Tall buildings

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Lecture 13: 25/02/2014

European Erasmus Mundus Master Course

Sustainable Constructions
under Natural Hazards and Catastrophic Events

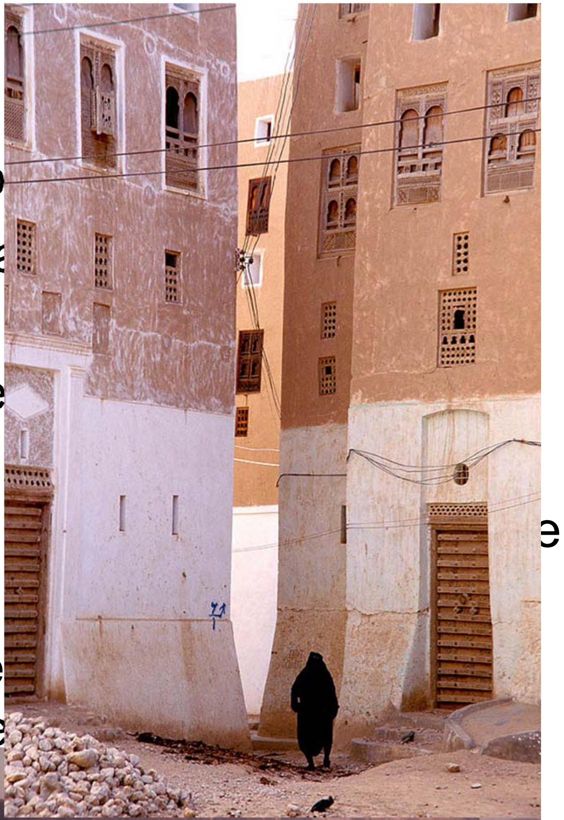
520121-1-2011-1-CZ-ERA MUNDUS-EMMC

Part II – Multistorey buildings

- Tall buildings, History, Systems, Peculiarity of design, New developments

Tall buildings

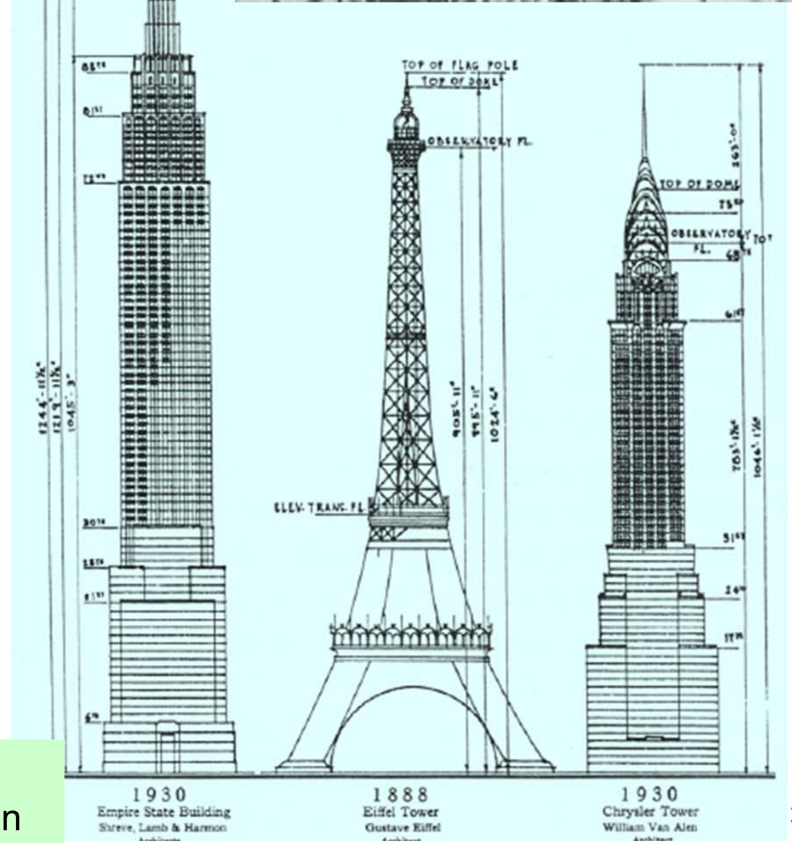
- Multistory buildings
  - Tall buildings has always fascinated peop
  - The construction techniques, both for infra
suprastructure, changed during the time
- A building can be considered as tall when the
reflected in the design
- It is important to take into account the effects ell
as seismic loads
- In order to achieve a good performance unde
deflections and accelerations should be limite



Old Walled City of Shibam, Yemen
Most of the city's houses come mainly from the 16th century. Shibam is often called "the oldest skyscraper-city in the world“. Buildings reach 40 m height.

Home Insurance Building

- A tall building boom in the late 1920s and early 1930s in urban centers Chicago and New York
  - Home Insurance Building located in Chicago (1885) - 12 stories tall with a height of 55 m (cast iron), is considered the first skyscraper
  - 1930, the Chrysler Building in New York became the world’s tallest,
  - the Empire State Building - completed in April 1931 (built in one year and 45 days), at 382 m, surpassed the Chrysler Building by 62.2 m



Drawing from Fortune Magazine, September 1930, Skyscraper Comparison

The evolution of New York City’s skyline from 1879 to 2013

http://workattheyard.com/the-evolution-of-the-new-york-city-skyline/

Evolution of tall buildings

- Multi-storey frame buildings
  - Skyscrapers also began to appear in other parts of the world (Mexico City, Tokyo, Shanghai, Hong Kong, Singapore, Kuala Lumpur, Taipei, Jakarta, etc.).
  - Modern multistory buildings use steel for the main structural members (or in combination with concrete – composite structure)
  - Despite the recent events that threatened the construction of very tall buildings, their developments have been continuously increasing worldwide.
  - Many tall buildings were recently completed or are going to be completed in the near future – Dubai has 18 completed buildings that rise at least 300 metres !!!!!! This includes the tallest man made structure Burj Khalifa


Dubai, 1990

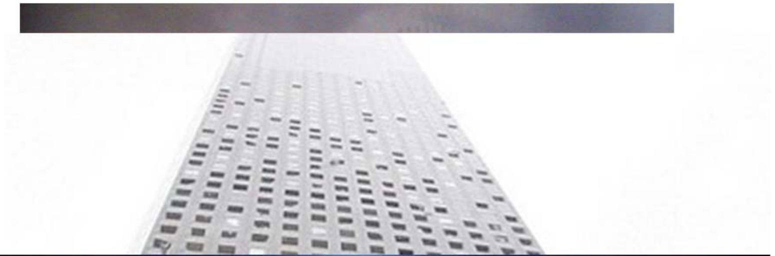

Dubai, 2003


Dubai, 2007

Present development

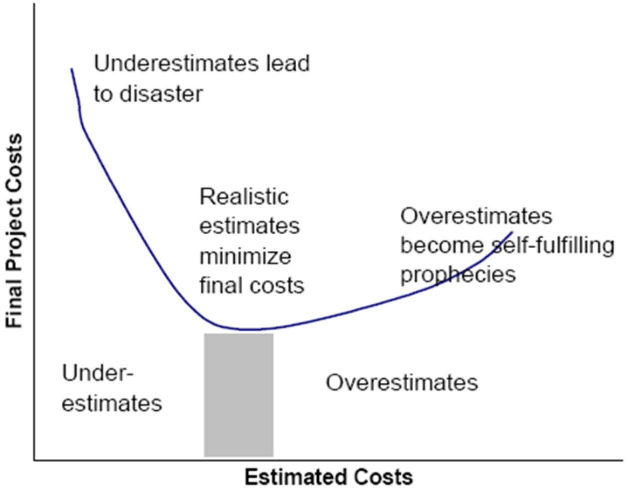
Burj Dubai: 818m

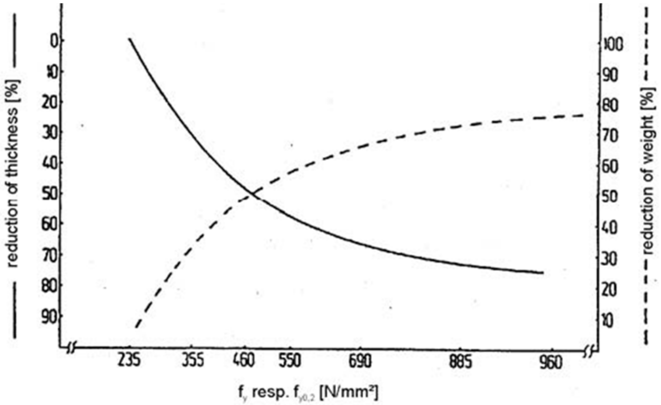
Challenges and uncertainties



Challenges and uncertainties

- Cost
  - initial costs
  - operational costs
  - dismantling
- Design and erection
  - new design methodologies (PBD)
  - new systems, materials, technologies
- Sustainability ("Green" or "sustainable" buildings)
  - Life Cycle Assessment
  - Energy use
  - Emissions from energy
  - Water use
  - Waste reduction
  - Productivity and health





Lateral-load resisting systems

- A rigid unbraced frame may be capable of resisting lateral loads without relying on an additional bracing system in case of a low to medium-height building
- High-rise building systems should use structural systems that are effective in resisting the larger lateral loads
- Types of lateral-load resisting systems (R. Plank, M. McEvoy):
  - Shear frames: beams and columns connected with rigid joints
  - Shear truss: bracing between columns to form vertical shear trusses
  - Shear truss-frames: shear frames + shear trusses
  - Shear truss-frame-outrigger and belt trusses: internal core is connected to perimeter frames by deep girders – outriggers.
  - Framed tubes: close spacing columns on the exterior frames forming a vertical tube. The tube behaves as a cantilever
  - Truss tubes: the same system as framed tubes, tied by a system of diagonals
  - Bundled or modular tubes: framed or trusses tubes grouped together like cells
  - Super-frame: megaframe in the overall form of a Vierendeel frame
  - Composite systems: mixed RC and steel systems (concrete shear walls or concrete framed tubes combined with various structural steel framings
- Recommended limits for typical multistory frames are given in the next table

