SEISMIC STRUCTURAL COMPONENTS

Dr. Robert B. Fleischman
University of Arizona
24 September 2019
Presentation Outline

- Grand Challenges in Earthquake Engineering Structural Research
- Approaches for Integrating Physical Experiments & Computer Simulation using NHERI resources
- Example Projects: Seismic Design of Horizontal Elements
  - Case Study 1: NSF GOALI: Development of a Seismic Design Methodology for Precast Floor Diaphragms (DSDM)
  - Case Study 2: NSF NEES: Inertial Force-Limiting Anchorage Systems (IFAS)
  - Case Study 3: NSF ENH: Development of New Knowledge for Steel Seismic Floor and Roof Collectors
Grand Challenges in Earthquake Engineering Structural Research
The NHERI Five-Year Science Plan identifies three Grand Challenges:

Three Grand Challenges

- Identify and quantify the characteristics of earthquake, windstorm, and associated hazards — including tsunamis, storm surge, and waves — that are damaging to civil infrastructure and disruptive to communities.

- Evaluate the physical vulnerability of civil infrastructure and the social vulnerability of populations in communities exposed to earthquakes, windstorms, and associated hazards.

- Create the technologies and engineering tools to design, construct, retrofit, and operate a multi-hazard resilient and sustainable infrastructure for the nation.
Grand Challenges in Earthquake Engineering

1. **Community Resilience Framework**: interactive comprehensive framework for measuring, monitoring, and evaluating community resilience at different scales

2. **Decision Making**: decisions based on a clear understanding of the built environment, simulation-based decision-making strategies. State-of-the-art decision-making tools for more efficient resource allocation based on comparing different strategies for earthquake mitigation

3. **Simulation**: knowledge of the inventory of infrastructure, scalable tools. Powerful simulation technologies to model the time and spatial impacts of a seismic event from the component to the regional scale

4. **Mitigation**: strategies to measure, monitor, and model community vulnerability to establish mitigation strategies. Better approaches for retrofit of the built environment’s most vulnerable sectors

5. **Design Tools**: emerging sustainable materials and innovative structural concepts to significantly change the way infrastructure is designed and constructed, integrated with design tools that could dramatically improve earthquake resilience. Harness the power of performance-based earthquake engineering (PBEE).

## Grand Challenges in Earthquake Engineering

<table>
<thead>
<tr>
<th>Dimension (Breakout Group)</th>
<th>Grand Challenge Problem</th>
<th>OVERARCHING CHALLENGES</th>
<th>GRAND CHALLENGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community Resilience</td>
<td>1. Framework for Measuring, Monitoring, and Evaluating Community Resilience</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>2. Motivating Action to Enhance Community Resilience</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pre-event Prediction and Planning</td>
<td>3. Develop a National Built Environment Inventory</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Design Infrastructure</td>
<td>4. Multi-Scale Seismic Simulation of the Built Environment</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>5. Integrated Seismic Decision Support</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>6. Risk Assessment and Mitigation of Vulnerable Infrastructure</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>7. Protect Coastal Communities</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>8. Regional Disaster Simulator</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Post-event Response and Recovery</td>
<td>9. High Fidelity Simulation</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>10. New Sustainable Materials and Systems for Earthquake Resilience</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>11. Harnessing the Power of Performance Based Earthquake Engineering (PBEE) to Achieve Resilient Communities</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Figure from Proposed NEES2 Science Plan, 2015-2019
Fleischman, Deierlein, Mahin, Kijewski, Leon, Frost.
Experimental research in earthquake engineering has shifted from isolated characterization testing of existing structural components:

- System Behavior & System Interactions
- Vulnerable or Poorly Understood Systems
- New Materials and Processes
- Low Damage, Protective and Smart Systems
- Non Structural Components and Contents
- Sensors and Monitoring
- Risk Assessment and Hazard Mitigation
- Multi-Hazard, Multi Scale Investigations
- Special Structures
Complex System Behaviors:

• Tall Buildings
• Discontinuities (e.g. Transfer Conditions)
• Diaphragm action, Tie Structures
• Structural Irregularity in Plan, Vertical Offsets
System Behavior and System Interactions

- **System Interactions:**
  - Seismic Force Resisting System (SFRS) – Gravity Load Resisting System (GLRS) coupling
  - Soil-Structure-Foundation Interaction
  - Axial Force Interactions:
    - Gravity Load,
    - Overturning
    - Vertical Acceleration

