Automatic shape optimization of structural components with manufacturing constraints

Stefano Porziani, Corrado Groth, Marco E. Biancolini

Università degli Studi di Roma *Tor Vergata*

Contact email: porziani@ing.uniroma2.it

AIAS2018 - 5-8 Settembre VILLA SAN GIOVANNI (RC)

Outline

- Introduction
- RBF Background
- BGM Background
- Challenges
- Applications Description
- Optimization Results
- Conclusions

Introduction

- Mechanical component **optimization** is a paramount target in every engineering application.
- A valuable tool for optimization in complex load and constraint configuration is the **Finite Element Method** (**FEM**), which allows to test **different configurations** before the prototyping phase.
- Optimization strategies are often based on **parametrization** of the FEM model: the optimal configuration is found among a family of configurations obtained **varying** the **parameters** describing the model geometry.
- Another possible optimization strategy exploits the results coming from FEM: **Biological Growth Method** (**BGM**) derives the component shape modification analysing the surface stress levels.

Introduction

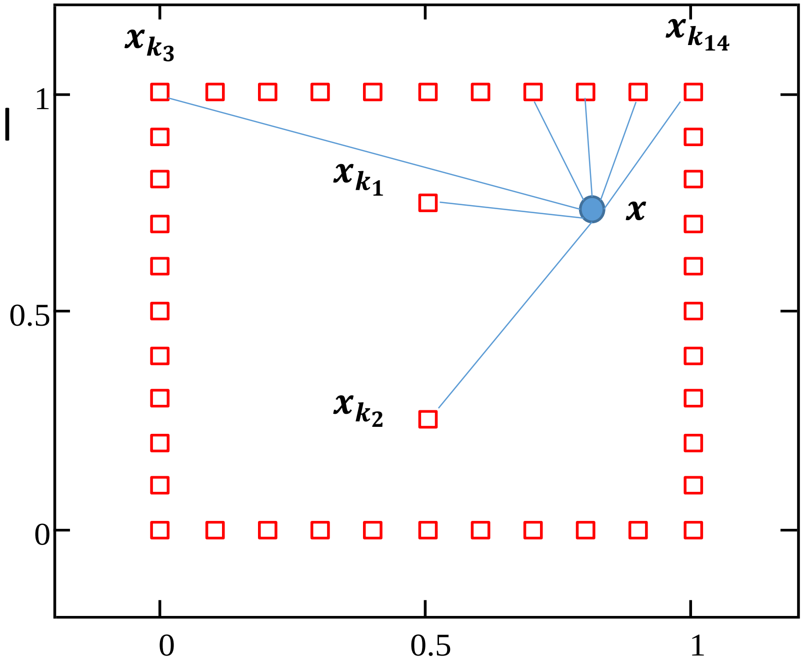
- Both procedures, parameter based and BGM, require the **generation** of **additional FEM models**: this task can be very **time-consuming** specially dealing with complex shape components.
- To overcome this problem **Mesh morphing** can be adopted: it allows to generate new FEM models without modifying the geometry and without remesh it.
- Furthermore, in conjunction with the BGM approach, thanks to mesh morphing a **high grade of automation** can be achieved.
- In the present work, the tool adopted for morphing the **FEM** mesh is **RBF Morph™**, which is based on Radial Basis Functions (**RBFs**).

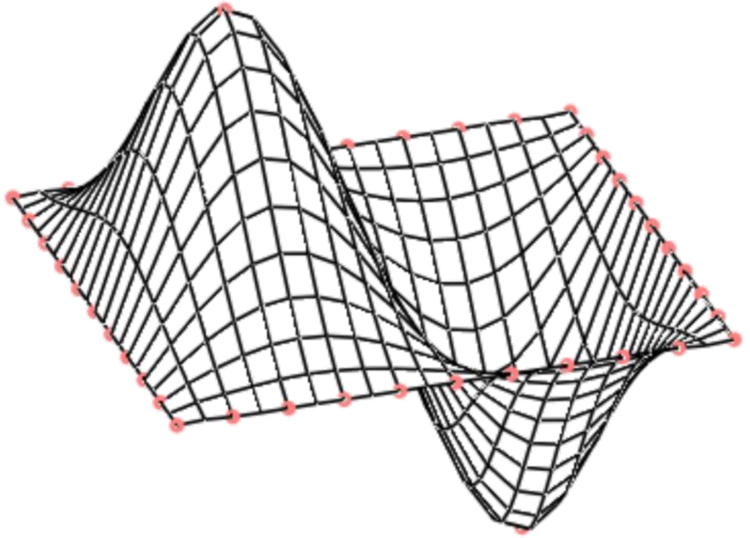
- RBFs are a mathematical tool capable to **interpolate** in a generic point in the space a function **known** in a discrete set of points (**source points**).
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

