Reducing uncertainty in the assessment of the masonry buildings by moving from empirical to analytical drift capacity models

Katrin Beyer, EPFL

http://eesd.epfl.ch/

The 42nd Risk, Hazard & Uncertainty Workshop, Hydra, Greece June 2016
Acknowledgments

Collaborators

- Bastian Wilding, Dr. Sarah Petry, Marco Tondelli, Dr. Panos Mergos

Grants

- FP7-Programme for access to TREES laboratory of EUCENTRE
- Swiss National Science Foundation
- Federal Office for the Environment in Switzerland (OFEV)
- In-kind contributions by Morandi Frères SA
Drift capacity of unreinforced masonry walls

State of practice (e.g. Eurocode 8)

Empirical model

- Shear failure: $\delta_u = 0.4\%$
- Flexural failure: $\delta_u = 0.8\% \frac{H_0}{L}$

$H_0 =$ Shear span
$L = $ Wall length

State of the art

Empirical models with further parameters

- Axial stress ratio
- Parameter describing moment profile $H_0/H$
State-of-the-art: Unreinforced masonry walls

• Determining the displacement capacity from quasi-static cyclic tests

• Assemble data bases + fit empirical models
State-of-the-art: Unreinforced masonry walls

Prediction of drift capacity $\delta = \Delta / H$ with empirical model

Walls failing in flexure

- Poor prediction of mean response
- Very large scatter

Walls failing in shear

Empirical model (EC8)

Masonry typology: Clay brick masonry with normal cement mortar
Drift capacity of masonry walls

Drift capacity reduces with the size of the test unit.

- Biased towards unrepresentative small test units
- General problem of structural engineering: Large tests required → number of tests will always be limited

→ Limits for empirical models
Change the scale at which we measure and predict

Global response

Local response
Analytical model of masonry walls: Critical Diagonal Crack Model

- System simulating crack growth and decompression:
  - $V_p$
  - $V_{cr,2}$

- System before onset of cracking and decompression:
  - $V_e$

- Pre-peak domain:
  - $\delta_p$

- Post-peak domain:
  - $\delta_{pp}$
  - $\delta_{ult}$

- Peak load by means of direct stress determination in virtual section - shear or compressive stresses exceed respective resistance

- Completion of crack growth
- Onset of diagonal cracking
- Can also be switched
- Onset of flexural decompression

- Crack degradation completed
  - No stress transfer in the diagonal crack

- System simulating post-peak behaviour:
Analytical model of masonry walls: Critical Diagonal Crack Model

Validation of analytical model against experimental results on the global and local level
Performance of empirical vs analytical model

Walls failing in flexure

- Drift capacity of masonry walls

1.8 ± 1.1
0.7 ± 0.3

Walls failing in shear

- Drift capacity of masonry walls

1.7 ± 1.0
0.9 ± 0.4

Empirical model (EC8)
Analytical model

Research results

Proof of concept that developing such analytical models for predicting the drift capacity of unreinforced masonry walls is feasible.

→ Better because they connect local to global deformation measures
Analytical model of masonry walls: Critical Diagonal Crack Model

System simulating crack growth and decompression:

System before onset of cracking and decompression:

\[ V [N] \]

\[ V_p \]
\[ V_{cr,1} \]
\[ V_{cr,2} \]
\[ V_e \]

Peak load by means of direct stress determination in virtual section - shear or compressive stresses exceed respective resistance

pre-peak domain

post-peak domain

\[ \delta_p \]
\[ \delta_{pp} \]
\[ \delta_{ult} \]

\[ \delta [%] \]
\[ u [m] \]

System simulating post-peak behaviour:

Completion of crack growth

Onset of diagonal cracking

Can also be switched

Onset of flexural decompression

Crack degradation completed

No stress transfer in the diagonal crack
Loading history

Suite of cycles with increasing amplitudes

- Variables:
  - Number of cycles per drift amplitude (often $n=2$ or $n=3$)
  - Increase of amplitudes $\Delta\delta$
Does the choice of the loading history influence the obtained drift capacities?
Systematic study on cumulative damage effects on URM walls missing
Pairs of monotonic and cyclic tests:

Ganz & Thürlimann (1984)
• W1 (monotonic) & W6 (cyclic)
• W2 (monotonic) & W7 (cyclic)

Magenes & Calvi (1992)
• MI1m (monotonic) & MI1 (cyclic)
Does the choice of the loading history influence the obtained drift capacities?

