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Design in nature

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Abstract

The axiom of uniform stress is identified as a basic design rule for biological load carriers. Based on this condition and by use of the Finite Element Method (FEM) three computer programs have been developed at Forschungszentrum Karlsruhe to transfer these biological optimization mechanisms to mechanical engineering as well as to simulate biological growth. The **C**omputer **A**ided **O**ptimization design procedure (**CAO**-method) simulate the principle of adaptive growth which biological structures, like trees, use to minimise stress concentrations on the surface. The **S**oft **K**ill **O**ption (**SKO**-method) copies the biological optimization mechanism of adaptive bone mineralization. And finally the **C**omputer **A**ided **I**nternal **O**ptimization (**CAIO**-method) optimizes the performance of composite materials by aligning the fibre distribution with the force flow in order to avoid shear stresses in between the fibres, again mimicking the structure of trees.

1 Introduction

Optimization in nature takes place by non-optimized species being defeated. The result of this natural selection over millions of years: the designing mechanisms and the structure of each biological load carrier is optimally adapted to its natural load. The biomechanical structures are adapted to the loads they experience by two different strategies. First, the trial and error strategy, which creates better designs by accident and therefore with slow stochastic success. The second and more intelligent survival strategy is self repair by the adaptive growth. This survival strategy enables biological structures such as trees and bones to adapt flexibly their original optimum designs to changes in the loading conditions. Trees and bones are able to record local stress concentrations and repair these

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predetermined breaking points by the adaptive growth. This process leads to a reduction of notch-stresses and homogenize the stress distribution on the surface.

Already in 1893 the first work on uniform stress distribution in biological load carriers was published by the forester and author Metzger [1]. He pointed out that bending stresses caused by wind loading are homogeneously distributed over the length of spruce trees as a result of load adapted tapering. Mattheck [2] and co-workers generalised this principle and verified by several examples that the axiom of uniform stress is a universal design rule for biological structures.

2 Methods and results

Based on the axiom of uniform stress and by use of the Finite Element Method (FEM) three computer programs have been developed at Forschungszentrum Karlsruhe to transfer these biological optimization mechanisms to mechanical engineering as well as to simulate biological growth.

2.1 Computer Aided Optimization (CAO)

In most cases local stress concentrations on the surface due to notches or changes in geometry are responsible for fatigue failure. Therefore, a prevention of such stress raising effects is of great importance in nature as well as in engineering design. Trees for example make any effort to grow into a homogeneous state of stress on their surface. The outermost annual ring always tries to adapt to the external loading by locally increased or reduced growth according to high or low stresses. CAO [3] simulates this effect by a FE-calculation with a fictitious thermal expansion dependent on previously calculated stresses whereat high stresses lead to a great thermal expansion and vice versa. By this, the stress peaks will be reduced and finally a homogeneous state of stresses on the surface is achieved.

Figure 1 shows the flow diagram of the CAO-method. First a finite element structure of the component needs to be produced. Then a FE-computation with the planned future loadings and supports is calculated. In this example, the tension plate is pulled on the left and clamped on the right. The "simple trick" of the CAO-method: the computed stresses are formally set equal to a fictive temperature distribution. Then the modulus of elasticity is set at 1/400 of its initial value in the growth layer. The previous mechanical load is set at zero. Only the soft surface layer of the component will have a thermal expansion factor bigger than zero. The result is a soft upper layer which is hot at the over-loaded zones and rather cold in the unloaded zones. In computation step 2 the zones with the previously highest loads now have the highest temperature and expand most strongly. The component starts to grow in the highly loaded zones and, in analogy to trees, forms the locally thickest "annual rings". The procedure is done iteratively until a constant stress state on the surface is achieved.

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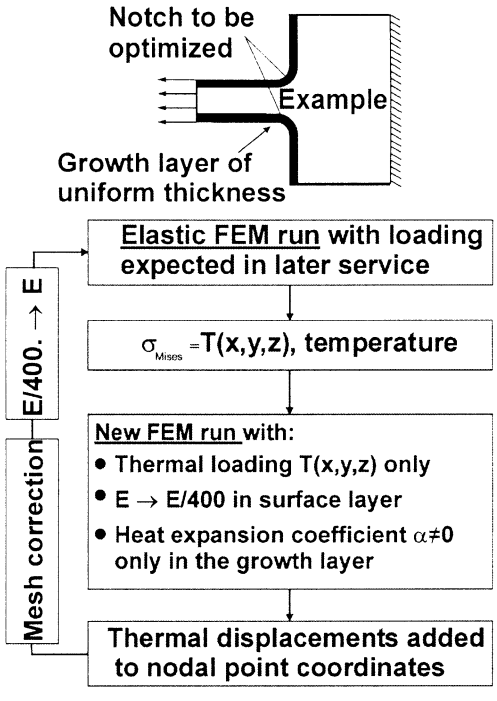


Figure 1: The flow diagram of the CAO-method.

