Bio-Inspired Optimization Based on Biological Growth Method and Mesh Morphing Surface Sculpting

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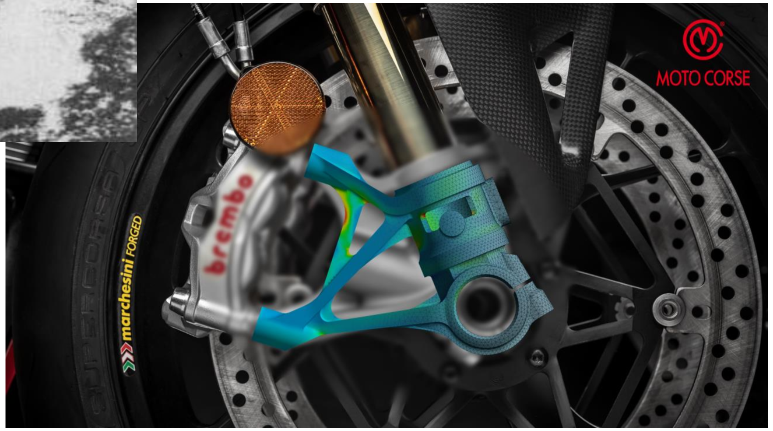
Outline

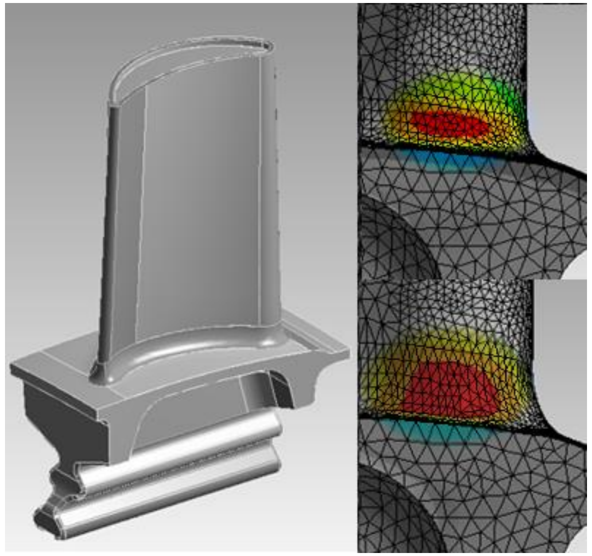
- Introduction
- Radial Basis Functions (RBF) Background
- Biological Growth Method (BGM) Background
- RBF and BGM Coupling
- Biological Application: **a tree trunk**
- Industrial Application: **Ducati Panigale V4** front wheel support
- Conclusions
- Acknowledgements

$$s(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i \cdot \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right\|\right)$$



Introduction and motivation

- **Optimization** techniques are gaining a high importance in design and manufacturing of new products
- Numerical simulations, as Finite Element Method (FEM), allow engineers to **virtually test different configurations**
- Nevertheless, research of an **optimal configuration** can be time-consuming and techniques to automate both model generation and configuration optimization are requested
- **Mesh morphing** is an innovative technique that allow to reduce time needed to obtain a new configuration of a numerical model by simply applying shape modification to the model mesh



Introduction and motivation

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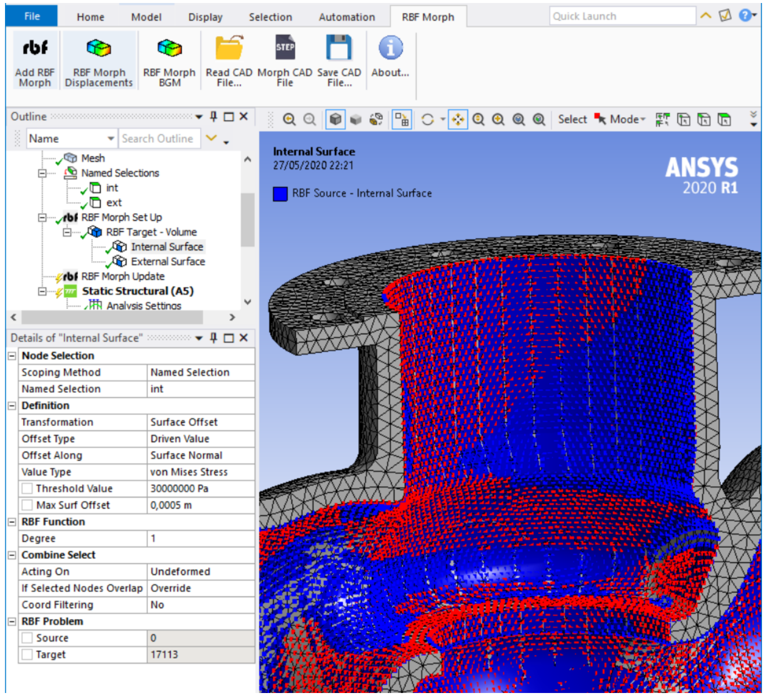

- **Mesh Morphing** can be driven using several approaches, one of the most promising is the Biological Growth Method (BGM)
- **BGM is inspired** by the way in which **natural tissues** react to a surface load, let the tissues to growth in order to reduce surface stresses
- BGM and Mesh Morphing can be **successfully coupled** to obtain a surface sculpting methodology which is effective in mechanical component optimization
- Methodology has been developed and is presented in the framework of **ANSYS Mechanical** Finite Element Analysis (FEA) tool using the **RBF Morph ACT** extension as mesh morpher

RBF Background

- Radial Basis Functions (RBF) are a mathematical tool capable to **interpolate** in a generic point of the space a function **known** in a discrete set of points (**source points**)
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

radial basis

polynomial

$$s(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i \varphi\left(\left\| \boldsymbol{x} - \boldsymbol{x}_{k_i} \right\| \right) + h(\boldsymbol{x})$$

distance from the i-th source point

RBF Background

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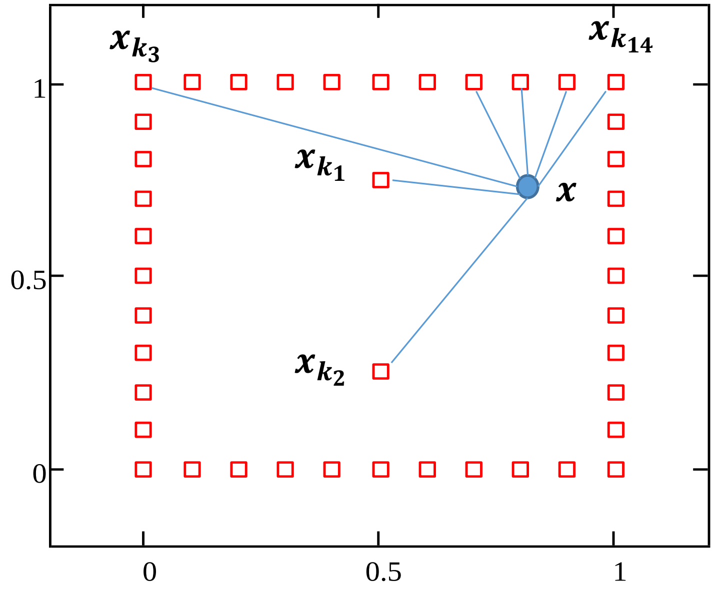
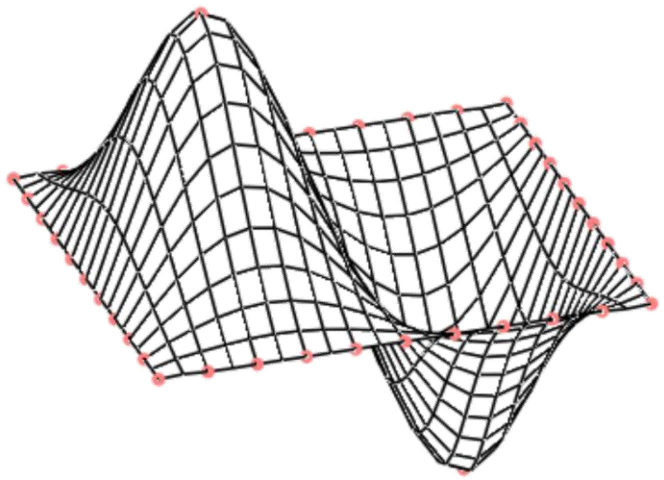