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

radial basis — polynomial

$\left\|\mathbf{x} - \mathbf{x}_{k_i}\right\|$: distance from the i-th source point





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

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

- 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:

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

RBF Background

- Once solved the RBF problem each displacement component is interpolated:

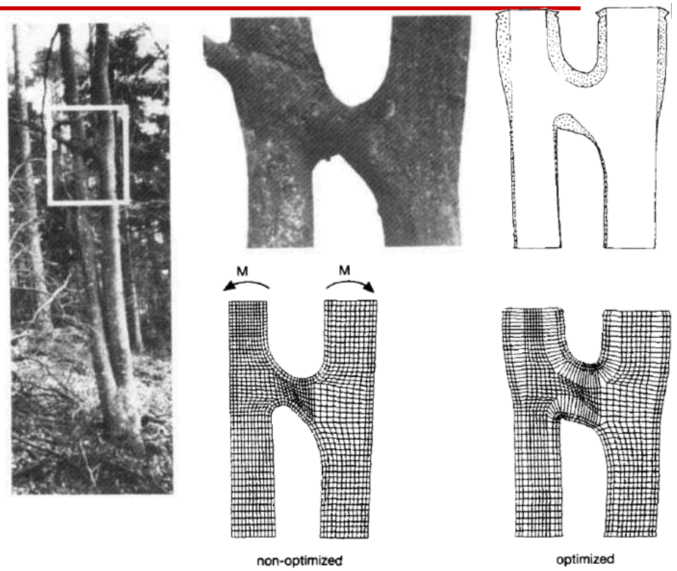
$$\begin{cases} s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right)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

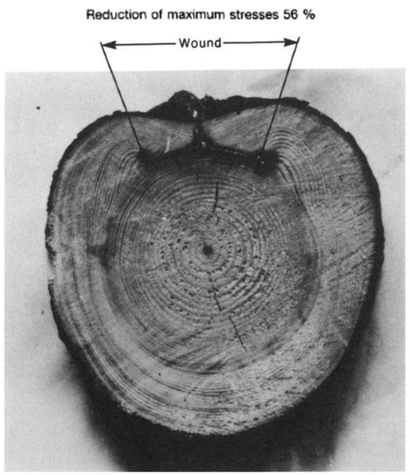
- Several different radial function (kernel) can be employed:

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:

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

- 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 extension** a different implementation is present 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	Equation	Stress/strain type	Equation
von Mises stress	$\sigma_e = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$	Stress intensity	$\sigma_e = max(\lvert\sigma_1 - \sigma_2\rvert, \lvert\sigma_2 - \sigma_3\rvert, \lvert\sigma_3 - \sigma_1\rvert)$
Maximum principal stress	$\sigma_e = max(\sigma_1, \sigma_2, \sigma_3)$	Maximum Shear stress	$\sigma_e = 0.5 \cdot (max(\sigma_1, \sigma_2, \sigma_3) - min(\sigma_1, \sigma_2, \sigma_3))$
Minimum principal stress	$\sigma_e = min(\sigma_1, \sigma_2, \sigma_3)$	Eqv. plastic strain	$\varepsilon_e = [2(1+\nu')]^{-1} \cdot \left(0.5\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}\right)$

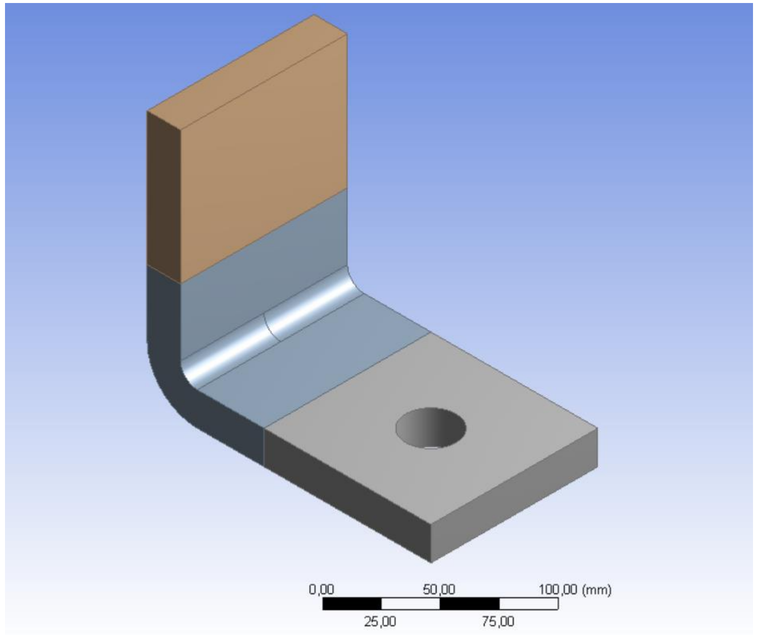
*Waldman W., Heller M., 2015. Shape optimization of holes in loaded plates by minimization of multiple stress peaks, Defence Science and Technology Organisation Fisherman Bend, Australia, Aerospace Div, http://www.dtic.mil/docs/citations/ADA618562.

