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Biomimetics — Biomimetic structural optimization

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National foreword

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 266, *Biomimetics*.

Introduction

Biomimetic optimization methods are based on the knowledge gained from studying natural biological structures and processes.

Structural optimization is a special branch of optimization dealing with the ideal design of components while taking the current boundary conditions into account. Commonly optimized properties include the weight, the load capacity, the stiffness, or the lifespan. The goal is to optimize one or more of these properties by maximizing or minimizing their values.

Generally, the idea is to utilize the construction material as efficiently as possible while avoiding overloaded and underloaded areas. Since almost every technical component for functional reasons exhibits changes in section and, hence, notches, minimizing notch stress is especially important in structural optimization. In classic structural optimization, the notch shape factor, i.e. the stress concentration factor on the notch, is reduced by selecting the largest possible radius of curvature for the notch or by utilizing the mutual interaction of notches and adding relief notches. The shapes of the notches are not changed by this procedure. The use of other notch shapes (Baud curves, ellipses, logarithmic spirals, etc.) was suggested as early as in the 1930s. But they are not widely applied in technology and are only used occasionally.

Computer-based biomimetic optimization tools, such as Computer Aided Optimization (CAO) and the Soft Kill Option (SKO), modify the shape and topology of the component, respectively, and thus homogenize the stresses using the finite element analysis (FEA). Such tools have been available since 1990 and are used in industry. The need to use FEA for optimization in this case limits the number of possible users, though, because a powerful computer, special software, and an expert are needed for its operation. The demand for even simpler and faster methods that cannot only be used by specialists to optimize components, but also by design engineers, led to the development of the "Method of Tensile Triangles". Although development of this method began in 2006 only, it is already being used for verified applications because it is easy to understand and apply. The wide range of applications of biomimetic optimization methods together with the relative ease with which users are able to understand and apply the methods enables users to perform component optimization early in the design process. In the case of the Tensile Triangle Method, this is possible simply by implementing the method in CAD systems.

As every optimization means specialization for the selected cases of load, service loading can be well known. Other unconsidered loading conditions might even result in higher stresses in a component.

Biomimetics — Biomimetic structural optimization

1 Scope

The International Standard specifies the functions and scopes of biomimetic structural optimization methods. They consider linear structural problems under static and fatigue loads. The methods described in this International Standard are illustrated by examples.

Based on the biological model of natural growth and by use of the FEM optimization methods for technical components, computer-based biomimetic optimization tools are described as Computer Aided Optimization (CAO), Soft Kill Option (SKO), and Computer Aided Internal Optimization (CAIO). The purpose of these methods is an optimal materials application for weight reduction or enhanced capability and lifespan of the components.

Additionally, a simpler and faster “Method of Tensile Triangles” is described that can be used by every design engineer. The wide range of applications of biomimetic optimization methods together with the relative ease with which users are able to understand and apply the methods enables users to perform component optimization early in the design process.

The purpose of this International Standard is to familiarize users with biomimetic optimization methods as effective tools for increasing the lifespan, reducing the weight of components, and promoting the widespread use of these methods in support of sustainable development.

This International Standard is intended primarily for designers, developers, engineers, and technicians, but also for all persons entrusted with the design and evaluation of load-bearing structures.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 18458, *Biomimetics — Terminology, concepts and methodology*

ISO 2394, *General principles on reliability for structures*

ISO 4866, *Mechanical vibration and shock — Vibration of fixed structures — Guidelines for the measurement of vibrations and evaluation of their effects on structures*

ISO 13823, *General principles on the design of structures for durability*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
mechanical adaptive growth
appropriate reaction of biological structures, such as trees and bones, to changing conditions (e.g. mechanical loads) by locally adding material to high-stress areas or removing material from low-stress areas

EXAMPLE Thicker annual rings.

3.2
algorithm
precisely described procedure to complete a task in a finite number of steps

3.3
design space
volume available for a component

Note 1 to entry: The edges of the component to be designed shall not extend beyond the limits of the design space.

3.4
Computer Aided Internal Optimization
CAIO
method based on the *finite element analysis* (3.6) for the optimization of the local fibre orientation in fibre composites with the goal of increasing their load capacity

3.5
Computer Aided Optimization
CAO
method for optimizing the shapes of components based on the *finite element analysis* (3.6)

Note 1 to entry: The stresses in highly stressed areas, such as *notches* (3.8), are reduced and the component lifespan is increased.

3.6
finite element analysis
FEA
numerical method for obtaining approximate solutions of partial differential equations subject to boundary conditions

Note 1 to entry: In the engineering sciences, it is used as an analysis method, for example, to answer questions relating to structural mechanics. With FEA, a complex structure is divided up using small, simple, and interlinked elements (FEA mesh). When boundary conditions (loads, bearings, etc.) and material properties are defined, it is possible to calculate stresses, deformations, etc. in any section of the complex structure.

3.7
shape optimization
modification of the surface of the component to modify a certain target function in a defined manner (for example, to minimize stresses)

3.8
notch
concavities in components that weaken a component locally due to the *notch effect* (3.9)

Note 1 to entry: Such weak points are not desired in most cases, but notches are used as predetermined breaking points in certain cases in order to specify where the component should fail and to limit the load that can be placed on the component.

3.9
notch effect
local arising of stress peaks on *notches* (3.8) subjected to a load

Note 1 to entry: The height of the peak usually depends on the size and shape of the *notch* (3.8). The stresses decrease as the curvature is decreased and as the size of the *notch* (3.8) contour is increased.

3.10
Method of Tensile Triangles
simple graphical method for homogenizing stresses in components

Note 1 to entry: It can be used to reduce stresses in high-stress areas, for example, on *notches* (3.8), and increase the component lifespan, as well as to remove underloaded areas and save material.

3.11
Soft Kill Option
SKO
method for optimizing the *topology* (3.12) of components based on the *finite element analysis* (3.6)

Note 1 to entry: Lightweight design proposals are generated by successively removing low-stressed material from the *design space* (3.3).

3.12
topology
relationship (position and orientation, for example) between the structural elements (holes, supports, etc.) of a component

4 Symbols and abbreviated terms

E	modulus of elasticity
E	variation of the modulus of elasticity, $E = f(\sigma)$
F	force
M	torque
T (x,y,z)	thermal load
α	coefficient of thermal expansion
σ_{mises}	equivalent stress according to *von Mises*

5 Principles of self-optimization in nature and hence transferred optimization methods

With the help of the finite element analysis (FEA), numerous studies of biological load-bearing structures, such as trees, bones, claws, and thorns, revealed that these load-bearing structures are optimally adapted to the stresses they are subject to and that the same design principles apply to all structures. The axiom of uniform stress has been shown to be a fundamental principle that applies when load-bearing biological structures, such as trees or the bones of mammals, grow. This axiom states that the surface of a load-bearing structure will not exhibit weak points (areas under high stress) or underloaded areas (unnecessary ballast or wasted material) so that a uniform stress is applied to the surface. This mechanically advantageous stress state is realized through adaptive growth. Trees, for example, detect local stress concentrations using internal receptors and repair themselves by growing adaptively. On overloaded areas, they grow annual rings that are thicker locally and therefore reduce stress peaks. However, trees cannot remove superfluous material from areas relieved of stress, in contrast to the bones of humans and animals.

