EN 1998-1-2 Buildings
Specific Rules for Masonry Buildings

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24th January 2023

First generation of EC8 (2004)

Chapter on Masonry Buildings

Force-based design

- Behaviour factor q: NDP
- Recommended values
  - Unreinforced masonry (URM): q=1.5-2.5
  - Confined masonry (CM): q=2.0-3.0
  - Reinforced masonry (RM): q=2.5-3.0

Note: Most countries adopted q=1.5 for URM

→ Assumption of an elastic behaviour of the structure

Seismic response of URM buildings

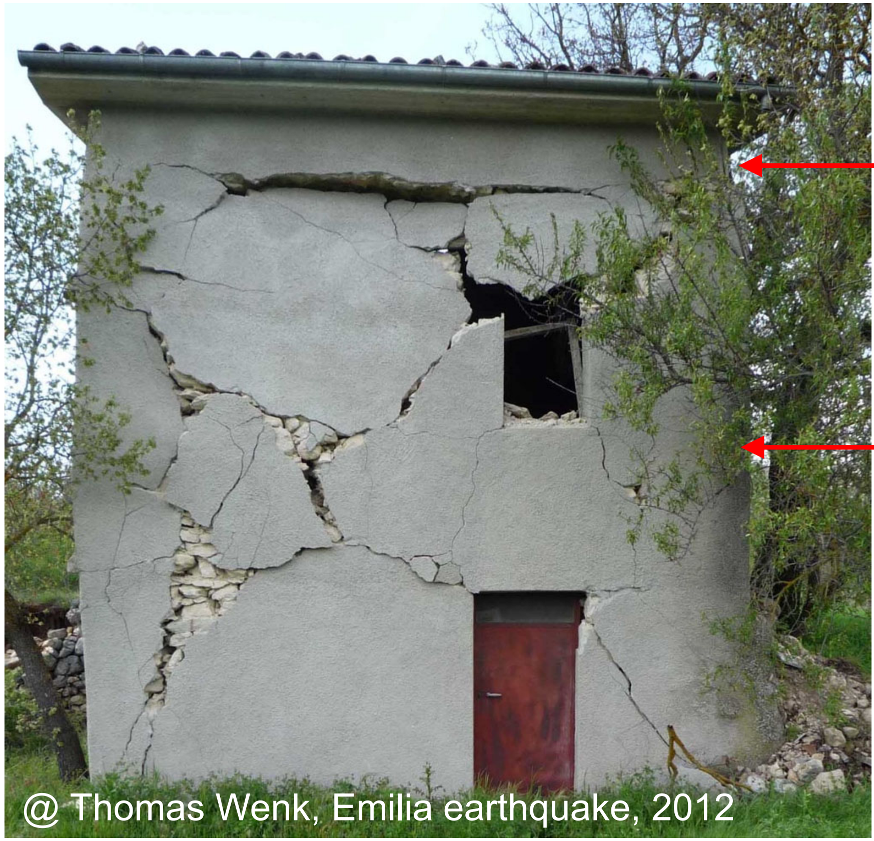
Amatrice, Italy, M_w=6.2, August 24, 2016. http://freakyfeeds.com

Since 2004

@ Katrin Beyer, L'Aquila, 2009

- Observation: Modern URM buildings with stiff slabs behaved well in several Italian earthquakes (Penna et al., 2014; Sorrentino et al., 2019)

Important structural features of URM buildings – Box behaviour



Box behaviour at top floor due to RC ring beam and roof that was installed as part of a retrofit measure

Lack of box behaviour at first floor

Important structural features of URM buildings – Stiff floor and wall-slab connections

Lack of stiff floors and poor wall-slab connections

→ Missing redistribution of forces from out-of-plane loaded walls to in-plane loaded walls

Modern URM building with RC slabs

@ Katrin Beyer, L'Aquila, 2009

Box behaviour

Required characteristics

- Good wall-slab and wall-wall connections
- Floor diaphragms with a certain shear stiffness

Resulting behaviour

- Redistribution of forces between in-plane loaded walls
- Out-of-plane stability of walls is improved by good wall-slab connections and diaphragm stiffness; out-of-plane forces are transferred to in-plane loaded walls
- Inertia forces are transferred to foundation as in-plane forces in walls

Since 2004

- Observations after earthquakes - Box behaviour as basis for a good seismic response
- New shear-compression test data on URM walls available
- New shake table test data on URM buildings available
- New research on q-factors for URM buildings
  Morandi P, Butenweg C, Breis K, Beyer K, Magenes G. Latest findings on the behaviour factor *q* for the seismic design of URM buildings. *Bull Earthquake Eng* **20**, 5797–5848 (2022)

European database on shear-compression tests (Gams et al.)

