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DIAPHRAGM BEHAVIOR OF DECONSTRUCTABLE COMPOSITE FLOOR SYSTEMS

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Laboratory for Structural Testing of Resilient and Sustainable Systems

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Engineering of Structures and Building Enclosures

Introduction

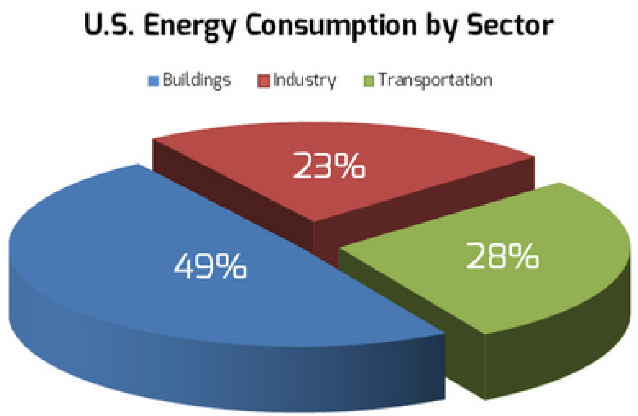
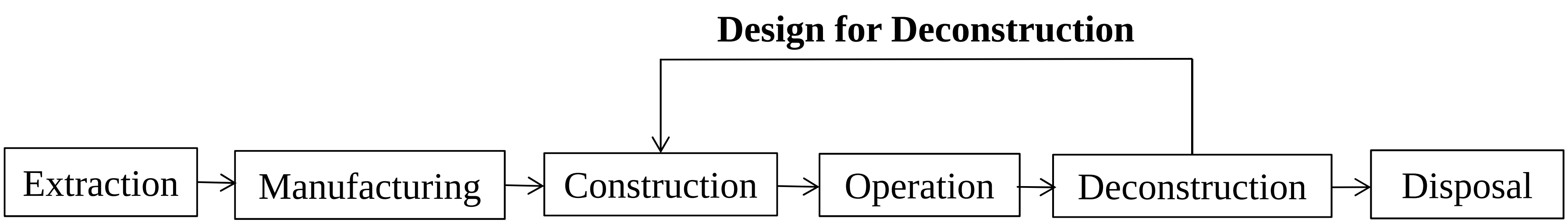


Image from US Energy Information Administration (2011)

Sustainable Buildings

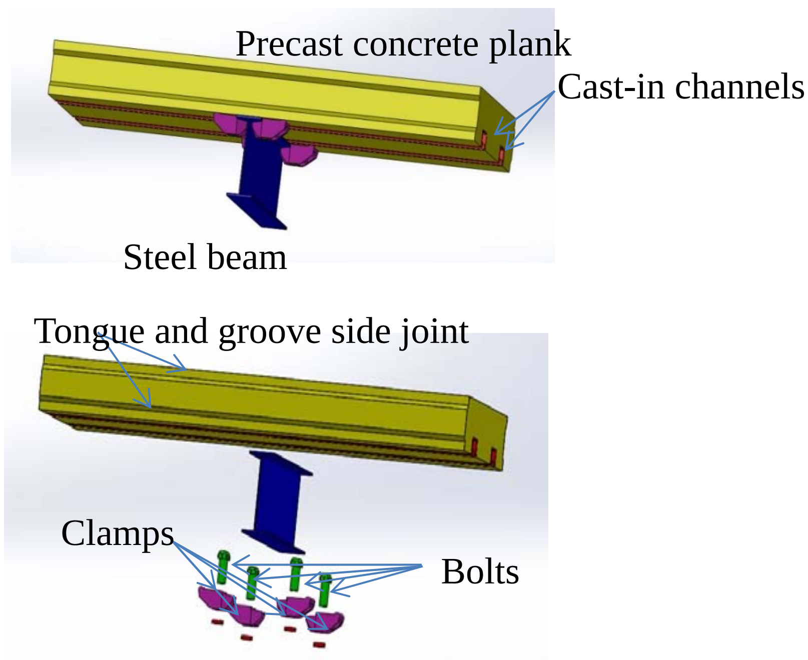
- Material manufacture
  - Environmentally friendly, renewable and low embodied energy materials
- Use phase
  - Efficient heating, ventilating and lighting systems
  - Adaptation or reconfiguration
- End of life
  - Minimum amount of waste and pollution
  - Reusable and recyclable materials