The self-optimization of biological structures is not limited to their exterior structure; even their inner structures are superbly adapted to the stresses they are subjected to. Adaptive mineralization processes in bones make areas subject to higher stresses stiffer, while less stressed areas are softened and finally removed.

In general, biological materials can be considered as fibre-composite materials consisting of several components. In addition to the component mixture, other decisive factors contributing to their extraordinary mechanical properties include the hierarchical organization of their molecules over several orders of magnitude to form entire structures and the inner orientation of material adapted to the force flow. In soft curves, the wood fibres in the trunk are deflected around imperfections, such as knots, to follow the direction of force. The same applies to the wood rays which wrap around the vascular cells in a corresponding manner. Even the cellulose fibrils forming the walls of wood cells exhibit this type of optimization. On all scales in trees, fibres oriented in the direction of the force flow can be found. The same applies to bones, which basically consist of plywood-like lamellae structures with tough fibres and more brittle material. Areas near joints, for example, on the femur (thigh bone), are filled with trabecular bone, which is also referred to as spongiosa or cancellous bone. This type of bone is a micro-framework made of fine trabeculae that fill the entire femoral head and neck and is oriented to follow the flow of force.

As a fundamental design rule, the axiom of uniform stress was implemented systematically in computer-based methods first, which made it possible to apply this optimization principle for biological load-bearing structures to any type of load-bearing structure. This is a major prerequisite for utilizing the wealth of nature's experience in technical designs.

Computer Aided Optimization (CAO) and Soft Kill Option (SKO) are methods used in industry that were developed to optimize the shape and topology of technical components. CAO is used very effectively to homogenize stresses. Local stress peaks are reduced, which then increases the lifespan of the components significantly, especially when they are subject to vibrating or alternating loads. In contrast, SKO provides design proposals that do not contain underloaded material anymore. This allows the designer to identify the relevant paths of force in the component and design lightweight components while simultaneously taking into account manufacturing limitations, for example.

Finally, Computer Aided Internal Optimization (CAIO) allows designers to transfer the internal designs of biological load-bearing structures containing fibres oriented in the direction of the force flow to technical fibre-composite materials using computer simulations and increase their load capacities.

A deeper understanding of notch stress[1] and further development work led to the purely graphical "Method of Tensile Triangles", which allows components to be optimized with minimal effort. The optimization methods developed contribute significantly to the elimination of weak points during the development process. In the case of the computer-based methods, its application results in longer calculation and simulation times, but in the end leads to shorter overall development times, fewer prototypes, and shorter test phases. The biomimetic structural optimization methods presented here are examples; further methods are under development.

As defined in ISO 18458, a product or technology is biomimetic when three criteria are met namely, when there is a biological system available, the model has been abstracted, and the model has been transferred to a technical application in the form of a prototype at the minimum. As shown in Table 1, according to these three criteria, the methods described above fulfil the three steps given in ISO 18458.

The CAO method is biomimetic, because the biological system is the growth of trees, a part of this phenomenon has been abstracted to a load-adaptive process, and this process has been implemented in simple algorithms, transferred to technical application, and is used in industry to optimize technical components.

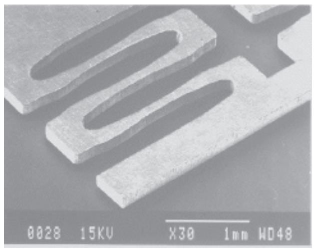
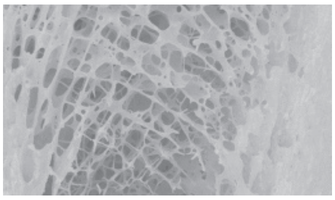
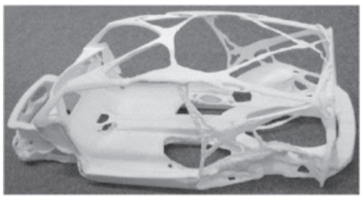
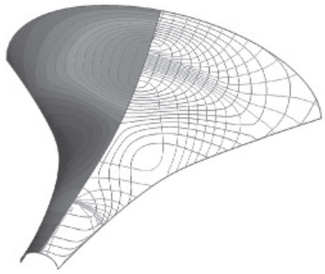
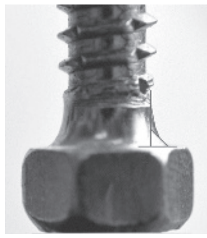
The SKO method is biomimetic, because the biological system used for SKO is the mineralization of bone, a part of this phenomenon has been abstracted to a load-adaptive process, and this process has been abstracted, implemented in simple algorithms, and also transferred to technical application. SKO is used for designing lightweight components.

The CAIO method is biomimetic, because CAIO is based on the biological system of the alignment of wood fibres in trees, a part of this phenomenon has been abstracted to a load-adaptive process, and this process has been abstracted, implemented in simple algorithms, and transferred to application for the optimization of technical fibre composites.

The Method of Tensile Triangles is biomimetic, because the Method of Tensile Triangles is based on the system of stem root junctions of trees, a part of this phenomenon has been abstracted to a load-adaptive process, and this process has been implemented in simple algorithms, transferred to technical application, and is used in industry to optimize technical components.

Table 1 lists the methods for biomimetic structural optimization, their biological system, main aim, and an example of use which shows their application in technology.

Table 1 — Biomimetic structural optimization methods, their biological system, main aim, and technical application

Method	Biological system	Main aim	Technical application
Computer Aided Optimization (CAO)	adaptive growth of trees 	shape optimization for increasing the lifespan or the load capacities of components by stress homogenization	microactuator 
Soft Kill Option (SKO)	mineralization process in bone 	topology optimization for designing lightweight components by removing underloaded material	car frame 
Computer Aided Internal Optimization (CAIO)	alignment of fibre orientation in trees 	optimization of local fibre direction for increasing the load capacities of fibre composites by adapting the local fibre orientation to the load	bicycle seat 
Method of Tensile Triangles	stem root junction 	shape optimization for increasing the lifespan or the load capacities of components by stress homogenization	screw 

6 Application of methods

6.1 Application range and limits

The optimization methods mentioned in this International Standard consider linear structural problems under static load. The results of FEM can serve as static strength verification.

Where dynamic loads are in place, they may be transformed into equivalent static loads (ESLs).

NOTE Structures, optimized by these methods for static loads, will respond to dynamic loads as well, much better than non-optimized structures.

The notch shape optimization is most effective when high numbers of load cycles are expected and for components made of brittle material. Statically loaded ductile materials are little notch-sensitive and can release stress by plastic deformation.

The choice of the stress to optimize depends on the mechanical problem. Mostly, the von Mises stress or normal stresses are used. If needed, other equivalent stresses can be implemented.

Several loadings can be analysed and optimized separately or as load collectives. Often, an optimization of the critical cases is sufficient, but the results should be verified for all loadings.

Instable failure, e.g. buckling, is not covered by these methods. Therefore, optimization results are to be checked to that effect.

In general, optimization results shall be verified by FEA or experiments. General principles on reliability for structures are described in ISO 2394. To verify dynamic strength, vibration strength, and durability of a structure, ISO 13823 and ISO 4866 may be considered.

6.2 Computer Aided Optimization (CAO)

The CAO method is an aid for optimizing the shape of components. It was developed to counteract stress concentrations on critical sections in components through “growth”.