(EERI 2011)
Photo: Sritharan
(Elwood 2011)
Vulnerable or Poorly Understood Systems

- Near Collapse Behavior
- Identifying "Killer" Buildings
- Underdesigned or Failure Critical
- Complex Response:
  - e.g. Infills

Department of Building and Housing, Canterbury Earthquake Royal Commission
New Materials and Processes

- Polymer concrete, Ductile concrete
- Self-healing materials and systems
- High Performance Materials
- 3D Printed Components
- 3D Printed Concrete
- New materials being used for sustainability:
  - Recycled / upcycled materials
  - Energy efficient materials, high albedo, thermal mass, etc.
Protective Systems, Low Damage Systems

- Innovative Devices and Structures
  - Active, Semi-Active, Passive
  - Negative Stiffness Devices, Energy Sinks
  - Self Centering
  - Low Damage Systems
  - Protective Systems
  - Semi-Active Cladding Systems
  - New Devices, New Systems
Non Structural Components and Contents

- Stairs, Elevators
- Cladding, Glazing
- Mechanical Systems
Special Structures

- Lifelines: Water, sewer, gas, electric
- Wind Turbines
- Rooftop Solar
- Power Substations
- Marine structures, Ports, Piers
- Control Towers
Risk Assessment and Hazard Mitigation

- Fragility of structures in aftershocks after damage in the mainshock
- Monitoring, sensors networks

(Maffei, et al., 2008 EQ Spectra)

Collapse after June 2011 aftershock
(Kam, Pampanin & Elwood, 2011)
Grand Challenges

Grand Challenges are Evolving

• Construction methods are perpetually changing based on new knowledge, new materials, new manufacturing processes
• Some new methods are introduced directly for resilience; while others may be necessitated by sustainability needs, shifting demographics, limited resources or economic constraints
• These new materials and techniques require evaluation on a system basis
Research Tools are Evolving

New Testing Capabilities:
  • e.g. NHERI UCSD 6-DOF Shake Table

New Simulation Tools:
  • e.g. SimCenter quoFEM – PBE work flows

Emerging Testing techniques using existing NHERI or other facilities:
  • e.g. Hybrid shake table testing method,
  • Nonstructural demand simulators, fault displacement effects
  • real time hybrid testing of axially stiff systems,
  • soil-foundation testing at larger scales (e.g. soil box)

New Measurement Techniques
  • e.g. DIC, etc.
Approaches for Integrating Experiments & Simulation
SWOT of Physical Experiments & Simulation

**Laboratory Testing**

Ability to straightforwardly characterize components and subassemblies from the elastic range to ultimate limit states under well-defined loading and measurement

**Shake Table Testing**

Ability to examine system behavior, including the ability to generate realistic inertial force paths and realistically enforce distributed boundary conditions

**Comp. Simulation**

Ability to cost-effectively evaluate and comprehensively measure many scenarios, design parameters, and loading conditions, without *physical* limitations on model size.
Grand Challenges

- PBEE
- Community & Regional Resilience
- Societal and Economic Impacts
- Simulation, Monitoring
- NHERI EFs
- Geoscience (e.g. SCEC), Simulation, Ground Motion Scaling, etc.
An Approach for Integrating NHERI EFs & SIM

- Component Tests
- Sub-assemblage Tests
- System Tests

Build Models → Calibrate Models → Validate Models

Plan & Design

Data Sets → Validated Models → Parametric Studies
Case Studies
Illustrative Topic: Horizontal Elements

Horizontal Elements
• How behave? How interact? Failure critical?
• Force Demands (Restrepo, Rodriguez)
• Vertical Compatibility (Sritharan, Henry)
• Big Box Rigid-Wall Flex Diaphragm (Koliou, Filliatrault)
• Flexible unfilled metal deck (Tremblay)
• Steel diaphragms (Schafer, Eatherton, Hajjar, Easterling)
• Composite Systems (Gravity Load, Moment Frame)
• Disproportionate Collapse (Main, Sadek, Fahnestock, etc.)
• Fire (NIST, Choe etc.)
Example Projects

