Universitatea Tehnică de Construcții București

Challenges of earthquake resistant design for buildings in Bucharest

Viorel Popa

History of design regulations

1940 Major seismic event (M 7.7, 150 km depth) >> some seismic design rules were introduced in day to day practice

- 1963 First seismic design code P13-63, revised edition in 1970

1977 Major seismic event (M 7.4, 109km depth)

- 1980 New seismic design code P100-80

1986 Large seismic event (M 7.1, 133km depth)

1990 Large seismic event (M 7.1, 133km depth, M 6.9, 91 km)

- 1992 New seismic design code P100-92
- 2006 New code based on EN 1998-1, revised in 2013

Existing housing units in Bucharest

Bucharest

- 1963 – 1977

  3303 buildings (3-11 stories) were built in Bucharest

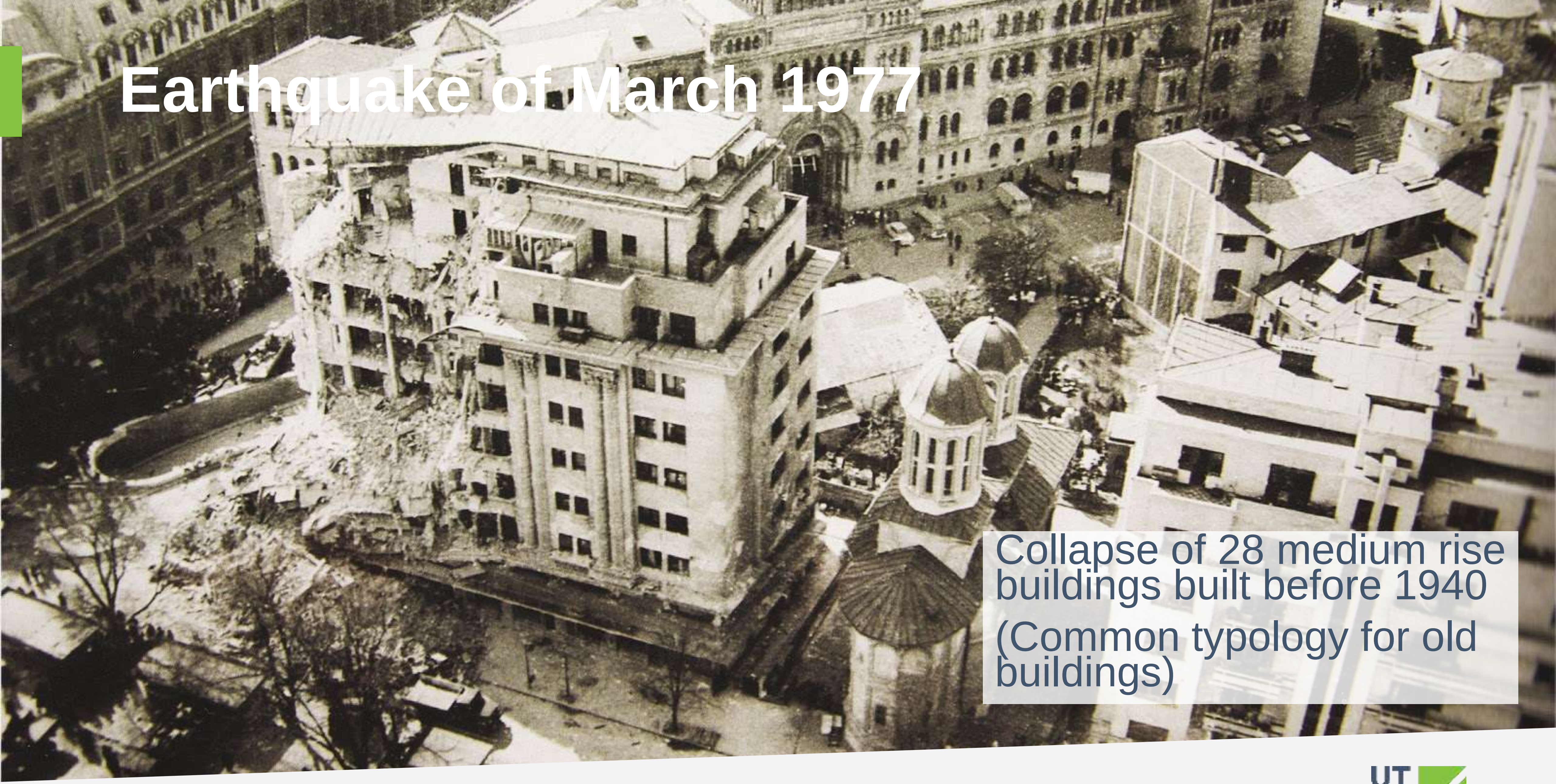
  - Concrete frames
  - Concrete, lightly reinforced, shear walls
  - Prefabricated – large panels
  - Soft-storey – most vulnerable

Digital Image (2004) University of Wisconsin-Milwaukee Libraries

Existing housing units in Bucharest

UTCB
Universitatea Tehnică de Construcții București

Earthquake of March 1977



Collapse of 28 medium rise buildings built before 1940

(Common typology for old buildings)

Earthquake of March 1977

Collapse of 3 concrete buildings built after 1950

(picture: soft story buildings, still under use)

Seismic design practice

Seismic design code

P100-1/2013

- Compulsory for entire RO territory, enforced RO Gov’t
- Similar to EN1998-1 (procedures, format, symbols) with specific recommendations for Romania (seismic action, capacity design, detailing rules)
- Performance based approach – 2 performance objectives
- Capacity design method

Fundamental requirements

	Damage control	Life Safety
MRI = 40 years (22% probability of exceedance in 10 years)	Check stiffness (drift limitation 0,5%; 0,75%; 1,0%)	
MRI = 225 years (20% probability of exceedance in 50 years)		Check strength, drift (2,5%); ductility measures

Normal importance buildings

Importance classes

- P100-1 classifies the structures into IV importance classes
- Seismic requirements dependent on consequences of failure
- Classification similar to ASCE 07

- Classification based on building height
  - $\geq$ 28m – importance class II, 20% increase of the PGA
  - $\geq$ 45m – importance class I, 40% increase of PGA

Ductility classes

DC High – large reduction factors (2 .. 6.75),
capacity design with severe local ductility conditions

DC Medium – medium reduction factors (1.50 .. 4.75)
capacity design with average local ductility conditions

DC Low – small reduction factors (1.50 .. 2)
no capacity design, no special detailing conditions
(valid for a_g<0,1g)

Concrete buildings

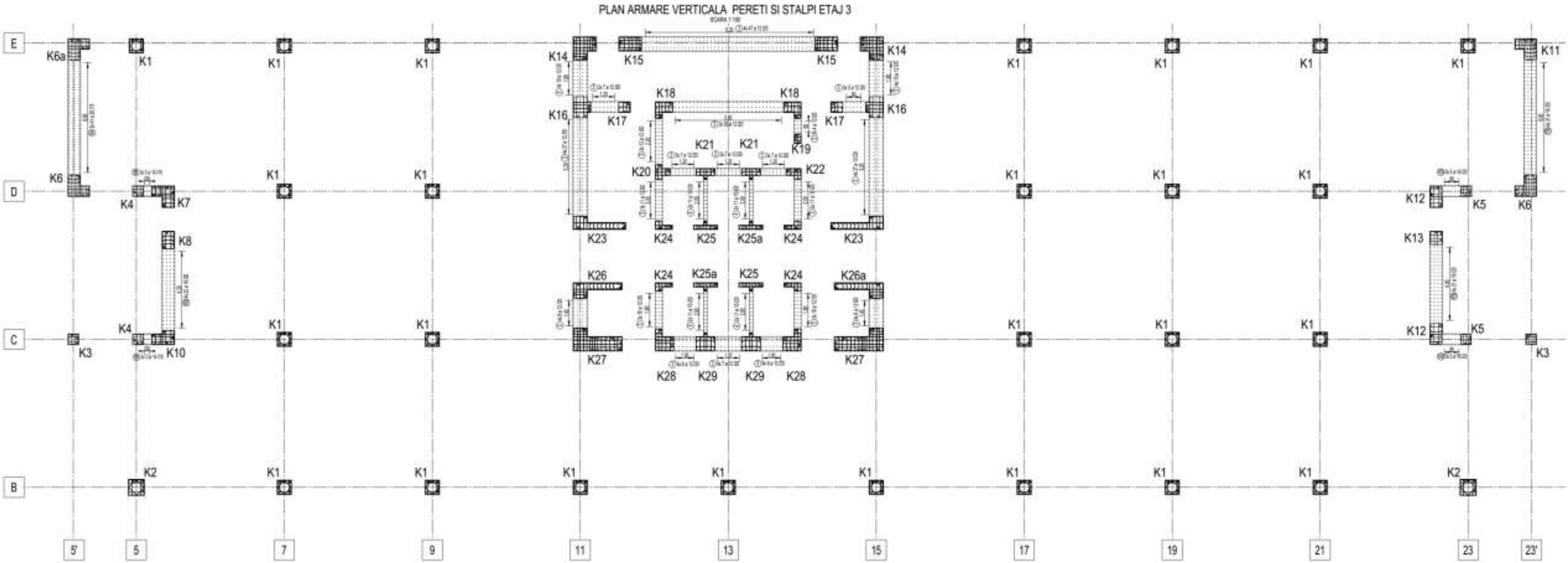
Key objectives (DCH):

