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Design for Deconstruction for Sustainable Composite Steel-Concrete Floor Systems

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Simpson Gumpertz and Heger, Inc.

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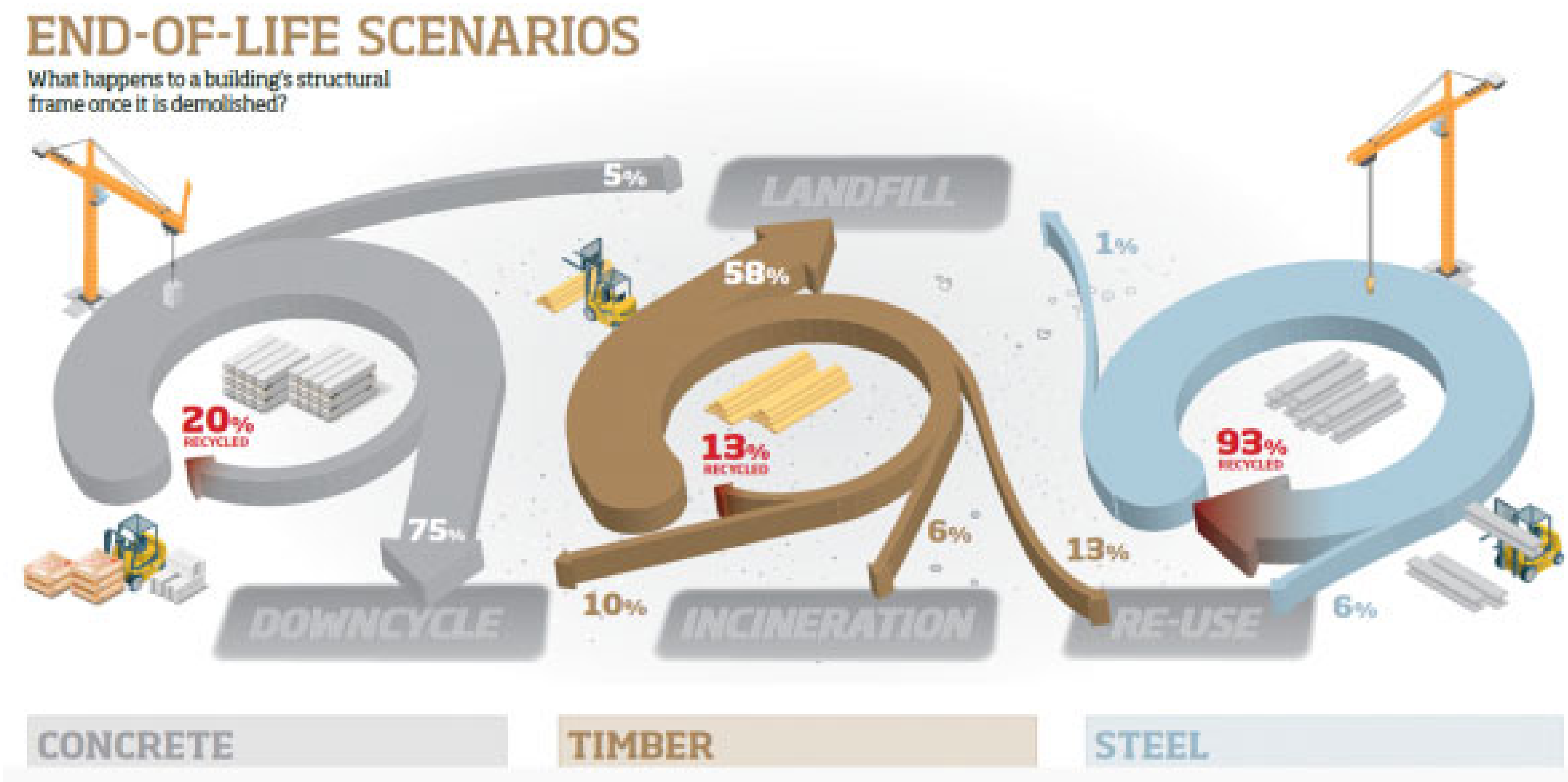
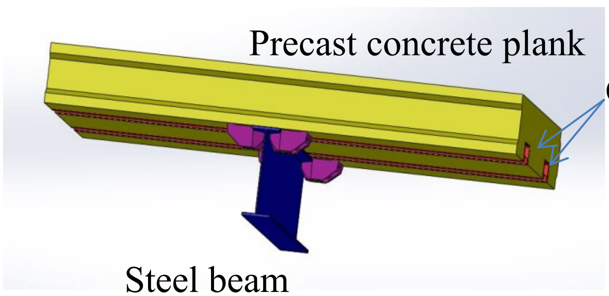
End-of-life of Construction Materials

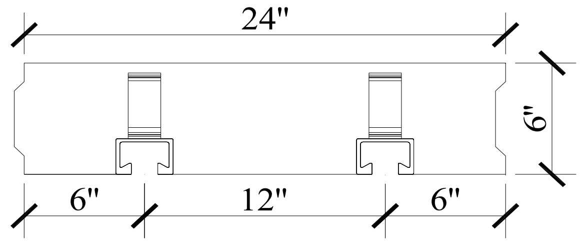


End-of-life of construction materials
Image from SteelConstruction.Info

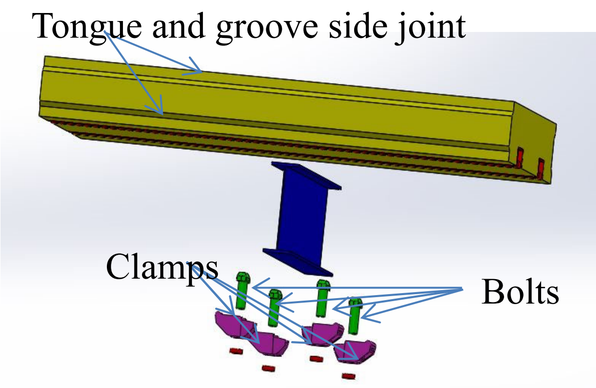
Composite Floor System

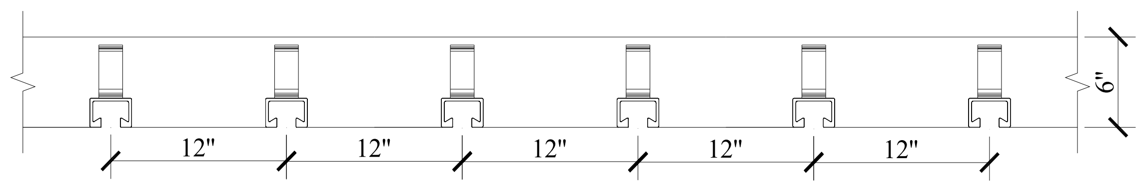
- Conventional composite floor systems are cost-effective solutions for multi-story buildings
- The integration of steel beams and concrete slab limits separation and reuse of the components
- Proposed DfD System: Clamp precast planks to steel beams/girders in a steel framing system
    - Both the steel members and the precast planks may be reused





a) Plank perpendicular to the steel beam





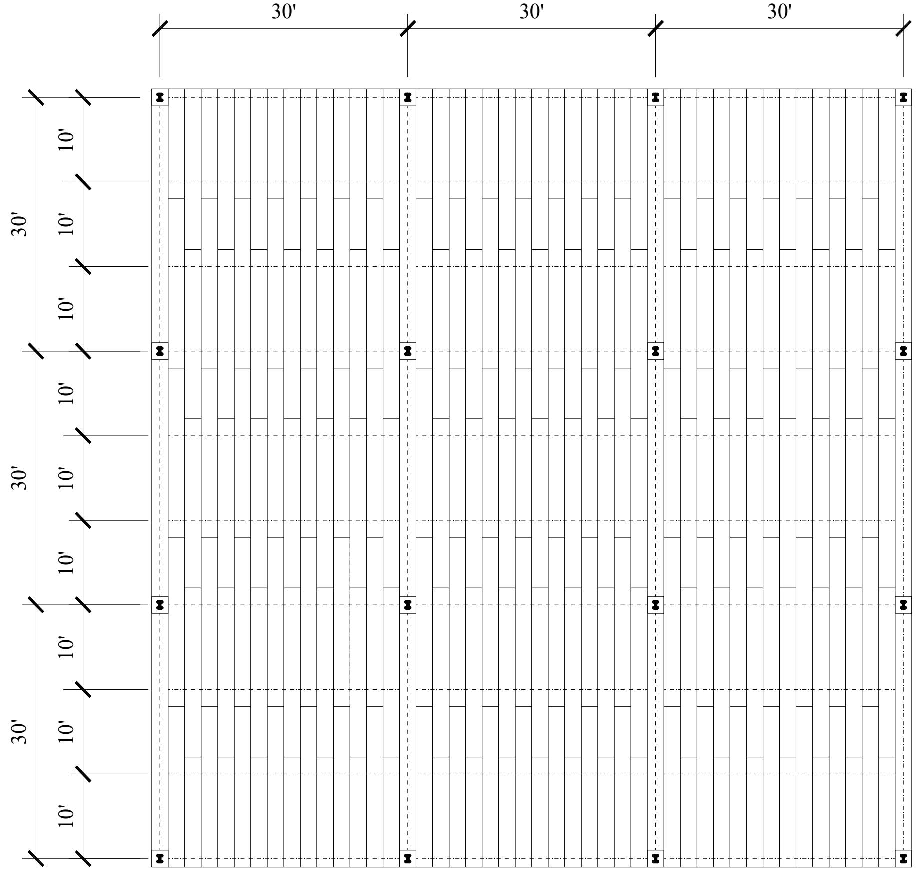
b) Plank parallel to the steel girder

Deconstructable composite beam prototype

Precast concrete plank cross section

DfD Floor System

Goal: Achieve nearly 100% direct reusability for composite floor systems within the context of bolted steel framing systems