Goals for the revision of the masonry chapter

Formal brief

- Reduce the number of NDPs

Additional goals

- Aim for a robust structural behaviour
    - Box behaviour
    - Redundancy
    - Limited axial load ratio
- Update q-factors based on new findings from experimental and numerical studies
- Document background information

Scope of Chapter 14 «Specific rules for Masonry Buildings»

Covered:

- (Modern) Unreinforced masonry
- Reinforced masonry
- Confined masonry

} buildings

Not covered:

- Masonry infills → Chapter 7.4

Structure of chapter

Focus of this presentation

Ductility classes for masonry buildings

Masonry buildings should be designed to either DC1 or DC2.

- $S_\delta \leq 3.0$ m/s^2: DC1 or DC2
- $S_\delta > 3.0$ m/s^2: DC2

DC1:

- Flexible diaphragms allowed (no effective redistribution of forces from one wall plane to another → reduced redundancy)
- No limit on axial load ratio of walls (potentially brittle wall behaviour)

Note: The q-factor is here used as maximum permissible q-factor, i.e., q=1.5 means q ≤ 1.5.

Ductility classes for masonry buildings

DC1:

- Only overstrength considered
- Behaviour factor for in-plane analysis: q=1.5

DC2:

- No criterion for global mechanism
- Control of deformation capacity by limiting the maximum axial load ratio in the masonry walls
- Behaviour factor for in-plane analysis: Function of
  - Structural configuration (number of walls & coupling effect)
  - Masonry type
  - Axial load ratio

Note: The q-factor is here used as maximum permissible q-factor, i.e., q=1.5 means q ≤ 1.5.

DC2: Behaviour factors for in-plane analysis

$$q = q_D \cdot q_R \cdot q_S$$

- q_D - Deformation capacity
- q_R - Redistribution of forces
- q_S - All other sources

DC2: Behaviour factors for in-plane analysis

Table with q-factors

- Masonry type
- Building configuration

Structural configuration in the earthquake direction	q_R	Masonry type	q_D	q_{max}
At least 6 piers of various lengths and a significant coupling effect	1.4	URM (general)	1.2	2.6
	1.4	Calcium silicate (hollow and solid)	1.0	2.2
	1.4	AAC Gr 1 and 1s	1.4	2.8
	1.4	URM Gr 1 and 1s clay	1.6	2.8
	1.4	Confined masonry (general)	1.65	3.4
	1.4	Reinforced masonry (general)	1.8	3.8
At least 6 piers of various lengths, or at least 4 walls and a significant coupling effect	1.2	URM (general)	1.2	2.1
	1.2	Calcium silicate (hollow and solid)	1.0	1.8
	1.2	AAC Gr 1 and 1s	1.4	2.5
	1.2	URM Gr 1 and 1s clay	1.6	2.8
	1.2	Confined masonry (general)	1.65	2.9
	1.2	Reinforced masonry (general)	1.8	3.2
Less than 6 piers of various lengths or axial load ratios, and no significant coupling effect;	1.0	URM (general)	1.2	1.8
	1.0	Calcium silicate (hollow and solid)	1.0	1.5
	1.0	AAC Gr 1 and 1s	1.4	2.1
	1.0	URM Gr 1 and 1s clay	1.6	2.4
	1.0	Confined masonry (general)	1.65	2.5
	1.0	Reinforced masonry (general)	1.8	2.7
Buildings with flexible diaphragms (confined and reinforced masonry only; URM buildings with flexible diaphragms must be designed for DC1)	1.0	Confined masonry	1.35	2.0
	1.0	Reinforced masonry	1.6	2.40

1) Walls are considered to have various lengths if the ratio of the wall lengths that correspond to the 100%ile and 75%ile is at least 1.2.

2) A significant coupling action can be assumed if the stiffness of the building is at least 1.5 times as high when the coupling is considered than when it is not considered. Single storey buildings are not likely to develop a significant coupling action.