- Ductility DCH
- Lateral stiffness for damage limitation
- Lateral strength to control displacement demand

Concrete buildings

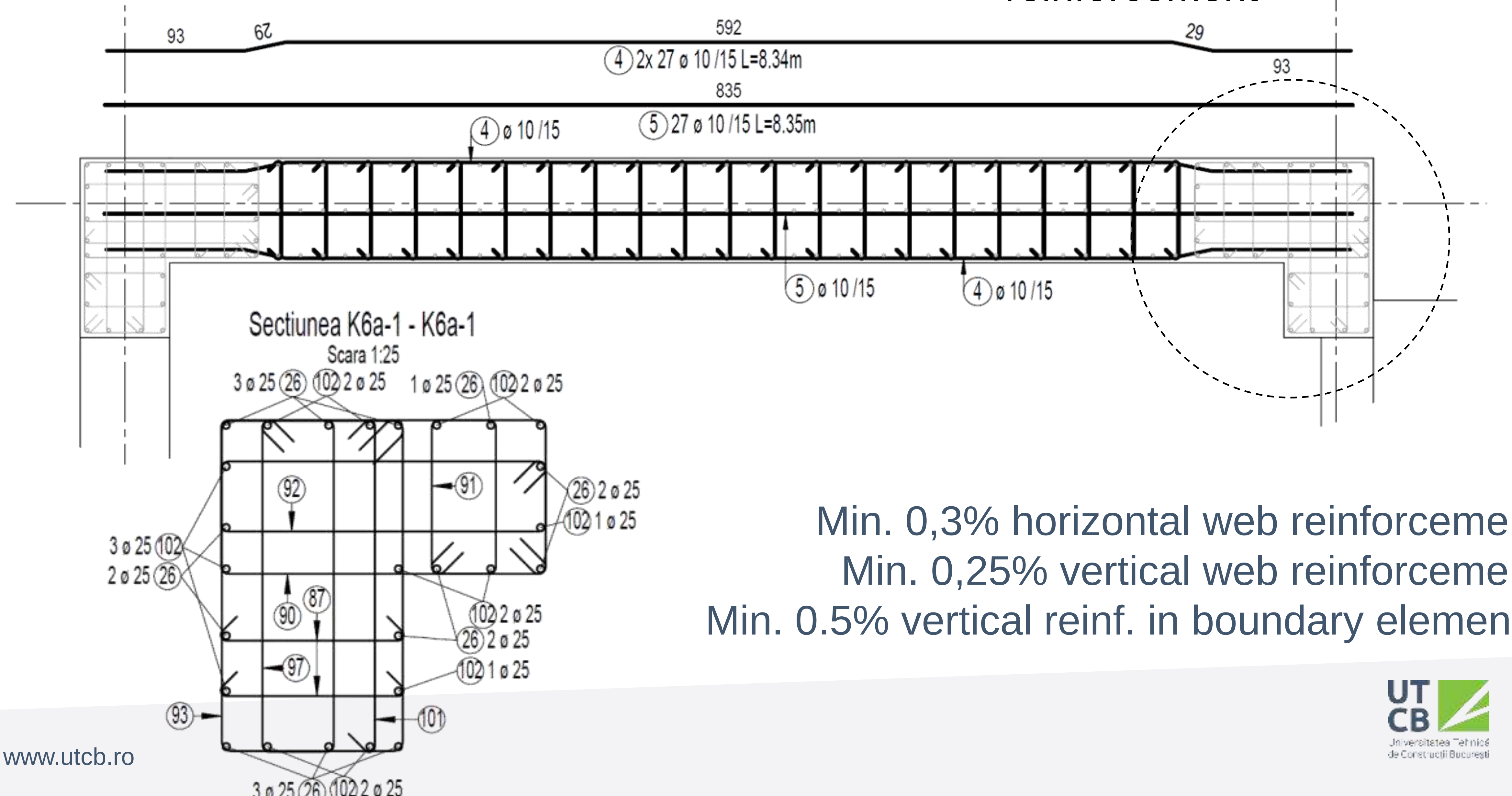
- Inner concrete core with concrete frames
- Inner concrete core with flat slabs and outer frames
- Inner concrete core with flat slabs
- Concrete coupled shear walls
- Concrete frames

Concrete buildings



Detailing for ductility

Min. 0.3% vertical reinforcement



Min. 0,3% horizontal web reinforcement

Min. 0,25% vertical web reinforcement

Min. 0.5% vertical reinf. in boundary elements

Detailing for ductility

Concrete buildings

- Beam sections – drift limitation criteria (0,5% or 0,75% for service eq. and 2,5% for design eq.)
- Columns sections
  - Ductility $N<0,45A_g f_{cd}$ or $N<0,55A_g f_{cd}$ (if rotational ductility is checked by calculation)
  - Drift limitation (0,5% or 0,75% for service eq. and 2,5% for design eq.)
- Walls sections
  - Shear strength of concrete section: $V<0,15b_w l_w f_{cd}$

Concrete buildings

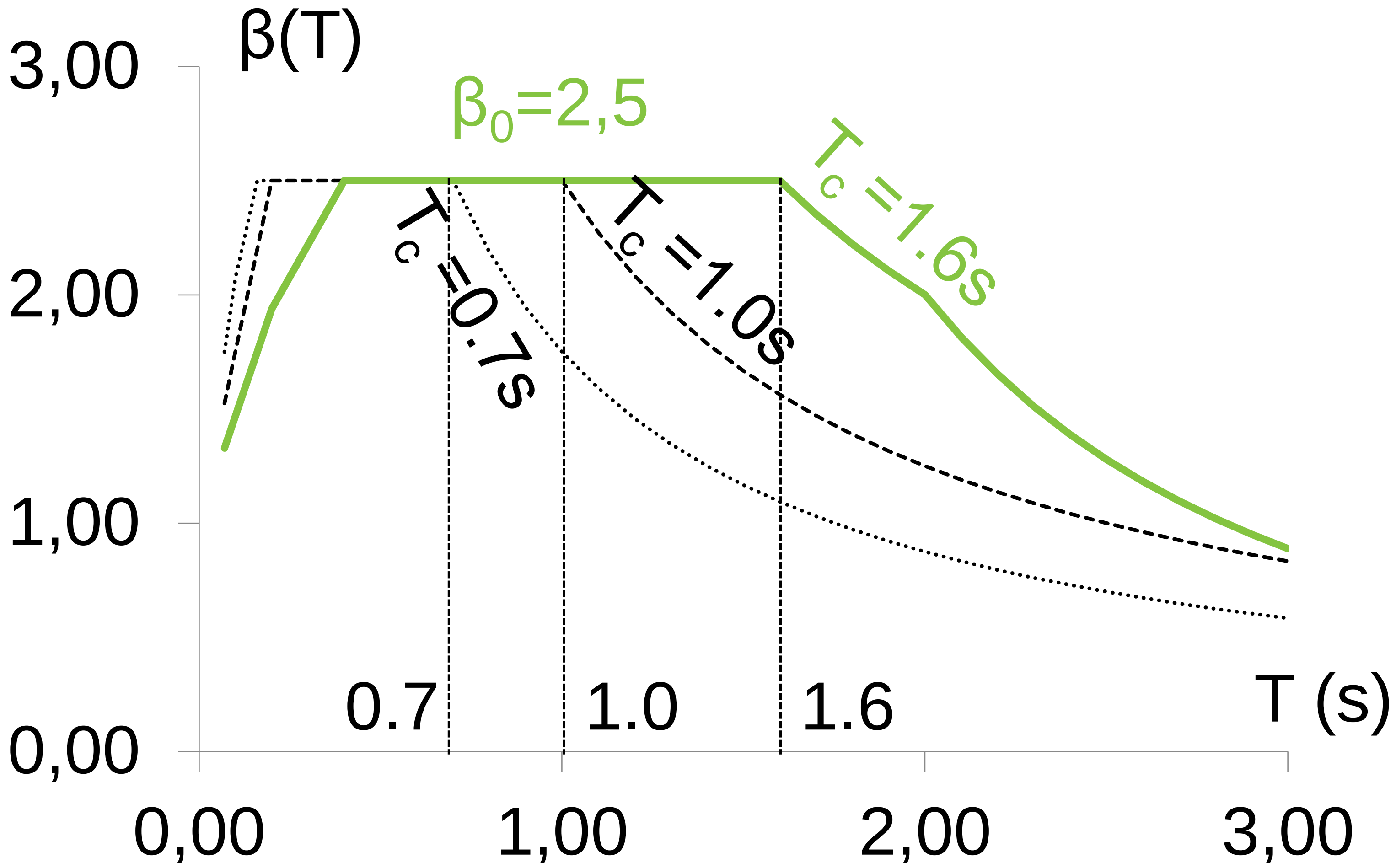
- Concrete 32-48 MPa – average compressive strength
- Steel 435 MPa
- Monolithic structures
- Columns: rectangular, square sections – 500 mm to 1000 mm width, longitudinal reinforcement ratio 1-2%
- Shear walls: 300-600 (800) mm thickness, with diagonally reinforced coupling beams
- Spacing of transversal reinforcement in plastic region 100 mm (for columns, beams, shear walls boundary elements)

