Multi storey buildings

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European Erasmus Mundus Master Course
Sustainable Constructions
under Natural Hazards and Catastrophic Events
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Part II – Multi storey buildings

• Disposition of multi-storey buildings: layout of columns, floor arrangement, bracings
• Floor structure: floor, primary and secondary beams, slim floors, simple and frame detailing
• Static calculation, imperfections

Design of steel structures:

a) Disposition of the structure.

b) Structural system: steel, composite (steel + concrete).

c) Choice of material.

d) Static calculation + dimensioning.

e) Fabrication, transportation, erection, corrosion, fire protection and maintenance.

To solve simultaneously: but first principle, then details.
The design has to secure:

- Functionality during structure lifetime.
  - Eurocode:
    - temporary structures 10 years,
    - buildings 50 years,
    - bridges and monumental structures 100 years.
- Safety, speed of fabrication and assembly, economy.
- Aesthetical solution.
Example of a multi-storey building (up to approx. 30 storeys):
(the static scheme and the security of space rigidity)

Approximate weight:

\[ G = 12 + \frac{n}{2} \text{ [kg/m3 of space]} \]

... \( n \) is number of storeys
Typical arrangements:

Cross section

Longitudinal section

Section A-A’

Roof layout (view)
Disposition

Follows from structural and operational arrangement → cooperation of civil and structural engineer is essential.

Includes:
- arrangement of columns in plan,
- design of floor structure,
- arrangement and design of bracings.

Arrangement of columns in plan

Optimal is regular mesh. Skew connections are however common.

Column spacing

- Optimum $L = 6 \div 9 \text{ [m]}$, tendency up to 18 m:
- Lower spacing for steel is not economical.
Design of floor structure

Requirements:

- static,
- structural (height, ducts for services ...),
- insulating (acoustical, thermal),
- economical.

Acoustical and economical requirements are contrary to each other:

Mass from acoustic view maximal (> 350 kg/m²), otherwise acoustic ceilings are necessary.

Height of structure:

(systems according to ducts of services)

- separated (traditional)
- integrated
- integrated (using „stub girders”)

Multi storey buildings
**Bracings**

1. Vertical bracing – transversal and longitudinal  
   (transfer horizontal forces into basements)
2. Horizontal bracing – in floor and roof plane  
   (transfer horizontal forces into vertical bracing)

**Design of bracings**

**Types of framing:**

a) Non braced (hinged, articulated, swinging)
   - transfer only vertical loadings,
   - connections are non-rigid (or semi-rigid).

b) Vertical bracing

Usually some framing only, transfer also horizontal loadings.

*either permanent or during erection only*
Choice of bracing type:

**Truss: always preferred**

advantages:  
- only axial forces $N$ (→ smaller sections),  
- simple (cheap) hinge joints,  
- high rigidity.

drawbacks:  
- limitation of layout.

**Frame: only if free layout is necessary**

advantages:  
- free space,  
- lower moments in horizontal beams:

drawbacks:  
- moments and forces in columns $M$, $N$, $V$ (→ large sections),  
- stiff joints (laborious),  
- less stiff (usually necessary in all framing),  
- complicated for both directions:
**Wall:**

- reinforced concrete wall or core,
- steel walls:
  - masonry (exceptionally, for low buildings only).

**Advantage:** both moment and shear behaviour $\rightarrow$ big rigidity, limited number of walls.

**Distribution of bracing**

**View of layout:**

- trusses or walls were possible,
- if free space needed - frames.
Static view (for more see later):

a) Only necessary number of bracings (they are expensive).
   i.e.: transfer of horizontal loadings, secure horizontal rigidity ($\delta \leq h/500$),
   prevent tension in columns (if possible).

b) Choose wide bracing which are more effective then narrow bracings.
   They have greater stiffness, which depends roughly on square of width.

c) Bracings centre of gravity in plan arrange into resultant of loadings (if possible).
   Otherwise the building is twisted – can damage especially facade.

d) The random torsion must always be transferred.
   Bracings must not cross in 1 point!
Floor system

a) Systems with primary and secondary beams (the most common)

Recommendation based on economic studies:

- orientation of primary beam to weak column axis,
- preference of $L_1 \neq L_2$ and secondary beams for longer span,
- spacing of composite secondary beams roughly $2 \div 3.5$ [m].