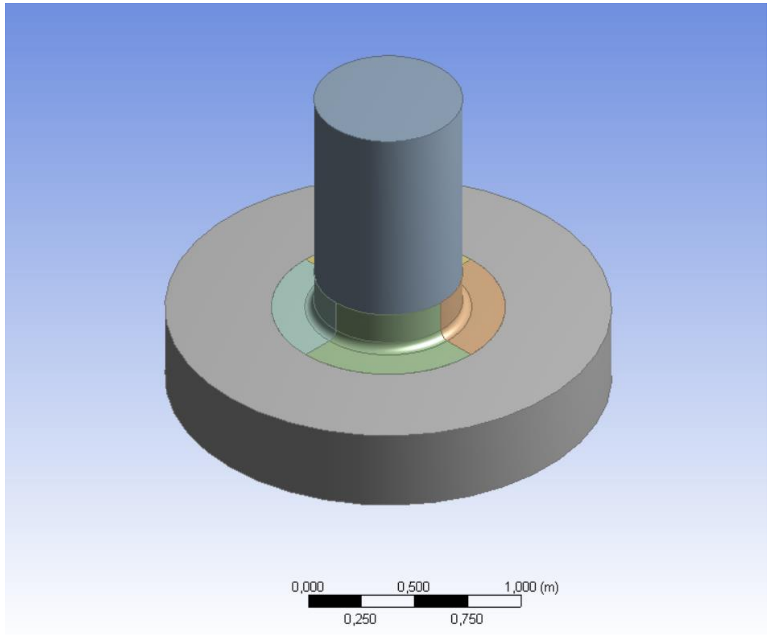
Challenges

- Currently the mesh morphing allows to obtain complex shape modifications without remeshing, but can require a **lot of efforts** in order to maintain specific manufacturing constraints.
- In several industrial application the capability of replicate the shape modification along a direction or around an axis is a **strong requirement**.
- RBF Morph ACT extension introduced in the last version a new feature in order to satisfy these requirements.
- The **Coordinate Filtering feature** allows the user to replicate a specific RBF solution (i.e. shape modification) **along** or **around** a specified **axis**.

Applications Description

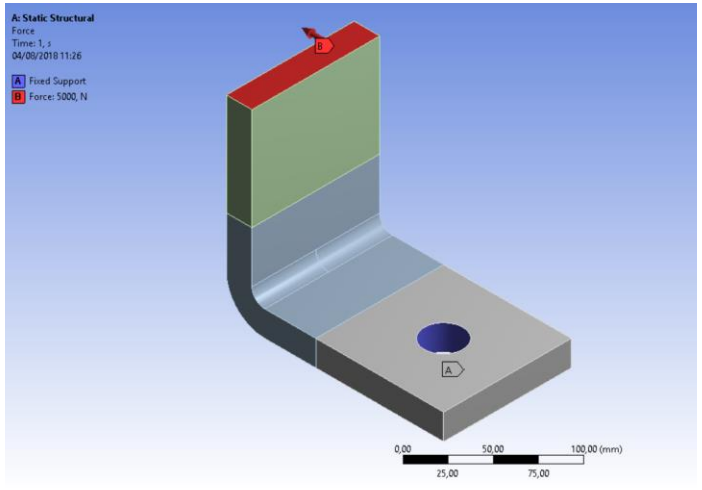
- To demonstrate the effectiveness of the Coordinate Filtering feature two applications were developed: a first one to apply a **linear manufacturing constraint** and a second one to apply a **circular manufacturing constraint**.