Typical floor plan for DfD system

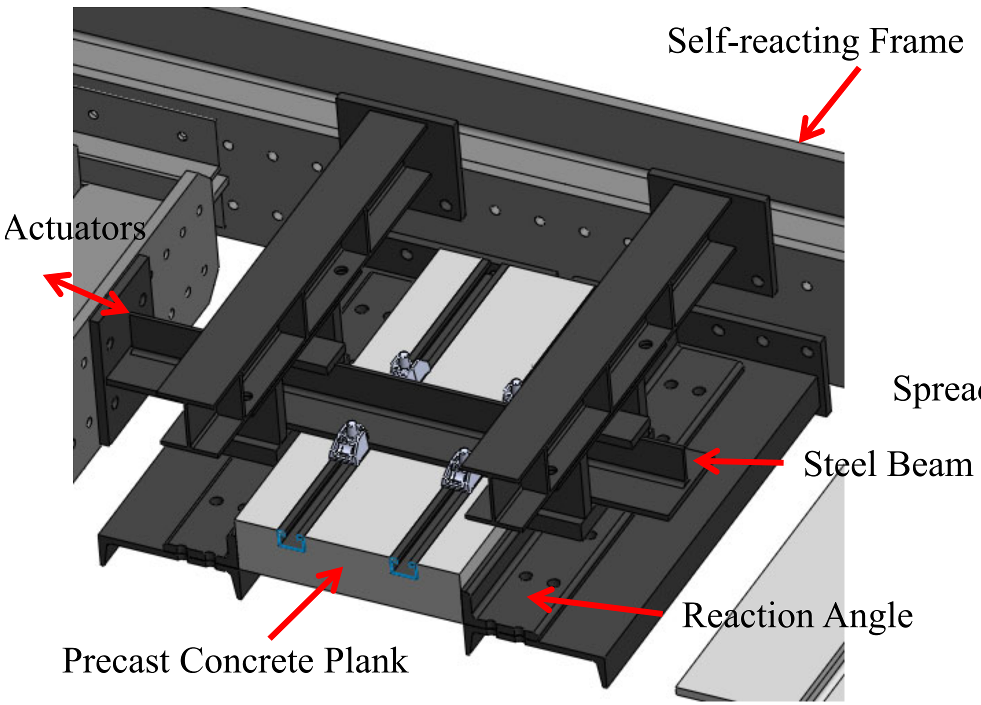
ConXtech moment connection
Image from ConXtech Website

Example of deconstructable bolted connection

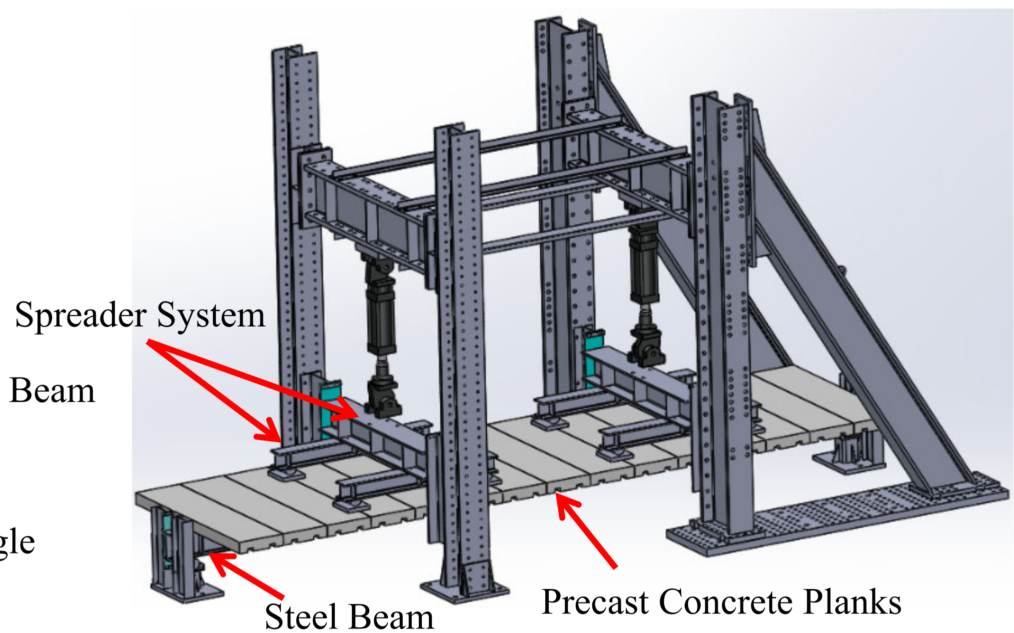
Test Program

- Pushout tests: evaluate a wide range of parameters and formulate strength design equations for the clamping connectors

- Beam tests: study the clamp connector behavior and associated composite beam strength and stiffness for different levels of composite action



