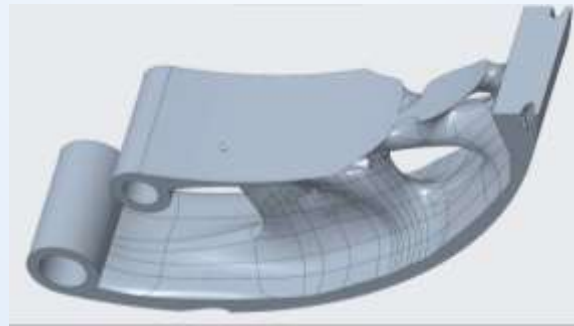




# 2018 VR&D Users Conference

*Experiences in Design Optimization*

## ***Democratization of Topology Optimization with GENESIS & CREO***



Dr. Andreas Vlahinos  
Principal at Advanced Engineering Solutions

October 2, 2018 | Plymouth, MI

# What is Generative Design?

- **Generative design** (GD) is the automatic process to generate optimum feasible designs from a set of performance requirements and design rules
- Generative Design is a fundamentally disruptive **paradigm shift**. In traditional design process we build virtual or physical prototypes and then we evaluate with simulation or experiment their performance requirements. GD spawns the designs
- The emerging Generative Design technologies use algorithms to generate every possible permutation of a design solution. The designer simply enters a **range of parameters** (mass fraction, safety factor) and then chooses the *best* outcome generated by the software
- First enabler is **Topology Optimization**



Elbe Philharmonic Hall



Foam Lattice structures

# First Enabler of GD: Topology Optimization

- Only Genesis-CREO TO automatically Reconstructs the Geometry
- Design Automation “brakes down” with all other Topology Optimization tools
- CAD reconstruction is not trivial (SC, Sub-D, PTC/Freestyle, Altair/Inspire, Dassault Systems 3DX, SANDIA)
- Why bother with **CAD/NURBS**?
  - Size optimization, morphing, post-processing
  - High quality mesh for validation step
  - In the age of MBD/MBE we need:
    - Accurate mass properties
    - Semantic GD&T
    - Automated Assembly Tolerance Analyses
    - Inspection/Verification & process definition for metrology (QIF)
    - Technical Data Package (TDP) for NASA & DOE projects
- Why bother with **Facets/.stl**
  - Validation step becomes easy (re-mesh skin and then volume)
  - File size matters (i.e. larger number lattice members)
  - Cellular Lattice generation

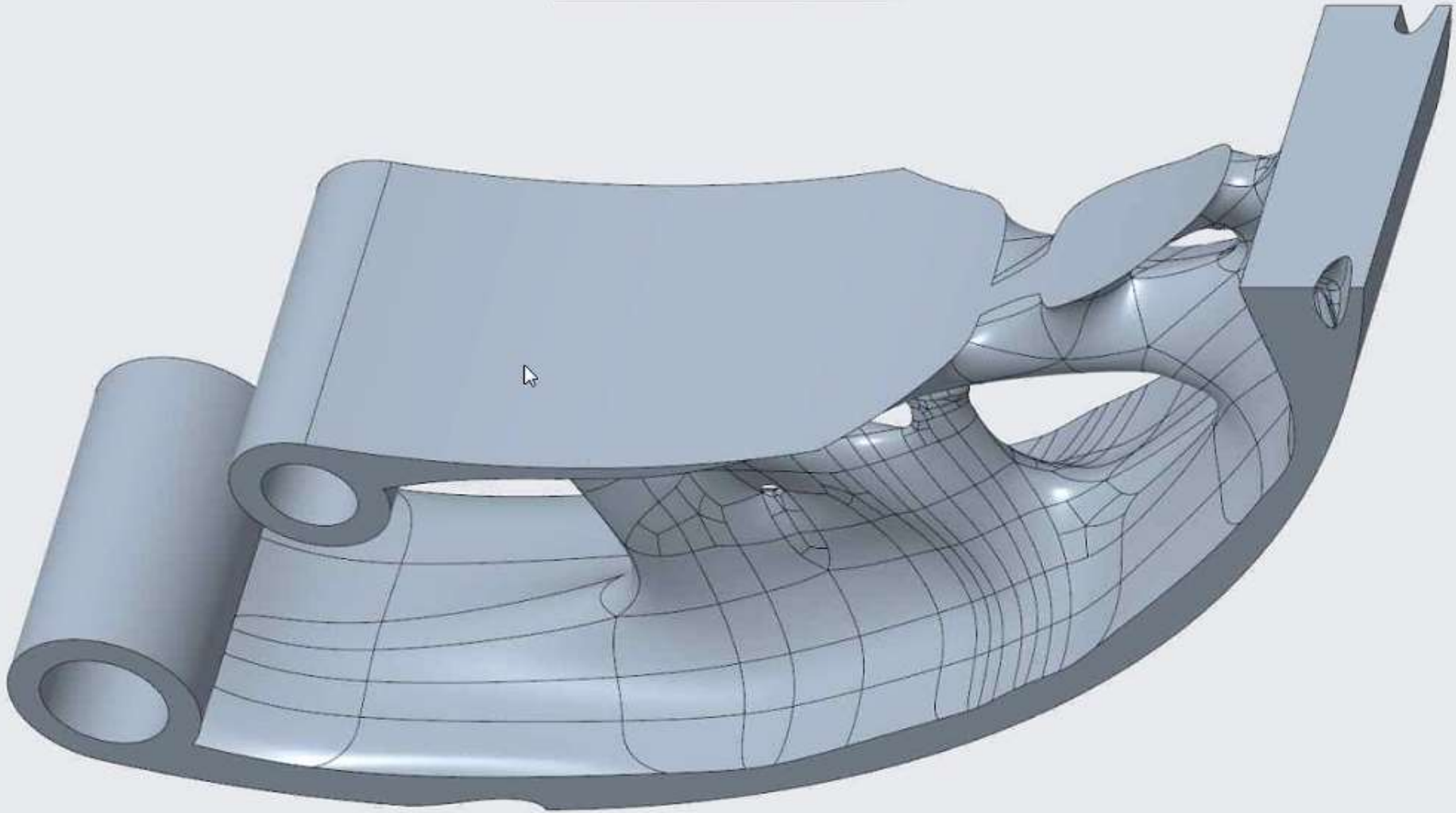




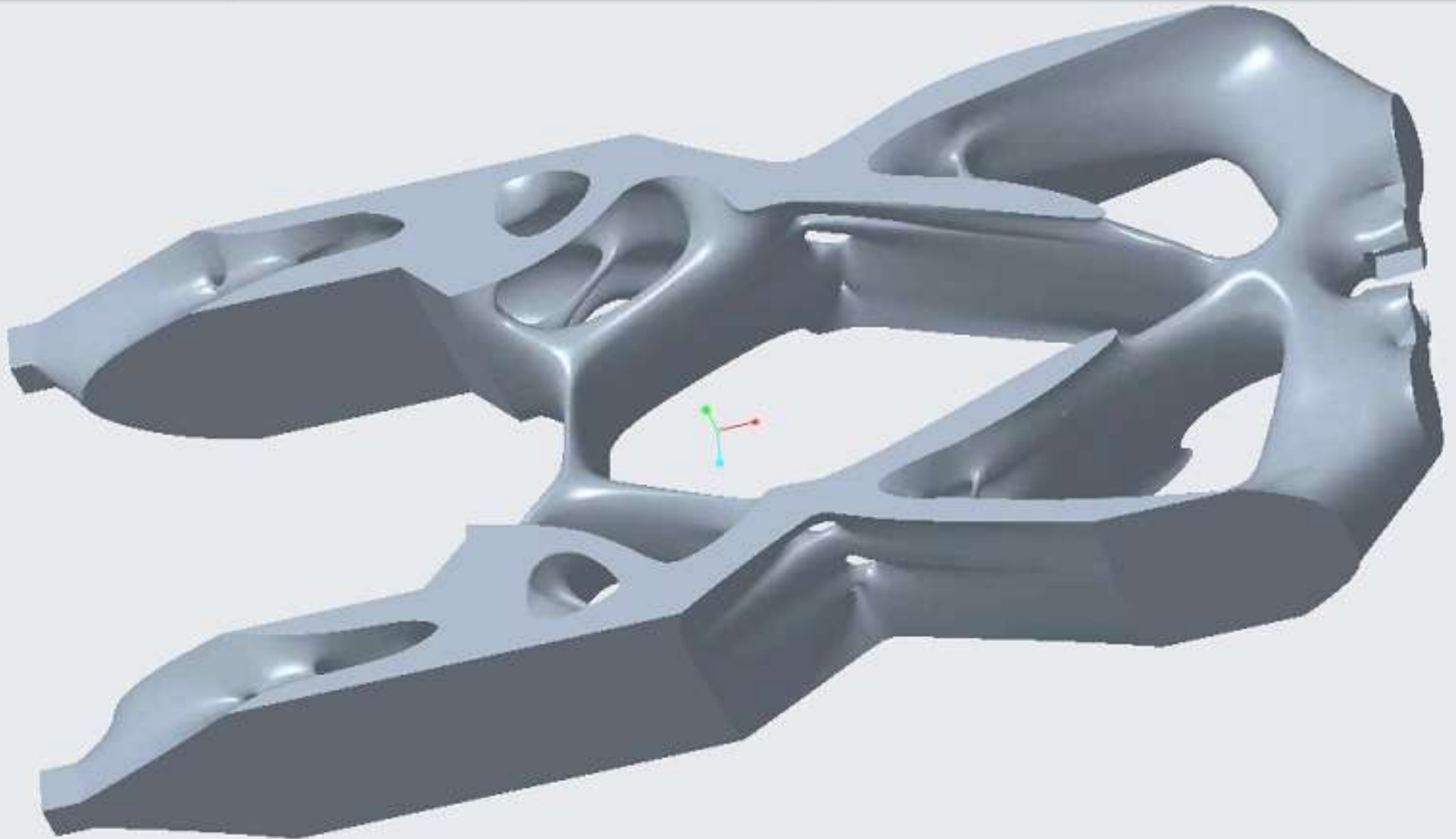


# CAD Reconstruction can be automated with CREO 5

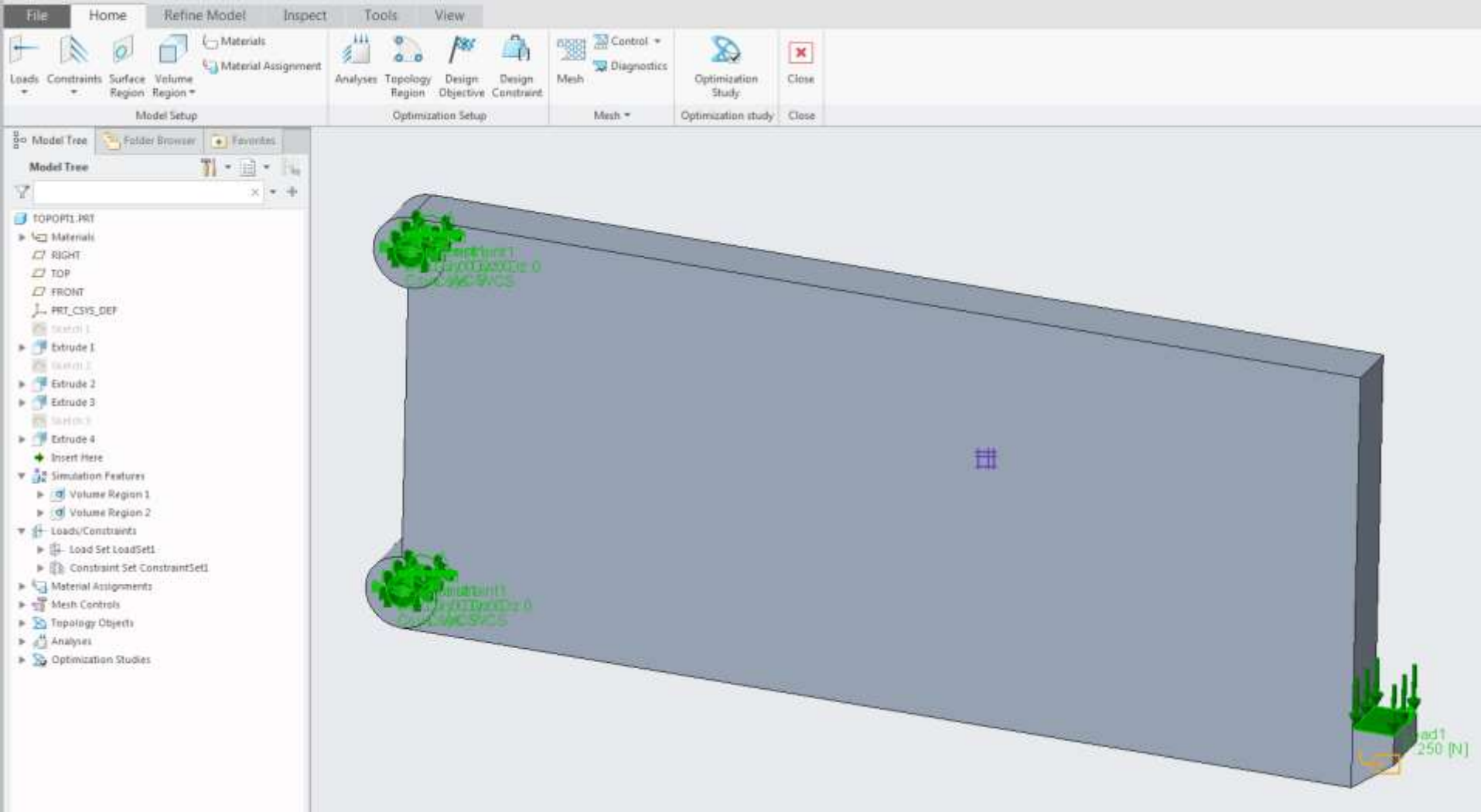
## 1 Sub-Divisional Surface Modeling with free-style feature



Sub-D models are great for:  
Geometry morphing, MBD and Meshing for Validation  
Compliance mechanism with automatic CAD reconstruction



# Simple setup of Topology Optimization Regions Loading, BC and Volume Regions within CREO





# Simple Definition of Fabrication Constraints

The image shows a CAD software interface with a 3D model of a rectangular plate. The model is gray and has a green mesh control applied to its top surface, labeled "MeshControl0 MaxSize: 125 [in]". The software interface includes a menu bar (File, Home, Refine Model, Inspect, Tools, View), a ribbon with various tool icons, and a Model Tree on the left. The Model Tree shows a hierarchy of features including TOPOPT1.PRT, Materials, Etrude 1-4, Mesh Control, and Topology Regions. A "Topology Region Definition" dialog box is open on the right, showing the following settings:

- Name: TopologyRegion1
- Init. mass fraction: 0.3
- References: Component (Part: TOPOPT1.PRT)
- Excluded regions: Volumes (Volume, Volume)
- Fabrication Constraints:
  - Coordinate system: World (WCS)
  - Constraint 1: E2 - Extrude along Z axis
  - Constraint 2: None
  - Constraint 3: None
  - Min. size control: Yes (Min. member size: 0.3, Spread fraction: 0.5)
  - Max. size control: No
- Power Rule:
  - Real value 1 (RV1): 3
  - Real value 2 (RV2): 1e-06

At the bottom right, there is a small 3D coordinate system diagram labeled "WCS" with X, Y, and Z axes.

