Technical Session III: Example Prior Projects Conducted at Lehigh

Large Scale Testing of Existing and Innovative Floor Diaphragm Components

Dr. Robert B. Fleischman
University of Arizona
5 December 2016
Presentation Outline

- Project 1: NSF GOALI (Existing Details)  
  Development of a Seismic Design Methodology for Precast Floor Diaphragms (DSDM)

- Project 2: NSF NEESR (Innovative Sys.)  
  Development of an Inertial Force-Limiting Floor Anchorage System (IFAS)
Presentation Outline

- Multi-University Research Projects
- Lehigh co-PIs and Grad Students
- Large Scale Sub-assembly Testing
- Lehigh Testing Program used for:
  - Component Characterization
  - Analytical Model Construction
  - Demonstration of Concept
  - Guidance for Large Scale System Tests
Project 1: NSF GOALI - DSDM

Development of a Seismic Design Methodology for Precast Floor Diaphragms (DSDM)

- NSF GOALI (2005-07) / NEESR (2008-09)
- Co-funded by PCI & CPF
Diaphragm action carries seismic forces horizontally in the floor slab to walls and frames...
Precast Diaphragm Past Performance
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 (UA)
Ge Wan, M. Mielke, A. Mullenbach
Matthew Schoettler, Andrea Belleri (UCSD)
Ruirui Ren, Liling Cao (LU)
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

MDOF Dynamic Analysis
Scaled Shake Table Test
FE Pushover Analysis
3D FE Dynamic Analysis
Full-Scale Detail Tests
Hybrid Testing of Joints
Isolated Connector Specimens

SIDE ELEVATION

TOP PLAN
(6x6 W2.9xW2.9)

SIDE ELEVATION

TOP PLAN
(6x6 W2.9xW2.9)
Shear Connector Model Calibration

Cyclic response

V (kips)

TEST
Model

δ_v (in)

-20 -10 0 10 20

-0.6 -0.4 -0.2 0 0.2 0.4 0.6

TEST
Model
Ductile Mesh Model Calibration

![Graph showing test and model results with axes labeled V (kips) and δv (in).](image_url)

- Test
- Model

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Diaphragm Analytical Models

“Discrete Connector” FE models

- Web Connector (Shear and Tension)
- Chord Steel

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

(a) Plan View

Fixed support

TOP

ACT1

ACT2

ACT3

Fixed Support

Movable support

Specimen panel A

Specimen panel B

Fixed support

Fixed support

Framing angles

Teflon plates

Fixed support

(b) Section A-A

(a) Plan view

(b) Side elevation

(c) Photo
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>
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<tbody>
<tr>
<td>PDH 1</td>
<td>Charleston (CH)</td>
<td>SVC</td>
<td>Transverse</td>
<td>South</td>
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<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>Bidirection (Bi)</td>
<td>North</td>
</tr>
<tr>
<td>PDH 5</td>
<td>Berkeley (BK)</td>
<td>MCE</td>
<td>Transverse</td>
<td>South</td>
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</tbody>
</table>

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

Fig. 14. Joint force: (a) axial; (b) shear; (c) moment
PDH Test Results: Flexure

CH DBE

CH MCE

Weld Fracture

Minor Cracking

Major Cracking/Crushing

BK MCE
Critical Shear Joint: Hybrid Test

DT units: Plane stress elements
Precast spandrel: 2D beam element
Symmetry boundary

Shear wall: Shell element
Global CS joint (See Fig.8a)
Base plastic hinge: Bi-axial fiber elements

Foundation Block / Overturning Moment Counterweight
Post Tension Bars
Rail System

Nonlinear springs & contact
Nonlinear shear springs
Nonlinear rotational spring
Floor: 2D beam
Nonlinear spring & contact
Nonlinear shear spring
Plane stress element
Nonlinear springs & contact
Nonlinear shear springs
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 Kv (kN/mm)

(b) 100 N (kN)

Hybrid test

Hybrid simulation
Reduced NLTDA

Opening (in.)

