INTERNATIONAL CAE CONFERENCE

35th INTERNATIONAL CAE CONFERENCE AND EXHIBITION

THE ENGINEERING SIMULATION PATH TO DIGITAL TRANSFORMATION

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Vicenza Convention Centre @Fiera di Vicenza

Optimization of industrial parts by mesh morphing enabled automatic shape sculpting

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Outline

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- BGM Background
- Adjoint Background
- RBF Background
- Automatic Surface Sculpting
- Applications
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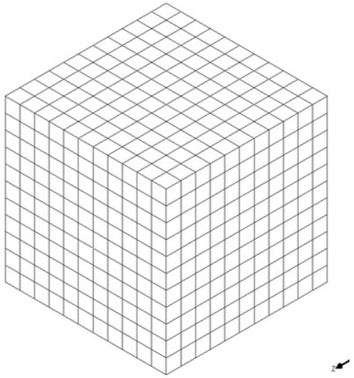
  - Industrial component
- Conclusions

Introduction

- Mechanical component **optimization** is a target for engineering applications.
- **Finite Element Method** is a tool for optimization given load and constraint configuration
- CAD based optimization requires the **generation** of **additional FEM models.** It can be very **time-consuming** specially dealing with complex shape components.
- To overcome this, **Mesh morphing** can be adopted:
  It generates new FEM models without modifying
  the geometry and without the need to remesh it.

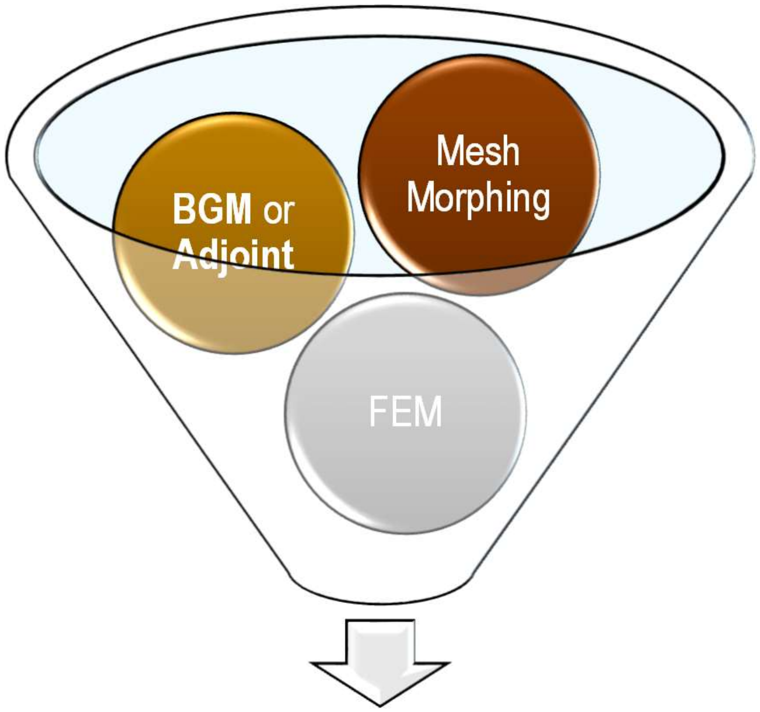


Introduction

- **Biological Growth Method** (**BGM)** and **Adjoint Method** exploit data coming from numerical analysis to define a shape modification that will sculpt model surfaces so that stress levels are optimized.

- The tool adopted for morphing the **FEM** mesh is **RBF Morph™**, which is based on Radial Basis Functions (**RBFs**). FEM pre-processor and solver used is ANSYS® Mechanical™.

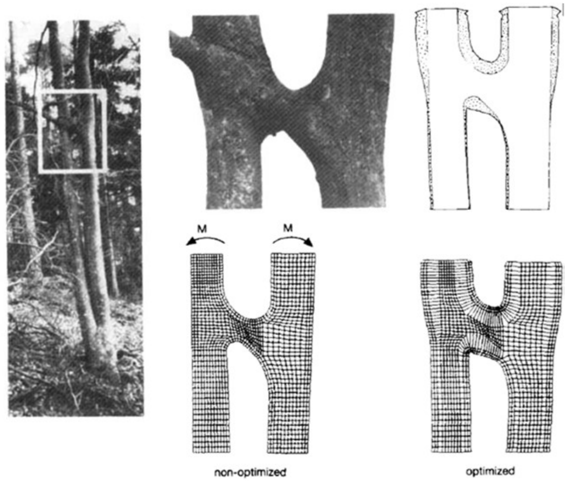
(rbf-morph)™



Automatic Shape optimization

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.