6.2.1 Stress-controlled growth

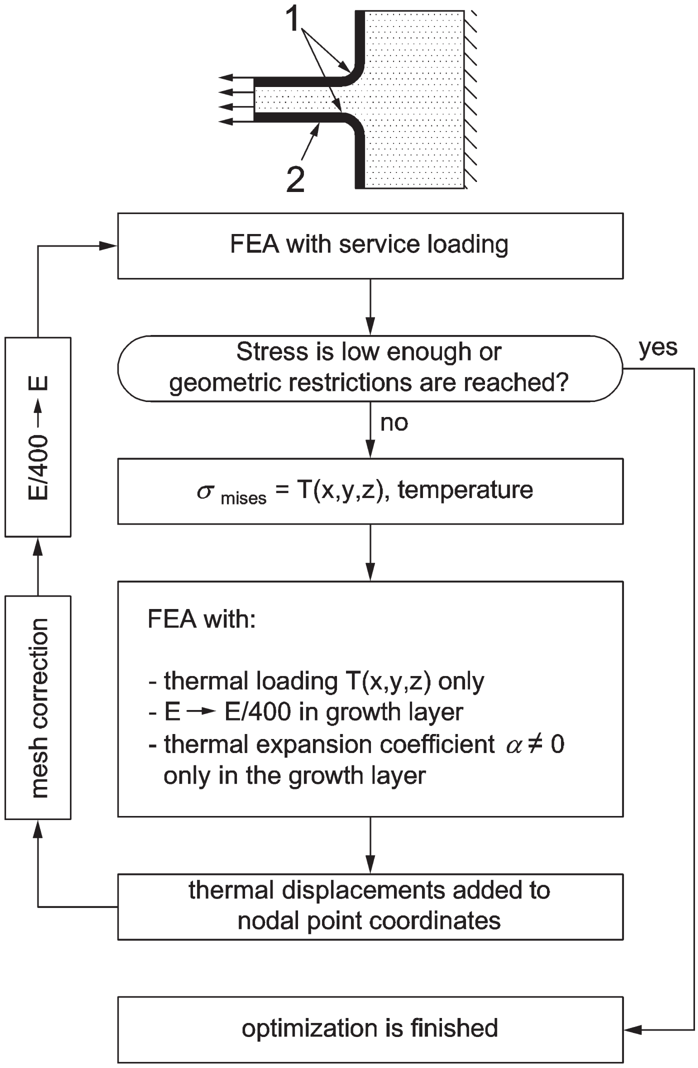
The process of load-adaptive growth of a component can be simulated on a computer by displacing the surface of the component in the direction of its normal according to the local magnitude of the stress. Using finite elements as a basis, this can be achieved by determining the direction of the normal to the surface and the stress values on nodes or with the help of the thermal displacement method.

An FEA model and, as a rule, the von Mises reference stresses calculated from the model serve as the basis for performing a stress optimization. It is also possible to use other stress values, such as the principal normal stress or other reference stresses, instead of von Mises stresses. The first step after specifying the load and position conditions is to perform an FEA stress analysis. After that, growth is simulated on the model based on the stresses calculated. This can be done in a variety of ways.

For example, the second step may consist of modelling the applied stress distribution by a fictitious temperature distribution. A “soft” growth layer with constant thickness and a prescribed coefficient of thermal expansion is then defined. Reducing the modulus of elasticity to 1/400 of its original value helps to avoid deflection of the underlying structure, which means the growth simulated in the form of thermal expansion is restricted to the soft boundary layer. Growth is now performed based on an FEA calculation of the thermal expansion of the material. In this case, the locations subject to higher stress, and, hence, to higher (fictitious) temperatures, expand more than those areas subject to less stress.

The thermal displacements calculated in this step are then added to the coordinates of the nodes of the FEA mesh, which creates a new mesh with a new geometry. Finally, the modulus of elasticity of the growth layer is reset to its original value and a new FEA stress analysis can be performed. The optimization can be considered complete when geometric restrictions are reached or when a homogeneous stress distribution is achieved (see Figure 1).

In addition to simulating growth, CAO can also be used to simulate shrinking, although stress-controlled growth is used more frequently in nature, as well as in technology.



Key

1 notch to be optimized

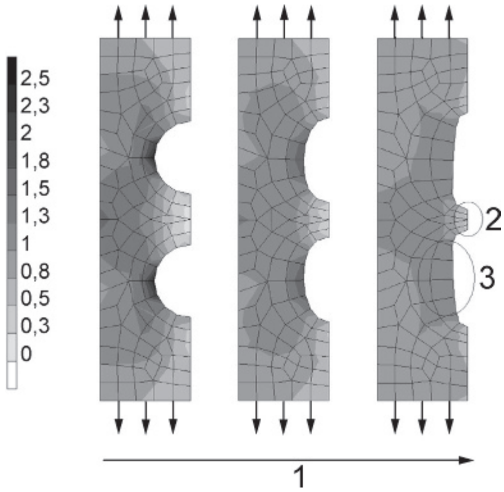
2 growth layer of uniform thickness

Figure 1 — Schematic flowchart of the CAO method according to Reference [3]

6.2.2 Shrinking

CAO can be used to shrink components using the same procedure as for stress-controlled growth. In this method, areas with low stresses are defined to be "growth areas" or more appropriately, "shrink areas". Shrinking is performed just like in the previous subclause after executing an FEA stress analysis. In this case, however, the displacement vector points into the material and not away from it. A value is specified for the temperature that defines the point up to which the elements are allowed to shrink. To ensure faster processing, it also makes sense to include a weighting factor in the calculation. However, do not select weighting factors that are so large that the nodes of the mesh are moved out of the design space when the shrink area shrinks to its minimum size. If the displacements are large, then problems can arise in practice. Displacing the neighbouring nodes in the same direction can also help in this case. If the displacements are large, then the mesh shall be regenerated. An iterative procedure is recommended for this version of CAO and it is also recommended to perform a stress analysis after regenerating the mesh.

CAO growth and shrinking can be combined in a single process (see Figure 2).



Key

1 iterative progression of a CAO optimization

2 shrinkage area

3 growth area

NOTE High-stress areas appear darker.

Figure 2 — Example of combined growth and shrinking on the half-model of a perforated plate subject to a tensile load

6.2.3 Finite elements in practical applications (FEA)

The finite element analysis[2] is an engineering tool which is used for calculations. It is not a biomimetic optimization method. The CAO method is performed using a mesh consisting of h-elements. The most commonly used element types when applying the CAO method are 4-node quadrilateral elements for plane symmetric and rotationally symmetric problems and 8-node hexahedron elements for spatial problems, but triangular and tetrahedron elements can also be used. When selecting the mesh type, it shall be ensured that the intermediate elements are also moved together with the mesh.

The usual mesh criteria (resolution, angle, aspect ratio) shall be taken into account when generating the mesh in order to model the stress states with sufficient precision.

If local notch stresses are to be optimized, then the growth area selected shall be large enough so that the entire stress increase caused by the geometry can be calculated and the surrounding area should also be included so that a homogeneous stress distribution can be generated. When using an iterative procedure, the size of the growth area should be increased, if new concentrations of stress appear on the edge of the current growth area.

