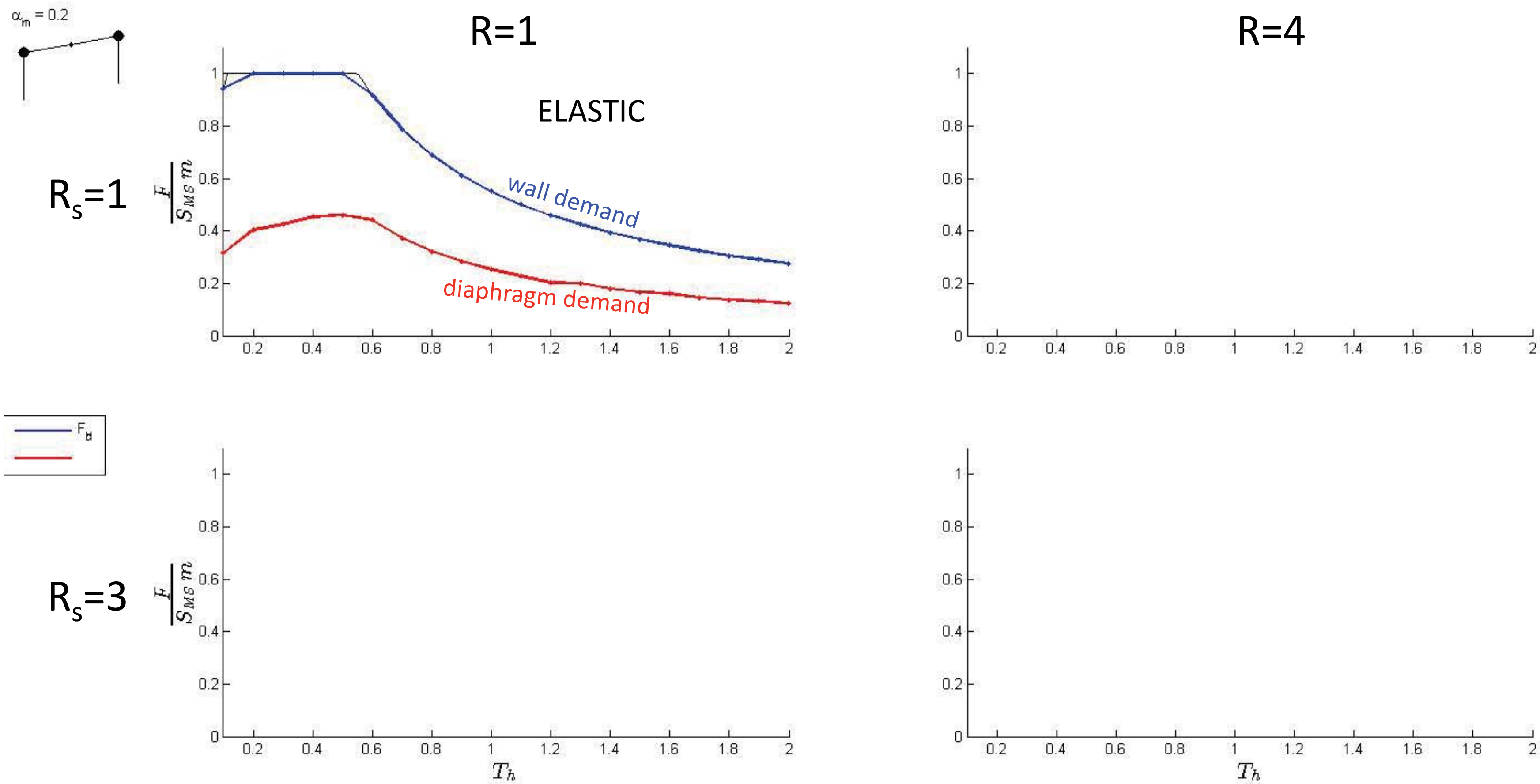
System	R_s	R_{so}	R_{sd}
Precast EDO	0.7	0.7	1
Cip Shear	1.5	1.25	1.2
Precast BDO	1	0.83	1.2
Precast RDO	1.4	1	1.4
CIP Flexure	2	1.25	1.6
Wood	3	1.2	2.5
Steel 1	2.2	1.1	2.0
Steel 2	4	1.6	2.5

