EXPERIMENTAL STUDY OF FORCE-LIMITING DEFORMABLE CONNECTION BETWEEN FLOOR SYSTEM AND LATERAL FORCE RESISTING SYSTEM

G. Tsampras¹, R. Sause², R. Fleischman³, J. Restrepo⁴, Z. Zhang³, U. Shakya³, D. Zhang⁵, J. Maffei⁶, D. Mar⁷

¹SIMPSON GUMPertz & HEGER INC., WALTHAM, MA
²ATLSS RESEARCH CENTER, DEPT. OF CIVIL AND ENVIRONMENTAL ENGINEERING, LEHIGH UNIVERSITY, BETHLEHEM, PA
³DEPT. OF CIVIL ENG. AND ENG. MECHANICS, UNIVERSITY OF ARIZONA, TUCSON, AZ
⁴DEPT. OF STRUCTURAL ENGINEERING, UNIVERSITY OF CALIFORNIA, SAN DIEGO, CA
⁵DEPT. OF CIVIL ENGINEERING, NAZARBAYEV UNIVERSITY, ASTANA, REPUBLIC OF KAZAKHSTAN
⁶MAFFEI STRUCTURAL ENGINEERING, OAKLAND, CA
⁷MAR STRUCTURAL DESIGN, BERKELEY, CA

Tuesday, June 26 – Friday, June 29
Acknowledgements

- National Science Foundation (Award No. CMMI-1135033)
- George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program (Award No. CMS-0402490)
- PI Dr. Robert Fleischman
- Co-PI Dr. Jose Restrepo
- Co-PI Dr. Richard Sause
- Dr. Joe Maffei, Mr. David Mar
- Dr. Dichuan Zhang, Dr. Zhi Zhang, Ulina Shakya, Arpit Nema
- NEES@UCSD staff
- NEES@Lehigh staff and ATLSS Center staff

NEES @ UCSD

NEES @ Lehigh
Conventional Building Systems

Three Main Systems
• Gravity Load Resisting System, GLRS
• Floor Systems, FS
• Lateral Force Resisting Systems, LFRS
Alternative System Developed in this Study

Openings in the Floor Systems (FS)
Deformable Connections between FS – LFRS with two types of components:

1. Limited-Strength Hysteretic (LSH) components
2. Bearing Components

• Limit the transferred forces by using deformable connections
• Reduce the floor accelerations and force responses

Deformable Connection Components

- **Deformable Connection Components**
  - **BRB+RB**
    - Buckling Restrained Brace (BRB)
  - **FD+RB**
    - Friction Device (FD)
    - Low Damping Rubber Bearings (RB)

Reference:

Example Installation of Deformable Connection

Half-Scale 4-story Precast Rocking Shear Wall Structure at NEES @ UCSD
Example Installation at NEES @ UCSD

EQ.14: Berkeley MCB - Floor 4

[Images of installation site and graphs showing force versus deformation]
Tests of Full-Scale Deformable Connections at NEES @ Lehigh

BRB+RB

FS
LFRS
NEES Hydraulic Actuators
Steel Reinforced RB
BRB
Tests of Full-Scale Deformable Connections at NEES @ Lehigh
Tests of Full-Scale Deformable Connections at NEES @ Lehigh
Tests of Full-Scale Deformable Connections at NEES @ Lehigh

Tests of Full-Scale Deformable Connections at NEES @ Lehigh

FD+RB

Carbon Fiber Reinforced RB

FD
Tests of Full-Scale Deformable Connections at NEES @ Lehigh
Force-Deformation Responses
Numerical Simulations with Calibrated Models

Deformation [mm]
-80 -60 -40 -20 0 20 40 60 80

Force [kN]
-2000 -1500 -1000 -500 0 500 1000 1500 2000

BRB + RB

FD + RB

Period [sec]
0 0.5 1 1.5 2 2.5 3

Spectral Acceleration [g]
0 0.5 1 1.5 2 2.5 3 3.5 4

EQ0
Design Spectrum
Median Spectrum

(EQ0)