Material Flow of Current Buildings

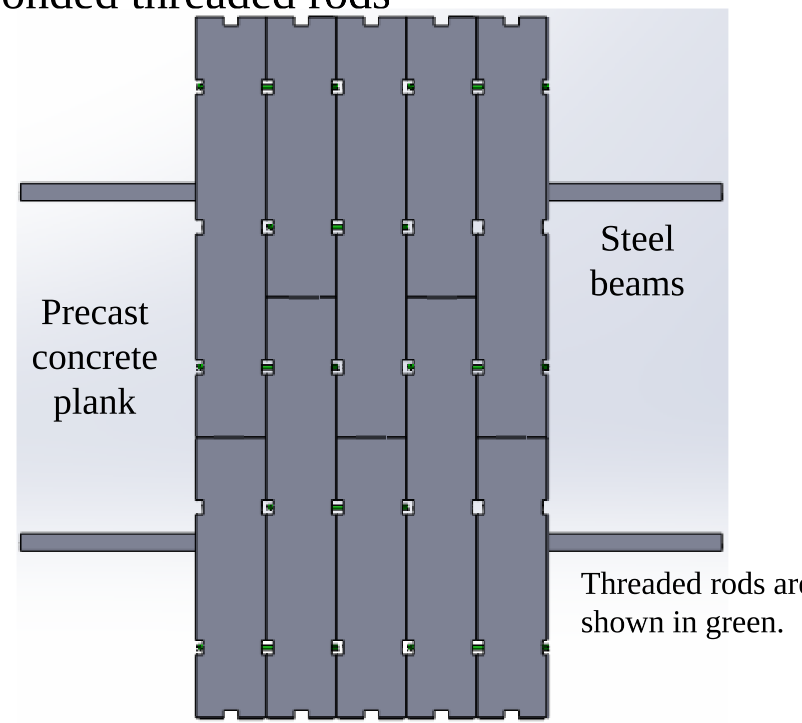


Composite Floor System

- Conventional composite floor systems are cost-effective solutions for multi-story buildings
- The integration of steel beams and concrete slabs limits separation and reuse of the components
- Proposed DfD System
  - Clamp precast planks to steel beams/girders in a steel framing system
  - Connect adjacent precast planks using unbonded threaded rods



Deconstructable composite beam prototype

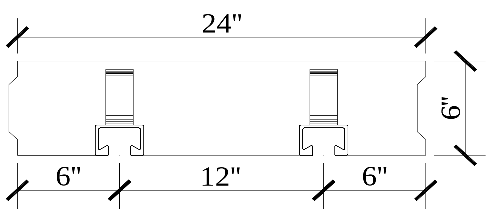


Precast concrete plank connections

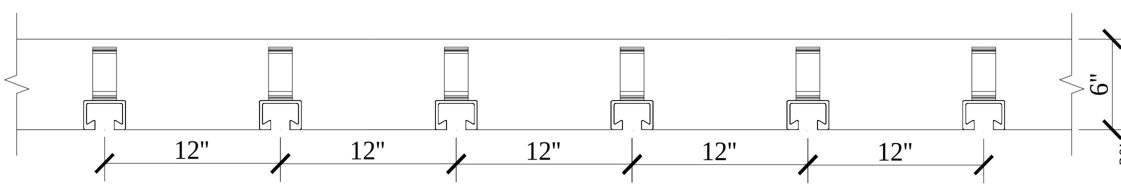
DfD Floor System

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

Future: Planks stocked in different sizes and concrete strength for ready use, comparable to how steel is currently stocked at supply centers