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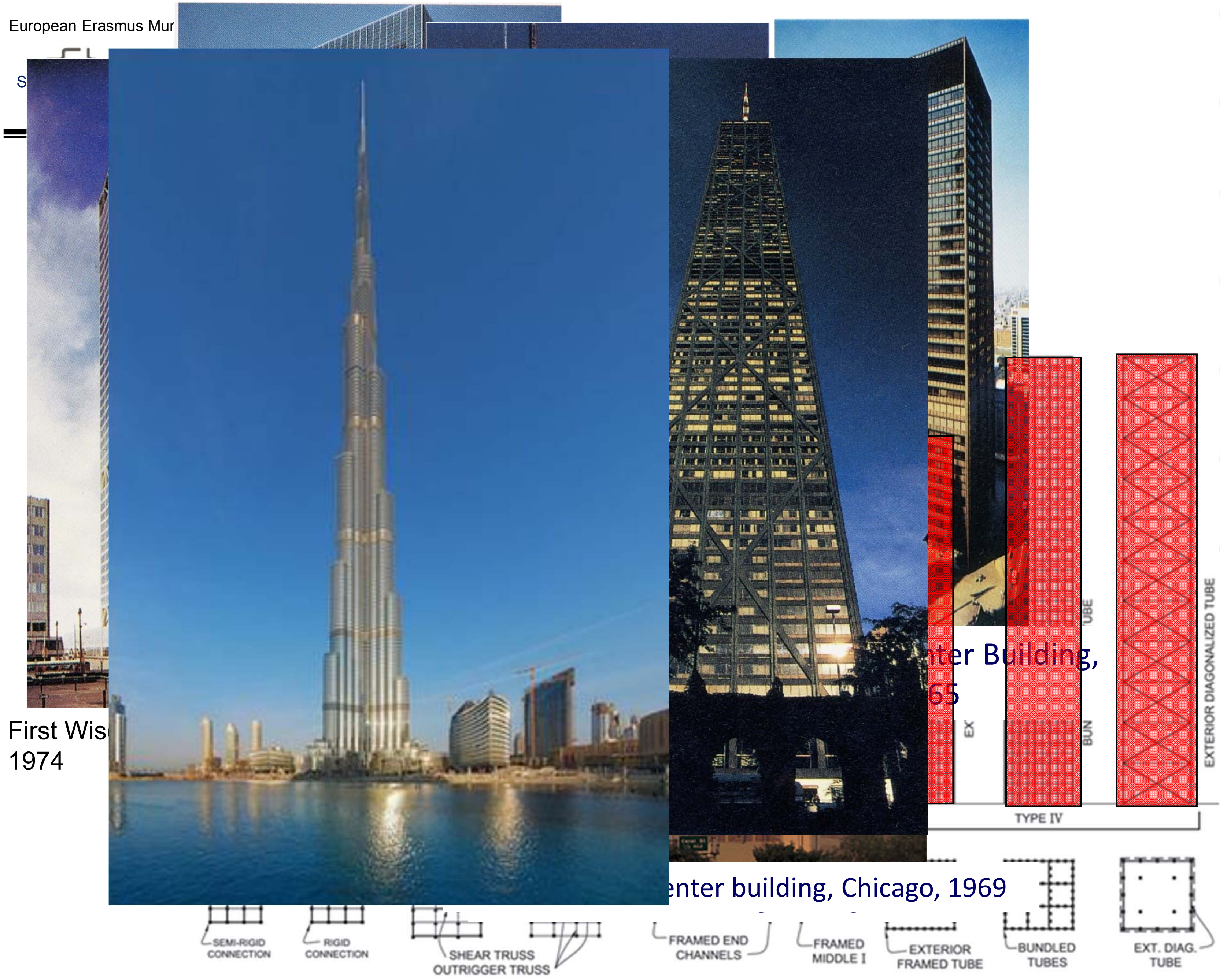
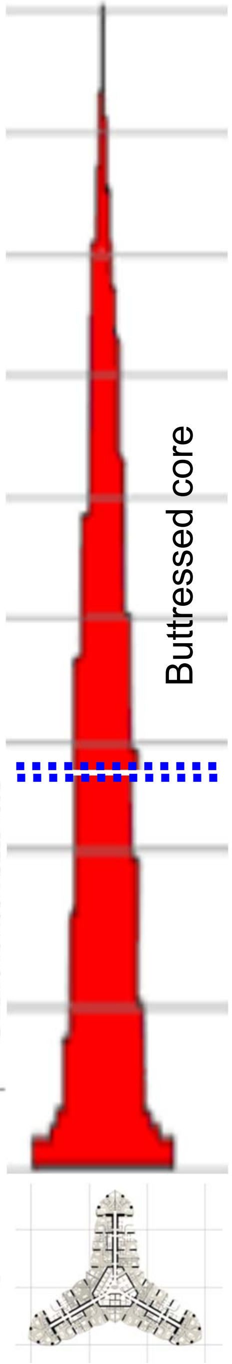


First Wis
1974

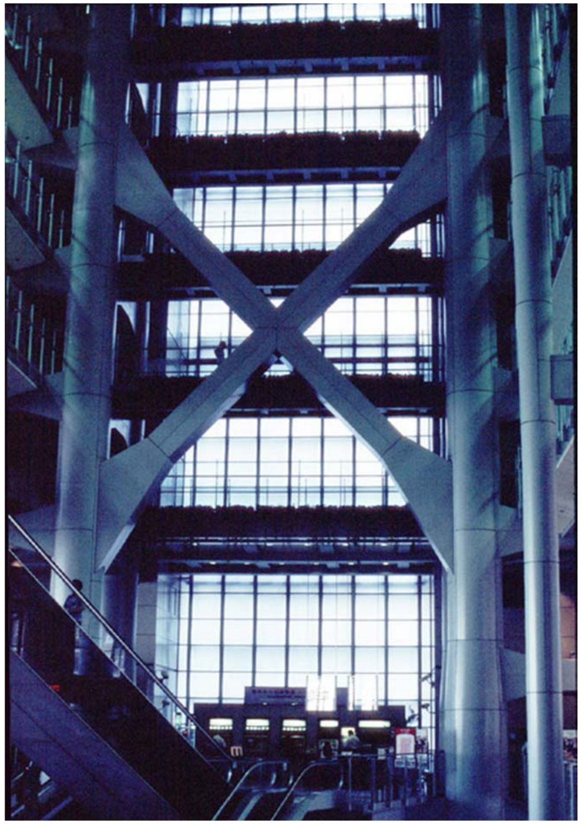
nter Building,
65

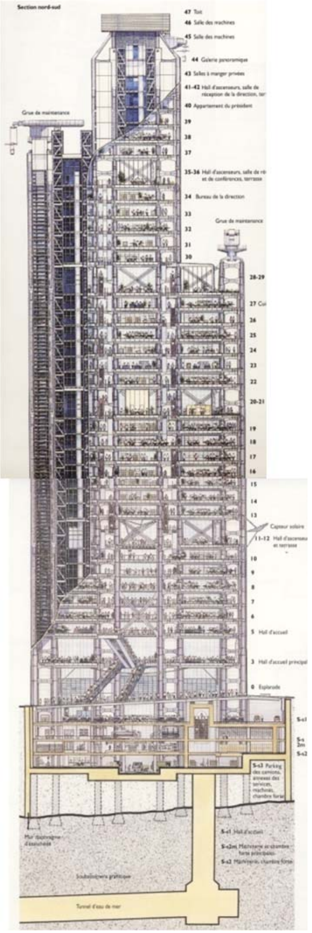
enter building, Chicago, 1969



Structural systems for multistory buildings

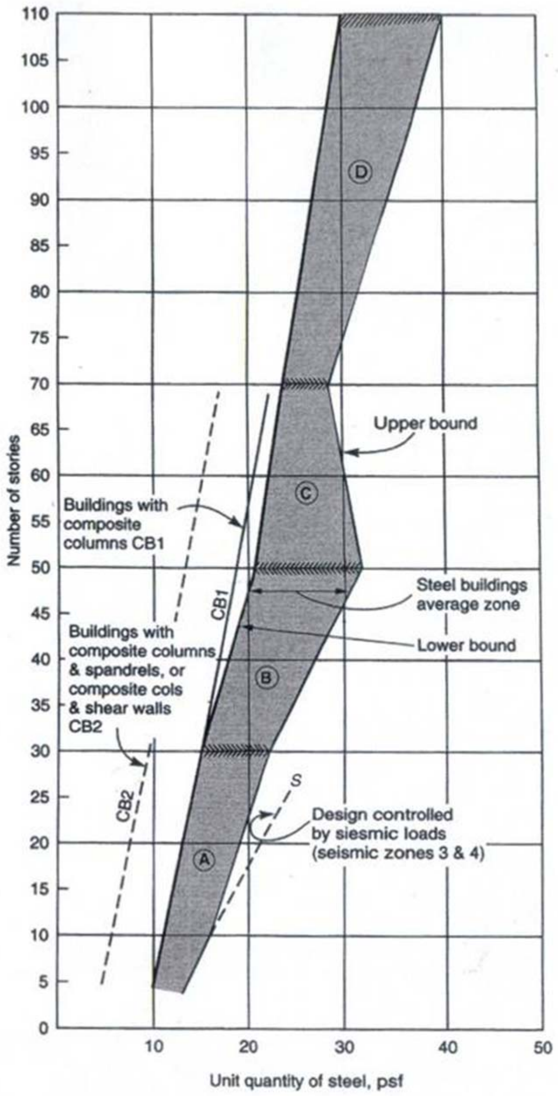
Hongkong and Shanghai Bank
Completed 1986
180 meters height





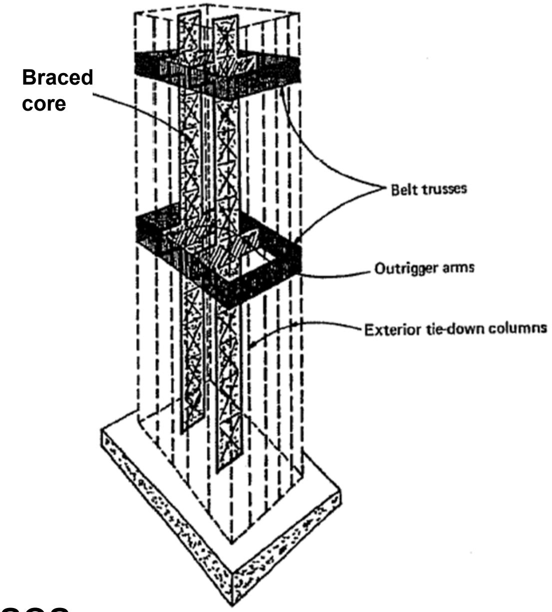
Structural systems

- Even for high seismic areas, for buildings with more then 25-30 stories, the wind load becomes predominant in design
- However, seismic design philosophy should taken into account (structural system, local detailing, ….)