Example Projects: Seismic Design of Horizontal Elements

• Case Study 1: NSF GOALI: Development of a Seismic Design Methodology for Precast Floor Diaphragms (DSDM)

• Case Study 2: NSF NEES: Inertial Force-Limiting Anchorage Systems (IFAS)

• Case Study 3: NSF ENH: Development of New Knowledge for Steel Seismic Floor and Roof Collectors
Project Case Studies: Characteristics

• Multi-University Research Projects
• Lehigh & UCSD co-PIs and Grad Students
• Full- or Large-Scale Testing
• Strong Simulation Component
• Design Consultant Oversight
• Industry Partners
• General Topic: Floor Systems
Laboratory simulations and tests enabled by the **NHERI Lehigh EF** include:

1. **Hybrid simulation (HS)**
2. Geographically distributed hybrid simulation (DHS)
3. Real-time hybrid earthquake simulation (RTHS)
4. Geographically distributed real-time hybrid earthquake simulation
5. **Dynamic testing (DT)**
6. **Quasi-static testing (QS)**

Laboratory simulations and tests enabled by the **NHERI@UCSD EF** include:

1. **Shake Table Testing**
2. Blast Simulator
Project Case Studies: NHERI EF Usage

- **Lehigh Testing Program used for:**
  - Component Characterization
  - Analytical Model Construction
  - Prototype Development
  - Guidance for Large Scale System Tests

- **UCSD Testing Program used for:**
  - System Level Experiments
  - Model Validation
  - Demonstration of Concept
Project 1: NSF GOALI - DSDM

Development of a Seismic Design Methodology for Precast Floor Diaphragms (DSDM) 2005-2009
DSDM Research Team

University of Arizona
Robert Fleischman
Consortium Leader

University of California
San Diego
Jose’ Restrepo, PI

Lehigh University
Clay Naito, PI
Richard Sause, Co-PI

Industry Liaison
S. K. Ghosh, Co-PI

DSDM Task Group

Producer Members

Producer Members

Industry Advisory Panel

Graduate Students: Dichuan Zhang, Ge Wan, M. Mielke, A. Mullenbach (UA)
Matthew Schoettler, Andrea Belleri (UCSD)
Ruirui Ren, Liling Cao (LU)
Precast Concrete Diaphragms

Diaphragm action carries seismic forces horizontally in the floor slab to walls and frames…

Precast floor diaphragms have shown a vulnerability in past earthquakes…
Research Challenges: Precast Concrete Floor Diaphragms

- Vulnerable System
- Poorly known Capacities
- Poorly known Demands
- Absence of Applicable Design Rules
- Complex Dynamic Response
- Complex Load Paths
- Complex Boundary Conditions
Research Objective: Precast Concrete Floor Diaphragms

- Characterize the precast diaphragm reinforcement/connectors
- Develop and validate reliable nonlinear dynamic models for structures with precast diaphragms: including diaphragm flexibility and diaphragm limit states
- Enable direct measurements of force and deformation demands on precast diaphragm connectors
- Perform extensive parameter studies examining capacity and demand
- Develop and codify new design provisions
Rationale for Large Scale Laboratory Testing

• Rationale for laboratory testing:
  • Limited information existed on the characteristics of precast diaphragm connectors
  • No information on the response of precast diaphragm connectors under non-proportional shear and tension
  • No models existed for the nonlinear or non-ductile response of precast floor diaphragm systems

• Rationale for ATLSS Laboratory:
  • Ability to create multi-axis control for cyclic shear, tension/compression, and positive/negative moment
  • Ability to perform hybrid testing to develop realistic combinations of force, and adapt as the joint and connectors degrad.
Rationale for Large Scale Shake Table Testing

• **Rationale for shake testing:**
  
  • Boundary Conditions of a distributed system such as a diaphragm do not lend themselves to concentrated actions (e.g. from actuators)
  
  • Finite Element Analysis can produce realistic boundary conditions, but calibrated models are required for code change.