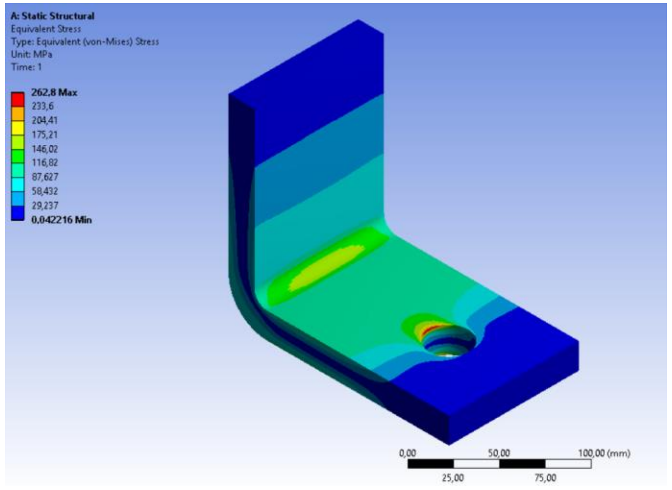


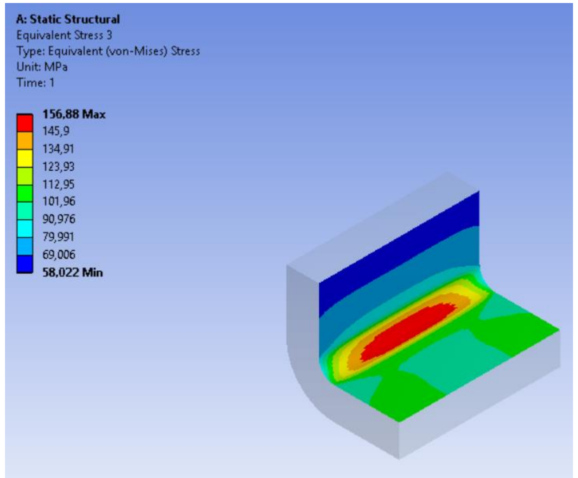


Applications Description – linear manufacturing constraints

- The bracket was constrained at the hole and loaded at the upper surface.
- Von Mises stress hot spots are located at hole and at fillet. The latter one will be the target of the optimization.
- Maximum von Mises stress at fillet in baseline configuration is 156 MPa.

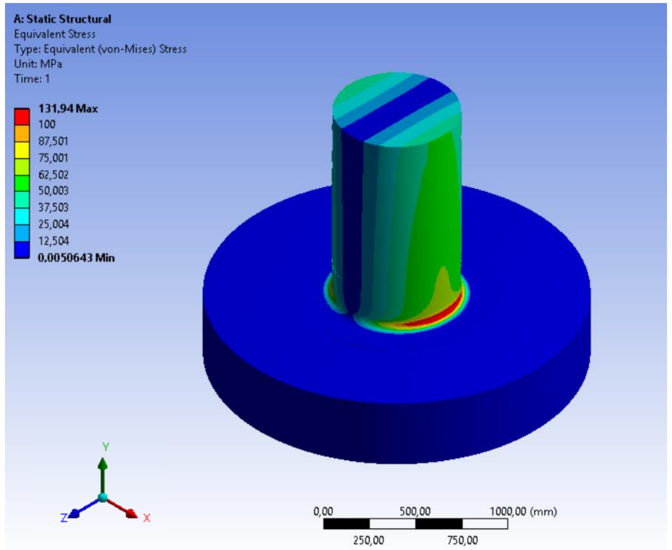


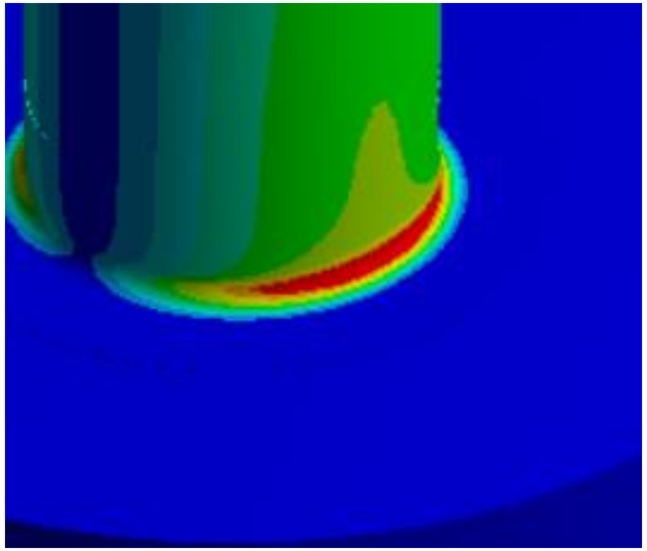




Applications Description – circular manufacturing constraints

- The pin was constrained at the lower surface and loaded at the upper surface by means of a remote force.
- Von Mises stress hot spots is located at fillet and will be the target of the optimization.
- Maximum von Mises stress at fillet in the baseline configuration is 132 MPa.