RBF Background

- If evaluated on the **source points**, the interpolating function gives exactly the input values

$$\begin{aligned} s(\boldsymbol{x}_{k_i}) &= g_i \\ h(\boldsymbol{x}_{k_i}) &= 0 \end{aligned} \qquad 1 \le i \le N$$

- The RBF problem (evaluation of coefficients γ and β) is associated to the solution of **the linear system**, in which **M** is the interpolation matrix, **P** is a constraint matrix, **g** is the vector of known values on the source points

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix} \quad M_{ij} = \varphi\left(\boldsymbol{x}_{k_i} - \boldsymbol{x}_{k_j}\right) \quad 1 \le i, j \le N \quad \mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

RBF Background

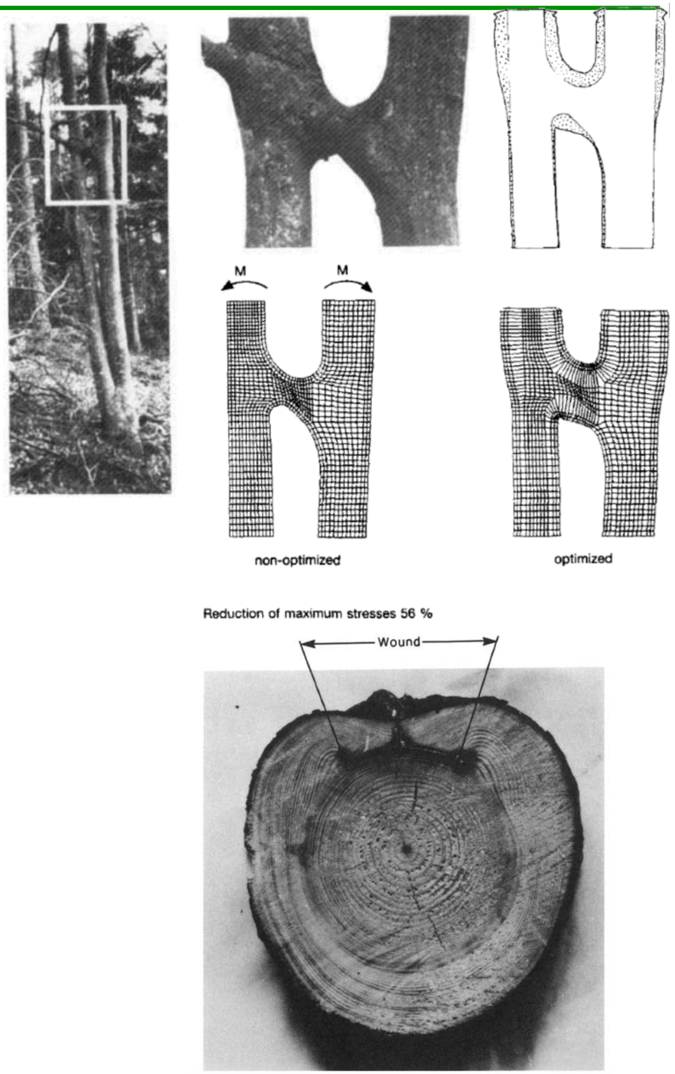
- Once solved the RBF problem each displacement component is interpolated to obtain the **displacement field**
- Several different **radial functions** (kernel) can be employed

$$\begin{cases} s_x(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\mathbf{x} - \mathbf{x}_{\mathbf{k}_i}\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\mathbf{x} - \mathbf{x}_{\mathbf{k}_i}\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\mathbf{x} - \mathbf{x}_{\mathbf{k}_i}\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

RBF	φ(r)	RBF	φ(r)
Spline type (Rn)	r^n, *n odd*	Inverse multiquadratic (IMQ)	$\frac{1}{\sqrt{1+r^2}}$
Thin plate spline	$r^n \log(r)$ *n even*	Inverse quadratic (IQ)	$\frac{1}{1+r^2}$
Multiquadratic (MQ)	$\sqrt{1+r^2}$	Gaussian (GS)	e^{-r^2}

BGM Background

- **BGM** approach is based on the observation that **biological** structures growth is driven by **local** level of **stress**.
- Bones and trees’ trunks are able to **adapt the shape** to mitigate the stress level due to external loads.
- The process is driven by stress **value at surfaces**. Material can be **added or removed** according to local values.
- Was proposed by Mattheck & Burkhardt in 1990*



*Mattheck C., Burkhardt S., 1990. A new method of structural shape optimization based on biological growth. Int. J. Fatigue 12(3):185-190.

BGM Background

- The BGM idea is that surface growth can be expressed as a **linear law** with respect to a given threshold value

$$\dot{\varepsilon} = k\left(\sigma_{Mises} - \sigma_{ref}\right)$$

- In this study we extend the concept and different **stress types** can be used to modify the surface shape

$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Stress/strain type	Stress/strain type
von Mises stress	Stress intensity
Maximum principal stress	Maximum Shear stress
Minimum principal stress	Eqv. plastic strain