DC2: Behaviour factors for in-plane analysis

Masonry type

URM (general)
Calcium silicate
AAC Gr 1 and 1s
URM GR 1 and 1s clay
Confined masonry
Reinforced masonry

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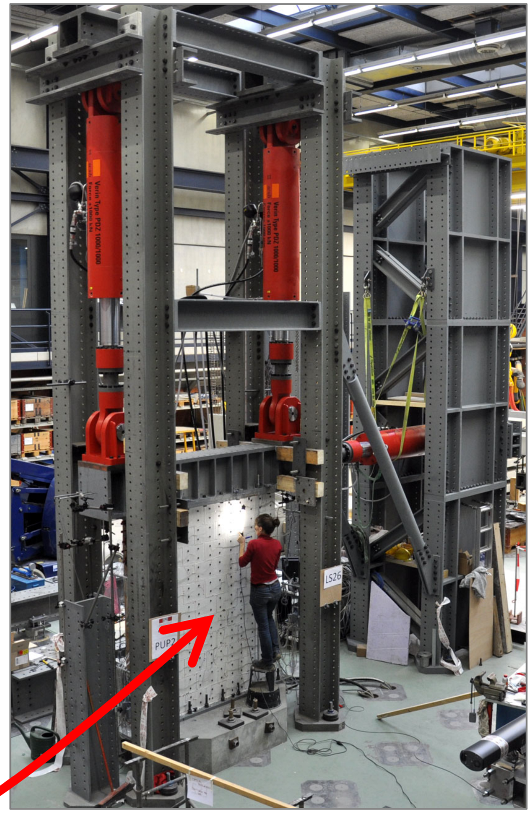
Behaviour factors

$$q = q_D \cdot q_R \cdot q_S$$

- q_D - Deformation capacity
- q_R - Redistribution of forces
- q_S - All other sources

Behaviour factor q_D

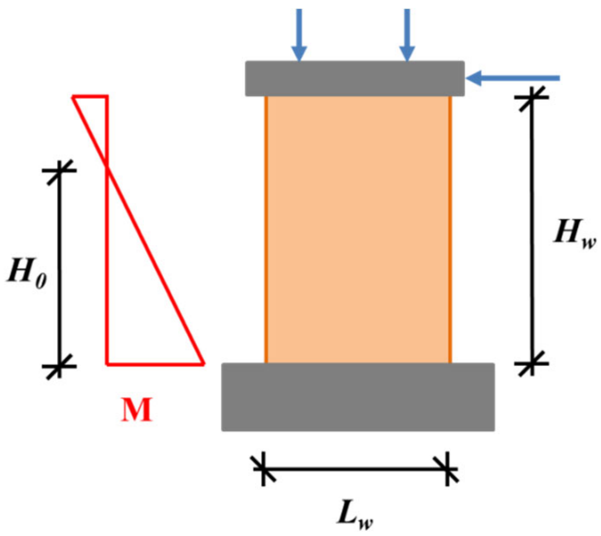


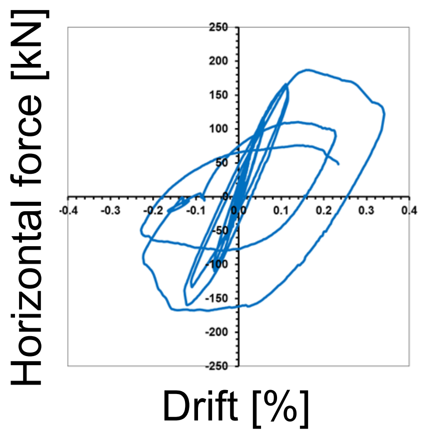
Displacement ductility of a URM building depends on the deformation capacity of the walls

Drift capacity values

Experimental values from shear-compression tests

- Axial force constant
- H_0 constant





European Database

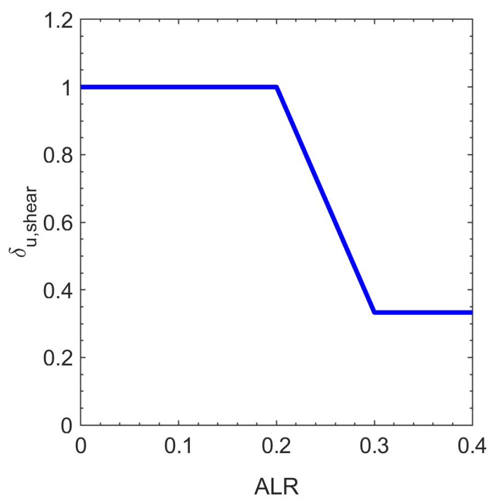
- Collects quasi-static cyclic shear compression tests on masonry walls
- U of Pavia (Italy), ZAG (Slovenia) and EPFL (Switzerland)
- Modern brick masonry amd historical stone masonry walls

Masonry typology	Number of tests
Hollow core clay bricks (HC)	141
Solid clay bricks (SB)	83
Calcium silicate bricks (CS)	26
Autoclaved aerated concrete units (AAC)	26

Which parameters influence δ_u?