Outrigger and belt truss system

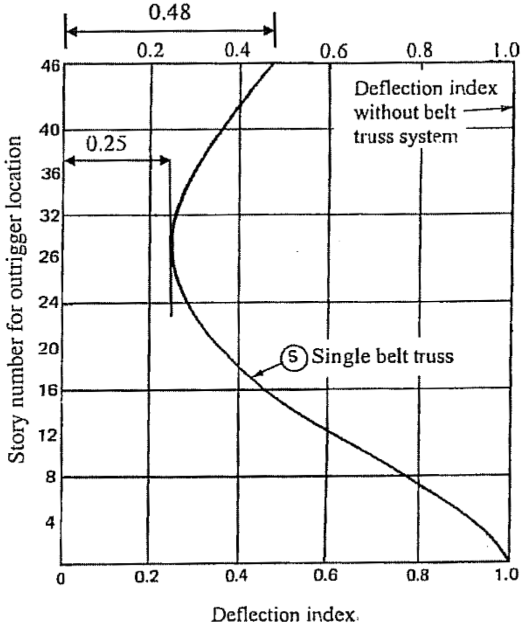
- The outriggers couple the columns and the core
- The lateral deflections are smaller than if the core is freestanding
- Belt trusses around the building



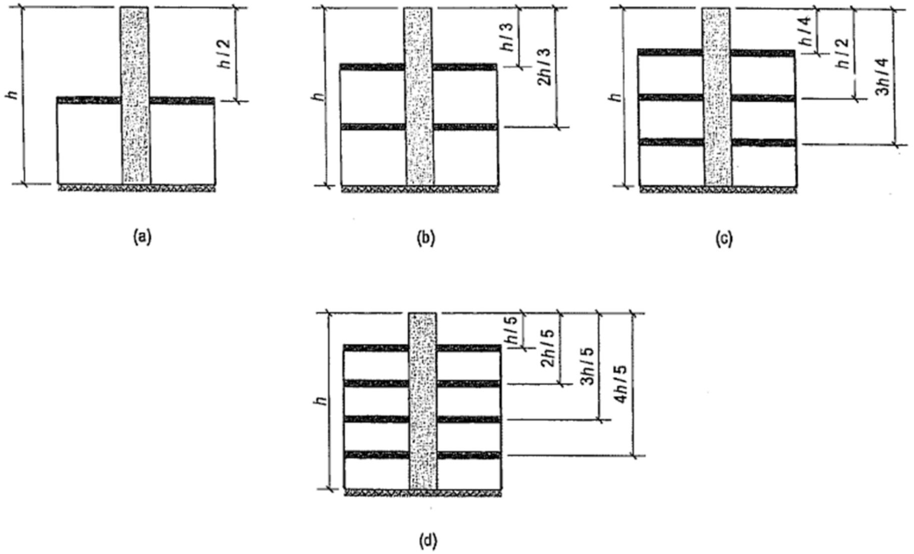
Advantages:

- Reduce building deflections and core bending stresses
- Reduce the rotational reactions
- Minimize the structural cost penalty associated with stability of slender buildings
- Effective for improving 3D behavior of irregular buildings

Outriggers and belt trusses at several locations



Deflection index vs. level of the outrigger



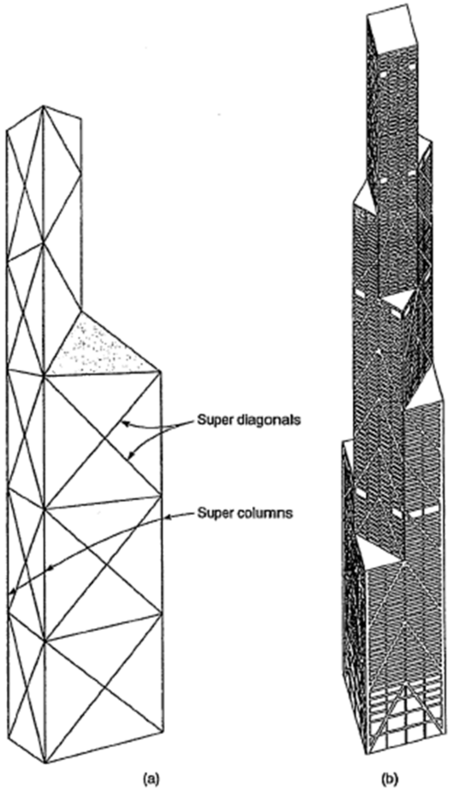
Optimum location of belt and outrigger trusses: a) one outrigger; b) two outriggers; c) three outriggers; d) for outriggers

Note:

$$\text{Deflection index} = \frac{\text{Top displacement with/without outriggers}}{\text{Top displacement with outriggers}}$$

Tube building with diagonals

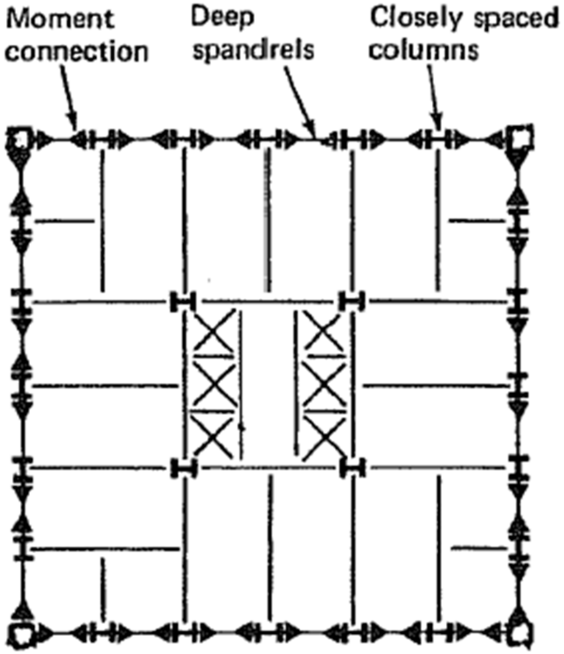
- Structures with closely columns (tube) and perimetral bracings



a) Tube building with diagonals on multiple stories; b) Building with rotated tubes and super diagonals

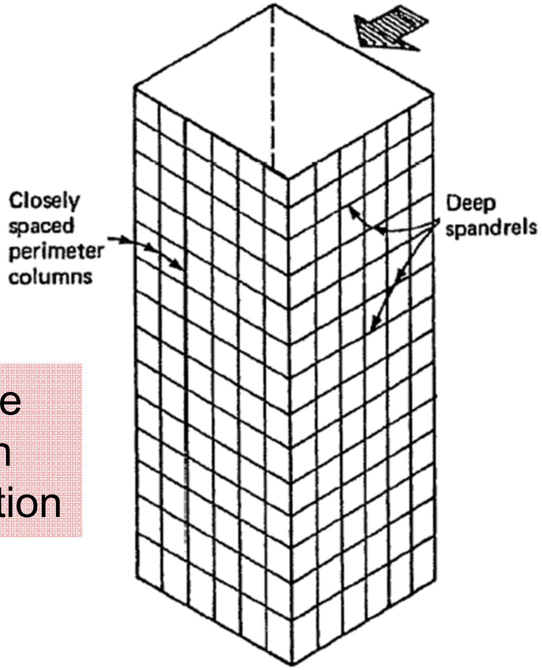
Tube effect

- Structures with closely spaced columns and deep spandrels (tube effect)



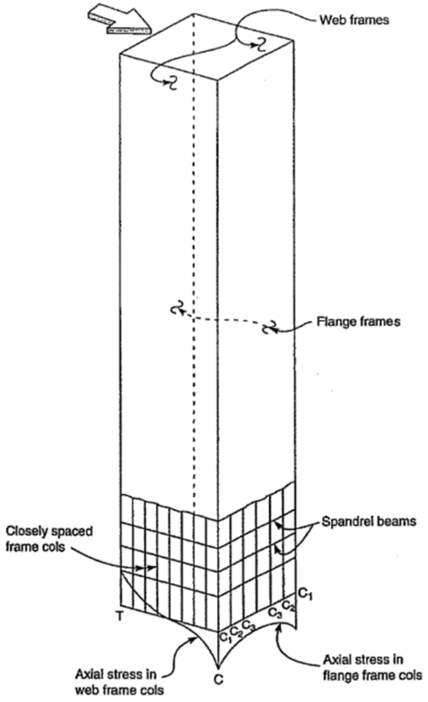
Schematic plan of framed tube

Columns have major axis on perimeter direction



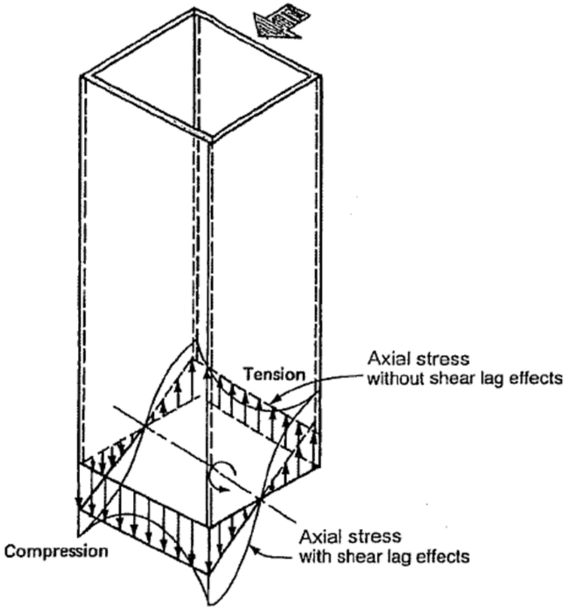
Isometric view of framed tube

Shear lag effect



Bending effect and “shear lag” in case of a tube with free transversal displacement

Important: distribution of axial stresses in the square tube with/without “shear lag” effect