RBF and BGM Coupling

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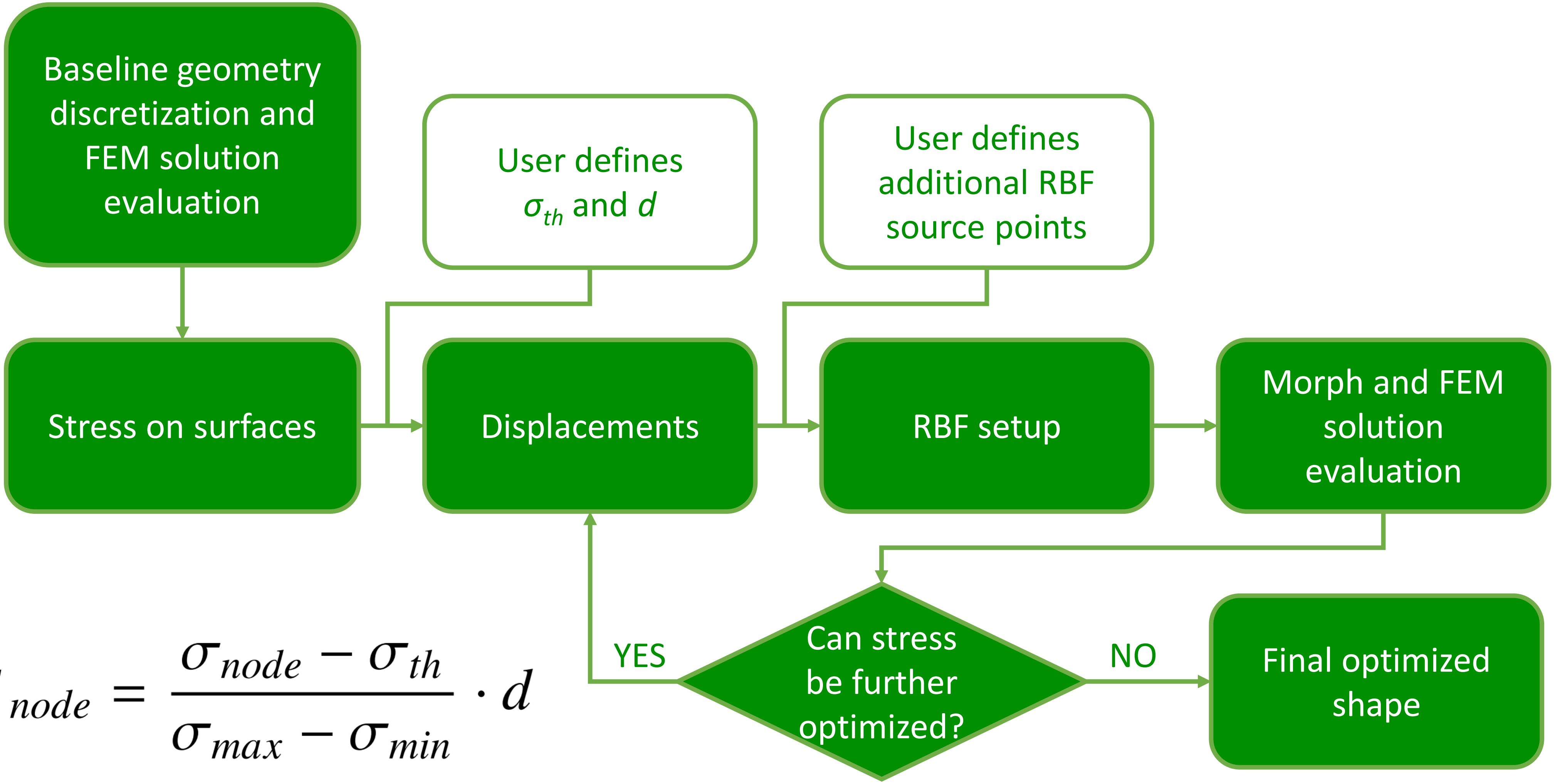
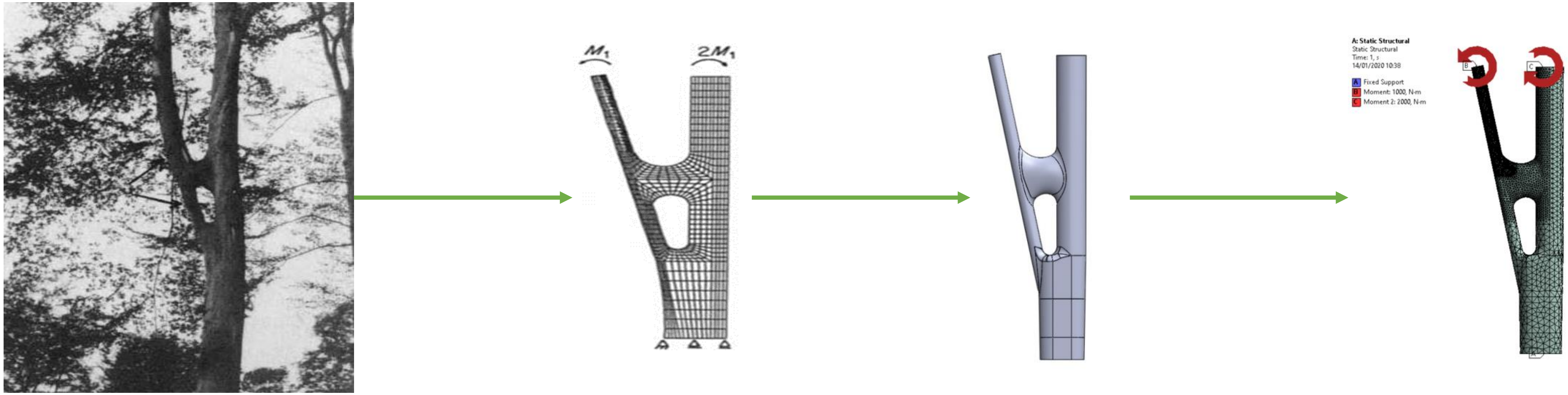


$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Biological Application

- Mattheck and Burkhardt application of BGM to a 2D biological case* has been replicated into a 3D case
- Same load and constraint condition of the 2D case have been translated into the 3D case



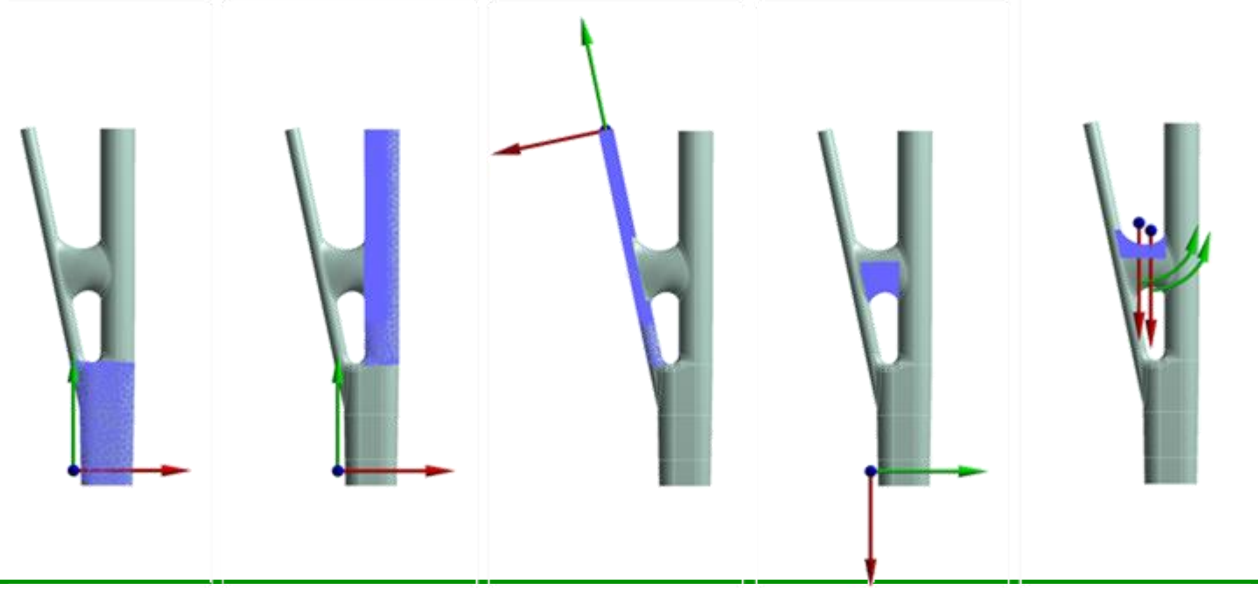
*Mattheck C., Burkhardt S., 1990. A new method of structural shape optimization based on biological growth. Int. J. Fatigue 12(3):185-190.