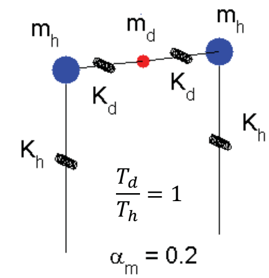
note R_{so} are educated guess by BWS

note steel values are educated guess by BWS

FORCE SPECTRA: ELASTIC

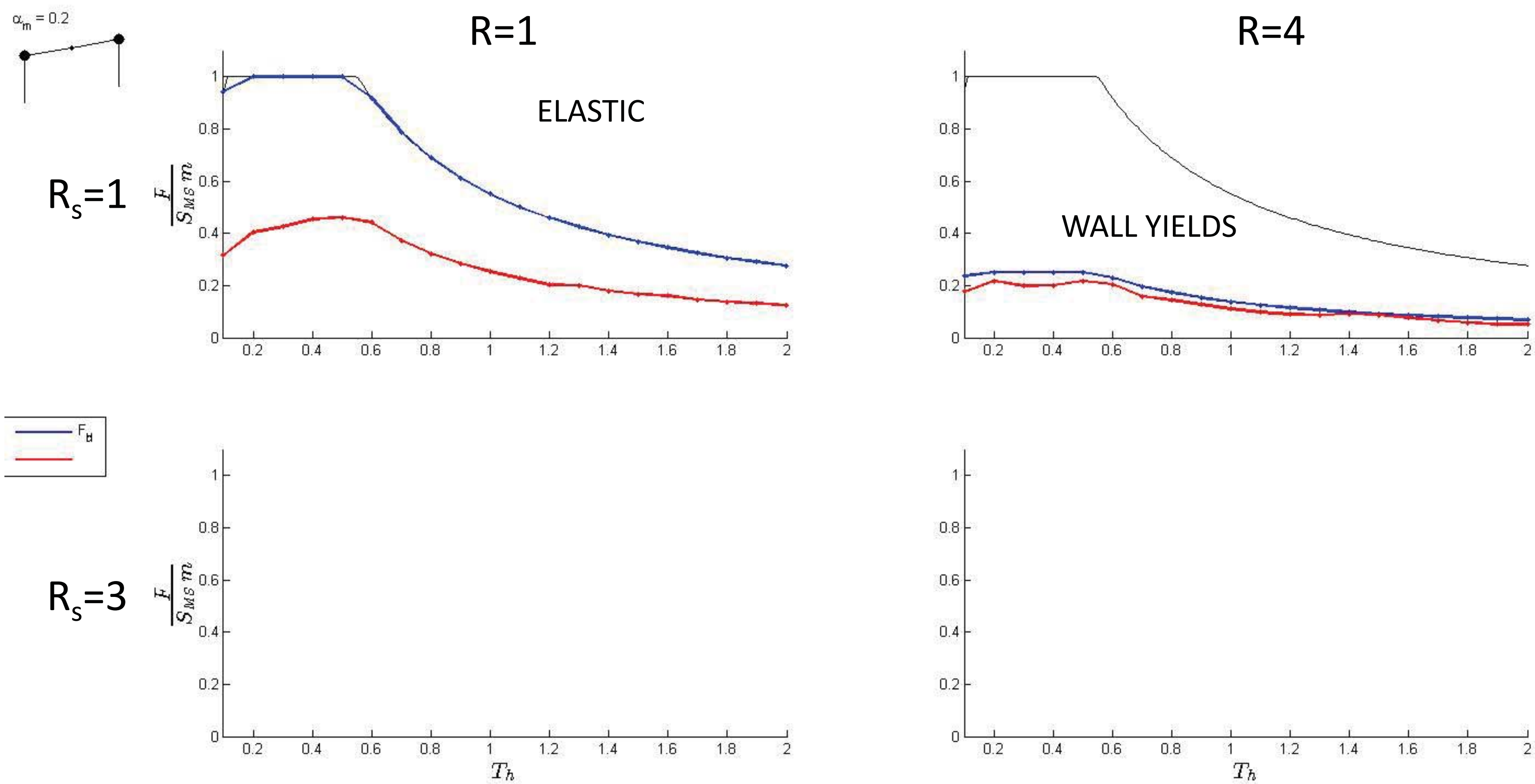
Average response over FEMA P695 Suite of Earthquakes

