1. Large Span Structures

1.1 INTRODUCTION

When do we consider a span ‘large’?

- if it is larger than the usual spans for conventional structures.

Examples (for the limits for conventional structures, above these numbers the span is too large):

- Reinforced concrete beam/slab of a residential house: > 8-10 m
- Precast concrete slab: > 15-18 m
- Steel frames: > 20-25 m

How can we increase the load-bearing capacity of bended structures?

- By increasing the height of the beam/slab (wall-beam instead of normal beam, truss instead of steel beam).
- Changing the statical model or the geometry (e.g. multi-span beam, arcs, folded plates).

1.2. BEAM-LIKE STRUCTURES

Beam-like structures are usually bended structures. Bending moment result in normal stresses and shear force result in shear stresses in the structure.

![Image of a simply supported beam](image.png)

**Figure 1. An example of a bended beam: simply supported beam loaded by uniformly distributed load.**

The maximal strain and stress are in the extreme fiber of the beam (top and bottom fibers). These extreme fibers carry most of the bending moment. That’s why it is economical to increase the area of the cross-section at the top and bottom (where the extreme fibers are) and decrease in the middle → we usually use I-beams for normal bended beams. In case of I-beams, the flanges carry most of the normal stresses and the web the shear stresses (the location of the maximal shear stress is in the middle of the cross-section).
Steel beams
The material properties of steel make it an great candidate to create economical bended structures. Typically, steel beams are I-beams. The web and the flange are shaped to avoid

- local flange buckling (https://www.youtube.com/watch?v=QimlY0XCa08)
- local web buckling (https://www.youtube.com/watch?v=cM1mVXSFnq0). (To avoid local web buckling, we can use SIN beams.)

The utilization of the web for shear stress is only 10-20% (we need to use a thick web to avoid web buckling). As a result, we can remove material from the web to create an economical structure.
**Truss**

A conventional truss is made of bars connecting to each other by pinned joints (hinges). If the structure is loaded only on its nodes (the joints), then no shear force arises in the members (the rods). The force in the members is either compressive or tensile.

However, there is another way of thinking about trusses: they can be considered to work as high beams, where the top flange is the top chord and the bottom flange is the bottom chord. The web of the beam is created by the diagonal members (they are also called webs). In case of vertical loads, the bottom chord is under tension, the top chord is under compression. The moment is balanced by the normal forces in the top and bottom chords.

![Diagram of internal forces in a truss](image)

*Figure 5. Internal forces in the members of a truss. (The M and V diagrams are from the beam analogy.) Hinge is assumed in each node of the structure.*

Practically, it is not possible to create true hinges in the nodes, but we neglect the small bending moments arising in the members. Moreover, the top and bottom chords of the trusses are often continuous (without hinges intersecting them). If the truss is well-constructed, we can neglect these factors.

The requirements of a well-constructed truss:

- **Statically determinate**
- The members running into one node intersect each other in one point.
- Avoid acute angles.

![Image of an archaic truss](image)

*Figure 6. Archaic truss not following the requirements of a well-constructed truss.*
Figure 7. Well-constructed trusses

Vierendeel truss

The main difference between a truss and a Vierendeel truss is in the construction of the nodes. In the Vierendeel truss the joints are fixed, therefore bending moment and shear force arises in the members of the structure. As a result, they are statically indeterminate (with a high degree of indeterminacy). It would be time consuming to calculate such structure, therefore we make some simplifications.

From numerical computations carried out by computer software we can see that the bending moment is zero approximately at the mid-point of the members. → We can assume hinges in these points which simplifies the problem.

Figure 8. Internal forces in a Vierendeel truss computed by a computer software.
However, it is still statically indeterminate, so we also need to utilize symmetry to calculate the forces. Hence, we make further assumptions:

- The shear force is distributed equally between the top and bottom chords.
- Bending moment is balanced by the forces in the top and bottom chords.

From the beam analogy, in the same way as for trusses:

- Bending moment (in the beam analogy) results in normal forces in the top and bottom chords.
- Shear force (in the beam analogy) is balanced by the bending moment arising in the members (vertical members + top and bottom chords).

In case of the same geometry and material, a Vierendeel truss is less economical than a common truss (because of the bending moments arising in the Vierendeel truss).

**Wall beam**

The main difference between a conventional beam and a wall beam is, that the deformations resulting from the shear forces cannot be neglected in case of wall beams. As a result, the Bernoulli-Navier hypothesis is not valid everywhere (the cross-sections cannot be assumed to stay flat).

There are three zones depending on the $h$ height of the wall beam:

1. near the supports, where the shear deformations are dominant ($h/2$ long zone measured from the supports)
2. transitional zone ($h/2$ long zone after zone 1)
3. mid-zone, where the Bernoulli-Navier hypothesis is valid

If we carry out numerical computation, we can see, that the structure behaves as an arch with a tie-bar (arced compressed zone + tensioned zone at the bottom).

![Diagram](image)

*Figure 9. Stress trajectories in a wall beam. Green denotes compression, red denotes tension.*

Analyzing the stresses from numerical computations, we can deduce, that openings can be cut above the arced line or between the arced line and the tension zone. If the length of the beam is less than $5h$, then we should consider it to be a wall beam.
Storey height structures
Storey height structures can be created from the abovementioned structures. It is beneficial, because it fits the architectural concept and the slabs stabilize the “beams”. Storey height trusses, wall beams and Vierendeel trusses are high enough to cover large spans.