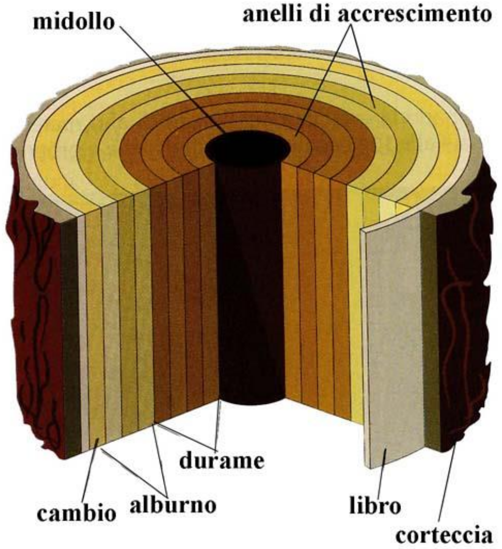
Biological Application

- Material was modeled using a **transverse isotropic** material

- 6 local coordinate systems were used to assign the **element orientation**

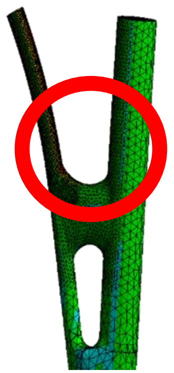
Elastic property	Value
E_x,E_z	1.000 $[GPa]$
E_y	11.520 $[GPa]$
G_{xy},G_{yz}	0.810 $[GPa]$
G_{xz}	0.355 $[GPa]$
ν_{xy}, ν_{zy}	0.0301 $[-]$
ν_{xz}, ν_{zx}	0.4080 $[-]$
ν_{yz}, ν_{yx}	0.3470 $[-]$

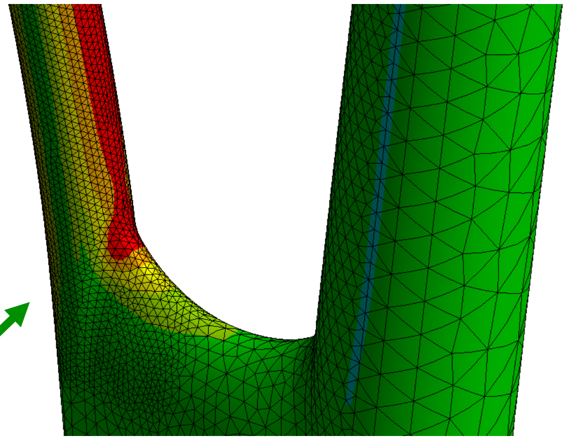




Biological Application

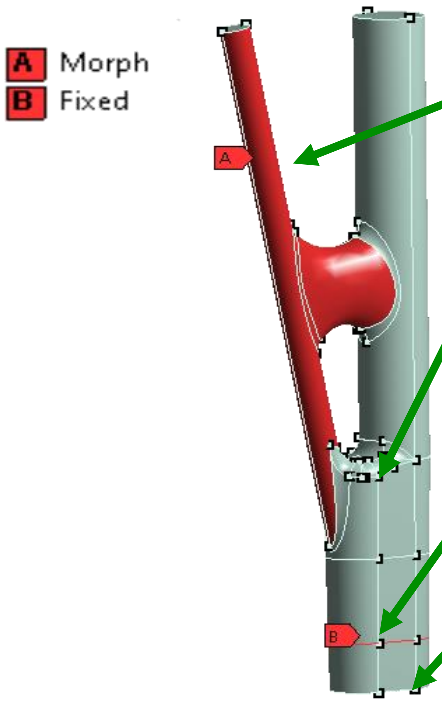
- Analyzing baseline **von Mises stress concentrations**, model surfaces on which apply Mesh Morphing action were identified





$\overline{\sigma_{VM}} = 1{,}749\ MPa$

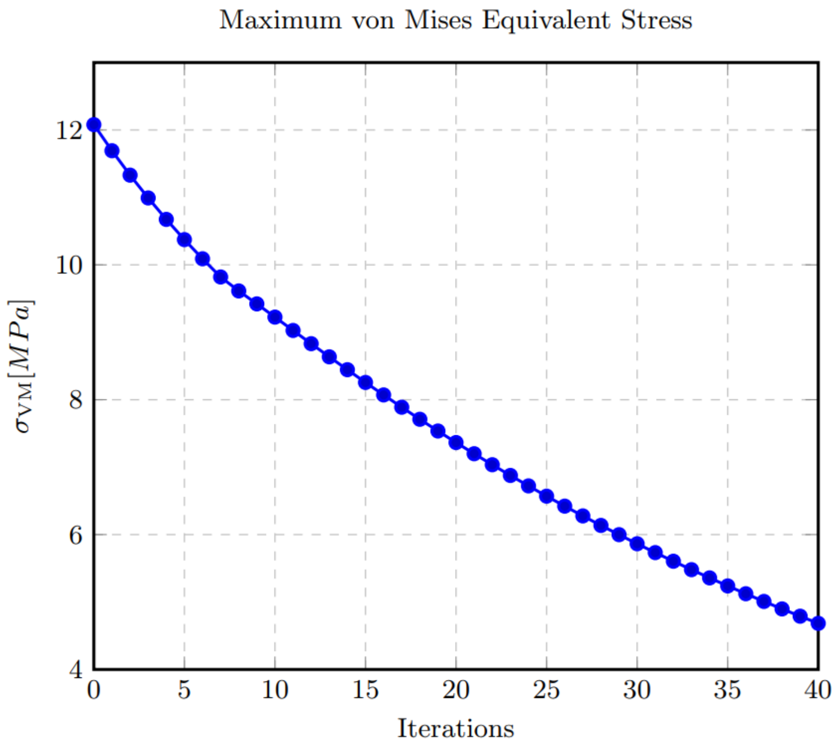
$\max \sigma_{VM} = 12{,}079\ MPa$

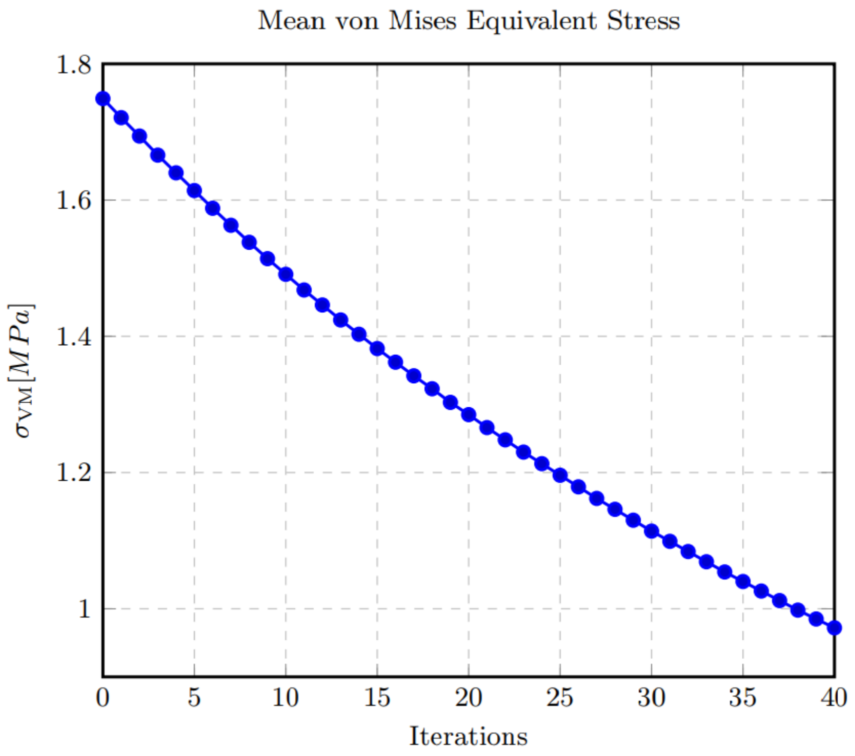


- Surfaces to be sculpted
- Buffer zone: mesh is free to deform accordingly to given set-up
- Fixed edges
- Mesh not influenced by morphing action

