The Force Cone Method: a new thinking tool for lightweight structures

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Abstract

The Force Cone Method developed by Claus Mattheck enables computer-free topology designing and offers a profound knowledge for lightweight structures. Thus the recently developed method enhances the series of so-called thinking tools. The methods basic idea is the force distribution of a single force in an elastic plane. Symmetrically placed cones appear in front of the force and behind it. These cones intersect with 90-degree angles at primary points that quickly lead to a structural design proposal. Furthermore the method is very useful for the evaluation of structures and their lightweight potential. With the knowledge of the load case it is easy to identify main tension and compression paths leading to a deeper understanding of lightweight results. Also natural structures such as trees can be understood in another way, highlighting structural principles at the root, the leaf, the treetop or even the entire tree. Nowadays technical lightweight solutions can be found with different methods, including the Soft Kill Option (SKO) developed at the Karlsruhe Institute of Technology (KIT) 20 years ago. The method resembles the biological mineralization process of living bone and results in structures that can be seen as optimized lightweight design proposals. The comparisons of those structures with the state of the art designs used in the industry and with the ones found by the Force Cone Method indicate the high potential of the new method. For the confirmation of the basic rules and principles different assembly positions of force and supports as well as different types of supports, such as fixed supports or torsion anchors, have been analyzed.
Keywords: force cone method, topology design, lightweight structure.

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1 Introduction

In mechanical engineering a design needs to meet several demands. At first the design needs to withstand the given tasks with regard to applied loads and the durability during its lifetime. Besides optical issues nowadays the weight often counts the most. With rising energy costs the weight reduction within mechanical constructions gets more and more important. Thus almost everything has to be lightweight.

In nature there are further reasons for lightweight designs. Running faster than someone else makes hunting more effective or prevents from being eaten. Low weight enables flying and consequently unlocks new territory. Million years of evolution brought up an advanced degree of lightweight optimization. Several starting points exist, e.g. the skeleton as the structural framework of many species. The framework itself is built up of bones, muscles and sinews, resembling a first step of lightweight design. The second step can be found with a closer look on the bones. The bone material is placed perfectly in correlation to the force flow. Highly loaded zones are filled with trabecular bone, also called spongiform bone, which is a micro-framework of very fine small struts of bone.

With the Soft Kill Option (SKO) the lightweight principle of the bone growth was transferred into technical application and is used for the optimization of technical components. Topology optimized designs can be derived from that computer method. The Force Cone Method enlarges SKO. The method conveys an understanding for lightweight design. Without the use of a computer, optimized topology designs can be found and given structures, both natural and man-made, can be understood and evaluated concerning the lightweight potential.

2 Material and methods

2.1 Soft Kill Option

The Soft Kill Option SKO was developed at the Karlsruhe Institute of Technology 20 years ago and it is one of the empirical topology optimization methods. With given design spaces and the load and support boundary conditions the method finds optimized topology designs which can be used as design proposals [1].

The basic principle of the method was found in nature. The biological mineralization process of living bone is used as a model. Bone building occurs also stress-controlled. In areas of higher stresses bone-building cells called osteoblasts make sure that more material is accumulated. Where the stress is lower osteoclasts shrink away the weakly loaded or even unused material. The fins of the lamella structure that can be seen in part A of figure 1 are oriented in the main stress directions. This framework structure instead of solid material reduces the weight [1].

The first step of the SKO-procedure includes the determination of loads, supports and the maximum available design space (see part B of figure 1). After computing and analyzing the stress distribution the material is made softer in places of lower stress. On the contrary the young's modulus is raised in areas of higher stresses. With the new material properties a new stress distribution can be computed. This is an iterative process and will be repeated until the separation of the weak and the strong material is sharp. The result depends on several parameters, e.g. the reference stress or the number of iterations, and it can look like the structure in part C of figure 1. This is a design proposal that still needs to be dimensioned [2].