Appropriate design influences total weight of entire building!!! Evaluate more alternatives.
b) Systems without secondary beams

Simple system, but some drawbacks:
- heavy structure → suitable for small spans (≈ 4.5 m),
- higher height (flushed are laborious)

Modern solutions
Slim floor systems
### Slab types

<table>
<thead>
<tr>
<th>Type</th>
<th>Application</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite slab</td>
<td>$10\text{cm} \leq d \leq 30\text{cm}$&lt;br&gt;$2\text{kN/m}^2 \leq q \leq 6\text{kN/m}^2$&lt;br&gt;for spans $2\text{m} \leq L \leq 6\text{m}$</td>
<td><img src="image1.png" alt="Composite slab" /></td>
</tr>
<tr>
<td>Prefabricated composite slabs</td>
<td>Sheeting / Rockwool / Concrete&lt;br&gt;for $d = 20\text{cm} \Rightarrow q = 2\text{kN/m}^2$&lt;br&gt;for spans $4\text{m} \leq L \leq 7\text{m}$</td>
<td><img src="image2.png" alt="Prefabricated composite slabs" /></td>
</tr>
<tr>
<td>Slabs with deep rolled profile sheetings</td>
<td>$h = \text{ca. } 200\text{mm}$, $d = \text{ca. } 25\text{cm}$&lt;br&gt;for spans $L \leq 6\text{m}$</td>
<td><img src="image3.png" alt="Slabs with deep rolled profile sheetings" /></td>
</tr>
<tr>
<td>Concrete slab</td>
<td>on-site or partially prefabricated&lt;br&gt;$d = \text{ca. } 20\text{cm} \Rightarrow q = 5\text{kN/m}^2$&lt;br&gt;for spans $L \leq 6\text{m}$</td>
<td><img src="image4.png" alt="Concrete slab" /></td>
</tr>
<tr>
<td>Prestressed hollow core slabs</td>
<td>$16\text{cm} \leq d \leq 40\text{cm}$ (1.20m width)&lt;br&gt;$2.5\text{kN/m}^2 \leq q \leq 6\text{kN/m}^2$&lt;br&gt;for spans $8\text{m} \leq L \leq 14\text{m}$</td>
<td><img src="image5.png" alt="Prestressed hollow core slabs" /></td>
</tr>
</tbody>
</table>
**Requirements:**

- rigid,
- simple erection,
- low mass (in reverse requirem. of acoustics).

1. In situ non-composite reinforced concrete slab

**Drawbacks:**
- laborious,
- heavy,
- wet process.

2. Pre-cast concrete slabs

**Advantages:**
- fast,
- wet only at grouted joint.
Reinforced concrete slab usually acts compositely with floor beams:

- saving in steel (approx. 25%)
- reduction of floor depth.

3. Metal decking

Thin-walled cold-formed sheeting, $t \approx 0.7 \div 1.5$ mm.

a) High profiles ($h \approx 150 \div 300$ mm):

Floors without secondary beams or slim floors.
b) Shallow sheeting ($h \approx 50 \div 150$ mm)

- span up to 3 m

Position of sheeting

- normal – usually higher section modulus $W_{eff}$,
- reverse – concrete slab is heavier but shear connectors earn higher resistance.

c) Flat sheeting with ribs

- $t \approx 1.25 \div 2$ mm
- May act as a membrane!!
Secondary floor beams

Check for ULS and SLS: total deflection $\delta_{\text{max}}$ is not limited (precamber is possible),
deflection under variable loading:
$$\delta_2 \leq \frac{L}{250} \text{ (for cantilevers } L = 2l),$$
vibration in building floors:
$$f_1 \geq 3 \text{ Hz (or } \delta_{\text{max}} \leq 28 \text{ mm})$$
vibration in gyms, dance halls:
$$f_1 \geq 6 \text{ Hz (or } \delta_{\text{max}} \leq 10 \text{ mm})$$

Design: - steel sections
- composite sections (savings $\approx 25\%$ of steel)

Usual shear connectors:
- studs
- perforated connector
- fired brackets
- Ribcon HILTI
- Stripcon HILTI
## Floor main beams