Biological Application

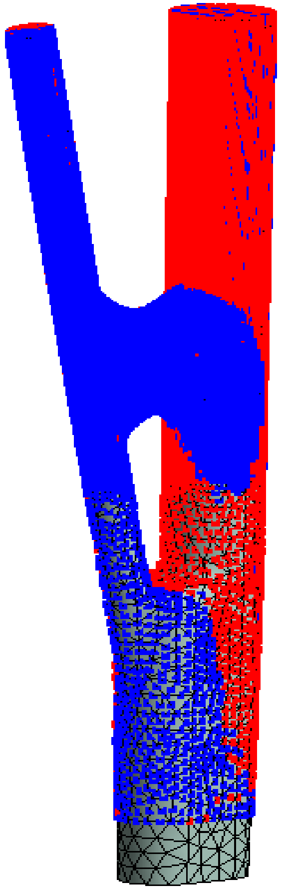
- 40 iterations of the BGM driven surface sculpting using Mesh Morphing have been performed, setting d parameter to 0.0005 m and σ_{th} parameter to 50000 Pa



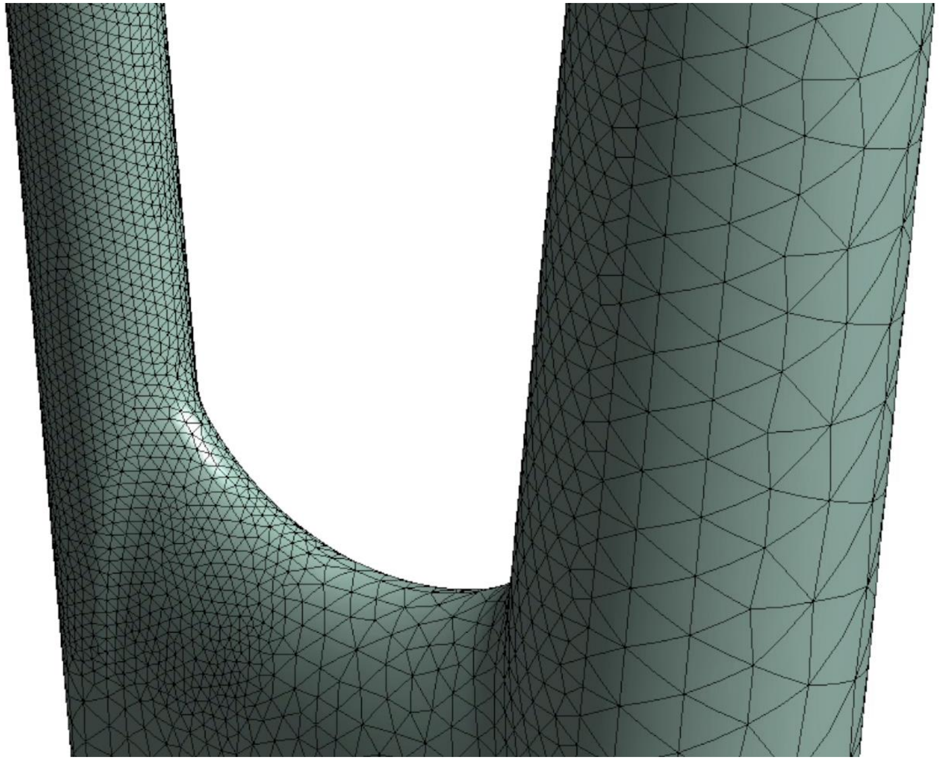


- Von Mises equivalent stress reduction: maximum -61%, mean -44%

Biological Application



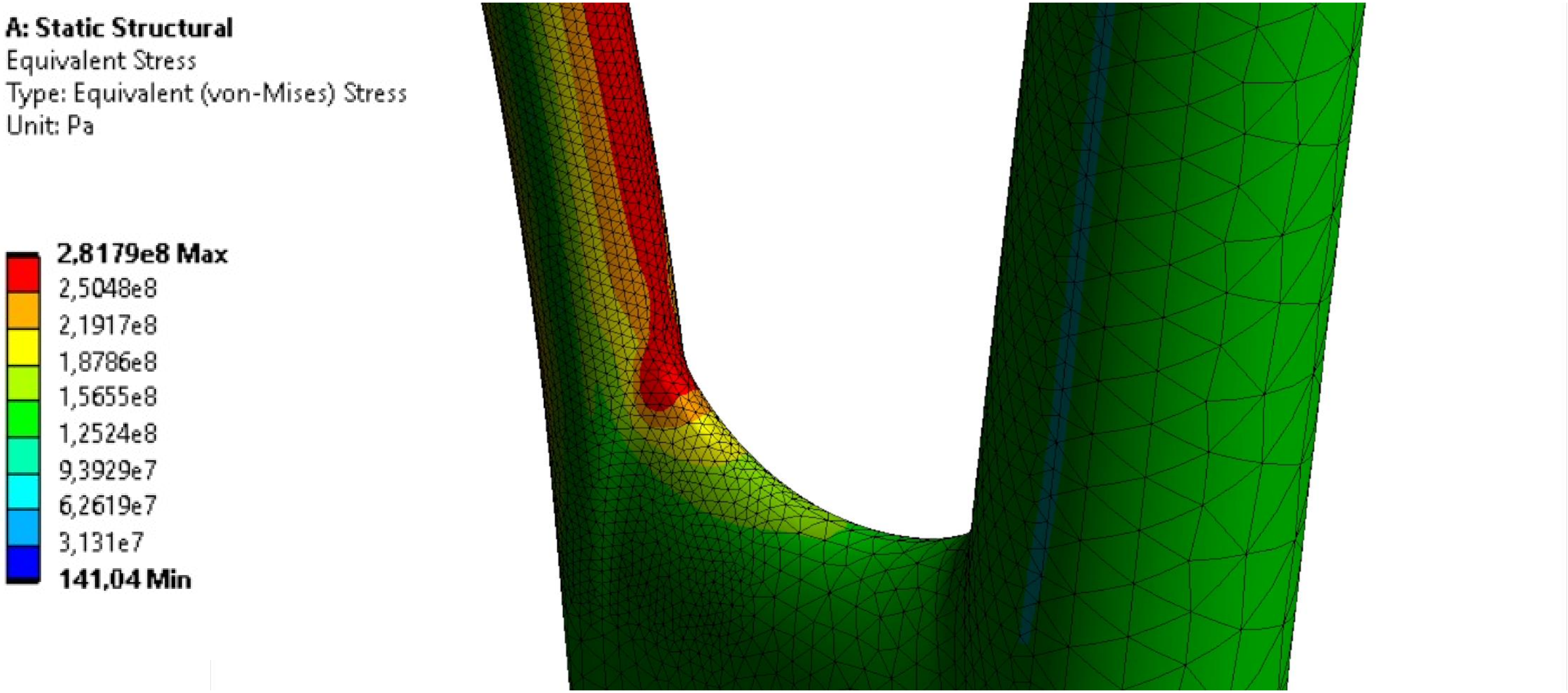
Morphed nodes preview



BGM evolution of the mesh

Biological Application

- BGM driven shape sculpting optimization results



- max σ_{VM} placed on smallest trunk, immediately after the fillet
- max σ_{VM} decrease at the cost of a small added volume (4%) of the morphed area