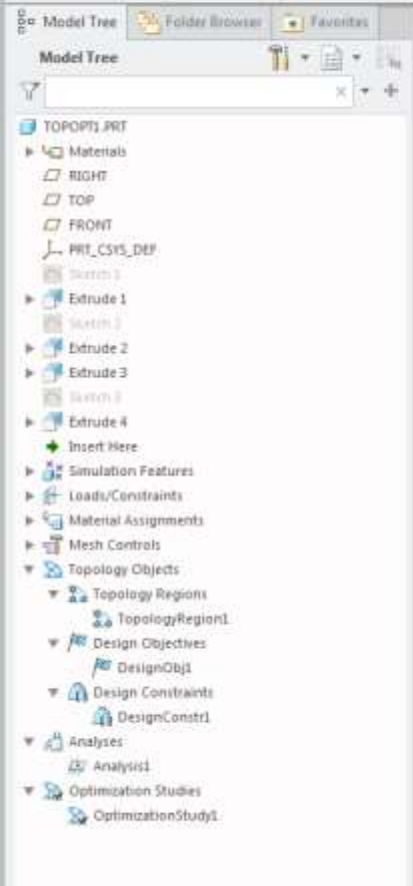


# Simple Optimization Study setup

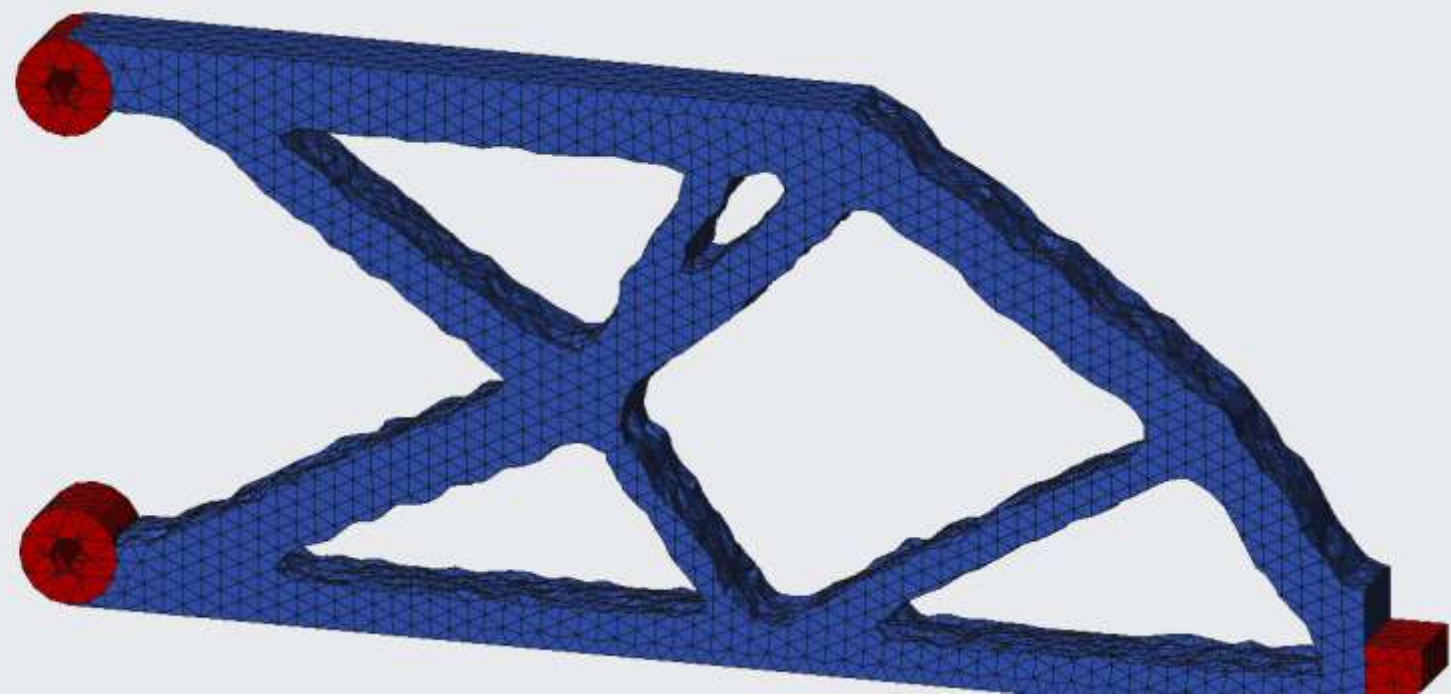
The screenshot displays the 'Optimization Study Setup' dialog box in a CAD application. The dialog is configured as follows:

- Design study:** OptimizationStudy1
- Topology regions:** 1 topology region selected
  - TopologyRegion1**
    - Init. mass fraction: 0.3
    - Fabrication Constraint 1: *EZ : Extrude along Z axis*
    - Min. size control: **Yes** | Min. member size: 0.3
    - Max. size control: **No**
- Design objectives:** 1 design objective selected
  - DesignObj1**
    - Strain Energy* | Goal: **Min.** | Weight factor: 1.000000
    - Analysis: *Analysis1 (Structural)*
- Design constraints:** 1 design constraint selected
  - DesignConstr1**
    - Mass Fraction* | Bounds: .2 - .3 | Bound type: **Actual**

Buttons at the bottom of the dialog include 'Advanced Settings', 'Run', 'OK', and 'Cancel'. The background shows a 3D model of a mechanical part with a mesh overlay, and a 'Model Tree' on the left side of the interface.



OPTIMIZATIONSTUDY1  
TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 23  
Isosurface enclosing 34% of topology region



# Design Region and Topology Optimization Results

The screenshot displays the results of a topology optimization study in a CAD environment. The top toolbar includes settings for Responses (23), Isosurfaces (0.43), Color Mesh (1.00 and 0.00), Deform (Show Undeformed Shape), Hide Elements with No Value, Section, Display, Tesselated Model Only, and Close buttons.

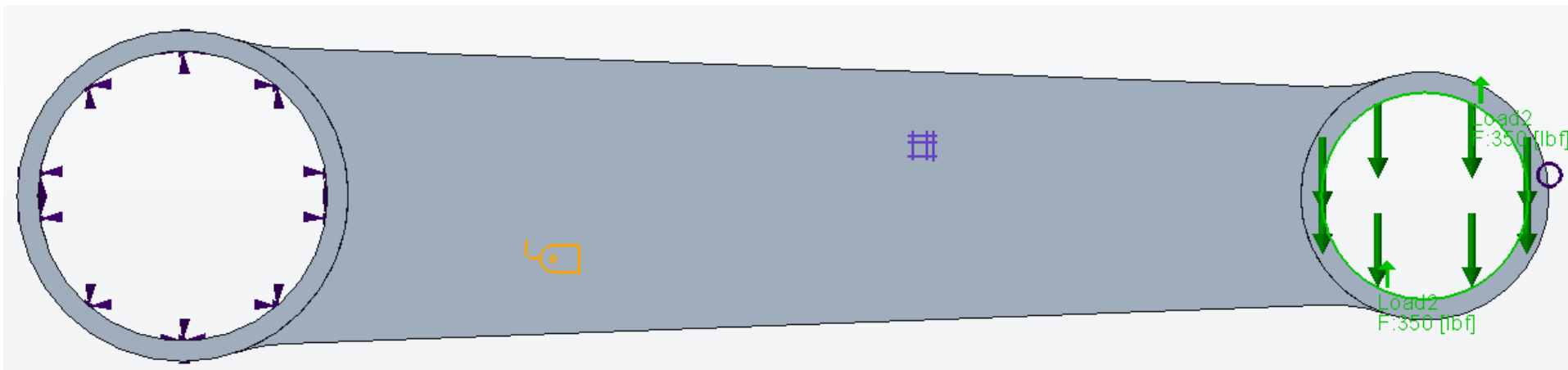
The Model Tree on the left lists the following items:

- Model Tree
- Folder Browser
- Favorites
- Model Tree
- TOPOPT1.PRT
- Materials
- RIGHT
- TOP
- FRONT
- PRT\_CSYS\_DEF
- Sketch.1
- Extrude.1
- Sketch.2
- Extrude.2
- Extrude.3
- Sketch.3
- Extrude.4
- Insert Here
- Simulation Features
- Loads/Constraints
- Material Assignments
- Mesh Controls
- Topology Objects
  - Topology Regions
    - TopologyRegion1
  - Design Objectives
    - DesignObj1
  - Design Constraints
    - DesignConstr1
- Analyses
  - Analysis1
- Optimization Studies
  - OptimizationStudy1

The central 3D view shows the optimization results for **OPTIMIZATIONSTUDY1**. The text indicates: **TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 23** and **Isosurface enclosing 33% of topology region.** The 3D model is a blue mesh structure with two red circular features on the left, representing the optimized design.

# Example 2 Robotic Arm Link

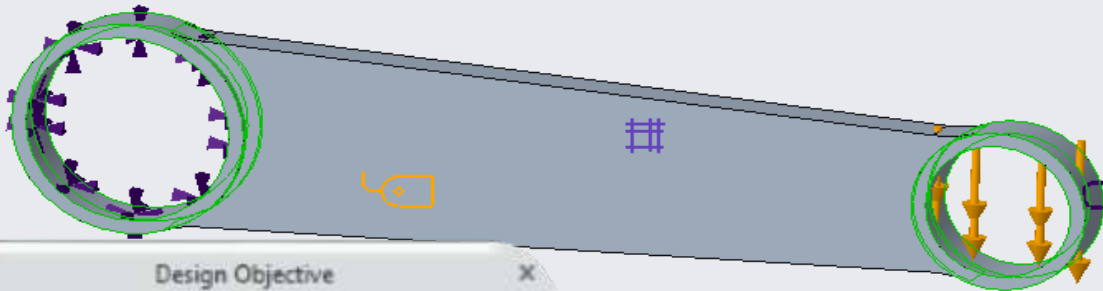
- Objective: Minimize Mass
- Constraints:
  - Maximum Von Mises Stress < 36 ksi
  - Maximum Vertical Displacement < 0.04 in
  - First Natural Frequency (out of Plane Mode) > 75 Hz
  - Third Natural Frequency (in Plane Mode) > 400 Hz





# Topology Region & Design Objective Setup

- Topology Region
  - Initial mass fraction 1.0
  - Volume Regions are excluded
  - Fabrication Constraint 1 Extrude along Z axis
  - Fabrication Constraint 2 Mirror about XZ plane
  - Minimum Member Size 0.7 in
  - Power Rule RV1 8
- Design Objective
  - Minimize mass Fraction



Topology Region Definition

Name: TopologyRegion1

Init. mass fraction: 1

References: Component  
Part: TO\_TEST1.PRT

Excluded regions: Volumes  
Volume  
Volume

Fabrication Constraints

Coordinate system: World Selected  
y z x WCS

Constraint 1: EZ : Extrude along Z axis

Constraint 2: MZX : Mirror about XZ plane

Constraint 3: None

Min. size control: Yes Min. member size: 0.7  
Spread fraction: 0.5

Max. size control: No

Power Rule

Real value 1 (RV1): 6

Real value 2 (RV2): 1e-06

OK Cancel

Design Objective

Name: Min\_MF

Response type: Mass Fraction

Objective target:  All design regions

Goal: Min Weight factor: 1

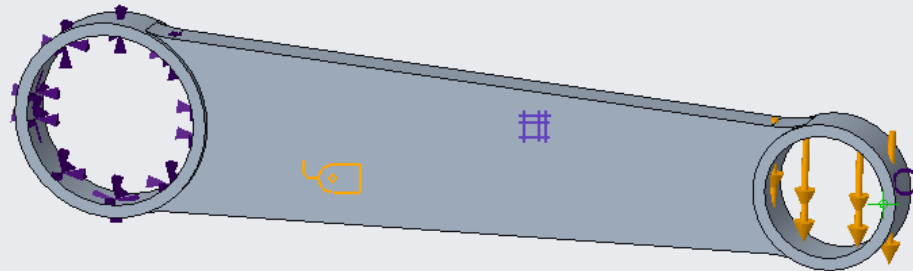
OK Cancel

# Design Constraints Setup

- Design Constraint #1
  - Maximum displacement less than 0.4 in
- Design Constraint #2
  - Maximum Stress less than 36,000 psi

The screenshot shows the 'Design Constraint' dialog box for 'Displacement\_limit'. The 'Name' field is 'Displacement\_limit', 'Response type' is 'Displacement', and 'Response Component' is 'Translation Magnitude'. The 'Constraint target' is 'Vertex (EdgeStart)'. The 'Upper Bound' is set to 0.04. The 'Bound Type' is 'Actual'.