Which parameters influence δ_u?

- Failure mode
- Shear span
- Axial load ratio
- Brick type
- Wall size



Masonry typology	$\delta_{u,shear}$
Hollow core clay bricks (HC)	0.31%
Solid clay bricks (SB)	0.69%
Calcium silicate bricks (CS)	0.28%
Autoclaved aerated concrete units (AAC)	0.37%

Katrin Beyer, Bastian Wilding, & Amir Rezaie. (2022). Drift capacity models for modern URM walls for EC8 Part 1 (V1.2b). Zenodo. https://doi.org/10.5281/zenodo.6224940

Deriving δ_{NC} from δ_u

- Account for
  - Difference between collapse drift and ultimate drift
  - Load history effects
  - Partial safety factor

- LS of Near Collapse (NC)

$$\delta_{NC,50\%} = \delta_{u,50\%} \cdot R_{LH,NC} \cdot \frac{\delta_{max}}{\delta_u}$$

Beyer K, Magenes G (2020) Proposal for q-factors of modern masonry buildings for EC8 Part 1 – background document for the masonry chapter in EC8 Part 1, Tech. Rep. Version 1.1, DOI 10.5281/zenodo.3776654.

Behaviour factor q_D

- Assumption: Displacement capacity of building is controlled by walls failing in shear subjected to double-bending
- Morandi and Butenweg: for shear drift capacity of 0.3% q_D=1.6-2.95
- Assume: q_D=2.0 for $\frac{\delta_{SD,shear}}{\gamma_{Rd}} = 0.3\%$
- Scale q_D linearly with drift capacity (but limit q_D to 1.6)

Masonry typology	q_D
Hollow core clay bricks (HC)	1.2
Solid clay bricks (SB)	1.6
Calcium silicate bricks (CS)	1.0
Autoclaved aerated concrete units (AAC)	1.4

Behaviour factors

$$q = q_D \cdot q_R \cdot q_S$$

- q_D - Deformation capacity
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DC2: Behaviour factors for in-plane analysis

Structural configuration

At least 6 piers of various lengths and a significant coupling effect

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DC2: Behaviour factors for in-plane analysis

Less than 6 piers of various lengths or axial load ratios and no significant coupling effect

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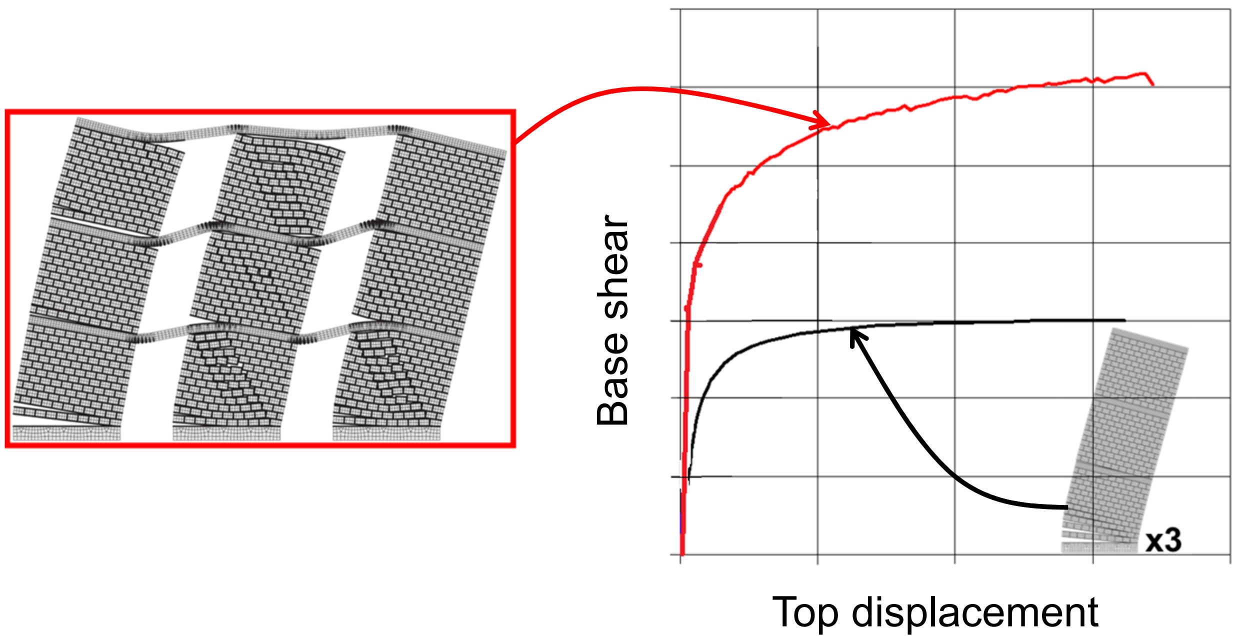
Behaviour factor q_R – Coupling effect provided by slabs, beams and spandrels