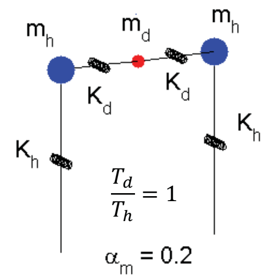




FORCE SPECTRA: INELASTIC WALLS

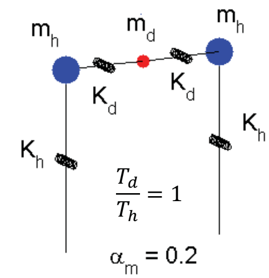
Average response over FEMA P695 Suite of Earthquakes

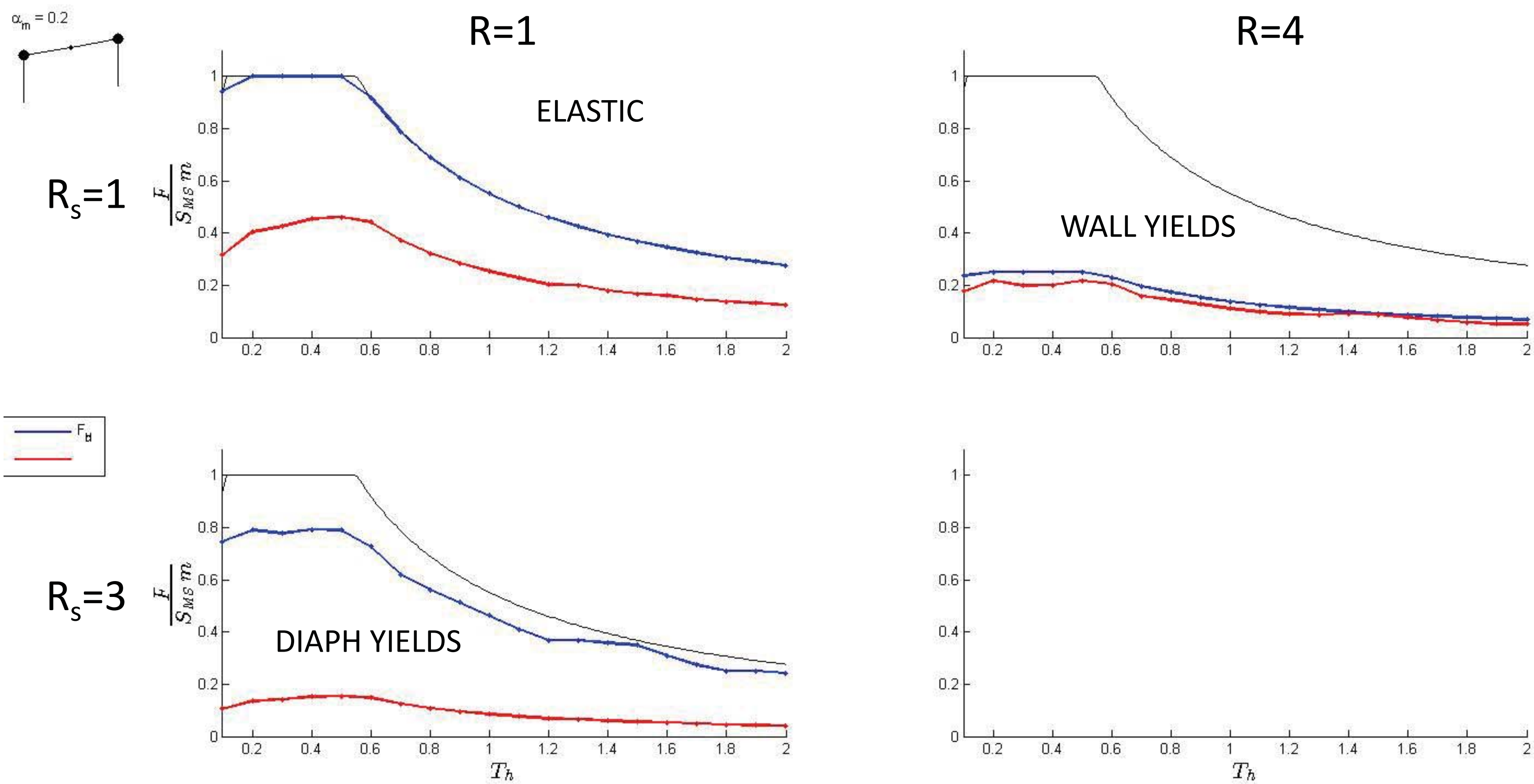




FORCE SPECTRA: INELASTIC DIAPHRAGM

Average response over FEMA P695 Suite of Earthquakes

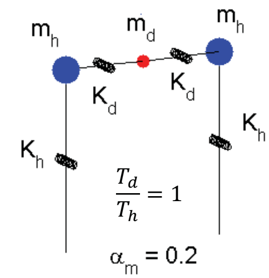


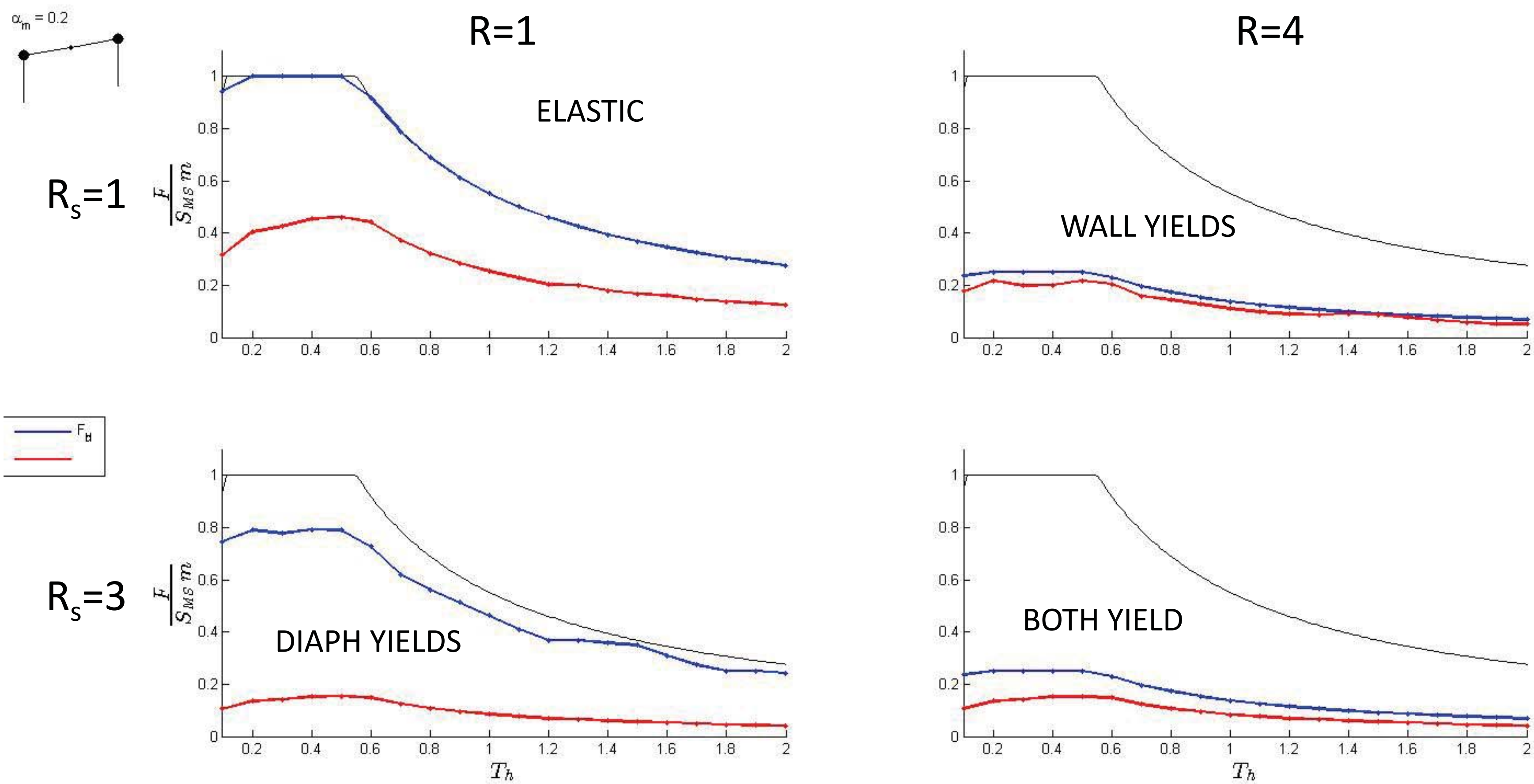


SDII

FORCE SPECTRA