Figure 2 reveals that tree forks found in nature are notches without notch stresses. The constructed specimen is inferior to the natural design on account of its semicircular inner contour, which causes high notch stresses. The computer aided optimization produces the real tree fork with a uniform stress distribution on the surface.

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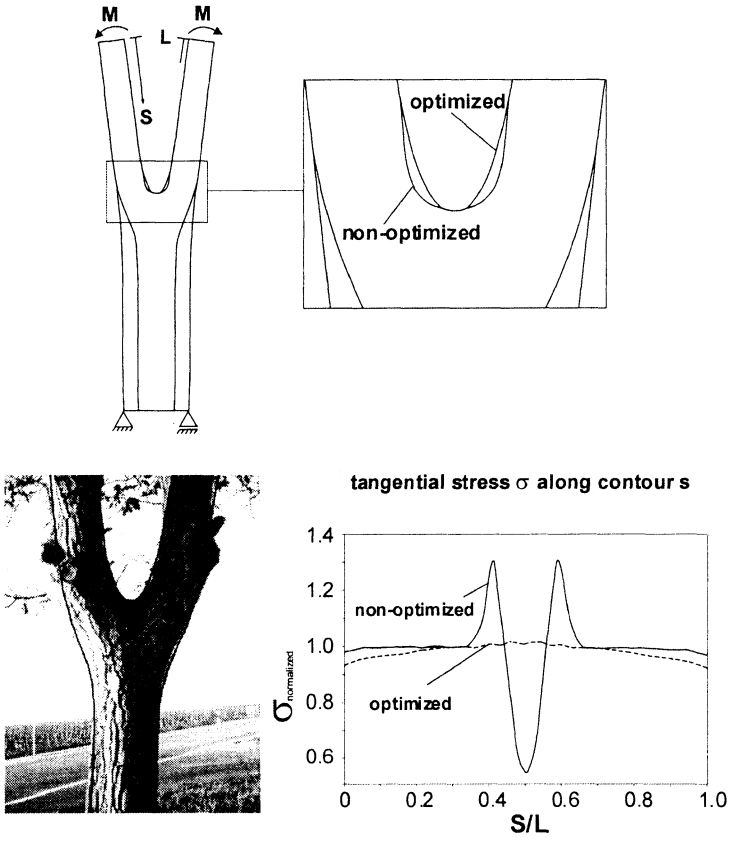


Figure 2: The effect of shape optimization on stress distribution in the tree fork, which grows into a notch form without notch stresses.

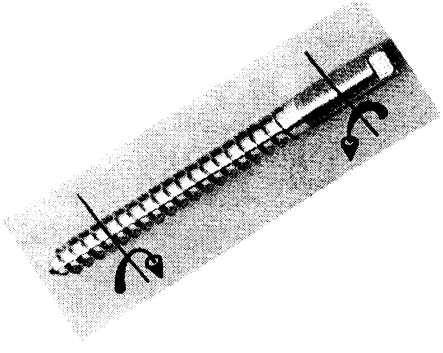
The possibilities of CAO are not limited to the domain of biology. Figure 3 shows a treatment of a backbone fracture an breakage of the bone screws. The radiograph reveals that fragments of the orthopaedic screws remain in the bone of the patient after implant removal.

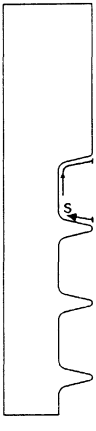
The orthopaedic screw is used to fix implants to bone, and generally bridges over broken regions of bones. The screws must not exceed a certain thickness in order to fit into the pedicle, a narrow bone channel. The non-optimized threat design of the orthopaedic screw is formed by a circular arcs at the base of the threat and the first threat in particular is usually the weak point of this construction. Shape optimization by CAO has provided a screw which is free of notch stresses. The shape optimized screw was manufactured and tested in repetitive bending test under laboratory conditions. The optimized screw withstood 20 times as many cycles as the non-optimized one, and exhibits no visible crack formation.