Step

Kv (kN/mm)

N (kN)
Shake Table Demonstration Test

![Graphs showing ground motion and shake table demonstration tests.](image)
Analytical Simulation

Diaphragm Force

Diaphragm deflection

Test
Prediction
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
# Project Team

## Academic collaborators

<table>
<thead>
<tr>
<th>The University of Arizona</th>
<th>University of California, San Diego</th>
<th>Lehigh University</th>
<th>Nazarbayev University</th>
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</thead>
<tbody>
<tr>
<td>Dr. Robert Fleischman, PI</td>
<td>Dr. Jose Restrepo, Co-PI</td>
<td>Dr. Richard Sause, Co-PI</td>
<td>Dr. Dichuan Zhang</td>
</tr>
<tr>
<td>Zhi Zhang, Ph.D. student</td>
<td>Arpit Nema, Ph.D. student</td>
<td>Georgios Tsampras, Ph.D. student</td>
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<tr>
<td>Ulina Shakya, Ph.D. student</td>
<td>Gabrielle Guerrini</td>
<td>Alronil Pacheco, REU</td>
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<tr>
<td>Anshul Agarwal</td>
<td>David Duck</td>
<td>(San Jose State University)</td>
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<tr>
<td>Austin Houk, REU</td>
<td>Nelson Angel</td>
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<tr>
<td>Scott Kuhlman, REU</td>
<td>Armita Pebdani</td>
<td></td>
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<tr>
<td>Mackenzie Lostra, REU</td>
<td>Steve Mintz, Ph.D. student</td>
<td></td>
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<tr>
<td>Daniel Lizarraga, REU</td>
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<tr>
<td>Fernando Gastelum, REU</td>
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<tr>
<td>Patrick Hughes, REU</td>
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<td>Ziyi Li, REU</td>
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## Seismic Design Consultants

- **Tipping Mar**
  - David Mar

## K12 partner

- **Utterback Middle School**
  - Gricelda Meraz

## Technical University of Bari

- Dr. Beppe Marano
- Dr. Giuseppe Quaranta

## Joe Maffei Association

- Joseph Maffei
- Saeed Fathali
Industry Partners: NEESR Shake Table Test
Research Team

Research Meeting #3 at R&C Offices
IFAS Concept

IFAS Concept

GLRS
LFRS

Deformable Connections

Moat
Bracing / Restoring Elements

Anchorage system

Anchorage system

EQd

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IFAS Components

Polyurethane Bumper

Buckling Restrained Brace (BRB)

Low Damping Rubber Bearings (RB)

Friction Device (FD)
IFAS Prototype

Prototype IFAS System

Gravity load resisting system (GLRS)

Lateral force resisting system (LFRS)

Dampers

Rubber bearings (RB)

Moat
IFAS Shake Test Installation

Half-Scale 4-story Precast Rocking Shear Wall Structure

NEES @ UCSD
IFAS Shake Table Response: NEES@UCSD
Berkeley BE05 MCE
Traditional system vs IFAS

PLAN VIEW COMPARISON
Shake Table Testing: NEES@UCSD

Shake Table test
Rocking of Main(North) wall

PHASE I VS PHASE II
Shake Table Test Results: NEES@UCSD

Comparison to Traditional Structure
Subassemblage Testing: NEES@Lehigh

Lehigh Test Specimen

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Full-Scale IFAS Testing: BRB

Floor Slab  Wall Stub  NEES Hydraulic Actuators

Steel Reinforced RB

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
Bumper Impact Tests: NHERI@Lehigh

Bumper Test (1-22)
Bumper Test Results: NHERI@Lehigh

Bumper hysteresis behavior

- Vo = 15 in/s
- Vo = 5 in/s
- Vo = 1 in/s

Yellow bumper
Black bumper

Bumper force (kips) vs. Bumper deformation Control LVDT (in)
Thank You!