• **Rationale for NEES@UCSD Shake Table:**
  
  • Scaling of precast elements, reinforcement and connectors has lower limit of 1/3\textsuperscript{rd} to ½ scale before testing details become “toys”
  
  • Observed diaphragm failures in precast diaphragms have historically occurred in longer span floor decks
Research Flow

Structure Level (UCSD)
- Diaphragm Inertial Forces
- Flexible Diaphragm Structures

Diaphragm Level (UA)
- Diaphragm Capacity
- Diagram Load Paths & Limit States

Detail Level (LU)
- Connector Properties
- Connector Classification
Shear Connector Model Calibration

Cyclic response

- TEST
- Model

V (kips)

-0.6 -0.4 -0.2 0 0.2 0.4 0.6

δv (in)

-20 -10 0 10 20

Natator
Diaphragm Analytical Models

“Discrete Connector”
FE models

Ramp Cavity

Nonlinear coupled springs and contact elements
Nonlinear Dynamic Analysis
Test Substructure: Panels at Critical Joint
Lehigh MDOF Test Fixture

(a) Plan View

(b) Side elevation

229 mm 67 mm 51 mm 381 mm 330 mm

4.88 mm (16')

WWR 305x915

-MD83xMD29

(16')

140 mm

7 Anchor holes @ 610 mm = 3.66 m

2 spaces @ 54 = 108 mm

(b) Scale elevation

3 JVIs @ 610 mm

(c) Photo

Teflon plates

3 JVIs @ 610 mm

457 mm

305 mm

305 mm

457 mm

ACT1

ACT2

ACT3

Fixed support

Movable support

Fixed support

Framing angles

Fixed support

Specimen panel A

Specimen panel B

Framing angle

Fixed support

2 # 4 bars Flange

UP FOR UP FOR UP FOR UP FOR

1.22 m

7.62 m

4.88 m

5.17 m

1.37 m

5.17 m

4.88 m

1.37 m

(a) Plan view

(b) Section A-A

NHERI Lehigh Joint Researcher Workshop w/ UCSD & SimCenter, 23-24 September, 2019
Predetermined Displacement History Tests

Fig. 11. Instrumentation layout

Fig. 12. DOF and force transformations: (a) FE model; (b) test specimen; (c) deformed shape; (d) free body diagram
Table 2. Test Sequence

<table>
<thead>
<tr>
<th>Test</th>
<th>Earthquake</th>
<th>Intensity</th>
<th>Direction</th>
<th>Test panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDH 1</td>
<td>Charleston (CH)</td>
<td>SVC</td>
<td>Transverse</td>
<td>South</td>
</tr>
<tr>
<td>PDH 2</td>
<td>Charleston (CH)</td>
<td>DBE</td>
<td>Transverse</td>
<td>North</td>
</tr>
<tr>
<td>PDH 3</td>
<td>Charleston (CH)</td>
<td>MCE</td>
<td>Transverse</td>
<td>South</td>
</tr>
<tr>
<td>PDH 4</td>
<td>Charleston (CH)</td>
<td>DBE</td>
<td>Bidirectional (Bi)</td>
<td>North</td>
</tr>
<tr>
<td>PDH 5</td>
<td>Berkeley (BK)</td>
<td>MCE</td>
<td>Transverse</td>
<td>South</td>
</tr>
</tbody>
</table>

Fig. 5. Reinforcement: (a) connector shear; (b) top chord tension; (c) bottom chord
PDH Test Response
PDH Test Results: Flexure

- Minor Cracking
- Weld Fracture
- Major Cracking/Crushing

CH DBE

CH MCE

BK MCE
Critical Shear Joint: Hybrid Test

DT units: Plane stress elements

Precast spandrel: 2D beam element

Symmetry boundary

Global CS joint (See Fig. 8a)

Base plastic hinge: Bi-axial fiber elements

Nonlinear shear springs

Nonlinear springs & contact

Shear wall: Shell element

Nonlinear rotational spring

Floor: 2D beam

Nonlinear spring & contact
Lehigh Test Algorithms: Hybrid Testing

Hybrid Testing:
- Matlab based program
- Alpha method with fixed number of iterations (Mercan and Ricles 2005)
- Restoring force provided by RDOF Model (ANSYS)
- Actuator displacement commands ($\Delta_1$, $\Delta_2$, $\Delta_3$) controlled through a multiple loop architecture
- Inner loop iterates for kinematic compensation of three actuator system
Test Results: Hybrid Testing

(a) 400
(b) 100

Kv (kN/mm)

N (kN)