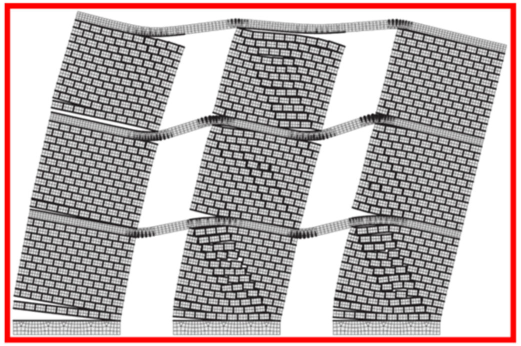


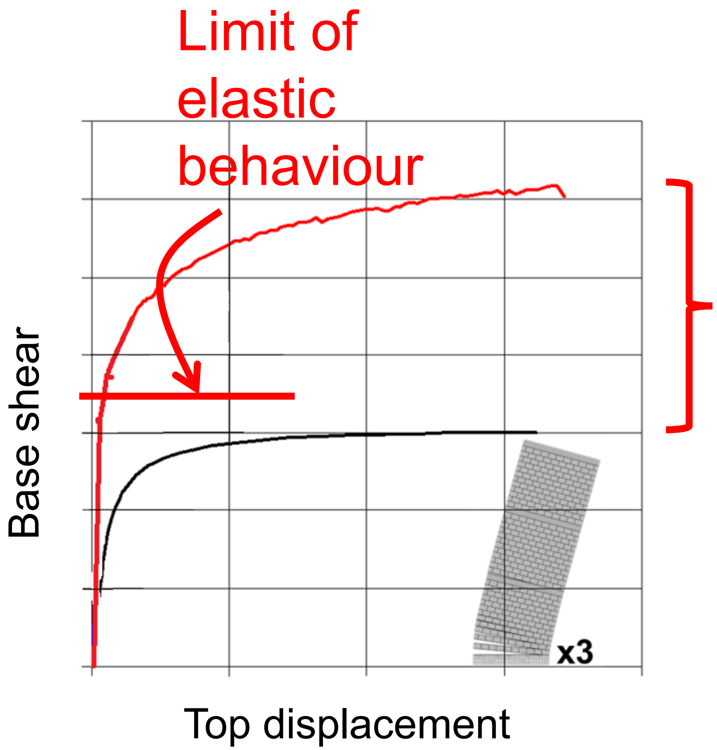
Required for a significant framing effect

- More than 1 storey
- Stiffness of the building model with coupling at least 1.5 times the stiffness of building model without coupling

Behaviour factor q_R – Coupling effect provided by slabs, beams and spandrels

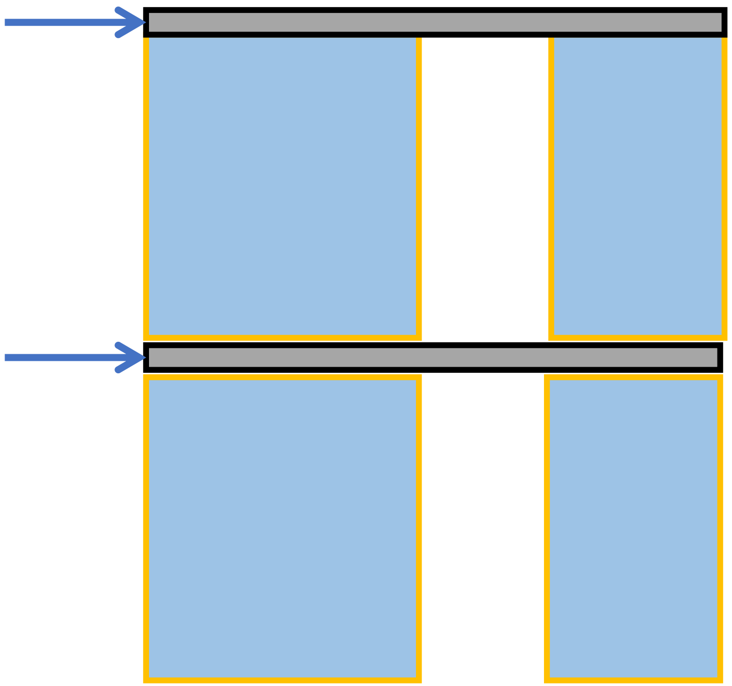
Reserve capacity if out-of-plane bending stiffness of slab *is* modelled

