Adaptive Biological Growth

Introduction to Shape (CAO)
& Topology (SKO) Optimization
Derived from the Growing of Trees

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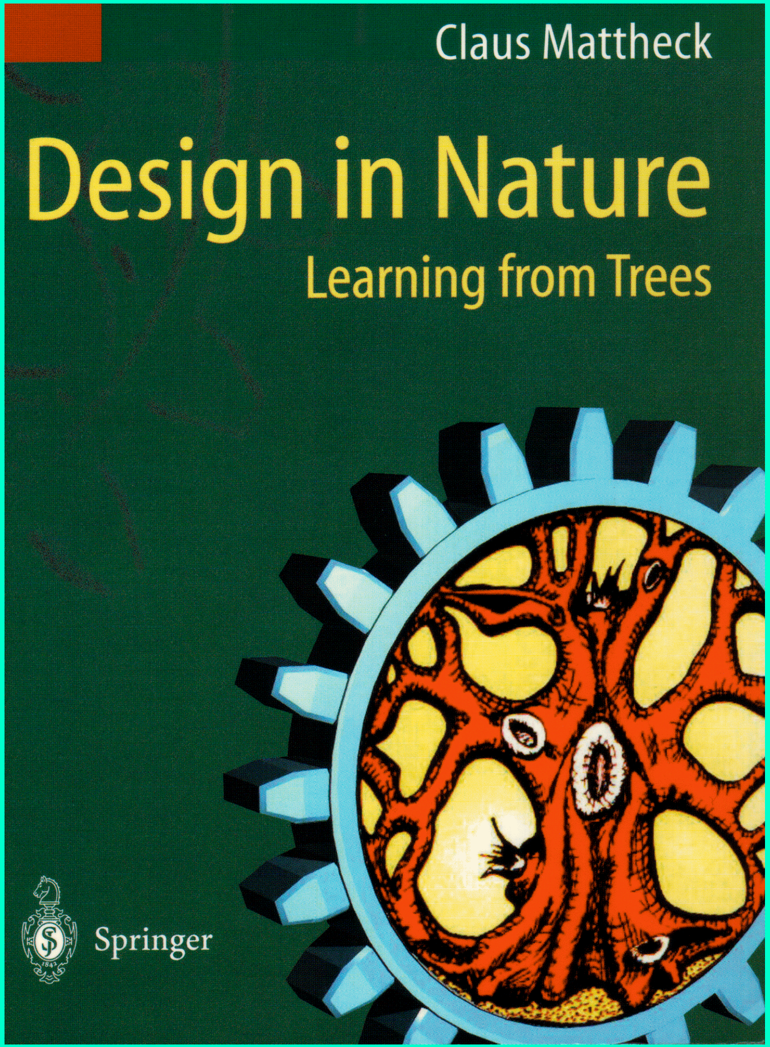
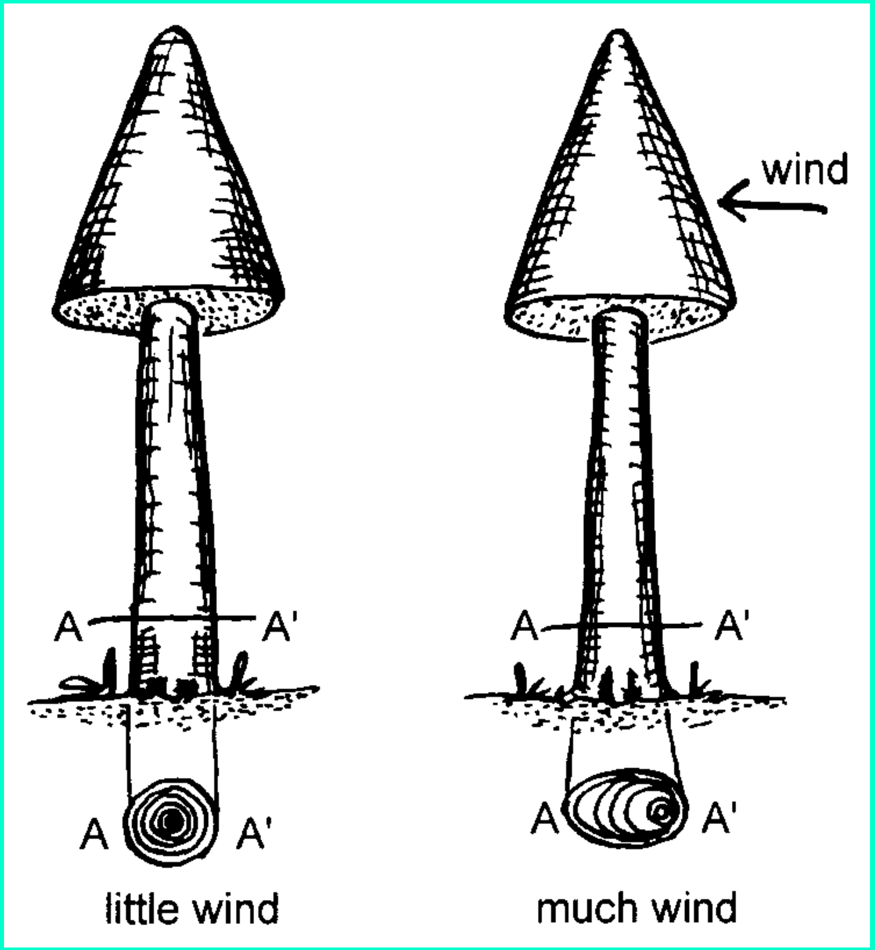


Adaptation to the Loading

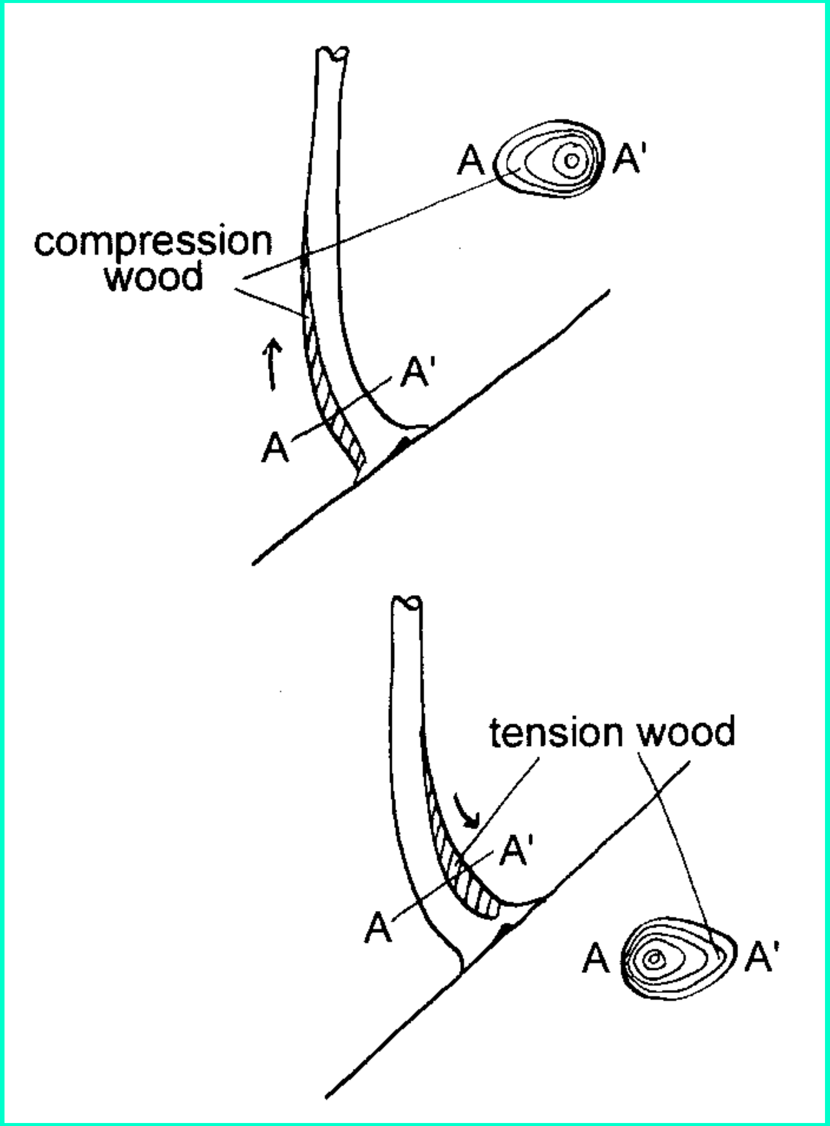
Trees adapt the spacing of their annual rings (Cambium) due to the loading e.g. permanent winds



Adaptation to the Loading

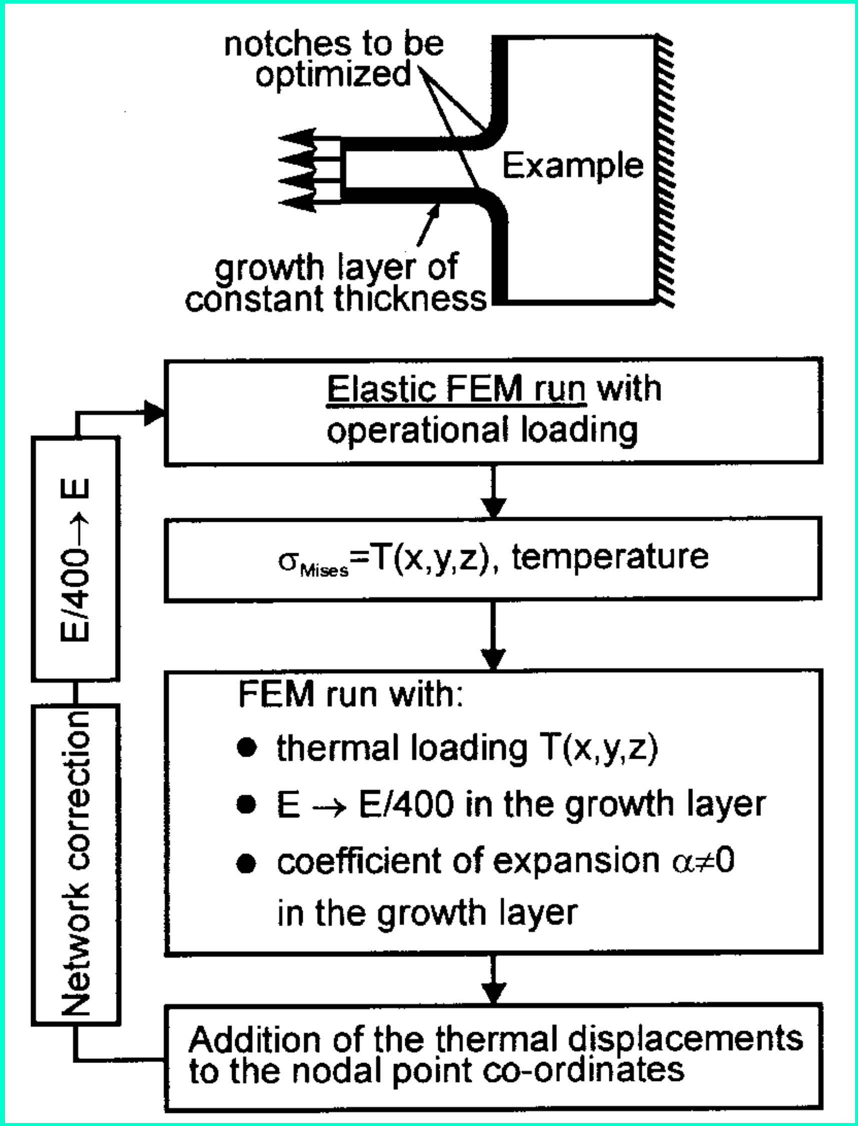
- Conifers form Compression Wood

- Broadleaves form Tension Wood



Shape Optimization (CAO)

- Define the area of interest and discretize
- Determine the stresses in your structure (von Mises)
- Define the surface to be optimized (Cambium)
- Define a thermal load proportional to the stresses
- Lower the Young's modulus for the surface elements
- Determine the displacements due to the thermal expansion
- Add the relative displacements to the nodes on the surface
- Run your initial FE analysis again



Shape Optimization (CAO)

- Instead of changing the Young‘s moduli increase the temperature
  --> Less computational effort

- Instead of having different thermal expansion coefficients use an additional set of boundary conditions where all but the nodes in the area of interest are constraint and therefore kept from ‘moving‘
  --> No need to change properties of the initial system

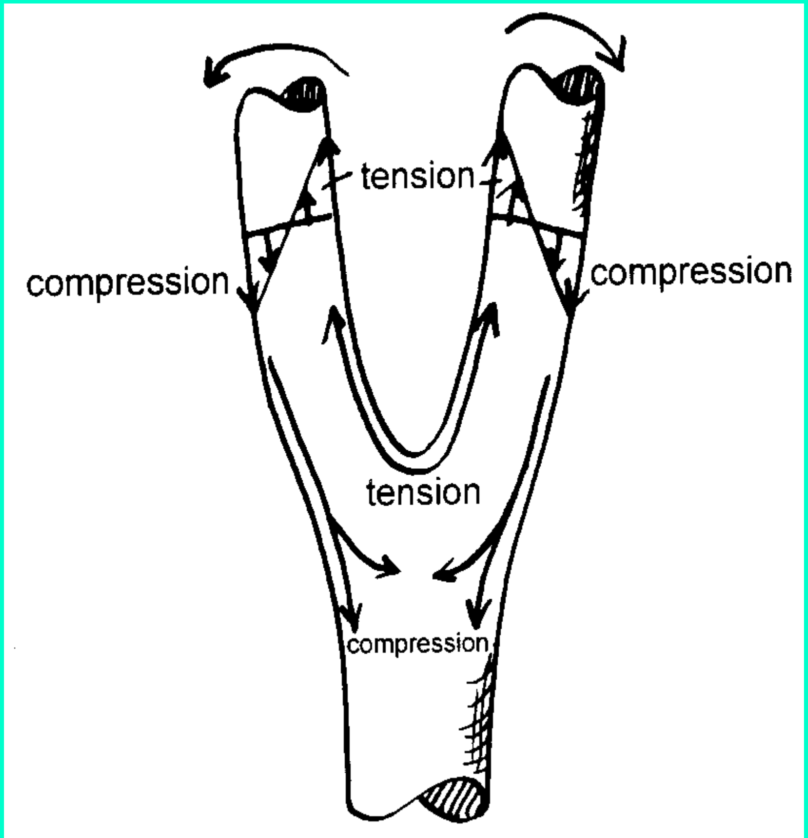
- Use the displacement field obtained from the temperature loading as enforced displacements in an additional FE run to have the ‘inner‘ nodal coordinates updated (also advised by Prof. Mattheck)
  --> Better Mesh Quality

Commercial programs try to determine normal vectors for the surface nodes and therefore do not need the thermal expansion and the enforced displacement run. But this is a tricky job to do !!