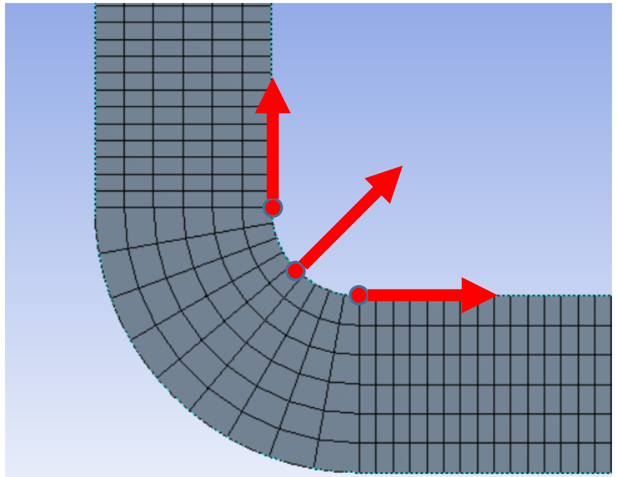


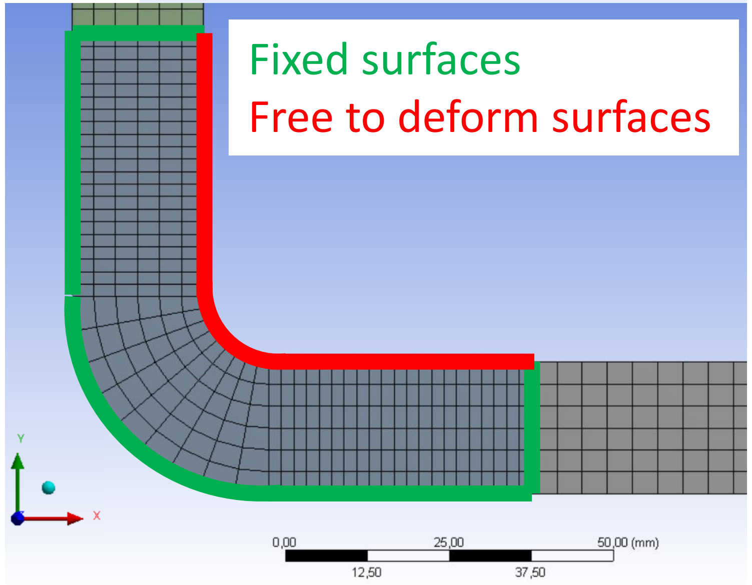


Results – linear manufacturing constraints – parameters

- Parameter based optimization was set up with **3 parameters**. Shape resulting from points displacement was replicated using **Coordinate Filtering**.
- **Ansys Design Xplorer** was employed to optimize shape using the **Response Surface Optimization**:

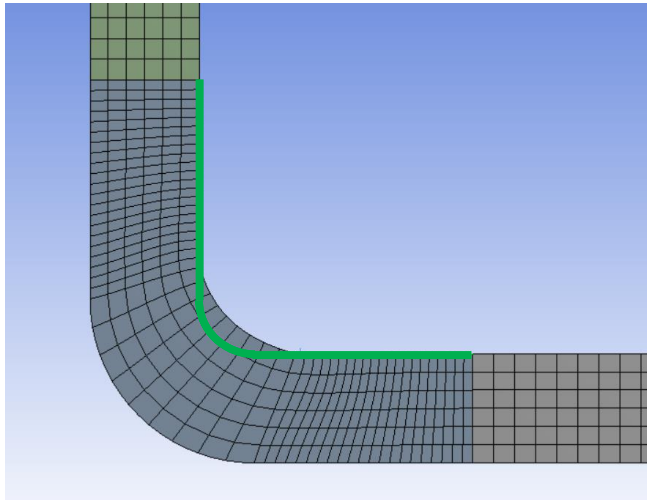
Design of Experiment type	Latin Hypercube
Samples type	CCD Samples
Response Surface type	Kriging
Kernel type	Variable
Refinement points	3 – candidate points