Trusses: problematic if there is a need of opening on the structure.

Vierendeel truss: easy to create openings, because of the empty panels. But as it was mentioned before, it is less economical compared to a truss.

Wall beam: openings should be placed according to the stress distribution (where the stresses are small).

Another benefit of using storey height structures is, that they support two slabs (the bottom and top slab), therefore it is enough to place a storey height beam in every second storey of the building.

Arcs
It can balance the load with normal forces which is more economical than balancing moments. (If moment arises in the cross-section, tensile and compressive stresses arise at the same time.) As a result, using arcs, we can balance the structure with normal forces which results in covering large spans with small cross-sectional areas.

When designing arcs, it is important to provide horizontal support for the structure! If there is not enough horizontal support, the same large bending moments arise in the beam that arises in case of straight beam.

![Figure 10. Bending moment diagrams of arcs loaded by vertical forces a) without sufficient horizontal support, b) with sufficient horizontal support.](image)

Folded plates
Folded plates are surfaces with generatrixes parallel (or almost parallel) to the direction of the loads and they are arced (or triangular) in the perpendicular direction.
We can create folded structures with parallel or non-parallel edges, many combinations are possible. However, the most common are prismatic, triangular and trapezoidal shapes. Moreover, they can be created from non-flat surfaces as well.

Using folded plates, we can further create different structures: multi-span structures, frames, shell-like structures or space trusses.

Folded plates carry the loads efficiently. By folding the sheets, we increase the height of the cross-section, without increasing its weight. If the plate is bended and behaves as a beam or plate, the folding results in increasing the load-bearing capacity.

Folded plates carry the loads with normal forces arising in the plate panels and shear forces arising in the edges (where two panels are joined). We must provide support for folded plates at the ends, to avoid warping!
Figure 14. Examples of supporting the ends of folded plates using diaphragms or tie-bars. Diaphragm is a stiff, continuous plate perpendicular to the folded plate.

1.3. PLATE-LIKE STRUCTURES
Plate-like structures are bended structures covering two-dimensional spans. A traditional material for plates is reinforced concrete (RC). In case of RC slabs, the serviceability limits the maximal load (here the serviceability requirement is: the deflection of the beam coming from the loads should not exceed a certain value). To satisfy this requirement, traditional RC slabs can cover max. 8m spans (with a thickness of 26-28 cm). If the span exceeds 8m, then the traditional RC slab is insufficient.

Voided slabs
By creating voids on the slab, we can decrease the self-weight of the structure resulting in smaller deflections. One example is the waffle slab. The load-bearing capacity for bending is the same as for a traditional RC slab, but its deflection is smaller. The main difference between a waffle slab and an RC slab is in the load-bearing capacity for shear forces. An RC slab cannot carry large shear forces; therefore, we cannot use them at areas where large shear forces emerge (e.g. where the columns are, there is a risk of punching).

Figure 15. Waffle slab. Near the column, the slab is filled to reduce the risk of punching shear.

The main disadvantage of a waffle slab is the complexity of its construction. It requires a huge amount of formwork which is non-reusable, leading to the structure being extremely uneconomical. One possible solution is to use cheap and light permanent formwork, such as polystyrene (PS).
We can decrease the weight of the slab by placing plastic spheres between the top and bottom reinforcing bars of the RC slab, this technology is called Bubble-deck slab. With this technique, the weight of the structure can be reduced by 30%. It is cheap and easy to implement.

![Figure 16. Permanent polystyrene formwork.](image)

1.4. PRESTRESSED CONCRETE

Main problems of RC structures:

- large bending moment causes cracks on the tensile side
- in case of large spans, the deflections are also large → the strength of the cross-section is not utilized, inefficient construction
- cracks are unaesthetic and undesirable, because the steel bars can become unprotected (this is a serviceability limit)
- large deflections are also undesirable (this is also a serviceability limit)

We can improve RC structures by prestressing the steel bars. Prestress is applied to the bars before the load is applied to the structure. If we apply tension in the bars, then compression arises in the concrete → cracks can be avoided. Moreover, tension causes deformation upwards (opposite to the direction of the deflection) → the deflections are smaller.

The reinforcement bars are prestressed with 80-90% of their strength. A disadvantage of prestressed concrete is that we need to use high strength steel, which is sensitive for fire loading. Moreover, it is not cheap unless it is produced in a factory.

![Figure 17. Bubble-deck slab.](image)
Types of prestressed concrete:

- **Pre-tensioned concrete.** It can be produced only in a factory. The *tendons* (prestressed steel bars) are placed in a precasting bed and fixed with end anchorages, then they are tensioned. The next step is the filling of the precasting bed with concrete. After the concrete is sufficiently cured, the anchorages are released.

![Diagram of pre-tensioned concrete process](image)

- **Post-tensioned concrete.** It can be produced in a factory or during the building construction (“in-situ”). At first a protective sleeve is inserted in the cast and after the concrete is sufficiently cured, the tendons are inserted in the sleeves, fixed with end anchorages and pulled to create tensile stress. The shape of the protective sleeve is determined to follow the shape of the moment diagram of the beam. For example, in case of a simply supported beam, the shape of the sleeve is parabolic.

![Diagram of post-tensioned concrete process](image)
Figure 20. Prestressed concrete beams. a) Pre-tensioned, b)-c) Post tensioned.


Further reference for prestressed structures: https://civilsnapshot.com/pre-tensioning-post-tensioning-method/