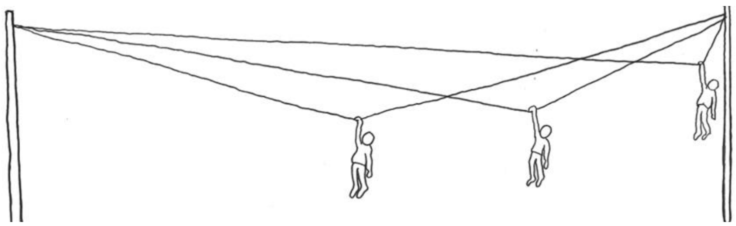
5. Cable structures

5.1. INTRODUCTION

Cable structures have negligible compressive strength, usually due to their geometry. For example, steel can bear compression if the cross-sectional area is large (e.g. an I-beam), but it is unable to transfer compressive forces in the form of a cable. This property determines the geometry of the structure, it should carry the loads in such way, that all members are under tension.



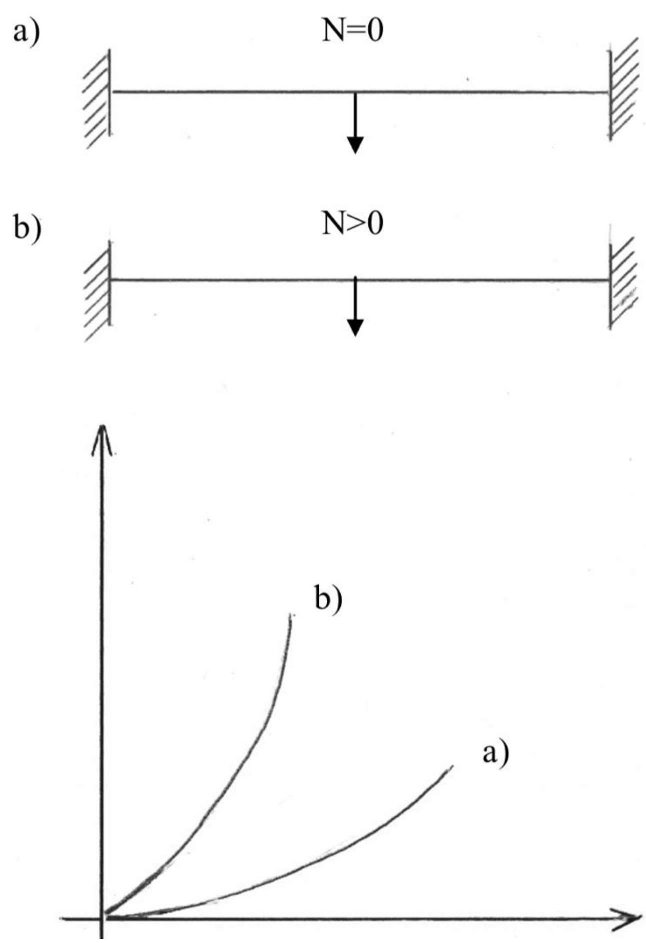
The shape of a cable between two fixed points.

If we hang a cable between two points, the cable deforms under its self-weight and the resulting shape is a **catenary curve**. The cable always deflects to be able to carry the loads, even if its original shape is straight, in which case the final shape is the same as the shape of the bending moment diagram.

Due to the large deflections, the methods usually used for beams (assuming small deflections) are unsuitable for the calculation of curves. As a result, a **finite deformation theory** is necessary to take the **geometrical nonlinearities** into account.

If the cable is prestressed, then the deflections are smaller. Moreover, the stiffness perpendicular to the cable axis is not zero anymore (e.g. tennis racquet). This stiffness is the **geometric stiffness**. Most of the commercial finite element software are unable to incorporate geometric stiffness in the computation, leading to numerical instabilities in the calculation of cable structures.

What is the main problem during the calculation of a cable structure? We start the calculation assuming an initial shape, which changes as the structure deforms under the loads. Subsequently, we need to recalculate the structure starting from this new shape. These steps need to be repeated, the final shape is found in an iterative manner. Note: in theory, all structure deforms under the loads which changes the geometry and a recalculation is necessary with this new geometry, but the deformations are usually negligible.