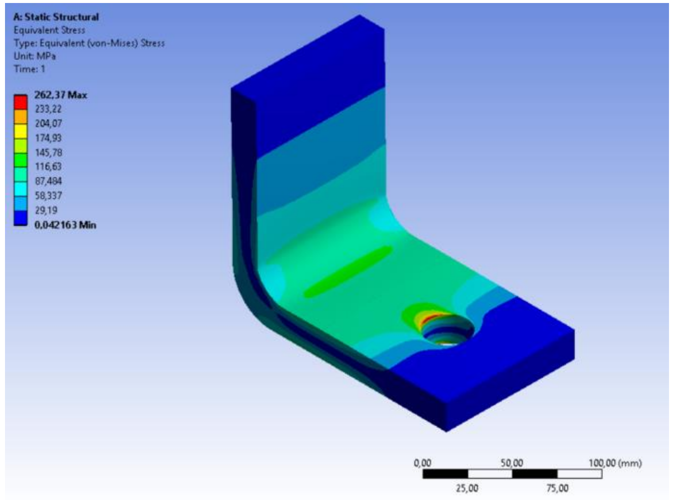


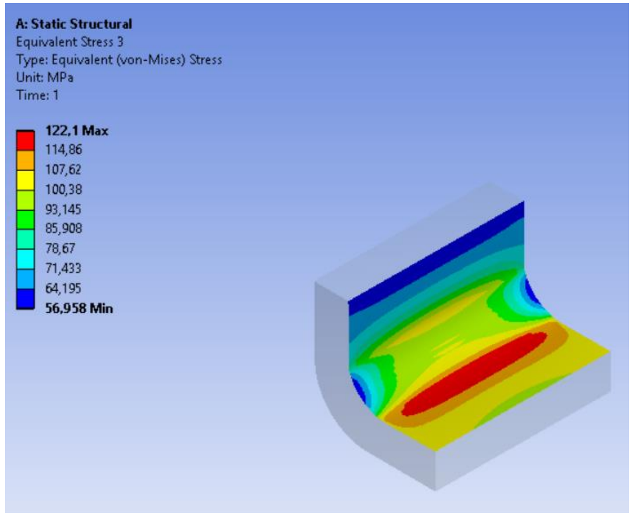


Results – linear manufacturing constraints – parameters

- With the optimized configuration obtained by Response Surface Optimization, the maximum von Mises stress value is 122 MPa, **reduced by 21.8%**.
- The optimized shape is compliant with linear manufacturing constraint even if it was obtained controlling only 3 points.

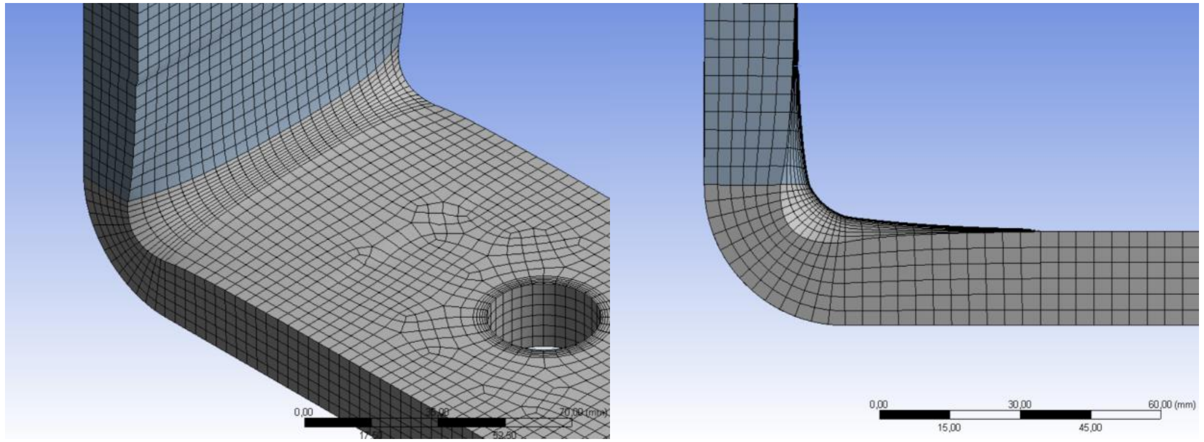




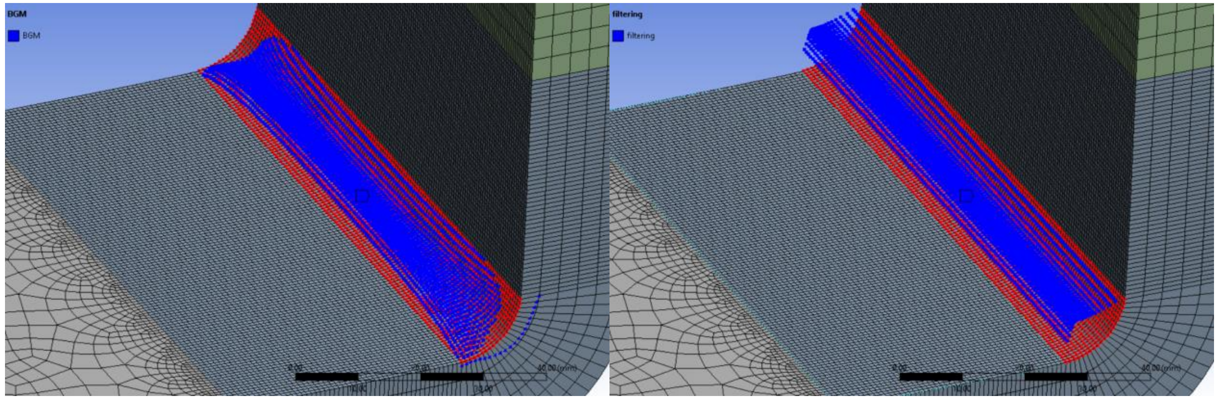


Results – linear manufacturing constraints – BGM

- When using BGM final **shape** can be very **complex**.
- Coordinate Filtering is **required** if manufacturing constraints are required.