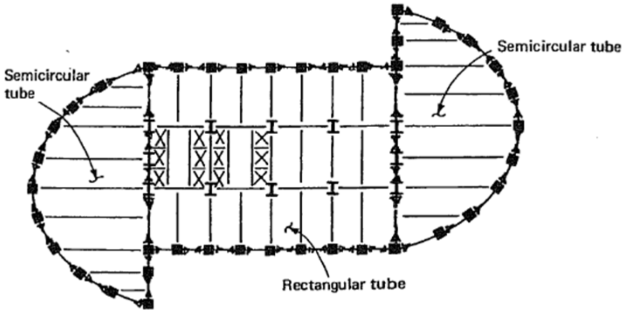


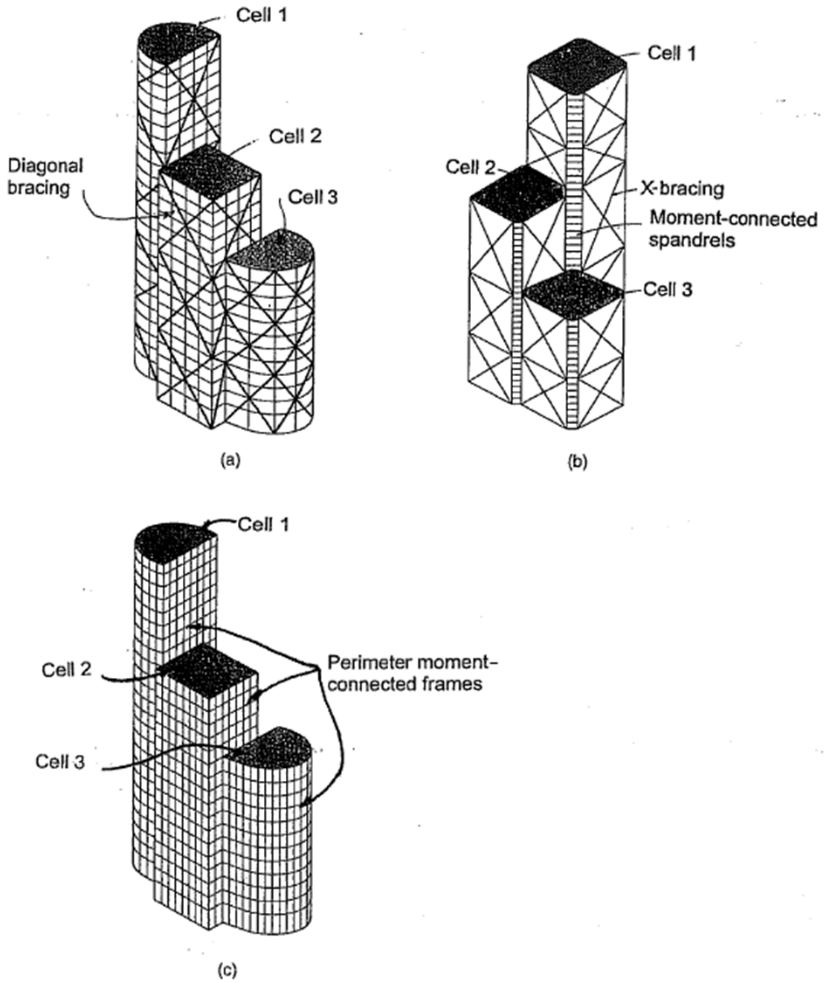
Bending effect and “shear lag” in case of a tube with closely spaced columns

“Shear lag” effect in the tube. Important: distribution of axial stresses is different comparing to classical bending theory

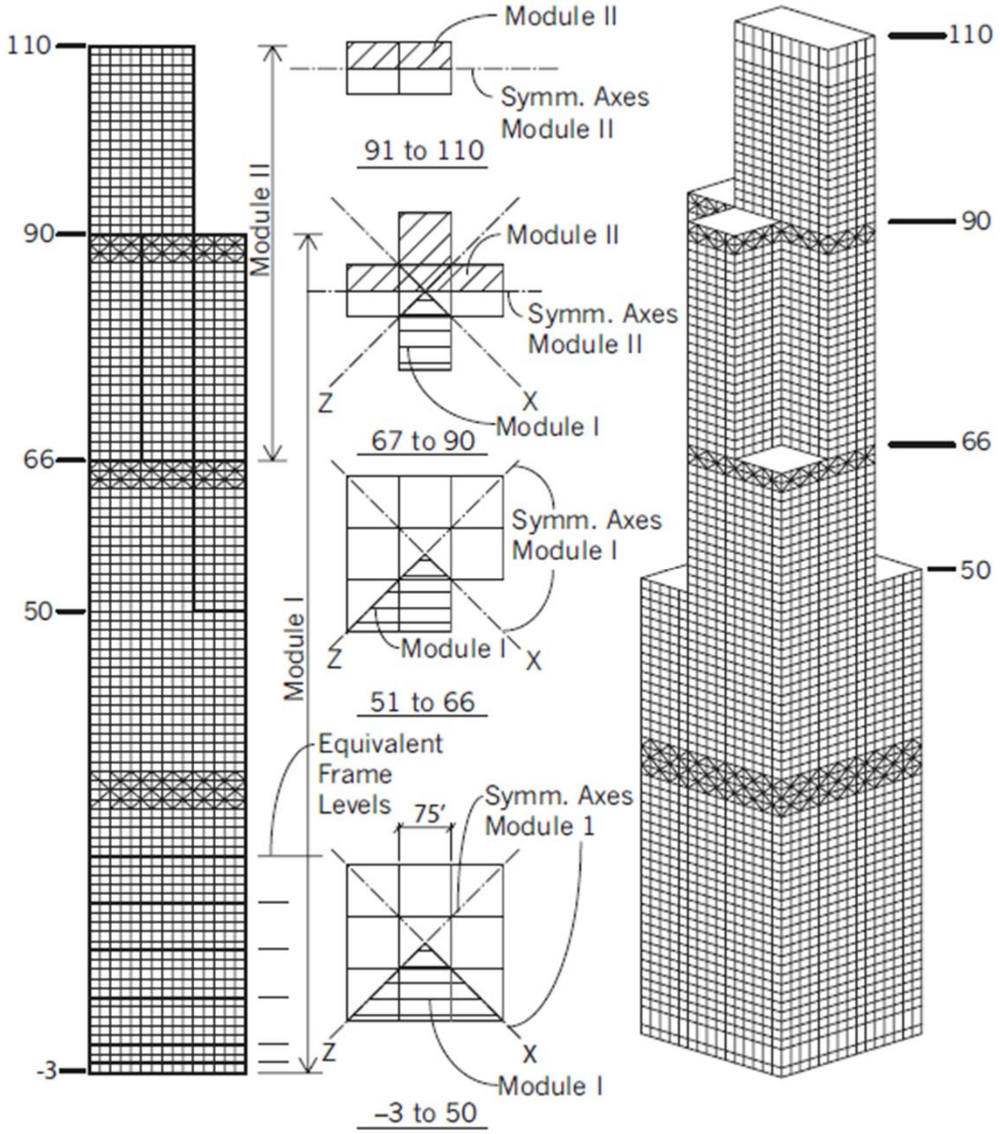
Multiple tubes

- Structures with multiple tubes



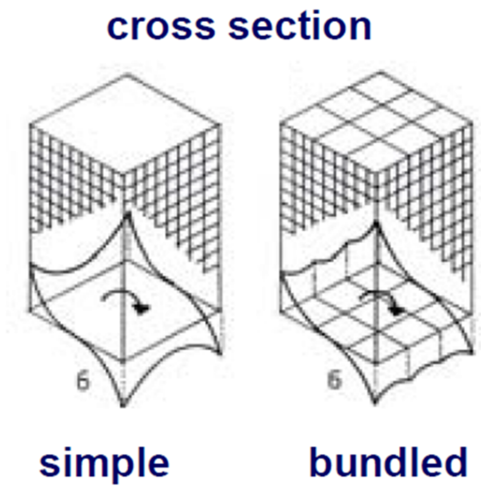


Concept of a structure with multiple tubes: a) perimetral diagonal bracings; b) X bracings and moment connected spandrels; c) perimeter moment connected frames



Willis Tower (formerly Sears Tower), Chicago, Illinois

Better distribution of stresses due to bundled cross section (smaller shear lag)

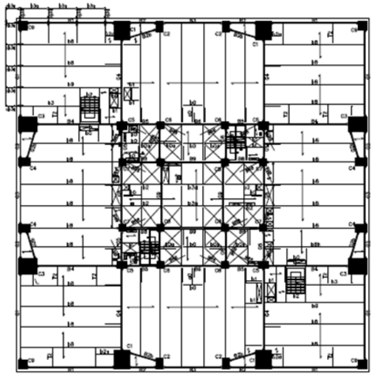


Trend:

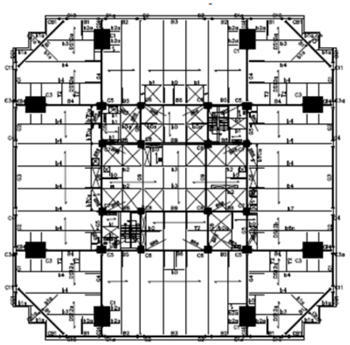
steel → composite → high-strength concrete and steel → combination

Taipei 101, 448 m (2003)

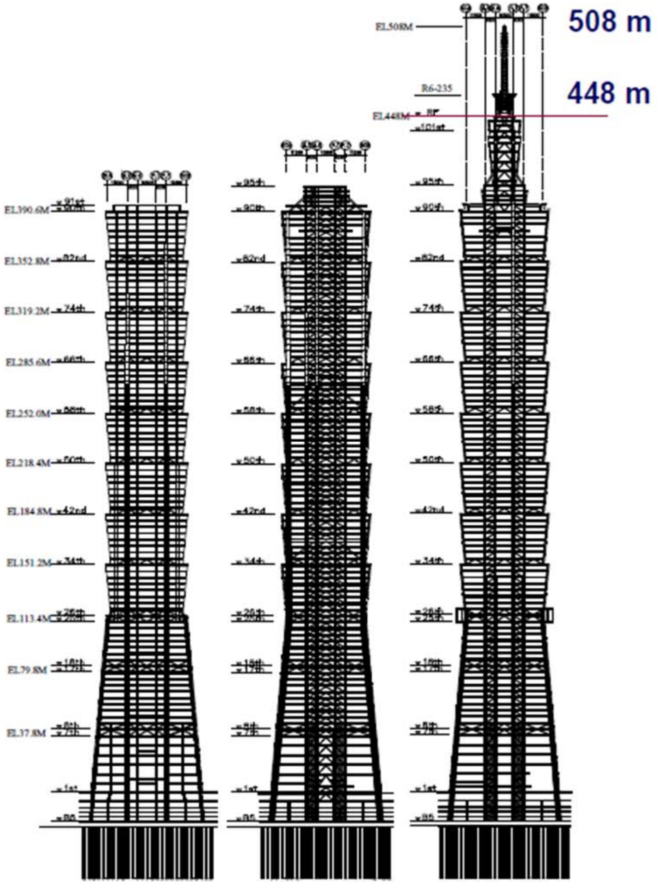
8 compos. mega-col. + core 16 comp. col.