Challenges in seismic engineering

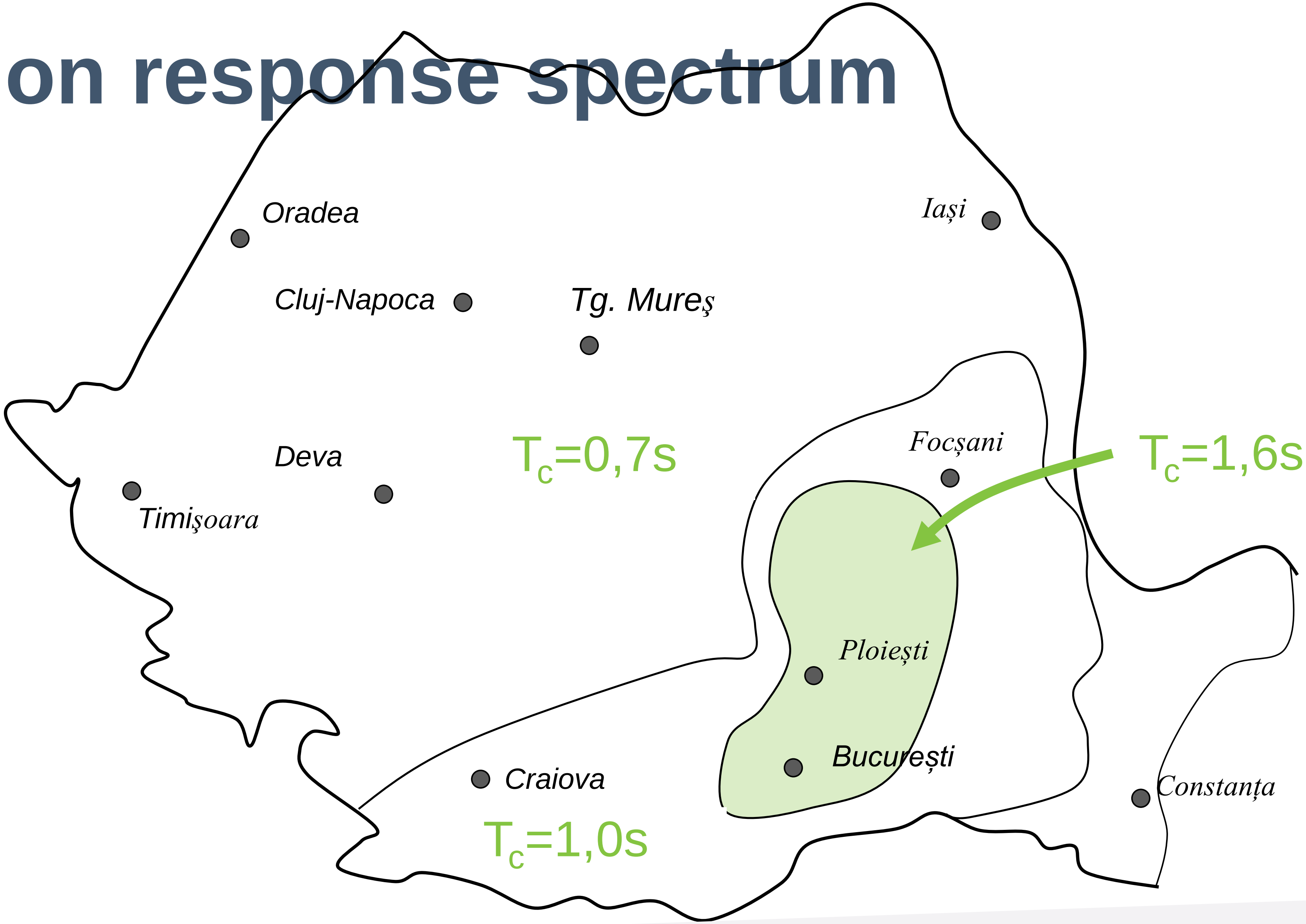
Acceleration response spectrum

Design peak ground acceleration

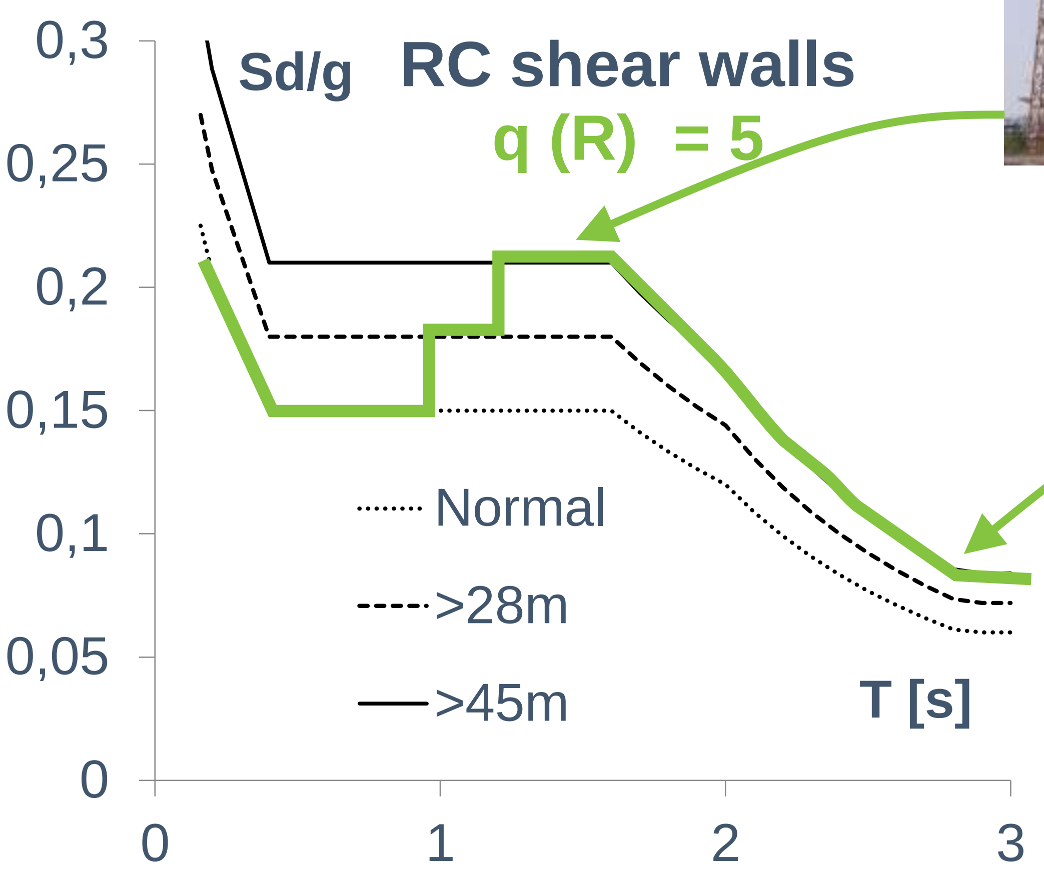
0.10g..0.40g



Acceleration response spectrum

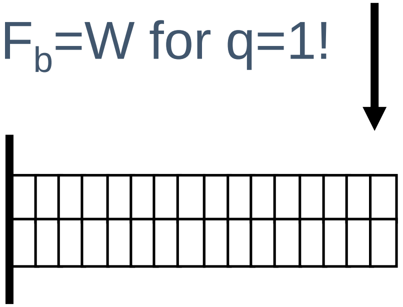


Base shear coefficients - Bucharest



F_b=0,22W for q=5
F_b=0,37W for q=3

F_b=W for q=1!