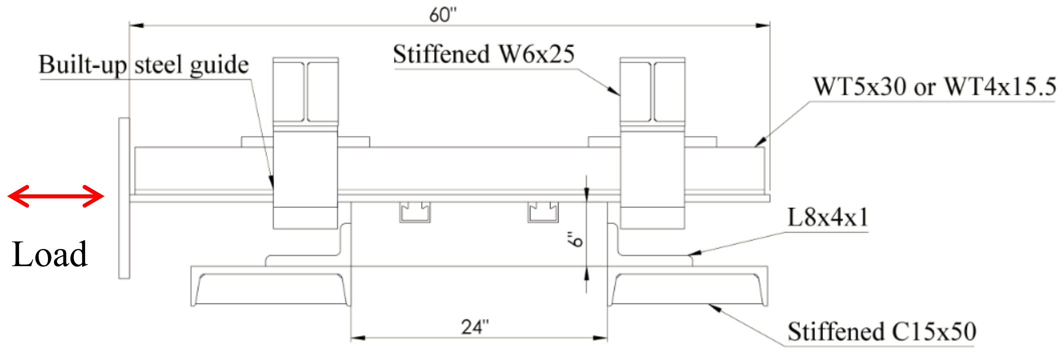
Pushout test setup



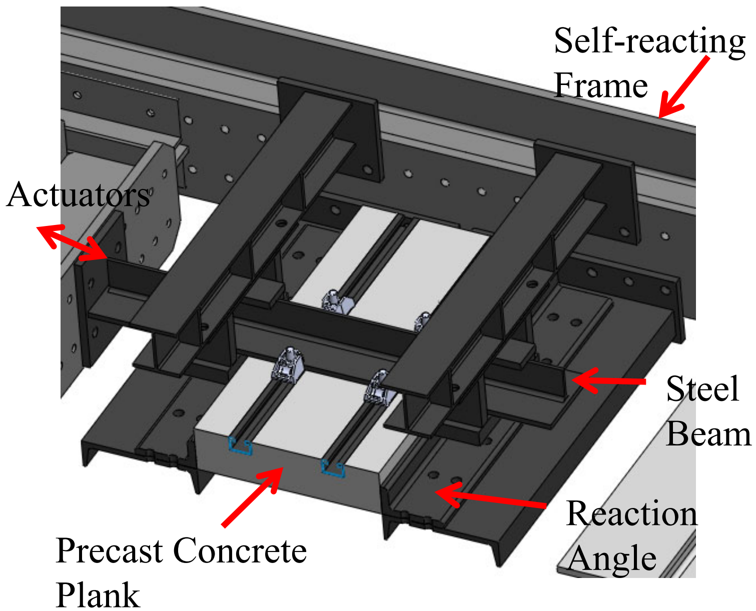
Composite beam test setup

Pushout Test Setup

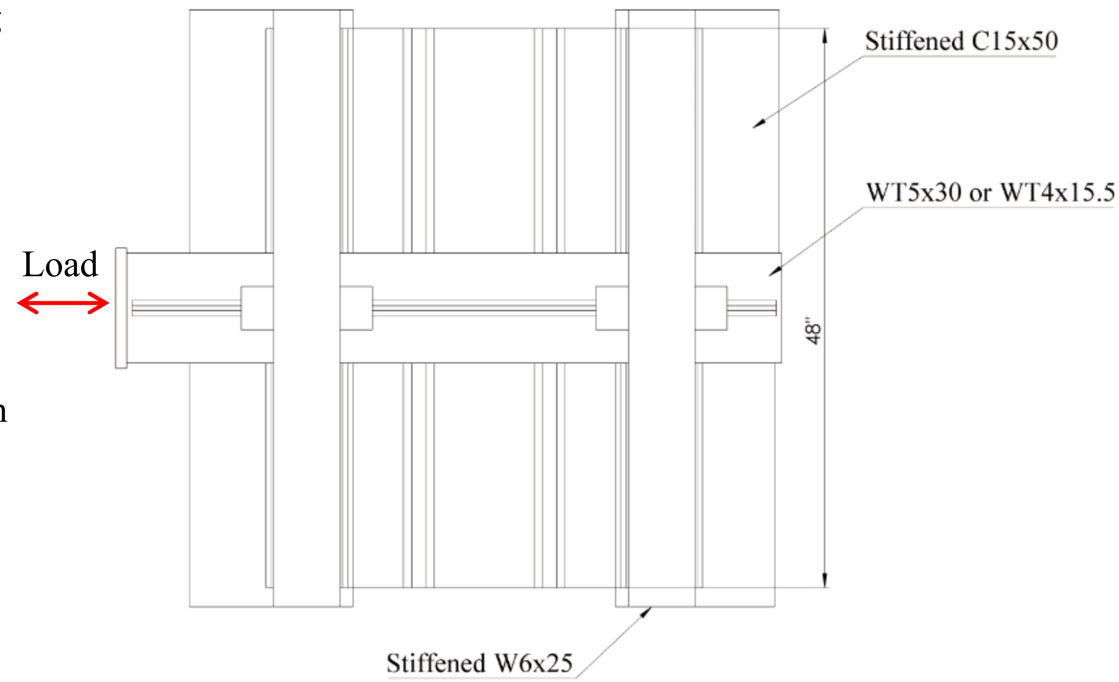
Pushout Test Configuration



Elevation View



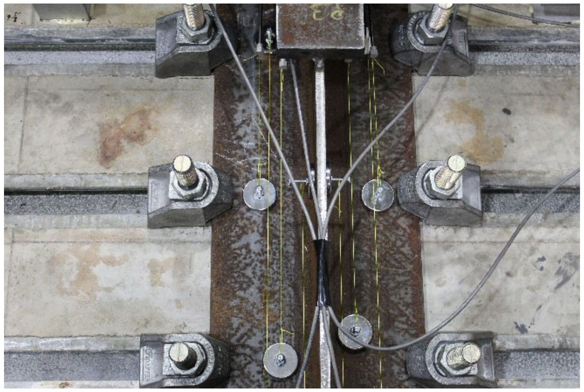
Pushout test setup



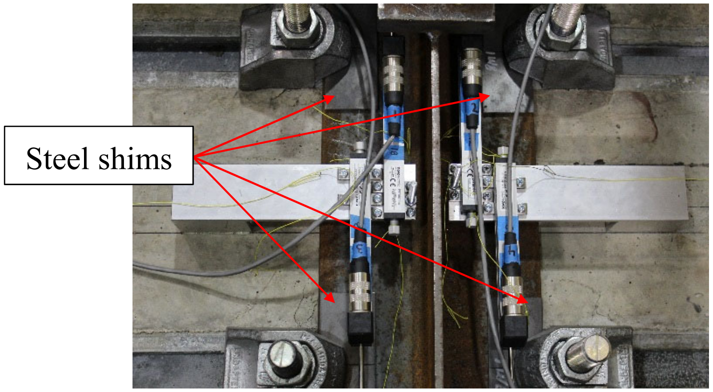
Plan View

Pushout Test Matrix

Series	Specimen	Test parameters			
		Bolt diameter	Number of T bolts	Reinforcement configuration	Shim
M	2-M24-T4-RH	M24	4	Heavy	No
M	3-M24-T4-RH-S	M24	4	Heavy	Yes
M	4-M24-T6-RH	M24	6	Heavy	No
M	5-M20-T4-RH	M20	4	Heavy	No
C	6-C24-T4-RH	M24	4	Heavy	No
C	7-C24-T4-RL	M24	4	Light	No
C	8-C24-T4-RH-S	M24	4	Heavy	Yes
C	9-C24-T6-RH	M24	6	Heavy	No
C	10-C20-T4-RH	M20	4	Heavy	No



Three-channel specimen

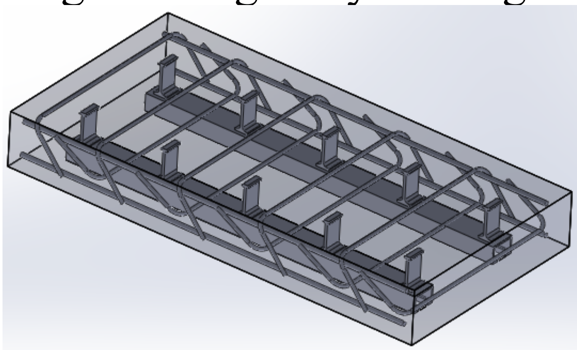


Two-channel specimen with shims

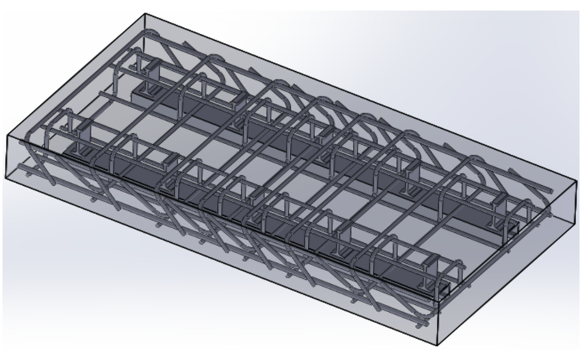
Pushout Test Parameters

Reinforcement pattern

- Light pattern: Contains reinforcement designed for gravity loading only

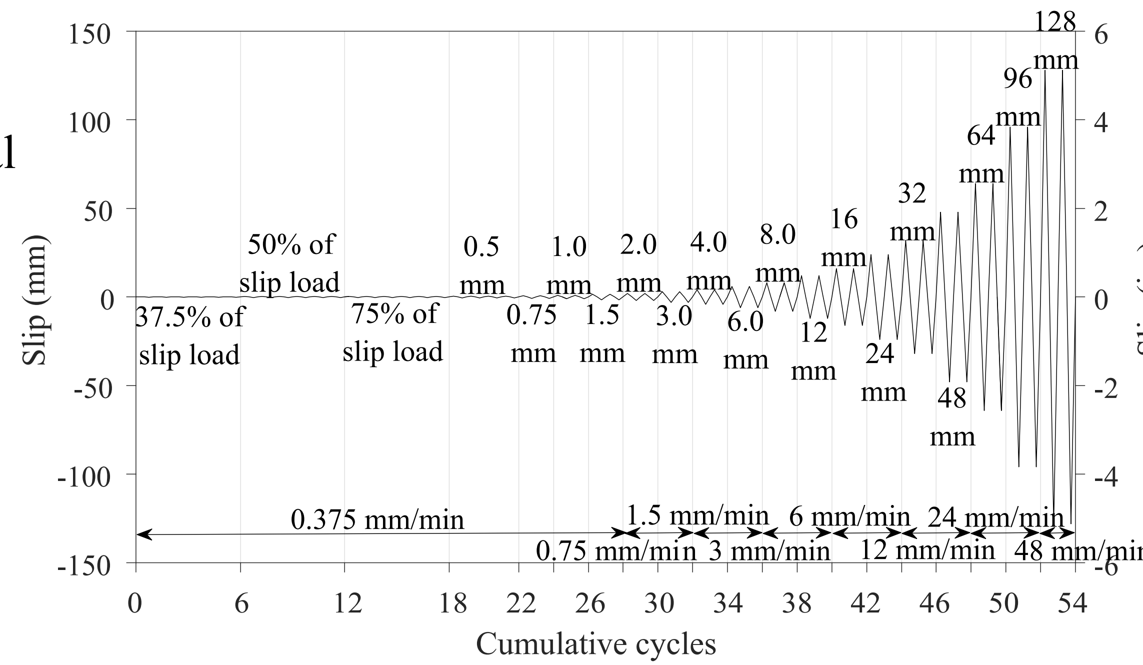


- Heavy pattern: Supplementary reinforcement bridges all potential concrete failure planes



Loading protocols

- Monotonic test: Displacement control
- Cyclic test:
  - Displacement control
  - Emulate AISC 341-10 K2.4b “Loading Sequences for Beam-to-Column Moment Connection”