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<thead>
<tr>
<th>Type</th>
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<tr>
<td>Rolled beam: IPE, HEA, HEB, HEM</td>
<td>Columns / Beams w/o composite for spans ≤ 18m</td>
<td><img src="example1.png" alt="Example" /></td>
</tr>
<tr>
<td>Welded sections</td>
<td>Beams w/o composite action for spans ≤ 30m</td>
<td><img src="example2.png" alt="Example" /></td>
</tr>
<tr>
<td>Slim-floor beams</td>
<td>Beam embedded in the slab for economic spans ≤ 7m</td>
<td><img src="example3.png" alt="Example" /></td>
</tr>
<tr>
<td>Cellular beams</td>
<td>Sections with web openings for spans ≤ 24m</td>
<td><img src="example4.png" alt="Example" /></td>
</tr>
<tr>
<td>Divided structural members</td>
<td>e.g. trusses economic for spans ≥ 30m</td>
<td><img src="example5.png" alt="Example" /></td>
</tr>
<tr>
<td>Stub girders</td>
<td>US/UK system to easify passage of installations for spans ≤ 20m</td>
<td><img src="example6.png" alt="Example" /></td>
</tr>
<tr>
<td>Type</td>
<td>Application</td>
<td>Example</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Rolled beam:</td>
<td>Columns / Beams w/o composite for spans ≤ 18m</td>
<td><img src="image" alt="Example" /></td>
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Shanghai Financial Center

- IPE 80 - 750
- HE 100 - 1000

- IPE 80 - 750
- HE 100 - 1000
### Welded section beams

- Welded section beams can be made with parallel flanges or tapered.
- The economic advantage of welded beams is that they can be designed to provide the required moment and shear resistance.
- When tapered, their characteristics can be varied along the beam span in accordance with the loading pattern.
- Several forms of tapered beams are possible.

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#### Table: Application of Welded Sections

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Tapered beam: simply supported beam

• A simply supported beam design with a maximum bending moment at the mid-span would require that they all effectively taper to a minimum at both ends, whereas a rigidly connected beam would have a minimum depth towards the mid-span.
• To make best use of this system, services should be placed towards the smaller depth of the beam cross-sections.

Tapered beam is found to be economical for spans of 13 to 20 m.
Tapered beam: haunched beam

- The span length of a composite beam can be increased by providing haunches or local stiffening of the beam-to-column connections.
- The length of haunch is typically 5 to 7% the span length for non-sway frames or 7 to 15% for sway frames.
- Service ducts can pass below the beams as in conventional construction.

![Haunched composite beam](image)
Cellular beams can be made with parallel flanges, tapered or curved.

Castellated beams have limited shear capacity and are best used as long span secondary beams where concentrated loads can be avoided.
Applications
• Trusses are frequently used in multistory buildings for very long span supports
• The openings created in the truss braces can be used to accommodate large services
• Truss configuration creates difficulty for fire protection. Fire protection wrapping is labor intensive and sprayed-protection systems cause a substantial mess to the services that pass through the web opening
• From a structural point of view, the benefit of using a composite truss is due to the increase in stiffness rather than strength
Applications

Composite Trusses – WTC application

Innovative WTC Tower Structural System

- Innovative structural system when built; incorporated many new and unusual features

- Two features require additional consideration:
  - Composite floor truss system using long span open-web bar joists and spray-applied fireproofing
  - Design for wind loads and control of wind-induced vibrations
WTC application – views during construction
WTC application – fire performance

**Fire Performance of Composite Floor System**

- Fire-protection of a truss-supported floor system with spray-on fireproofing was innovative and not consistent with then-prevailing practice.

- **No evidence found of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
  - 1/2 in. specified when WTC towers were built to maintain Class 1-A (not 1-B) fire rating requirement of the NYC Building Code
  - 1-1/2 in. specified for upgrades some years prior to 2001
  - 2 in. for similar floor system in an unrestrained test (model code evaluation service recommendation in June 2001, unrelated to WTC buildings)

- **No evidence that full-scale fire resistance test of the WTC floor system was conducted** to determine the required fireproofing thickness; in 1966, the Architect of Record and, in 1975, the Structural Engineer of Record stated that the fire rating of the WTC floor system could not be determined without testing.
Truss types

- Several forms of truss arrangement are possible. The three most common web framing configurations in floor truss and joist designs are:
  - Warren Truss
  - Modified Warren Truss
  - Pratt Truss

Truss configuration: (a) Warren truss, (b) Modified Warren truss, and (c) Pratt truss.
The stub girder system involves the use of short beam stubs that are welded to the top flange of a continuous, heavier bottom girder member, and connected to the concrete slab through the use of shear studs. Continuous transverse secondary beams and ducts can pass through the openings formed by the beam stub. The natural openings in the stub girder system allow the integration of structural and service zones in two directions, permitting story-height reduction when compared with some other structural framing systems.
**Special types**