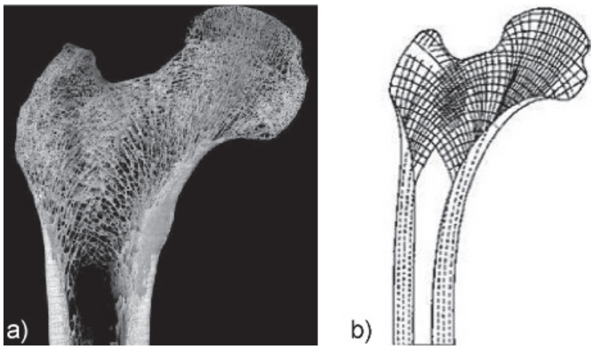
If large sections of the component are to be optimized using the CAO method, then the user should specify appropriate growth areas. It is even possible to completely cover the component with a growth layer.

6.3 Soft Kill Option (SKO)

6.3.1 Principle of the SKO method

The SKO method according to Reference [3] is based on the principles of bone growth, which allow bones to grow as lightweight structures and to be used to enhance human and animal mobility. Bone growth is based on adaptive mineralization processes and can generally be described as follows: parts of the bone subject to high loads are supplied with more minerals and, hence, become stiffer, while parts of the bone subject to less stress are actively reabsorbed.

Bones are rebuilt by bone cells (osteoclasts and osteoblasts). Bones consists of a hard outer layer (corticalis) that is filled with spongy bone (spongiosa or cancellous bone) in areas subject to high loads. Inside the cancellous bone, the trabeculae transfer the load. The direction of the trabeculae is determined by the direction of the load[3][4][5]. The trabeculae are therefore subject to compression and tensile forces. Bending strain and, hence, underloaded material in the neutral fibres, are avoided just like in a well-built timber frame construction. Near the bone shaft where bending is unavoidable, the bone basically is a tube with a very stiff wall, which means load-bearing material has been moved to the outer boundary. A good example of this is the human thigh bone (see Figure 3).



a) Cross-section of a thigh bone **b) Pattern of tension and compression lines**

NOTE The micro-framework consisting of trabeculae and platelets can be recognized easily and matches the pattern of tension and compression lines described by Reference [4].

Figure 3 — Cross-section of a thigh bone

6.3.2 Implementing the SKO principle in the finite element analysis

The SKO algorithm simulates the integration of cells into bones through their growth and reabsorption process. Only the principle of softening and, finally, removal of non-load-bearing material is applied in this case, though. These mineralization processes in the bones are modelled on mechanical components using the finite element analysis. In this case, the modulus of elasticity is varied depending on the stresses arising in the component. The user defines a reference stress, whose height primarily determines which structures will be formed in the specified design space. The higher the value selected for this reference stress, the less material the optimized structure needs, because all material exhibiting lower stress values than the reference stress value is softened and finally removed.

This procedure is iterative. At the beginning of the optimization process, it makes sense to select a low value for the desired reference stress and to increase it incrementally until it reaches the desired value. This incremental increase of the reference stress prevents the optimization from “removing” too much material at the start of the optimization and, hence, from disrupting any relevant load paths.

This method can be used easily in all finite element solvers by specifying the modulus of elasticity of the elements as a function of the temperature of the elements. The modulus of elasticity is usually mapped linearly to the element temperature in this case, with a temperature of 0 representing the lowest modulus of elasticity and a temperature of 100 the highest modulus of elasticity. These temperatures do not have any physical meaning, but they make it easy to control the modulus of elasticity during optimization. It is also possible in principle to control the modulus of elasticity using existing parameters, such as the density or other defined parameters.

A typical SKO optimization procedure (see Figure 4) consists of the following steps.

a) Specification of the boundary conditions and of the design space as a FE model with the most uniform distribution of elements possible. The dimensions of the design space represent the limits of the area available for designing the load-bearing component. The sizes of the individual elements of the design space limit the fineness of the structures that will be formed in this case.

b) In an initial FE calculation, all elements of the design space are assigned a constant modulus of elasticity. This allows the stresses arising from the material characteristics and from the load conditions to be determined.

c) The modulus of elasticity of each element of the design space is varied depending on the stresses calculated in the previous FE analysis. This yields a distribution of the moduli of elasticity with high modulus of elasticity values at locations subject to high stress and low modulus of elasticity values at locations subject to little stress.

d) Calculation of the new stress distribution with the help of FEA using the new modulus of elasticity distribution. In areas of the design space that need to be left untouched for functional reasons, the original value of the modulus of elasticity is left unchanged.

e) After several calculation cycles, the degree of separation between the areas with a high modulus of elasticity and those with a low modulus of elasticity is assessed. The final step is to remove the "soft" areas.

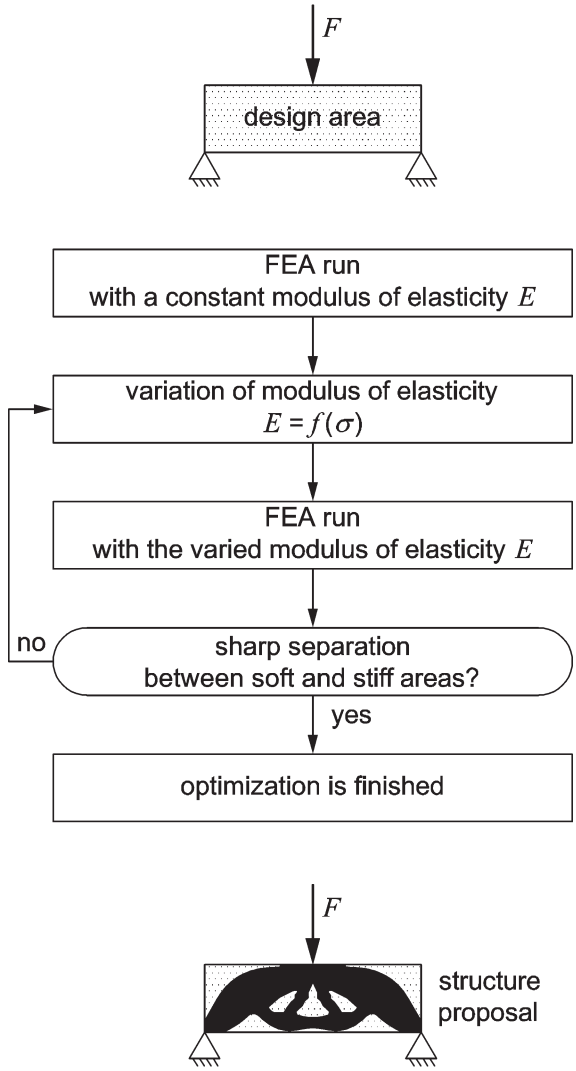


Figure 4 — Schematic flowchart of an SKO optimization according to Reference [3]

In the SKO method, areas subject to little stress are removed, while high-stress notches remain. A subsequent CAO optimization can reduce the still remaining notch stress. The step-by-step application of SKO and CAO leads to a lightweight design with a high fatigue strength.

6.3.3 Examples of applications of the SKO method

6.3.3.1 Concept car

The vision behind the biomimetic concept car was to design a frame structure that could bear the load surrounded by an ideally aerodynamic hull using the boxfish as an aerodynamic model (see Figure 5).

The boxfish was selected as a model because its shape ensures excellent utilization of the volume available and simultaneously offers very favourable aerodynamic characteristics.

To obtain an ideal lightweight design of the frame, a structural optimization was performed using the SKO method. The knowledge of the primary load paths gained from the optimization was then used in the subsequent development process of the frame.