Large lateral displacement

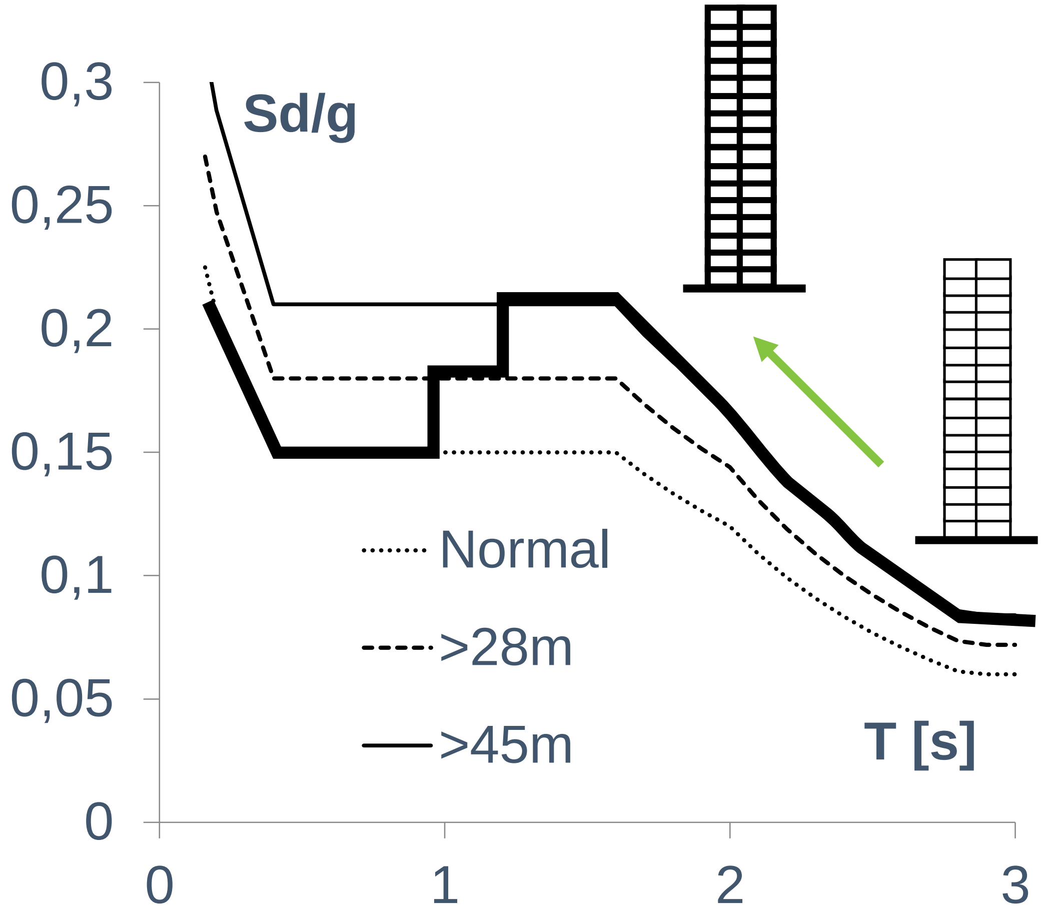
- Design for large lateral displacement demand: > 60 cm under design earthquake (> 80 cm for buildings over 45 m in height)
  - Limited international experience
  - High rotational ductility demand (beams (θ>0.03) and coupling beams (θ>0.06))

  - Design for ductility, protection of non-structural elements

  - Increase damping – vibration control
  - Limited option for base isolation

Large lateral displacements

- Stiffness increase >> base shear force increase
- High additional structural cost necessary to limit the lateral displacement
- Shear strength and histeretic behaviour of thick concrete walls (>40cm going up to 100cm with 3-5 curtains of reinforcement)
- Punching strength of slabs under high rotations