The screenshot shows the 'Design Constraint' dialog box for 'Stress\_limit'. The 'Name' field is 'Stress\_limit', 'Response type' is 'Stress', and 'Response Component' is 'von Mises'. The 'Constraint target' is 'Surfaces, Volumes, Components' with 'Part: TO\_TEST1.PRT' selected. The 'Upper Bound' is set to 36000. The 'Bound Type' is 'Actual'.



# Optimization Study Setup

Optimization Study Setup

Design study: OptimizationStudy1

Topology regions: 1 topology region selected

**TopologyRegion1**

Init. mass fraction: 1  
Fabrication Constraint 1: *EZ : Extrude along Z axis*  
Fabrication Constraint 2: *MZX : Mirror about XZ plane*  
Min. size control: **Yes** | Min. member size: 0.7  
Max. size control: **No**

Design objectives: 1 design objective selected

**Min\_MF**

*Mass Fraction* | Goal: **Min.** | Weight factor: 1.000000

Design constraints: 2 design constraints selected

**Displacement\_limit**

*Displacement* | Bounds: 0.04 | Bound type: **Actual**

**Stress\_limit**

*Stress* | Bounds: 36000 | Bound type: **Actual**

Advanced Settings

Run OK Cancel

Optimization Study Advanced Settings

Analysis **Design** File Output

Max. design cycles: 100

**Methods**

Topology index: Normalized Reciprocal

Linearization: Regular

**Convergence**

Hard absolute: 0.001 Hard relative: 0.001

Hard max. violation: 0.005

Soft constraint: 0.001 Soft variable: 0.001

**Move Limits**

Fractional topology: 1e-06 Min. topology: 0.1

+ Screening

+ Parameters

Reset OK Cancel

# Convergence Monitoring & Results Viewing during execution

Optimization Status (OptimizationStudy1)

- □ ×

## Optimization Status

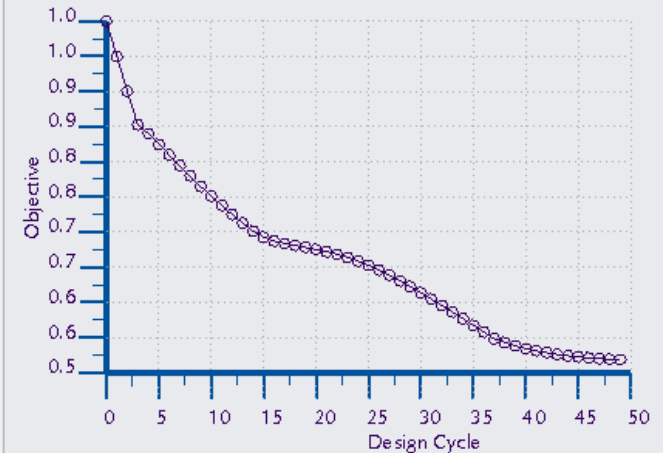
Design Cycle : 49  
Objective : 5.183537E-01  
Maximum Violation : 0.0%  
Time Elapsed : 00:14:45  
Status : Hard Convergence

10	7.5113E-01	0.0%
11	7.3786E-01	0.0%
12	7.2498E-01	0.0%
13	7.1265E-01	0.0%
14	7.0133E-01	0.1%
15	6.9269E-01	0.2%
16	6.8717E-01	0.1%
17	6.8360E-01	0.0%
18	6.8068E-01	0.0%
19	6.7793E-01	0.0%
20	6.7513E-01	0.0%
21	6.7194E-01	0.0%
22	6.6828E-01	0.0%
23	6.6387E-01	0.0%
24	6.5859E-01	0.0%
25	6.5252E-01	0.0%
26	6.4579E-01	0.0%
27	6.3844E-01	0.0%
28	6.3050E-01	0.0%
29	6.2220E-01	0.0%
30	6.1353E-01	0.0%
31	6.0458E-01	0.0%
32	5.9542E-01	0.0%
33	5.8613E-01	0.0%
34	5.7667E-01	0.0%
35	5.6715E-01	0.0%
36	5.5749E-01	0.0%
37	5.4780E-01	0.0%
38	5.4264E-01	0.0%
39	5.3795E-01	0.0%
40	5.3392E-01	0.0%
41	5.3084E-01	0.0%
42	5.2816E-01	0.0%
43	5.2564E-01	0.0%
44	5.2382E-01	0.0%
45	5.2229E-01	0.0%
46	5.2086E-01	0.0%
47	5.1959E-01	0.0%
48	5.1878E-01	0.0%
49	5.1835E-01	0.0%

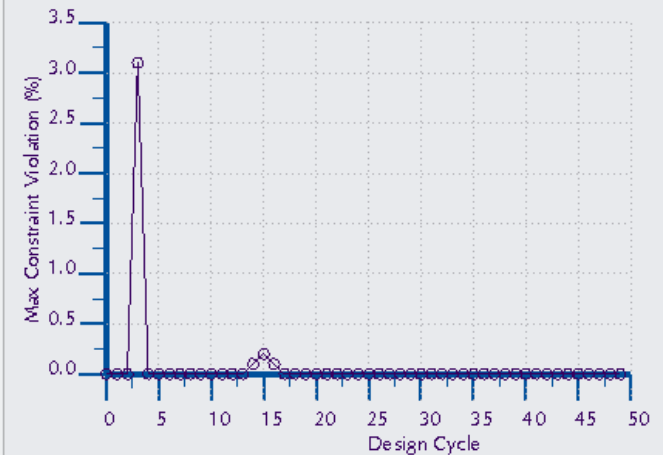


COMPLETION CODE: 1  
CPU TIME SPENT IN MODULE HCONVG = 49.06 SEC, IN TOTAL = 842. SEC  
ELAPSED TIME IN MODULE HCONVG = 49.00 SEC, IN TOTAL = 884. SEC  
CPU TIME SPENT IN MODULE TSURF = 0.78 SEC, IN TOTAL = 843. SEC  
ELAPSED TIME IN MODULE TSURF = 1.00 SEC, IN TOTAL = 885. SEC  
CPU TIME SPENT IN MODULE FINISH = 0.08 SEC, IN TOTAL = 843. SEC  
ELAPSED TIME IN MODULE FINISH = 0.00 SEC, IN TOTAL = 885. SEC

### Objective History



### Constraint History



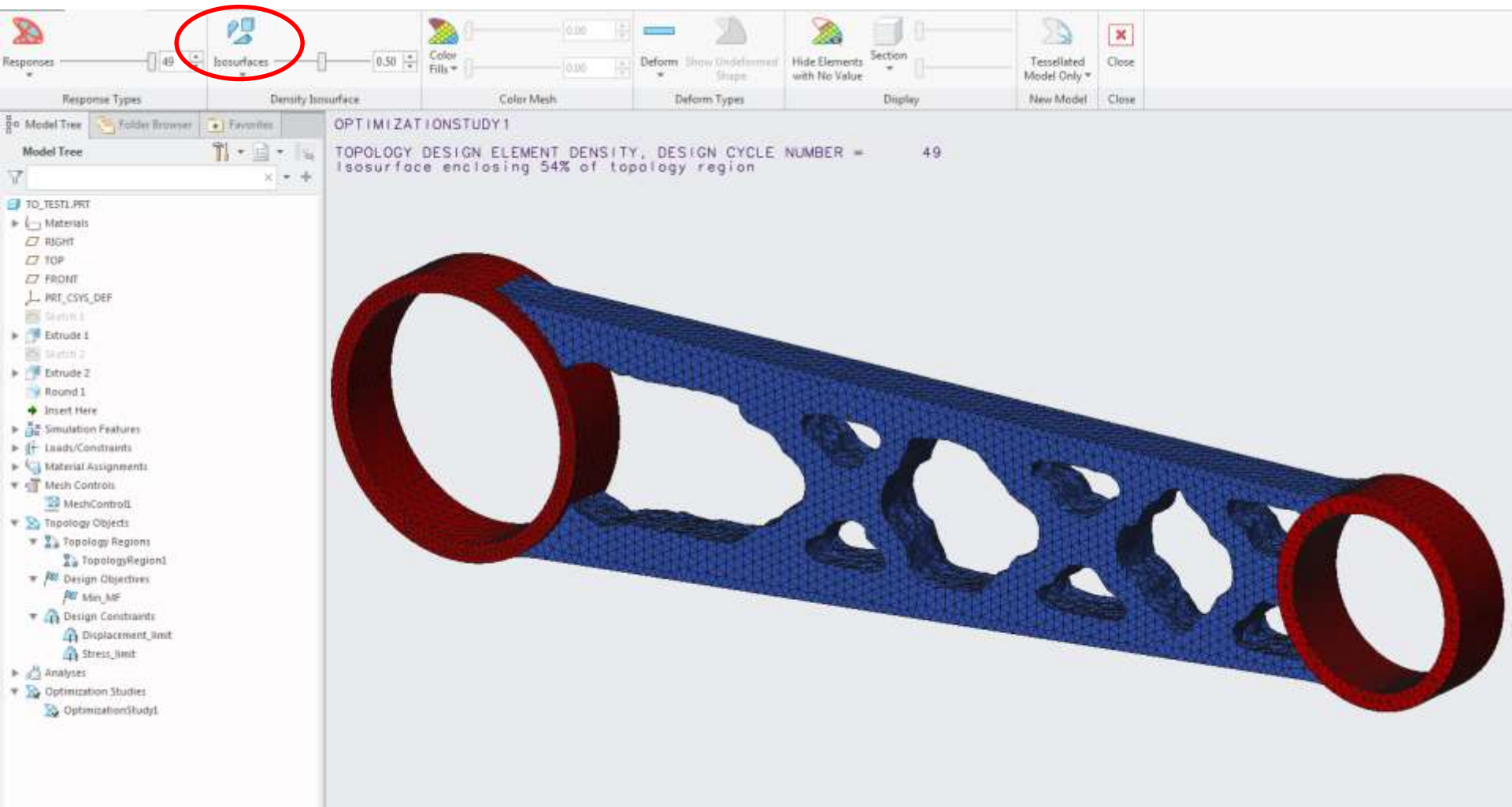
Show Results

Abort

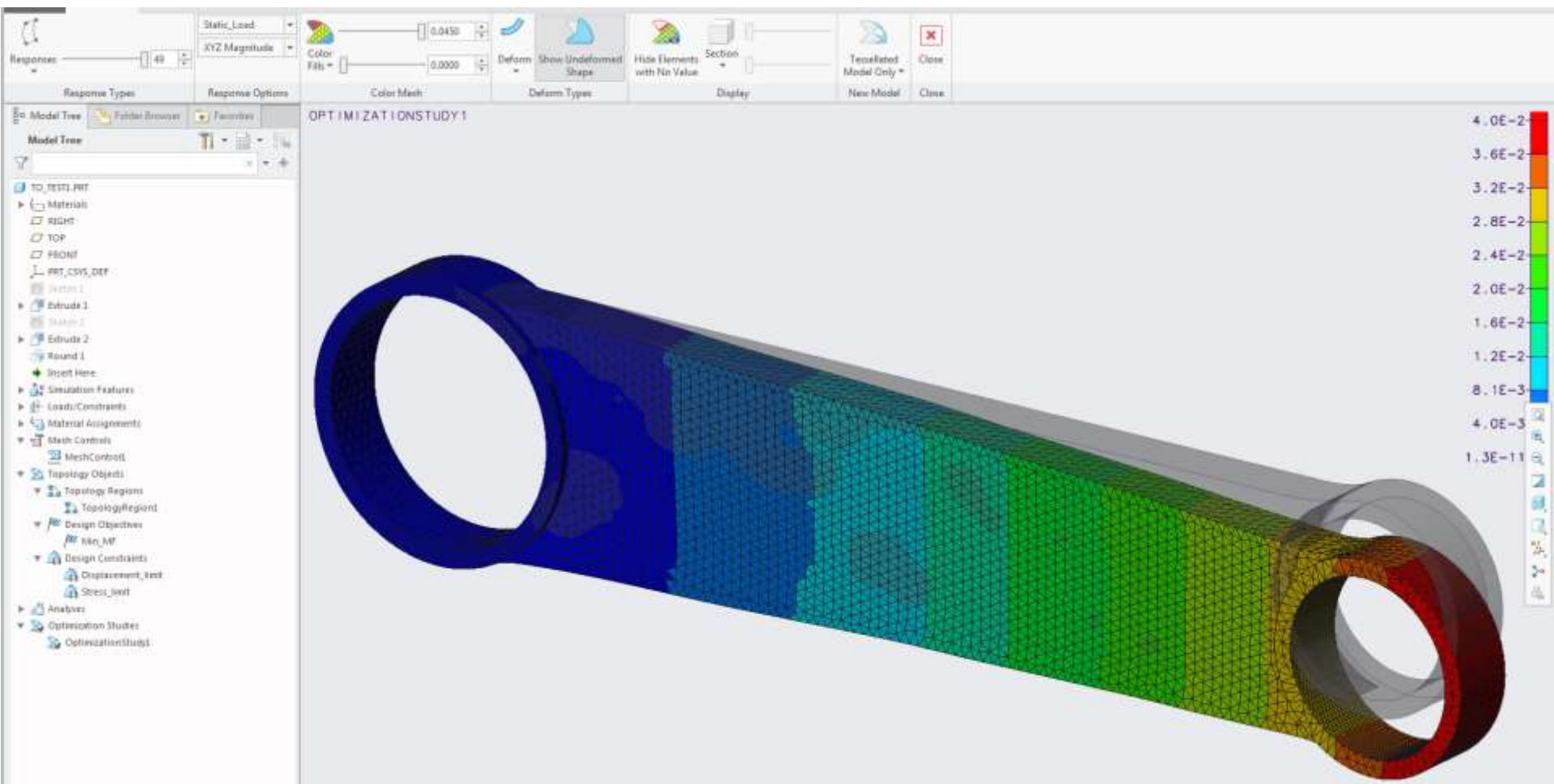
Close



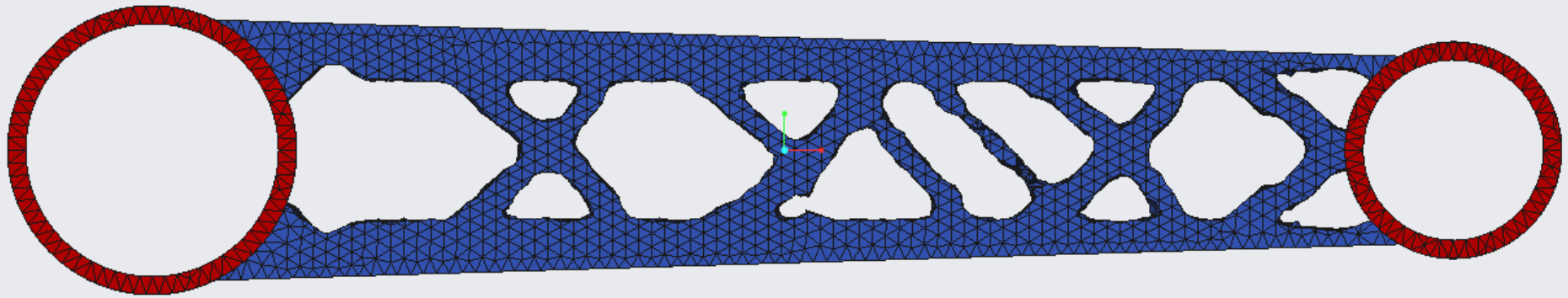
# Isosurface Enclosing 54% of Topology Region