The design space for the SKO optimization was defined by the exterior of the boxfish on the one hand and restricted by specifications, such as the engine compartment, windows, door openings, covers, and interior space, on the other hand. The loads on the suspension turret of the vehicle were defined as boundary conditions. The load cases used as the basis for optimization were the same load cases used to define the stiffness of a frame, i.e. torsion and bending load cases. In addition, static equivalent loads were used to simulate the loads arising during a frontal, side, and rear-end crash. The optimization was performed using the loads mentioned above. The design suggestion (see Figure 6) only contained 30 % of the total amount of initial material (utilization level = 0,3).

The result of the SKO optimization was used as a design proposal for the development of the frame. Some of the features integrated into the design that are visible from the outside can be seen in Figure 7, for example, the shape of the rear window and parts of the roof structure.

Figure 5 — From an example in nature to a product or from a fish to an automobile

Figure 6 — Result of SKO optimization, an optimal frame in terms of stiffness and weight for the loads applied

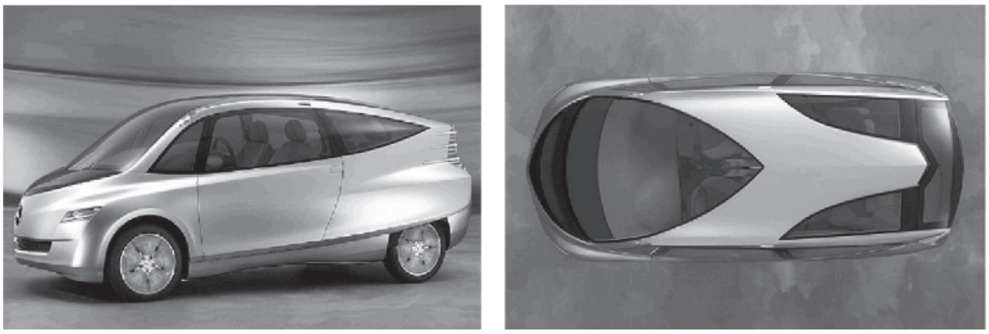
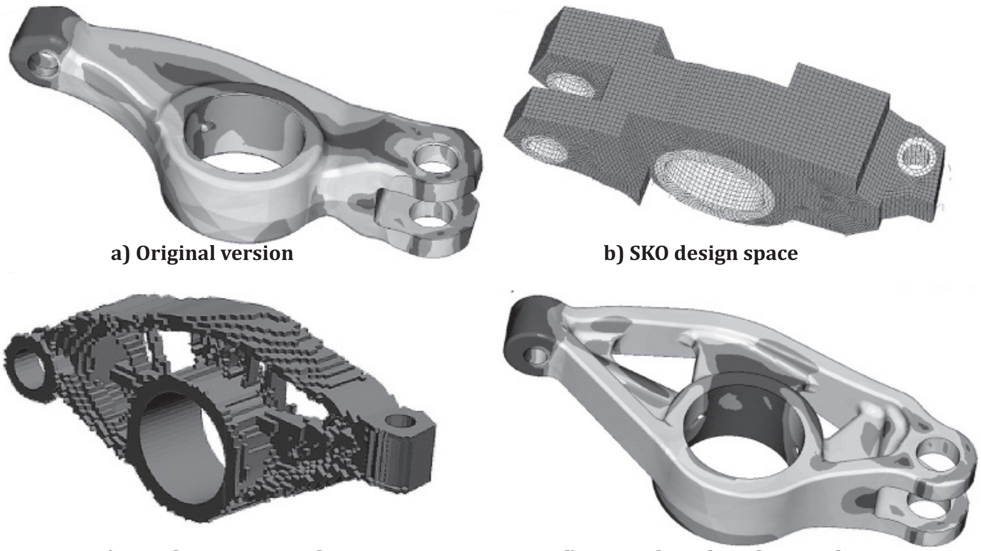


Figure 7 — Concept car with recognizable effects of biomimetic optimization on the shape of the vehicle [Source: © Daimler AG]

6.3.3.2 Rocker arm

Figure 8 shows a rocker arm optimized using SKO. Compared to its original version [see Figure 8 a)], it was not only possible to save material but also to reduce the von Mises stresses by 29 %. This made it possible to manufacture the optimized version as a cast part and to reduce manufacturing costs, since the original version was designed to be manufactured by forging. The amount of material saved, in combination with the use of a lighter casting material, led to total weight savings of approximately 35 %.



a) Original version

b) SKO design space

c) SKO design proposal

d) Design based on the SKO design suggestion

Figure 8 — SKO optimization of a rocker arm

6.4 Computer Aided Internal Optimization (CAIO)

One advantage of fibre-composite materials is that they can be used to design high-strength, high-stiffness, and lightweight structures. In conventional technical fibre composites, the fibres are often cut when an interruption in the geometry, such as a hole, is encountered. This significantly weakens the component. To utilize the potential of technical fibre composites, it is also necessary to orient the fibres of technical components along the flow of force. If this is successful, then the fibres are subjected to defined tensile and compressive stresses and the shear stresses between the fibres, which are critical for fibre composites, are minimized.

CAIO allows determining a fibre orientation that can handle the applied forces and, hence, reduce the shear stress on a component to a minimum for a prescribed load[3][7]. The method is based on commercial finite element programs. First, the model to be optimized is assigned an orthotropic material with an arbitrary orientation. A stress analysis follows the calculation of the optimized material orientations by the CAIO routine. The CAIO routine then reads in the results of the stress analysis and calculates a new orientation for the material axes based on these results. A new stress analysis is then performed on this variable orthotropic material.

The shear stresses between the fibres are reduced after the first iteration by up to 90 % due to the reorientation of the orthotropic axes of the material along the main stress trajectories. By iterating the alternation of CAIO calculations and stress analyses, it is possible to reduce the shear stresses even further. The steps involved when applying CAIO are shown in Figure 9.

Using CAIO, it is possible to illustrate the flow of force in a statically loaded component. Representing the flow of force using streamlines has turned out to be particularly practical. A relationship between the density of the streamlines and the stress gradients can be defined as desired in order to generate a dependency between the fibre density and the load placed locally on the structure.

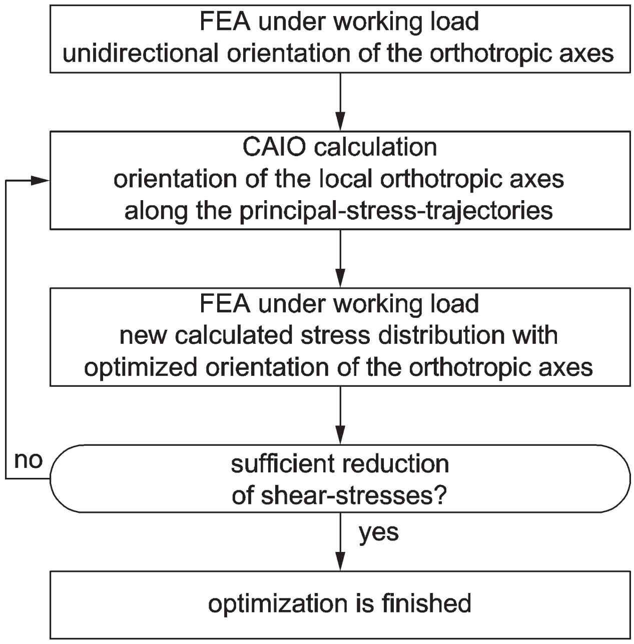
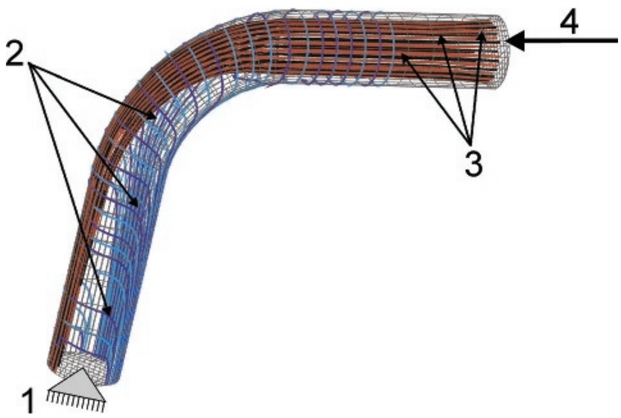