- Force capacity is not affected by cumulative damage demand
- Displacement capacity from monotonic tests is twice as large as from cyclic tests.

→ Displacement capacity depends on the demand.
Loading history: Influence of number of cycles on $\delta_u$

- Flexural failure: Unaffected by number of cycles
- Shear and hybrid failures: Displacement capacity reduces with increasing number of cycles that are applied
  → Displacement history that is applied in cyclic tests matters.
Many protocols have been proposed:

- One specific for URM structures: SPD protocol (Porter 1987), result of US-Japan workshop
- One that is most frequently used: SAC protocol (ATC 1992)
Loading protocols for quasi-static cyclic tests

- All existing loading protocols derived for regions of high seismicity
- When applied to structural elements for regions of moderate seismicity: Test units subjected to too many cycles

De-aggregation Results for Switzerland for T=2475 yrs (2/50)
Sion (\(a_{gd}=0.15g\) for T=475 yrs)           Basel (\(a_{gd}=0.12g\) for T=475 yrs)
Loading protocols for quasi-static cyclic tests

New loading protocols: Moderate vs. High Seismicity

<table>
<thead>
<tr>
<th></th>
<th>T=0.2s</th>
<th>T=0.3s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismicity</td>
<td>$n_{tot} = 14$</td>
<td>$n_{tot} = 10$</td>
</tr>
<tr>
<td>$\alpha = 2.4$</td>
<td></td>
<td>$\alpha = 2.2$</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismicity</td>
<td>$n_{tot} = 24$</td>
<td>$n_{tot} = 20$</td>
</tr>
<tr>
<td>$\alpha = 2.8$</td>
<td></td>
<td>$\alpha = 1.9$</td>
</tr>
</tbody>
</table>

\[ f(t) = 0.50 - 0.55 \exp(t^{2.4}) \]

\[ f(t) = 0.50 + 0.55 \exp(t^{2.2}) \]
Summary & Outlook

Summary

• Analytical drift capacity models seem feasible (for all limit states)
• As long as we do not have a model that captures cumulative damage effects on masonry performance, we should test with realistic testing protocols.

Future research

• Effect of cyclic degradation / cumulative damage
• Effect of strain rates
• Failure criteria for other masonry typologies (thin bed mortar, stone masonry, …)
Change the scale at which we measure and predict

**Coupling of shear and flexural deformations**

Shear strains concentrate in the compression strut

**Axial strain profiles**

Linear strain profile in compression zone is a reasonable assumption
Change the scale at which we measure and predict

Confinement effect at the base of the wall

Onset of crushing in 2\textsuperscript{nd} joint

Strength of masonry $f_u$
determinant in 2\textsuperscript{nd} joint

Strength of brick $f_{cB}$ in base joint
Analytical model of URM walls: CDC Model

Shear critical walls: Critical Diagonal Crack Model

Assumptions:
- Deformations in diagonal crack can be lumped in a single diagonal crack ("Critical Diagonal Crack" = CDC)
- Geometry of CDC:
  - Geometry of wall
  - Geometry of bricks

Critical diagonal crack
Analytical model of URM walls: CDC Model

Onset of formation of CDC: Modified Mann – Müller criterion
- Stress demand: Plane section analysis
  - Compute position along the CDC where the vertical bed joint stresses due to $N$, $M$, $T$ are for the first time zero
  - Location where diagonal crack starts to form
Analytical model of URM walls: CDC Model

Peak strength: Mohr-Coulomb criterion based on local stresses
- Stress demand:
  - Axial stresses: Plane section analysis
  - Shear stresses: Parabolic stress distribution, shear only carried by area in compression
- Peak strength reached when
  - Mohr-Coulomb criterion is exceeded
  - Compressive strength is exceeded (confinement effect considered)
Analytical model of URM walls: CDC Model

Stiffness of wall

• Only area in compression contributes to the stiffness
• The diagonal crack divides the wall section into two sections (composite beam)
• Limited shear stress transfer between the sections allowed
Analytical model of URM walls: CDC Model

Residual strength: Zero stress transfer in CDC

- Stress demand:
  - Axial stresses: Plane section analysis
  - Shear stresses: Parabolic stress distribution, shear only carried by area in compression

- Residual strength reached when
  - Tensile strength of top and bottom brick exceeded (Turnsek-Cacovic)
  - Compressive strength is exceeded (confinement effect considered)