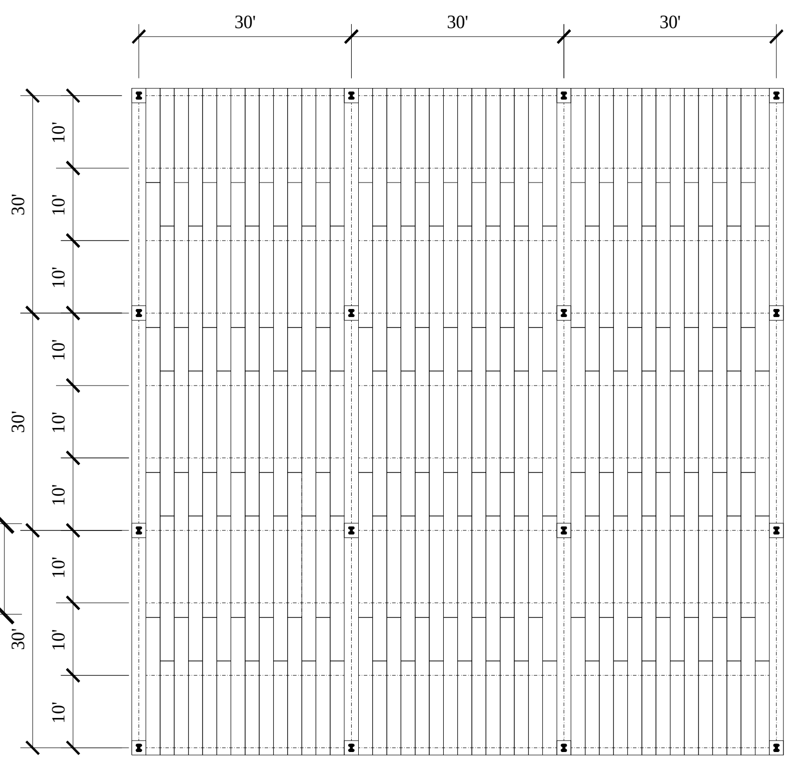


a) Plank perpendicular to the steel beam



b) Plank parallel to the steel girder

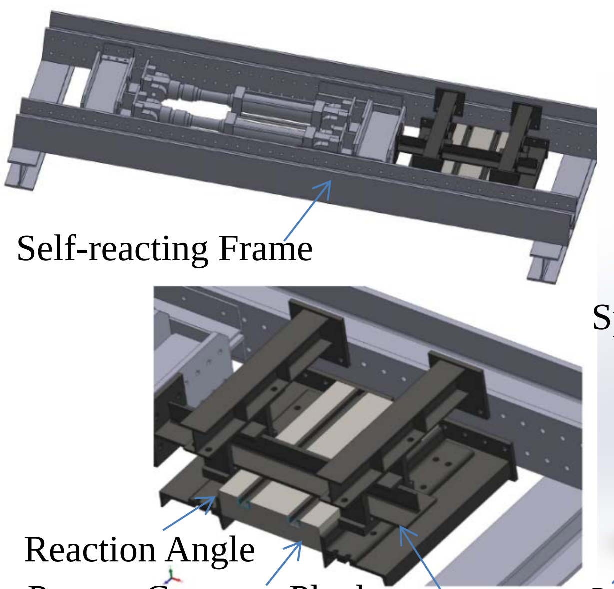
Precast concrete plank cross section



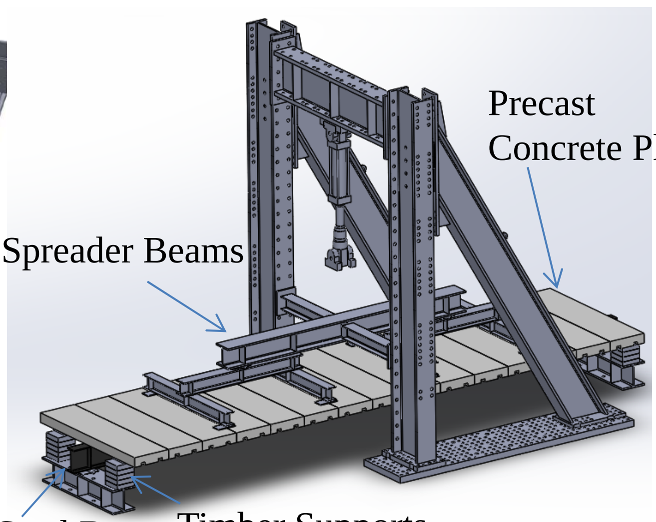
Typical floor plan for DfD system

Test Program

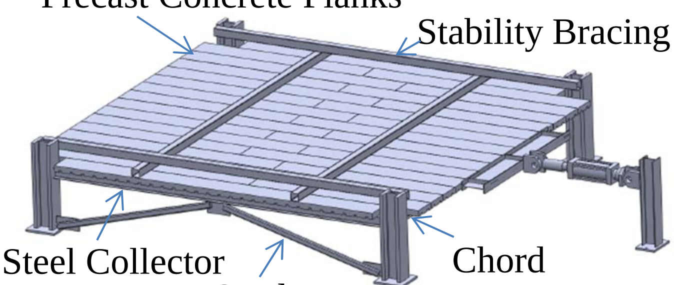
- Pushout tests: Evaluate a wide range of parameters and formulate strength design equations for the clamping connectors
- Beam tests: Study the clamp connector behavior and associated composite beam strength and stiffness for different levels of composite action
- Diaphragm tests: Investigate the in-plane seismic behavior of the deconstructable composite floor system