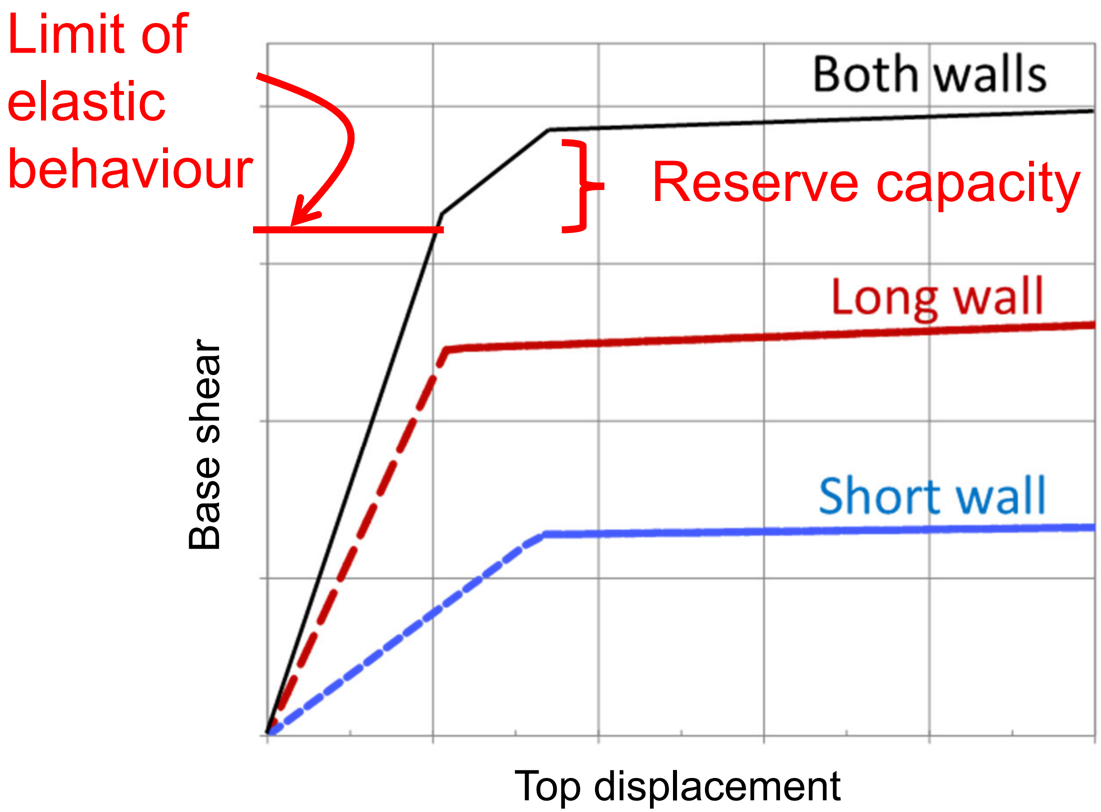




Reserve capacity if out-of-plane bending stiffness of slab *is not* modelled

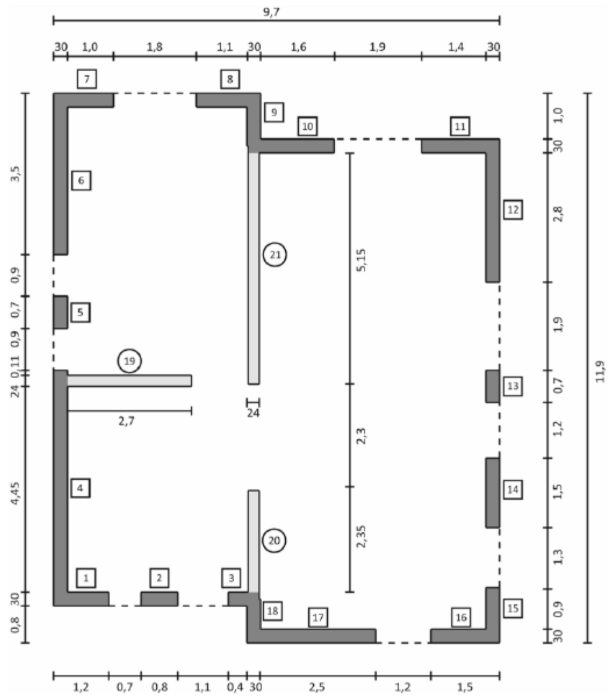
Behaviour factor q_R - Difference in wall length





Behaviour factor q_R

- Case studies by Morandi et al. and Butenweg et al.
  - q_R =1.0 - 2.0 depending on