10th floor



32th floor



- 8 composite mega-columns (size 3 x 2,4 [m])
- core: 16 composite mega-columns (22,5 x 22,5 m), *t* = 80 mm
- from 63rd floor steel only
- interconnected by trusses with height of 1- 3 floors
- deflection at top: h/200 = 2,2 m
- reinforced concrete walls up to 9th floor
- 380 steel piles Ø 1,5 m filled up by concrete; into depth of 30 m (expected settlement of 50 mm)

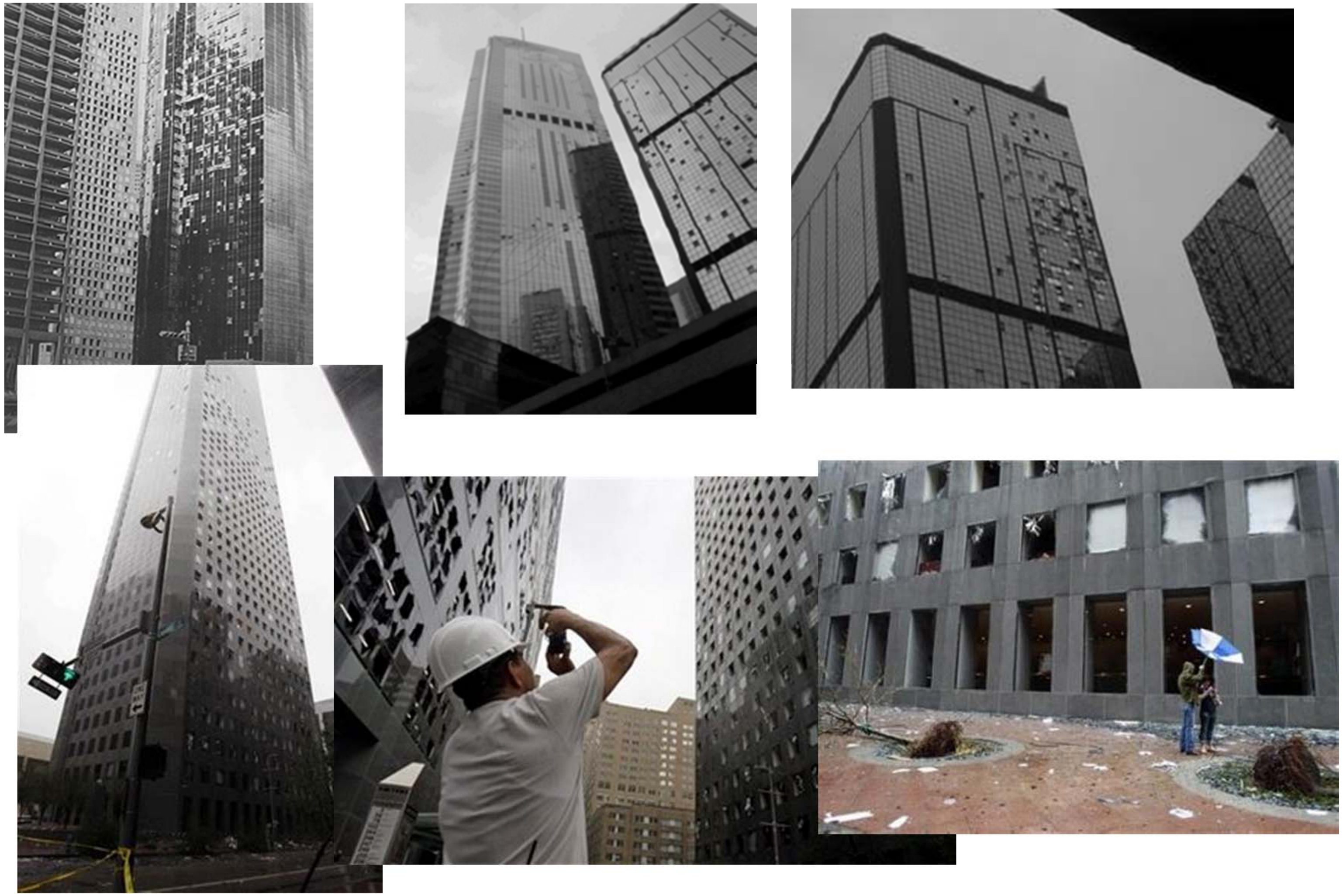
Wind load vs. seismic load

Wind load

- Strong winds may cause a variety of problems, particularly in tall buildings
- Modern tall buildings are even more prone to wind action, due to their lightweight walls and partitions, which reduce the mass and the damping
- Even for high seismic areas, for buildings with more then 25-30 stories, the wind load governs the design
- Attention should be paid to the following criteria:

– Strength and stability
– Fatigue of members and connections
– Excessive lateral deformations (may cause cracking of claddings or permanent deformations to nonstructural elements)
– Excessive vibrations that cause discomfort to the occupants

Wind load



Influence of extreme height to building frame

In addition to usual checks:

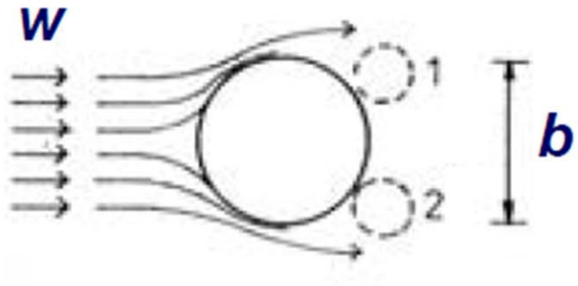
1. Dynamic effects of wind.
2. P - Δ effect (2nd order effect).
3. Influence of member shortening.
4. Static and dynamic rigidity:
   $\delta\mathrm{max} \le H/500$
   acceleration $a \le a_{\mathrm{max}} \approx 0{,}015\ g$

5. Interaction with ground (especially if $H/B > 5$).

Dynamic effects of wind

Generally:

- analysis including vibration:
    - longitudinal (in the wind direction)
    - lateral (in transversal direction):
        circular, elliptic shapes: "vortex shedding"
        rectangular shapes: "galloping" (occurs rarely)
        Vortex shedding, vortex separation (called also Karman periodic set of whirlwinds) results on condition that:



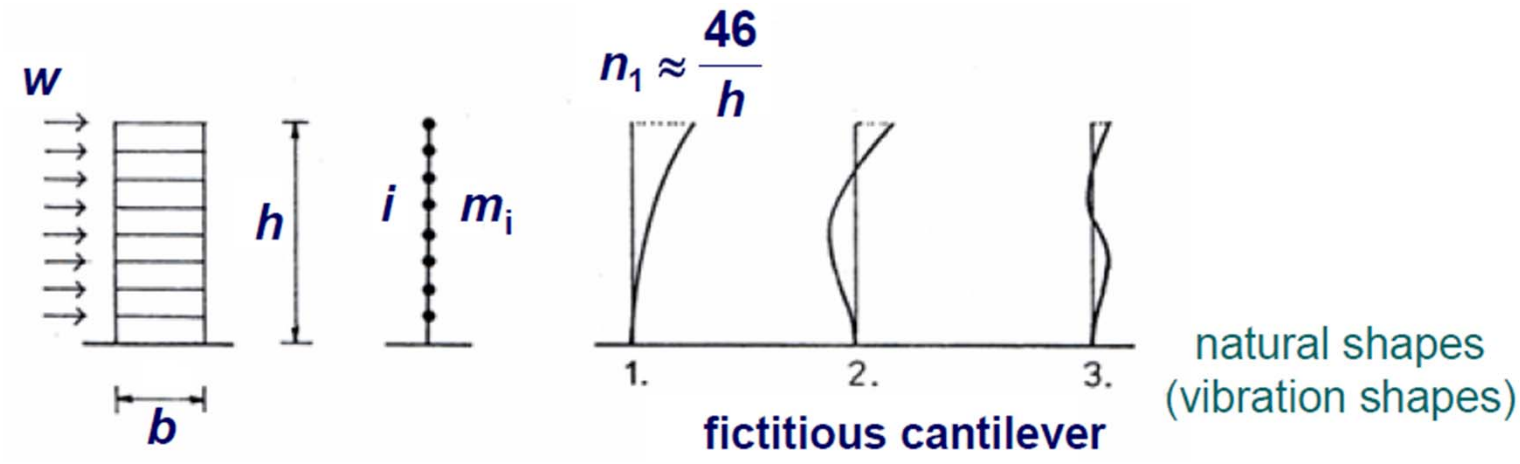
$$v_{\text{crit}} = \frac{b\,n}{St} \approx 5\,bn < 1{,}25\,v_{\text{m}}$$

mean wind velocity

The first frequency of a building: n ≈ 46/h
Strouhal number: circle $St = 0{,}18$

Rearrangement of the building shape → wind tunnel, each variation is significant.