Typical Notches found at Trees

- Tree Fork with typical loading of moments and compression forces

- Typical for mechanical components with stress peaks on the inner edge



Typical Notches found at Trees

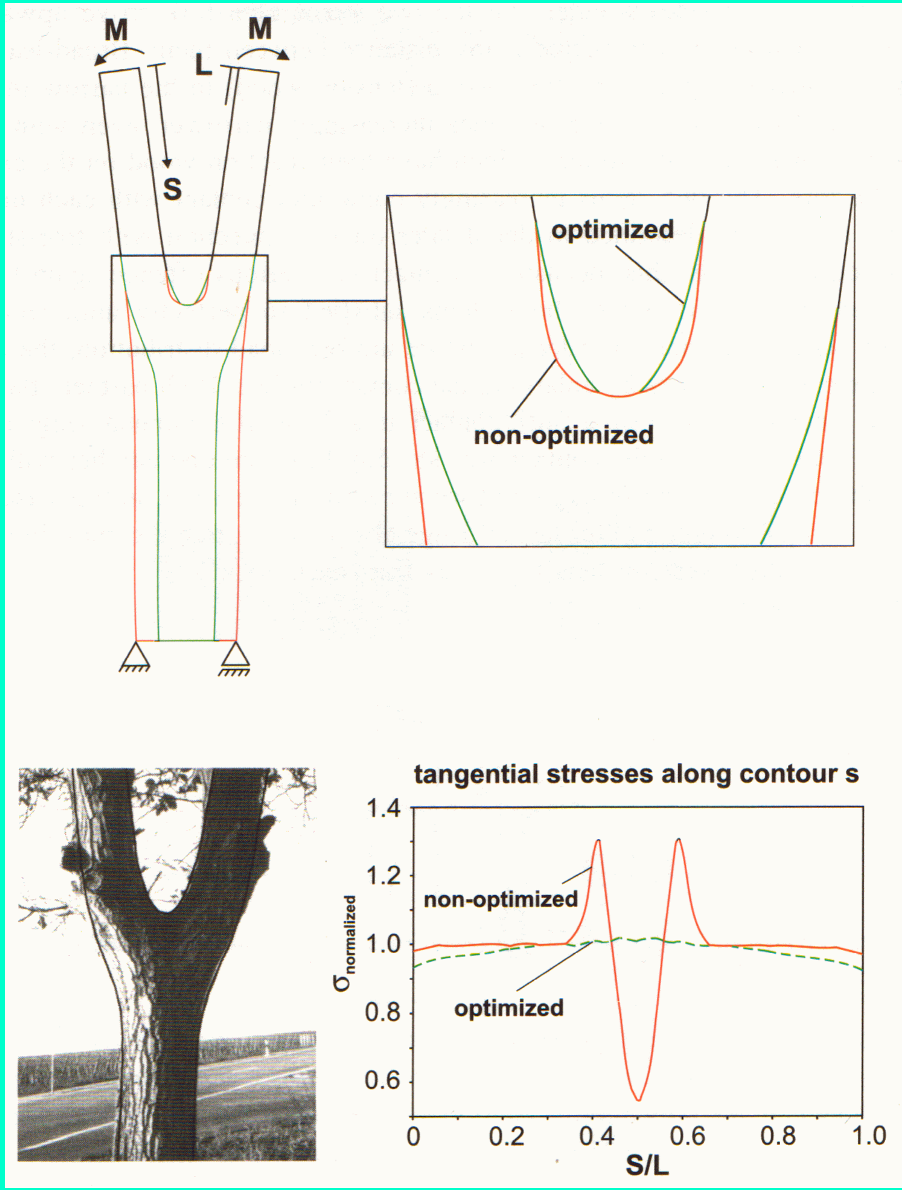
<u>Tree Fork</u>

- Using simple geometric elements like straight lines and circular curves will lead to notch stress

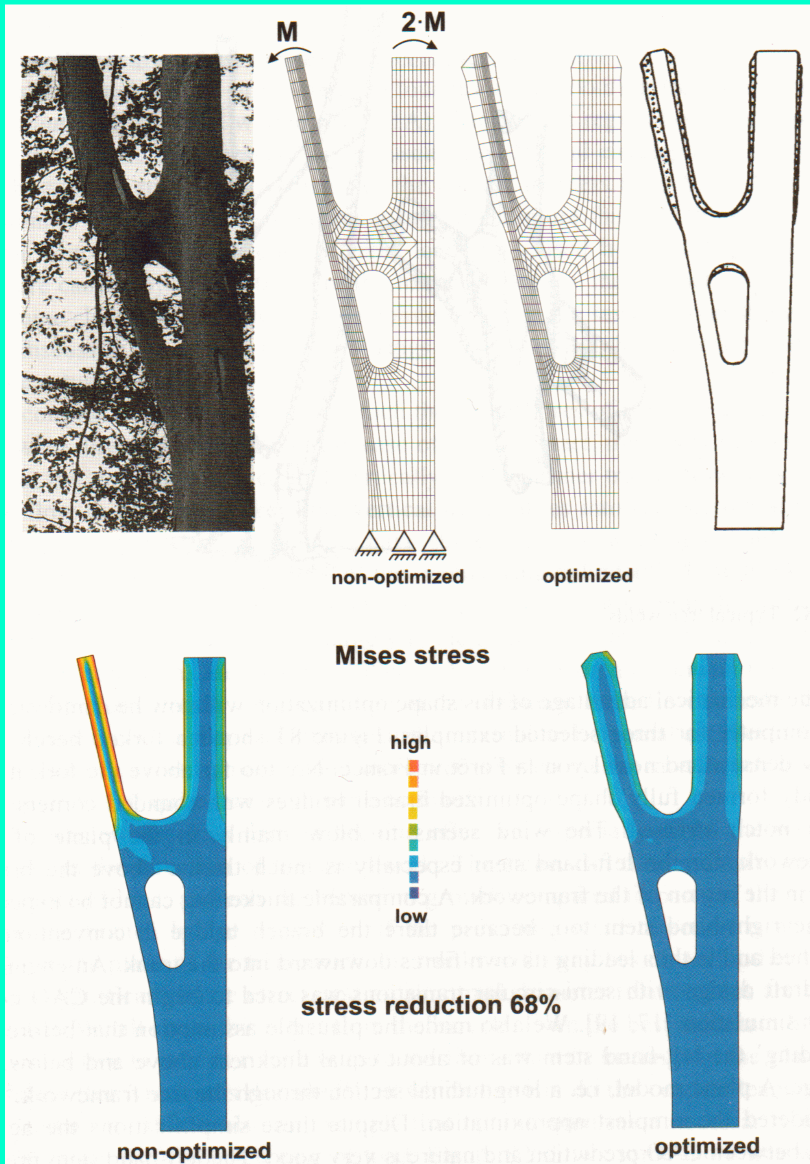
- The CAO shapes the contour to have uniform stresses along the inner edge

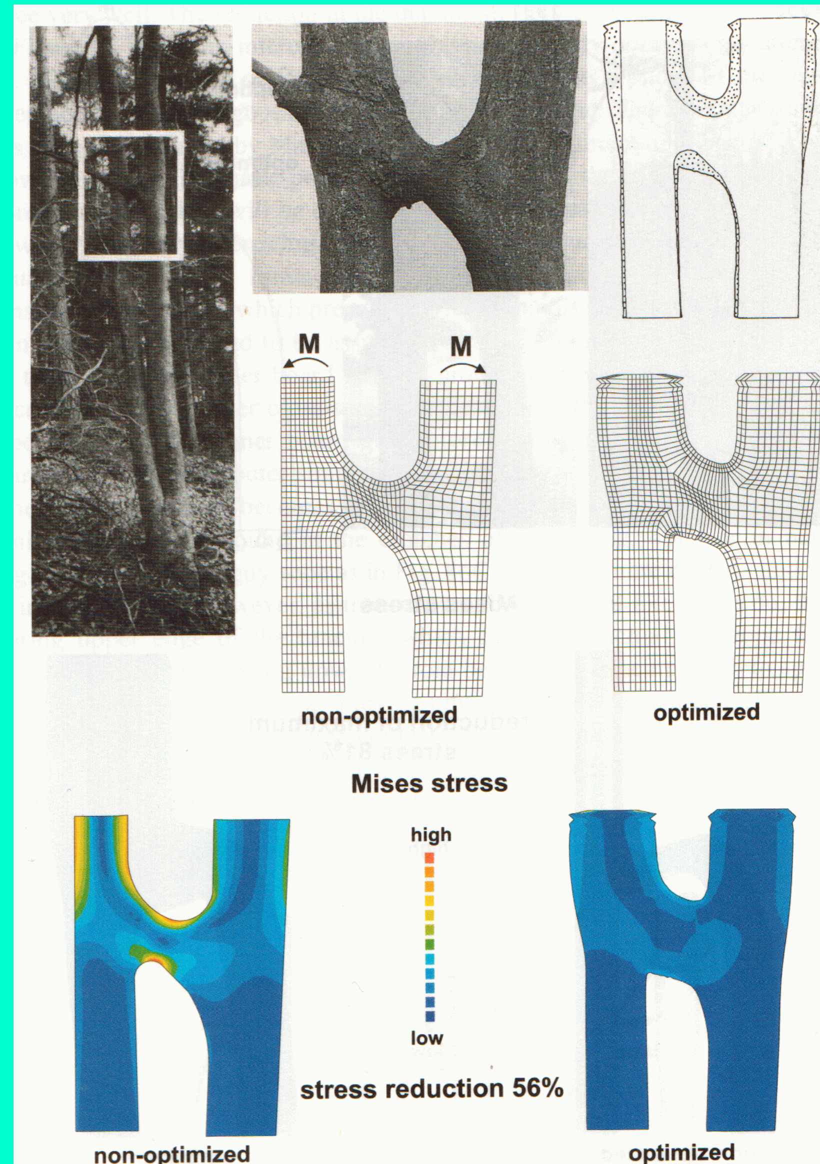
- The result will be a notch without notch stresses