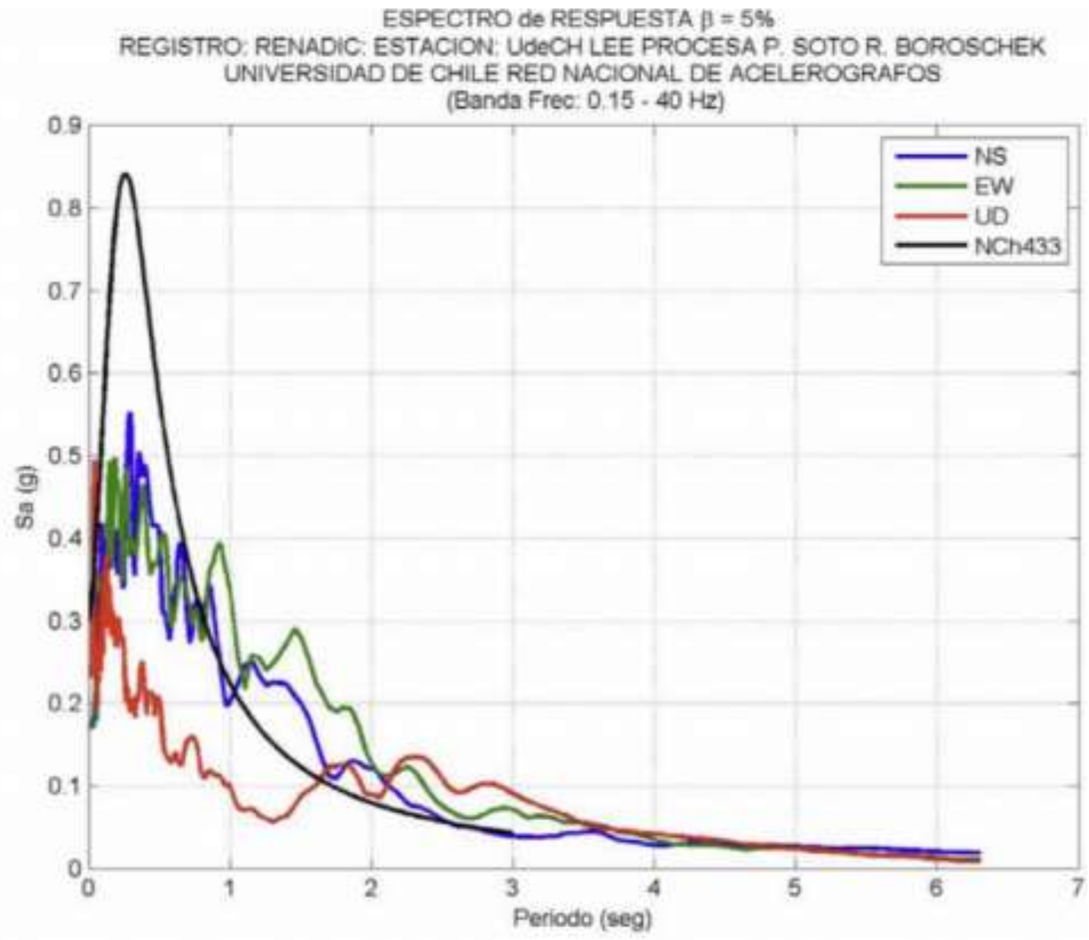


Ductility of shear walls

- Chilean experience

Acceleration response spectrum

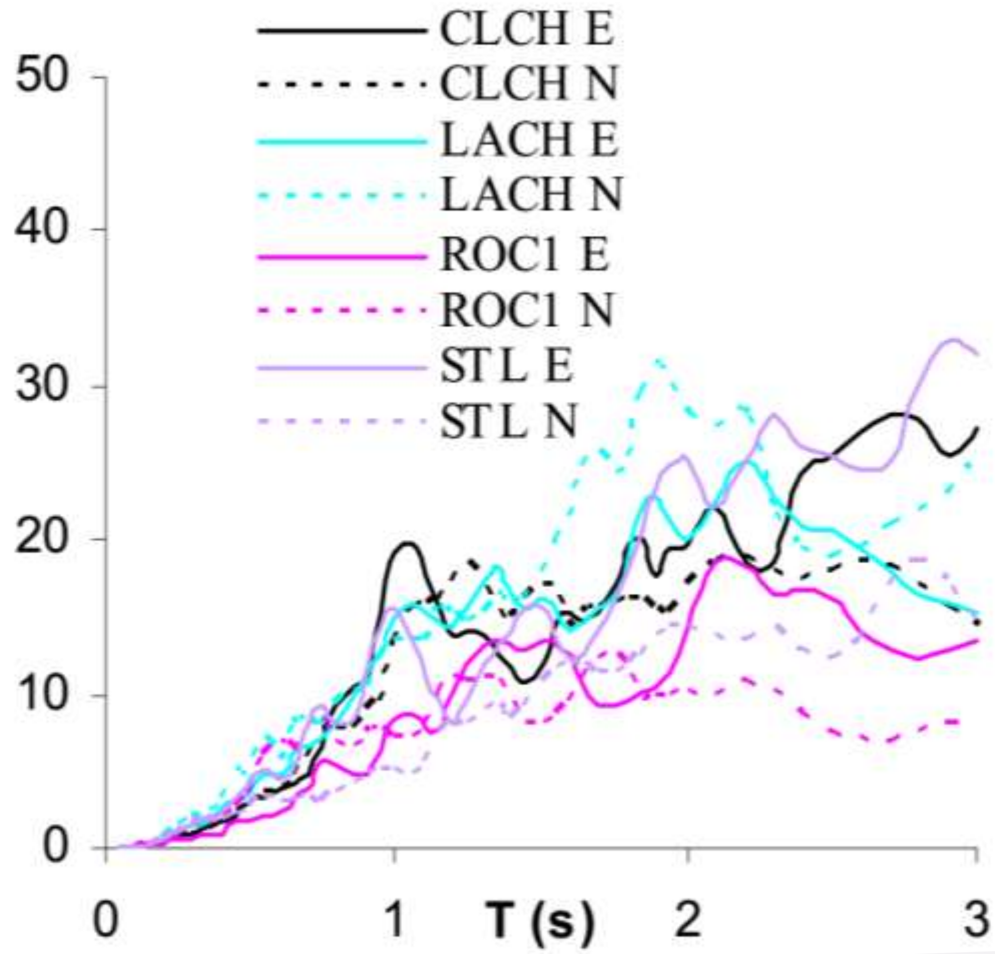
- Chilean experience - Maule 2010 Eq.,



Ductility of shear walls

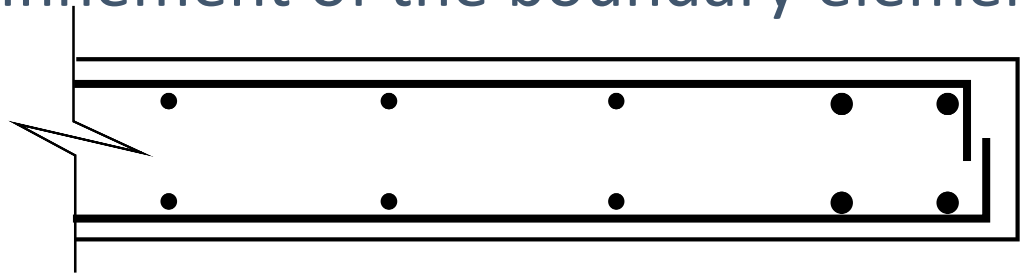
Engineering analysis of ground motion records of Chile, 2010 earthquake, Liberatore et al.

- Chilean experience - Maule 2010 Eq.,
- Vast majority of buildings designed for soil type II
- Spectral displacement values lower than 30 cm



Ductility of shear walls

- Chilean experience
- Before Maule 2010 Eq., followed ACI 318 recommendations, ch. 21, except for confinement of the boundary elements



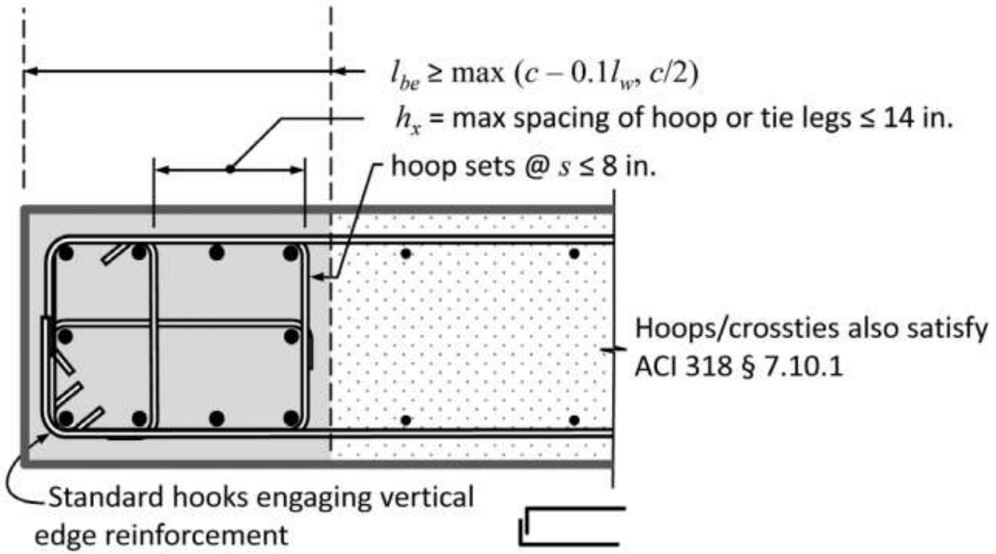
- Confinement provisions were included after the 2010 earthquake