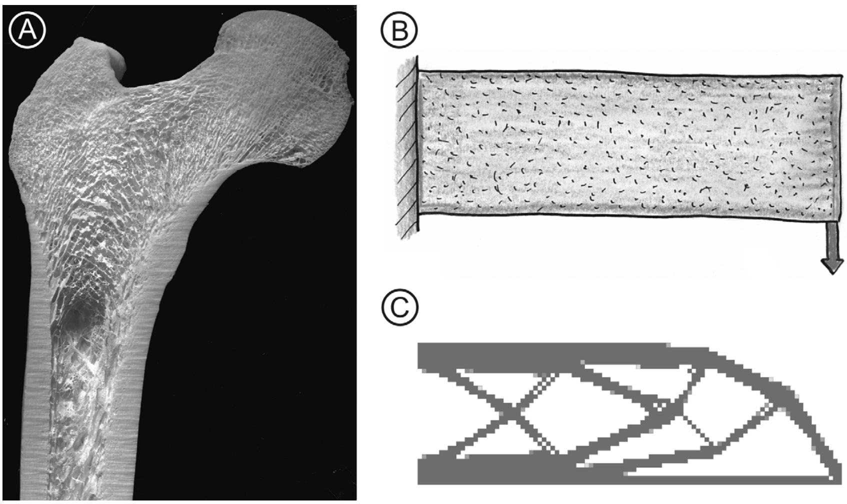

Figure 1: A) Human bone (femur), B) maximum design space for SKO, C) lightweight design by SKO [2].

2.2 The Force Cone Method

The Force Cone Method is one of the so-called thinking tools. Like all of the thinking tools the Force Cone Method can be used without a computer. The method determines topology designs and helps understanding and evaluating the lightweight potential of a given structure.

The basic idea is that a single force in a huge elastic plane pushes a 90-degree compression cone in front and pulls a 90-degree tension cone behind. The 90-degree angle becomes plausible when drawing the Shear Squares, another thinking tool (see part A of figure 2). The resulting compression and tension directions restrict the effective space of the cones.

This idea can be comprehended with the stress distribution of a single force in an elastic plane (analytic solution from [3]). Around 80 percent of the occurring radial stress will be included by a 90-degree cone symmetrically placed in front of the force and behind it. The radial stress distribution can be found in part B of figure 2 [2].

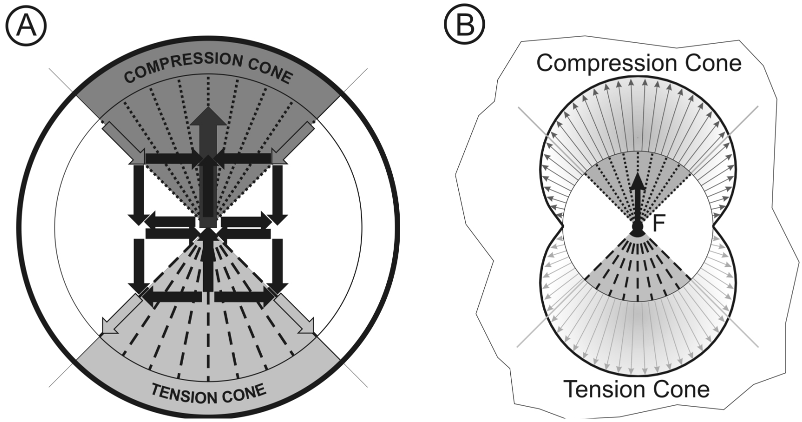

Figure 2: A) Force Cones constructed with the Shear Squares, B) Radial stress distribution of a single force in an elastic plane [2].

The approach of the Force Cone Method is described in figure 3. At first the boundary conditions need to be clarified. The direction and the point of application are important as well as the quantity, the arrangement and the type of supports (A). The Force Cones of the loads are added, a tension cone behind the force and a compression cone in front of the force (B). The reaction forces arrange for additional force cones (C). The above mentioned 90-degree angle provides the perpendicular crossings of cone borders that are used as primary points (D). This is valid for orthogonal intersections of tension and compression cone borders. In the next step the primary points need to be connected (E) to get the finished lightweight structure (F). Compression struts (dark grey) and tension ropes (bright grey) can be easily determined. The topology design is a proposal that requires further dimensioning [2].

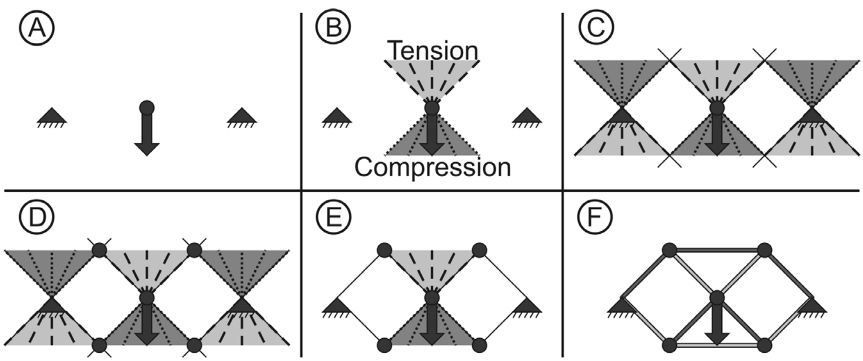

Figure 3: The stepwise approach of the Force Cone Method [2].