Average response over FEMA P695 Suite of Earthquakes

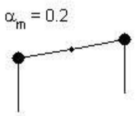


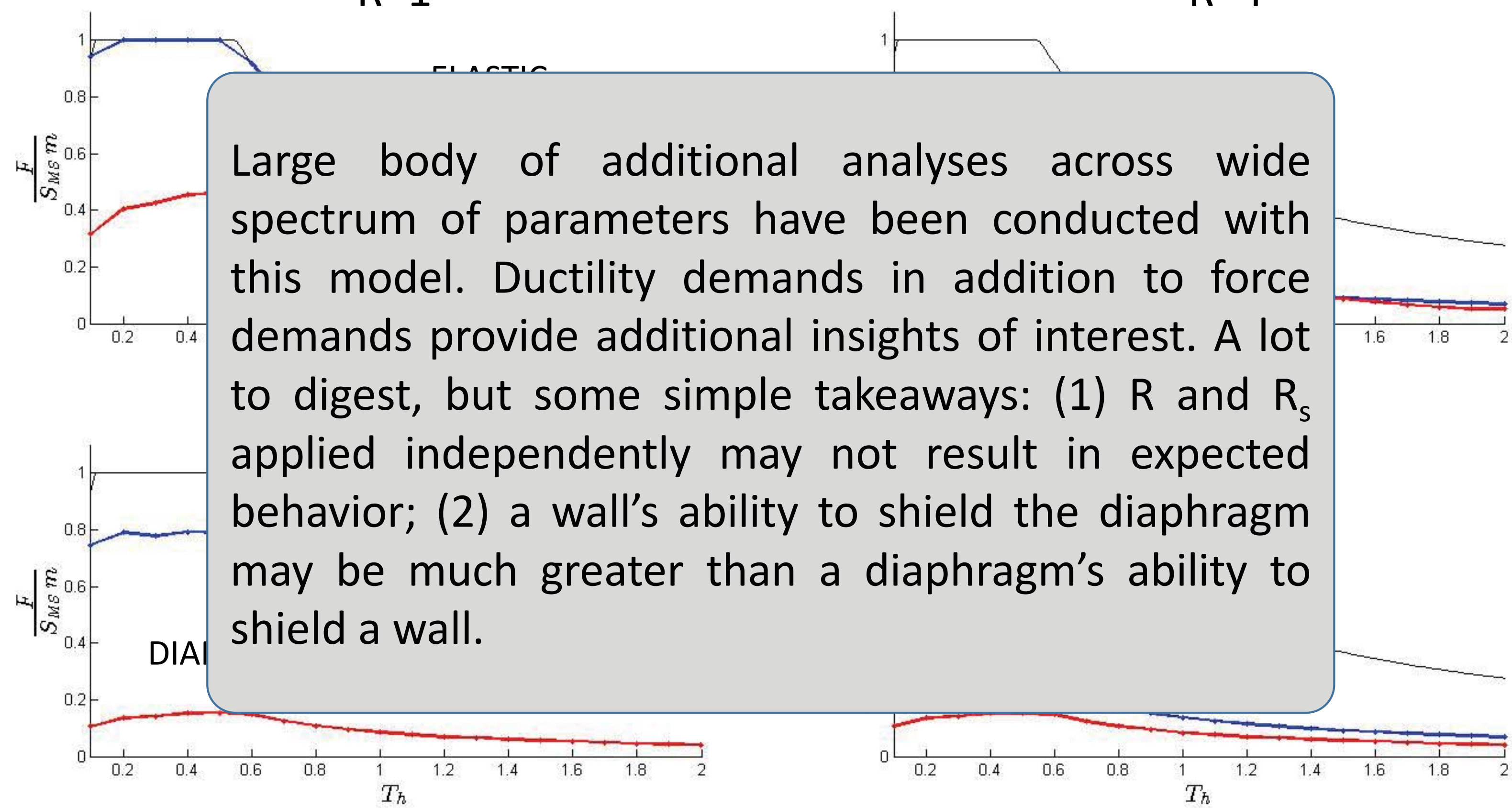


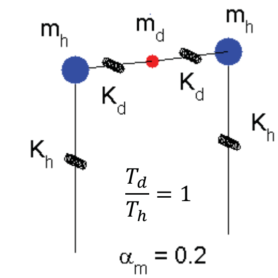
SDII

FORCE SPECTRA

Average response over FEMA P695 Suite of Earthquakes







Large body of additional analyses across wide spectrum of parameters have been conducted with this model. Ductility demands in addition to force demands provide