Experimental and analytical investigation of seismic performance of nonductile RC frames strengthened with CFRP

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Outline of the presentation

1. Research background
2. Axial stress-strain behavior of FRP-confined RC columns
3. Seismic performance of FRP strengthened RC members
4. Seismic performance of FRP strengthened RC frames
### Research background

**Nonductile frames:** designed and built according to out-of-date codes, in which the earthquake loads are either not considered or not sufficiently considered. Insufficient ductility and energy dissipation capacity, deficient lateral load resistance, high risk level of severe damage or collapses in future strong earthquakes.

<table>
<thead>
<tr>
<th>FRP (Fiber-Reinforced Polymer)</th>
<th>Characters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP GFRP AFRP</td>
<td>High strength-to-weight ratio</td>
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<tr>
<td></td>
<td>Resistance to corrosion</td>
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<td>Ease of installation</td>
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</tbody>
</table>
Most existing research was focused on material and member level, few research was conducted on the structural level.

**Issues:**

1. How to determine reasonable retrofit positions or members in a whole frame?
2. How to deploy the least amount of FRP for seismic retrofit requirement?
Research background

Main research contents and objects

Constitutive relationship of FRP-confined concrete
(Material level)

Seismic performance of FRP strengthened columns and joints
(Member level)

Seismic performance of FRP strengthened RC frames
(structural level)

Displacement-based seismic design method for FRP strengthened RC frames
Outline of the presentation

1. Research background
2. Axial stress-strain behavior of FRP-confined RC columns
3. Seismic performance of FRP strengthened RC members
4. Seismic performance of FRP strengthened RC frames
Axial stress-strain behavior of FRP-confined RC columns

Approximately 110 columns were conducted and tested under compressive, largest size 400×400mm
Axial stress-strain behavior of FRP-confined RC columns

Test stress-strain results
Axial stress-strain behavior of FRP-confined RC columns

Noncircular cross section

\[ f_{cc} = \psi f \cdot 3.3 \kappa_a f_l \]
\[ f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D} \]
\[ \varepsilon_{fe} = k \varepsilon_{fu} \]
\[ D = \sqrt{2b} \]

For square section:
\[ \kappa_a = \frac{A_c}{A_e} = 1 - \frac{2}{3} (1 - 2 \frac{r_c}{b})^2 \]

ACI 440.2R-2008

Are the compressive strength of these two confined concrete columns should be the same?

Size Effect: Do small and large specimens have similar axial compressive behavior under the same lateral confinement?

2 layers of CFRP
4 layers of CFRP

200 mm
400 mm

Have the same \( r_c/b \) and same lateral effective confining pressure
Axial stress-strain behavior of FRP-confined RC columns

Normalized axial stress ($\sigma_c/f_{c0}$) vs. Axial Strain ($\varepsilon_c$ (%))

- **GA1**
  - P100L1
  - P200L2
  - P300L3
  - P400L4

- **GA3**
  - P175L1
  - P350L2

- **GB3**
  - R175L1
  - R350L2

Normalized ultimate stress for different Size and FRP layers:
- 200L2
- 300L2
- 300L3
- 175L1
- 350L2
- 175L2
- 200L1

Normalized axial stress ($\sigma_c/f_{c0}$) vs. Axial strain ($\varepsilon_c$ (%))
Axial stress-strain behavior of FRP-confined RC columns

\[ \varepsilon_{fe} = \kappa_\varepsilon \varepsilon_{fu} \]

\[ \kappa_\varepsilon = \frac{\varepsilon_{fe}}{\varepsilon_{fu}} = 1 - 0.38 \left( \frac{B}{100} \right)^{0.41} \]

\[ f_{lf} = \kappa_a \frac{2E_f n t}{D} \varepsilon_{fe} \]

\[ \kappa_a = \frac{A_e}{A_c} = \frac{1 - \frac{2(B - 2r_c)^2}{3A_g}}{1 - \rho_g} \]

Graph showing the effective strain factor \( \kappa_\varepsilon \) vs. normalized cross-sectional size \( B/100 \), with data points from This study and Wang et al. (2011).
Axial stress-strain behavior of FRP-confined RC columns

Axial stress and strain, shape of envelop and unloading/reloading stress-strain path, and plastic strain
Axial stress-strain behavior of FRP-confined RC columns

Comparison between experimental and predicted stress-strain curves of FRP-confined circular columns
Axial stress-strain behavior of FRP-confined RC columns

Comparison between experimental and predicted stress-strain curves of FRP-confined square columns
Outline of the presentation

1. Research background
2. Axial stress-strain behavior of FRP-confined RC columns
3. Seismic performance of FRP strengthened RC members
4. Seismic performance of FRP strengthened RC frames
Seismic performance of FRP strengthened RC members

Quasi-static lateral load test of FRP strengthened full scale RC columns

Purpose: Investigate the influence of cross-sectional size and shape, axial compressive ratio, layers of wrapped FRP on the seismic performance of FRP strengthened RC columns.