http://www.nehrp.gov/pdf/nistgcr12-917-18.pdf

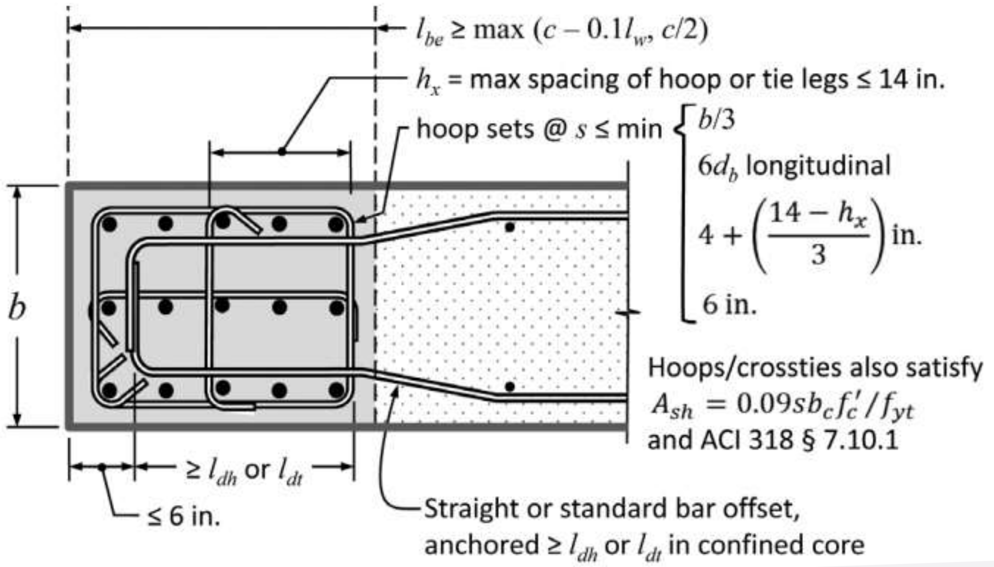
Ductility of shear walls

- ACI 318, Ch. 21

Ordinary boundary element



Special boundary element



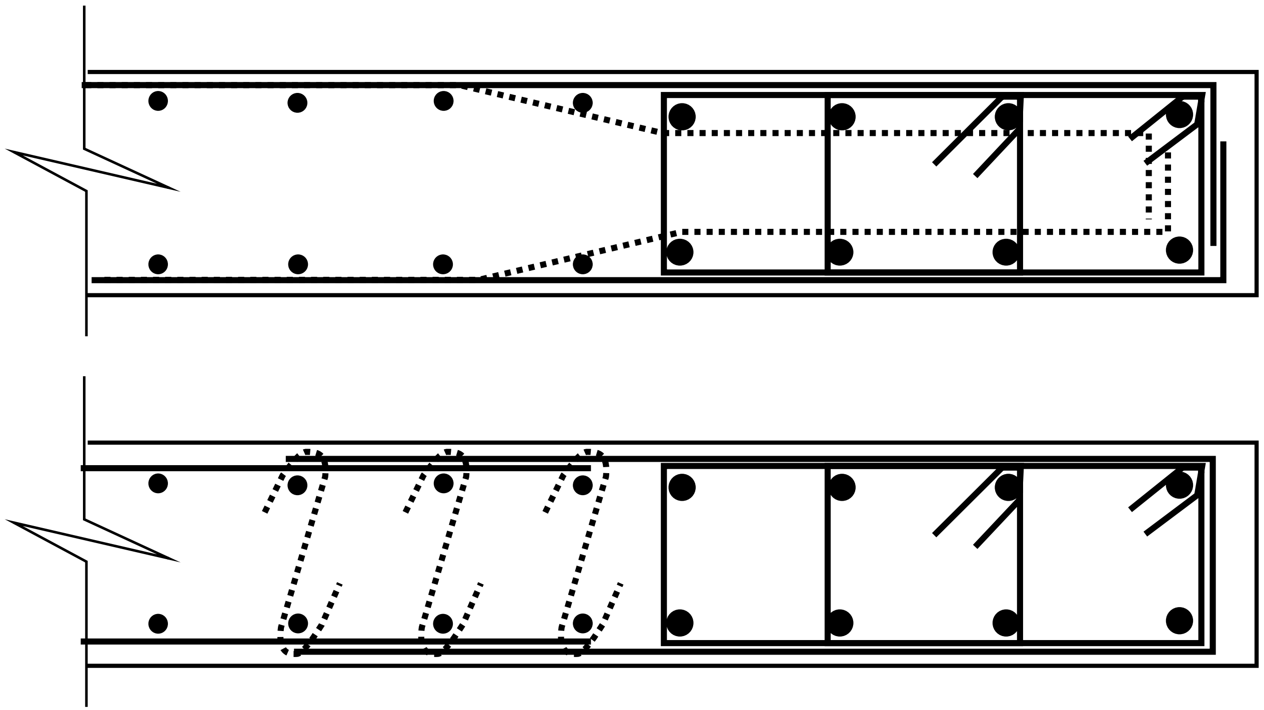
Ductility of shear walls

- Romanian practice: thick concrete walls with large flanges

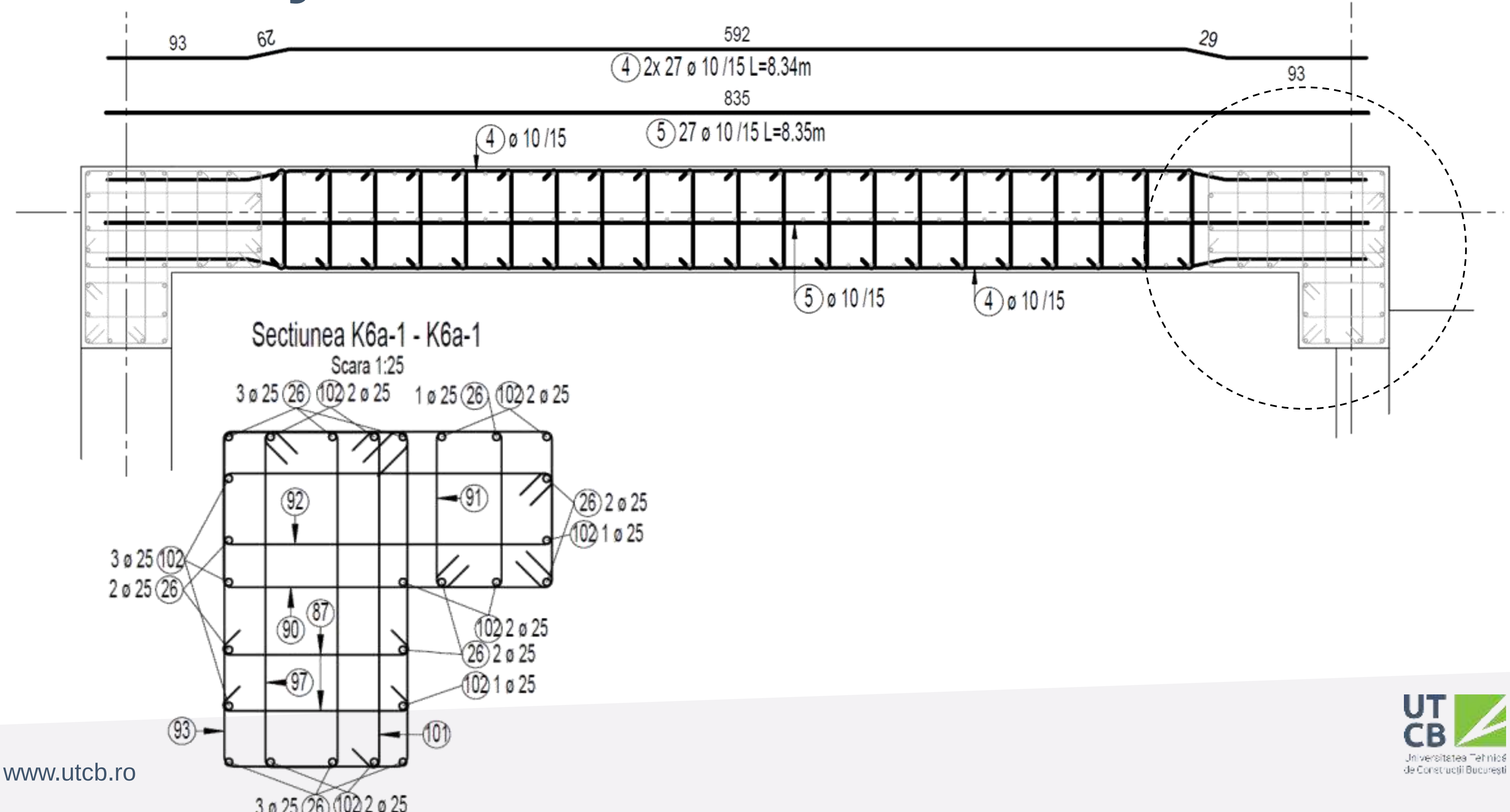
- Detailing for ductility
- Lacking information about rotation capacity and shear strength
- Difficult to test on real scale models

Ductility of shear walls

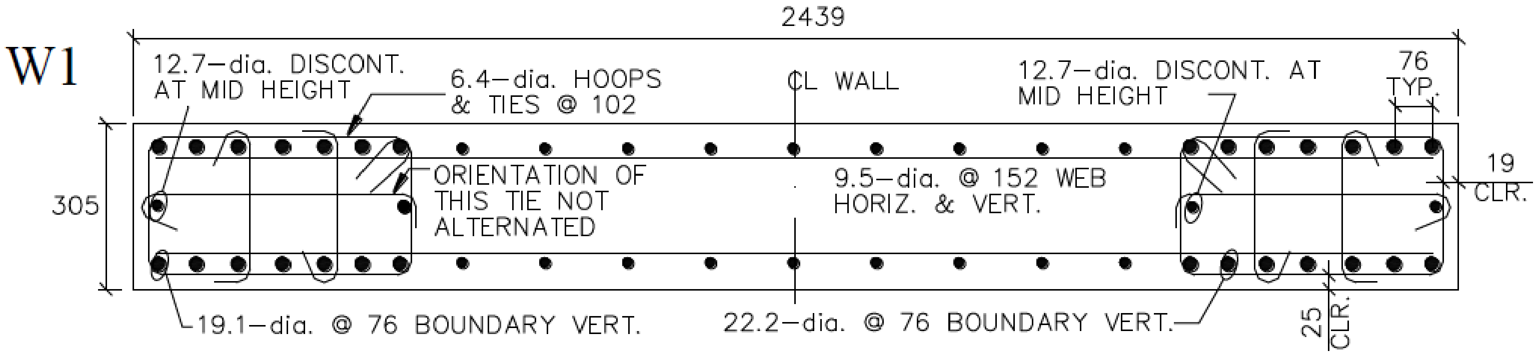
- Romanian practice
- Horizontal bars - anchored in the confined area of the boundary element
- Ties - in the overlapping regions for horizontal reinforcement, as prescribed by EC2.



