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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.

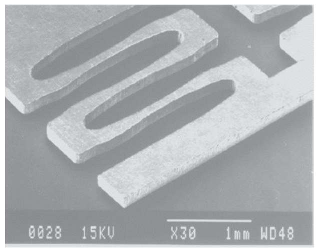
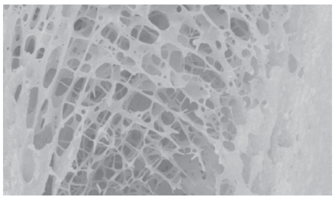
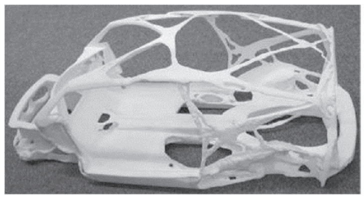
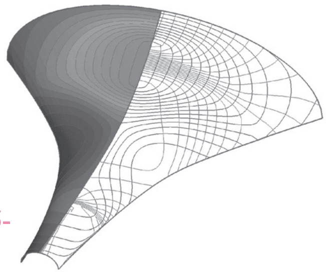
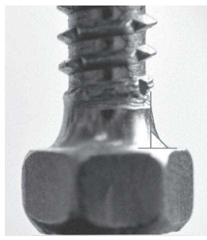
The SKO method is biomimetic, because the biological system used for SKO is the mineralization of bone, a part of this phenomenon has been abstracted to a load-adaptive process, and this process has been abstracted, implemented in simple algorithms, and also transferred to technical application. SKO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