(ASCE 7-10)

Median Spectrum

(EQ0)

(ASCE 7-10)

Median Spectrum

Design Spectrum

Median Spectrum

(EQ0)

(ASCE 7-10)

Median Spectrum

Design Spectrum

Median Spectrum

(EQ0)

(ASCE 7-10)

Median Spectrum

Design Spectrum

Median Spectrum

6/29/2018
Numerical Simulations Results

$F_c$: Connection force transferred from FS to LFRS

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>RE</td>
</tr>
<tr>
<td>□</td>
<td>FD+RB</td>
</tr>
<tr>
<td>◊</td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

$F_c$ [kN]

Numerical Simulations Results

$F_c$: Connection force transferred from FS to LFRS

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>RE</td>
</tr>
<tr>
<td>□</td>
<td>FD+RB</td>
</tr>
<tr>
<td>◊</td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

$F_c$ [kN]

Mean Peak | Peak |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>RE</td>
</tr>
<tr>
<td>□</td>
<td>FD+RB</td>
</tr>
<tr>
<td>◊</td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

Floor
Numerical Simulations Results

**$F_c$:** Connection force transferred from FS to LFRS

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
<th>RE</th>
<th>FD+RB</th>
<th>BRB+RB</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="null">Image</a></td>
<td><a href="null">Image</a></td>
<td>7100</td>
<td>1800</td>
<td>2100</td>
</tr>
<tr>
<td><a href="null">Image</a></td>
<td><a href="null">Image</a></td>
<td>3500</td>
<td>120</td>
<td>200</td>
</tr>
</tbody>
</table>

$\mu$ [kN]  | $\sigma$ [kN]
--- | ---
RE  | 7100 | 3500
FD+RB | 1800 | 120
BRB+RB | 2100 | 200

-70%
Numerical Simulations Results

$F_c$: Connection force transferred from FS to LFRS

<table>
<thead>
<tr>
<th>Mean Peak Peak</th>
<th>μ [kN]</th>
<th>σ [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE</td>
<td>7100</td>
<td>3500</td>
</tr>
<tr>
<td>FD+RB</td>
<td>1800</td>
<td>120</td>
</tr>
<tr>
<td>BRB+RB</td>
<td>2100</td>
<td>200</td>
</tr>
</tbody>
</table>

-70% -95%

Numerical Simulations Results

$a_f$: Floor total accelerations

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>RE</td>
</tr>
<tr>
<td>□</td>
<td>FD+RB</td>
</tr>
<tr>
<td>◇</td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

$ag = 0.54g$

- $af$: Floor total accelerations

Mean Peak

RE
FD+RB
BRB+RB

Floor

1 2 3 4 5 6 7 8 9 10 11 12

$ag = 0.54g$
Numerical Simulations Results

$V_{LFRS}$: LFRS story shear

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>RE</td>
</tr>
<tr>
<td>□</td>
<td>FD+RB</td>
</tr>
<tr>
<td>◆</td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

$\times 10^4$
**Numerical Simulations Results**

$V_{LFRS}$: LFRS story shear

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RE</td>
</tr>
<tr>
<td></td>
<td>FD+RB</td>
</tr>
<tr>
<td></td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ [kN]</th>
<th>$\sigma$ [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE</td>
<td>28000</td>
<td>10400</td>
</tr>
<tr>
<td>FD+RB</td>
<td>15500</td>
<td>1300</td>
</tr>
<tr>
<td>BRB+RB</td>
<td>15500</td>
<td>1650</td>
</tr>
</tbody>
</table>