Industrial Application

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- An aftermarket front wheel support for **Ducati Panigale V4** motorbike was analyzed with the proposed methodology, in order to perform additional optimization of the component
- It is the **connection** point between front suspension, braking system and front wheel
- The **wheel support** is manufactured in EN AW 7075 Aluminum alloy
- Some input data cannot be disclosed

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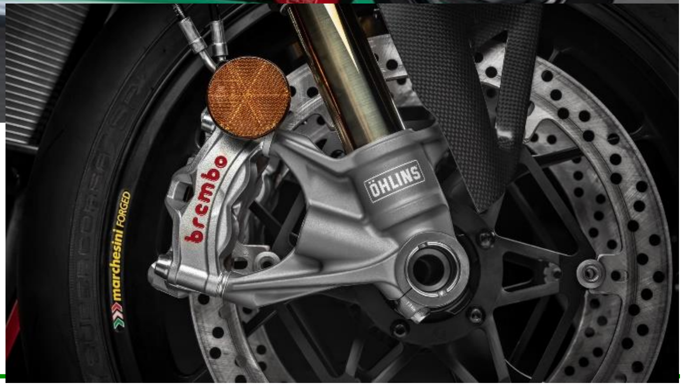
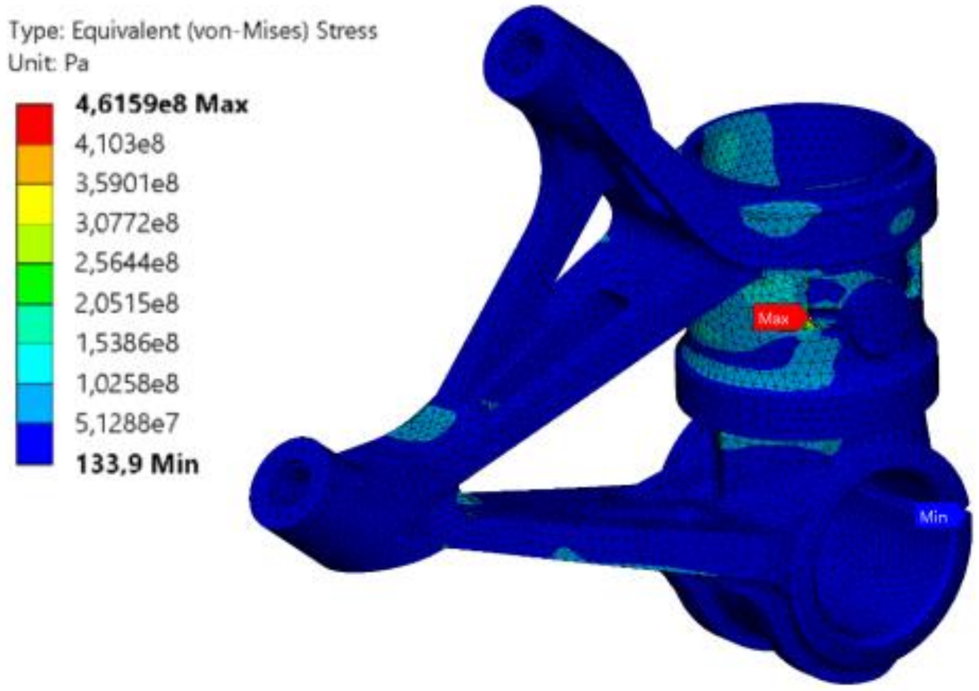


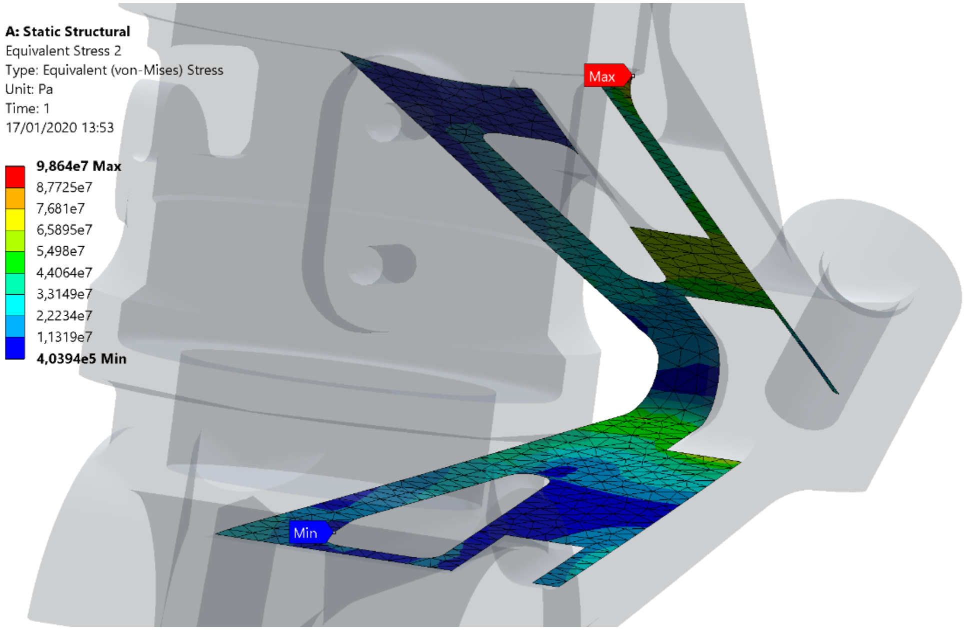
Industrial Application

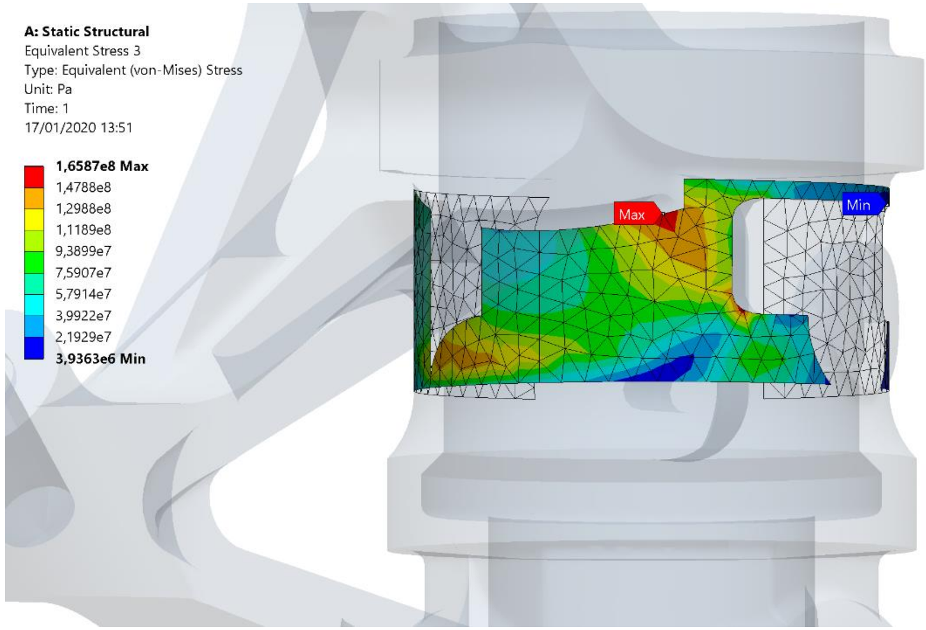
- According to the loading and constraint condition, the equivalent von Mises stress distribution is obtained