  --> ‘Axiom of uniform stresses‘



Typical Notches found at Trees

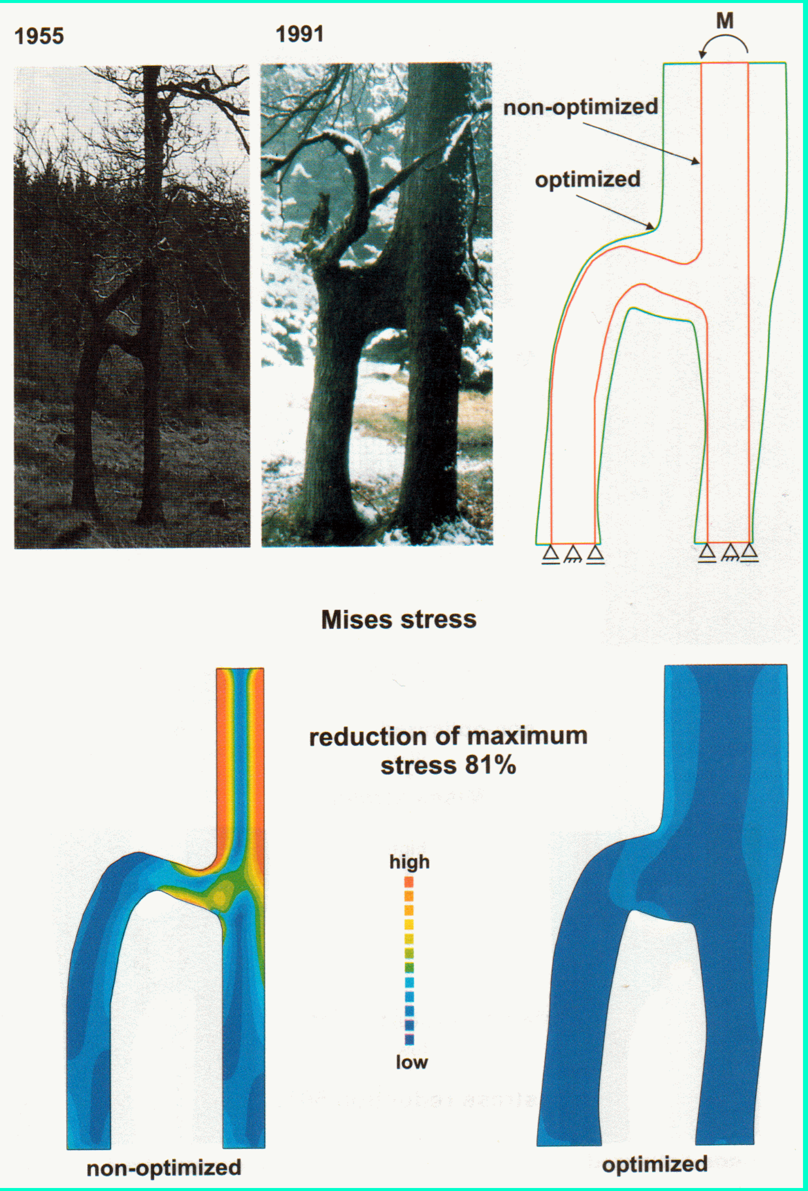




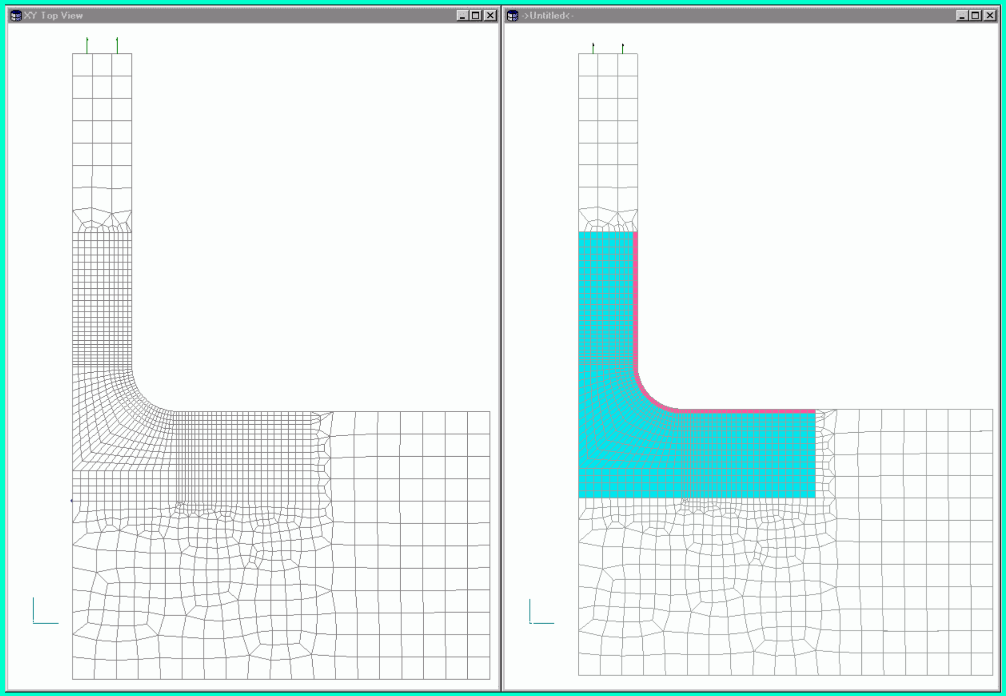
Typical Notches found at Trees

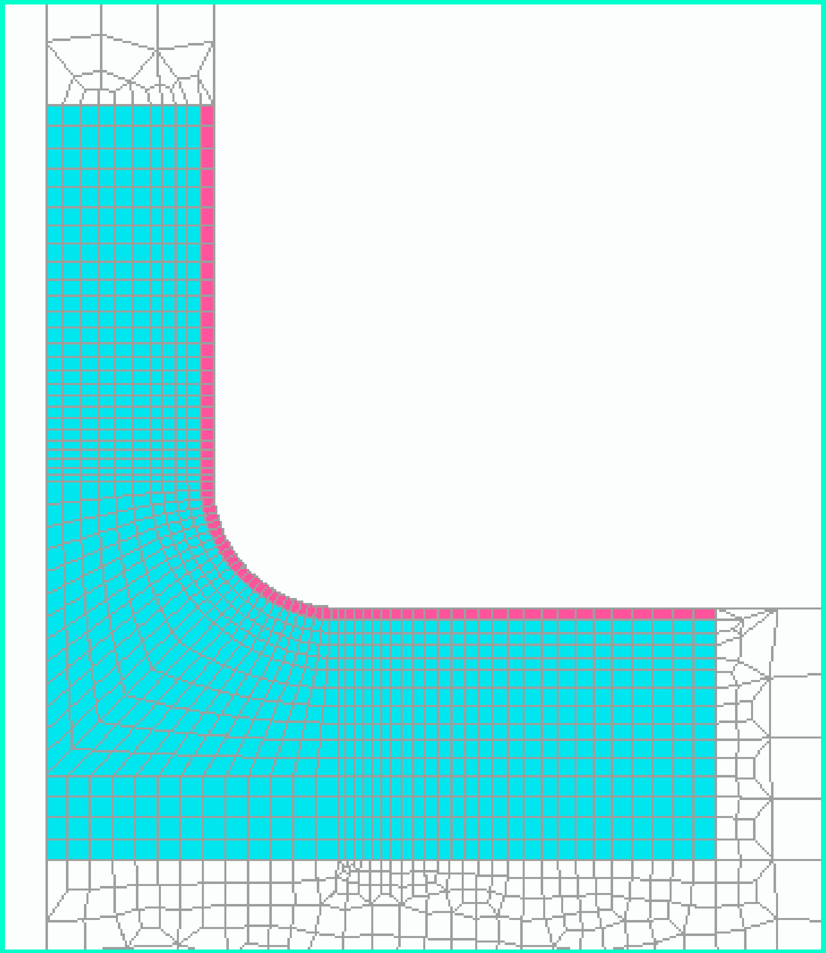
Comparison of the same tree over time

- 1955: after breakage of the trunk with stress peaks
- 1991: after 36 years of adaptation with uniform distribution along the contours



CAO Implementations



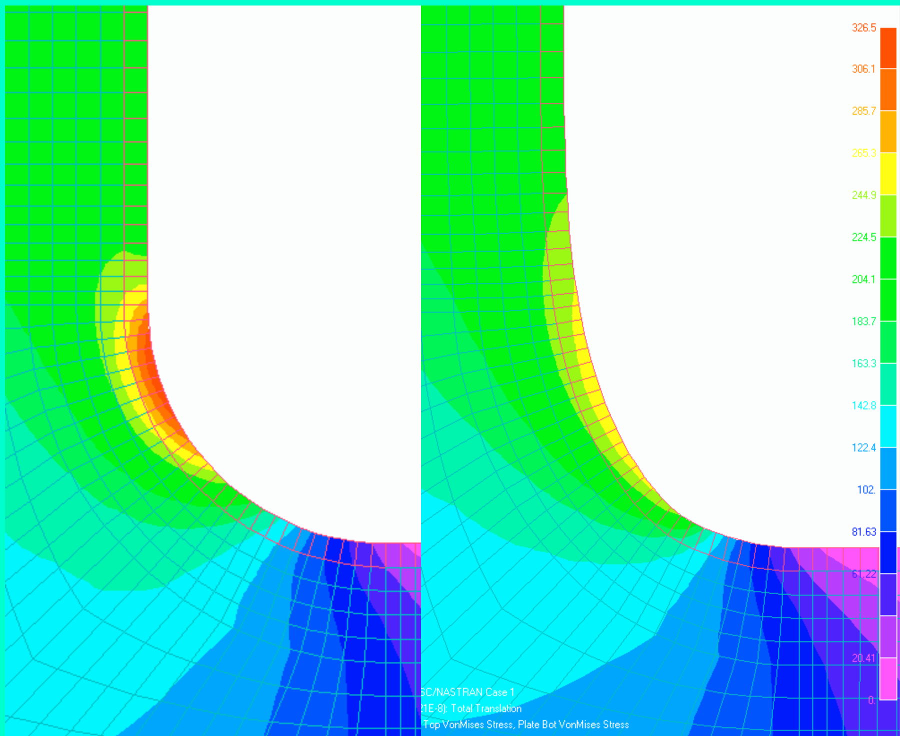


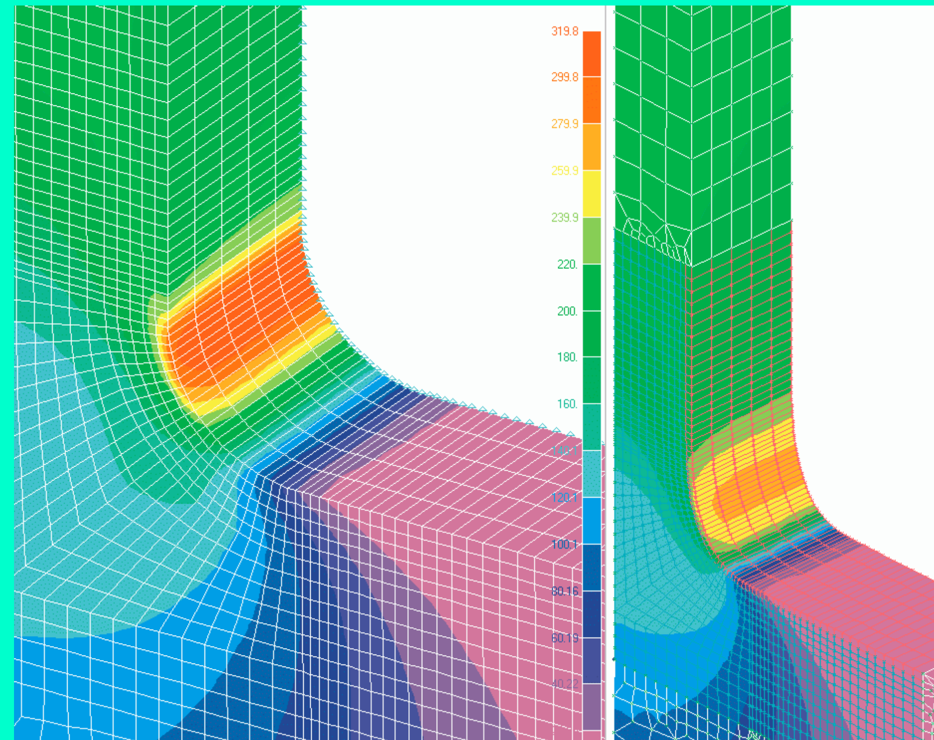
FEMAP Implementation :

Interactive Selection of
'Domain' Elements (blue&red) and
Cambium Elements (red)

'Domain' Elements get coordinate updates (--> mesh quality),
Cambium Elements will be the ones to grow (heated) on the surface

CAO Implementations

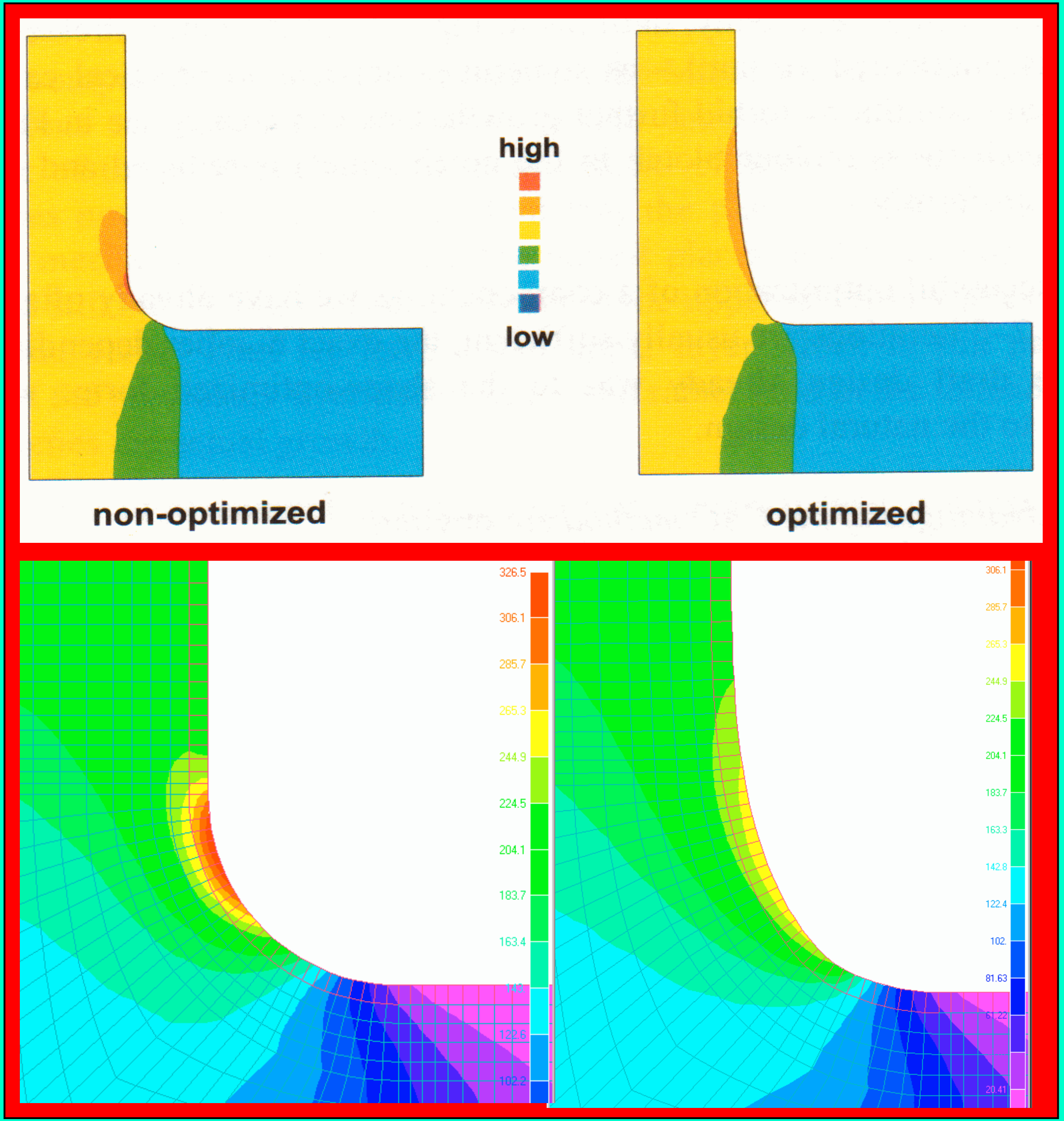




The general application of the method is not limited to planar structures. CAO can be used in conjunction with all types of Finite Elements. Since triangular planar and 4 or 10 noded Tetraeder have poor performances in the representation of high stress gradients and the tendency to be stiffer than QUAD or Hex Elements they should be avoided in areas close to the notch.