Figure 9 — Schematic flowchart of the CAIO method according to Reference [3]

6.4.1 Example of the CAIO method: bent cylinder

Figure 10 shows a bent cylinder and the fibre orientation calculated using the CAIO method. The bottom vertical end of the structure is fixed and pressure is applied to the front, as shown in the top right of the figure. The homogeneous axial pressure load results in a homogeneous flow of force which is visualized by equidistant fibres or bars in the horizontal section of the bent cylinder. In its vertical section, which is subject to a bending strain, the pressure is concentrated on the left side. On the right side of the vertical section, the calculations result in tensile cords that wind around the tensile fibres running along the left side and hold them together. In the horizontal part of the structure, the tensile cords form circular loops.



Key

(black/red)	pressure rods
(blue)	tensile cords
1	fixed
2	tensile cords
3	pressure rods
4	axial pressure

Figure 10 — Fibre orientation according to CAIO[7] in a bent cylinder

6.5 Method of Tensile Triangles

6.5.1 General

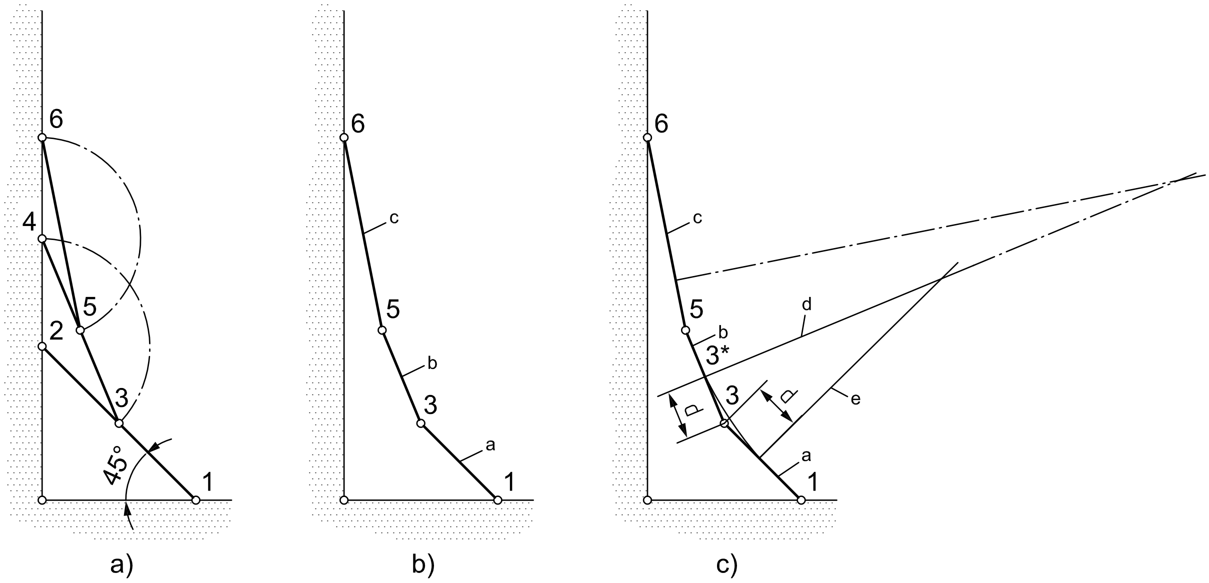
The Method of Tensile Triangles, in contrast to the methods described above, allows optimizing the lifespan and/or the material usage of components in a purely graphical manner, i.e. without the use of a computer[8].

The optimized edge contour is geometrically defined. As a general rule, the contour is composed of two to three isosceles tensile triangles. The size of the first tensile triangle determines the sizes of the subsequent tensile triangles. A transition, which usually forms a right angle, is covered by the first tensile triangle, whose base angle is 45°. The base angle of each of the following tensile triangles is one half of the previous tensile triangle. Correspondingly, the second base angle is 22,5° and the third base angle is 11,25°. The contour can be adapted to any design space by scaling accordingly.

The geometric construction is explained on a component by joining two parts with different cross-sectional areas (e.g. shoulder fillet). On the sharp corner, the first tensile triangle with a base angle of 45° is placed over the corner (see Figure 11) in the selected design space. This rounds the corner of the base model and creates two points: point 1, which is located on the shoulder, and point 2, which represents the other end of the hypotenuse and is located on the thinner shaft.

Another tensile triangle is inserted which starts at the centre of the hypotenuse (point 3) of the first tensile triangle and ends on the thin end of the shaft. The end point (point 4) of this second hypotenuse is determined by swinging an arc centred at the end of the first hypotenuse (point 2) with a radius equal to the distance to the centre (point 3) of the first hypotenuse.

The third tensile triangle is created by repeating the construction above while centred at point 4. This creates point 5 and point 6 as the starting and end points, respectively, of the hypotenuse of the third tensile triangle [see Figure 11 a)]. After using the individual triangles to form the contour, three lines are left and form the notch contour. These lines are labelled line 1 to line 3 in the order of their construction see Figure 11 b)]. To avoid the stress peaks at the transition points between the tensile triangles, these points are then rounded using the largest possible radii so that each arc swung is tangent to the outside contour of the tensile triangles. Alternatively, a good approximation of this edge contour can be obtained using the tangent function in the range from 0 to 1,32.



Key

a line 1

b line 2

c line 3

d normal 1

e normal 2

Figure 11 — Procedure for constructing and rounding a contour according to the Method of Tensile Triangles[9]

For uniaxial load cases, placing a tensile triangle contour in the notch will suffice. Multiaxial loads require a combination of two tensile triangle contours to round off the notch. The design space of each contour is then designed according to the specified load conditions. In Figure 12, the prong on the right is subject to three times the load of the other prong and the tensile triangle contour on this side accordingly requires more design space.

Delaying the growth of a fatigue crack by drilling holes at the ends of a crack is an old technique. As shown in Figure 13, the Method of Tensile Triangles can also be used to retard the growth of cracks and slit-like gaps instead of drilling holes at the tips of the cracks. Triangular slots can be placed on the original tips of the crack when the tension is uniaxial, such that the new ends of the redirected crack will be deflected into a compression zone. The ends of a crack are harmless when compressed and the notch stress of the deflection contour is low due to its optimized shape.

6.5.2 Tensile triangles for saving material

With the aid of the Method of Tensile Triangles, it is also possible to identify and eliminate underloaded material in a mechanical dead space, for example, in areas of transition between different cross-sections that are almost free of force flows due to the sudden change of direction. The procedure is illustrated in Figure 14. Applying the Method of Tensile Triangles reduces the angle of the shoulder from 90° to 45°. At the same time, the stress on this notch is reduced using additional tensile triangles as described above.