Industrial Application

- Analyzing the stress on surfaces **two sculpting areas** were identified

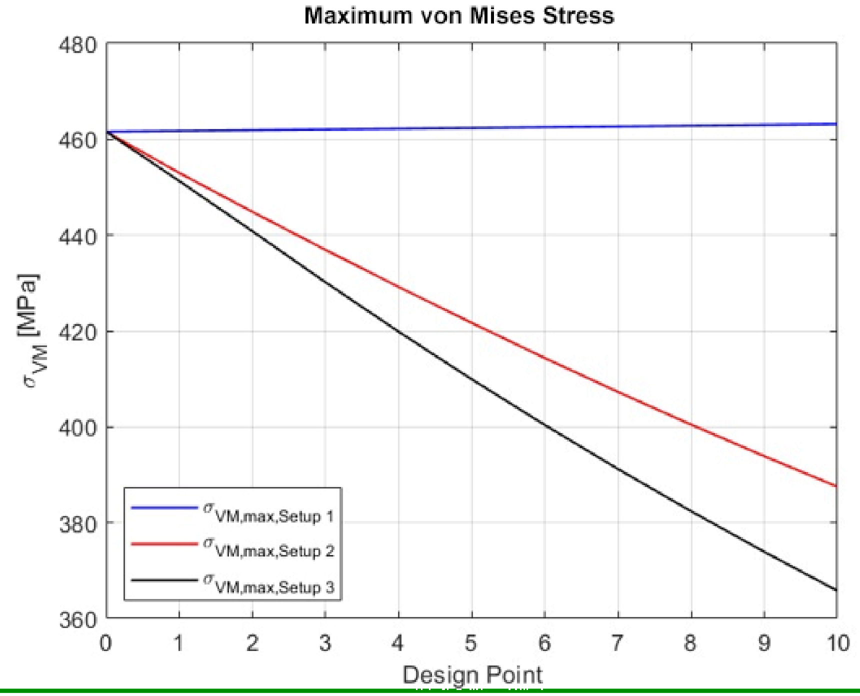


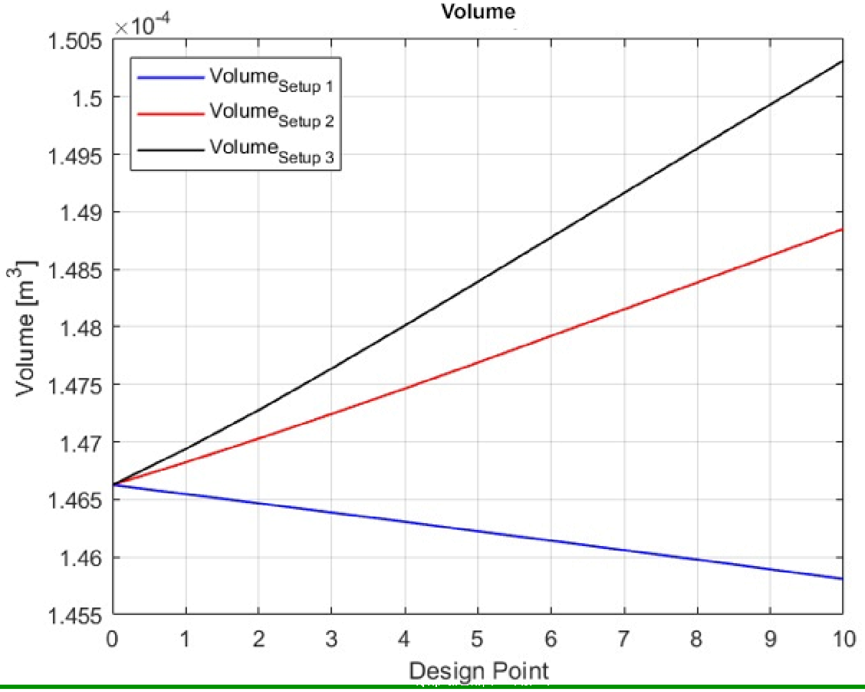


- **Three** different **approaches** were pursued: BGM applied on planar surfaces (Setup 1), BGM applied on circular surfaces (Setup 2) and BGM applied on both set of surfaces (Setup 3)

Industrial Application

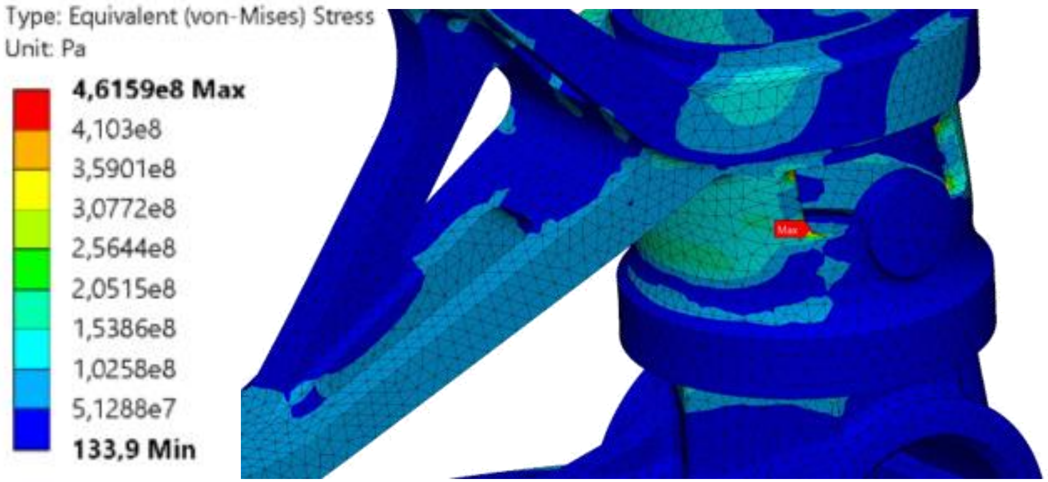
- After 10 iterations, the following volume and **maximum equivalent stress** are obtained:
  - Setup 1: volume -0,6%, maximum equivalent stress +0,3%
  - Setup 2: volume +1,5%, maximum equivalent stress -16,1%
  - Setup 3: volume +2,5%, maximum equivalent stress -20,8%