Hybrid test

Step
Practical Considerations

Proposal Planning

extends 15.5 ft each side
25 ft wide platen
Practical Considerations

Proposal Planning

7” thick, in situ concrete topping for stiff and strong diaphragm

outriggers to provide counterbalance weight to resist overturning… sliding on

pre-compressed hydrostatic slider bearings on mirrored-finish stainless-steel plates
Shake Table Demonstration Test
Analytical Simulation

Diaphragm Force

Diaphragm deflection

Time (s)

F (k)

D (in)

Test
Prediction

3rd floor
DSDM Project Outcome

- **Deliverable**: A new seismic design methodology for precast concrete diaphragms.
- **Outcome**: New design provisions approved for inclusion in **ASCE 7-16** and **Part 3 of the 2015 NEHRP Provisions**.
Project 2: NEESR IFAS

NEESR: Inertial Force-Limiting Floor Anchorage Systems for Seismic Resistant Building Structures (IFAS)

NEES @ UCSD

NEES @ Lehigh
IFAS Project Team

Academic collaborators

The University of Arizona
Dr. Robert Fleischman, PI
Zhi Zhang, Ph.D. student
Ulina Shakya, Ph.D. student
Anshul Agarwal
Austin Houk, REU
Scott Kuhlman, REU
Mackenzie Lostra, REU
Daniel Lizarraga, REU
Fernando Gastelum, REU
Patrick Hughes, REU
Ziyi Li, REU

University of California, San Diego
Dr. Jose Restrepo, Co-PI
Arpit Nema, Ph.D. student
Gabriele Guerrini
David Duck, Nelson Angel
Armita Pebdani
Steve Mintz, Ph.D. student

Lehigh University
Dr. Richard Sause, Co-PI
Georgios Tsampras,
Ph.D. student
Alronil Pacheco, REU
(San Jose State University)

Nazarbayev University
Dr. Dichuan Zhang

University of Rome
Dr. Giorgio Monti
Dr. Alessandro Scodeggio

Technical University of Bari
Dr. Beppe Marano
Dr. Giuseppe Quaranta

K12 partner
Utterback Middle School
Gricelda Meraz

Seismic Design Consultants

Rutherford + Chekene
Saeed Fathali

Maffei Engineers
Joseph Maffei

RUTHERFORD & CHEKENE

Tipping Mar
David Mar

NHERI Lehigh Joint Researcher Workshop w/ UCSD & SimCenter, 23-24 September, 2019
Industry Partners: NEESR Shake Table Test
Research Team

Research Meeting #3 at R&C Offices

Saeed Fathali
R&C

David Mar
T&M

Jose Restrepo
UCSD

Dom Campi
R&C

Richard Sause
UA

RBF

Joe Maffei
JMA

NHERI Lehigh Joint Researcher Workshop w/ UCSD & SimCenter, 23-24 September, 2019
IFAS Concept

• Provides a deformable (ductile) connection between the floor system (GLRS) and the primary vertical plane LFRS elements (e.g., shear walls, braced frames)

• Designed with a predefined design strength ($F_y$) to partially uncouple the GLRS and the LFRS

• The structure acts as a traditional structure for daily loads

![Diagram showing IFAS Concept](image)

Daily wind or minor earthquake
IFAS Concept

• The IFAS will reach its design strength in a strong earthquake...
• ...and deform, thereby transforming the seismic demands into relative displacement between the GLRS and the LFRS...
• ...dissipating energy and lowering seismic demands
Prototype IFAS System

- Gravity load resisting system (GLRS)
- Lateral force resisting system (LFRS)
- Dampers
- Rubber bearings (RB)
- Moat
IFAS Components

- Polyurethane Bumper
- Buckling Restrained Brace (BRB)
- Low Damping Rubber Bearings (RB)
- Friction Device (FD)
Subassemblage Testing: NEES@Lehigh
Full-Scale IFAS Testing: BRB

Floor Slab
Wall Stub
NEES Hydraulic Actuators
Steel Reinforced RB

BRB

NEES @ Lehigh
Full-Scale IFAS Testing: BRB
Full-Scale IFAS Testing: BRB
Full-Scale IFAS Testing: RB
Full-Scale IFAS Testing: FD

Carbon Fiber Reinforced RB

FD
Full-Scale IFAS Testing: FD
Bumper Impact Tests: NHERI@Lehigh

Control LVDT
BW_Bumper
TW_Bumper
TE_Bumper
BE_Bumper
Slab
Wall

Web camera
GoPro camera
Test specimen
High speed camera
Accelerometer on wall
Load cell
Accelerometer on slab
Slab
Wall