Reduction of maximum stresses 56 %

- The BGM idea is that surface growth can be expressed as a linear law with respect to a given threshold value: $\dot{\varepsilon} = k\left(\sigma_{Mises} - \sigma_{ref}\right)$

*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

- Waldman and Heller* refined this first approach proposing a **multi peak** one:

$$d_i^j = \left(\frac{\sigma_i^j - \sigma_i^{th}}{\sigma_i^{th}} \right) \cdot s \cdot c \,, \qquad \sigma_i^{th} = max(\sigma_i^j) \text{ if } \sigma_i^j > 0 \quad \text{or} \quad \sigma_i^{th} = min(\sigma_i^j) \text{ if } \sigma_i^j < 0$$

- In **RBF Morph ANSYS Workbench ACT** a different implementation is present

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

and different **stress types** can be used to modify the surface shape:

- Von Mises stress
- Maximum principal stress
- Minimum principal stress
- Stress intensity
- Maximum Shear stress
- Equivalent plastic strain

*Waldman W., Heller M., 2015. Shape optimization of holes in loaded plates by minimization of multiple stress peaks, Defence Science and Technology Organisation Fisherman Bend, Australia

Adjoint Background

- Adjoint method allows to obtain the **sensitivities** of an **objective function** with respect to a set of **input parameters**.

- This can be applied to the three displacement for each node of the computational mesh, so that a **shape modification** can be obtained.

- Largely used in Computational Fluid-Dynamics (CFD) but can be also applied in Computational Structural Mechanics (CSM).

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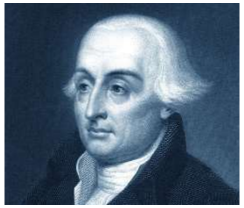


- It is possible to differentiate the discretised equation (**Discrete Adjoint method**) or to derive equation prior to their differentiation (**Continuous Adjoint method**).

Adjoint Background (discrete case)

- The objective function can be expressed as function of displacement and the derivative:

$$\Psi = f(\mathbf{X}(u), u) \qquad \frac{d\Psi}{du} = \frac{\partial \Psi}{\partial u} + \frac{\partial \Psi}{\partial \mathbf{X}} \frac{\partial \mathbf{X}}{\partial u}$$

- To obtain the displacement $\frac{\partial \mathbf{X}}{\partial u}$ two methods are available:
  - **direct method** → has to be re-evaluated for each input parameter)
  - **adjoint method** → need only one calculation no matter how many input parameters, it uses a Lagrange-like multiplier to obtain displacements:

$$\mathbf{KX} = \mathbf{F} \Rightarrow \mathbf{K}\lambda = \frac{\partial \Psi}{\partial \mathbf{X}}^{\mathrm{T}} \Rightarrow \frac{d\Psi}{du} = \frac{\partial \Psi}{\partial u} + \lambda^{\mathrm{T}}\left(\frac{\partial \mathbf{F}}{\partial u} - \mathbf{X}\frac{\partial \mathbf{K}}{\partial u}\right)$$