CAO Implementations

Mattheck:



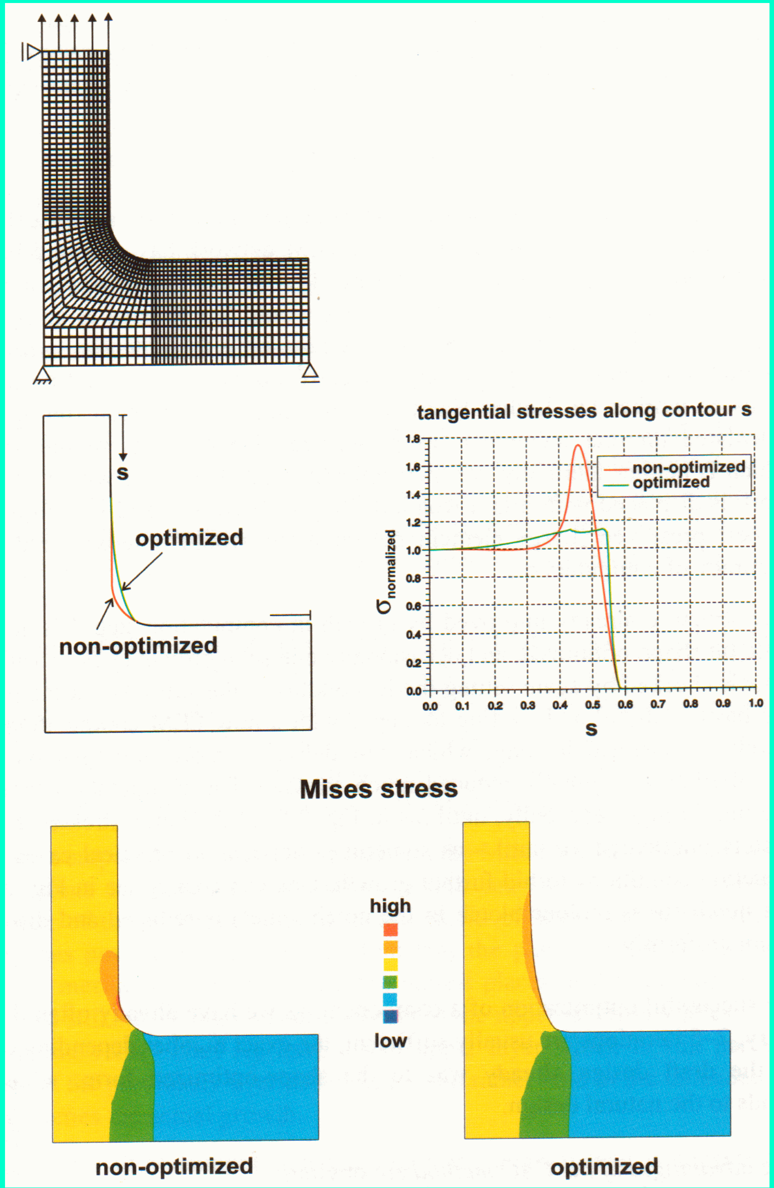
FEMAP/MSCN4W :

Change in vonMises stress from 326,5 N/mm^2 to 261,3 N/mm^2 (20% reduction) over only 3 iterations.

CAO Applications

Application of the CAO to a Mechanical Component

- Tension plate with a quarter circle as the initial design
- Shape Optimization will lead to a non-predictable irregular shape with almost uniform stresses along the notch

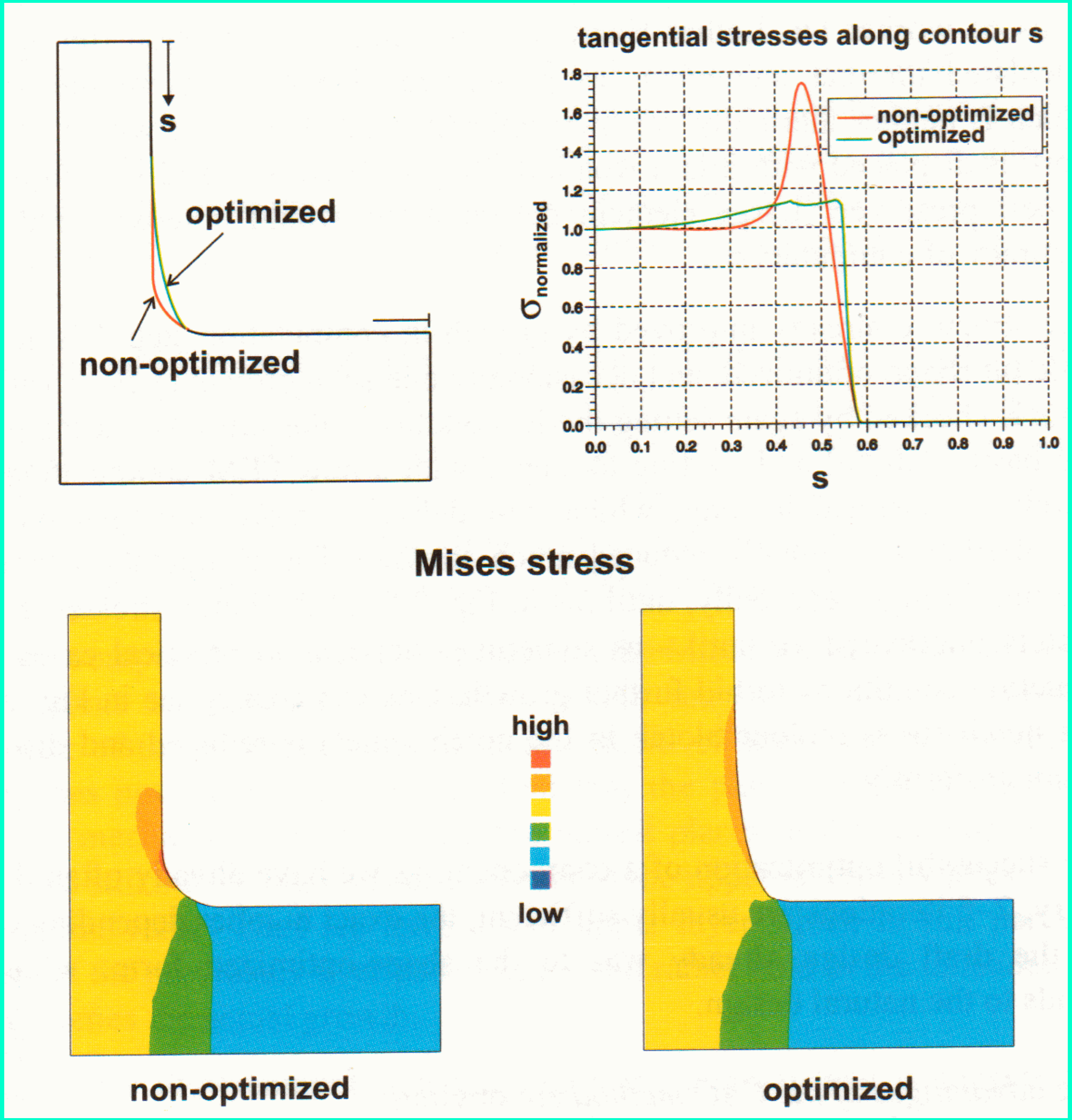


CAO Applications

‘Smoothing‘ of the stresses has direct impact on the durability of a structure.

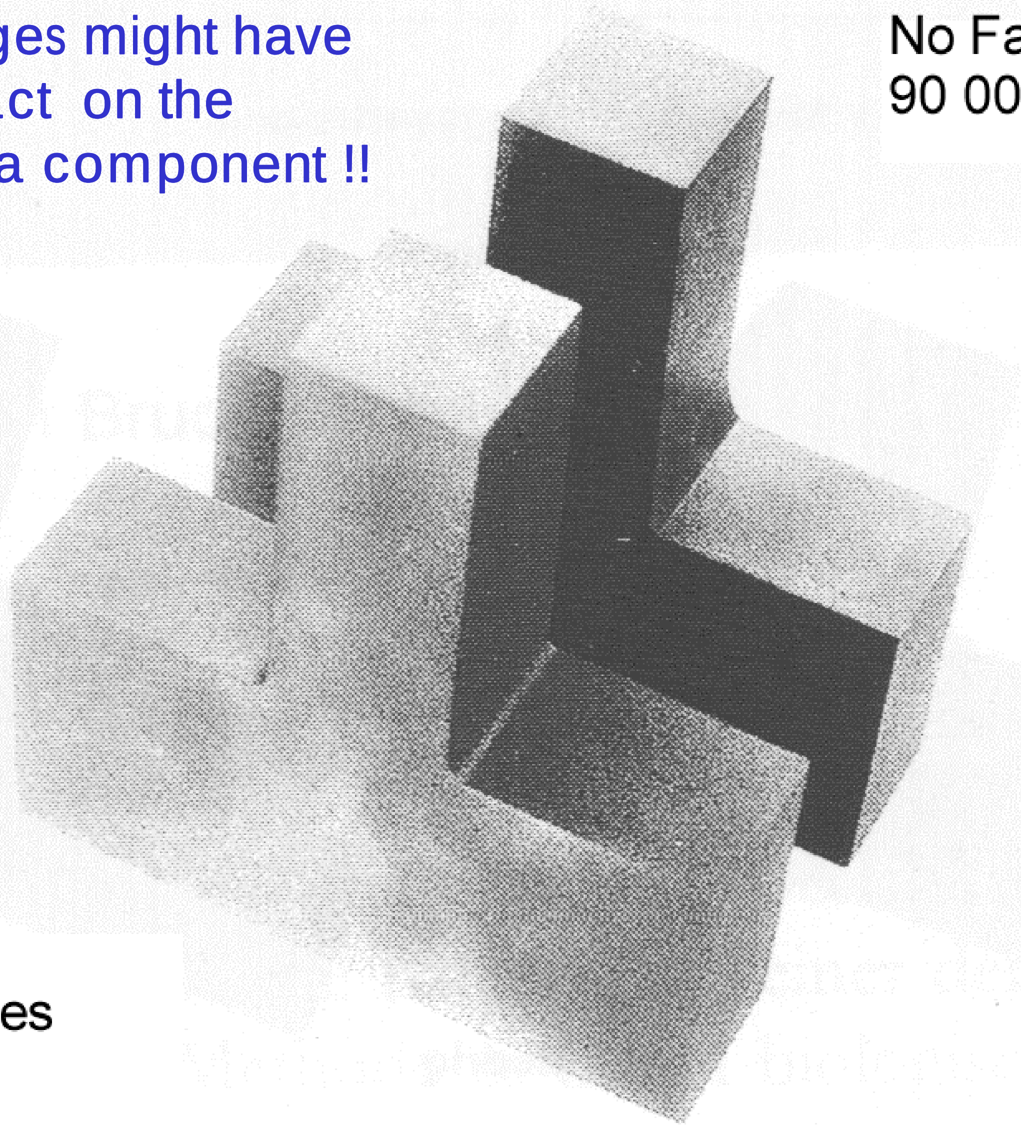
High stress gradients and sudden changes in the direction of the principal stresses play a major role in the fatigue analysis.

A decrease in the stress ratio from 1.7/1 to 1.1/1 may increase the durability by a factor of 30 or more.

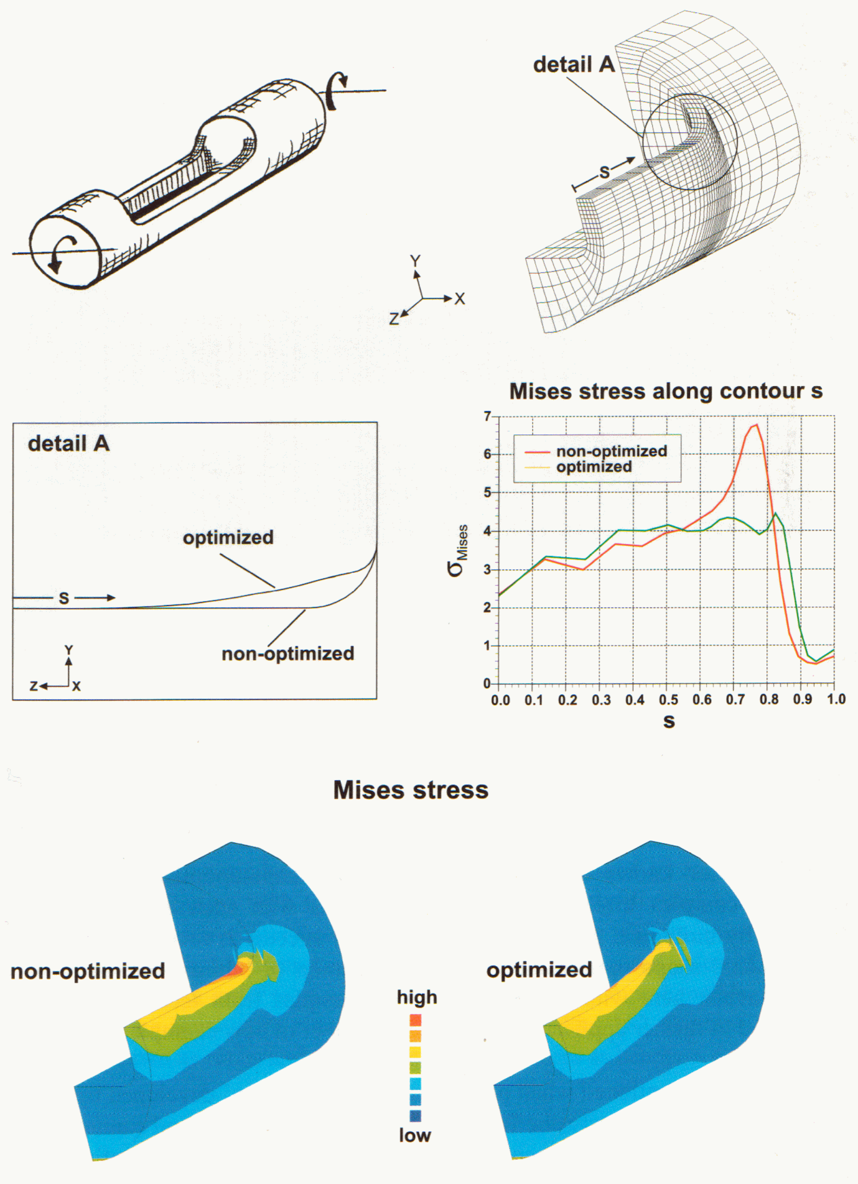


CAO Applications

--> small changes might have a high impact on the durabilty of a component !!