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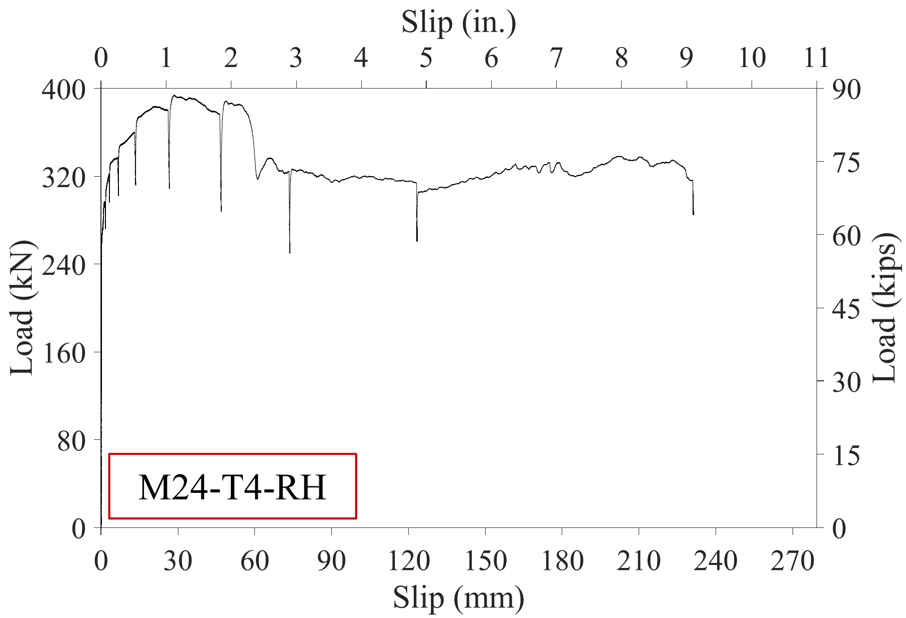
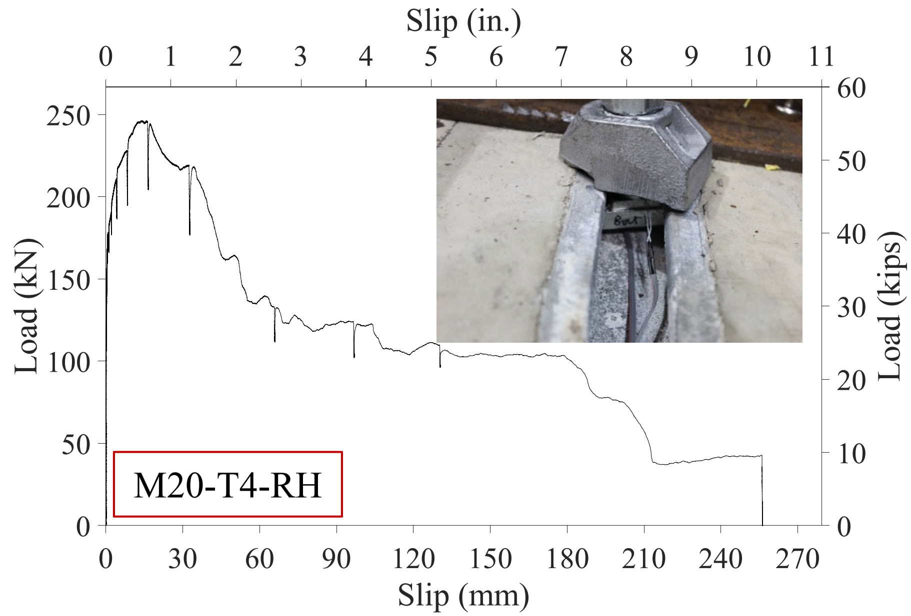
Pushout Test Results

Monotonic Test Results

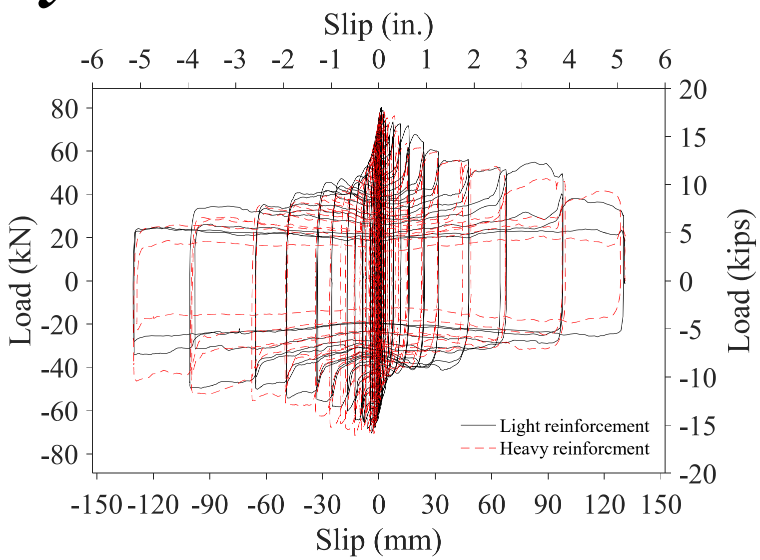




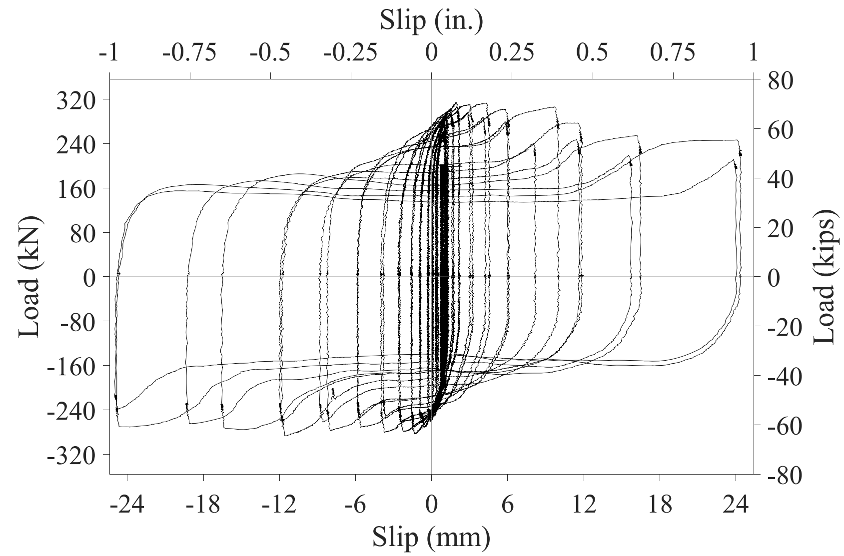
- The shear strength of a M24 clamp is 98.3 kN, while the strength of a 19 mm (3/4 in.) diameter shear stud embedded in a 27.58 MPa (4 ksi) solid concrete slab is 95.6 kN.
- The very large initial stiffness of the clamps reduces the slip at the steel-concrete interface at the serviceability and enhances the stiffness of the composite beams.
- The M24 clamps can retain almost 80% of the peak strength even at a slip of 125 mm, while shear studs usually fracture under much less deformation (~8 mm).
- The smaller M20 clamps are prone to rotate. The strength degradation starts at a slip of 17.3 mm, which is usually much larger than the maximum slip demand on shear connectors in composite beams.

Pushout Test Results

Cyclic Test Results



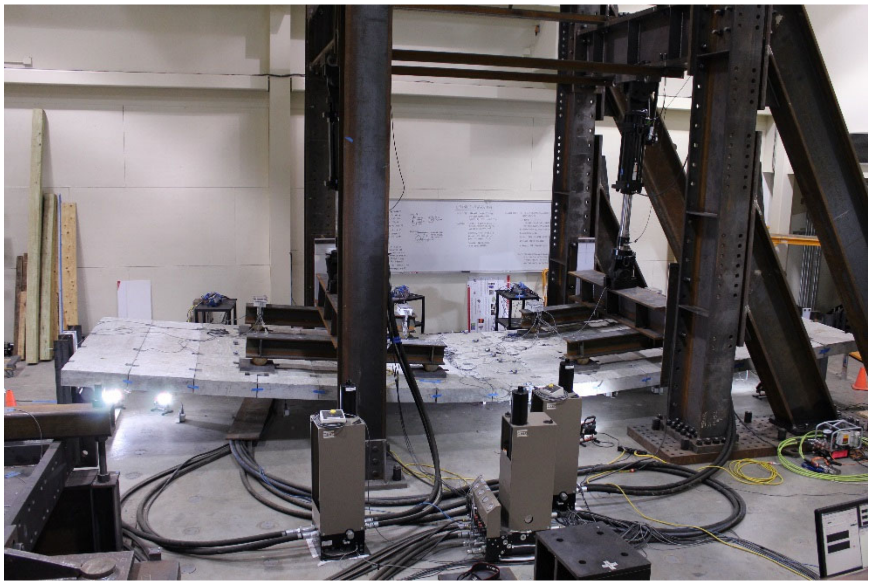
Specimens C24-T4-RH and C24-T4-RL

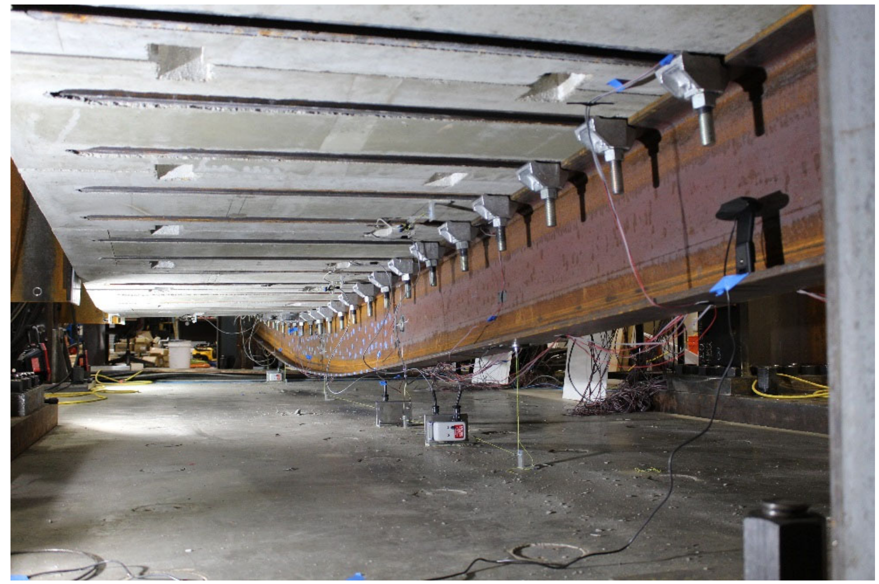


Specimen C24-T4-RH (within 25 mm slip)

- Strength reduction similar to shear studs which exhibit lower strength and ductility when subjected to cyclic loading
- The peak load reduces due to lowering of frictional coefficients and release of bolt tension caused by abrasion between the components.
- Clamps have the potential to connect composite diaphragms and collector beams and could be designed as inelastic components to dissipate energy.