additional insights of interest. A lot to digest, but some simple takeaways: (1) R and R_s applied independently may not result in expected behavior; (2) a wall's ability to shield the diaphragm may be much greater than a diaphragm's ability to shield a wall.

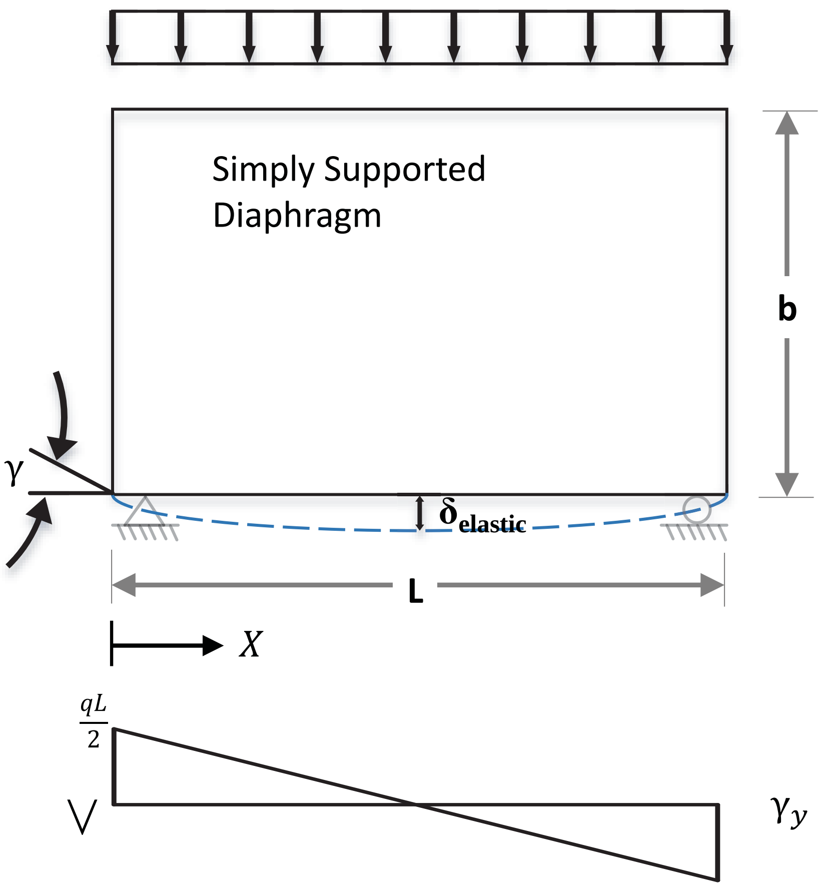
Conclusions

- SDII has significant activities underway that provide a path for steel diaphragms to leapfrog current conditions in: understanding, design, and technologies available
- SDII is fully engaged with standards process to advance findings and improve/remove gaps in coverage for steel diaphragms in design
- SDII is building out design methods, benchmark test results, and modeling methods and protocols that can broadly benefit all steel buildings and provide pathways for improving overall (seismic) building design/performance