CAO Applications

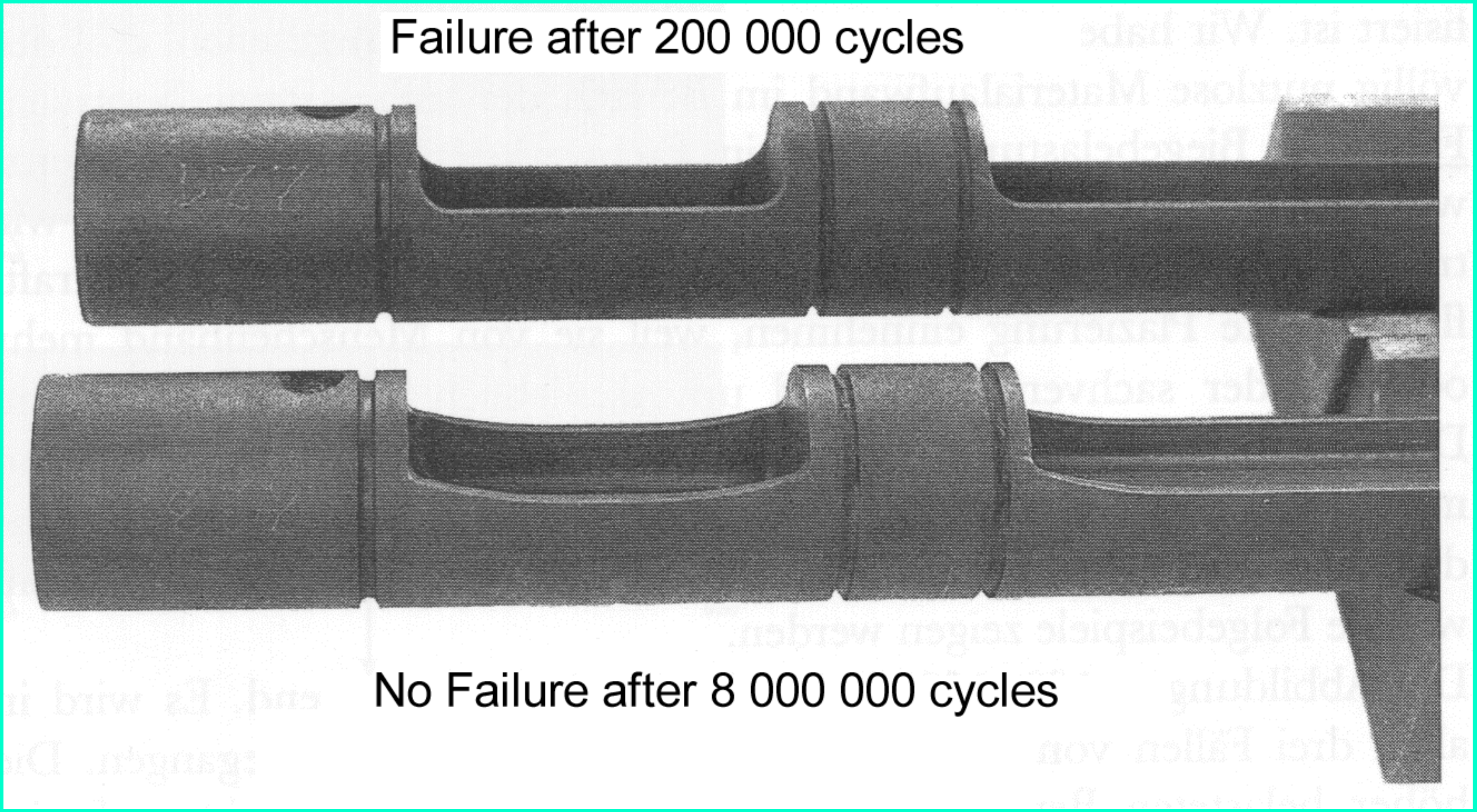


Mechanical Component (Shaft) under Bending

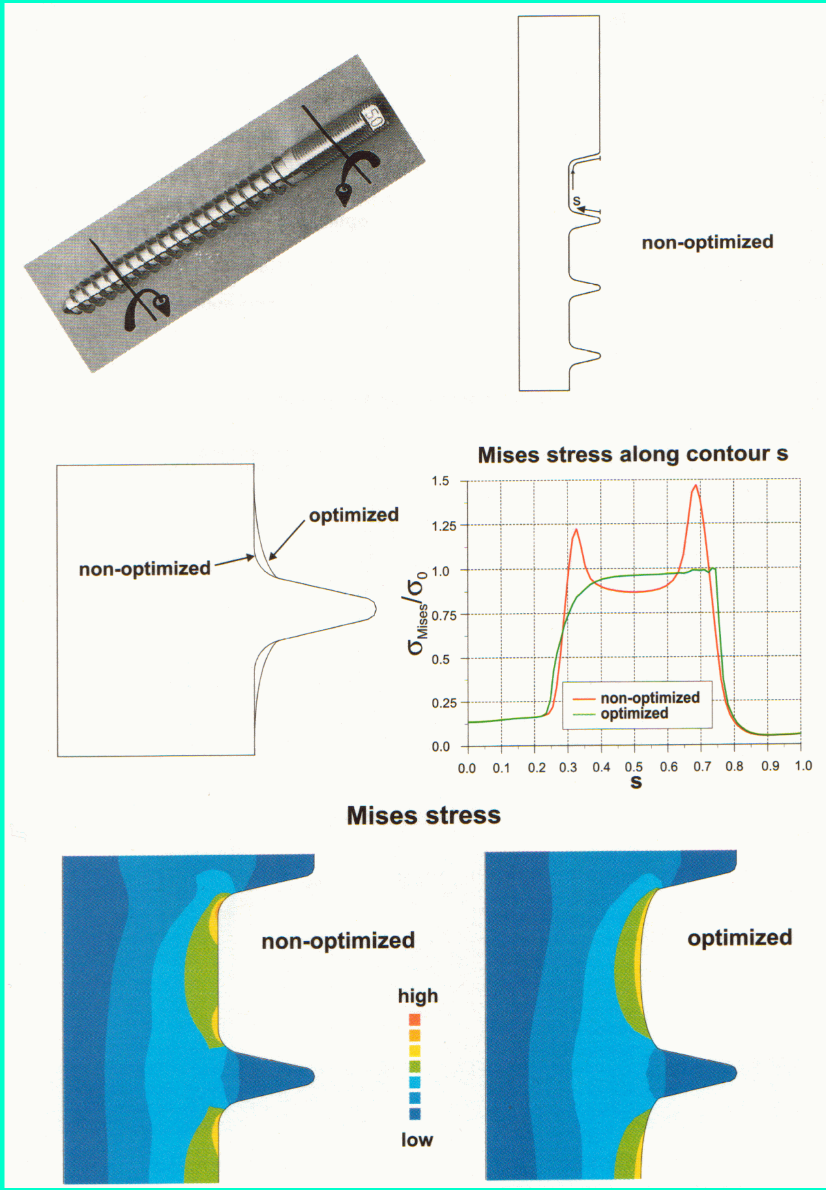
Decrease in stress along the contour from 6.8/1 to 4.4/1 will result in a significant increase (40x) in durability.

CAO Applications

--> minor modification in the contour of a part might lead to a significant increase of the durability of a component !!



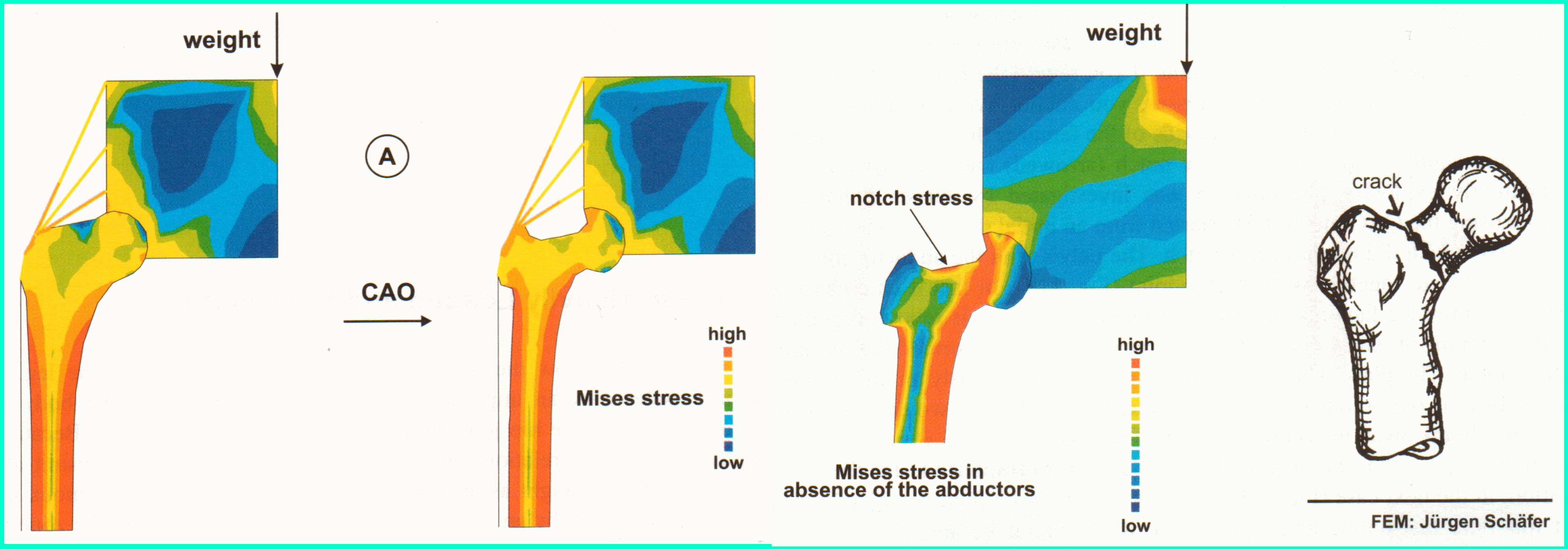
CAO Applications



Orthopaedic screw

Using a simplified planar discretization of the screw to optimize the thread.

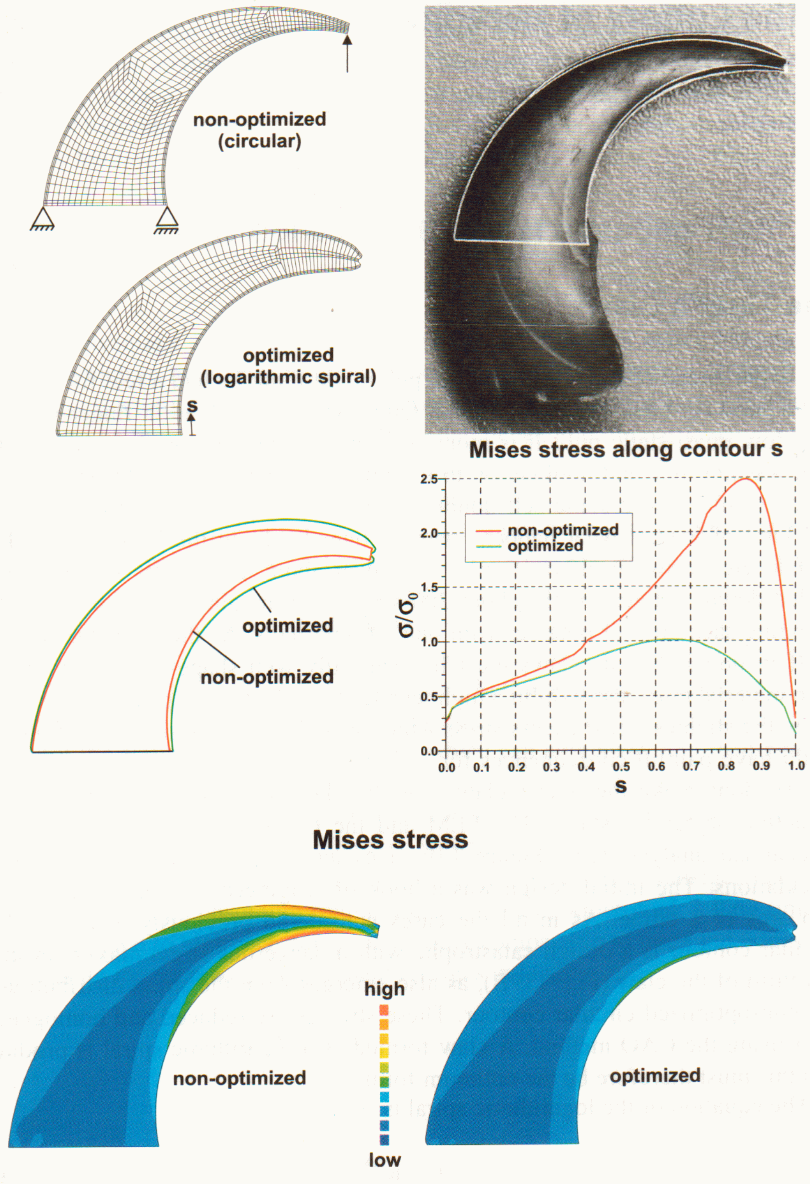
CAO Applications



Effect of abductor muscles on the shape of the neck of the femur

Discretizing the major elements of a human hip joint and using the CAO method will lead to a prediction of the shape of the neck of the femur which is close to the ones found in the human body. In the absence of the abductor muscles the stress distribution changes significantly and a crack might occur.