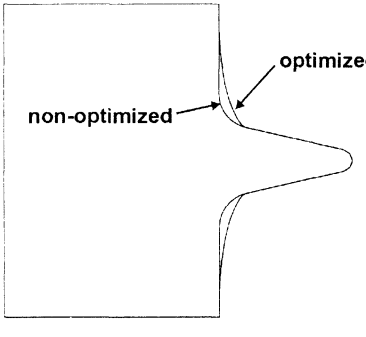
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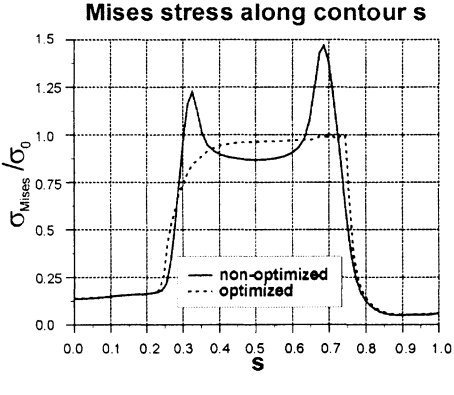


Figure 3: Treatment of a vertebra fracture, breakage of the orthopaedic screws and optimization of the thread of an orthopaedic screw.

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2.2 Soft Kill Option (SKO)

The SKO-method [4] copies bone mineralization: areas that are subjected to higher loads are hardened by adaptive minerilization, whereas less heavily loaded sections are softened and finally discarded or 'killed'. The main procedure which needs again a standard finite element program, is shown in Figure 4. The stress distribution is calculated for an initial design area, the limit dimensions and bearing and loading conditions of which correspond to those of the component in service. In accordance with the calculated stresses, the Young's modulus is increased in areas subjected to higher loads and is reduced in more lightly loaded areas. The load carrying sections are reinforced while the more lightly loaded sections are softened and increasingly relieved. Some iterations suffice to separate sharply the passive, idle areas from the active, useful ones. All areas serving no useful purpose are finally eliminated.

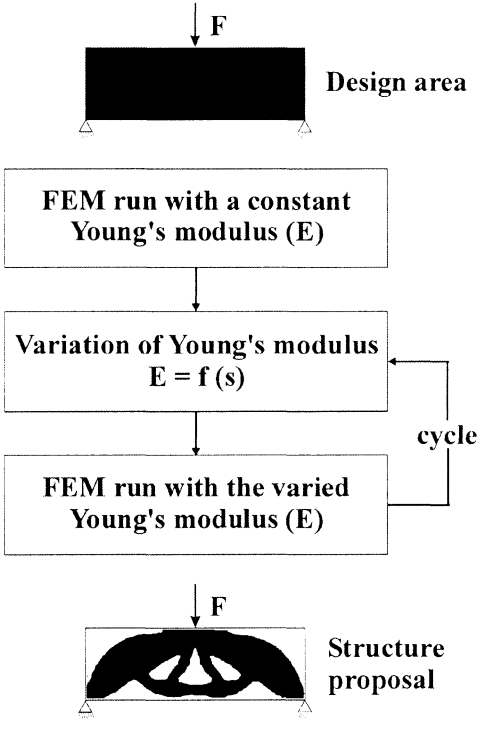


Figure 4: The SKO flow sheet.

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A reference stress in the variation formula of the Young's modulus/stress relation decides whether the value of the Young's modulus is increased (at places where the stresses are higher than the reference stress) or decreased. The higher this reference stress is chosen, the less material is needed to support the loading and the less and finer structures will develop.
A framework structure (bracket) which was developed by the use of SKO is shown in Figure 5. The design area is internally restricted by circular bolts which have to remain circular. The result is a lightweight design, a design proposal which comes close to the optimum. Its subsequent CAO smoothes and relieves the remaining notch stresses. The successive application of SKO and CAO provides the desired fatigue resistant lightweight design.

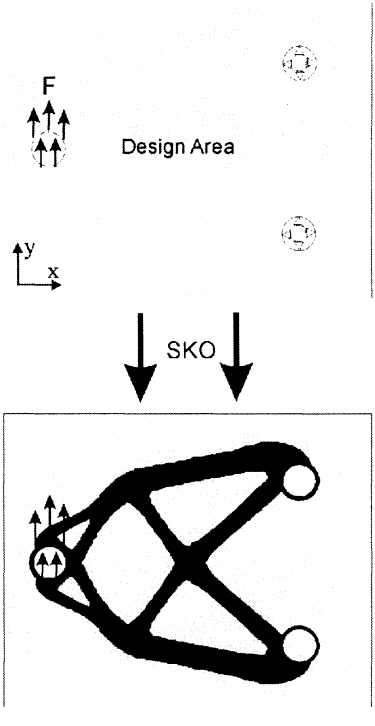


Figure 5: SKO design for loading by a transverse force out of a rectangle.

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The effects on SKO and CAO if the material used is not homogeneous and isotropic must also be taken into account. Wood, for example, is a fibre composite, but its orthotropic nature only seldom affects the optimum shape because of a uniaxial force flow in the fibre direction, and on account of negligible transverse effects.