Composite Beam Test



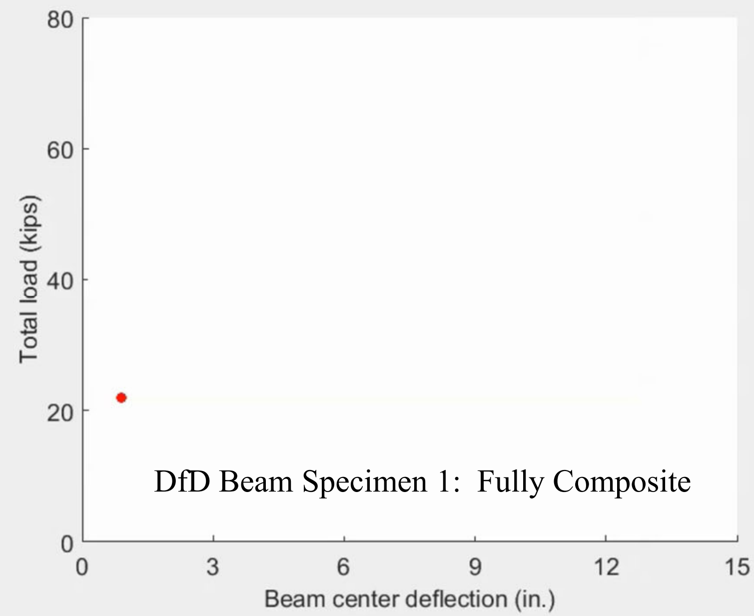


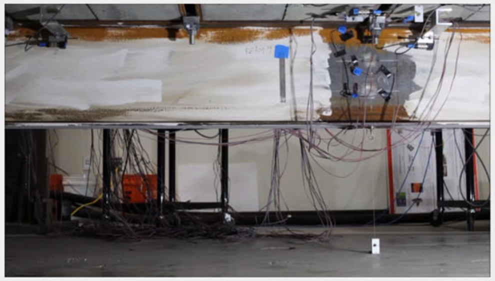
Composite beam test setup

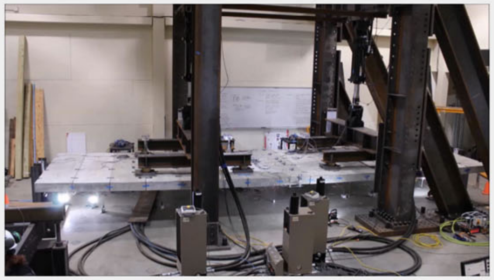
Composite beam #	Bolt size	# of channels per plank	Steel beam section	Reinforcement configuration	Number of bolts (clamps)	Percentage of composite action	
						Nominal	Actual
1-M24-2C-RH	M24	2	W14x38	Heavy	56	86.7%	82.7%
2-M24-1C-RL	M24	1	W14x38	Light	30	47.3%	45.1%
3-M20-3C-RL	M20	3	W14x26	Light	90	129.2%	137.8%
4-M20-1C-RL	M20	1	W14x26	Light	30	43.0 %	43.8%

DfD Composite Beam Tests at STReSS Lab

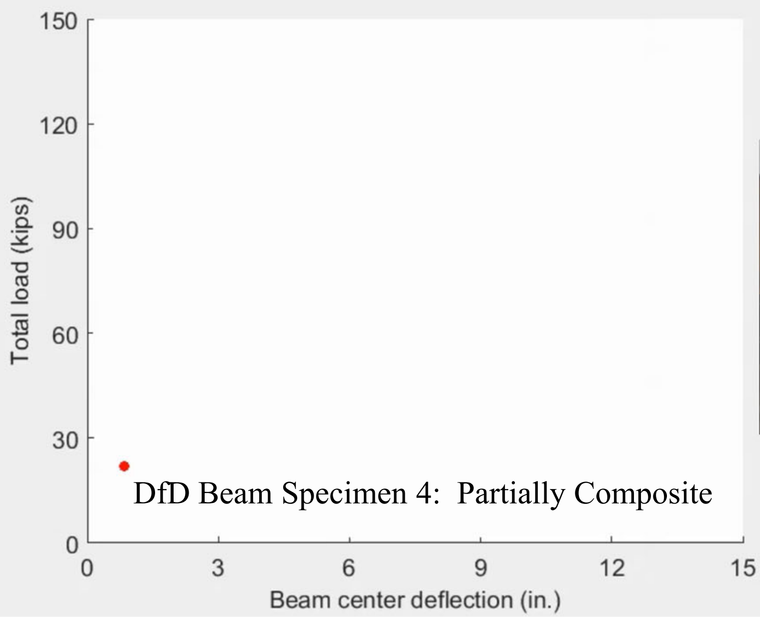
- Vertical load vs. vertical deflection
- Load transfer occurs through the clamps without causing damage to either the steel beam or concrete planks

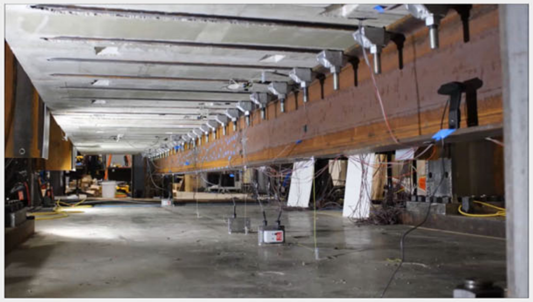






Overview of Specimen

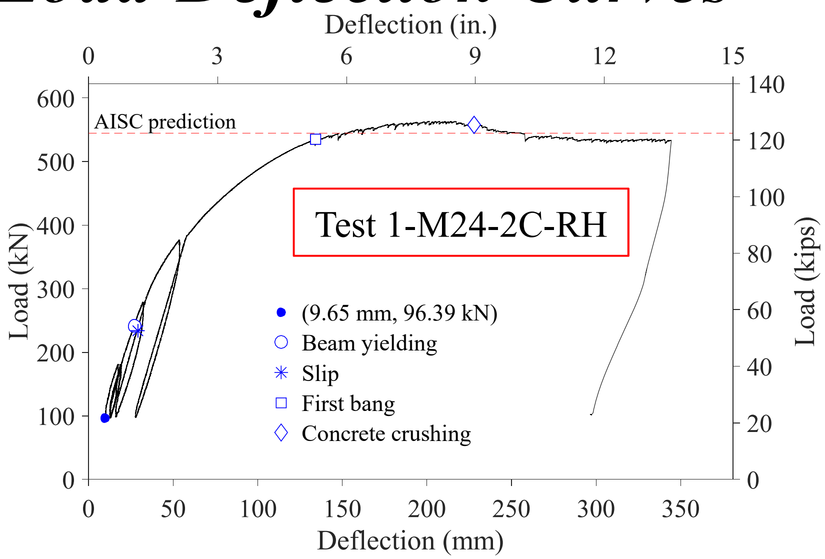


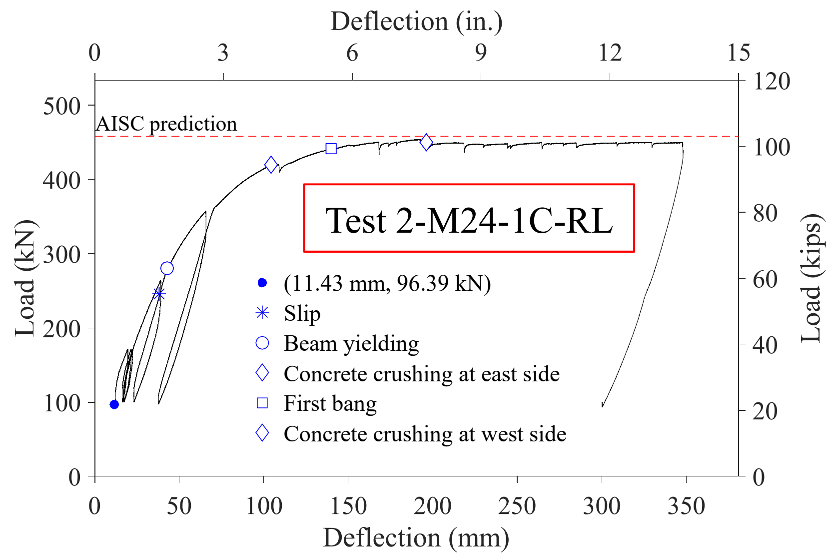


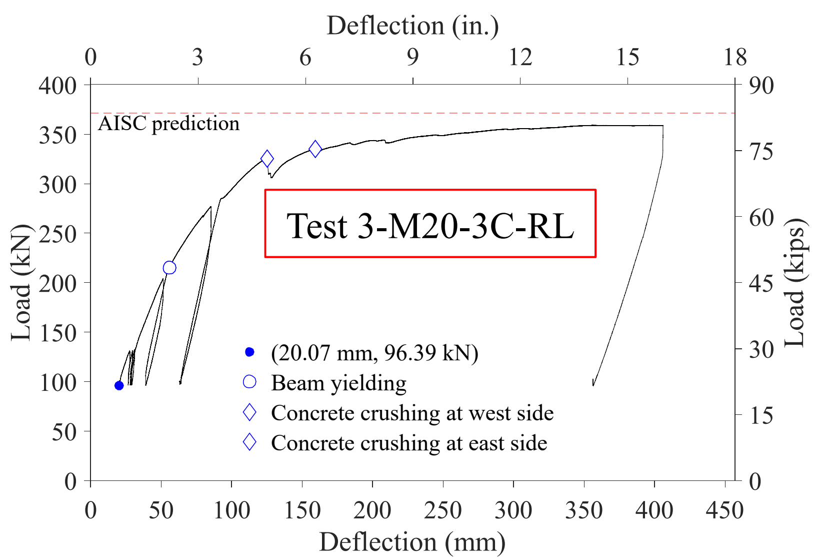
View Underneath Specimen Showing Clamps in Action