Pushout Test



Beam Test



Diaphragm Test

State-of-the-Art Research on Composite Diaphragms

Sabelli, R., Sabol, T. A., and Easterling, W. S. (2011).“Seismic Design of Composite Steel Deck and Concrete-filled Diaphragms” NEHRP Seismic Design Technical Brief No.5
Sabelli R., Pottebaum, W., and Dean, B. (2009). “Diaphragms for Seismic Loading,” Structural Engineer

Diaphragm Functions

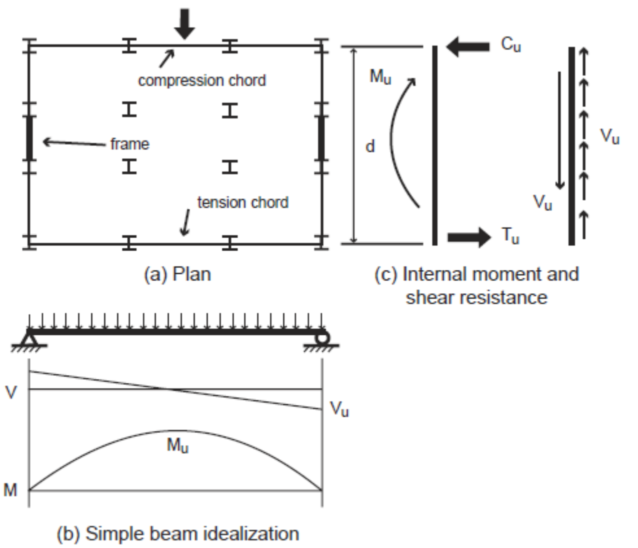
- Transfer inertia forces within the floor systems to seismic force-resisting systems
- Support gravity loading and provide lateral supports to vertical elements
- Resist out-of-plane forces developed by exterior walls and cladding
- Redistribute loads around openings and forces due to torsion

Diaphragm Components

- Diaphragm slab (bare steel deck or composite slab)
- Chord
- Collectors (also known as drag struts)
- Connectors (shear studs, arc-spot welds, screw, etc.)

Seismic Demand on Diaphragms

- Lateral seismic force F_x
- Diaphragm design force F_{px}
- Transfer force due to discontinuity in the vertical elements



Deep Beam Idealization
(Image from Sabelli et al. 2011)

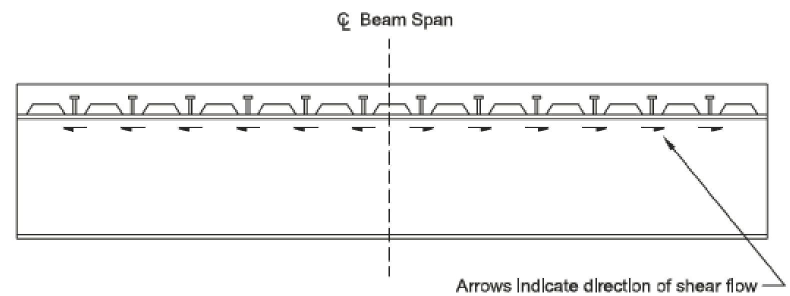
Component Design

- *Composite Deck*
  - Two design equations available for assessing the in-plane shear strength.

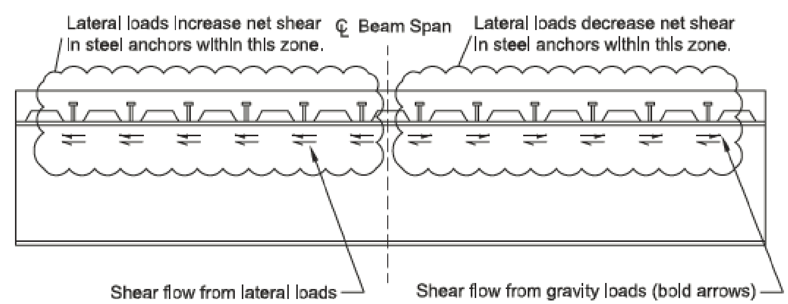
$V_n = 3.2\, t_e\, b \sqrt{f'_c}$ Easterling and Porter (1994)