Supplemental

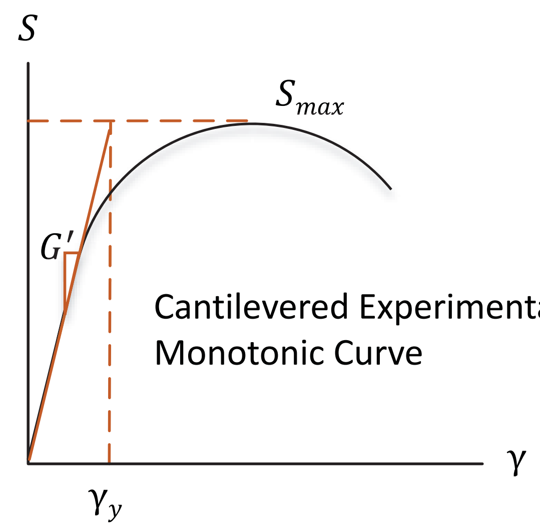
Calculating Elastic Deflection, δ_{el}

Constant Distributed Shear Load = q



Shear load, q, associated with peak load in cantilever test

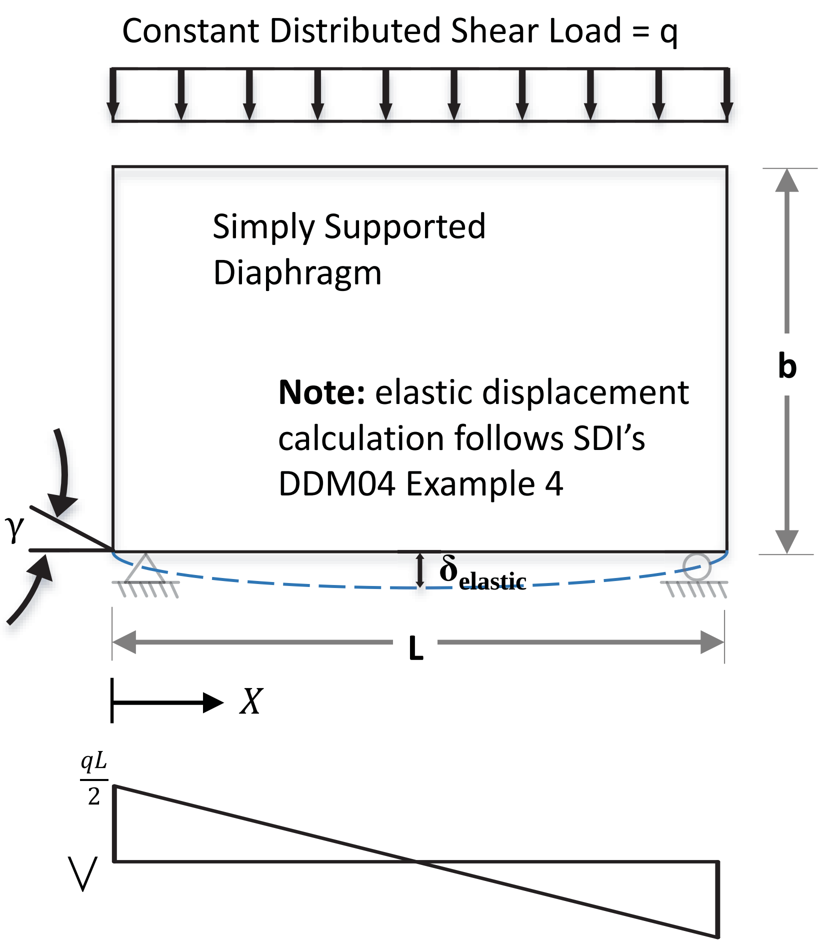
$$S_{max} = \frac{V_{max}}{b} = \frac{qL/2}{b} \rightarrow q = \frac{2Smaxb}{L}$$



$$\gamma_y = \frac{S_{max}}{G'}$$

Goal: Find elastic midspan deflection, δ_{el} that corresponds to γ_y from test

Calculating Elastic Deflection, δ_{el}



$$S_x = \frac{V_x}{b} = \frac{\frac{qL}{2} - qx}{b} = \frac{q}{b}\left(\frac{L}{2} - x\right)$$

$$\gamma_x = \frac{S_x}{G'} = \frac{q}{G'b}\left(\frac{L}{2} - x\right)$$

Note: shear angle is the slope of the deflected shape. Integrate shear angle for deflection.