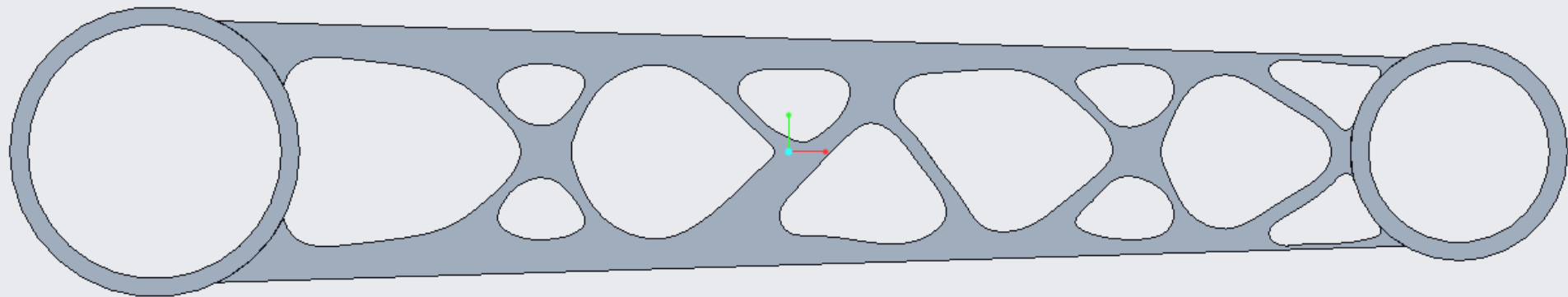
# Deformed and Un-deformed Shape Topology Optimization Model



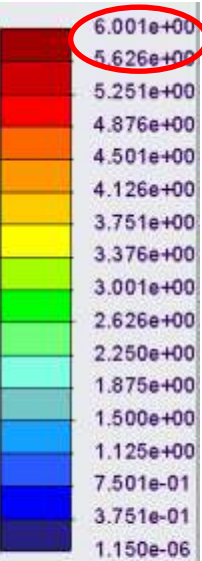
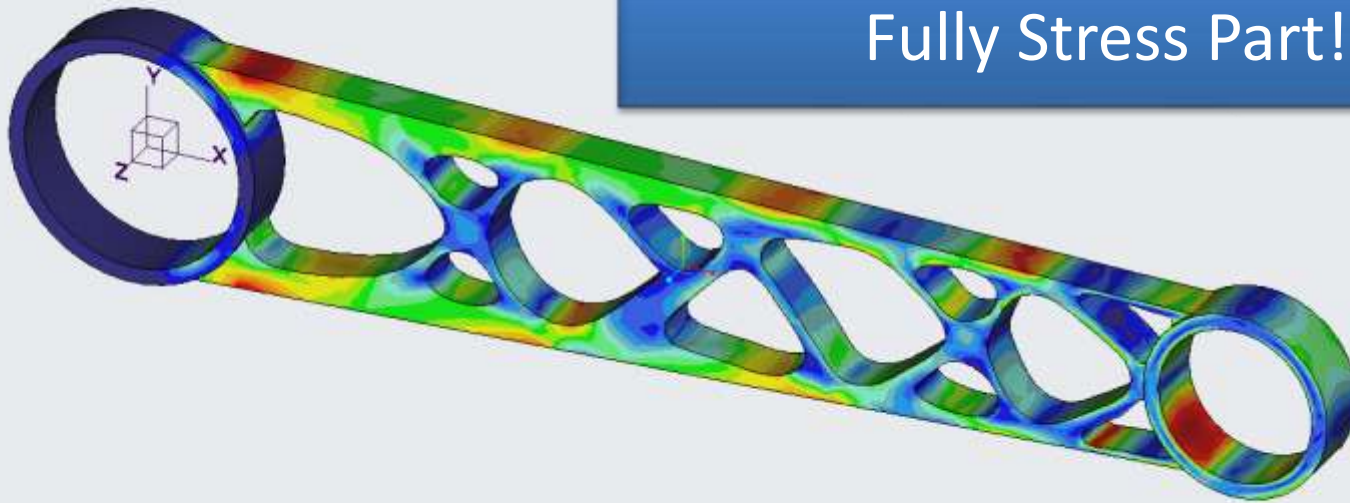
# CREO Topology tessellated output



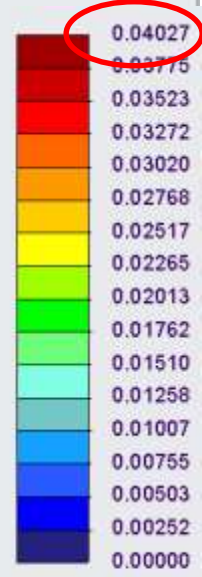
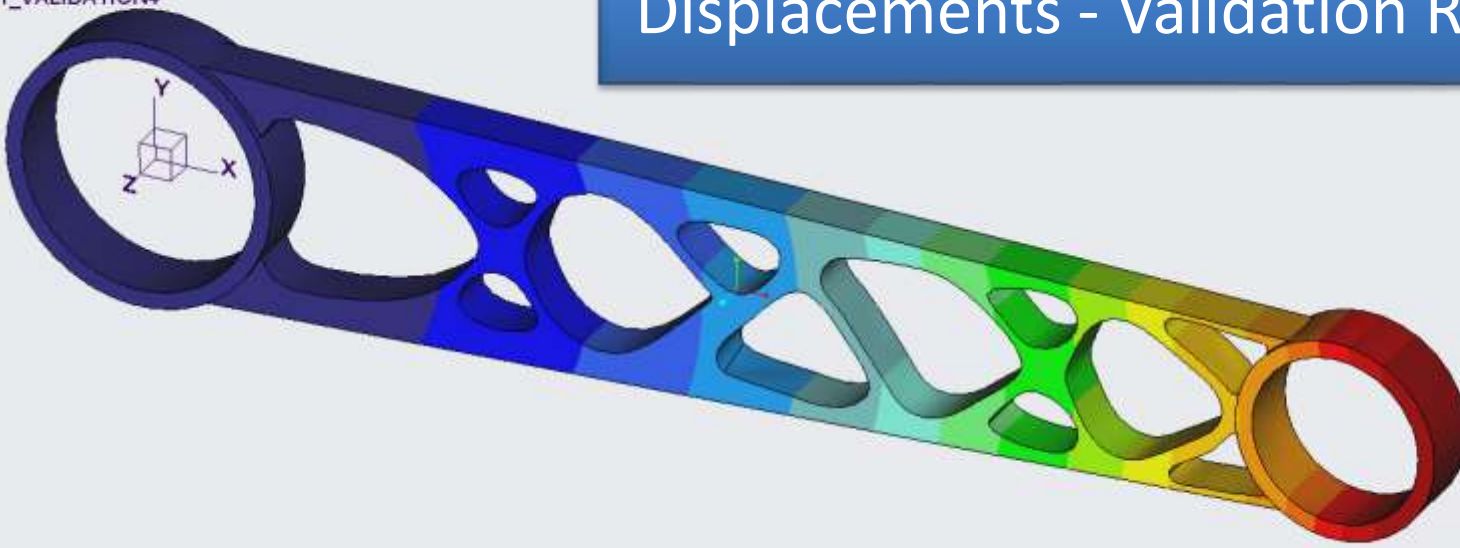
## Simple Manual Reconstruction



# Von Mises Stress Validation Run Fully Stress Part!



# Displacements - Validation Run

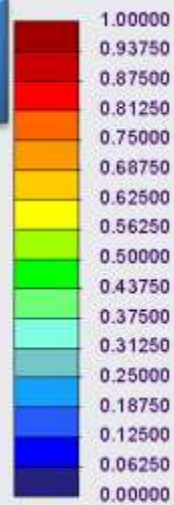
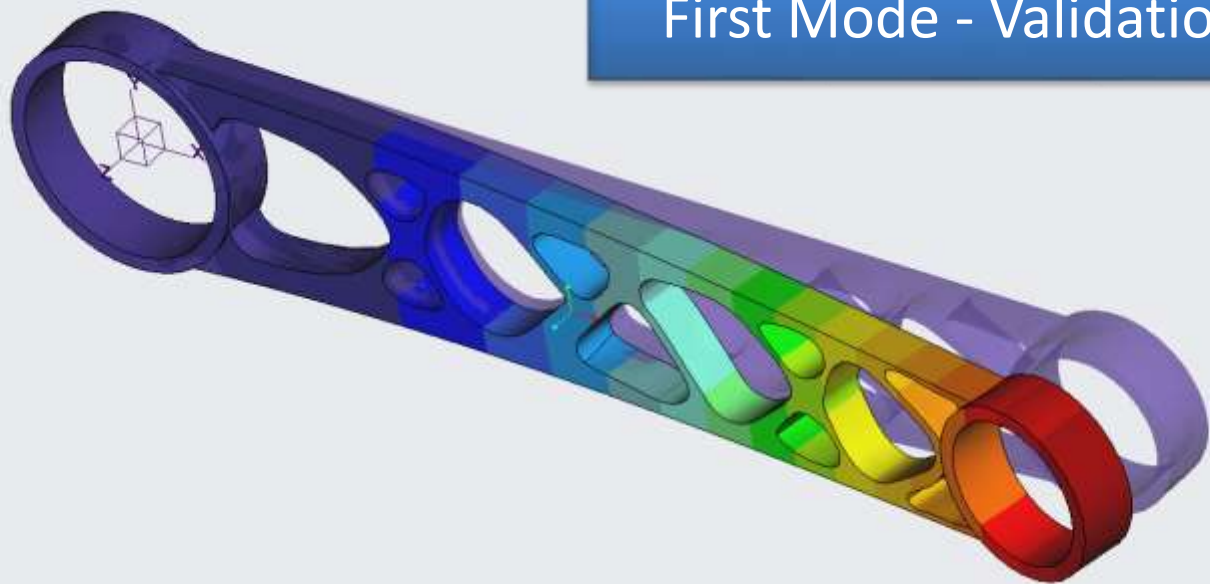




Displacement Magnitude (WCS)

(in)  
Deformed  
Max Disp 1.0000E+00  
Scale 2.1500E+00  
Mode 1, +7.5733E+01

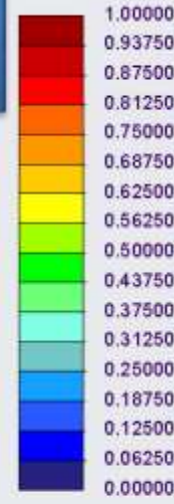
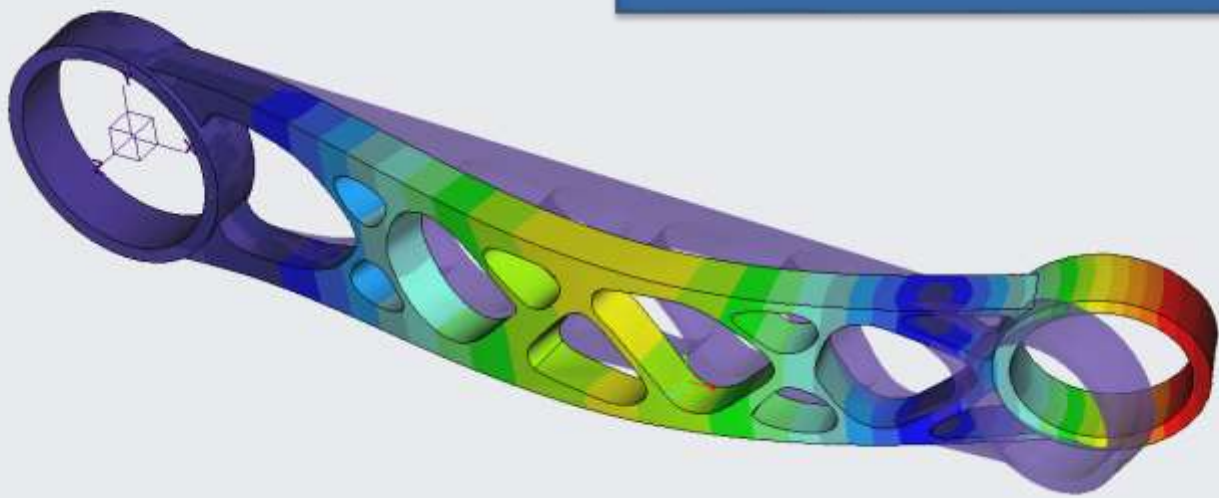
# First Mode - Validation Run