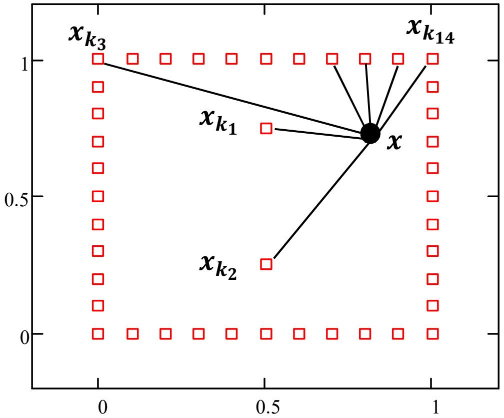
RBF Background

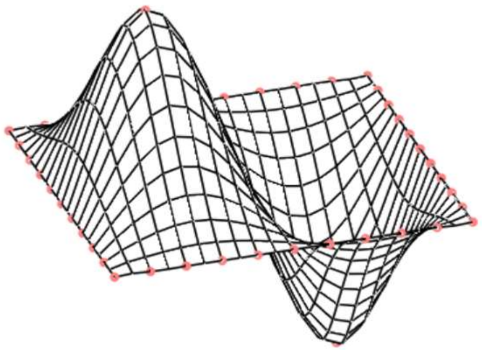
- RBFs = mathematical tool capable to **interpolate** in a generic point in the space a function **known** in a discrete set of points (**source points**).

- The interpolating function is composed by a **radial basis** and by a **polynomial**:

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

(radial basis; polynomial; $\left\| \boldsymbol{x} - \boldsymbol{x}_{k_i} \right\|$: distance from the i-th source point)





RBF Background

- If evaluated on the source points, interpolating function gives exactly the input values
- RBF problem (evaluation of coefficients γ and β) is associated to the solution of a linear system:
  - **M** = interpolation matrix
  - **P** = constraint matrix
  - **g** = vector of known values on the source points
- Once solved the RBF problem each displacement component is interpolated

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix}$$

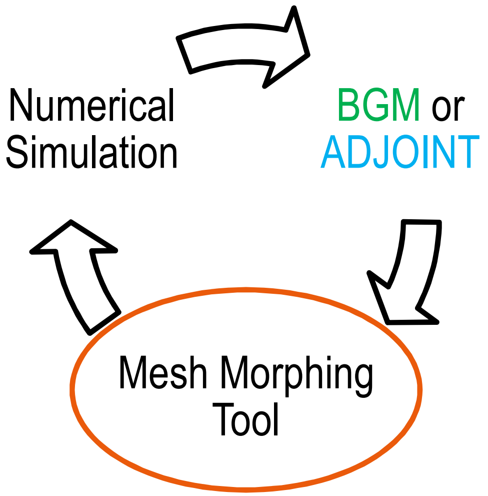
$$M_{ij} = \varphi\left(\boldsymbol{x}_{\boldsymbol{k}_i} - \boldsymbol{x}_{\boldsymbol{k}_j}\right) \qquad 1 \le i, j \le N$$

$$\mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

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

Automatic Surface Sculpting

- Automatic optimization is accoplished connecting BGM or ADJOINT data from numerical simulation to mesh morphing tool.



Offset Surface

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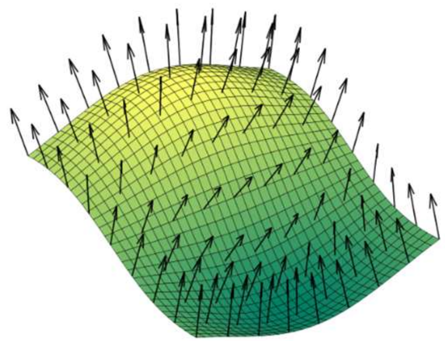
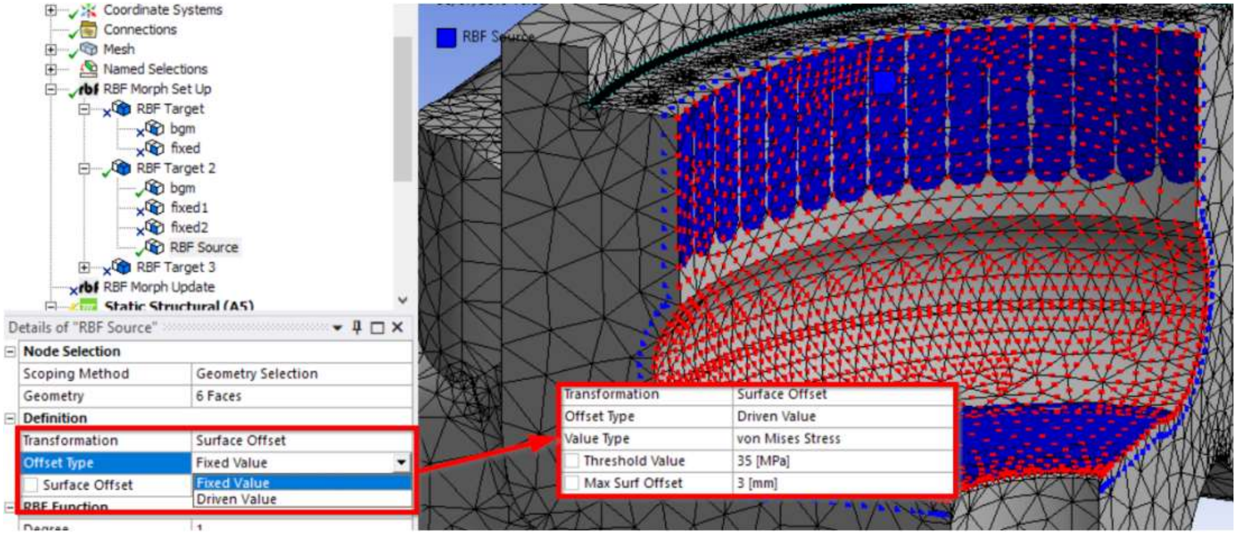
each node can displace according to the local normal direction