For a support in shape of a torsion anchor the Force Cone Method provides another approach (see figure 4). Each point on the anchor circle can be seen as a primary point where compression and tension orthogonally intersect (A). The force will be looped around intersecting the tangents in right angles until the struts meet the anchor (B). For an infinite number of tangents the result is the involute of the circle. The finished Force Cone structure can be seen in part C, while part D shows the SKO-result [2].

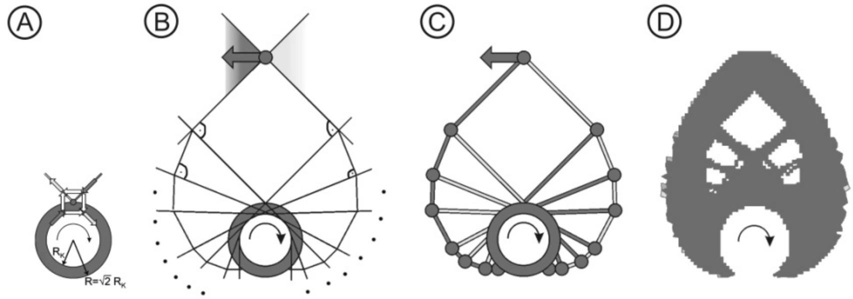

Figure 4: A-C) Construction of a torsion anchor for central force introduction, D) SKO-result for comparison [2].

3 Results and discussion

Figure 5 and figure 6 show the transitions to obtuse angles. The obtuse angle is avoided in both the Force Cone Method and SKO, because of the higher stresses within the struts. Figure 5 shows a setup with a symmetrically placed force downwards between two fixed bearings. The force point of application is varied in height. As long as the struts lie within the force cone the structure consists of only those direct struts. When they do not lie within the force cone any more primary points lead to auxiliary constructions, the so-called gallows [4].

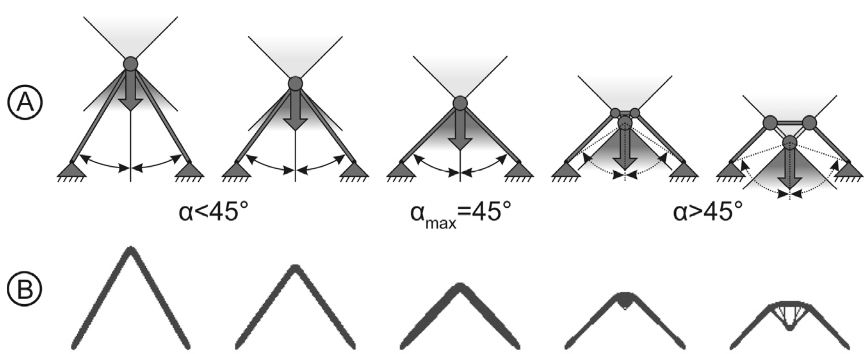

Figure 5: Symmetrically placed force downwards between two fixed supports, A) Force Cone Method, B) SKO [4].

If the force is pointing to the left, the struts lie within the force cones, if the force point of application is closer to the supports. Auxiliary constructions are used for a higher point of application (see figure 6) [4].

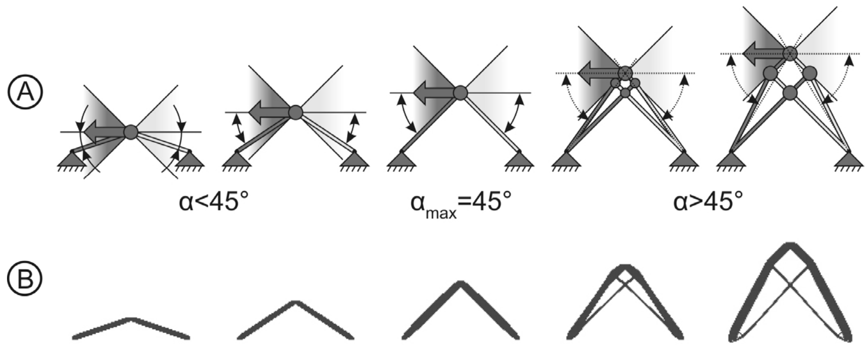

Figure 6: Symmetrically placed force to the left between two fixed supports, A) Force Cone Method, B) SKO [4].

The setup of a force interacting with a torsion anchor was used to compare structures derived from the Force Cone Method with state of the art structures and SKO structures (shown in figure 7). For the comparison of these structures the force was set constant and buckling of compression struts was added as a mode of failure. Thus it is possible to compare the necessary material to withstand the load without failure. As buckling is dependent on the magnitude of the force the setup was calculated for different forces.