CAO Applications



Tiger's Claw

Not only trees will adapt their biological growth to the most frequent situations. Horns, thorns, claws and others follow the same priciples.
In the end they all tend to obey the 'Axiom of constant stress'.

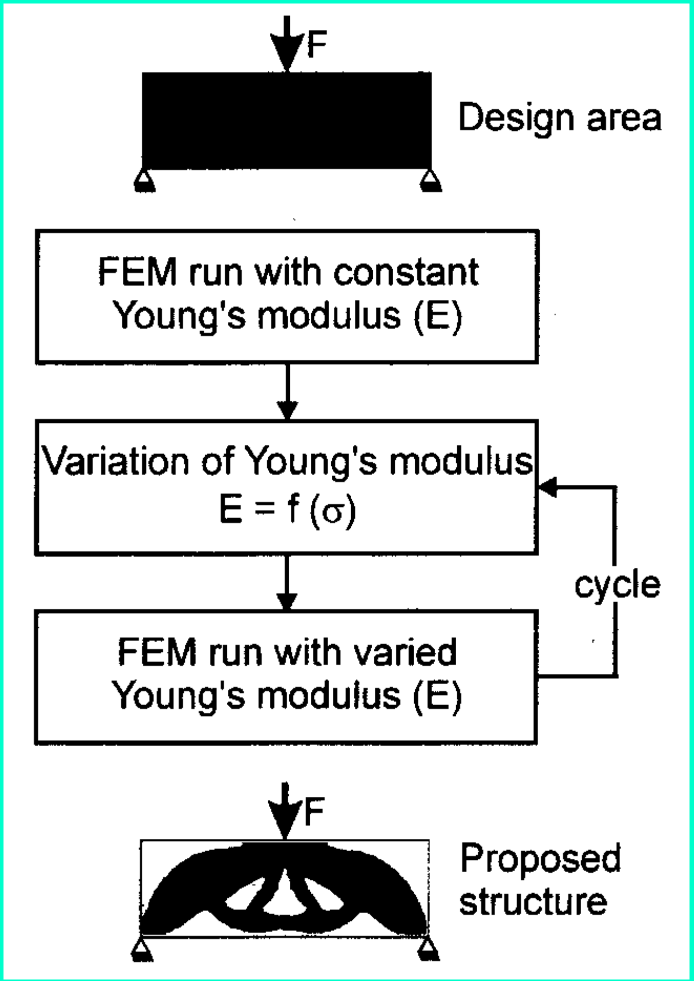
Topology Optimization
- Soft Kill Option (SKO)

Away with the Ballast !

In order to apply the CAO method the analyst has to have a proposal for the initial design.

But how do you know in general which areas in a given design space have to be preferably used for the design ?

The idea now is to eliminate elements that do not contribute much to the load bearing. In addition to the elimination, elements bearing much load get a reward for their contribution by strengthening them and the ‘lazy‘ ones will be punished by weakening. The effect is, that fewer but stronger elements bear more and more load, where the ‘lazy‘ elements withdraw themselfs more and more from the structure.

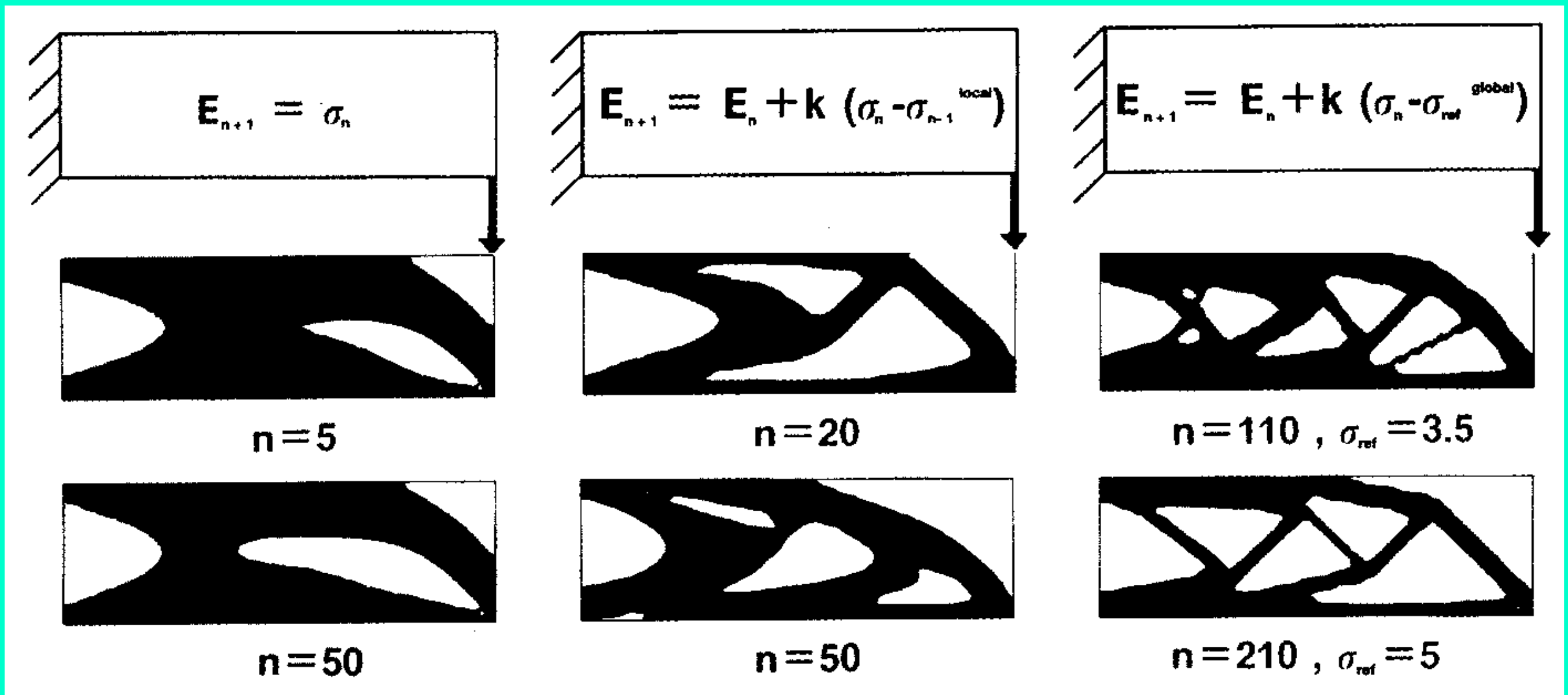


Topology Optimization (SKO)

SKO variants

The process of giving each element a Young's modulus in reference to the magnitude of stress in that element can be performed in different ways.

The Stress Method determines the Young's modulus directly proportional to the element stress. The Local Increment Method refers to the element stress in the previous analysis of the same element, where the Global Increment Method refers to a globally defined reference stress.

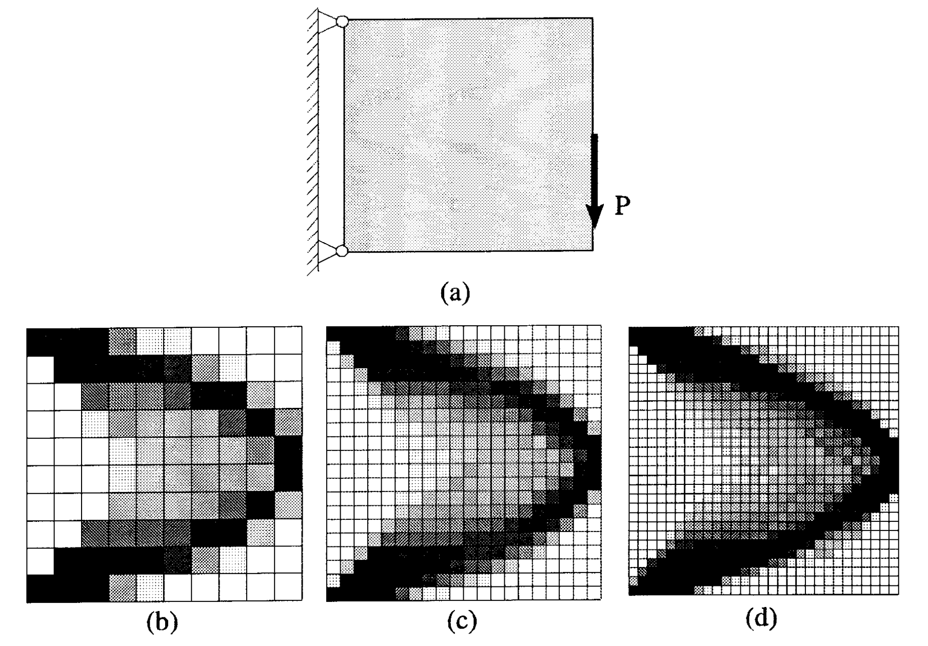


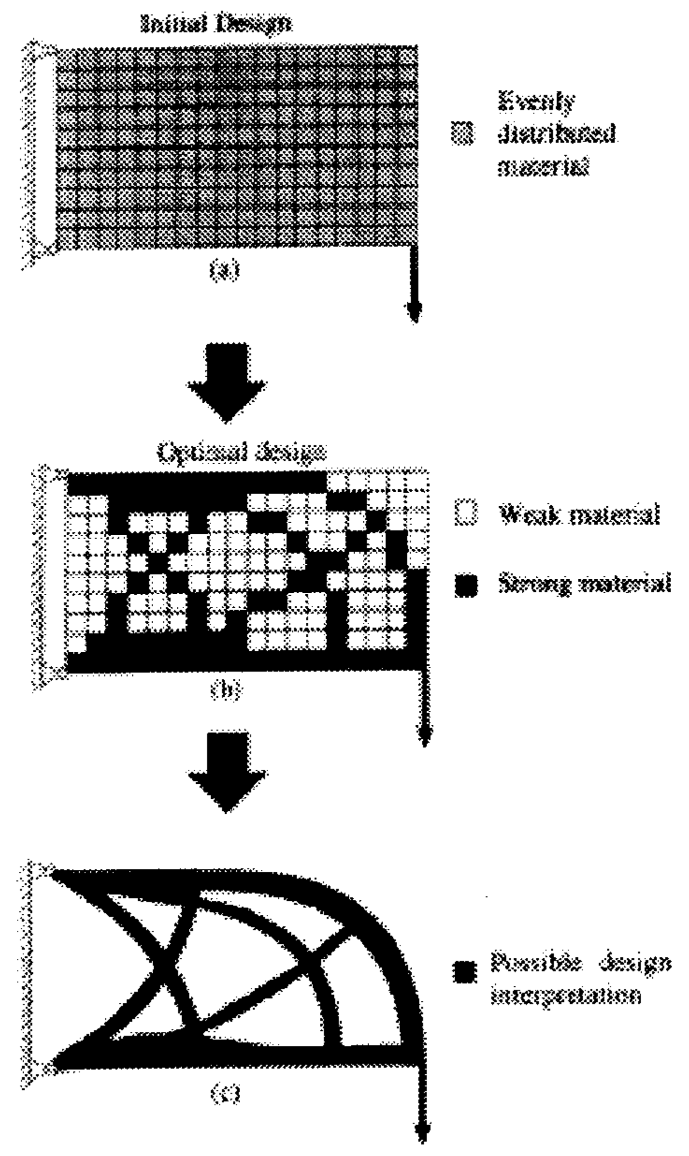
Topology Optimization (SKO)

Considerations

Since the SKO Method is based on elements, the size is of influence to the results obtained.

General 'Load Path's' can be achieved using a coarse mesh, where a finer mesh is able to give more detailed information.

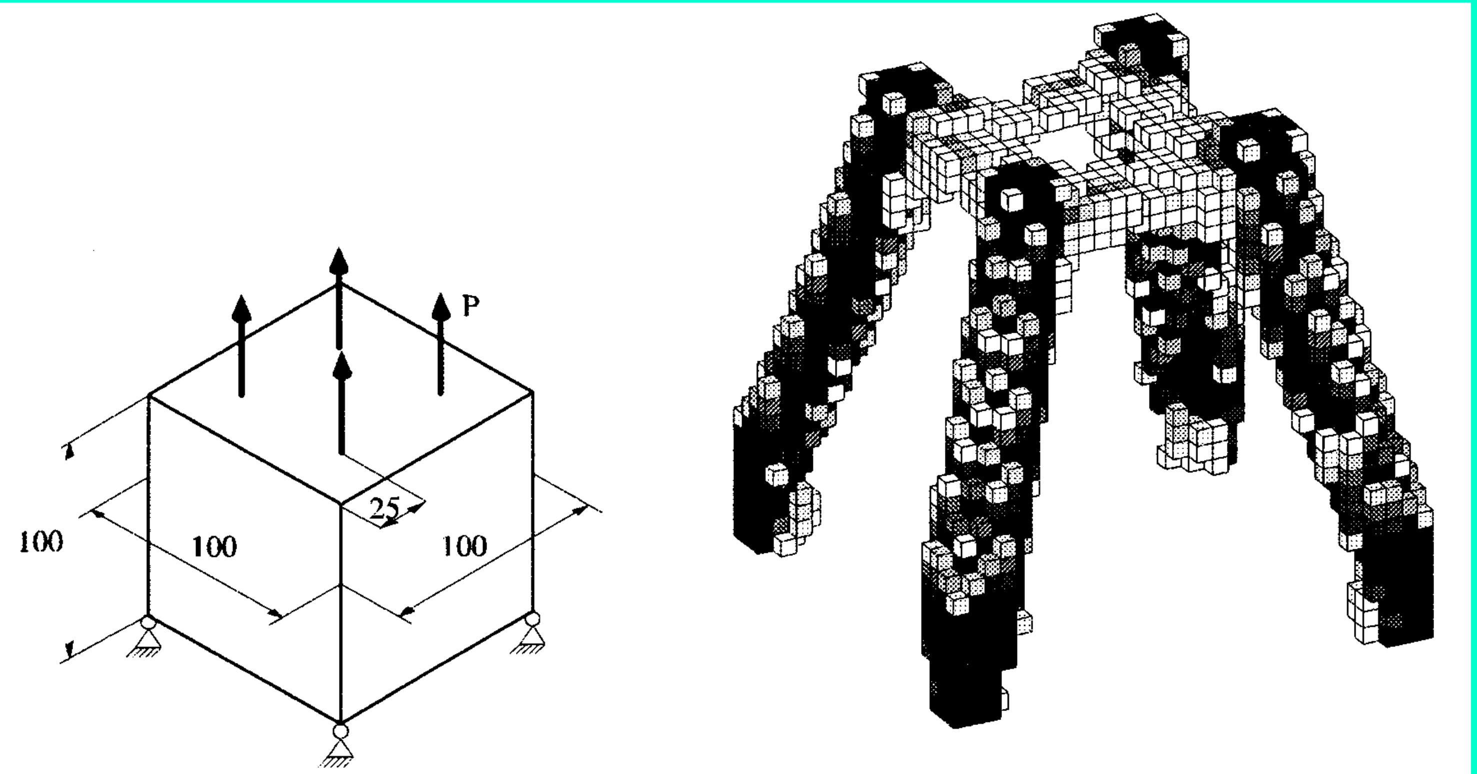




SKO Implementations

Example

From a publication the following test example was taken to explain the SKO method. The result shown in (b) was not achieved using SKO but another Design Sensitivity approach for Topological Design.