Automatic Surface Sculpting - BGM

- Direction and amplitude of displacement is defined according to stress data, considering the threshold stress value σ_{th} and the d maximum displacement.

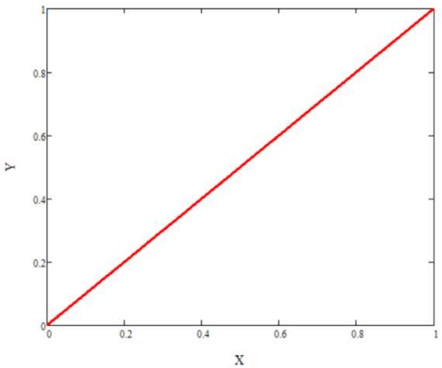


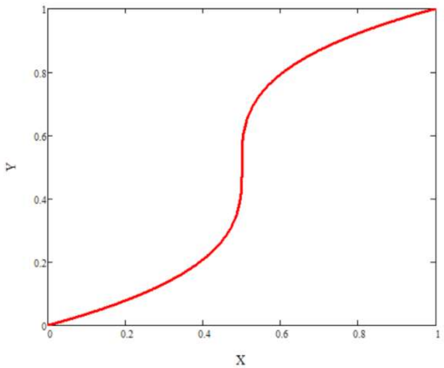
$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Automatic Surface Sculpting - Adjoint

- Direction and amplitude of displacement is defined according to topological optimization data, considering the topological density function, $\rho \in [0,1]$, interpolated using a linear or irrational function and the d maximum displacement.

linear





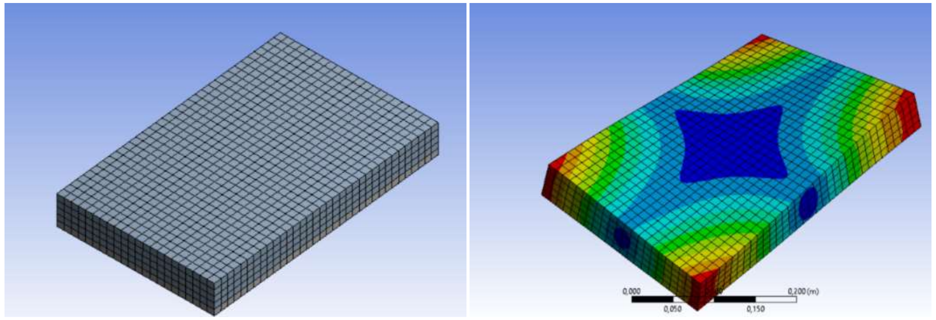
irrational

$$S_{node\ adj} = [(\rho - 0.5) + 0.5] \cdot d$$

$$S_{node\ adj} = \left[0.5\left(\frac{(\rho - 0.5)}{0.5}\right)^{\frac{1}{3}} + 0.5\right] \cdot d, \quad with\ \rho \in [0, 1]$$