NHERI Lehigh Joint Researcher Workshop w/ UCSD & SimCenter, 23-24 September, 2019

69
Bumper Impact Tests: NHERI@Lehigh
Bumper Impact Tests: NHERI@Lehigh

Bumper Test (1-22)
Analytical Research

Response Profile (DBE):

- Benefits
- Tradeoffs

10 Earthquakes

\[ \alpha = \sum \frac{F_y}{F_{px}} \]

- Reduced floor acceleration
- Reduced LFRS Demand
- Increased relative displacement
- Increased GLRS drift

\[ \alpha = 0.4 \]
\[ \alpha = 0.3 \]
\[ \alpha = 0.1 \]
\[ \alpha = 0.01 \]
Shake Table Test Structure

4-story reinforced concrete building
- Half-scale
- Provide direct comparison between IFAS and traditional
- Rocking Walls for repeatability
Test specimen description

- LFRS eccentricity was purposely introduced for torsional response
IFAS Shake Test Installation

Half-Scale 4-story Precast Rocking Shear Wall Structure

NEES @ UCSD
### Instrumentation

#### Project Testing Phase

- **Accelerometer**
- **String pot**
- **Linear pot**
- **Load cell**
- **Pressure transducer**
- **Strain gage**

Note: B2 layout also for Col. A3, C1, C2, C3 in the 2nd story.
Student Participation

Specimen Construction/Instrumentation

Guerrini, UCSD PhD

Tsampras, Lehigh PhD

Agarwal, UA PhD

Zhang, UA PostDoc

Duck, UCSD PhD

Lostra, UA REU

Nema, UCSD PhD

Zhang, UA PhD

Kuzuku, UA PhD

Shakya, UA PhD

Kuhlman, UA REU

Kuzuku, UA PhD

Lostra, UA REU

Zhang, UA PostDoc
IFAS Shake Table Response: NEES@UCSD

[Images of shake table equipment and data points on a graph showing force vs. deformation in inches.]
Shake Table Test Response

Bumper behavior
Shake Table test
Rocking of Main(North) wall

PHASE I VS PHASE II
Berkeley BE05 MCE
Traditional system vs IFAS

PLAN VIEW COMPARISON
Shake Table Test Results: NEES@UCSD

Comparison to Traditional Structure

(a) [Graph]
(b) [Graph]
(c) [Graph]
(d) [Graph]

Phase I
Phase II

North Wall
West
+qwall

West wall
South
+qwall

Comparison to Traditional Structure
Project 3: Steel Seismic Collectors

NSF ECI / ENH: Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures

NHERI @ UCSD

NHERI Lehigh
**Background**

**SFRS for Steel Structures**

---

**Vertical-plane SFRS elements** provide a laterally stiff load path to the foundation.

**Seismic Collectors** serve as the critical link between the diaphragm and the vertical elements.

**Floor diaphragms** transfer inertial forces laterally from the floor slab and attached elements.

---

**Load Path from the seismic mass to the foundation**
## Project 3: Research Approach

<table>
<thead>
<tr>
<th>Research Thrusts</th>
<th>Collector Connection</th>
<th>Collector Element</th>
<th>Collector System</th>
<th>Seismic System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DESIGN</strong></td>
<td><img src="image1" alt="Collector Connection" /></td>
<td><img src="image2" alt="Collector Element" /></td>
<td><img src="image3" alt="Collector System" /></td>
<td><img src="image4" alt="Seismic System" /></td>
</tr>
<tr>
<td><strong>ARIZONA</strong></td>
<td><img src="image5" alt="Collector Connection" /></td>
<td><img src="image6" alt="Collector Element" /></td>
<td><img src="image7" alt="Collector System" /></td>
<td><img src="image8" alt="Seismic System" /></td>
</tr>
<tr>
<td><strong>LEHIGH</strong></td>
<td><img src="image9" alt="Collector Connection" /></td>
<td><img src="image10" alt="Collector Element" /></td>
<td><img src="image11" alt="Collector System" /></td>
<td><img src="image12" alt="Seismic System" /></td>
</tr>
<tr>
<td><strong>UCSD</strong></td>
<td><img src="image13" alt="Collector Connection" /></td>
<td><img src="image14" alt="Collector Element" /></td>
<td><img src="image15" alt="Collector System" /></td>
<td><img src="image16" alt="Seismic System" /></td>
</tr>
</tbody>
</table>