The force-displacement diagram of a cable a) without and b) with prestress.

5.2. SHAPE

The shape of a cable structure should be formed such way, that it doesn’t change much under the design loads.

Ballast

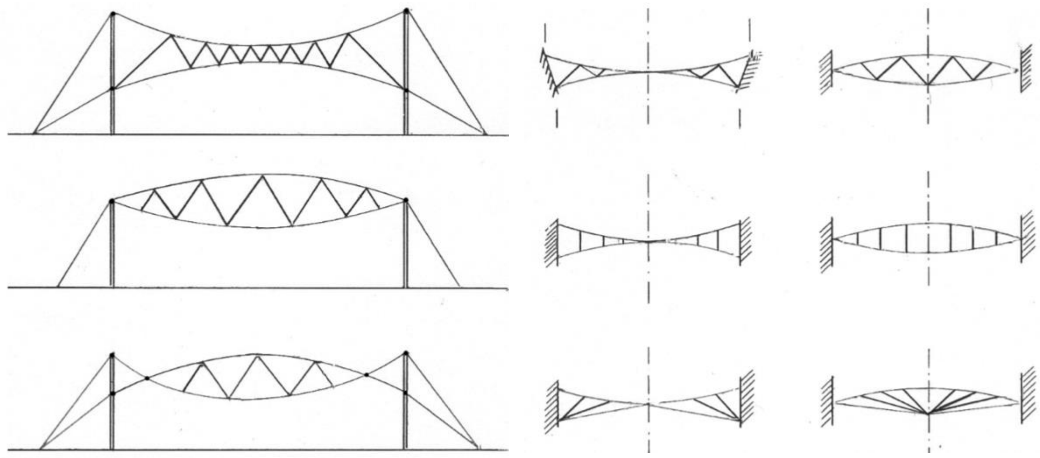
The ballast is a load on the structure, which is much larger than any other loads and therefore the shape is determined by the ballast. This can be an optimal solution, if the ballast has a function.

Connecting to a rigid structure

A structure with bending rigidity connected to a cable structure can be also considered as a ballast. How can we differentiate between *a cable structure combined with a rigid structure* and *cable suspended structure*? If the loads are carried mainly by the normal forces emerging in the cables, then it is a cable structure combined with a rigid structure.

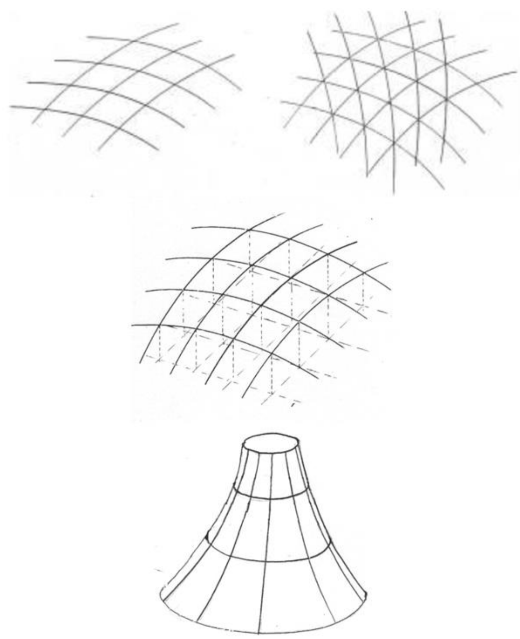
Cable-truss

It is possible to provide a self-sustaining shape by only using cables in the form of a cable truss. In cable trusses, prestress forces provide the shape of the structure. One of the main cables is the **snow-cable** carrying the vertical downward pointing loads and the other cable is the **wind-cable** carrying the upward pointing loads. One of these cables runs on the top, while the other one is on the bottom. Both cables should be prestressed, otherwise compression would occur in the cables. Since the arising forces in the members are much lower, it is possible to use members with bending rigidity and allow them to be under compression.



Cable trusses.