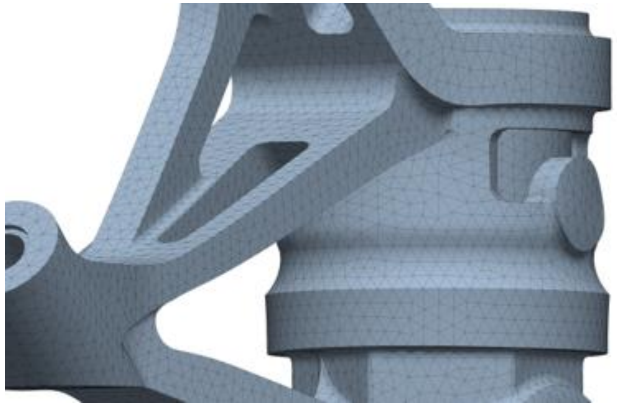




Industrial Application

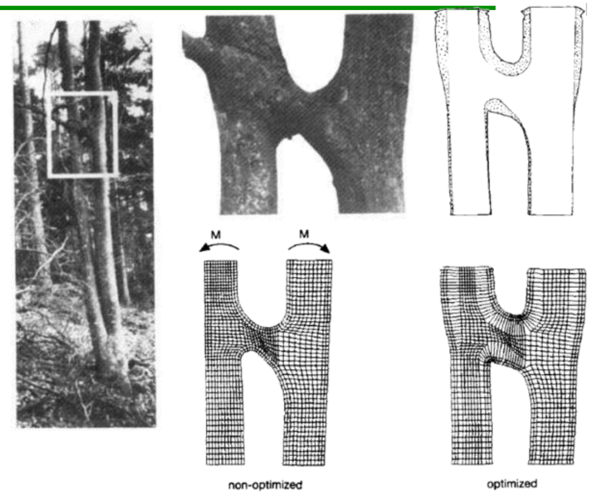
- Setup 3: stress distribution and final shape

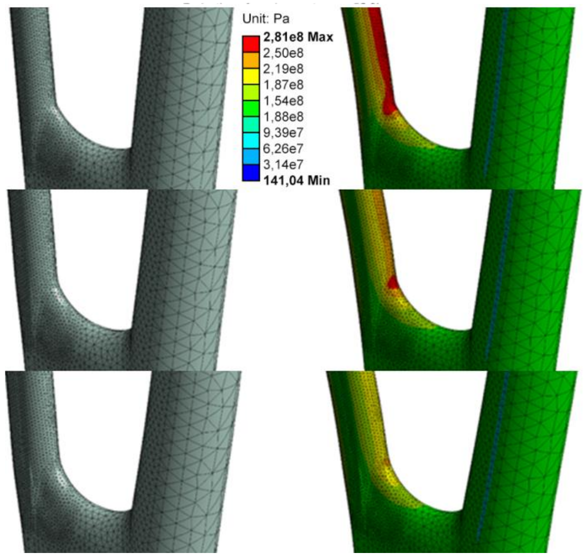




Conclusions

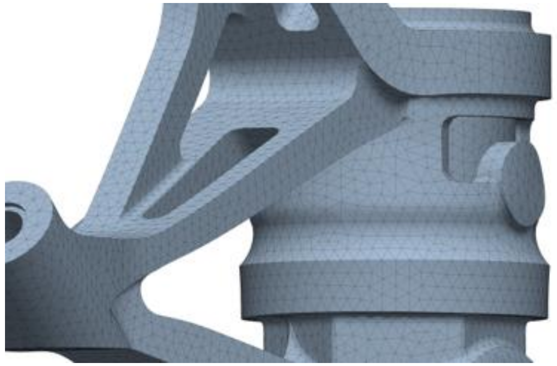
- A new parameter-less approach for shape optimization has been presented
- BGM and Mesh Morphing are combined into an innovative surface sculpting tool, capable to take advantage of surface stress levels
- BGM mimics the growth mechanism of natural tissue
- RBF based Mesh Morphing is used to modify shapes according to BGM data
- In the first application presented, a natural structure was modeled starting from a literature found test case





Conclusions

- Results gave a good agreement with literature case
- In the second application presented, the shape optmization of an aftermarket motorbike component was considered
- Three optimization Setup were investigated
- Setup involving optimization of both cilindrical and planar faces gave the best results, providing a 20.8% reduction of maximum equivalent stress



Acknowledgements

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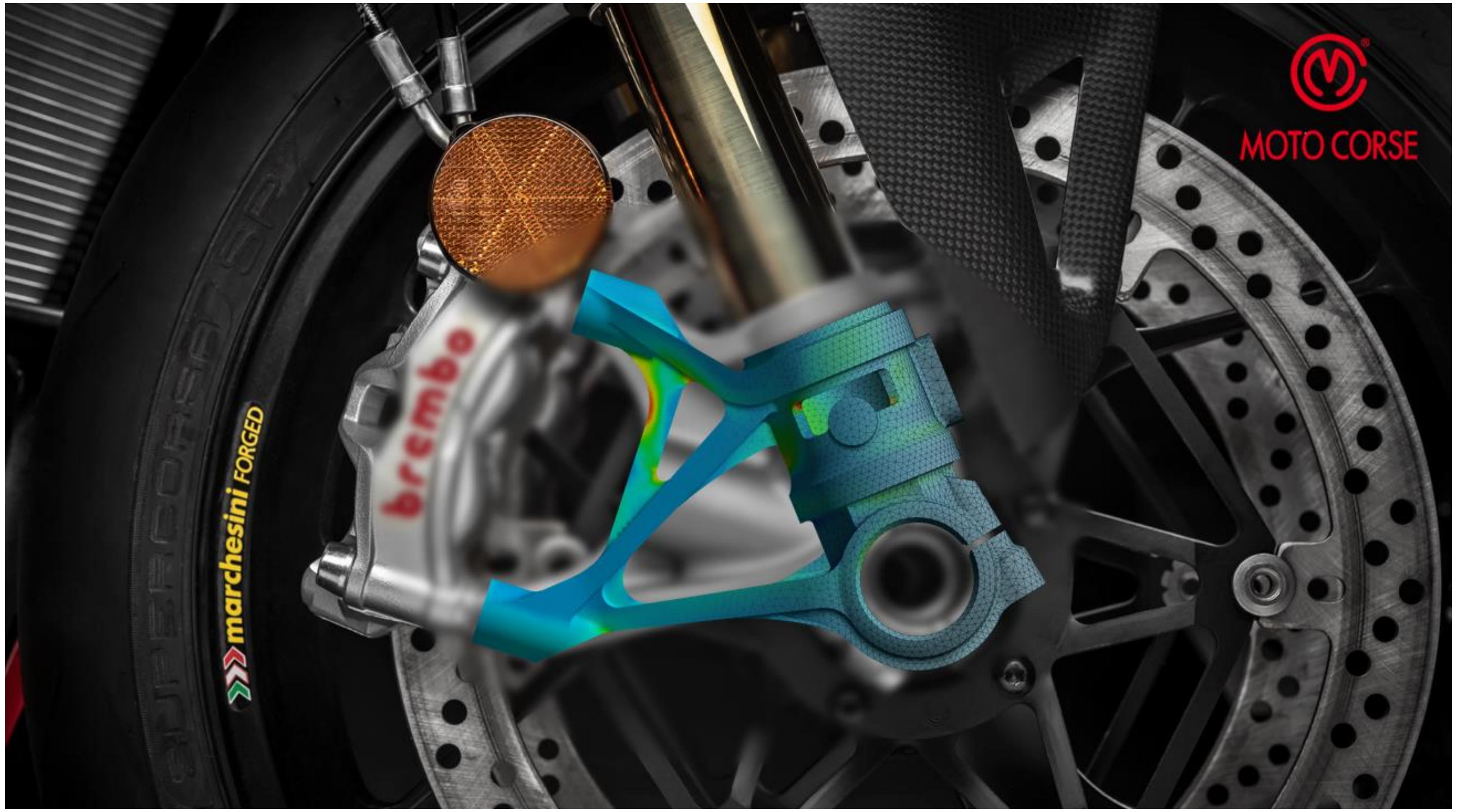
- Motocorse San Marino for sharing the geometry files of the presented study
- Ing. Andrea Ridolfi for supervising numerical analysis execution and results and for sharing his noticeable experience with us.



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