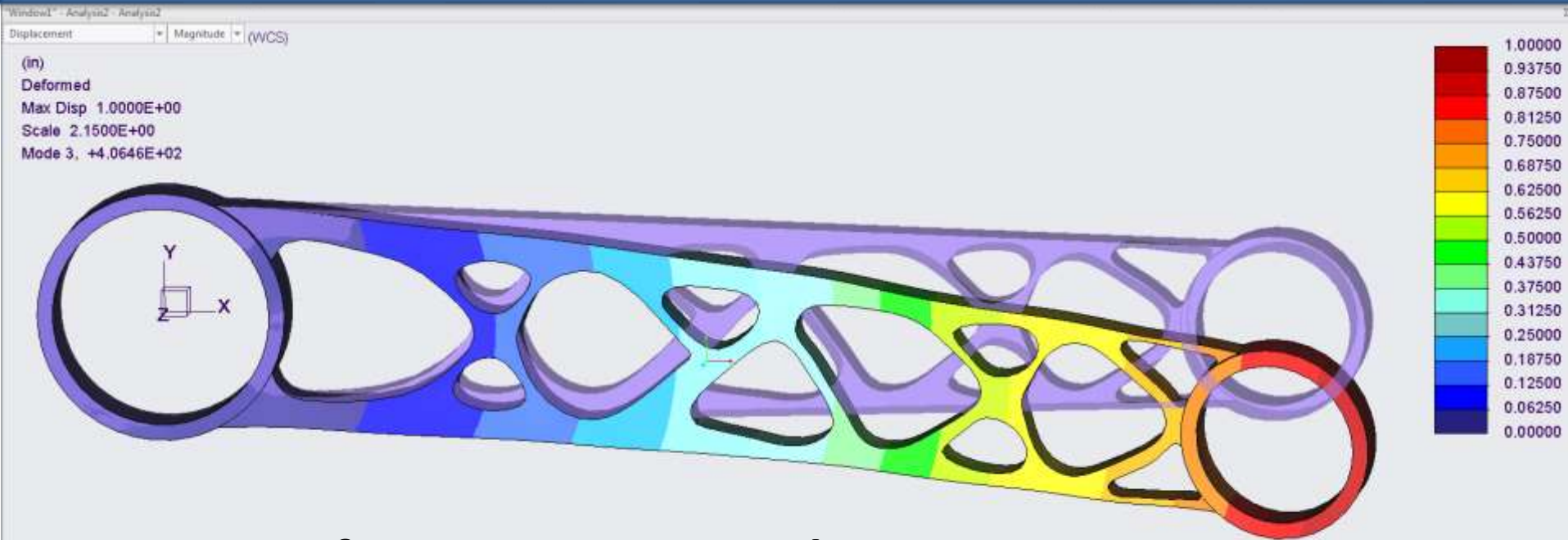
Displacement Magnitude (WCS)

(in)  
Deformed  
Max Disp 1.0000E+00  
Scale 2.1500E+00  
Mode 2, +3.8620E+02

# Second Mode - Validation Run



# Third Mode Shape (in Plane Mode) – Validation Run

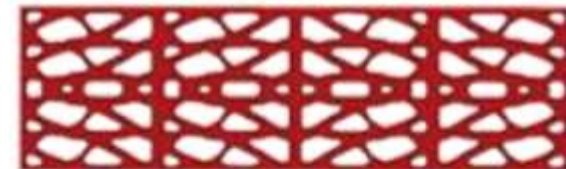
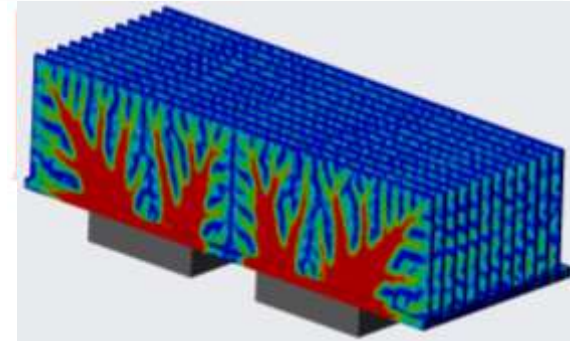


## Summary of Optimization Study

- Objective: Weight Reduction about 50%
- Constraints:
  - Maximum Von Mises Stress 6 ksi < 36 ksi
  - Maximum Vertical Displacement 0.04 < 0.05 in
  - First Natural Frequency (out of Plane Mode) 76 Hz > 75 Hz
  - Third Natural Frequency (in Plane Mode) 406 Hz > 400 Hz

# Useful Topology Optimization Features

- Manufacturing constraints
  - Symmetry / pattern grouping / **periodic patterns**
  - Minimum /Maximum Member Size Control
  - Draw direction constraints for **AM**, extrusion, casting, stamping, radial filling, machining, etc.
  - Sheet metal
  - Additive manufacturing (slopes for support-less elements)
- Multiphysics
  - Structural, **Thermal, Fluid**, Electromagnetics
- Optimization Constraints
  - Stress, deflection, natural frequency, temperature
  - Global and local buckling (lattice elements)
- **Robustness evaluation**
  - Load magnitude uncertainties ( $\mu, \sigma$ )
  - Load Orientation uncertainties ( $\mu, \sigma$ )
  - Material properties uncertainties ( $\mu, \sigma$ )
- **No Design Space Required**, only Loads and BC



Optimum using New P0X+P0Z  
4x4 = 16 Patterns repeated



Optimum using New P0X + P0Z  
8x2=16 Patterns repeated






# Fabrication Constraints in CREO TO

## Fabrication Constraints

World  Selected

Coordinate system:

 WCS

Constraint 1: MYZ : Mirror about YZ plane

None

MYZ : Mirror about YZ plane

MZX : Mirror about XZ plane

MYX : Mirror about XY plane

Constraint 2: EX : Extrude along X axis

EY : Extrude along Y axis

EZ : Extrude along Z axis

Constraint 3: FGX : Fill X axis (inside to out)

FGY : Fill Y axis (inside to out)

Min. size cont FGZ : Fill Z axis (inside to out)

FBX : Fill X axis (- to +)

FBY : Fill Y axis (- to +)

Max. size cont FBZ : Fill Z axis (- to +)

FTX : Fill X axis (+ to -)

FTY : Fill Y axis (+ to -)

FTZ : Fill Z axis (+ to -)

### Power Rule

Real value 1 (F F0X : Fill X axis (zero to + and -)

F0Y : Fill Y axis (zero to + and -)

F0Z : Fill Z axis (zero to + and -)

Real value 2 (F FSX : Fill X axis (outside to in)

FSY : Fill Y axis (outside to in)

FSZ : Fill Z axis (outside to in)

SBX : Sheet normal to X axis (- to +)

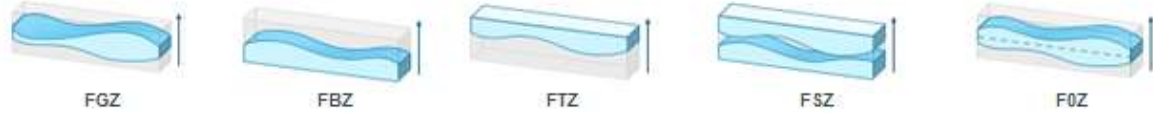
SBY : Sheet normal to Y axis (- to +)

- Symmetry
- Extrusion
- Filling and Filling Symmetric
- Stamping
- Uniform
- Radial Filling and Spokes
- Periodic
  
- Can impose up to 3 fabrication constraints
- Min/Max Member Size



# Visualization of Fabrication Constraints in CREO TO

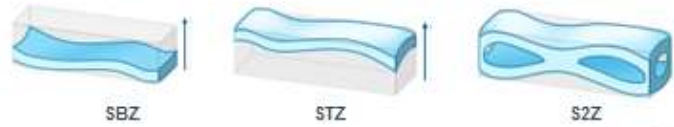
## Filling (Castings)



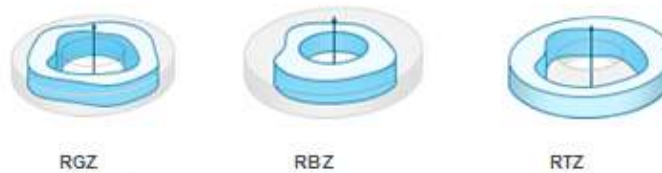
## Extrusion and Uniforms



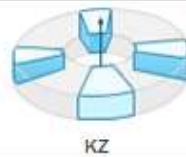
## Stamping



## Radial Filling



## Radial Spokes



## Mirror, Cyclic and Periodic Symmetry

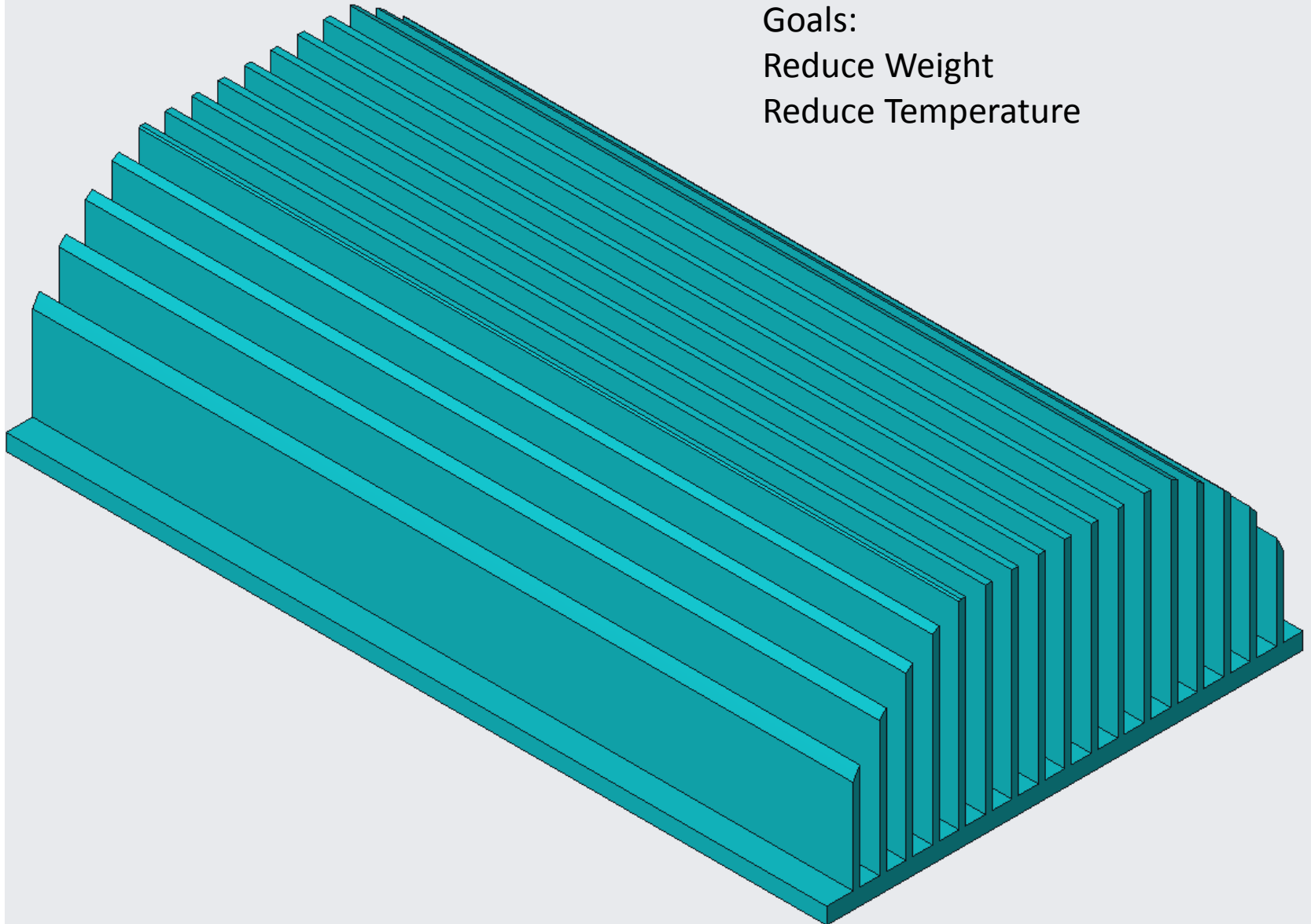


## Minimum & Maximum Member Size



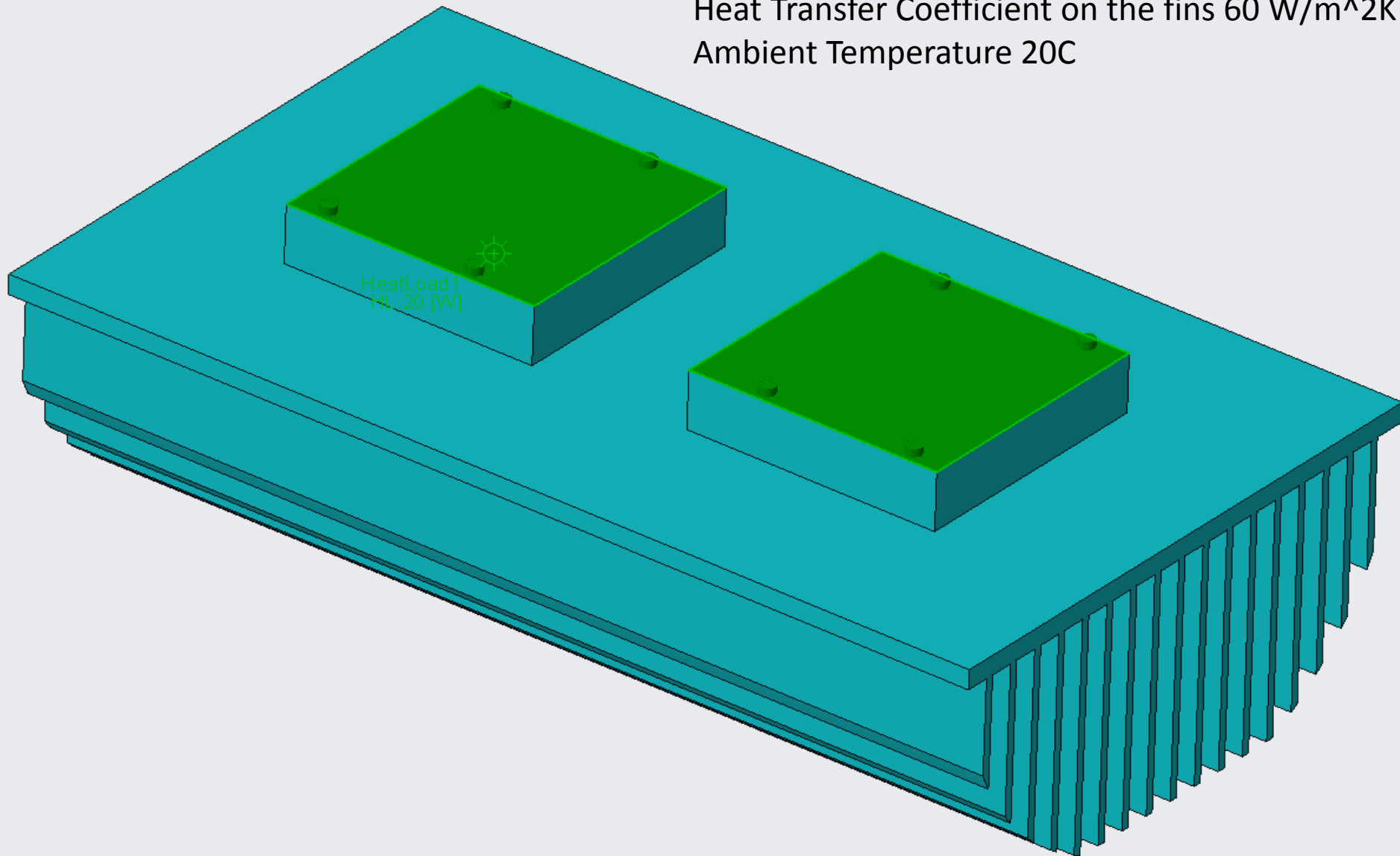
# Example 3 Lightweight the AM Heat Exchanger