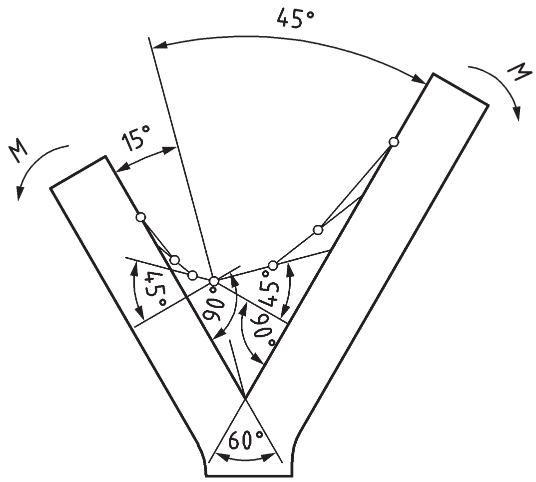
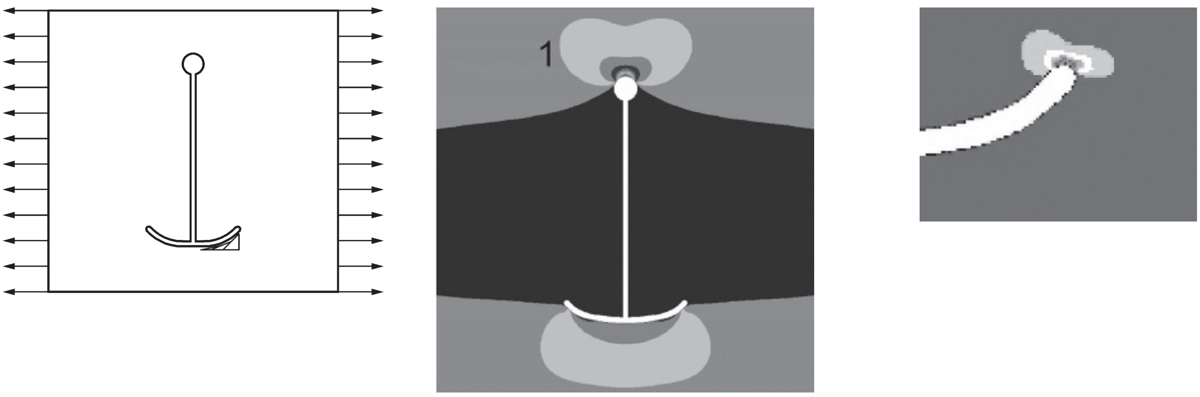


Figure 12 — Tensile triangle contour to round off a notch with a two sided, non-symmetric load

The right side of the prong is subject to three times the load of the left side and the design space selected for the tensile triangle contour on this side is three times larger than the design space of the left side.



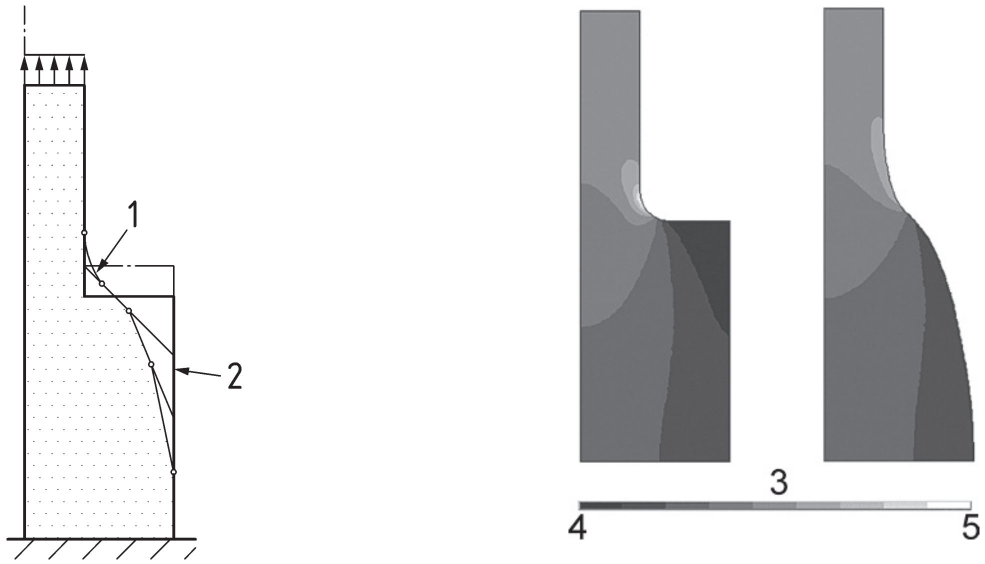
a) model	b) principal normal stress (tension)	c) detail with third principal stress (compression)

Key

1 tensile stress maximum

Figure 13 — FE analysis of a slotted plate subject to a tensile load

The ends of the slots are modified to reduce notch effects at the top by a hole and at the bottom by a tensile triangular deflection. A tensile triangle contour at the end of a slot subject to lateral tension reduces the maximum tensile stress significantly compared to the conventional drilling technique b) and subjects the new, deflected ends of the slots to lateral compression c).