$S_n = BQ_f / L + kbd_c\sqrt{f'_c}$ SDI DDM03

- *Shear Transfer*
  - Reduced demand from live load when in-plane forces are maximum
  - The direction of shear flow is not uniformly additive



(a) Shear flow due to gravity loads only



(b) Shear flow due to gravity and lateral loads in combination

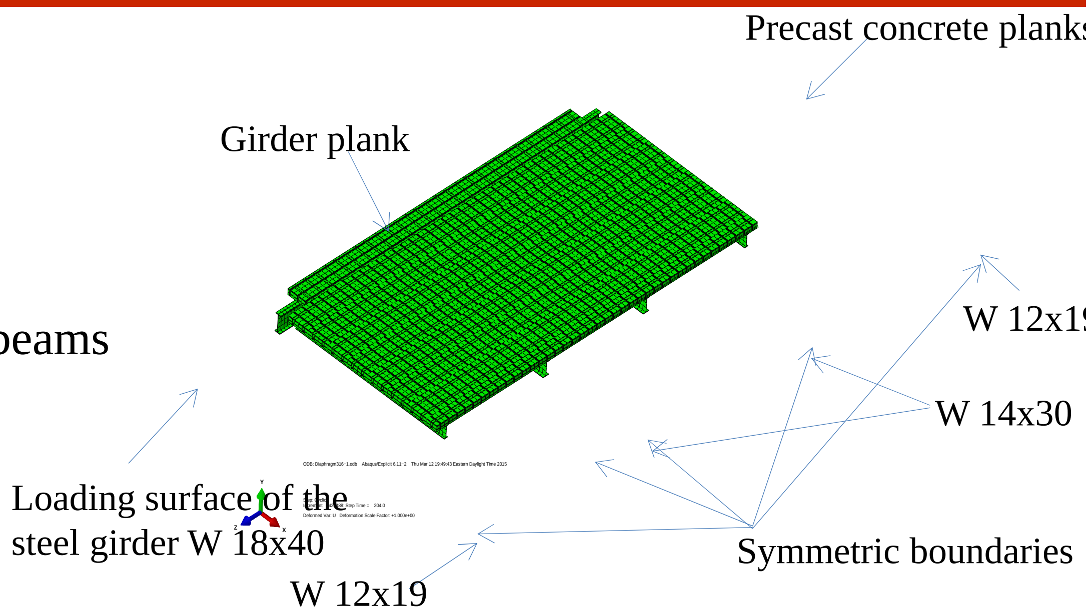
Shear flow at collector beams
(Images from AISC 360)

- *Collectors and Chords*
  - Composite beam-columns, which behave non-compositely under axial forces and compositely due to flexure
  - A minimum level of 25% composite action is required, even when these members are designed non-compositely
  - Beam-to-column connections will be designed for the combined effects delivered to the connection

Diaphragm Behavior

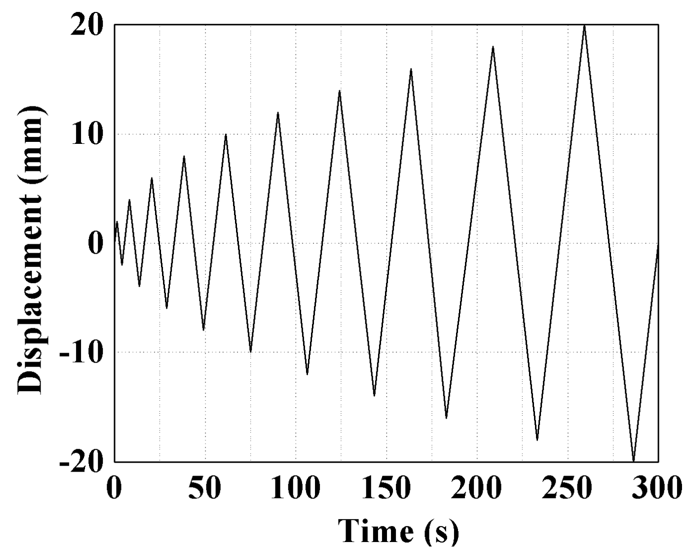
Finite Element Model

- Half of a 30 ft. by 30 ft. diaphragm
- Steel chords: W 12x19 and W 14x30
  - Designed as partially composite beams
- Steel collector: W 18x40
  - Designed as part of the LFRS
- No reinforcement in precast planks