Goals:  
Reduce Weight  
Reduce Temperature



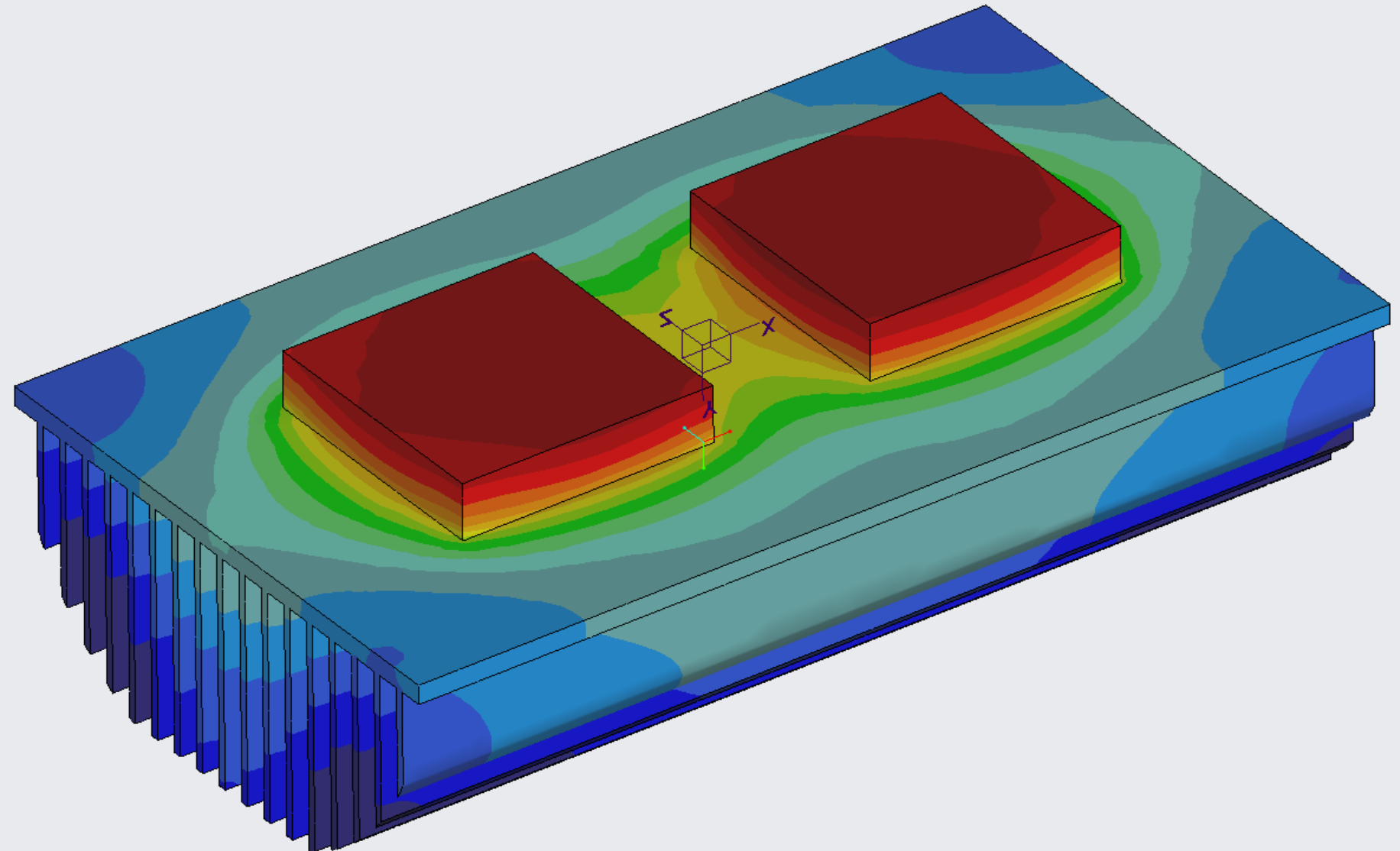
# Heat Load and Convection

Heat Transfer Coefficient on the fins  $60 \text{ W/m}^2\text{K}$   
Ambient Temperature  $20\text{C}$



# Temperature Distribution

HANGER

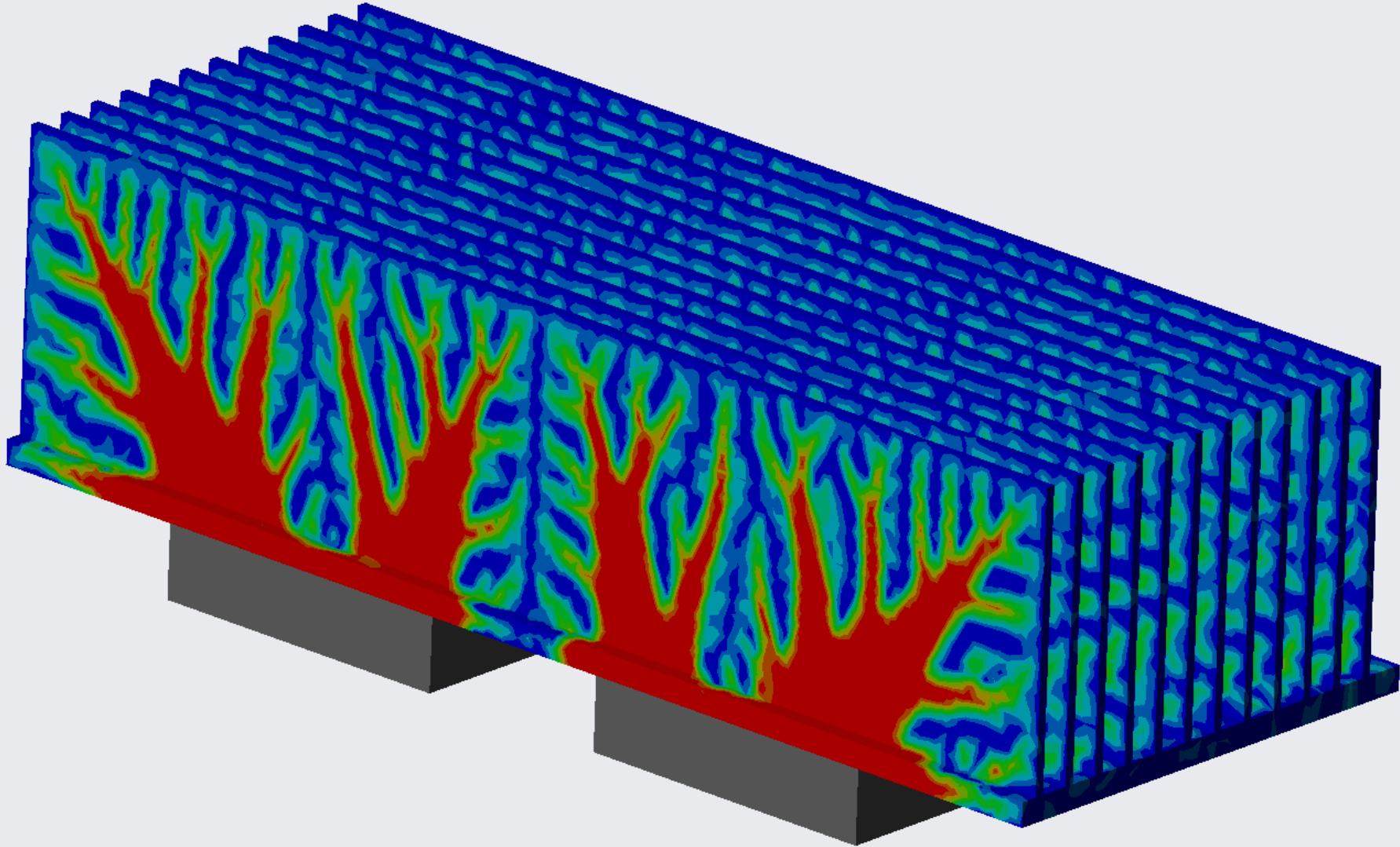




# Topology Density Field

OPTIMIZATIONSTUDY2

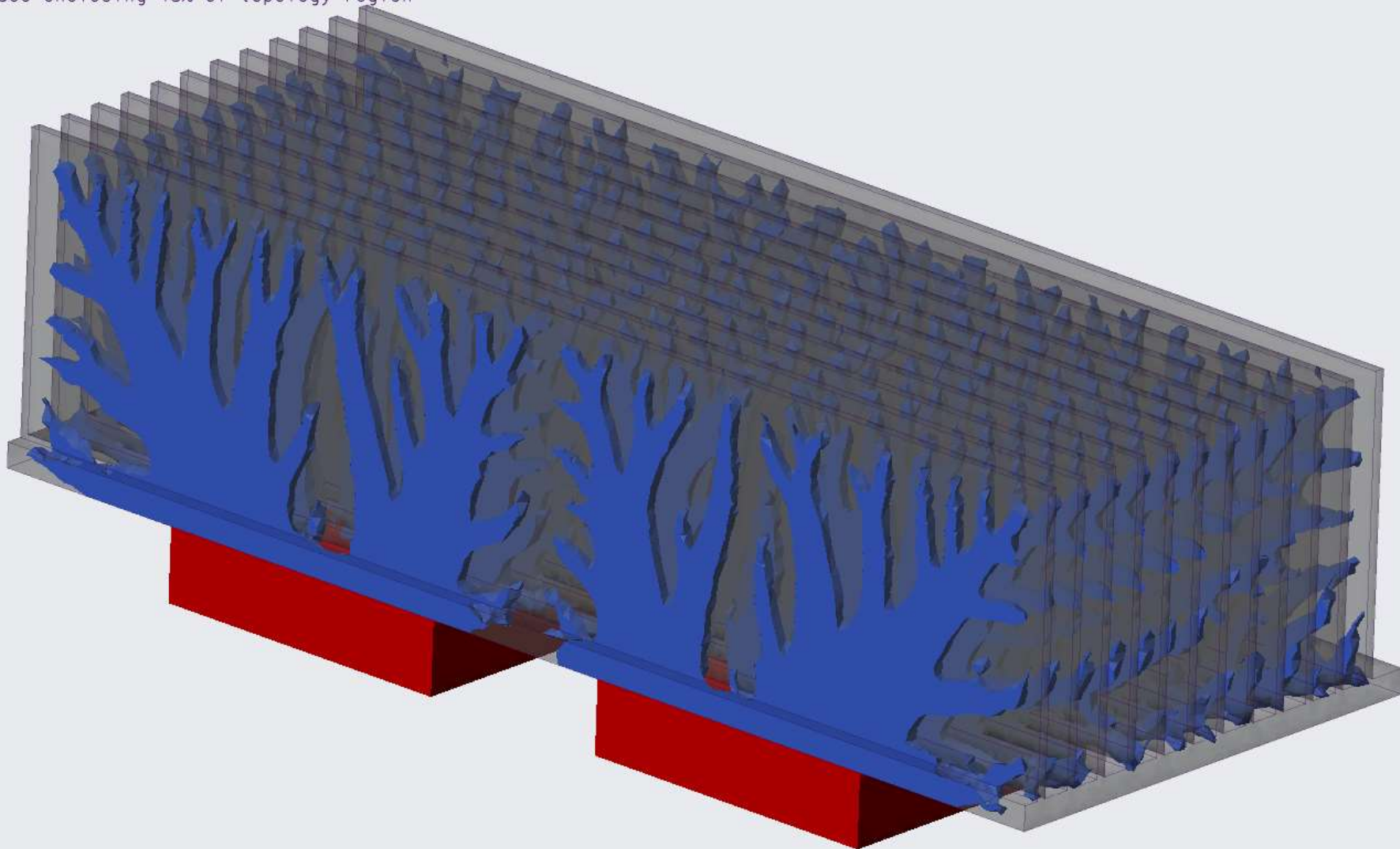
TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 25