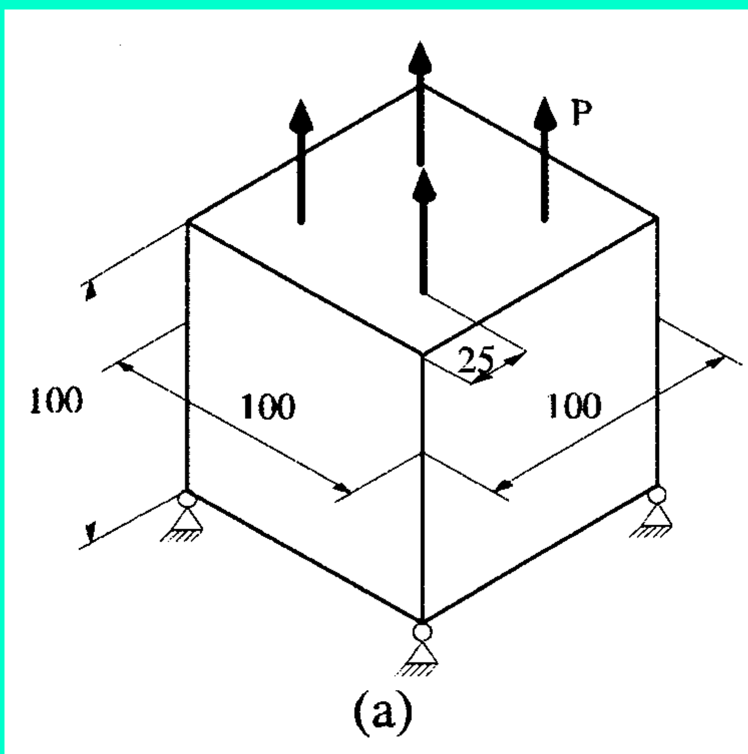


(a) (b)

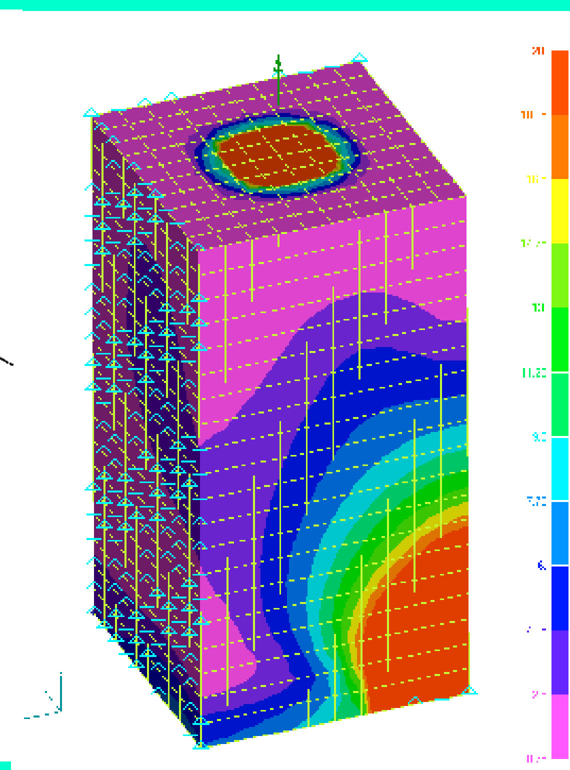
SKO Implementations

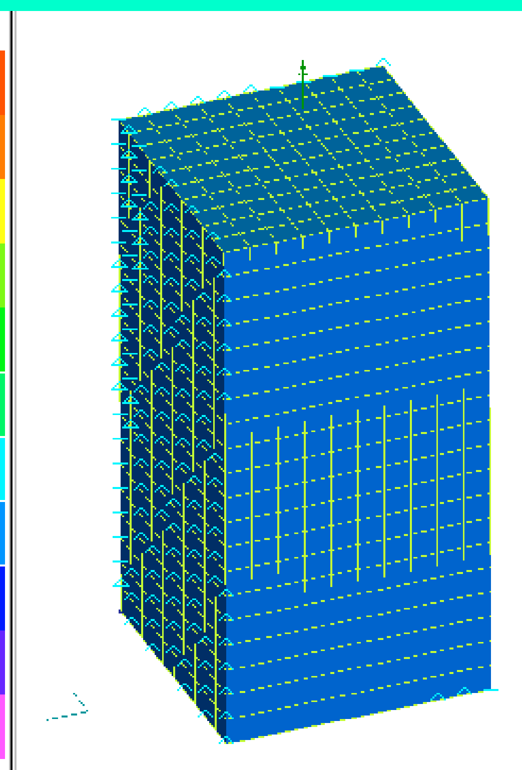
FEMAP Implementation

Using the double symmetry of the cube only a quarter was modelled.
Adequate boundary conditions for this symmetry were chosen.
Only the support conditions at the bottom were changed in a way that one support is horizontally fixed and tension members are needed.



(a)

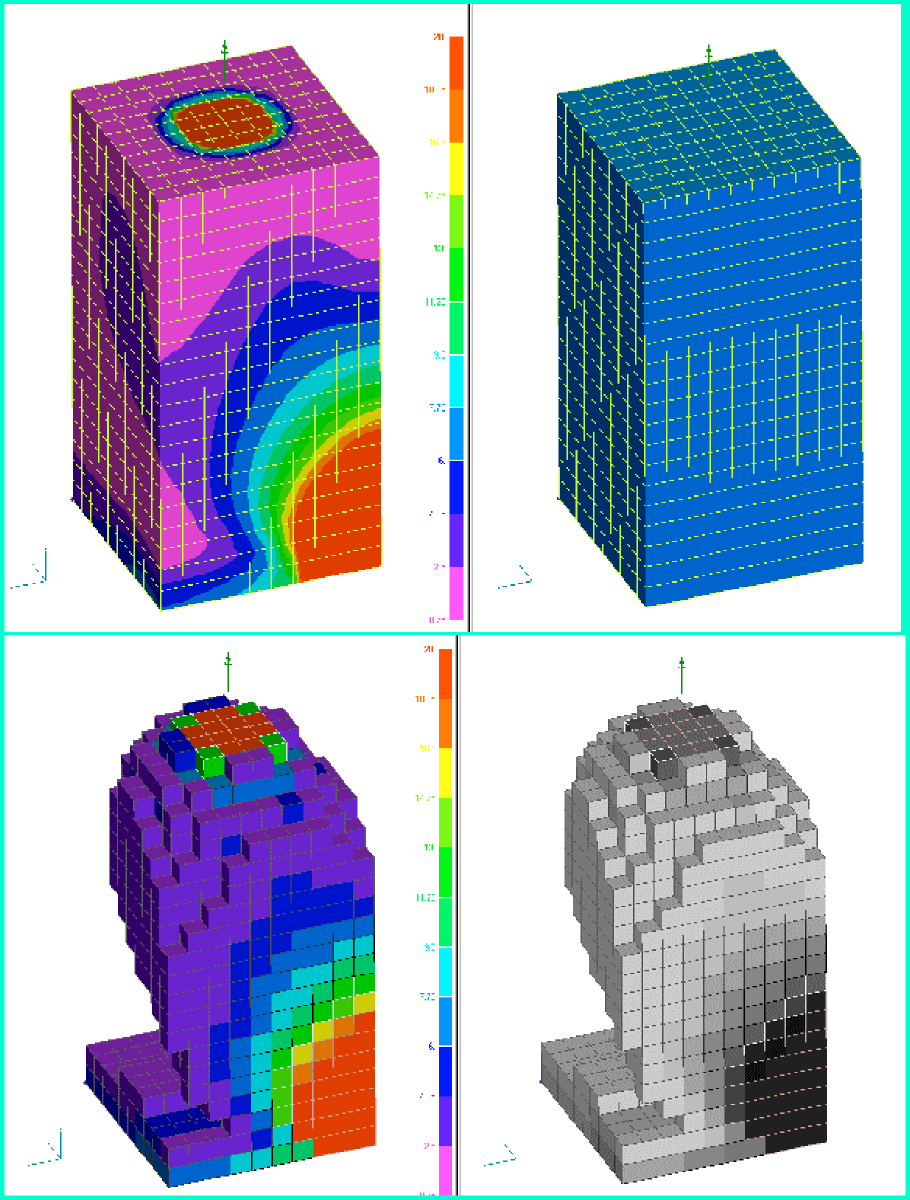




SKO Implementations

Soft Kill Option - 1st Step

The upper figure shows the initial situation where the red and orange elements have high stress and the purple ones have low stress.



The lower figure now shows the same structure after all purple elements have been removed.

The shades of grey show the distribution of the Young's modulus. The darker the colour the stronger the material.

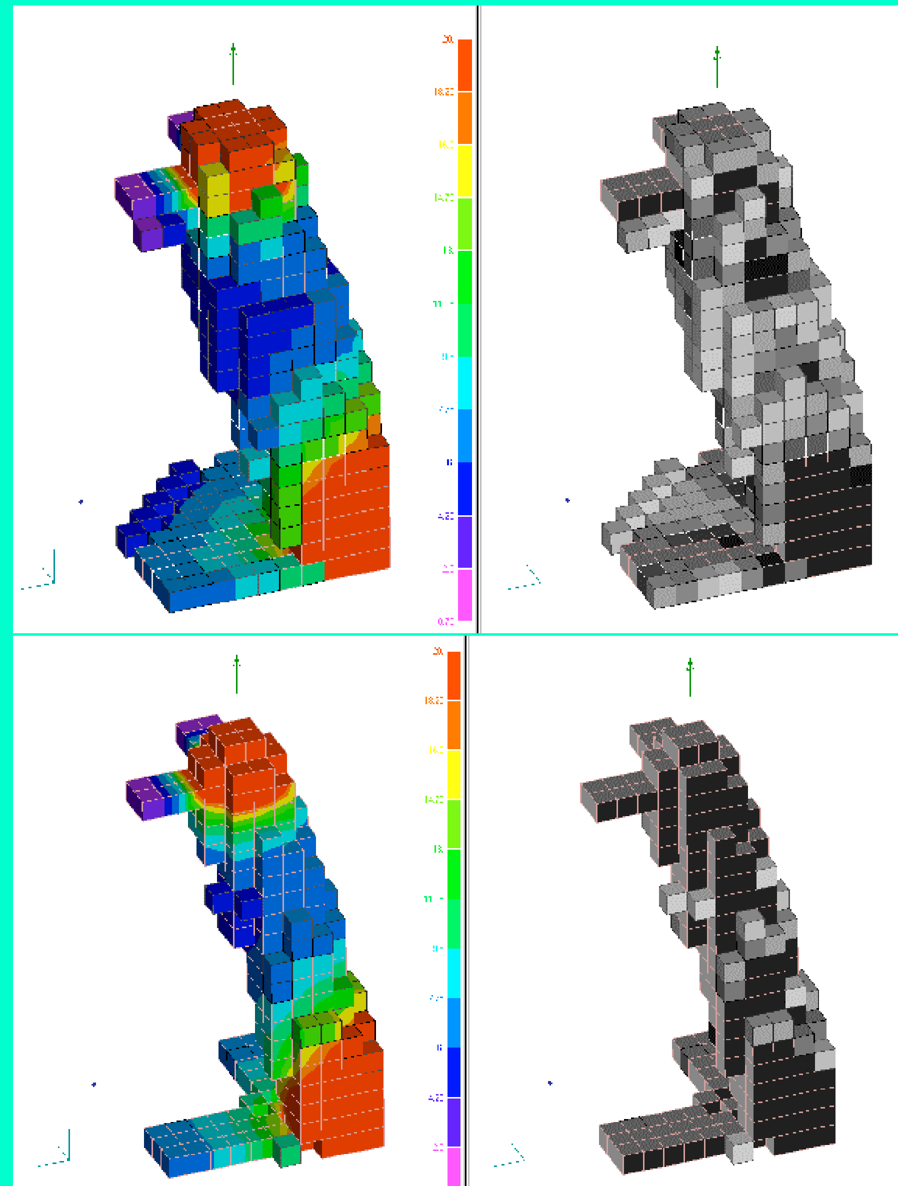
SKO Implementations

Soft Kill Option - 5th Step

A diagonal tension member is now clearly visible. For the necessary equilibrium some kind of base plate is active on the bottom. The material distribution still shows many weak elements (grey).