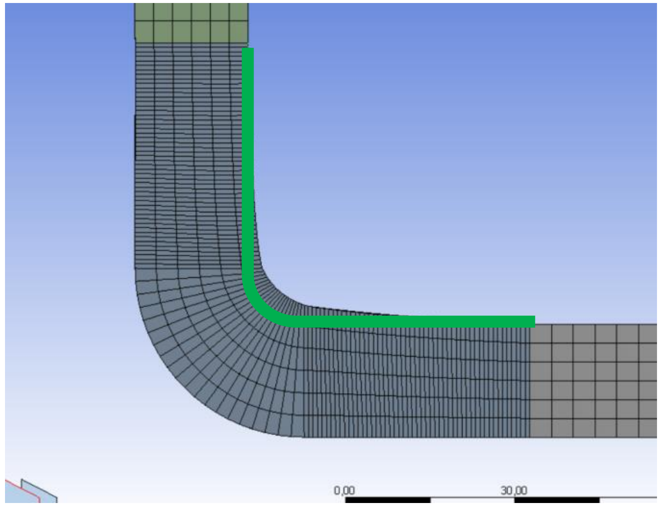
Not filtered BGM

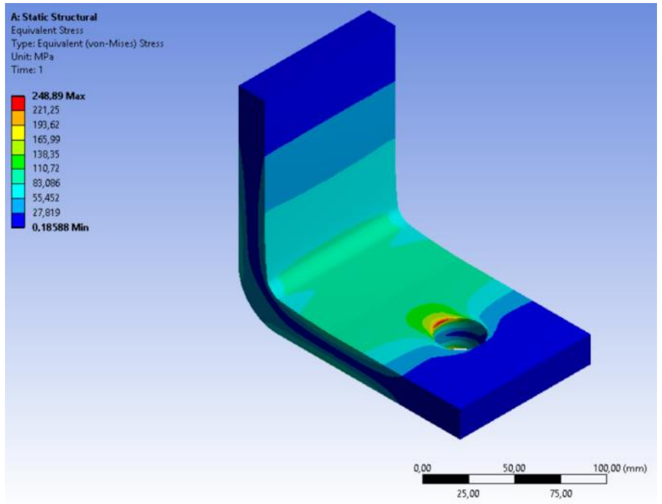


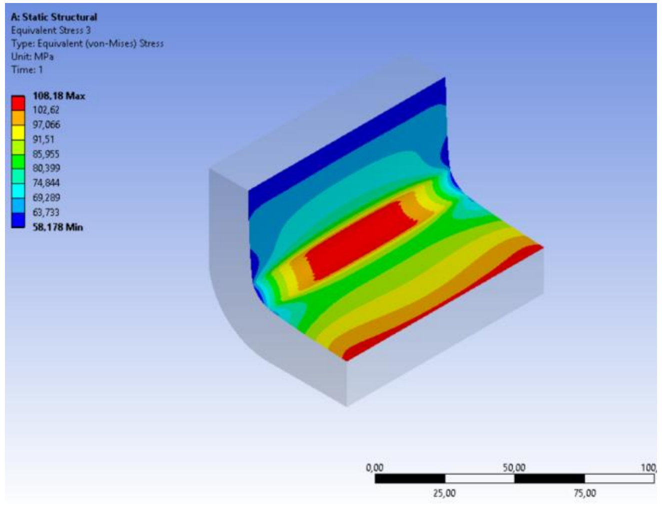
Not filtered vs. filtered BGM – amplified displacements

Results – linear manufacturing constraints – BGM

- **BGM** optimization was performed on the fillet surfaces using as **threshold** von Mises stress **100 MPa** and **maximum displacement 1 mm**. The BGM optimization was iterated **10 times**.
- With the optimized configuration obtained by BGM optimization, the maximum von Mises stress value is 108 MPa, **reduced by 30.7%**.