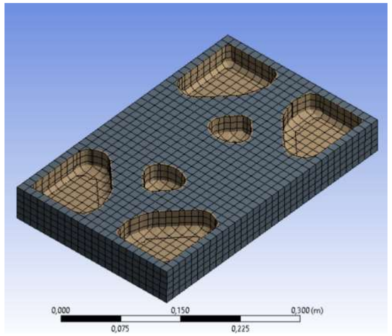
Applications – Simple Thick Plate – Adjoint

- Free and undamped dynamic analysis of a thick plate



Mode	Freq. (Hz)
1	1457
2	1542
3	3159
4	3800
5	3816

- Optimization problem:
  - decrease mass (target -50%)
  - maintain first frequency above 1220 Hz



Topology Optimization Result

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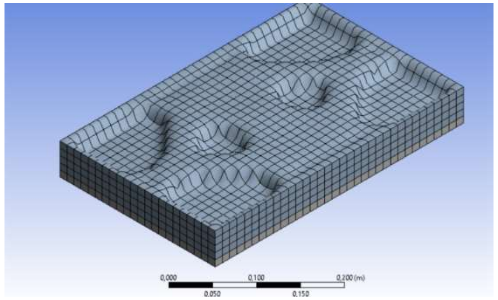
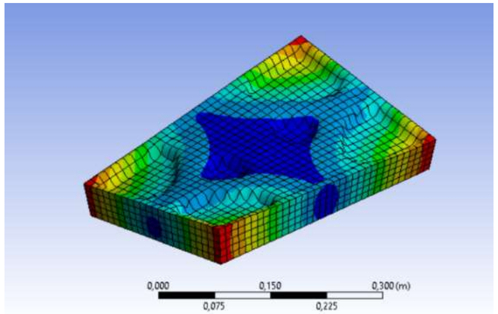
input for adjoint

Applications – Simple Thick Plate – Adjoint

Results $(d = 15mm)$



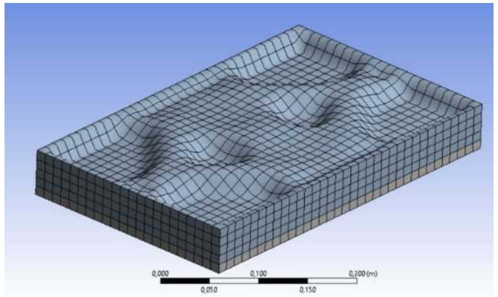
Irrational Interpolation



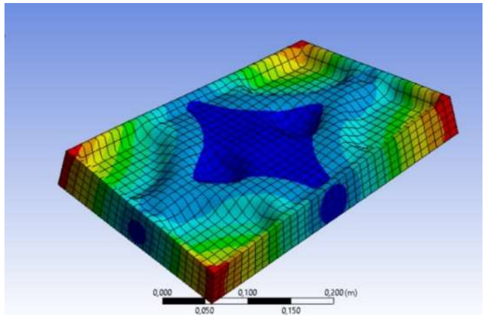
Mode	Baseline Freq. (Hz)	Linear int. Freq. (Hz)	Irrational int. Freq. (Hz)
1	1457	1316	1352
2	1542	1402	1441
…	…	…	…

Mass reduction = 20% (< 50%)

Topological Optimization removes material
→ mesh morphing moves nodes.