2.3 Computer Aided Internal Optimization (CAIO)

The CAIO-method [5] is based on the plausible assumption that the fibres should be arranged to coincide with the force flow transmitted by the component. The lines of force flow called principle stress trajectories are not subject to shear stresses. Shear stresses between the fibres are thereby avoided and the force flow truly follows the fibres without moving between them by shear transmission. This optimum fibre arrangement can be determined by CAIO (Figure 6).

Figure 7 shows an example of an optimum fibre arrangement of a rectangular plate with a cylindrical hole under tension loading and a branch joint. The result of the CAIO as shown in Figure 7 is a drastic reduction of shear stresses in comparison to the initial design. The suitability of the method for verifying the course of wood fibres around a branch joint is also demonstrated. The fibres ingeniously bypass the branch hole, defusing its dangerous notch effect by the course they choose.

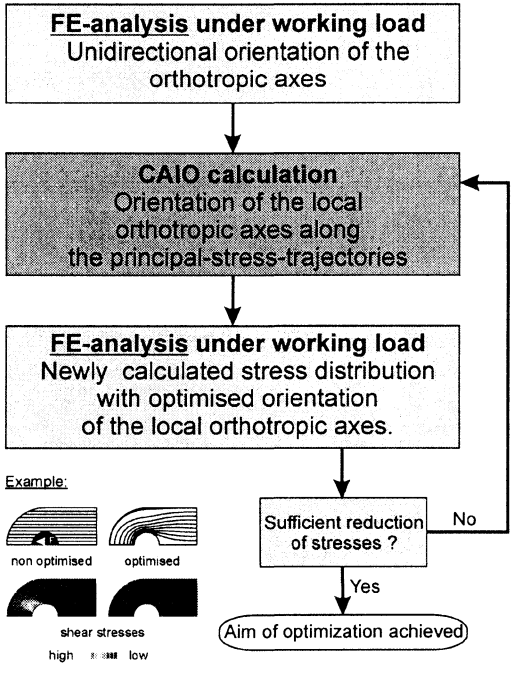


Figure 6: The CAIO flow sheet.

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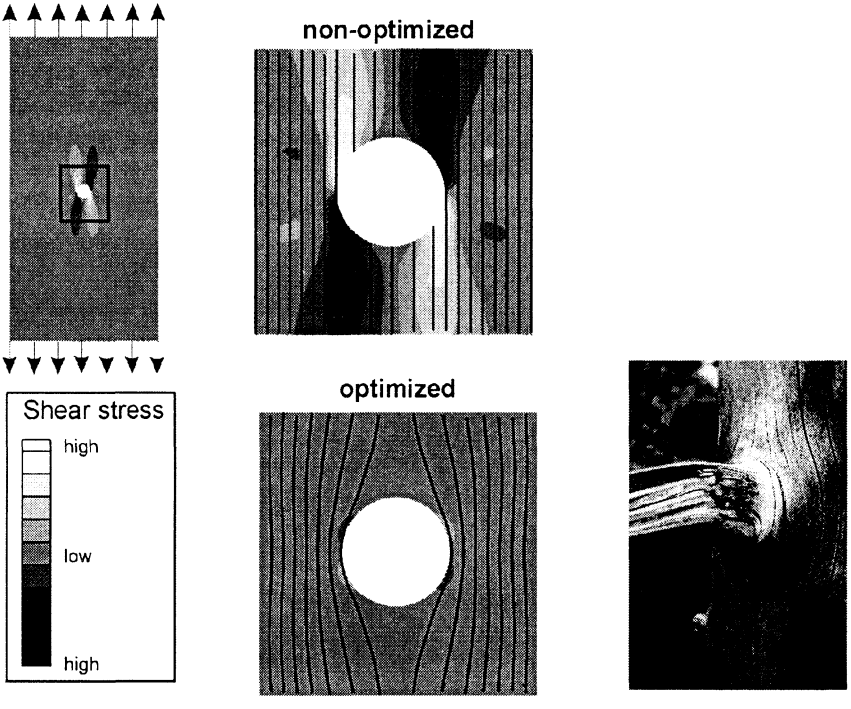


Figure 7: Example of an optimized fibre arrangement and grain direction around a branch joint shown by crack formation.

3 Conclusion

Nature offers custom made solutions, yet perfect technical counterparts are hardly ever found. It is advisable, therefore, to copy the mechanism of optimization rather than the entire individual design. In this way SKO, CAO and CAIO can transform practically any component into an ecodesign structure of ideal outer shape with optimum inner fibre architecture.

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