Cable-net



If the prestressed cables are not in a plane they comprise a net. The shape of this net needs to be hyperbolic to have both directions prestressed. It is possible to create an elliptic surface, but in that case additional forces are necessary to support the structure (similar to the pneumatic structures). If there are cables in only two directions (orthogonal net), the structure has no shear rigidity and it is unstable. This problem can be fixed by using cables in three directions (in the plane), but this solution is more expensive.

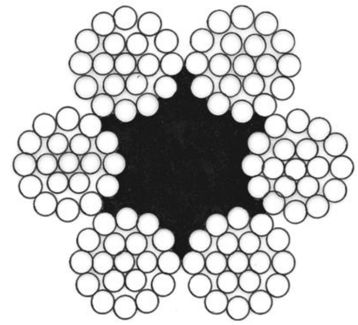
If the curvature of the surface is small, then the orthogonal net is sufficient. Orthogonal nets are also easy to calculate. Usually it is beneficial to align the net such way, that the cables are parallel to the direction of the **principal curvatures**. Otherwise, the cables would need to carry shear forces as well. This is possible with prestress.

Another option is to use the **geodetic lines** (the shortest distance between two points of the surface) to align the net, which results in visually attractive structure.

2D orthogonal nets can be fitted to any curved surfaces (but the squares become rhombuses). Such a structure is the **webnet** (https://neufert-cdn.archdaily.net/uploads/product_file/file/38111/Webnet_Jakob.pdf), which is used to create various surfaces.

5.3. CABLE MATERIAL

5.3.1. Structure



Traditional cables are made of **hemp**, while modern cables are made **polymer** or **steel**. However, most of them are composed of spiral strands. Cables constructed this way are flexible and have large tensile strength.

Many strands of metal wire are twisted into a helix which forms a rope (laid rope). These ropes are then twisted again to form the final cable. To stabilize the cable, the metal wires should be twisted in the opposite direction as the final cable. There are some metal wires with non-cylindrical profiles, that are usually used to create cables with smooth surfaces that are more dirt resistant. The strands are laid around a core, which can be made of natural (like sisal) or synthetic fibers. This helps to gain more flexibility for the cable.

The metal wires are usually made of high-strength steel with a strength around $1000 - 2000\ N/mm^2$. Since the cable is not completely made of steel, its tensile strength is usually around $500 - 1000\ N/mm^2$.

There is almost no limit for the length of a cable, because the metal wires can be welded (but the cable itself cannot be welded!). However, cables of the elevators and cables under dynamic loads are not allowed to be welded.

There are many surface finishing options. Painting is not suitable for wires due to the roughness of the surface. If the cables are lubricated with oil or grease, no additional finishing is required. In most cases, zinc-plating is a long-lasting solution to protect the cable if it doesn’t touch the ground (otherwise it corrodes quickly). Another option is to use stainless steel which need no finishing, but they are quite expensive and have lower strength.

5.3.2. Joints

5.3.2.1. Joining to cables

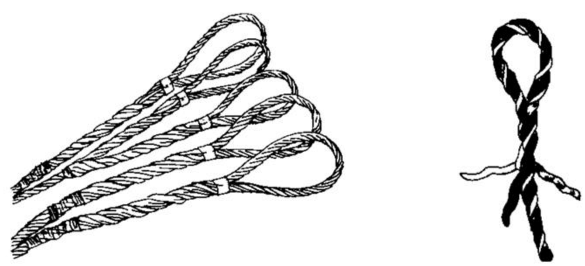
Due to the complex structure of a cable, the joints are also complicated. They cannot be welded or screwed together. There are basically two options to join the cables: with a **loop** or an **additional joining element**.

Possible solutions to close a **loop**:

- **Eye splice**: plaiting the strands of the cable back (effective but time-consuming method)

- **Swaged termination**: pressing the strands together and closing with a ferrule (leading to a metallic bond)

- **wire rope clamp**, which consists of a U-shaped bolt, a forged saddle and two nuts (this solution is usually used at the construction site, where there is no time/tools to create the other types)



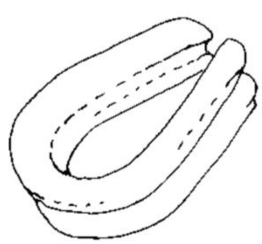
Eye splice.