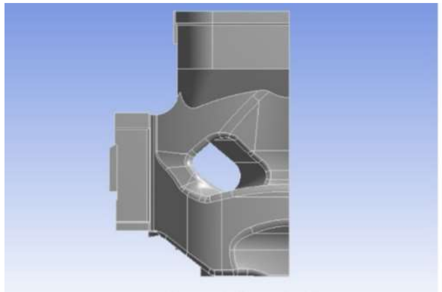


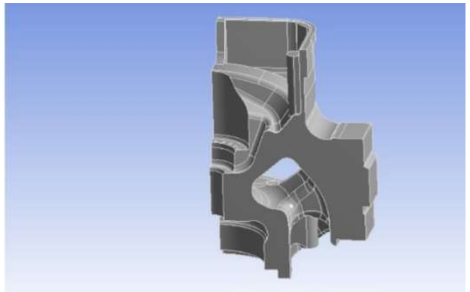
Linear Interpolation

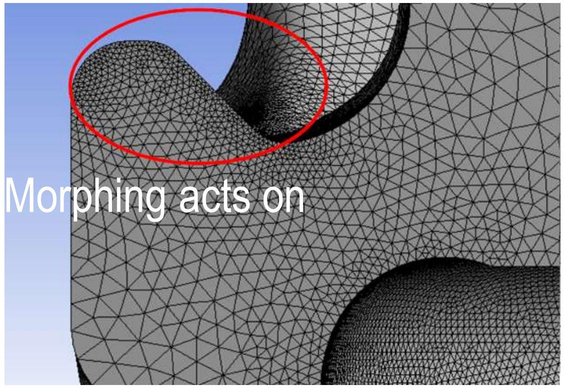


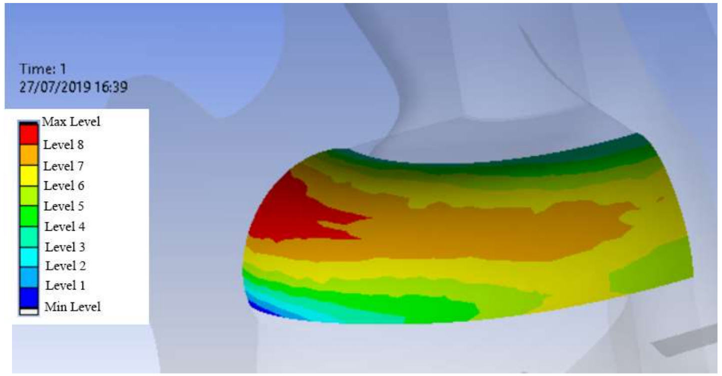
Applications – Industrial component – Adjoint

- Maximum reference stress reduction: **11.7 %**







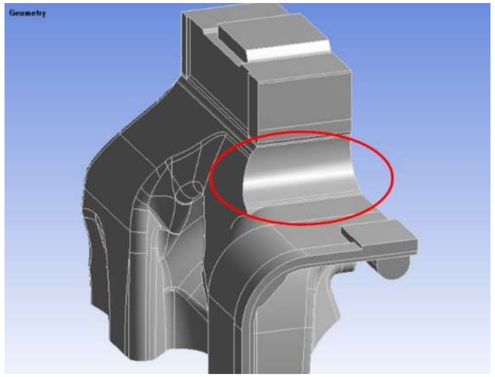


Applications – Industrial component – BGM

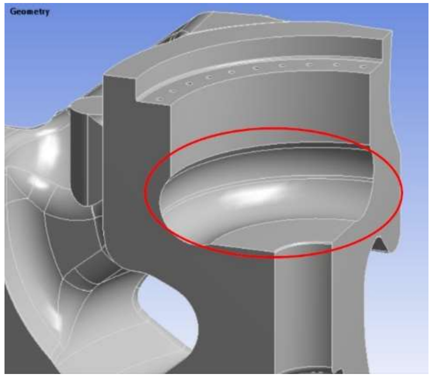
- 3 Hot Spots identified

Location	σ_{th}	$d\ [mm]$
Hot Spot 1	$0.5(\sigma_{max}-\sigma_{min})$	3
Hot Spot 2	$0.5(\sigma_{max}-\sigma_{min})$	3
Hot Spot 3	$0.5(\sigma_{max}-\sigma_{min})$	1

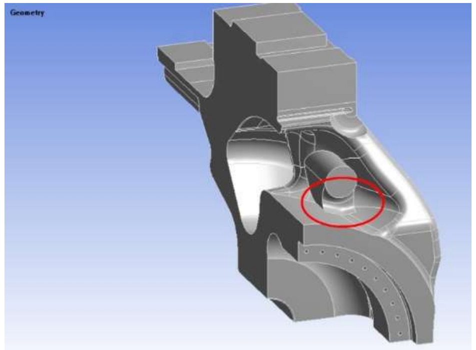
$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$