    - Number of walls in one direction
    - Framing action provided by slabs, beams and spandrels
    - Differences in wall lengths



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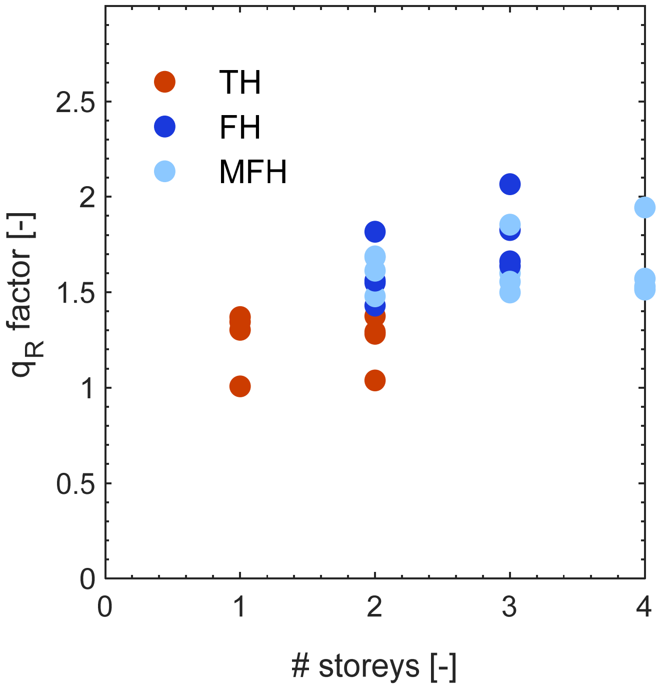
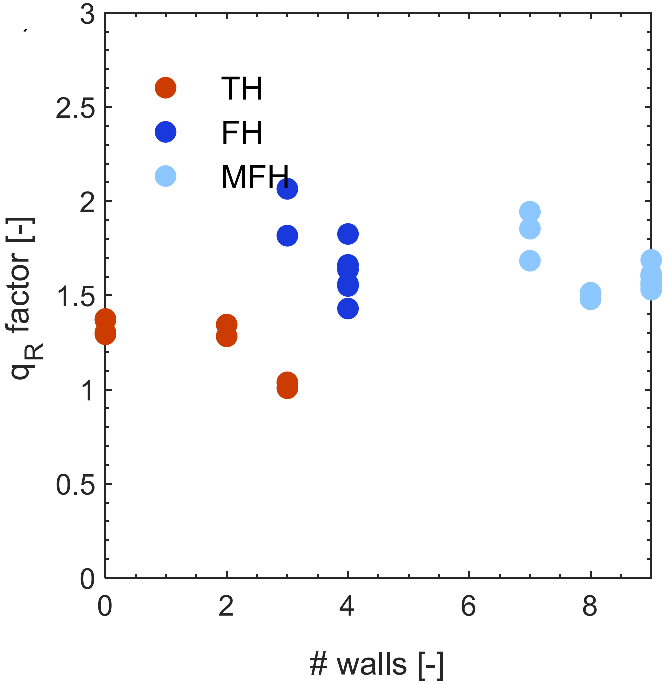
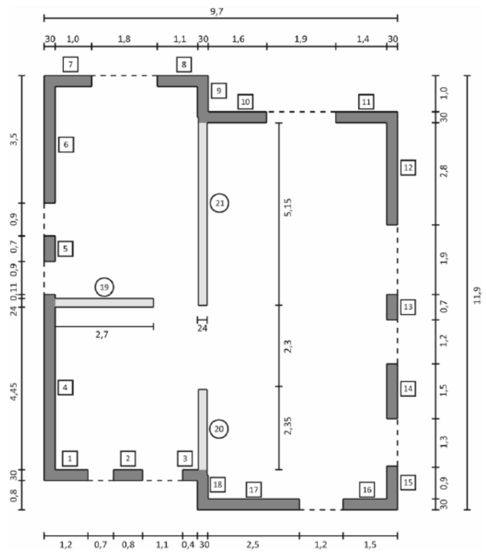
Behaviour factor q_R