Specimen: 1. circular, $D=400\text{mm}$, 3 layers of CFRP or GFRP, $n=0.45$;

2. square, $B=300\text{mm}, 400\text{mm}$, 2, 3, 4 layers of CFRP, $n=0.35, 0.45, 0.45$.

Specimen dimensions and reinforcement details
Seismic performance of FRP strengthened RC members

Quasi-static lateral load test of FRP strengthened full scale RC columns

Test setup and measurement system
Seismic performance of FRP strengthened RC members

Quasi-static lateral load test of FRP strengthened full scale RC columns

Failure modes
Seismic performance of FRP strengthened RC members

Quasi-static lateral load test of FRP strengthened full scale RC columns

Experimental lateral load-displacement curves
Seismic performance of FRP strengthened RC members

Finite element analysis on seismic performance of FRP-confined RC columns

Opensees: Open System for Earthquake Engineering Simulation

http://opensees.berkeley.edu

- OpenSees has been under development by PEER since before 1997.
- Core group of developers and users.
- PEER will continue research and development for PBEE applications in OpenSees.
- Copyrighted by UC Regents and free for use.
- Google search hits as proxy for interest (8/8/06)?
  - OpenSees-64,200
  - ABAQUS [finite]-266,000
  - SAP2000-336,000
Seismic performance of FRP strengthened RC members

Finite element analysis on seismic performance of FRP-confined RC columns

Element and Fiber Section used in OpenSees
Seismic performance of FRP strengthened RC members

Finite element analysis on seismic performance of FRP-confined RC columns

- Axial stress vs. strain for different confinement types:
  - Steel02: Steel confinement
  - Concrete01: Unconfined concrete
  - Steel-confined concrete
  - FRP-confined concrete
Seismic performance of FRP strengthened RC members

Finite element analysis on seismic performance of FRP-confined RC columns

Comparison between simulation and experimental results
Seismic performance of FRP strengthened RC members

- Quasi-static lateral load test of FRP strengthened full scale RC beam-column joints

Interior beam-column joints
Test setup
### Seismic performance of FRP strengthened RC members

#### Quasi-static lateral load test of FRP strengthened full scale RC beam-column joints

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Retrofitting patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0</td>
<td>Control specimen (without strengthening)</td>
</tr>
<tr>
<td>J1</td>
<td>Strengthen columns only</td>
</tr>
<tr>
<td>J2</td>
<td>Strengthen columns + beams (U-shape FRP stripe)</td>
</tr>
<tr>
<td>J3</td>
<td>Strengthen columns + beams (lateral wrapped FRP)</td>
</tr>
</tbody>
</table>
Quasi-static lateral load test of FRP strengthened full scale RC beam-column joints

<table>
<thead>
<tr>
<th>Top column</th>
<th>Bottom column</th>
<th>Core area of joint</th>
<th>Beam</th>
<th>Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0</td>
<td>J0</td>
<td>J0</td>
<td>J0</td>
<td>J0</td>
</tr>
<tr>
<td>J1</td>
<td>J1</td>
<td>J1</td>
<td>J1</td>
<td>J1</td>
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<tr>
<td>J2</td>
<td>J2</td>
<td>J2</td>
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<tr>
<td>J3</td>
<td>J3</td>
<td>J3</td>
<td>J3</td>
<td>J3</td>
</tr>
</tbody>
</table>
Seismic performance of FRP strengthened RC members

Quasi-static lateral load test of FRP strengthened full scale RC beam-column joints

Experimental lateral load-displacement curves
Seismic performance of FRP strengthened RC members

Finite element analysis of FRP strengthened RC beam-column joints

OpenSees FE modeling

Pinching4 Material (modified diagonal compression field theory (MCFT))
Seismic performance of FRP strengthened RC members

Finite element analysis of FRP strengthened RC beam-column joints

Comparison between simulation and experimental results
Outline of the presentation

1. Research background

2. Axial stress-strain behavior of FRP-confined RC columns

3. Seismic performance of FRP strengthened RC members

4. Seismic performance of FRP strengthened RC frames
4 Seismic performance of FRP retrofitted RC frames

- Shaking table test of FRP retrofitted large scale nunductile RC frames

Dimensions, general view and reinforcement details of test frame
## Seismic performance of FRP retrofitted RC frames