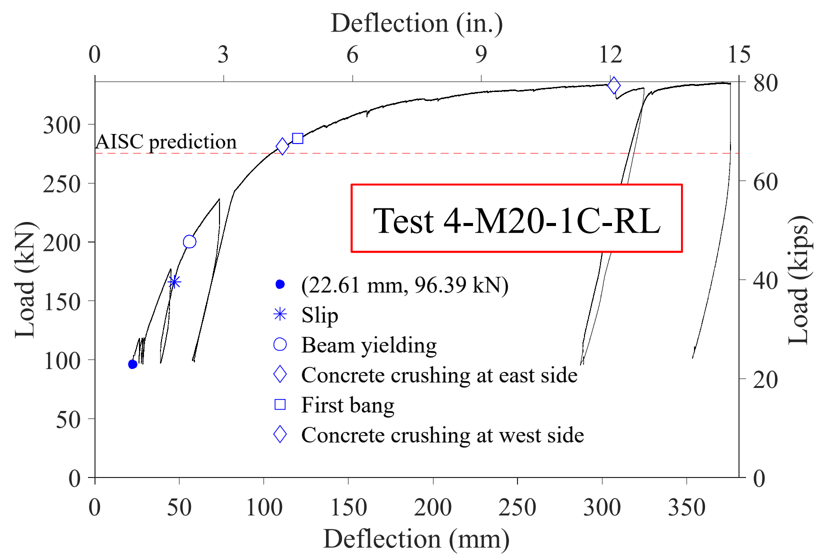
Beam Test Results

Load-Deflection Curves







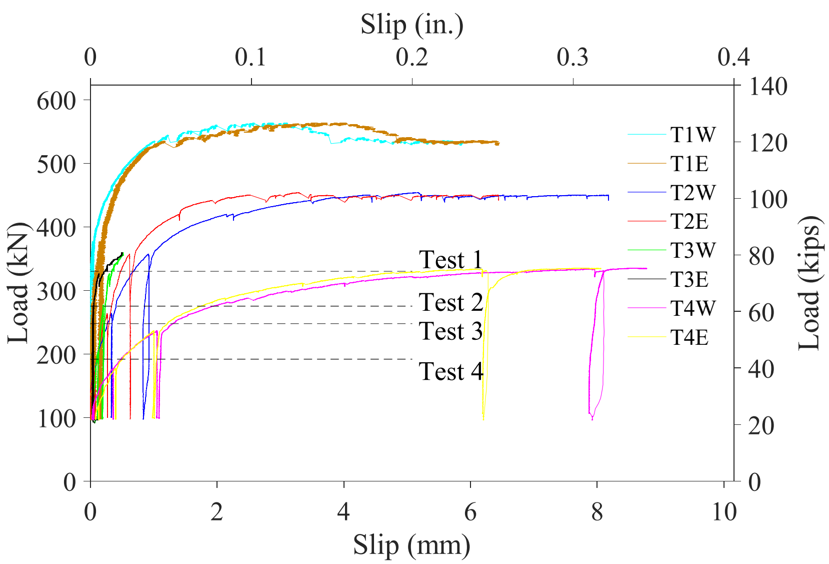


Beam Test Results

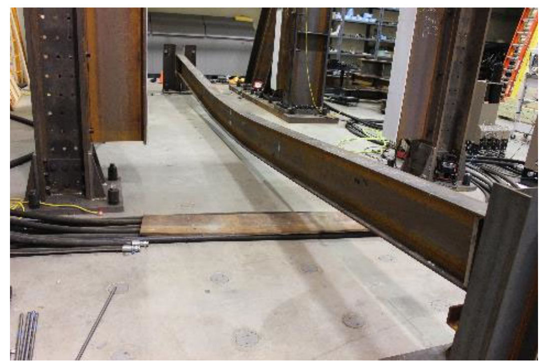
Test Results

Specimen #	Stiffness (kN/mm)			Moment (kN-m)			Maximum Slip (mm)	
	Test	AISC	Test/AISC	Test	AISC	Test/AISC	West Side	East Side
1-M24-2C-RH	9.24	8.67	1.07	777	767	1.01	5.94	6.43
2-M24-1C-RL	7.76	6.81	1.14	634	632	1.00	8.18	6.45
3-M20-3C-RL	6.46	5.99	1.08	494	510	0.97	0.46	0.23
4-M20-1C-RL	6.08	4.43	1.37	476	400	1.19	8.79	8.08

Applied load versus slip



Localized concrete crushing



Deconstructed steel beam

- Large initial stiffness demonstrated by the load-slip curves
- Small slip at full service loading (dashed lines)

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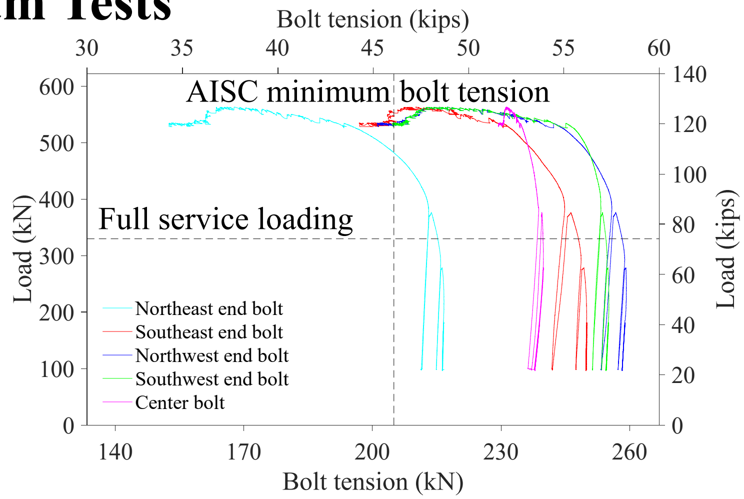
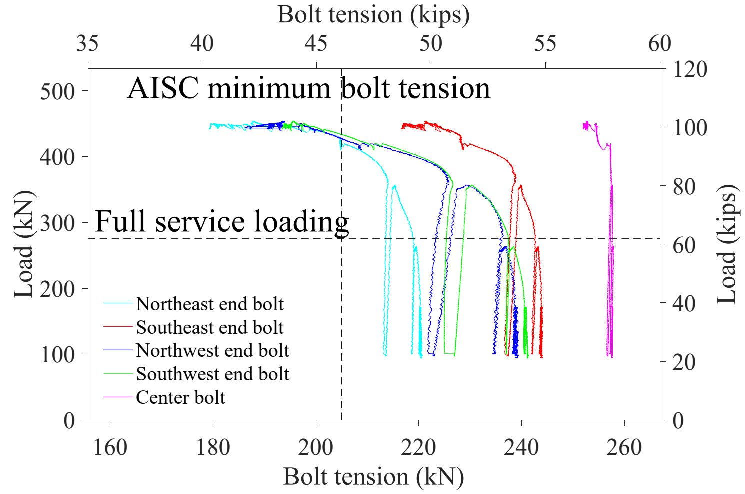
Behavior of T-bolts