Longitudinal dynamic wind effects



force coefficient   dynamic wind pressure

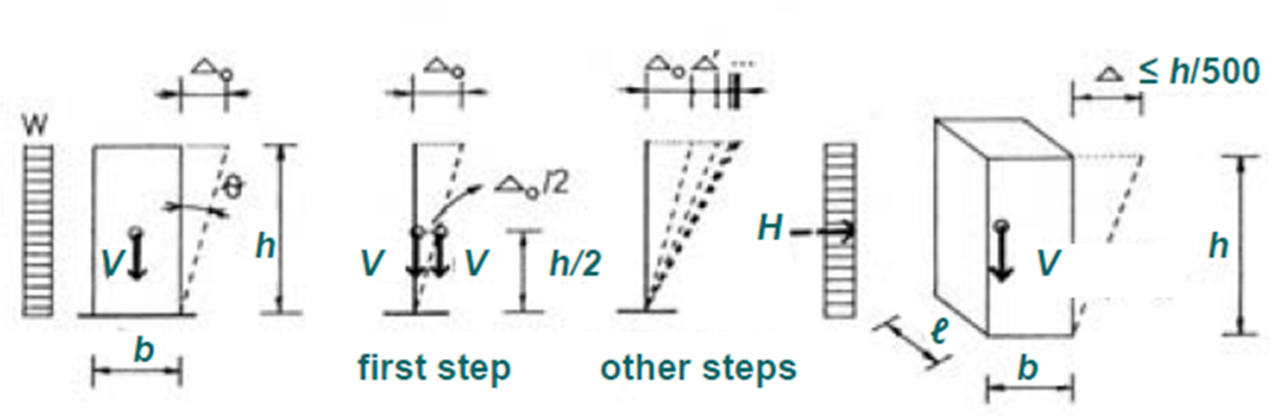
$$F_w = \underbrace{c_s c_d}_{\text{coefficient of the structure}} c_f q_{p(Z)} A_{ref}$$

Wind loading for area *A*ref according to EN 1993-1-4:
- if $h \leq 100$ m and b > 30 m, coefficient of the structure $c_s c_d = 1$;
- otherwise use „detailed method" (depends on natural frequency *n* , parameters of wind and structure ...)
- Eurocode enables to determine even deflection and vibration acceleration

P - Δ effect (2nd order effect)

Represents effect of horizontal shift on internal forces. Solution:

- 2^{nd} order theory (or geometrically nonlinear analysis GNA),



Iteration procedure:

1^{st} step base moment:

$$M_0 = M_H + V\frac{\Delta_0}{2}$$

next:

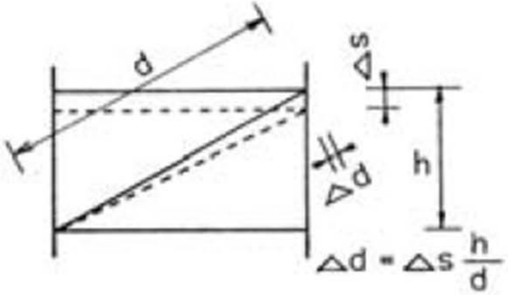
$$M' = M_H + V\frac{\Delta_0 + \Delta'}{2}$$

If SLS is fulfilled, the approximate guess of *V*, *H* (for all building or floor) gives coefficient of 2nd order *m*. The horizontal loading then multiply with *m*:

$$m \approx \frac{1}{1-\dfrac{1}{\alpha_{cr}}} \approx \frac{1}{1-\dfrac{1}{\left(\dfrac{H_{Ed}}{V_{Ed}}\right)\left(\dfrac{h}{\delta_{H,Ed}}\right)}} = \frac{1}{1-\dfrac{1}{\left(\dfrac{H_{Ed}}{V_{Ed}}\right)\left(\dfrac{h}{h/500}\right)}} = \frac{1}{1-\dfrac{V_{Ed}}{500\,H_{Ed}}} > 1$$

Influence of member shortening

The shortening of member axes is covered by computer FEM analysis!



Shortening of members due to stress:

$$\sigma_s = \frac{\Delta s}{h} E$$

Thereof stress of diagonal:

$$\sigma_d = E\varepsilon = E\frac{\Delta d}{d} = \sigma_s \left(\frac{h}{d}\right)^2$$

The stress in diagonals from vertical loading is, therefore, of the same order as in columns!

Measures:

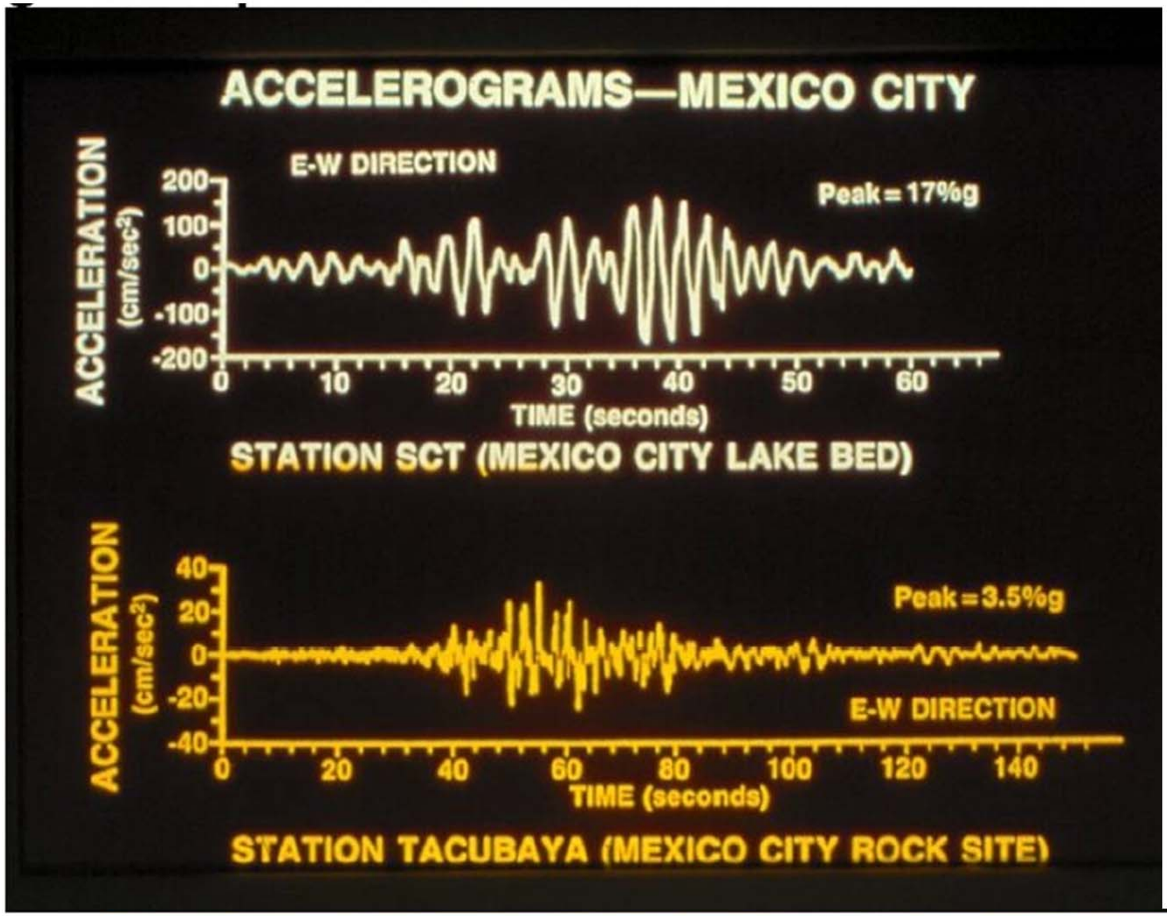
- final connection of diagonals not until assembly of all building,
- or prestressing of diagonals to eliminate compression due to vertical loading.

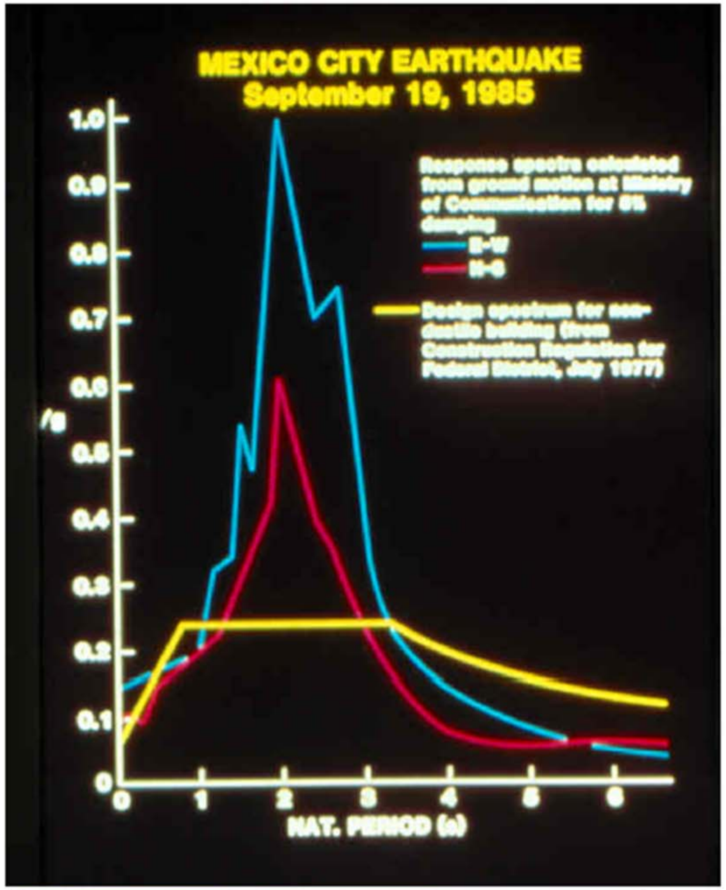
Seismic load

- Many of European areas are under seismic risk
- Southern Europe experienced very damaging earthquakes during the last decades.
- Many existing structures have inadequate protection against strong earthquakes. The vulnerability is very much increasing, due to the rapid grow of the construction industry.
- Seismic loading requires an understanding of the structural behavior under inelastic cyclic deformations
- Behavior under such loading is fundamentally different from wind loading (and gravity loading). It is necessary to pay more attention to type of analysis and detailing requirements, in order to assure acceptable seismic performance beyond the elastic range.
- Some structural damage in members and connections can be expected under design ground motion, as the majority of modern seismic codes allow inelastic energy dissipation in the structural system