# Design Region and Topology Optimization Results

OPTIMIZATIONSTUDY2

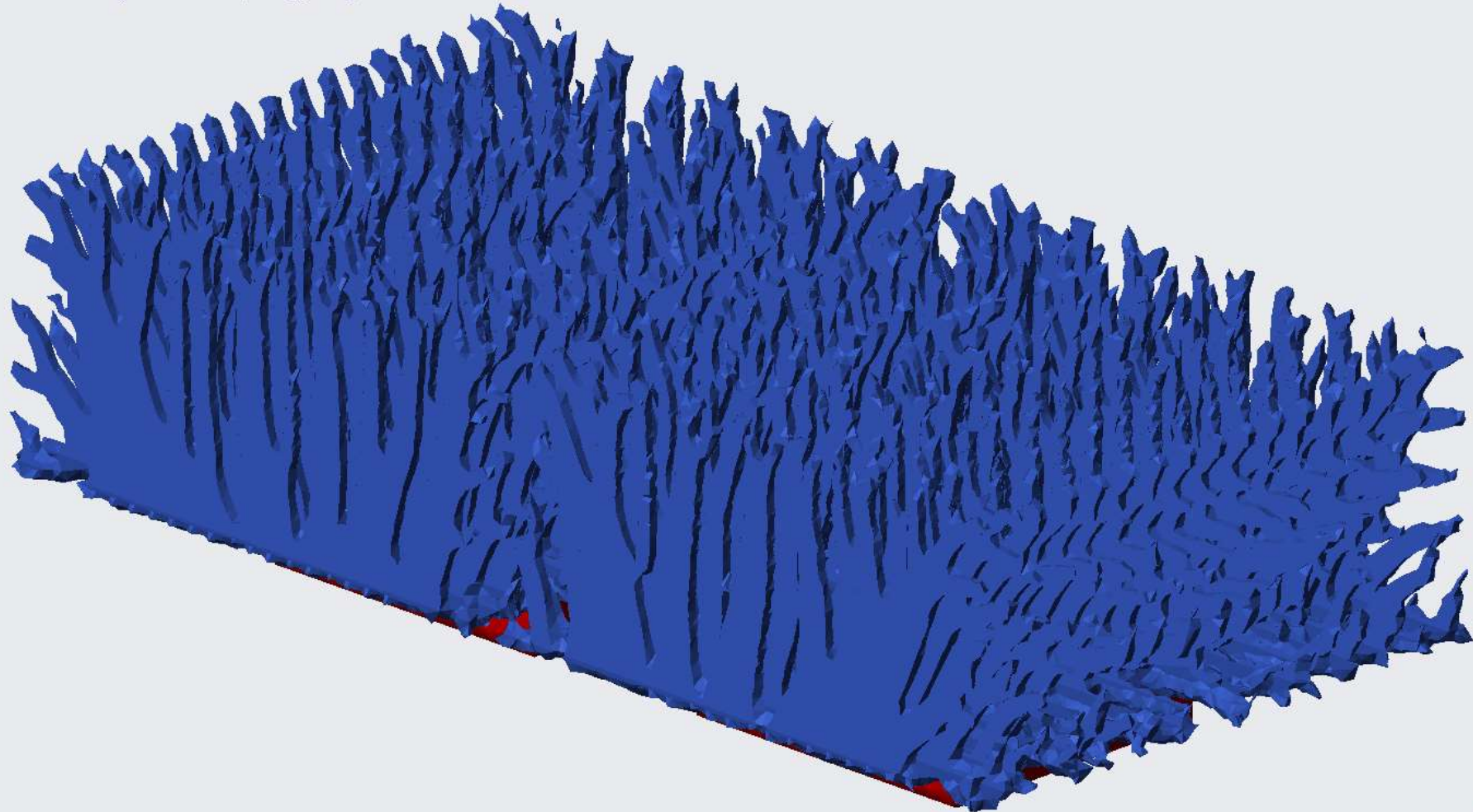
TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 25  
Isosurface enclosing 48% of topology region



# Topology Optimization Results

OPTIMIZATIONSTUDY2

TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 25  
Isosurface enclosing 48% of topology region





# Second Enabler of GD: Frame Lattice Generation Cell Homogenization into Topology Optimization

Cell Geometry Definition

Cell Size, Configuration, Shape, etc.

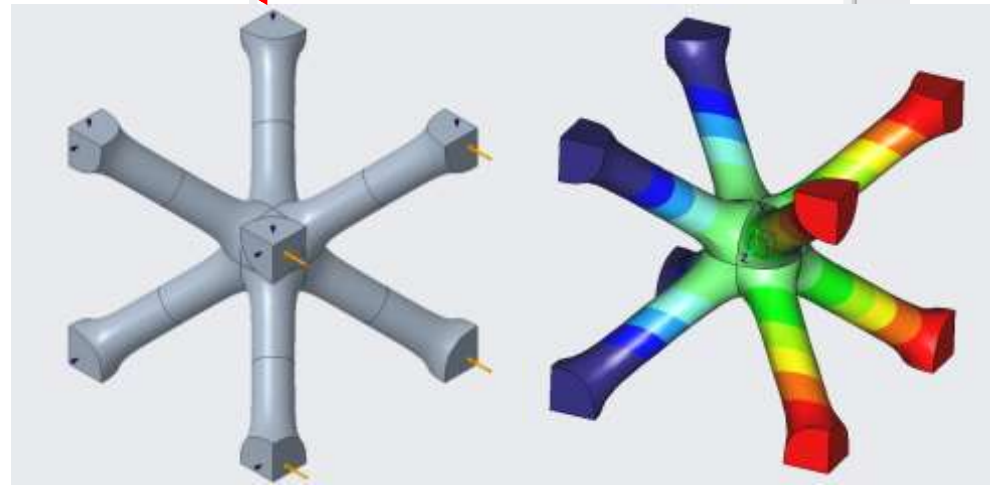
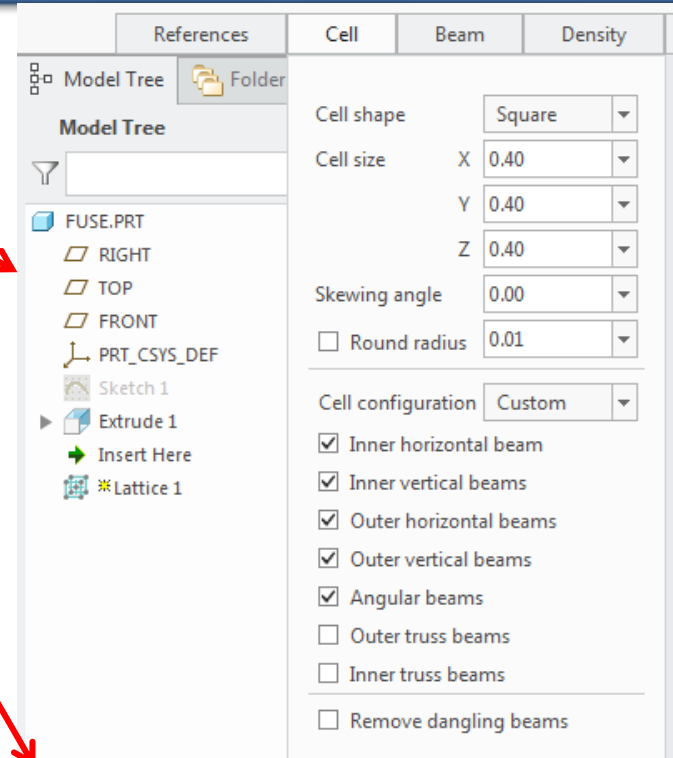
Homogenization

Material Properties Computation

Cell Size (periodic)  
Density  $\rho$  (mass fraction)  
Modulus of Elasticity ( $E_x, E_y, E_z$ )  
Poisson's ratio ( $\nu_x, \nu_y, \nu_z$ )  
Thermal Conductivity ( $K_x, K_y, K_z$ )  
Coefficient of Thermal Expansion  $\alpha$   
Porous Media properties for CFD

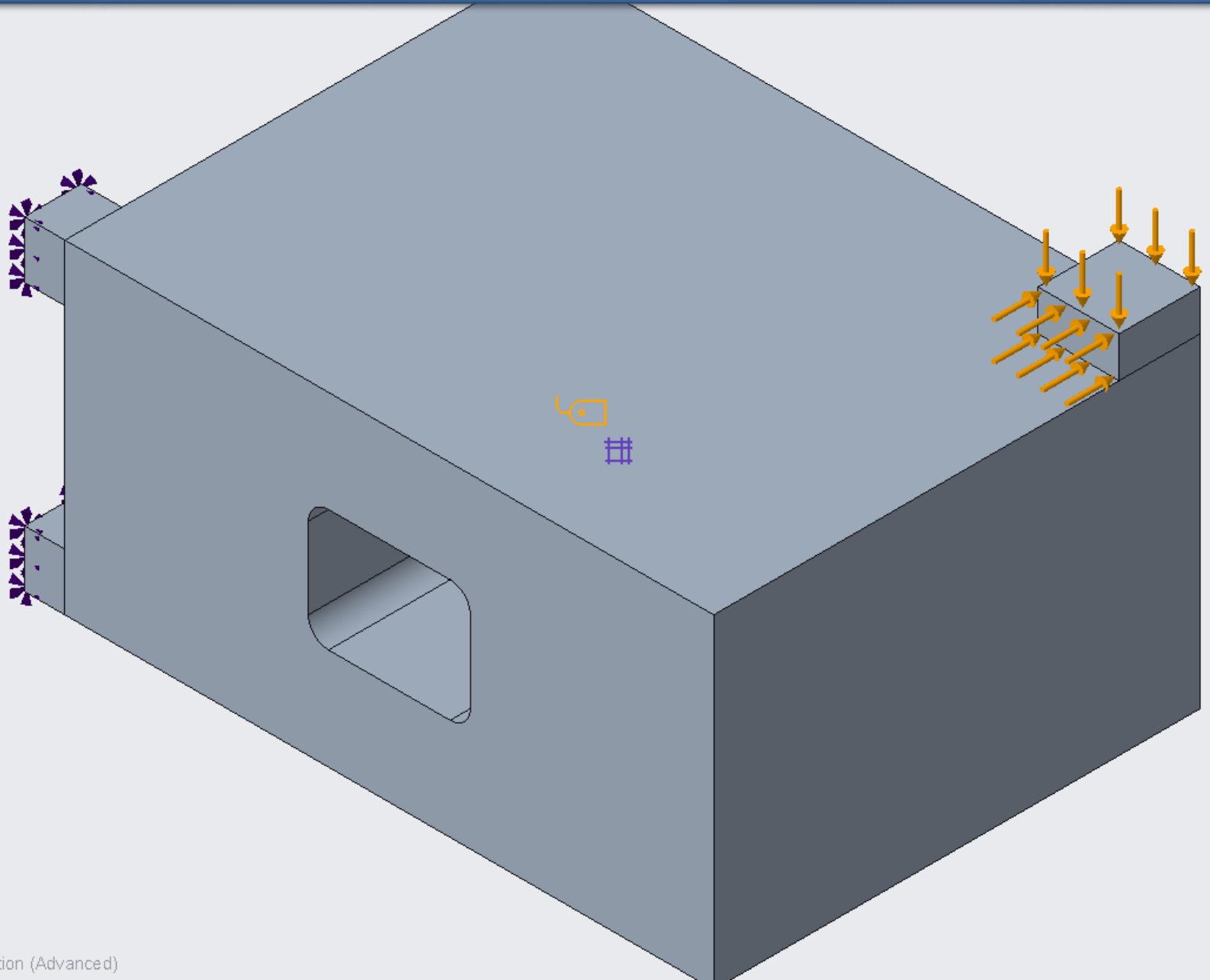
Design Space &  
Topology Optimization

Optimal Geometry with this cell

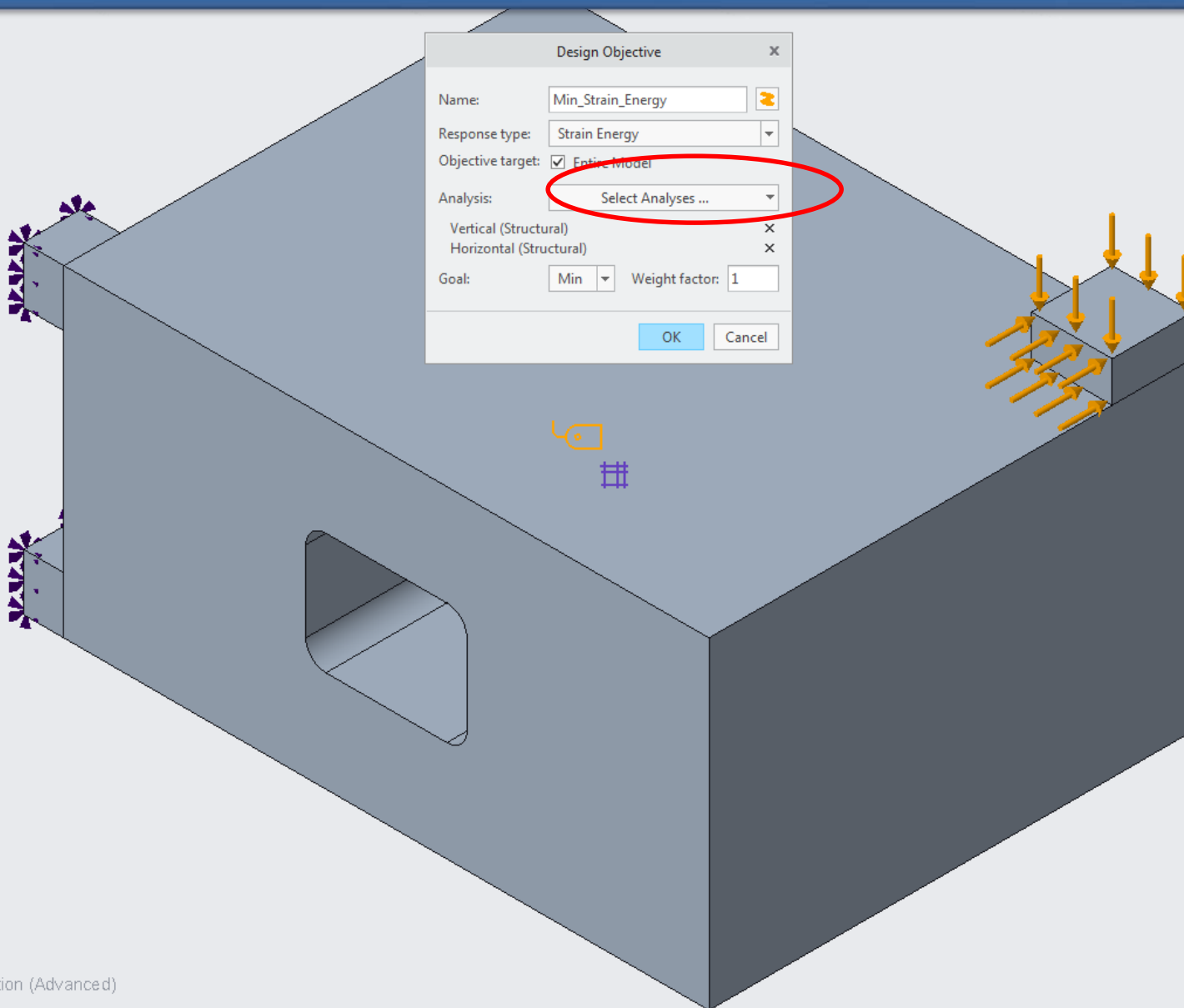




Design a light weight part that transfers the loads to the supports  
Use available design space shown for both Load cases