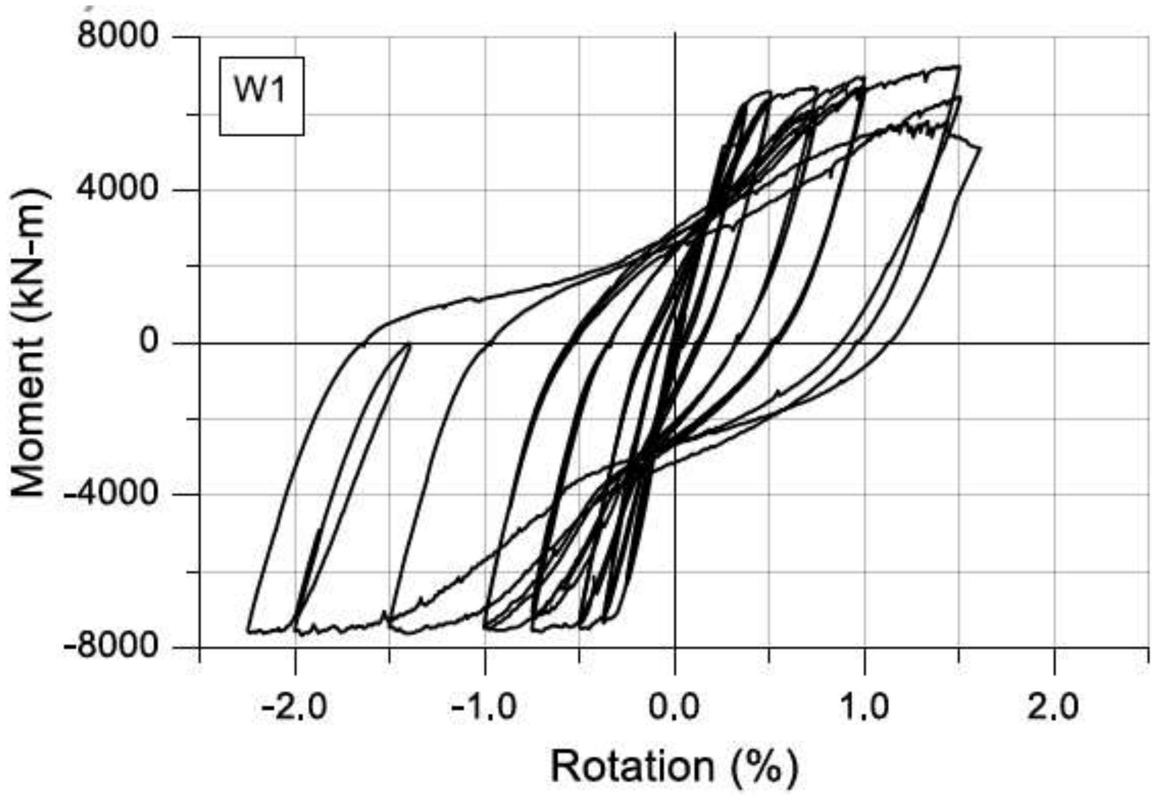
Ductility of shear walls



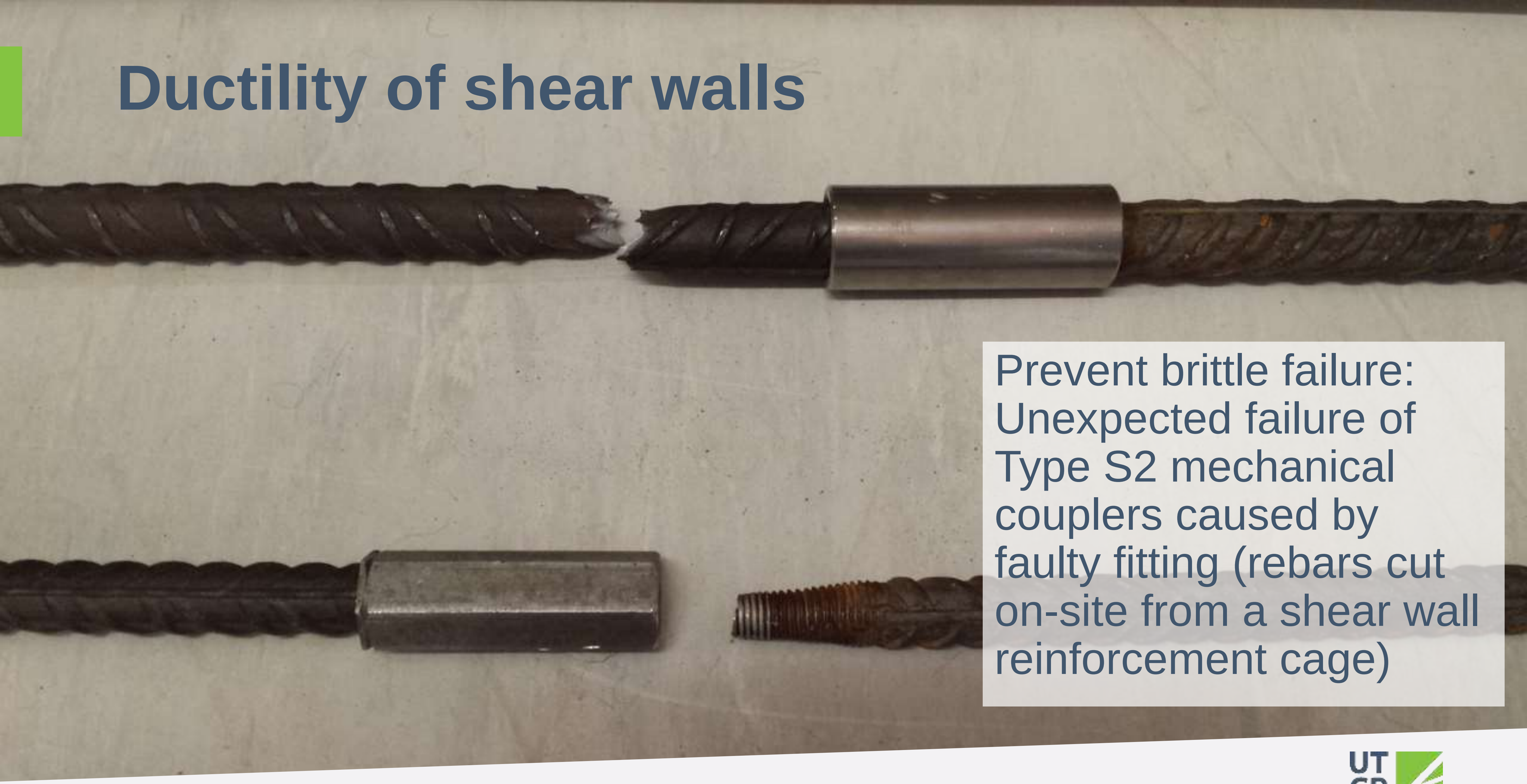
Ductility of shear walls



- C. Motter, J. Wallace - 16 WCEE 2017
- Quasy static test, simulating a 10 story building (applied moment, axial and shear)
- N=0,053Af_c'
- 1,5% rotational capacity



Ductility of shear walls



Prevent brittle failure: Unexpected failure of Type S2 mechanical couplers caused by faulty fitting (rebars cut on-site from a shear wall reinforcement cage)

Large lateral displacement

- Design for large lateral displacement demand: > 60 cm top disp. under design earthquake (> 80 cm top disp. for buildings over 45 m in height)
  - Behaviour of non-structural elements
    - Glass curtain walls (solutions from western Europe – little experience with strong eq.)
    - Masonry partition walls (residential buildings)
    - Roof systems for commercial buildings

Sensitive non-structural components

Emergency hospital building - reliable structure but sensitive non-structural elements

Sensitive non-structural components

1% lateral drift – damage level

Sensitive non-structural components

Van, Turkey 2011

Sensitive non-structural components

Van, Turkey 2011

Sensitive non-structural components

Van, Turkey 2011

Sensitive non-structural components

Van, Turkey 2011 – heavy damage in the ground floor

Sensitive non-structural components

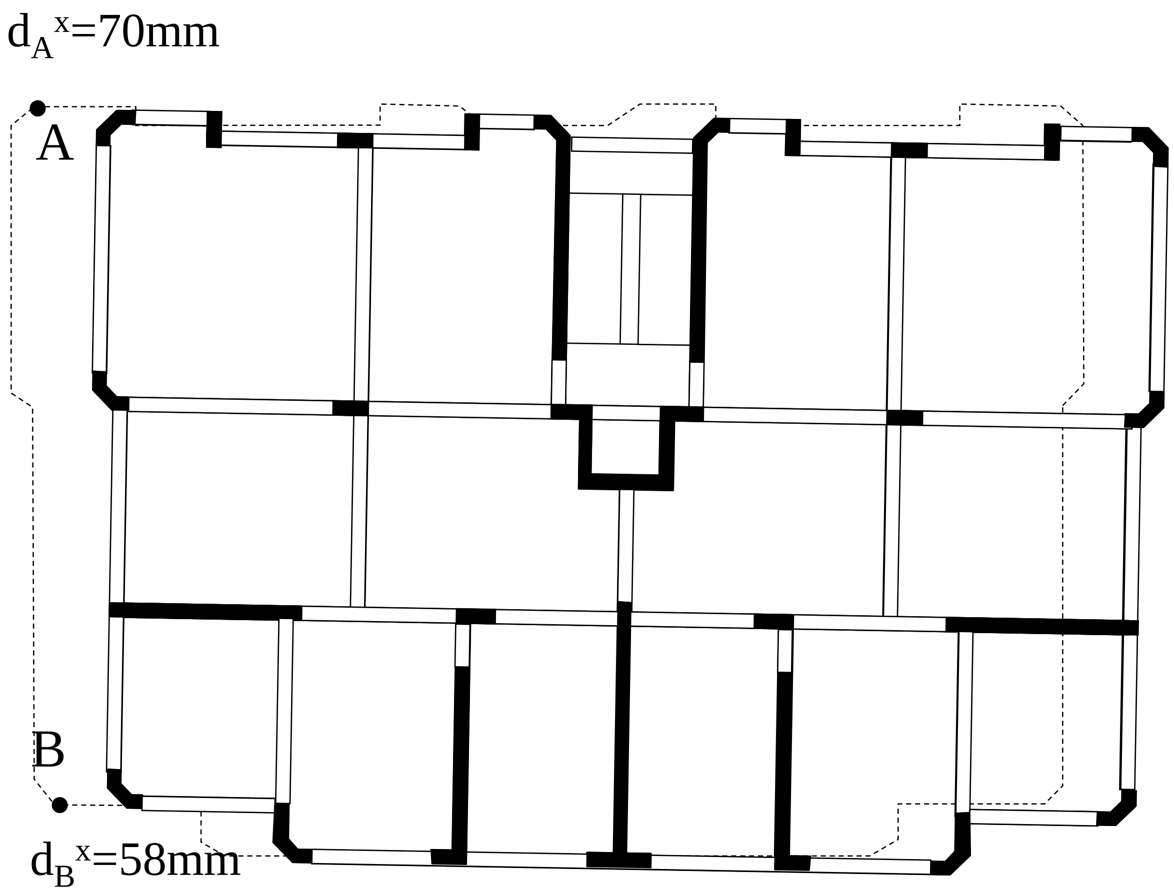
- Rather new buildings
- Concrete shear wall structures
- Limited structural damage
- Extended non-structural damage (partitions, pipes, wiring, doors and windows)
- Evacuated, listed for demolition