- **Parallel Beam System**
  - The system consists of two main beams with secondary beams run over the top of the main beams. The main beams are connected to either side of the column.
  - This will help in reducing the construction depth
  - The secondary beams are designed to act compositely with the slab and may also be made to span continuously over the main beams. The need to cut the secondary beams at every junction is thus avoided.
  - The parallel beam system is ideally suited for accommodating large service ducts in orthogonal directions
Special types

• Prestressed Composite Beams
  – Prestressing of the steel girders is carried out such that the concrete slab remains uncracked under the working loads and the steel is utilized fully in terms of stress in the tension zone of the girder.
  – It enhances the load-carrying capacity and stiffness of long-span structures
Floor secondary beams

a) Web girders: $h \approx L/20 \div L/30$

- rolled sections I (exceptionally U), $L < 9$ m,
- wide-flange H, with partially encased web for increasing fire resistance,

- welded plated girders, great $L$
- cold-formed sections, light floors, acc. to fabricator:

Static solution:

rolling length up to 18 m (usually 6, 2 m)
b) Castellated beams (or beams with lightening cuts): $L \leq 15$ m

- web openings may be used for services,
- aesthetical reasons.

c) Open-web joists: $h \approx L/15 \div L/10$

$L > 9$ m

- non-sliding
- sliding
Systems without secondary beams – Slim floor systems

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</table>

$\sim b + 200$ support $\sim 70$

$200 \div 400$ for $L = 5 \div 9$ m
Slim-floor system

Integrated steel beams for Slim-floor systems
• Request of modern architecture:
  • Transparent structural envelopes with column free ground floor design
  • Flexibility for sustainable conversion of use
  • Possibility to upgrade services for multifunctional living
• Slim-floor construction (IFB / SFB):
  • Combines advantages of prefabricated slab elements with steel framed construction
⇒ Economic solutions fulfilling the above specified demands

• The “slim floor” system cannot be used as part of the seismic load-resistance system
Slim-Floor beams - Fabrication

ASB beam (Asymmetric Steel Beam): developed by British Steel (Corus) in 1991, in use from 1995 (h = 280 and 300 mm, tw = 19 ÷ 27 mm, tf = 16 ÷ 24 mm)
Slim-Floor beams - Advantages

⇒ Floor thickness reduction
⇒ Constructing floors of variable thicknesses
⇒ Incorporating under-floor technical equipment
⇒ Freeing-up working space
⇒ Built-in fire resistance
⇒ Competitive pricing
⇒ Easy to build
⇒ Sustainable construction
⇒ Lighter structures
⇒ Less façade surface
⇒ Heating / cooling cost reduction
⇒ Lower building height
⇒ More natural light
Slim-Floor beams - Applications
Connection to primary beam

a) Placing from above (simple, provides continuity, but high floor depth).

b) Flush-mounted (usual).

c) Embedded, with minimum structural depth.
Flexible (hinged) connection of secondary to primary floor beams

1. Bolted/welded angle cleats
   (low-cost)

   ![Diagram of bolted/welded angle cleats]

   for bolt at primary beam web

   resultant for bolt at secondary beam web!
   (bolts at primary beam web only for V)

2. End plates
   Negative tolerances of secondary beams necessary
   (up to -2 mm)!!

   ![Diagram of end plates]

   preferred by fabricators

   - plate thickness 10 mm
   - trans. spacing 130 mm

   usually:
   - up to IPE 180 – 2 M20
   - up to IPE 240 – 4 M20
   - up to IPE 330 – 6 M20

3. Site welding
   (slow, exceptionally)
Continuous secondary floor beam (connection loaded by V, M)

a) splice on tension flange
- splice bolts loaded in shear (i.e. shear and bearing) due to M/h,
- bolts at web are loaded in shear due to V.

b) end plate (preloaded bolts are usually used to limit deformation)
- bolts are loaded by shear due to V and tension due to M
  (plastic or elastic distribution of forces at the bolt group may be used).

Tension in upper 4 bolts $\frac{M}{4h} \leq F_{T,Rd}$

"T-stub" (tension with prying)
Primary beams

Check for ULS and SLS is the same as for secondary beams.
(Note: for primary beams, the allowable deflection $\delta_2$ may range from $L/350 \div L/400$)

The variable (live) loading in large loaded areas may be reduced by coefficient $\varpi A$ (see EN 1991-1-1).