Loading Process

- Compression between planks: define pressure on side surfaces of the diaphragm slab
- Pretension in bolts
  - Assign a thermal coefficient to the bolt shanks
  - Decrease the temperature to create thermal shrinkage and generate tensile forces
- Steel beam loaded in the axial direction using displacement control



Loading history

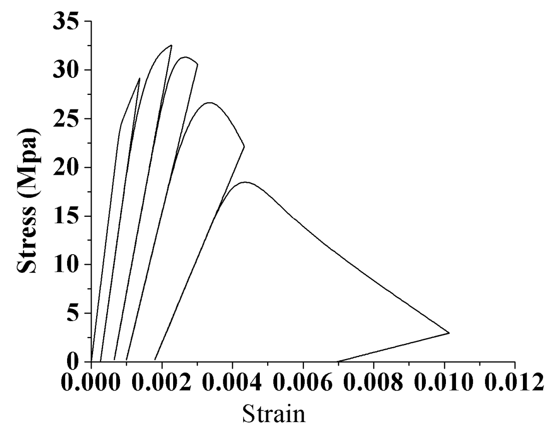
Material Constitutive Model

- Concrete damaged plasticity model, 28 MPa normal weight concrete
  - Failure mechanism: tensile cracking and compressive crushing
  - Capture stiffness recovery due to crack opening and closing under cyclic loading
  - Compressive stress-strain curve in the Eurocode is employed in the analysis
  - Stress-displacement relationship is defined for tensile stiffening to eliminate mesh dependency
- Steel beam and cast-in channels: elastic-perfectly-plastic material
  - Yield stress: 345 MPa
- Bolts: A325 bolts (Grade 8.8 bolts)
  - No failure criteria is defined

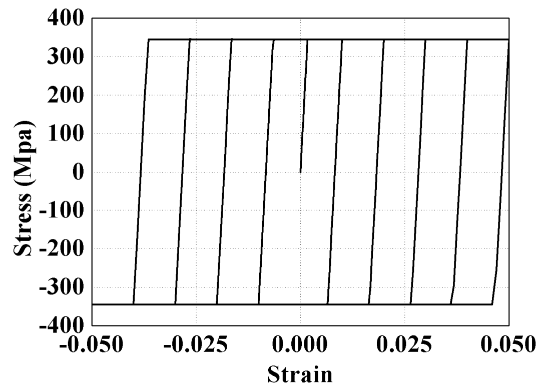
$$\frac{\sigma_c}{f_{cm}} = \frac{k\eta - \eta^2}{1 + (k-2)\eta}$$

