Displacement-based Seismic Design of Masonry Shear Wall Structures

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important points of this presentation

• current seismic design does not always work well for shear-wall structures

• proposed displacement-based seismic design works well for shear wall structures
  ▫ produces structures that behave reliably in strong earthquakes
  ▫ more consistent and more transparent than current seismic design
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Andreas Stavridis
Marios Mavros

Prof. David McLean
Jacob Sherman
Christina Duncan
Will Cyrier
contents of presentation

• review and examine current seismic design of masonry shear wall structures
• develop proposed displacement-based design
• check and validate displacement-based seismic design
current force-based design approach ...

• determine seismic design category (SDC) based on geographic location and soil
  ▫ select from ASCE 7 list of permitted structural systems
  ▫ special, intermediate reinforced masonry shear walls
  ▫ prescribed detailing for each wall segment

![SDC](image)

![Prescriptive reinforcement](image)

ASCE 7 list of permitted systems
... current force-based design approach

- based on structural system, assign seismic design factors \((R, C_d, \Omega_0)\)
  - design for elastic forces divided by \(R\)
  - design for elastic displacements multiplied by \(C_d\)
  - design elements that must remain elastic for elastic forces divided by \(R\) and multiplied by \(\Omega_0\)

<table>
<thead>
<tr>
<th>Seismic-Load Resisting Systems</th>
<th>(R)</th>
<th>(C_d)</th>
<th>(\Omega_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special RM Load Bearing Shear Walls</td>
<td>5</td>
<td>3 1/2</td>
<td>2 1/2</td>
</tr>
<tr>
<td>Intermediate RM Load Bearing Shear Walls</td>
<td>3 1/2</td>
<td>2 1/4</td>
<td>2 1/2</td>
</tr>
</tbody>
</table>
force-based design does not always work well

- final behavior is not always consistent with design intent

  - easy to design
  - may be impossible to design rationally

  - weakly coupled walls
  - irregular openings

- ductility required by $R$ and implied by detailing may not be available

  - a low-rise structure in SDC D will not achieve high ductility
force-based design requirements are not reliable

- emphasis on forces instead of deformations is misguided

- force-based principle is not valid for short-period structures
better design approaches?

• modified force-based
  ▫ R-factor accounts for actual system behavior

• displacement-based
  ▫ emphasizes deformations
  ▫ designer determines deformation limits
5 major tasks in this research . . .

- task 1- examined the behavior masonry buildings designed using force-based procedures

- task 2- developed displacement-based seismic design method
5 major tasks in this research

- **task 3-** conducted cyclic-load tests on masonry wall segments at UT Austin and WSU

- **task 4-** improved analytical tools

- **task 5-** validated displacement-based seismic design for masonry
task 1 - examine force-based procedures

- used shake-table tests to examine overall and local behaviors of masonry buildings
- evaluate the performance of special reinforced masonry walls
- assess the failure mechanism of a real wall system

plan view of prototype building

3-story specimen, UCSD-NEES
3-story specimen behaved well

- specimen was subjected to an extended series of ground motions

<table>
<thead>
<tr>
<th>Ground Motion</th>
<th>Scale Factor</th>
<th>Level of Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperial Valley 1979</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>El Centro</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120%</td>
<td>DE</td>
</tr>
<tr>
<td></td>
<td>150%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>180%</td>
<td>MCE</td>
</tr>
<tr>
<td></td>
<td>250%</td>
<td>above MCE</td>
</tr>
<tr>
<td>Imperial Valley 1940</td>
<td>300%</td>
<td></td>
</tr>
<tr>
<td>El Centro #5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northridge 1994</td>
<td>125%</td>
<td>MCE</td>
</tr>
<tr>
<td>Sylmar</td>
<td>160%</td>
<td>1.25 MCE</td>
</tr>
<tr>
<td>Chi Chi 1999</td>
<td>150%</td>
<td>2.0 MCE</td>
</tr>
</tbody>
</table>