Design:  
- steel sections
- composite sections (savings $\cdot 25\%$ of steel)

Beam types:  
- web girders (often welded),
- castellated,
- open-web joists.

Static solution:  
- flexible joints ... connected to weak axis of columns,
- frame joints ... connected to strong axis of columns
Flexible (hinged) connection to columns

1. **Angle cleats**
   (low-cost)

2. **End plates**
   Negative tolerances of primary beam necessary and fillers !!
Frame joints (more complicated, mind the stability of compression flange !!)

1. Welded
   Mind the possibility of column flange doubling !! (ultrasonic check, quality Z25)

2. Bolted - end plate
   Usually friction-grip bolts (to restrict deformation)
Connection to concrete core

Requirements:

Principle of connections:
- welded connection
- combined connection (bolts + site welds)
- additional anchorage

![Diagram of connection methods]
Static calculation and dimensioning

1. Method: Eurocode, limit states (ULS, SLS)

2. Global analysis (determination of internal forces):
   - according to effect of deformed geometry:
     I. order: equilibrium on undeformed structure,
     II. order: equilibrium on deformed structure – necessary for:
     • buckling behaviour, stability (include imperfections),
     • cable/membrane structures.
   - according to material behaviour:
     • elastic calculation
     • plastic calculation
     - with plastic hinges (kinematic mechanisms)
     - with plastic zones (elastoplastic)

Common (usual) calculation:
   I. order elastic or plastic.
   II. order effects are introduced via imperfections and reduction factors $X, X_{LT}$. 
Imperfections of steel structures

1. Global imperfection (sway of storey structure): with help of angle $\varphi$

$$\phi = \phi_0 \alpha_h \alpha_m$$
$$\phi_0 = 1/200$$
$$\alpha_h = \frac{2}{\sqrt{h}} \quad \text{but} \quad \frac{2}{3} \leq \alpha_h \leq 1.0$$
$$\alpha_m = \sqrt{0.5 \left(1 + \frac{1}{m} \right)} \quad h \ldots \text{total height}$$
$$m \ldots \text{number of loaded columns}$$

2. Local imperfection of members: with help of equivalent value $e_0$

All these imperfections (initial bow $e_{0g}$, residual stresses in cross sections $\sigma_r$, imperfections in boundary conditions $e_1$) are introduced in calculations as unique equivalent initial bow with amplitude $e_0$ (values given in Eurocode).
<table>
<thead>
<tr>
<th>Fabrication</th>
<th>consider facility of manufacturer (e.g. use of tubes) ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>consider size and weight of assembly parts ...</td>
</tr>
<tr>
<td></td>
<td>(e.g. railway $B_{\text{max}} = 3150$ mm)</td>
</tr>
<tr>
<td>Erection</td>
<td>whether at site weld or screw, erection aids ...</td>
</tr>
<tr>
<td>Corrosion protection</td>
<td>see Standards, question of price:</td>
</tr>
<tr>
<td></td>
<td>- without protection (dry place, Corten weathering steels),</td>
</tr>
<tr>
<td></td>
<td>- paintings,</td>
</tr>
<tr>
<td></td>
<td>- galvanizing (hot dip galvanizing),</td>
</tr>
<tr>
<td></td>
<td>- metal spraying (Zn; Zn85±Al/15 + painting).</td>
</tr>
<tr>
<td></td>
<td>Very important is surface preparation, e.g. $\text{Sa } 2\frac{1}{2}$ (shot or grit-blasting).</td>
</tr>
</tbody>
</table>

**Fire protection** see Standards, question of price:

Today with help of calculation (important is section factor $A_{m}/A$):

- fire-resistant boards (fixed by glueing, stapling, screwing),
- spray application (of vermiculite, pearlite etc., $t \approx 25\div50$ mm),
- intumescent coating ($t \approx 1$ mm but increases volume $\approx 50x$).

**Maintenance** secure access for paintings (or airtightness of sections).
This lecture was prepared for the 1st Edition of SUCSOS (2012/14) by Prof. Josef Macháček (CTU) and Michal Jandera, PhD. (CTU).

Adaptations brought by Florea Dinu, PhD (UPT) for 2nd Edition of SUCSOS

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