Hot Spot 1



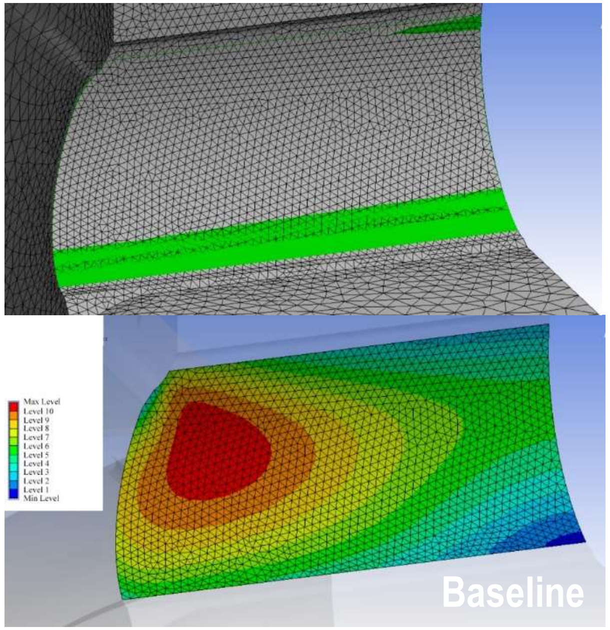
Hot Spot 2

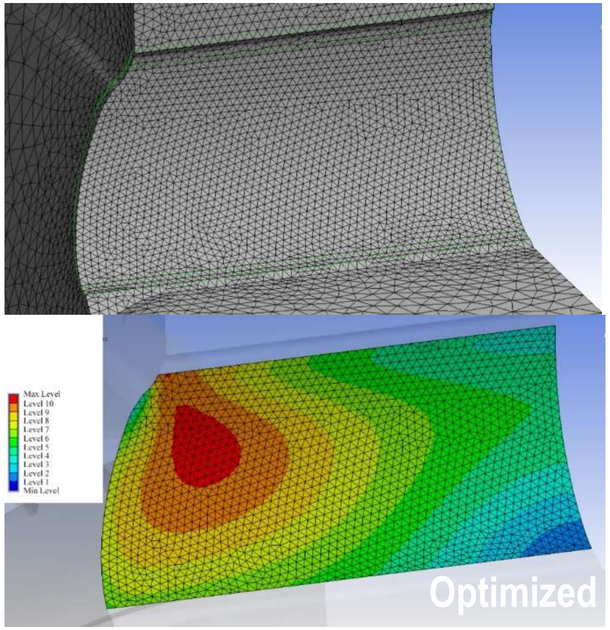


Hot Spot 3

Applications – Industrial component – BGM

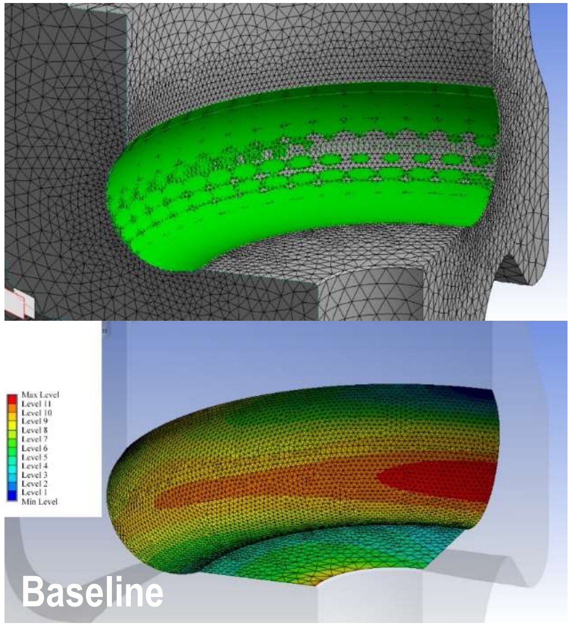
- Hot Spot 1
- Max stress reduction: **2.76%**