150 % Chi Chi 1990 (2 MCE)

Design Earthquake (DE), 10% in 50 years
Maximum Considered Earthquake (MCE), 2% in 50 years
task 2- develop displacement-based design

- based on achieving specified deformation limits under selected seismic hazard levels
- fundamental difference between force-based and displacement-based design

![MDOF structure](image1)

![idealized SDOF](image2)

![Graph](image3)
technical basis for displacement-based method

- select a reasonable target mechanism for each hazard level

- identify the inelastic deformation demands and adjust strength or detailing

- reinforce for sufficient inelastic deformation capacity in hinging regions
fundamental steps

Step 1: Define Seismic Hazard

Step 2: Define Design Target Local Deformation Ratios and Target Drifts

Step 3: Propose Initial Design, Conduct Inelastic Analysis, and Develop Design Mechanism

Step 4: Determine Equivalent Hysteretic Damping

Step 5: Determine Equivalent Structural Period

Step 6: Compute Required Base Shear, \( (V_{eq})_{req} \)

Step 7: Predict Actual Base Shear, \( (V_{eq})_{actual} \)

Step 8: Verify Base Shear

Step 9: Complete Structural Detailing

Not Good

Modify Lateral System

OK
task 3- conduct cyclic-load test of shear-walls

- designed and conducted cyclic-load tests of 41 masonry shear-walls at UT Austin and WSU
**task 4- improved analytical tools**

- predict nonlinear resistance and failure behavior
- predict local and global responses and deformations
- different modeling approaches were considered
  - nonlinear “macro” models, PERFORM 3D “General Wall Element”
task 5- validation of displacement-based design

- application of proposed displacement-based design and analytical tool
- a full-scale two-story reinforced masonry shear-wall system, complex geometry of openings
select seismic hazard levels and target drifts

<table>
<thead>
<tr>
<th>seismic hazard Level</th>
<th>damage state</th>
<th>deformation limits</th>
<th>corresponding inter-story drift ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Earthquake (DE)</td>
<td>Safety Damage State</td>
<td>0.8 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Maximum Considered Earthquake (MCE)</td>
<td>Collapse Damage State</td>
<td>1.5 %</td>
<td>1.0 %</td>
</tr>
</tbody>
</table>

![Diagram showing flexure-controlled and shear-controlled walls segments]
shake table test of 2-story specimen

- specimen was subjected to an extended series of ground motions

<table>
<thead>
<tr>
<th>order</th>
<th>ground motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30% El Centro 1979</td>
</tr>
<tr>
<td>2</td>
<td>43% El Centro 1979</td>
</tr>
<tr>
<td>3</td>
<td>86% El Centro 1979</td>
</tr>
<tr>
<td>4</td>
<td>108% El Centro 1979</td>
</tr>
<tr>
<td>5</td>
<td>145% El Centro 1979</td>
</tr>
<tr>
<td>6</td>
<td>160% El Centro 1979</td>
</tr>
</tbody>
</table>

160% El Centro response spectrum

T = 0.21 sec, beginning
T = 0.27 and 0.38 sec

spectral peaks at T = 0.27 and 0.38 sec
shake-table test of specimen above MCE

- specimen successfully resisted repeated ground motions up to MCE
measured vs. predicted responses

- walls exceeded expected deformation capacities

**Wall W - 1** was flexure-dominated, exceeded 1% drift ratio

**Wall W - 2** was shear-dominated, exceeded 2% drift ratio

**Wall W - 3** was shear-dominated one way, flexure-dominated the other way, exceeded 1% drift ratio
important points of this presentation

• current force-based seismic design does not always work well for reinforced masonry shear-wall structures

• proposed displacement-based seismic design works for masonry shear wall structures
  ▫ it produces structures that behave reliably in strong earthquakes
  ▫ it is more consistent and more transparent than current force-based seismic design