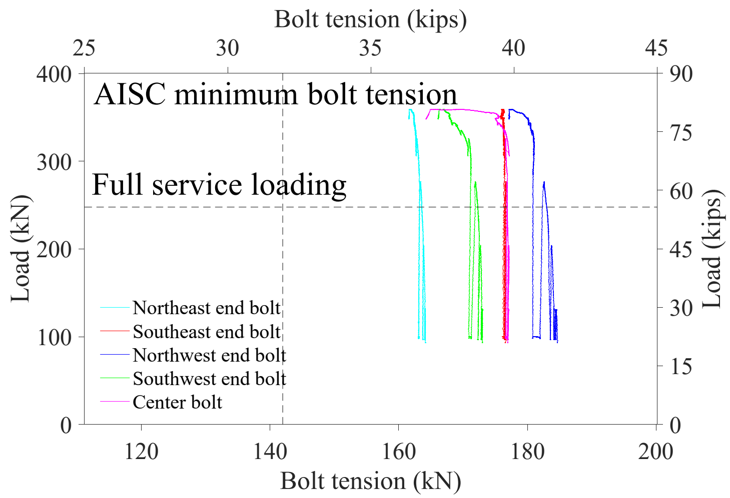
Beam Tests



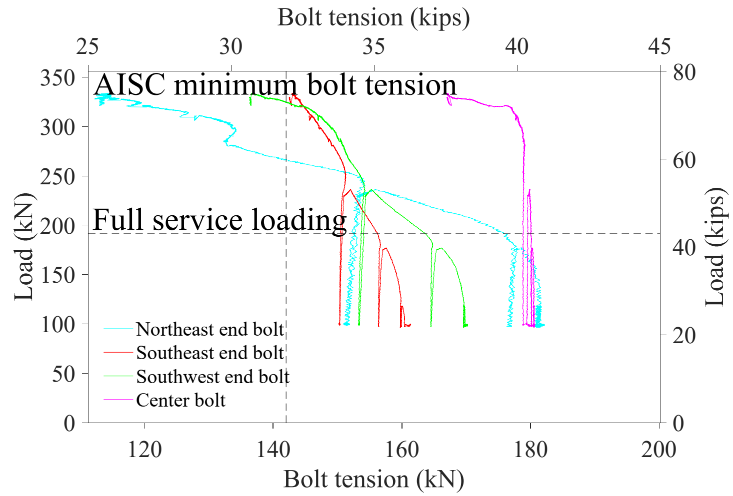
Test 1-M24-2C-RH



Test 2-M24-1C-RL



Test 3-M20-3C-RL

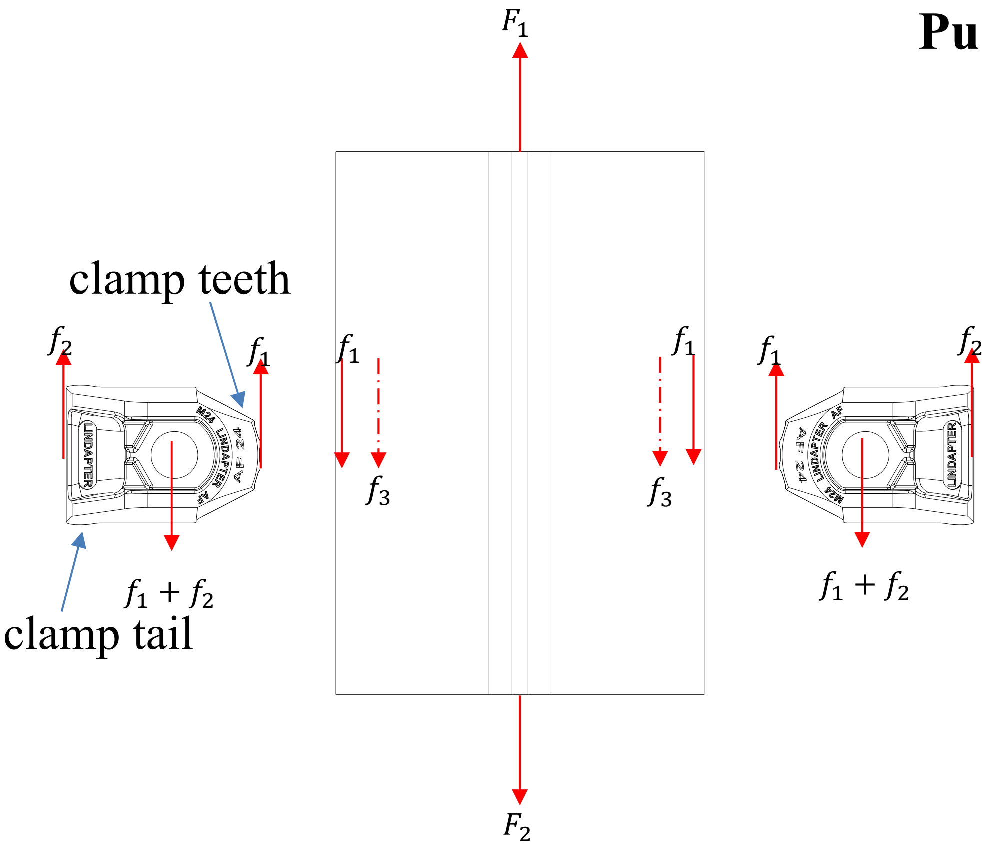


Test 4-M20-1C-RL

- The bolt tension reduction is insignificant at the serviceability of the beam specimens.
- The bolt tension reduction is greater for the center bolts than the end bolts.

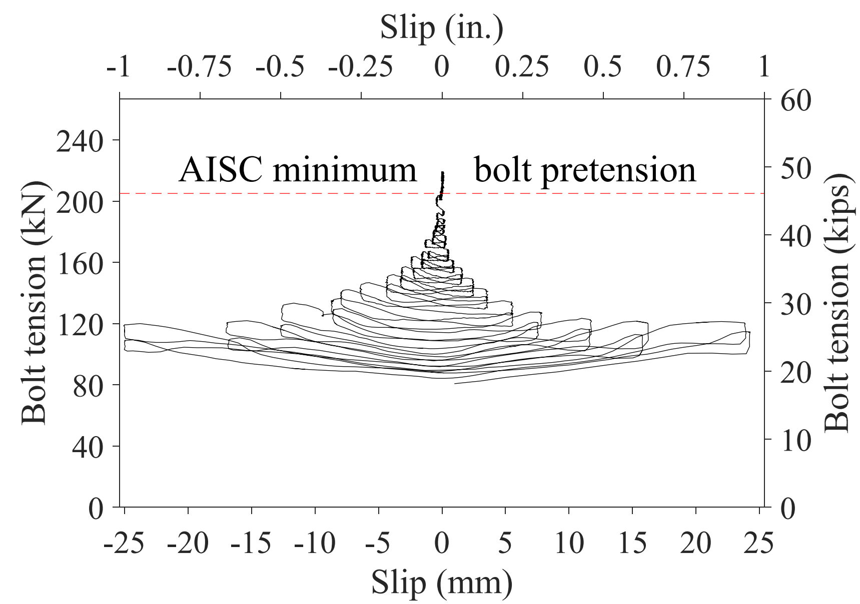
Bolt Tension Reduction

- High strength T-bolts are yielded after pretensioning.
- Shear force releases the axial deformation and tension of the bolts.



Free body diagram

Pushout Tests

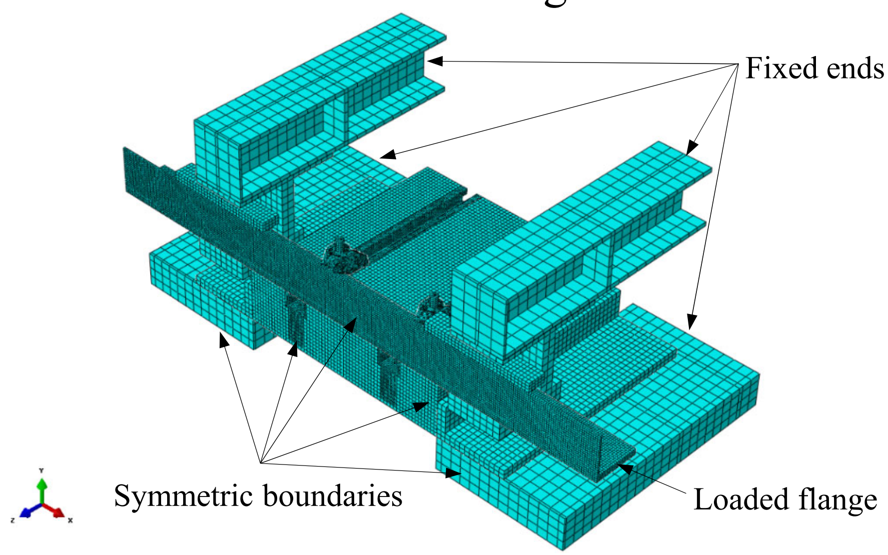


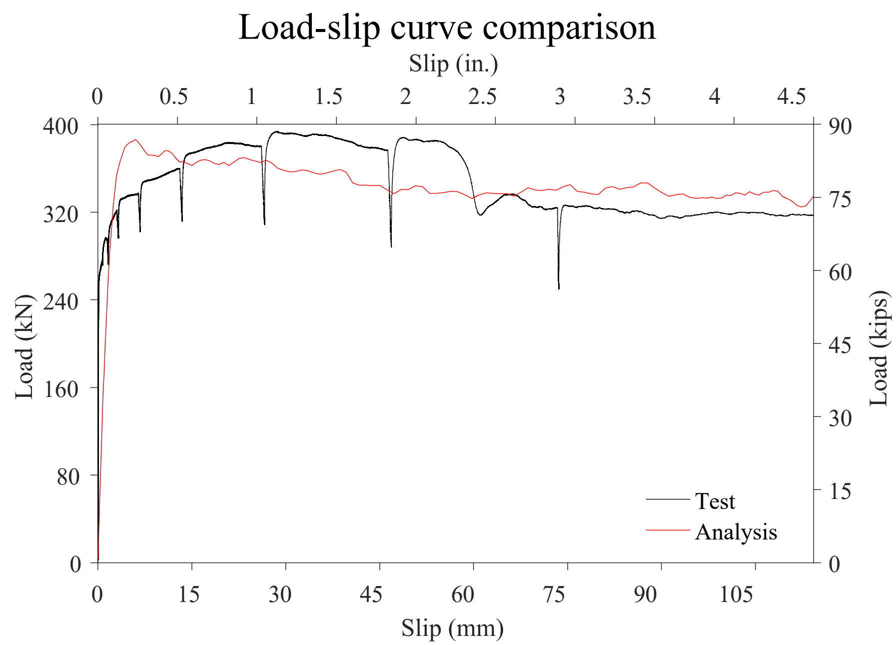
Pushout specimen C24-T4-RL

- The damage to the steel flange and clamp teeth in the cyclic pushout specimen releases the bolt tension.