In case of a loop there is a risk of breakage due to the bending of the cable, which can be prevented by using a **thimble**.

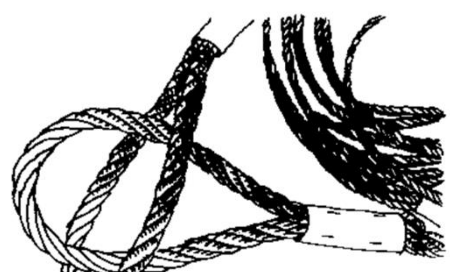
Additional joining elements can be:

- pressed to the cable usually with a thimble

- or molded to the cable



Thimble.



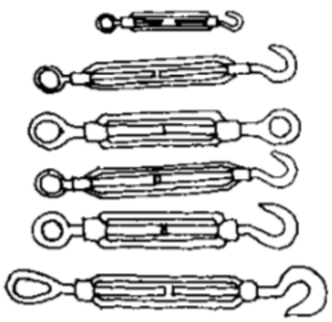
Swaged termination with a ferrule.

5.3.2.2. Joints for tensioning

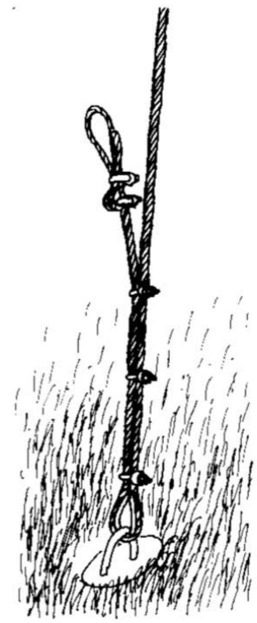
It is necessary to construct cable structure in such way, that the length of the cable is adjustable and it is possible to increase the tension in the cables, since most of the cables need to be prestressed. Possible joints that enable **tensioning**:

- a loop combined with a clamp

- tensioning poststs



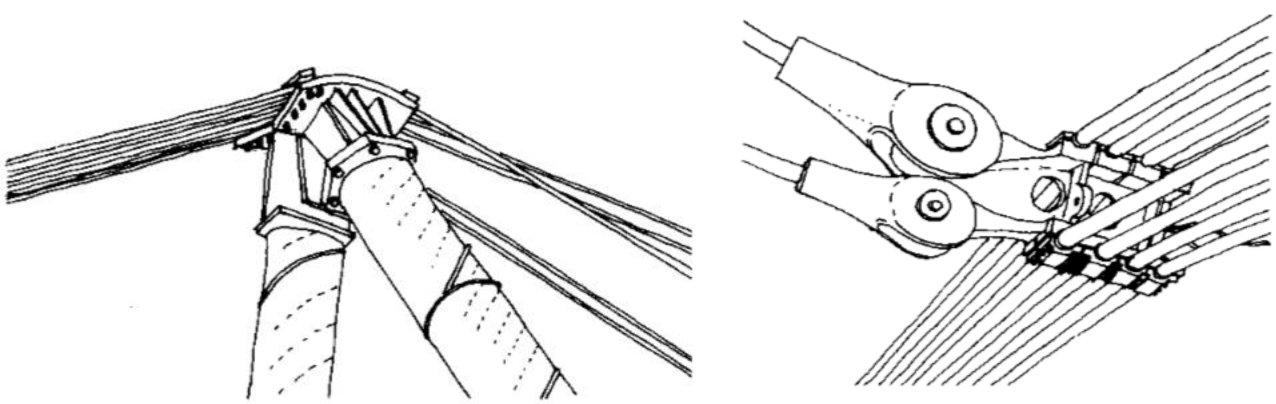
Tensioning posts.



Loop and clamps.

5.3.2.3. Joints for joining cables with other structural elements

When the cables are connected to other load-bearing components, the force is transferred by large joining elements.



Cables connected to other load-bearing components.