$$\gamma = \frac{d_y}{d_x}$$

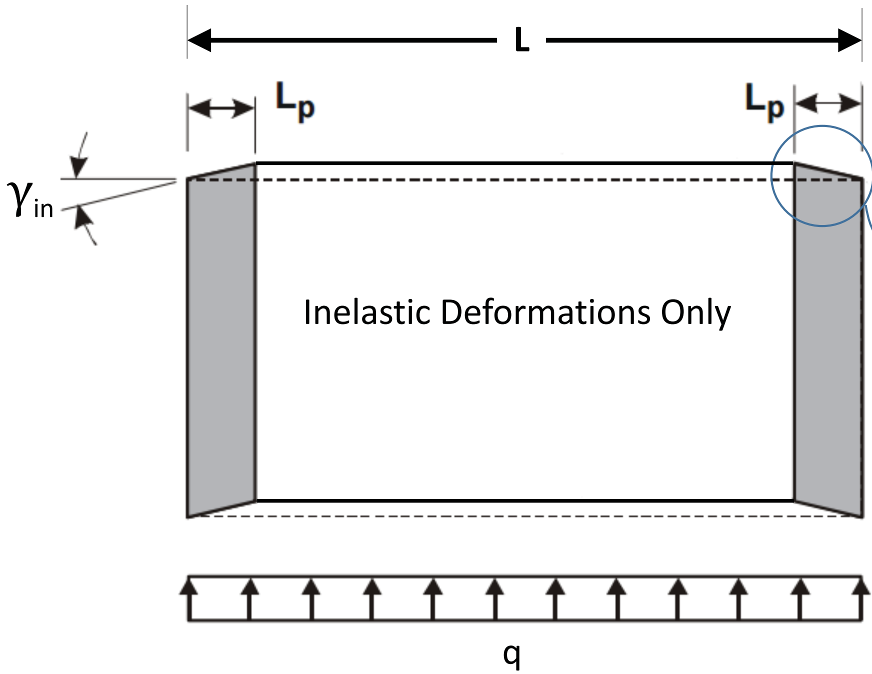
$$\delta_{el} = \int_0^{L/2} \frac{q}{G'b}\left(\frac{L}{2} - x\right) dx$$

$$\underbrace{\delta_{el} = \frac{qL^2}{8G'b} \qquad q = \frac{2Smaxb}{L}}$$

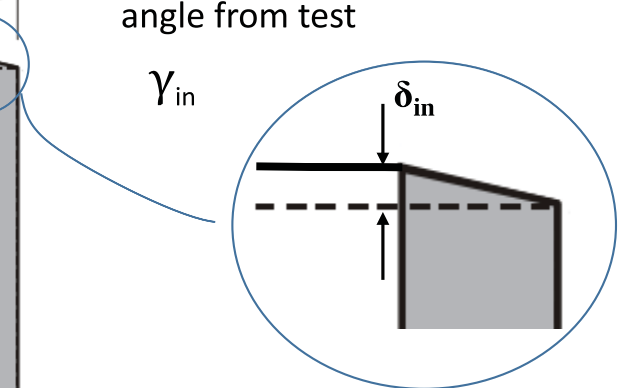
$$\boxed{\boldsymbol{\delta_{el} = \frac{S_{max}L}{4G'}}}$$

SDII

Calculating Inelastic Deflection $\boldsymbol{\delta}_{in}$



Assume constant inelastic shear deformation angle in a plastic edge zone = inelastic shear angle from test



$$\delta_{in} = \gamma_{in} L_p$$

$$\gamma_{in} = \gamma_{80\%} - \gamma_y$$ From Test

Similar Concept in: Ductile Design of Steel Roof Deck Diaphragms For Earthquake Resistance (Rogers et al. 2004)