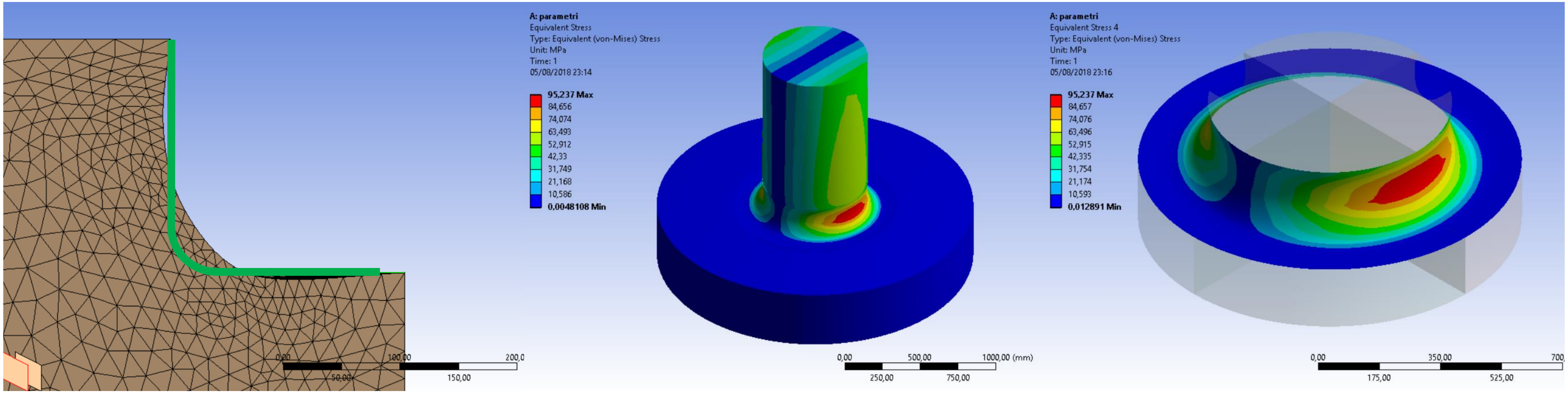






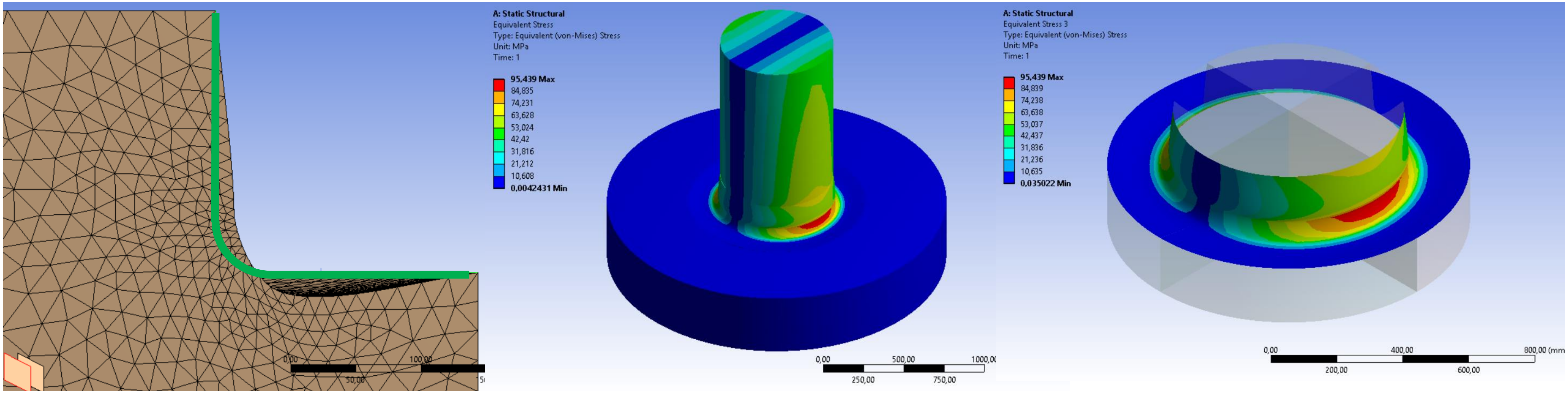
Results – circular manufacturing constraints

- The same **3-parameters** approach was applied to the pin model.
- In this case with the parameter based optimization the maximum von Mises stress in the fillet area is reduced to 95 MPa, a **reduction of 28%** with respect the baseline configuration.



Results – circular manufacturing constraints

- **BGM** optimization was performed on the fillet surfaces using as **threshold** von Mises stress **75 MPa** and **maximum displacement 5 mm**. The BGM optimization was iterated **10 times**.
- With the optimized configuration obtained by BGM optimization, the maximum von Mises stress value is 95 MPa, **reduced by 28%**.



Conclusions

- A **methodology** to obtain **optimized shape** suitable for traditional manufacturing processes **was developed**.
- The methodology was developed using **Ansys Workbench** and the **RBF Morph** ACT extensions.
- Optimization was performed using **BGM** and **parametric optimization** which, generally speaking, do not guarantee that linear or cyclic symmetry are respected.
- It was demonstrated that with these tools the **linear and circular features** can be **preserved** in the optimized configuration.
- Optimization was performed directly **controlling the shape** (parameter based) and **exploiting numerical results** regarding surface stresses (BGM).
- With both approaches stress reduction was between the range of **21% - 30%.**
- Proposed methodology can be successfully **adopted** and **implemented** in the design cycle of parts or components that are subjected to circular and linear manufacturing constraints.

Thank You For Your Kind Attention!

Automatic shape optimization of structural components with manufacturing constraints

Stefano Porziani, Corrado Groth, Marco E. Biancolini

Università degli Studi di Roma *Tor Vergata*

Contact email: porziani@ing.uniroma2.it