Local effects on site

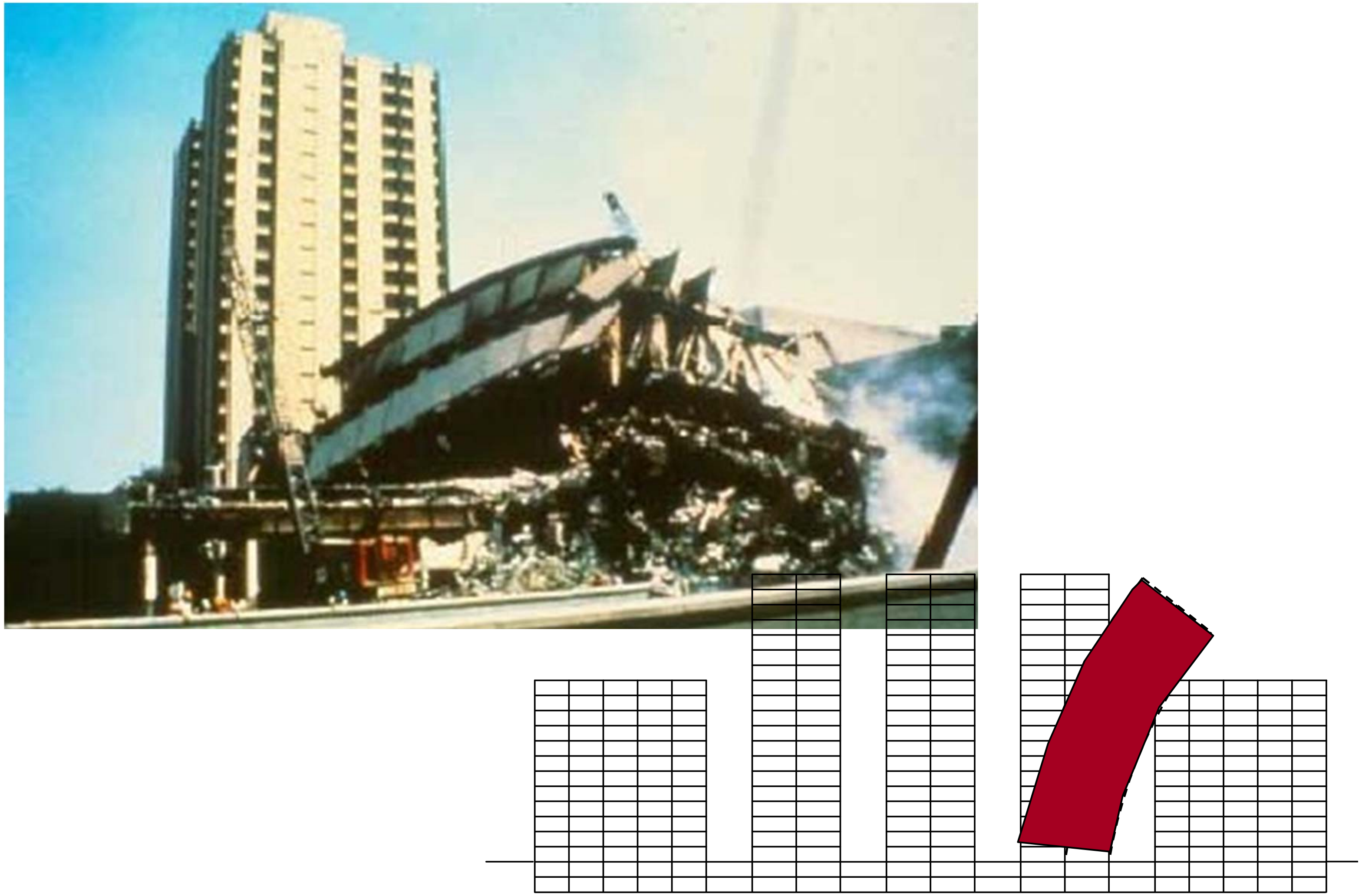
- Soil may act as a filter
- It can modify frequency content of the ground motion
- Amplification of the ground motion (or reduction) may be recorded on site
- Duration of the ground motion is increased


ACCELEROGRAMS—MEXICO CITY
E-W DIRECTION
Peak=17%g
ACCELERATION (cm/sec²)
200
100
0
-100
-200
0
10
20
30
40
50
60
TIME (seconds)
STATION SCT (MEXICO CITY LAKE BED)
ACCELERATION (cm/sec²)
40
20
0
-20
-40
0
20
40
60
80
100
120
140
Peak=3.5%g
E-W DIRECTION
TIME (seconds)
STATION TACUBAYA (MEXICO CITY ROCK SITE)

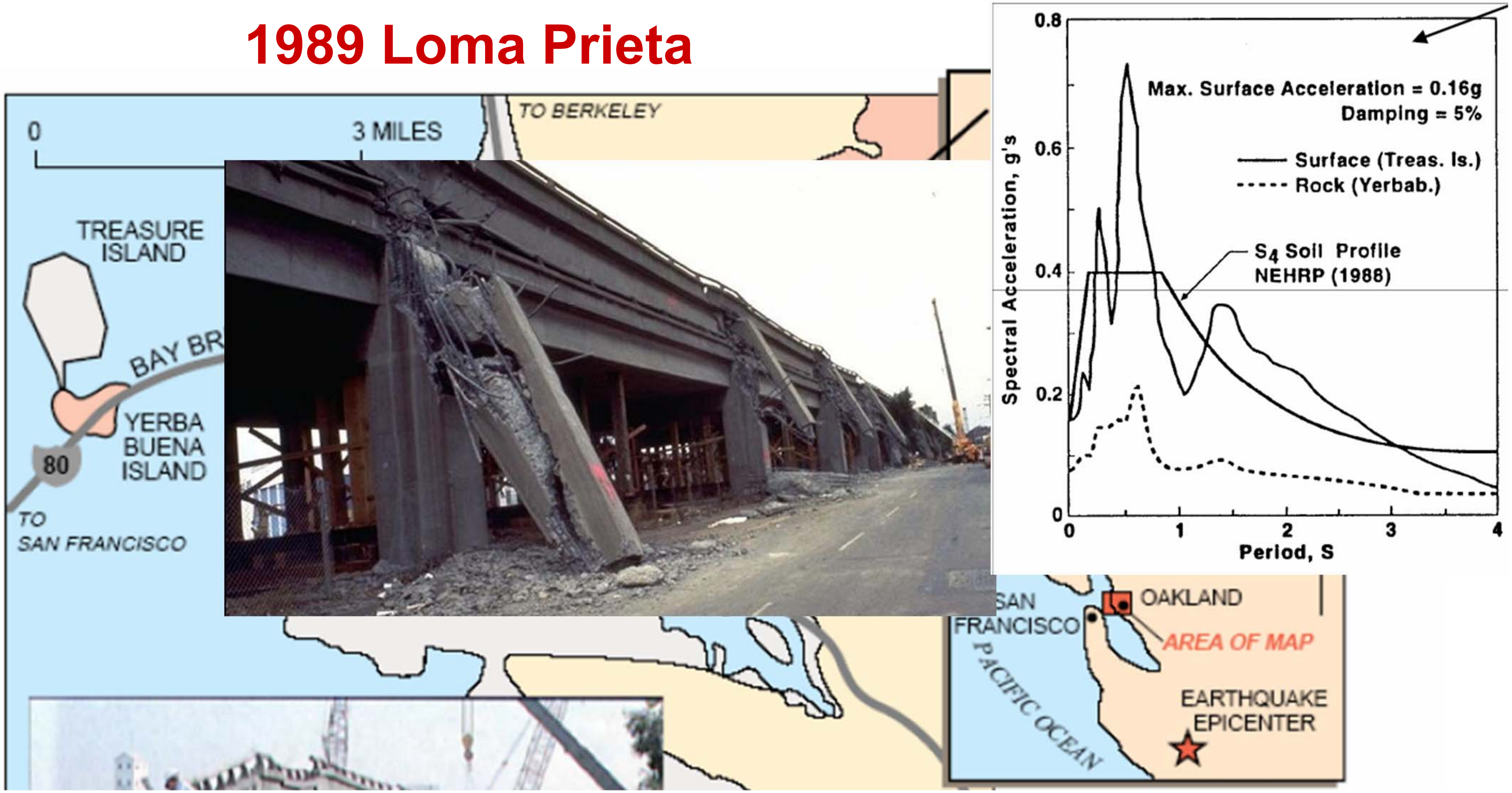

MEXICO CITY EARTHQUAKE
September 19, 1985
/g
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
NAT. PERIOD (s)
Response spectra calculated from ground motion at Ministry of Communication for 5% damping
E-W
N-S
Design spectrum for non-ductile building (from Construction Regulation for Federal District, July 1977)


MANTLE

1985 Mexico City - Pino Suarez



1989 Loma Prieta



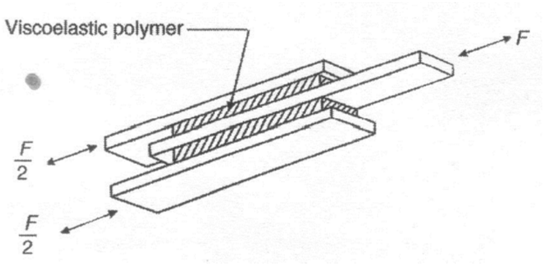
Effect of damping

- Structural response may be reduced by an increase of the damping properties
- Damping of the structural elements is limited
- One option for increasing the damping is the introduction of external damping devices
  - Viscoelastic passive dampers
  - Passive control (tuned mass dampers)
  - Active control (tuned active dampers)
- These systems are effective both against winds and earthquakes

Viscoelastic passive dampers

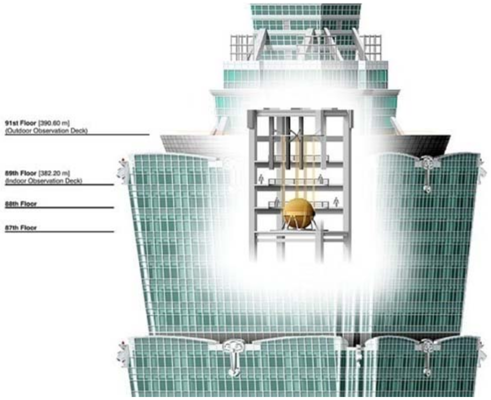
World Trade Center, 417 m

10 000 dampers in the structure, about 100 dampers at the ends of the floor trusses at each floor from the 7th to the 107th



Tuned mass dampers

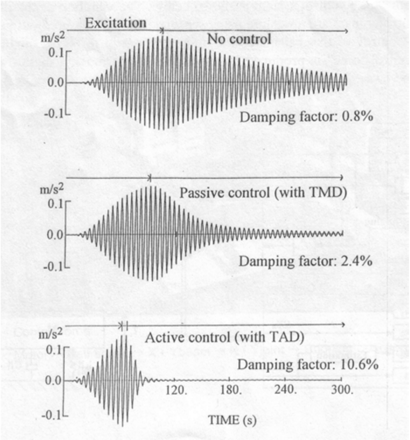
Burj al Arab, Dubai, 321 m
Taipei 101 , 509.2 m