Framing effect



Redistribution of forces





Case studies with 2-4 storeys & various floor plans

Based on data by Butenweg et al.

Behaviour factor q_R

Effect	Criteria
Framing action: Significant framing action provided by slabs, beams and spandrels	Stiffness ratio with/without framing action considered > 1.5 & more than 1 storey
Number of walls: Significant number of walls in one direction	At least 6 walls
Difference in wall lengths: Significant difference in wall lengths	Longest wall / second longest wall (for 6 walls)

	q_R
All effects	1.6
Two effects	1.3
In all other cases or if flexible diaphragms	1.0

Behaviour factors

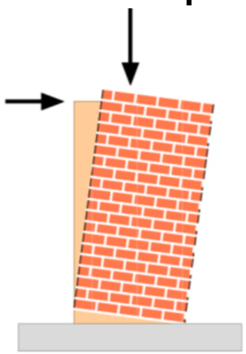
$$q = q_D \cdot q_R \cdot q_S$$

- q_D - Deformation capacity
- q_R - Redistribution of forces
- q_S - All other sources

Behaviour factor q_s

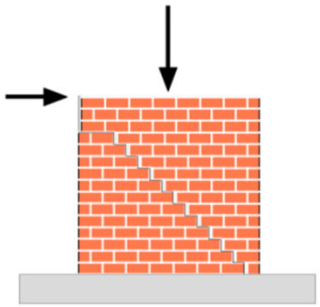
- For all other materials assumed as q_s=1.5
- Main sources: Safety factors on material properties

- However: For URM
  - Resistance results to a large extent from axial load
  - Material properties have a smaller effect on the resistance



Rocking failure

$$V_{Rd} = \frac{l_w N}{2H_0}\left(1 - 1.15\frac{N}{l_w t_w f_c}\right)$$



Shear failure

$$V_{Rd} = f_{vd0} l_w t_w + 0.4N$$

Behaviour factor q_S

- q_s should be smaller for masonry than for other materials
  - Partial safety factor on cohesion
  - Effects that are not modelled (flange effects, …)
- $q_S \cong 1.35$

- To be in-line with other materials
  - Increase q_S from 1.35 to 1.5
  - Reduce q_R from 1.0/1.3/1.6 to 1.0/1.2/1.4

Behaviour factors

- URM structures: Cap at q=2.8 to be consistent with RC structures
- RC wall structures: depending on degree of coupling q=2.0-2.5 (DC2)
- URM structures: typically
  - Higher redundancy
  - Stronger coupling

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Less than 6 piers of various lengths or axial load ratios, and no significant coupling effect;	1.0	URM (general)	1.2	1.8
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Behaviour factors for out-of-plane response

DC1:

- All masonry typologies q_{oop}=1.0

DC2:

- Unreinforced masonry q_{oop}=1.25
- Confined masonry q_{oop}=1.25
- Reinforced masonry q_{oop}=1.5

If slenderness limits are met, explicit out-of-plane design checks are not necessary.

Background document on oop limits:

Godio, Michele, & Beyer, Katrin. (2020). Limits of slenderness ratios for URM walls: proposal for EC8-Part 1 - Background document for the masonry chapter in EC8 Part 1 (Version V1). Zenodo. https://doi.org/10.5281/zenodo.3776804

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Acknowledgments

- Collaborators: Dr Savvas Saloustros, Dr Bastian Wilding, Dr. Sarah Petry, Ernesto Inzunza
- Colleagues from University of Pavia: Prof. Guido Magenes, Dr. Paolo Morandi, Prof. Andrea Penna
- Colleagues from RWTH Aachen: Prof. Christoph Butenweg
- Colleague from ZAG: Dr Matias Gams
- WG 1 Masonry
- PT2, in particular Prof. André Plumier, Prof. Philippe Bisch
- Prof. Dina D’Ayala

Thank you

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