-45%
**Numerical Simulations Results**

**$V_{\text{LFRS}}$: LFRS story shear**

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
<th>RE</th>
<th>FD+RB</th>
<th>BRB+RB</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td></td>
<td>RE</td>
<td>FD+RB</td>
<td>BRB+RB</td>
</tr>
<tr>
<td>□</td>
<td></td>
<td>RE</td>
<td>FD+RB</td>
<td>BRB+RB</td>
</tr>
<tr>
<td>●</td>
<td></td>
<td>RE</td>
<td>FD+RB</td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ [kN]</th>
<th>$\sigma$ [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE</td>
<td>28000</td>
<td>10400</td>
</tr>
<tr>
<td>FD+RB</td>
<td>15500</td>
<td>1300</td>
</tr>
<tr>
<td>BRB+RB</td>
<td>15500</td>
<td>1650</td>
</tr>
</tbody>
</table>

-45% -85%

---

6/29/2018
Numerical Simulations Results

$D_c$: Connection deformation

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RE</td>
</tr>
<tr>
<td></td>
<td>FD+RB</td>
</tr>
<tr>
<td></td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

Floor

$D_c$ [mm]

- 82mm
- 38mm

$D_c$: Connection deformation

Dc: Connection deformation

Mean Peak | Peak
---|---
RE | FD+RB | BRB+RB

6/29/2018

Numerical Simulations Results

$\theta_{GLRS}$: GLRS story drift

<table>
<thead>
<tr>
<th>Mean Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RE</td>
</tr>
<tr>
<td></td>
<td>FD+RB</td>
</tr>
<tr>
<td></td>
<td>BRB+RB</td>
</tr>
</tbody>
</table>

- $\theta_{GLRS}$: GLRS story drift
- $\theta_{GLRS}$ in radians
- Data points for different configurations (RE, FD+RB, BRB+RB)
- Graph showing $\theta_{GLRS}$ vs. Story number from 1 to 12

6/29/2018

But…Why forces and accelerations are reduced?
Higher Mode Responses

1\textsuperscript{st} Mode
Large Participation

Higher Modes
Smaller Participation

\( h_x \)

\( h_n \)

\( \Gamma_1 \phi_1 \)

\( \Gamma_2 \phi_2 \)

\( \Gamma_3 \phi_3 \)
Higher Mode Responses

- **Chi-Chi Taiwan** 1999 CHY101 EQ 6
- **Friuli Italy** 1976 TMZ000 EQ 1
- **Design ASCE 7-10**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Period [sec.]</th>
<th>RE</th>
<th>FD+RB</th>
<th>BRB+RB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4899</td>
<td>1.4918</td>
<td>1.4944</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.2432</td>
<td>0.3302</td>
<td>0.3429</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.0870</td>
<td>0.2396</td>
<td>0.2553</td>
<td></td>
</tr>
</tbody>
</table>
Higher Mode Responses

Second Mode Displacement Shape

Connection Force [kN]
Higher Mode Responses

![Graph showing spectral acceleration vs. period for different modes and periods.

1. Second Mode Displacement Shape

2. Comparison of spectral acceleration for ASCE7-10 and EQ1.


4. Time history of base shear for different systems (RE, FD+RB, BRB+RB).

5. Time history of base shear for different systems (RE, FD+RB, BRB+RB).

6. Time history of base shear for different systems (RE, FD+RB, BRB+RB).

---

6/29/2018


30
Higher Mode Responses

Second Mode Displacement Shape

Floor 6
Floor 10
Floor 12
Conclusions

1. The full-scale BRB+RB and FD+RB deformable connections could be designed and constructed

2. The deformable connections have experimentally validated stable hysteretic response under large deformation

3. Limiting the forces transferred from FS to LFRS led to reduction of floor accelerations, and LFRS story shears

4. Significant reduction of the dispersion of the forces transferred from the FS to the LFRS, the floor accelerations, and the LFRS story shears


TSAMPRAS G, SAUSE R, FLEISCHMAN RB, RESTREPO JI. EXPERIMENTAL STUDY OF DEFORMABLE CONNECTION CONSISTING OF FRICTION DEVICE AND RUBBER BEARINGS TO CONNECT FLOOR SYSTEM TO LATERAL FORCE RESISTING SYSTEM. *EARTHQUAKE ENGNG STRUCT DYN*. 2018;47:1032-1053. HTTPS://DOI.ORG/10.1002/EQE.3004