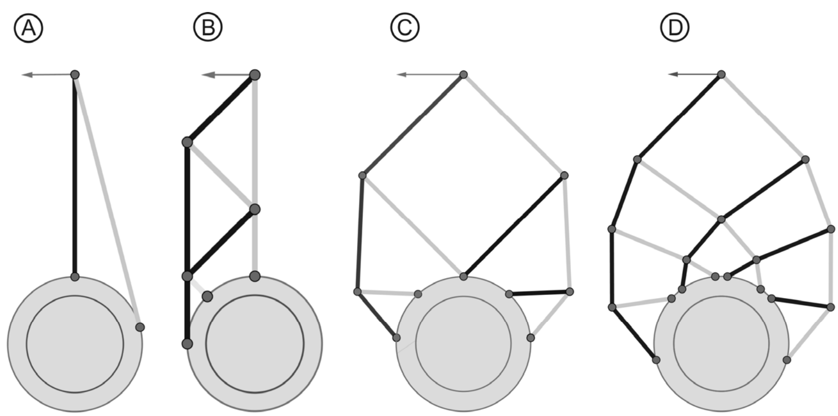

Figure 7: Structures for a torsion anchor as support, A) wired beam, B) ladder, C) Force Cone Method with 42.5-degree tangent angle, D) SKO.

The calculated results are shown in table 1. Design A was used as reference. The necessary material of other designs is relative to that number.

Table 1: Relative material for different designs of a torsion anchor support.

	Design A	Design B	Design C	Design D
Small force	100,0 %	81,7 %	84,4 %	78,0 %
Middle force	100,0 %	71,6 %	62,8 %	56,8 %
High force	100,0 %	70,4 %	46,6 %	43,2 %

Design A as a wired beam is a construction that does not need a lot of connections but needs the most material. Design B with similarity to a ladder saves 19 to 30 percent of weight. Design C derived with the Force Cone Method saves around 16 to 54 percent of weight. Design D generated with SKO is even a little bit better than the Force Cone Method but needs resources such as computer, time and know-how.

Force Cones can be found in nature and contribute to a better understanding of the results of the evolutionary optimization process. Figure 8 shows Force Cones within the tree. Rigid branches that are pressure resistant are acting as a series of compression cones and prevent the leaves from sliding down. The trunk would sink into the ground if there were no stiff roots forming the compression cone pointing downwards. The leaves are exposed to wind. The main vein is collecting the lateral veins within a tension cone. The shape of the outermost contour line of the leaf can be reconstructed with compression cones at the end of the lateral veins [2].

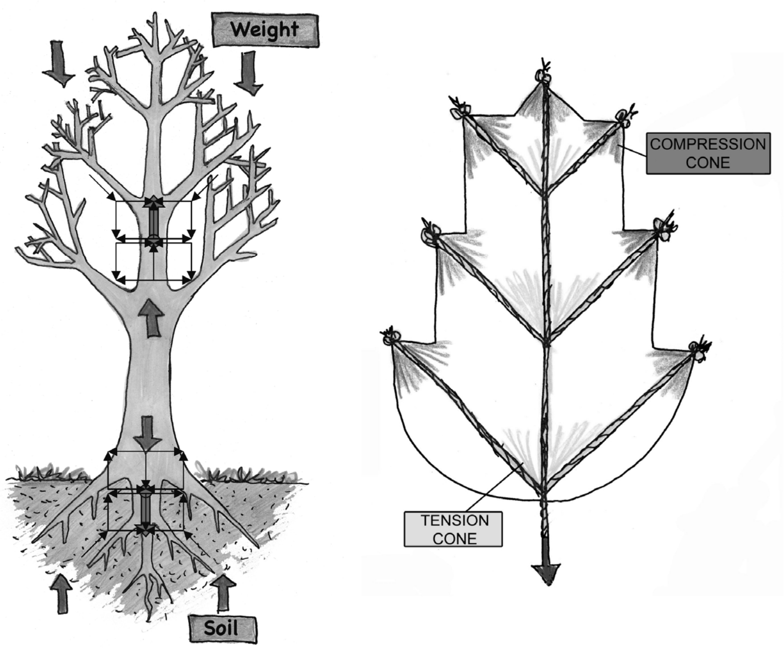

Figure 8: Force Cones in nature [2].

4 Conclusions

The Force Cone Method is a thinking tool that allows generating lightweight design proposals of optimized quality. Comparisons with state of the art structures show the huge potential of the easy to use method that seriously competes with computerized optimization methods but needs less resources. The method supports the understanding of lightweight structures, even the natural ones formed by the evolution.

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