Shear Strength of Clamping Connectors

- Bolt tension is distributed to clamp teeth and clamp tail.
- Bolt tension varies throughout the test.





Specimen:

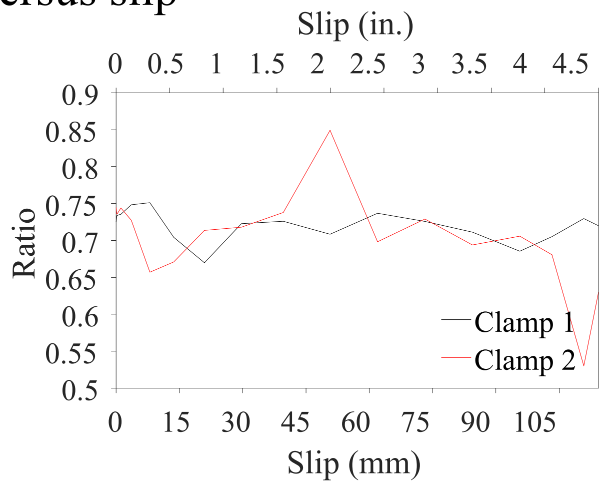
- Prior to slip, the shear resistance comes from static friction.
- After slip occurs, bearing, induced by clamp teeth digging into steel flanges, is another contributor to the shear resistance.

FEM:

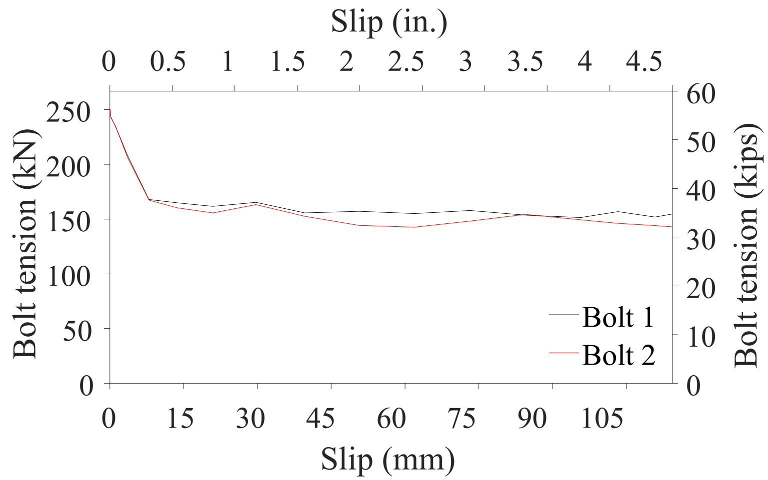
- A single frictional coefficient of 0.35 is assumed.

Design Recommendations

- Normal force at clamp teeth to bolt tension ratio versus slip



- Bolt tension versus slip



Monotonic shear strength design equation:

$$Q_p = k_d k_r \mu_p D_u T_b n_s$$

k_d and k_r= coefficients accounting for the portion of bolt tension transferred to the clamp teeth and the bolt tension reduction at peak strength, which are 0.70 and 0.67, respectively

μ_p= idealized frictional coefficient at peak strength, which is 0.35 in the pushout tests

D_u=1.13, a multiplier representing the ratio of the mean installed bolt pretension to the specified minimum bolt tension

T_b= minimum fastener tension given in AISC 360-16

n_s= number of slip planes, which is 2

Design Recommendations

Tested-to-predicted Strength Ratio for Pushout Specimens

Specimen	Tested strength kN (kips)	Predicted strength kN (kips)	Ratio
2-M24-T4-RH	98.3 (22.1)	76.1 (17.1)	1.29
3-M24-T4-RH-S	97.9 (22.0)	76.1 (17.1)	1.29
4-M24-T6-RH	96.5 (21.7)	76.1 (17.1)	1.27
5-M20-T4-RH	61.4 (13.8)	52.7 (11.8)	1.17

- The proposed design equation predicts the peak strength of the clamps conservatively.
- The difference mainly comes from D_u, which is about 1.30 in the pushout tests.

Cyclic shear strength:

- A coefficient of 0.8 could be used with the monotonic shear strength.

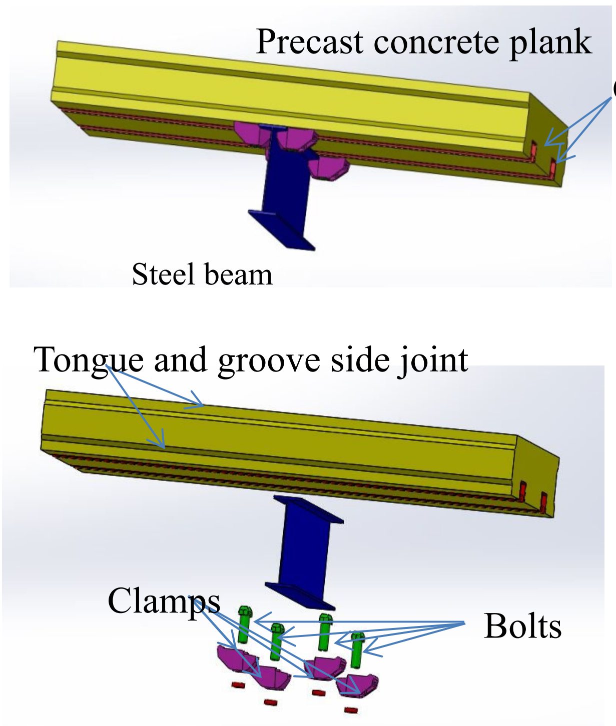
Deconstructable Composite Beams

- Elastic stiffness: could be conservatively estimated using a lower-bound moment of inertia
- Flexural strength: could be calculated using a rigid plastic design method
- Resistance factor: a factor of 0.9 is proposed for the flexural strength design equation in accordance with a reliability analysis

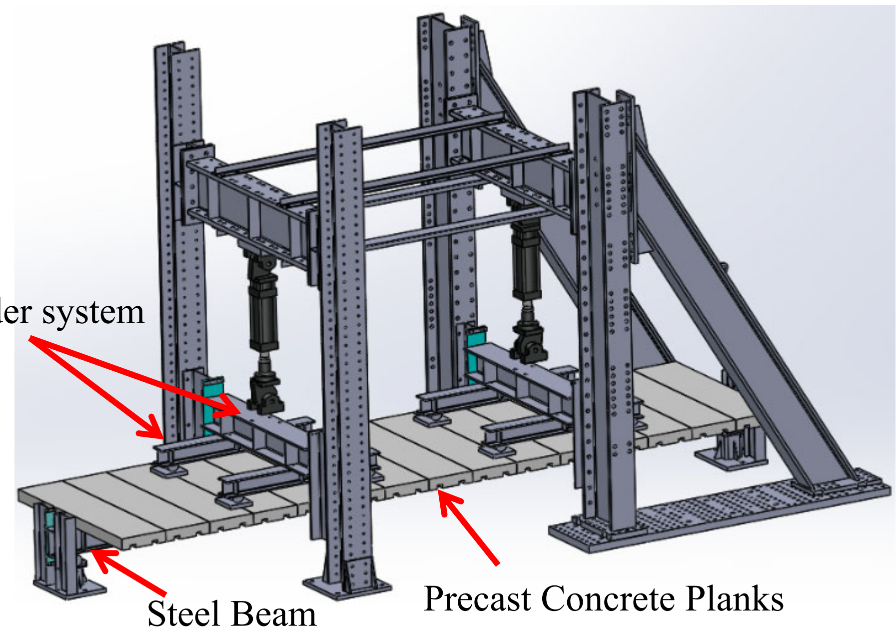
Conclusions

- A new deconstructable composite floor system is proposed to promote sustainable design of composite floor systems within bolted steel building construction through comprehensive reuse of all key structural components.
- 2 and 1.5 turns after a snug-tight condition are recommended for pretensioning the M24 and M20 bolts in the DfD plank system.
- The M24 clamps are highly robust under monotonic loading - compared to shear studs that fracture at much smaller slips (~8 mm), the clamping connectors can retain almost 80% of the peak strength even at 125 mm slip under monotonic loading.
- The strength of the M20 clamps declines quickly because the clamps are prone to rotate as the beam moves. Nonetheless, the slip at which the curve starts to descend is much larger than the slip demand on the clamping connectors in composite beams.
- The clamps could be utilized to connect composite diaphragms and collector beams due to their excellent energy dissipating capacity.
- All the beams deflected to L/25 and behaved in a ductile manner. The tested flexural strength of the beams is close to that predicted by the AISC design equations. The stiffness of the specimens is slightly underestimated by a lower-bound moment of inertia.
- Bolt tension reduction induced by shear force is insignificant at the serviceability of the beams and generally stayed above minimum bolt pretension at ultimate load; further study is needed for cyclid loading

Thank You



Deconstructable composite beam prototype



Composite beam test setup

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