Key

1 growth to reduce stress

2 shrinkage to reduce weight

3 von Mises stress

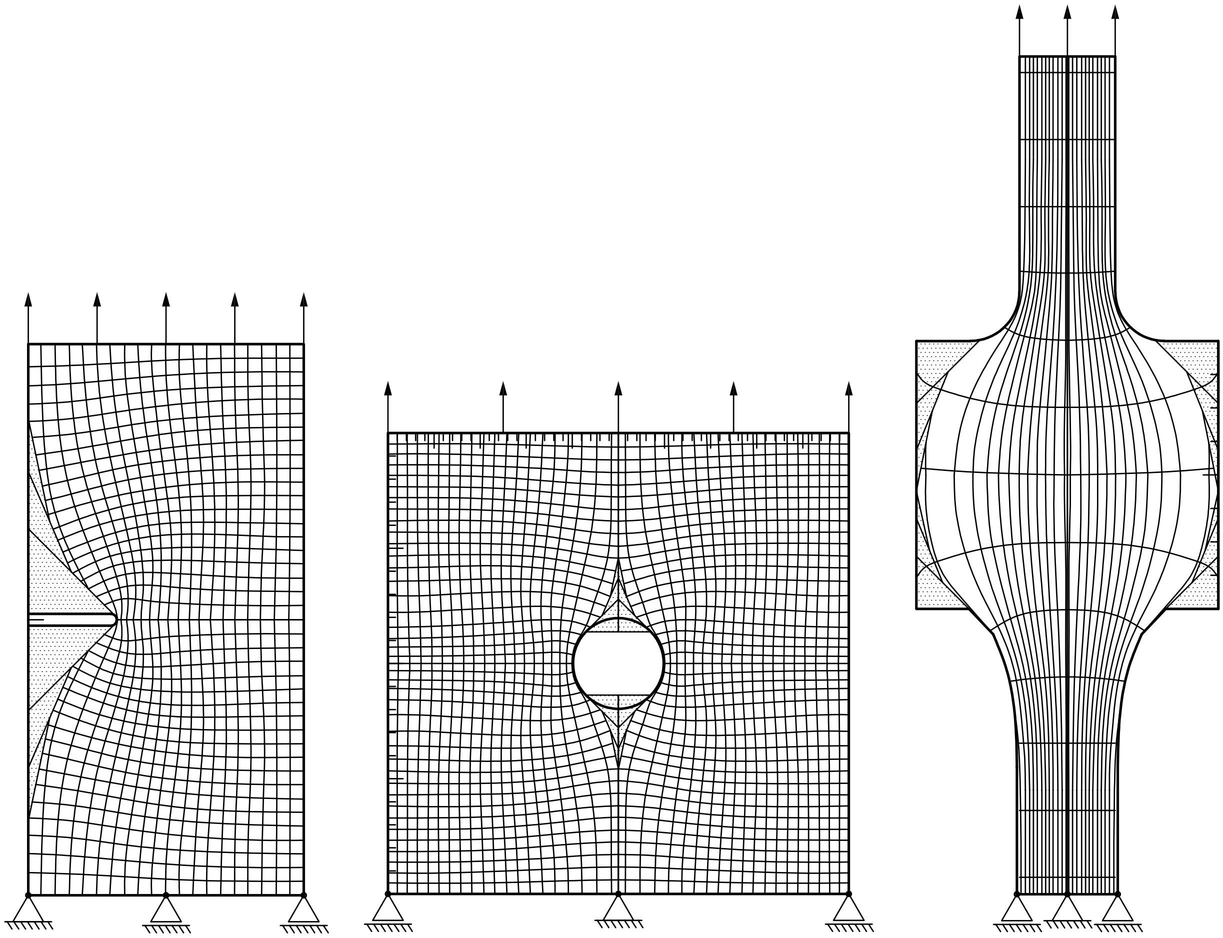
4 low

5 high

Figure 14 — Removing underloaded material using tensile triangles[10]

6.5.3 Tensile triangles for optimization of fibre orientation

As already illustrated in connection with the CAIO method, the load capacity of fibre-composite structures also depends on the local fibre arrangement. It is best when the fibre orientation and principal normal stress trajectories are identical, i.e. when the fibres are parallel to the direction of the flow of force[11]. The CAIO method can calculate the ideal fibre orientation for the entire structure. Particularly important for practical applications is the fibre orientation near disturbances, for example, near recesses or holes in the structure. If the fibre arrangement selected in these areas corresponds to the tensile triangle contour, then the results are a sufficient approximation of the CAIO solution (see Figure 15).



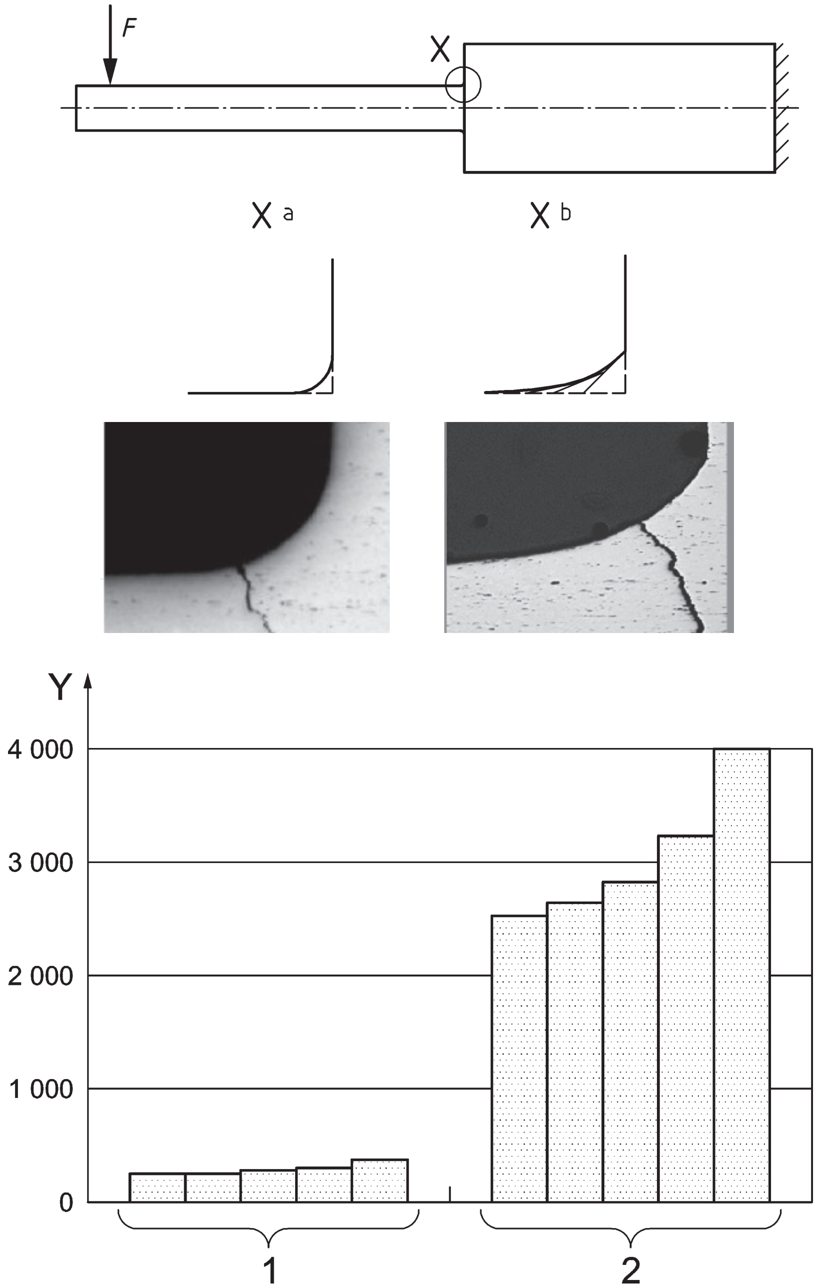
NOTE In order to ensure that irregularities (for example, a) slots, b) holes, and c) recesses and bulges) do not create weak spots in fibre composites, the fibre orientation in these areas needs to be adapted to the load.

Figure 15 — Optimization of fibre orientation

A good approximation can be obtained globally with the CAIO method or locally with the Tensile Triangle Method. The tensile triangle contours generated near the irregularities are coloured grey in the images and the lines visualize the flow of force calculated using CAIO.

6.5.4 Example of the Method of Tensile Triangles: shoulder fillet

Hardly any technical component can do without step-like shapes, which in turn generate local stress concentrations. Shafts, for example, are almost always stepped for driving, output, or for mounting purposes. Usually, the shoulder of a shaft, i.e. the transition point between the thick and thin parts of the shaft, is rounded off using a rounding radius. A tensile triangle contour was generated for this standard transition with the same design space as used for FEA and the results were compared experimentally. The shoulder fillet is clamped at the thick end and loaded at the thin end with many load cycles of bending. In the laboratory experiment, steel shoulder fillets optimized by the Method of Tensile Triangles on the average withstood nearly 10 times as many load cycles as the shoulder fillet, with the quarter-circle notch having an identical lateral design space (see Figure 16).



Key

X detail Z

X[a] quarter circle

X[b] tensile triangle optimization

Y load cycles to failure [× 1 000]

1 quarter circle

2 tensile triangle optimization

NOTE The photographs show micrograph images of the notch contours with cracks after the fatigue tests.

Figure 16 — Fatigue tests on shoulder fillets with quarter-circle and tensile triangle notch shapes subject to fatigue tests[8]

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