**Research Thrusts**: Collector Connection, Collector Element, Collector System, Seismic System

- **ARIZONA**
  - Added Mass
  - Collector Line
  - X-shaped Cables

- **LEHIGH**
  - Added Mass
  - Collector Line
  - X-shaped Cables

- **UCSD**
  - Added Mass
  - Collector Line
  - X-shaped Cables

---

*ASCE 7-16 MCE DBE ASCE 7-10 (b)*
Collector Axial Force Profile with Concrete Strut Action

Body Force Producing Compression in the Collector
Body Force Producing Compression in the Collector
Collector Connection Limit States
Roof Collector Members Stability Modes

Contour Plots of Lateral Displacement

Axial Force (k)

Lateral Displacement (in)

AISC WAFB (Unbraced)

Rolled WF @ 1/3, Bracing

OWJ Bracing @ 1/3, TF & BF Connection

OWJ Bracing @ 1/3, TF Connection

Bare Model (No Deck, No bracing)

 Rolle d WF @ 1/3, Connection

OWJ Bracing @ 1/3, TF & BF Connection

Contour Plots of Lateral Displacement

AISC WAFB* (1/3 Bracing)

Rolled WF @ 1/3, Bracing

OWJ Bracing @ 1/3, TF & BF Connection

OWJ Bracing @ 1/3, TF Connection

Bare Model (No Deck, No bracing)

Rolled WF @ 1/3, Bracing

OWJ Bracing @ 1/3, TF Connection

OWJ Bracing @ 1/3, TF & BF Connection

Contour Plots of Lateral Displacement
Fabricated Specimen: Top Flange Weld (TFW)

The TFW is a 3/4-scale test specimen based on a Full-Scale Prototype

<table>
<thead>
<tr>
<th>Scale</th>
<th>Section</th>
<th>Length</th>
<th>Shear Tab (H x W x t)</th>
<th>Bolt Dia</th>
<th># of bolts</th>
<th>Factored Strength</th>
<th>Maximum Exp. Axial Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>W24X162</td>
<td>30</td>
<td>18 x 4.5 x 1/2</td>
<td>1.00</td>
<td>6</td>
<td>714</td>
<td>1499</td>
</tr>
<tr>
<td>0.75</td>
<td>W18x97</td>
<td>20</td>
<td>13.75 x 3.25 x 3/8</td>
<td>0.750</td>
<td>6</td>
<td>435</td>
<td>940</td>
</tr>
</tbody>
</table>

6 – 3/4” dia. A325 Snug tight bolts

W12x136 Column

13.75”x3.25”x3/8” Shear Tab

W18x97 Collector

NHERI Lehigh Joint Researcher Workshop w/ UCSD & SimCenter, 23-24 September, 2019
The AFW is a **2/3-scale test specimen** based on a **Full-Scale Prototype**

<table>
<thead>
<tr>
<th>Scale</th>
<th>Section</th>
<th>Length (ft)</th>
<th>Shear Tab (H x W x t)</th>
<th>Bolt Dia (in)</th>
<th># of bolts</th>
<th>Factored Strength (k)</th>
<th>Maximum Exp. Axial Capacity (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>W24X162</td>
<td>30</td>
<td>18 x 4.5 x 1/2</td>
<td>1.00</td>
<td>6</td>
<td>1427</td>
<td>2633</td>
</tr>
<tr>
<td>0.67</td>
<td>W16x57</td>
<td>20</td>
<td>11.8 x 3.25 x 3/8</td>
<td>0.625</td>
<td>6</td>
<td>458</td>
<td>978</td>
</tr>
</tbody>
</table>

W12x136 Column

11.8”x3.25”x3/8” Shear Tab

W16x57 Collector

6 – 5/8” dia. A325 Snug tight bolts

**Fabricated Specimen: All Flange Weld (AFW)**
Test Set Up (3D Model)

- Rotation Actuators
- Test Specimen
- Lateral Bracing
- Reusable Test Fixture
- Loading Actuators
- K-Frame
UCSD Shake Table Specimen
Thank You!