$$E_{cm} = 22\left[\frac{f_{cm}}{10}\right]^{0.33}$$

Concrete compressive stress-strain curve



Concrete cyclic compression response

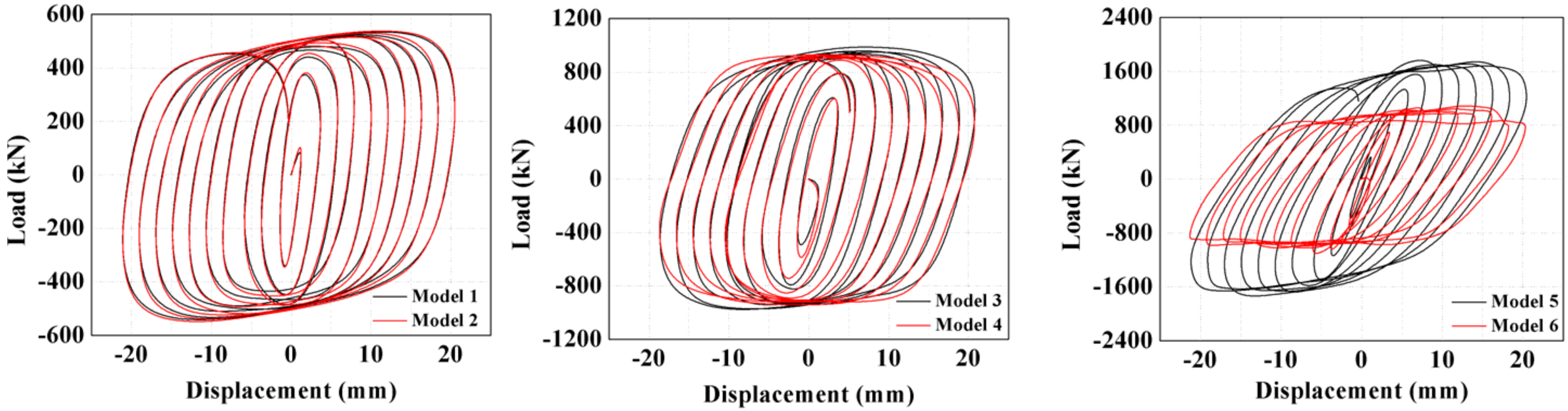


Steel material cyclic behavior

Computational Models

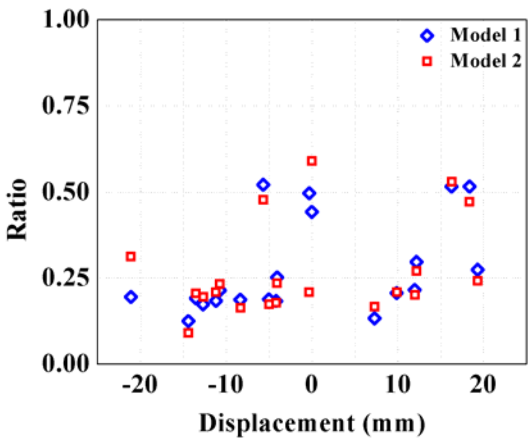
Model Number	Compressive stress (MPa)	Number of shear connectors on girder	Limit states
1	1.5	28 (32% composite)	Joint sliding
2	1.5	20 (23% composite)	Joint sliding
3	3.0	28	Joint sliding
4	3.0	20	Joint sliding
5	6.0	28	Slip of clamps
6	6.0	20	Slip of clamps

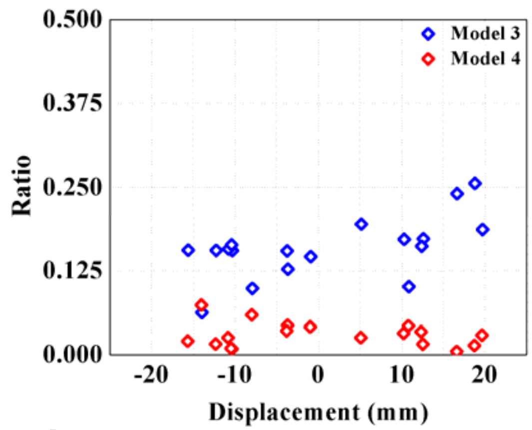
Load-Displacement Relationship

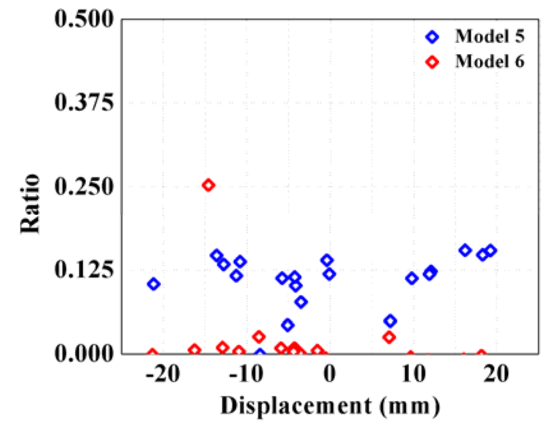


Load Distribution Between Concrete Slab and Steel Framing

- Load distributes between the concrete slab and steel framing, following the stiffest load path.