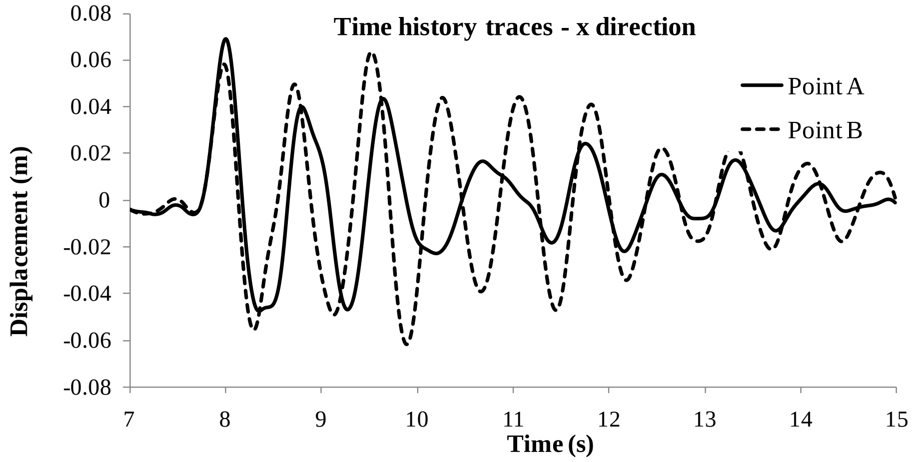
Limitations of structural analysis

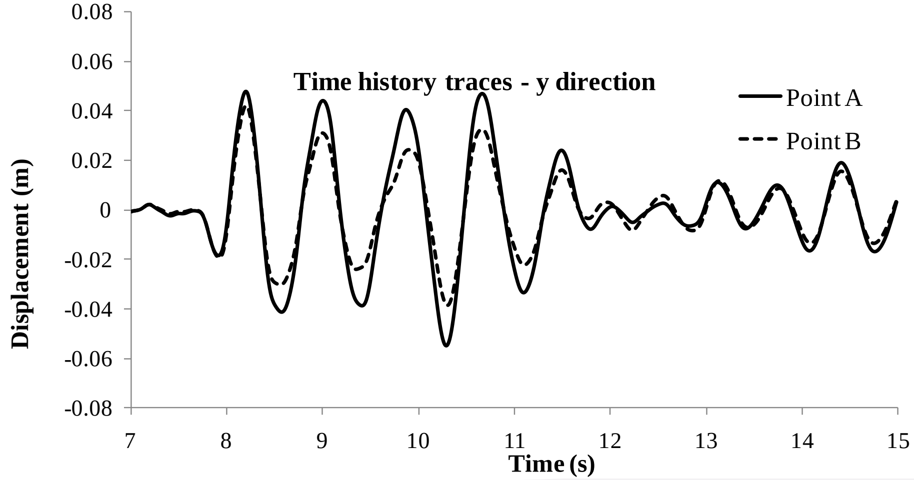
- Structural drawings and site inspection for confirmation
- Material (concrete) tests
- Acceleration time-histories in near-by stations (two ground motions), including directions

- Static linear analysis, static non-linear analysis, time-history nonlinear analysis

Limitation of structural analysis







Limitation of structural analysis

- Buildings have suitable lateral strength and deformation capacity
- Suitable strength, higher than required by Turkish earthquake standard (lateral overstrength of around 2.0)
- 1% lateral drift - most severe earthquake loading scenario

- All the assessment methods converged to a similar positive conclusion regarding the seismic vulnerability of the building.
- Seismic assessment methods could not predict the extensive damage sustained by the masonry partitions in the ground floor.

Limitation of structural analysis

- Structural analysis methods have certain limitations
- Structural lateral displacement cannot always describe local damage level (although displacement is a very convenient and reliable engineering parameter)
- Structural analysis should not overshadow engineering common sense or past experience

Limitation of structural analysis

- Refined structural analysis alone can not result in safe buildings

- Advanced structural analysis methods:
  - Who should be able to use in practical design?
  - Is additional certification of the design offices necessary?
  - How advanced analysis methods should be positioned with respect to the conventional linear elastic ones?

Quality in design and production

- Involvement of construction industry in research, development and good practice standardization
- Almost no involvement of insurance industry in quality assurance
- Weak involvement of the government in research and development in construction

Bucharest resilience to earthquakes

- 2011 Chirstchurch, M6,3 Eq. - 185 fatalities and 100000 damaged homes
- 1100 commercial buildings (80% of the central business district) subsequently demolished
- 6000 de bussineses vacanted the district
- 30 billions USD - total replacement cost
- 2017 Kamikoura Eq - caused a less severe but similar outcome in Wellington

Bucharest resilience to earthquakes

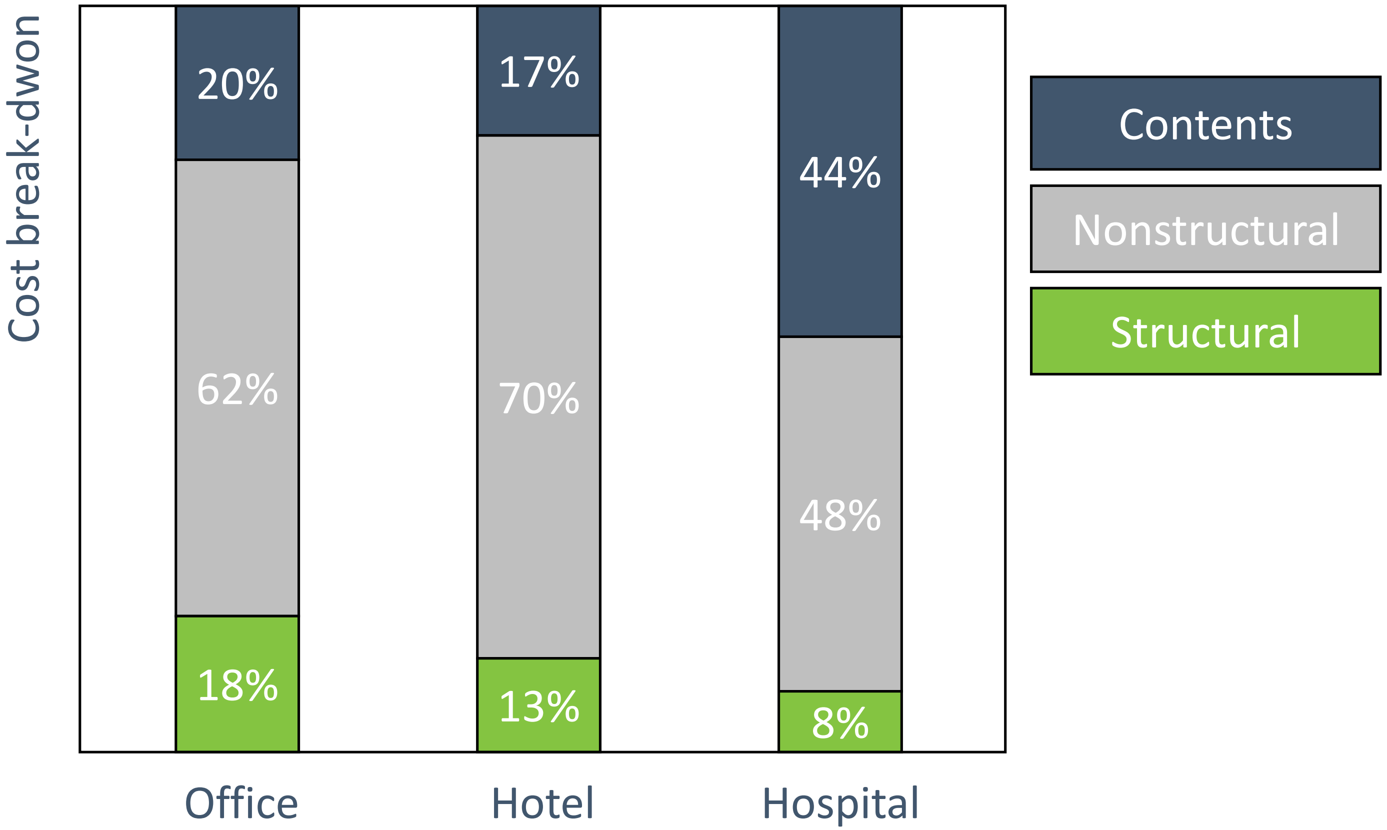
- Initial construction costs vs. life time costs for buildings

  (design for DCH - large behaviour factors (q (R) = 5...6))
- Direct pressure from developers to reduce structural costs (structural costs 120-150 €/m^2, total building costs 500-1000 €/m^2, expected life-cycle costs ? €/m^2), especially in the residential segment
- Lack of efficient tools to estimate life-cycle costs
- Lack of education of end users to ask for resilient structures

Construction cost break-down

- Taghavi and Miranda (2003)

- Bucharest – office buildings – structural cost <30% total construction cost



Economic life in Bucharest

- Income (GDP per head) more than double than the national income – largest ratio in the EU toghether with Warsaw
- High share of working – age population (20-64 years of age) – 68 % - by far the largest in the EU
- 15000 residents / km^2 in the first 5 km from the city center

http://ec.europa.eu/regional_policy/sources/policy/themes/cities-report/state_eu_cities2016_en.pdf

A strong earthquake is likely to generate a severe drop of the economic activity in Romania

Main concerns

- Higher attention building quality, both to structural and non-structural components
  - Large displacements demands
    - High non-linear deformation of structural elements
    - Severe damage of non-structural components
- Structural designers, consultants - uniform and fair application of codes – not to distort the economic competition of the design market

UTCB

Universitatea Tehnică de Construcții București

Thank You!

www.utcb.ro