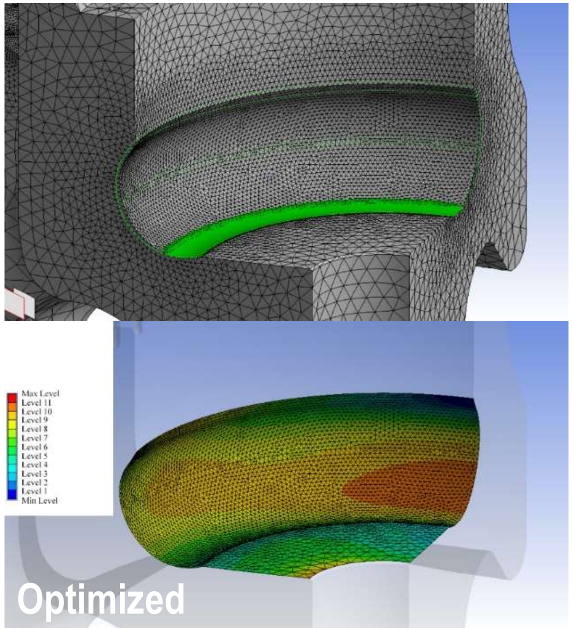




Applications – Industrial component – BGM

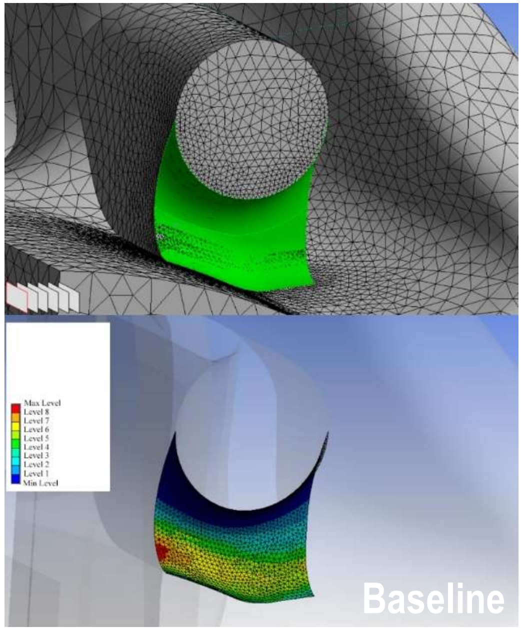
- Hot Spot 2
- Max stress reduction: **7.85%**

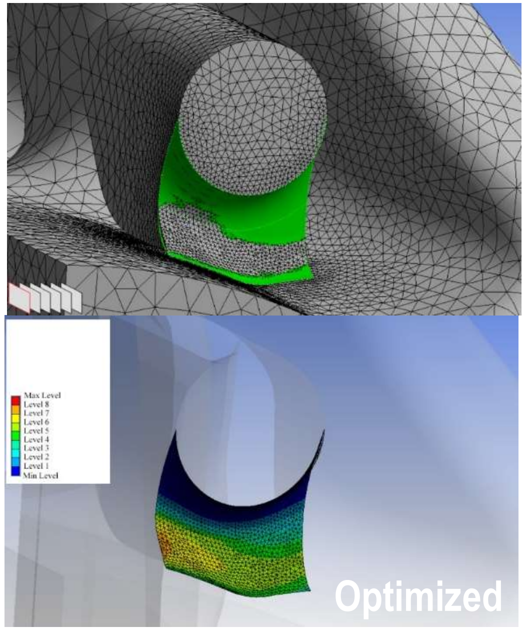




Applications – Industrial component – BGM

- Hot Spot 3
- Max stress reduction: **8.12%**

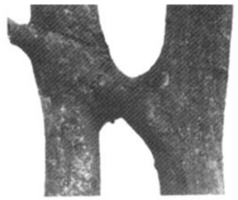




Conclusions

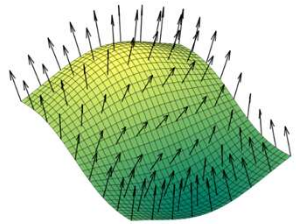
- A **methodology** to perform **automatic shape optimization via surface sculpting** was presented.

- Two approaches were investigated **Biological Growth Method** and **Adjoint Method**, which were successfully coupled with mesh morphing tool.
- **Adjoint** method, at the cost of an additional computation, gives sensitivities with respect of objective functions which were used to identify surface nodes to be moved inward or outward.
- **BGM** uses surfaces stress levels to identify model zones to be moved inward or outward, obtaining stress peak minimization and more uniform stress distribution



Conclusions

- Both approaches were illustrated on **simple geometries** and then applied to a more **complex case.**
- The proposed procedure allowed to reach **optimized shapes** matching different **objective functions** in an **automatic way**, with a **minimal effort from the user.**



- The framework adopted was composed by ANSYS Workbench with RBF Morph ACT extension, which provided an integrated tool to the user in which perform optimization task

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