Soft Kill Option - 8th Step

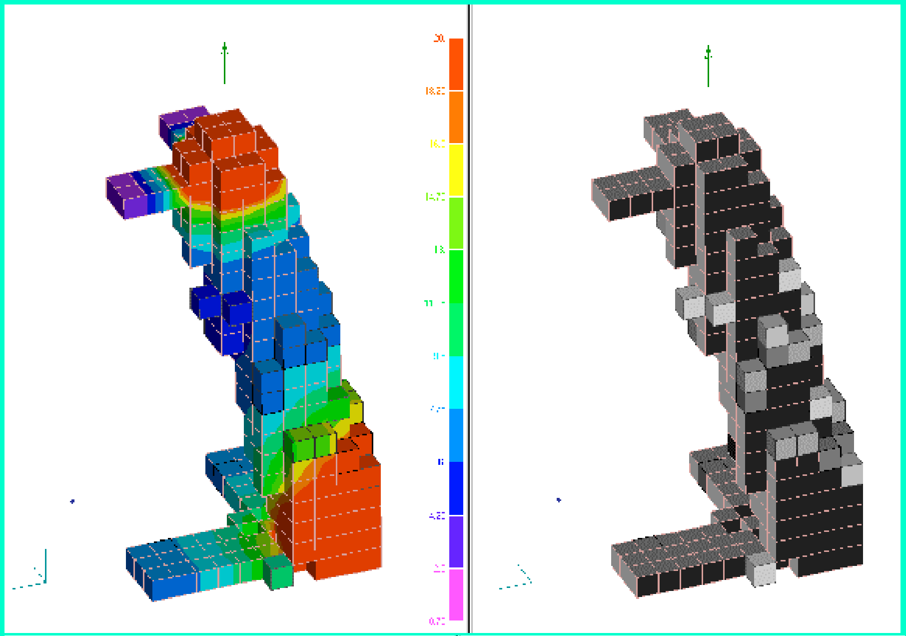
The load path in the structure is now clearly visible. The base plate has now been transformed to a high strength compression member.



SKO Implementations

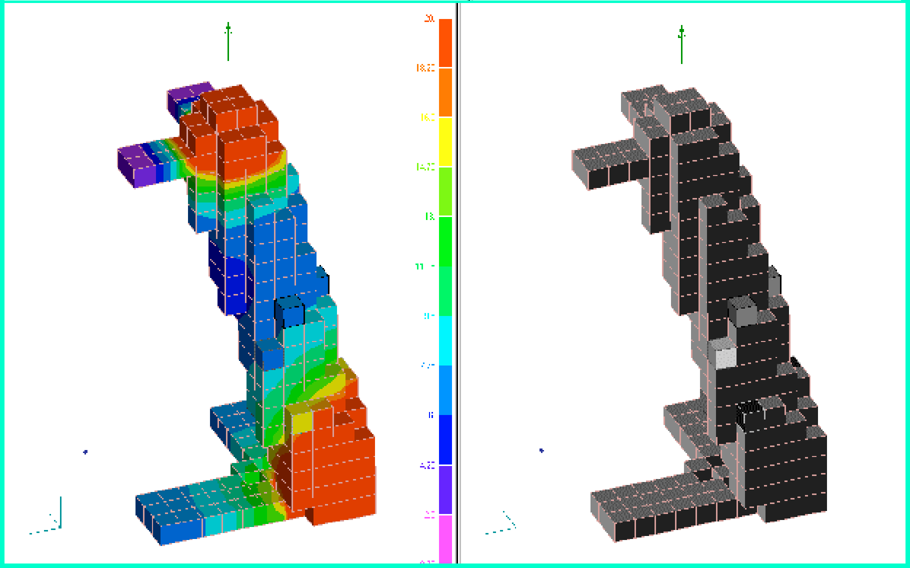
Soft Kill Option - 8th Step

Since there are now many elements removed a split of elements for refinement would be possible.
If a 'No Show' option is used instead of an elimination one could even reactivate deleted elements.



Soft Kill Option - 12th Step

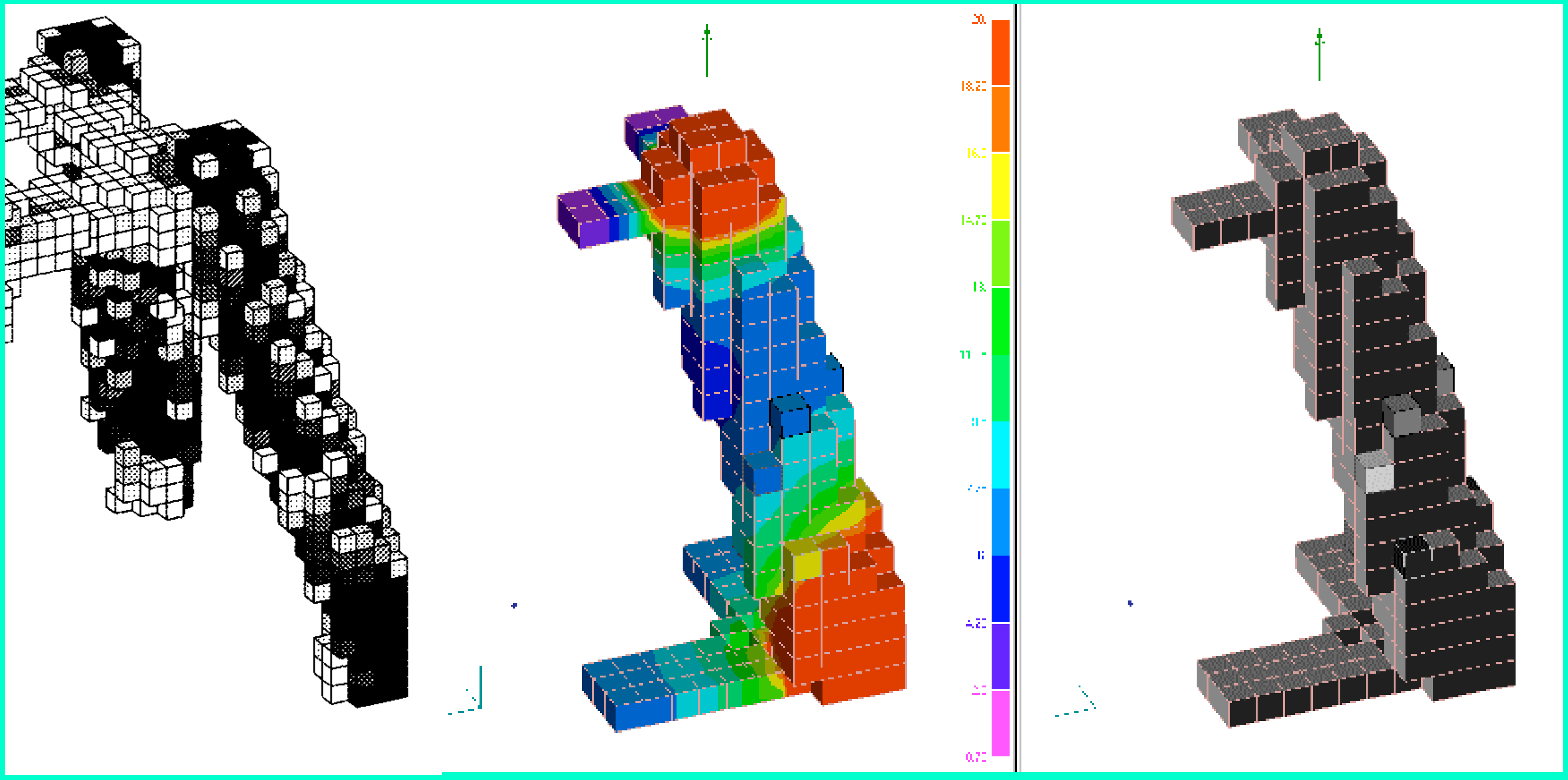
As can easily be seen, not many elements have been removed between the 8th and 12th iteration step. About 80% of the material was removed and evenly distributed.



SKO Implementations

Results

Comparing the results achieved by Design Sensitivity using far more elements and the solution obtained within 12 steps of iteration using the SKO approach obviously leads to the same essential results.



Topology Optimization

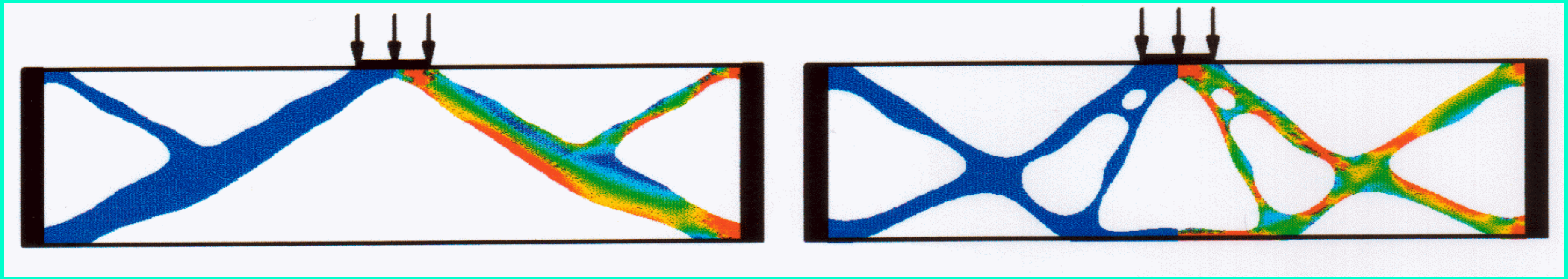
References

There have been extensive contributions recently, covering many aspects and improvements for topological optimization.

One interesting aspect is the use of elastoplastic materials.

It has been successfully shown that the methods can be extended so that not only a specific stress will not be yielded but also that plastification can be accounted for, giving even further information on the optimal design.

Redistributions can be obtained and in combination with stability and deviation of properties a reliable design can be obtained.



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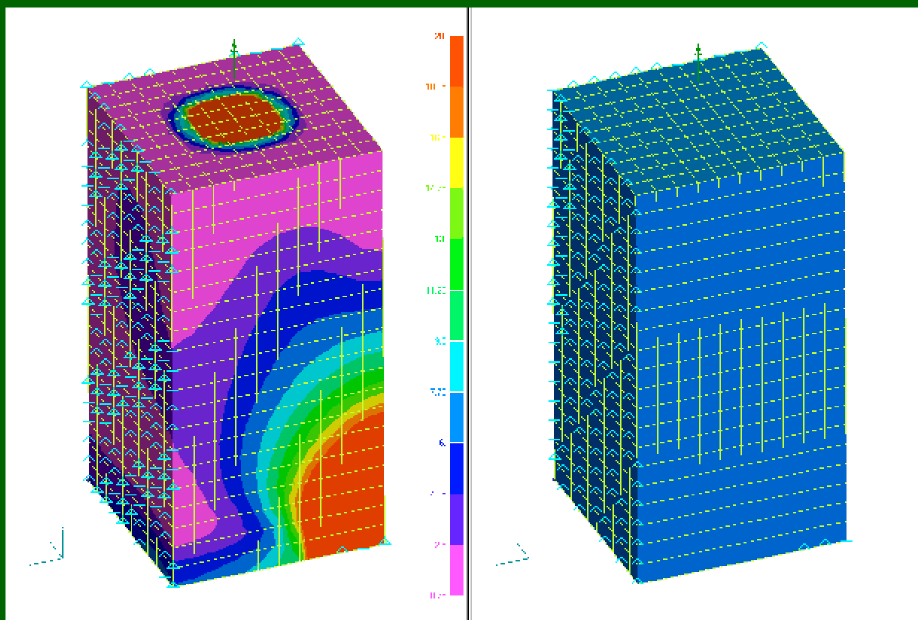

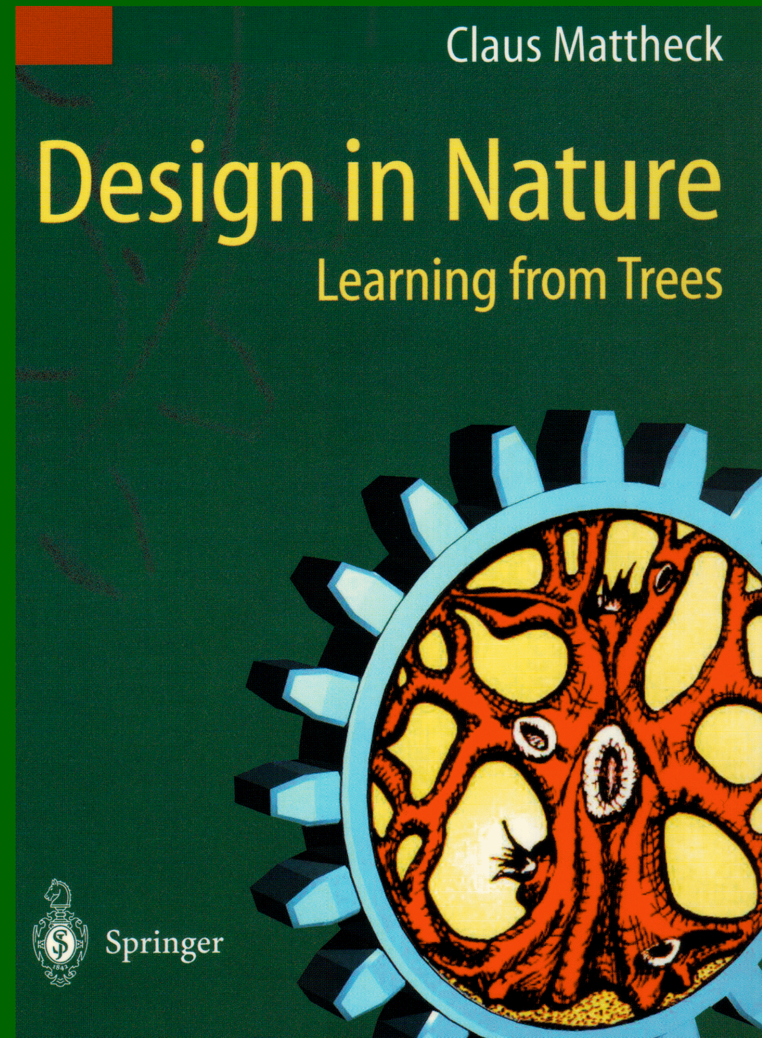

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