### Shaking table test of FRP retrofitted large scale nunductile RC frames

Similitude relations for dynamic model testing

<table>
<thead>
<tr>
<th>Properties</th>
<th>Physical quantities</th>
<th>Similitude equation</th>
<th>Model</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain $\varepsilon$</td>
<td>$S_\varepsilon = 1.0$</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stress $\sigma$</td>
<td>$S_\sigma = S_F$</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic modulus $E$</td>
<td>$S_F$</td>
<td>1.0</td>
<td>Model design control</td>
<td></td>
</tr>
<tr>
<td>Poisson ratio $\mu$</td>
<td>$S_\mu = 1.0$</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>$S_\rho = S_m / S_l^3$</td>
<td>1.008</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Geometric</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length $l$</td>
<td>$S_l$</td>
<td>1/2</td>
<td>Model design control</td>
<td></td>
</tr>
<tr>
<td>Area $S$</td>
<td>$S_S = S_l^2$</td>
<td>1/4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>linear displacement $X$</td>
<td>$S_X = S_l$</td>
<td>1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>angular displacement $\beta$</td>
<td>$S_\beta = 1.0$</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrated force $P$</td>
<td>$S_P = S_F, S_l^2$</td>
<td>1/4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Load $q$</td>
<td>$S_q = S_\sigma S_l$</td>
<td>1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dynamic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass $m$</td>
<td>$S_m$</td>
<td>0.126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness $K$</td>
<td>$S_K = S_F S_l$</td>
<td>1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time $t$</td>
<td>$S_t = (S_m / S_K)^{0.5}$</td>
<td>0.502</td>
<td>Dynamic loading control</td>
<td></td>
</tr>
<tr>
<td>Frequency $f$</td>
<td>$S_f = 1/S_t$</td>
<td>1.992</td>
<td>Dynamic loading control</td>
<td></td>
</tr>
<tr>
<td>Damping $c$</td>
<td>$S_c = S_m / S_t$</td>
<td>0.251</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity $v$</td>
<td>$S_v = S_l / S_t$</td>
<td>0.996</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration $a$</td>
<td>$S_a = S_l / S_t^2$</td>
<td>1.984</td>
<td>Dynamic loading control</td>
<td></td>
</tr>
</tbody>
</table>
4 Seismic performance of FRP retrofitted RC frames

- Shaking table test of FRP retrofitted large scale nunductile RC frames

CFRP retrofit strategies
Seismic performance of FRP retrofitted RC frames

Shaking table test of FRP retrofitted large scale nunductile RC frames

Measurement system

Shaking Table: 5m × 5m, Maximum load capacity 30t
Seismic performance of FRP retrofitted RC frames

- Shaking table test of FRP retrofitted large scale nunductile RC frames

The ground motion records selected based on:
- Maximum displacement capacity of shaking table
- Natural frequency of test model
4 Seismic performance of FRP retrofitted RC frames

Shaking table test of FRP retrofitted large scale nunductile RC frames

The maximum applied peak ground acceleration (PGA) can be resisted by the bare frame specimen was approximately equal to 0.6g.

Failure modes of unstrengthened RC control frame
Seismic performance of FRP retrofitted RC frames

Shaking table test of FRP retrofitted large scale nunductile RC frames

The can be resisted maximum PGA by the strengthened frame was more than 1.0g. The seismic performance improved about 1 times.

Failure modes of FRP retrofitted frame
Seismic performance of FRP retrofitted RC frames

Shaking table test of FRP retrofitted large scale nunductile RC frames

The peak relative displacement at each storey of CFRP retrofitted frame is much smaller than that of bare frame under the similar input PGA level.
Seismic performance of FRP retrofitted RC frames

Shaking table test of FRP retrofitted large scale nunductile RC frames

The inter-storey drift ratio at each storey of retrofitted frame is smaller than that of bare frame under the similar earthquake level, especially in Y direction.
Seismic performance of FRP retrofitted RC frames

Finite element analysis of FRP retrofitted large scale nductile RC frames

FE modeling based on OpenSees
Seismic performance of FRP retrofitted RC frames

Finite element analysis of FRP retrofitted large scale nunductile RC frames

Comparison between simulation and test results of acceleration time history
Seismic performance of FRP retrofitted RC frames

Finite element analysis of FRP retrofitted large scale nunductile RC frames

Comparison between simulation and test results of displacement time history
Thanks for your attention