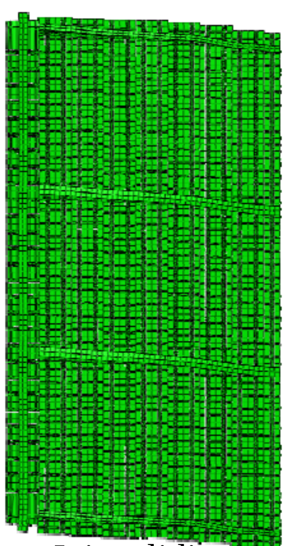




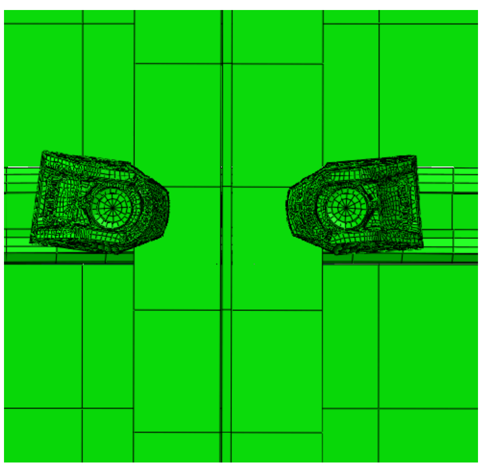


Steel moment to concrete moment ratio

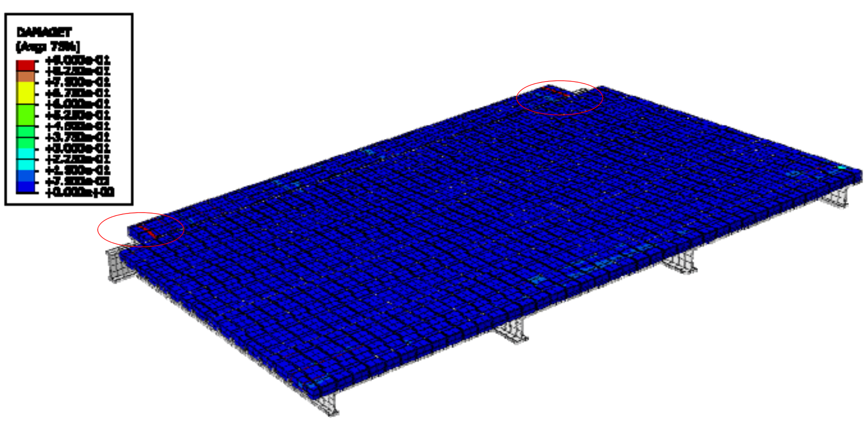
Limit States Observed



Joint sliding



Rotation of clamps



Localized concrete damage

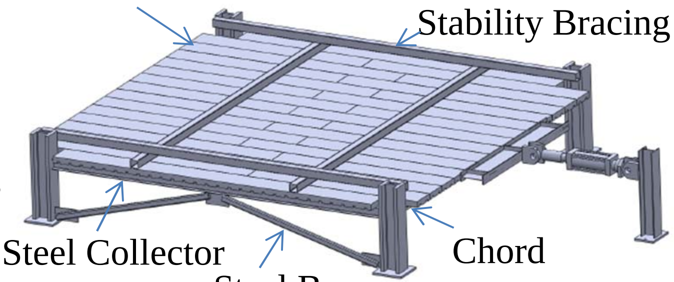
Comparison with a Cast-in-place Composite Diaphragm

Easterling, W. S., & Porter, M. L. (1994). Steel-Deck-Reinforced Concrete Diaphragms. I. Journal of Structural Engineering

- **Failure Modes**
  - Cast-in-place: Brittle inelastic behavior, which could be attributed to the absence of reinforcement in the slabs
    - Diagonal tension cracking in concrete
    - Concrete failure around the shear studs
  - DfD: Ductile behavior with no strength and stiffness degradation
    - Joint sliding between adjacent planks
    - Relative slip between steel girder and girder plank
    - Joint opening, another potential limit state in precast concrete floor systems, does not occur
- **Ultimate Strength**
  - Cast-in-place: $V_n = 3.2\, t_e\, b \sqrt{f'_c}$
    Assume: f_c'= 28 Mpa; t_e= 121 mm
    Diagonal tension strength: 168 kN/m
  - DfD: The strength varies from 58.6 kN/m to 194.7 kN/m for the FE models

Conclusions

- A new deconstructable composite floor system, consisting of steel framing, precast concrete planks and clamping connectors, is proposed to promote sustainable design of composite floor systems within bolted steel building construction through comprehensive reuse of all key structural components.
- The in-plane seismic performance of the DfD system will be investigated through composite diaphragm tests, complemented by pushout tests and composite beam tests to determine the strength and ductility of the clamping connectors and the flexural behavior of the system.



Diaphragm Test

- The diaphragm strength in analyses was strongly related to the magnitude of the normal stress generated by the connections. When the planks are firmly clamped, the diaphragm strength was governed by the number of clamps between the steel girder and girder plank rather than by sliding between the planks.
- Contrasting with the brittle behavior exhibited by the conventional composite diaphragms, the DfD systems behaves in a ductile manner, and the ultimate strengths were comparable to those of the cast-in-place composite diaphragms.

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