Tuned active dampers

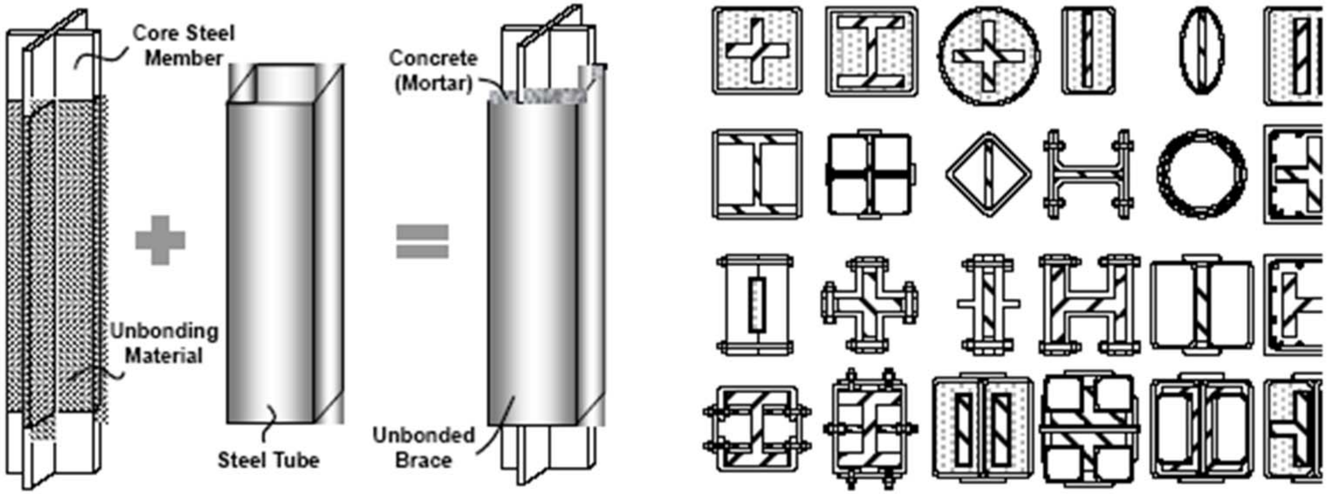
Yokohama Landmark Tower, 295.8 m

Reduction of the acceleration:
29% ÷ 39%



New structural systems for seismic applications

- Buckling-restrained braced frames (BRB)
- Steel plate shear walls (SPSW)
- Systems with removable dissipative members (RDM)



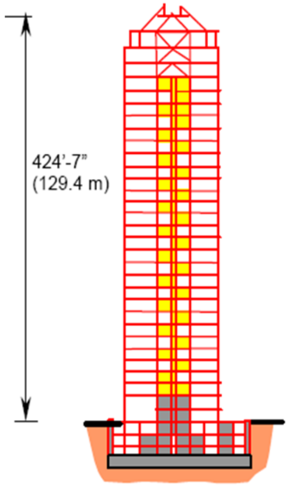
Schematic and typical types of buckling restrained braces

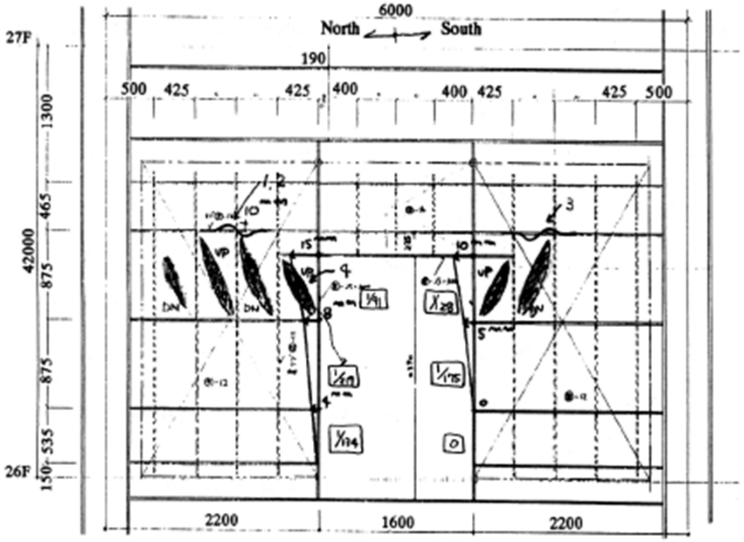
Application of BRB - Tzu-Chi Culture Building, Taiwan

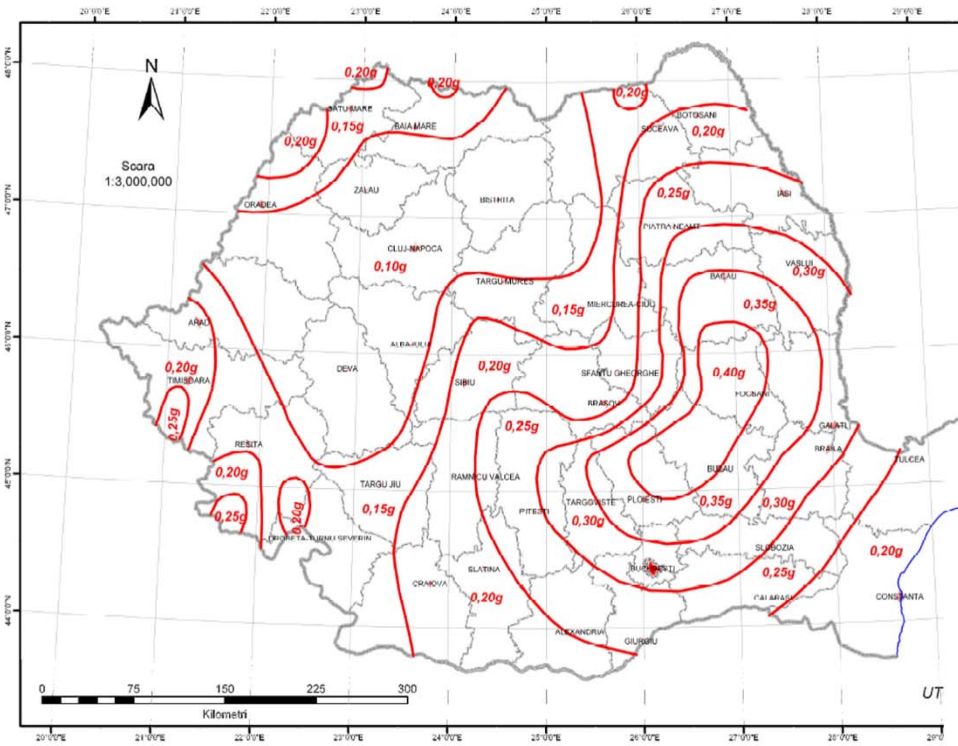
Steel plate shear walls

- The Steel Plate Shear Walls (SPSWs) application has increased in recent years. Design requirements for SPSWs are already implemented in the AISC 2005.
- One of the most important application of steel plate shear walls in a very highly seismic area is the 35-story high-rise in Kobe, Japan.
- The structure was constructed in 1988 and was subjected to the 1995 Kobe earthquake.

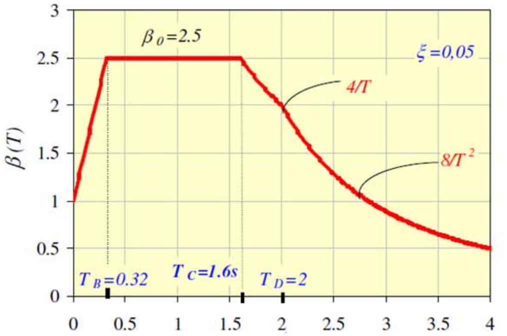
- Studies of this structure (Fujitani et al., 1996) (AIJ, 1995) have indicated that the damage was minor and consisted of local buckling of stiffened steel plate shear walls on the 26th story (Fujitani et al., 1996)
- Interesting to note the adjacent building was heavily damaged during the same earthquake, suffering a partial collapse due to a soft story mechanism

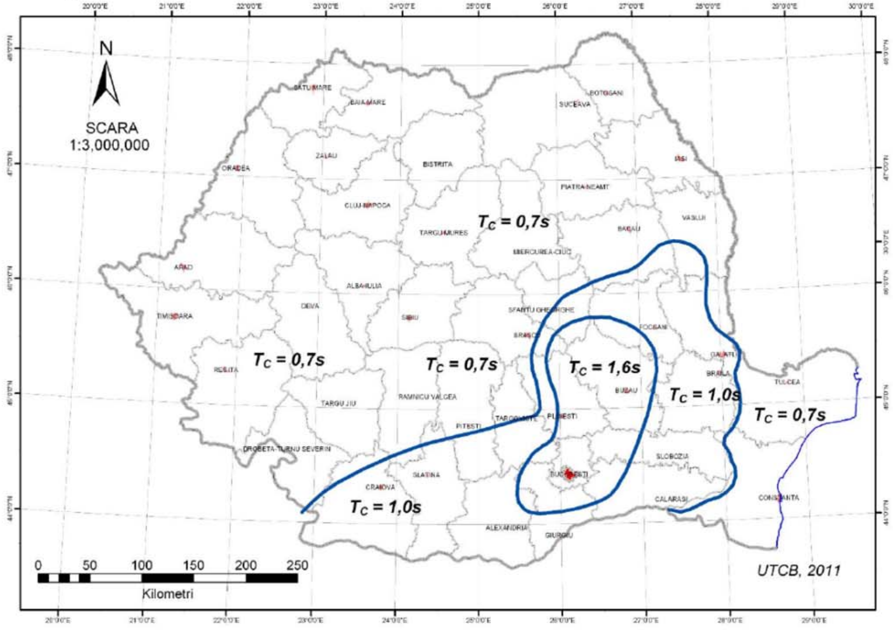






Seismic intensity map





Corner period

This lecture was prepared for the 1st Edition of SUSCOS (2012/14) by Prof. Josef Macháček (CTU) and Michal Jandera, PhD. (CTU).

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