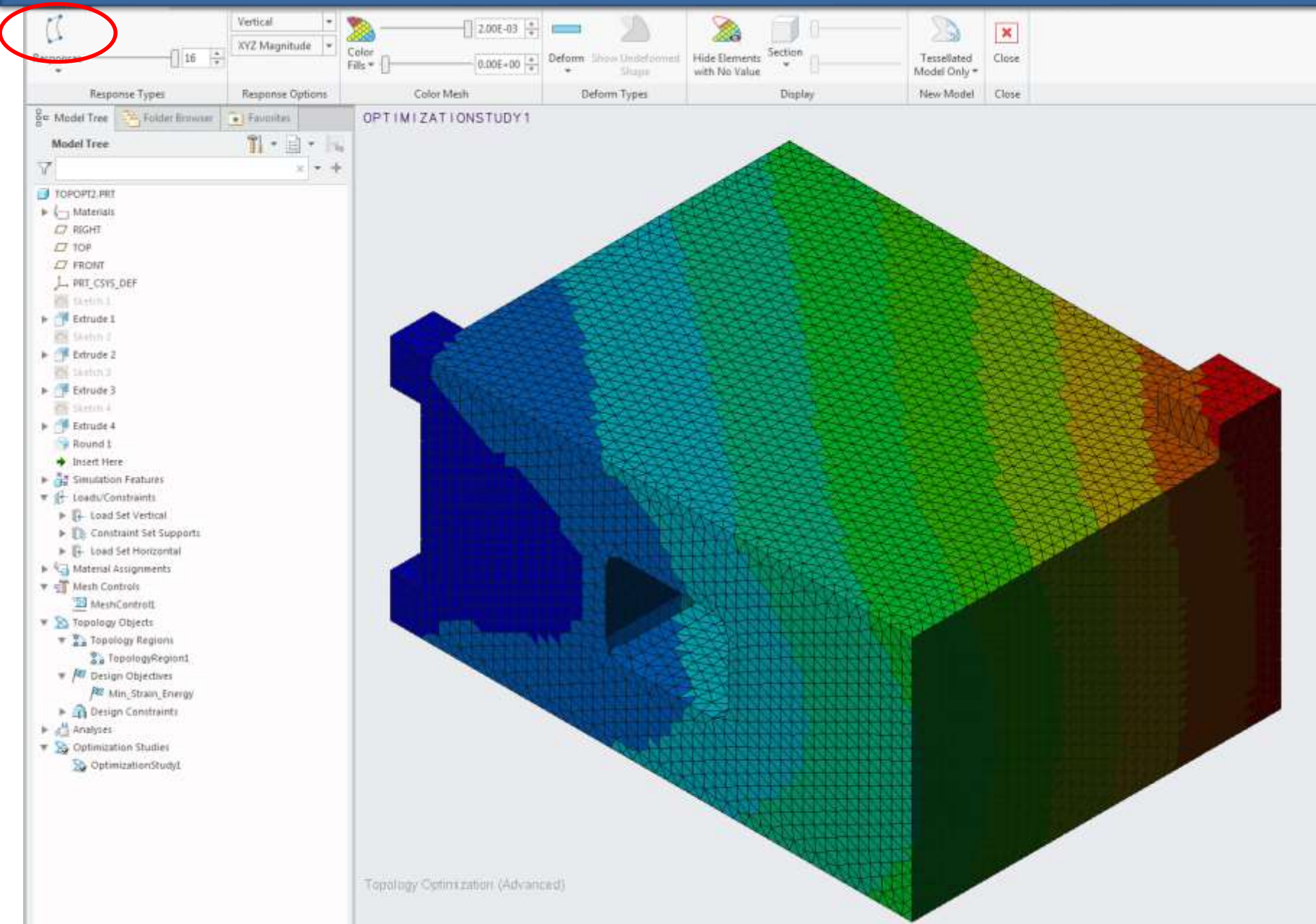


# CREO Topology Optimization Set up for Multiple Load cases



Optimization (Advanced)

# Displacement Distribution on the Entire Design Domain



# Iso-surface Enclosing 41% of Topology Region

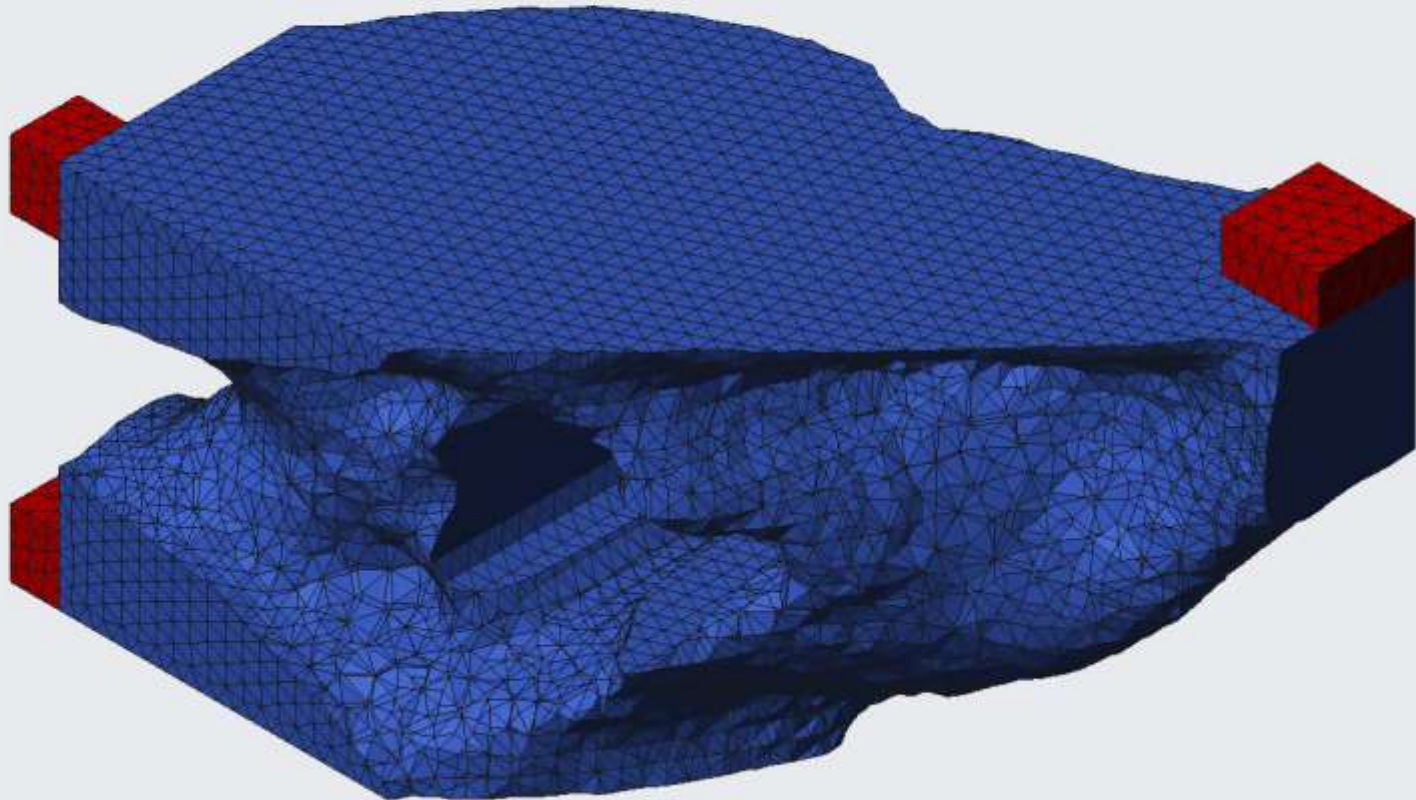
The screenshot displays the software interface for a topology optimization study. The top toolbar features several icons, with 'Isosurfaces' and 'Tessellated Model Only' highlighted by red circles. The 'Isosurfaces' icon is located in the 'Density Iso-surface' section, and the 'Tessellated Model Only' icon is in the 'New Model' section. The 'Responses' section shows a value of 16, and the 'Density Iso-surface' section shows a value of 0.50. The 'Color Mesh' section has two sliders set to 0.00. The 'Deform' section has a 'Show Undeformed Shape' button. The 'Hide Elements with No Value' button is also present. The 'Section' section has a 'Section' button. The 'New Model' section has a 'New Model' button and a 'Close' button.

The Model Tree on the left lists the following items:

- TOPOPT2.PRT
  - Materials
    - RIGHT
    - TOP
    - FRONT
  - PRT\_CSYS\_DEF
    - Sketch.1
  - Extrude.1
    - Sketch.2
  - Extrude.2
    - Sketch.3
  - Extrude.3
    - Sketch.4
  - Extrude.4
    - Sketch.5
  - Round.1
  - Insert Here
  - Simulation Features
    - Loads/Constraints
      - Load Set Vertical
      - Constraint Set Supports
      - Load Set Horizontal
    - Material Assignments
    - Mesh Controls
      - MeshControl.1
    - Topology Objects
      - Topology Regions
        - TopologyRegion.1
      - Design Objectives
        - Min\_Strain\_Energy
      - Design Constraints
    - Analyses
    - Optimization Studies
      - OptimizationStudy.1

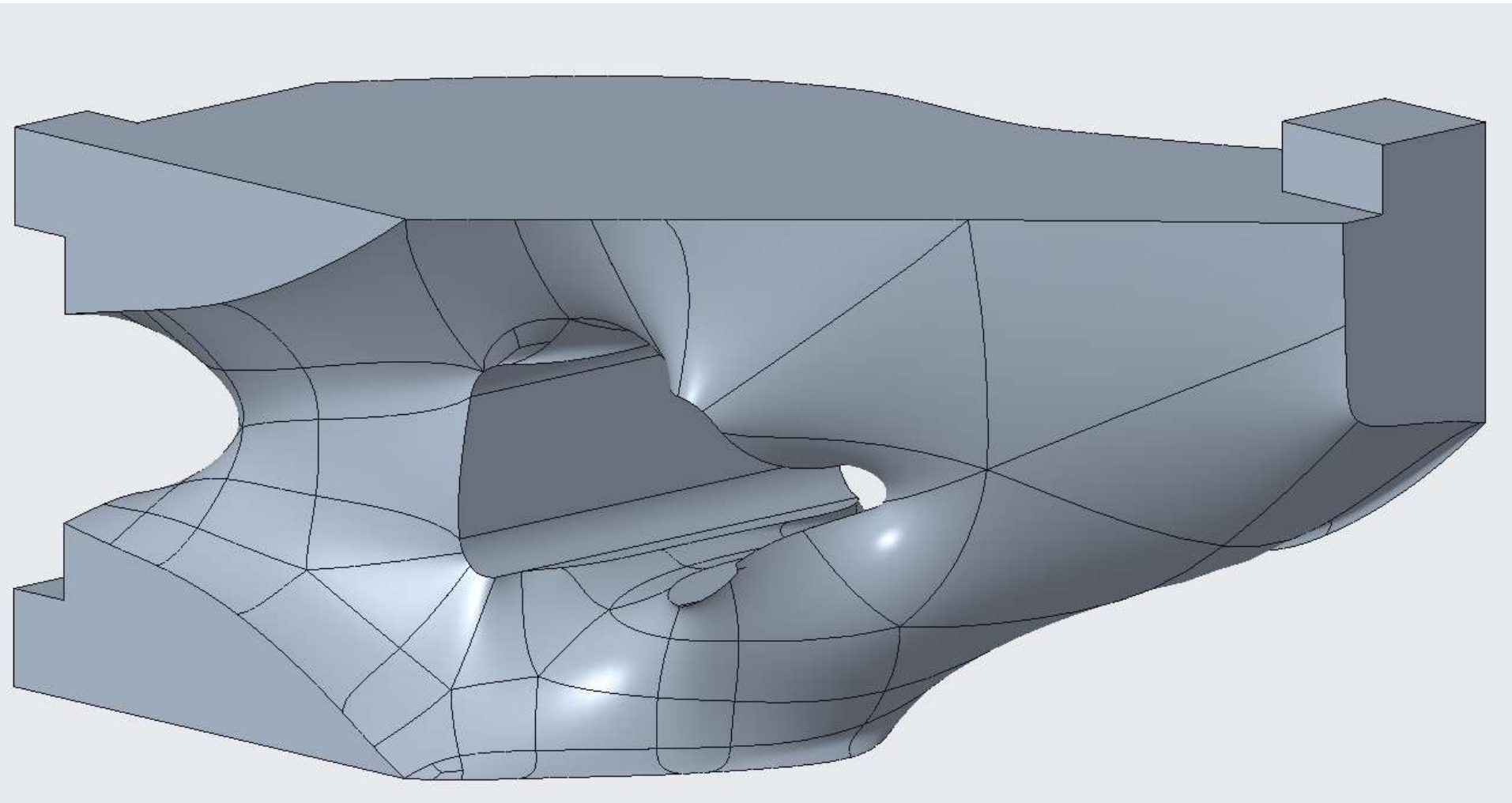
OPTIMIZATIONSTUDY1

TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 16  
Iso-surface enclosing 41% of topology region



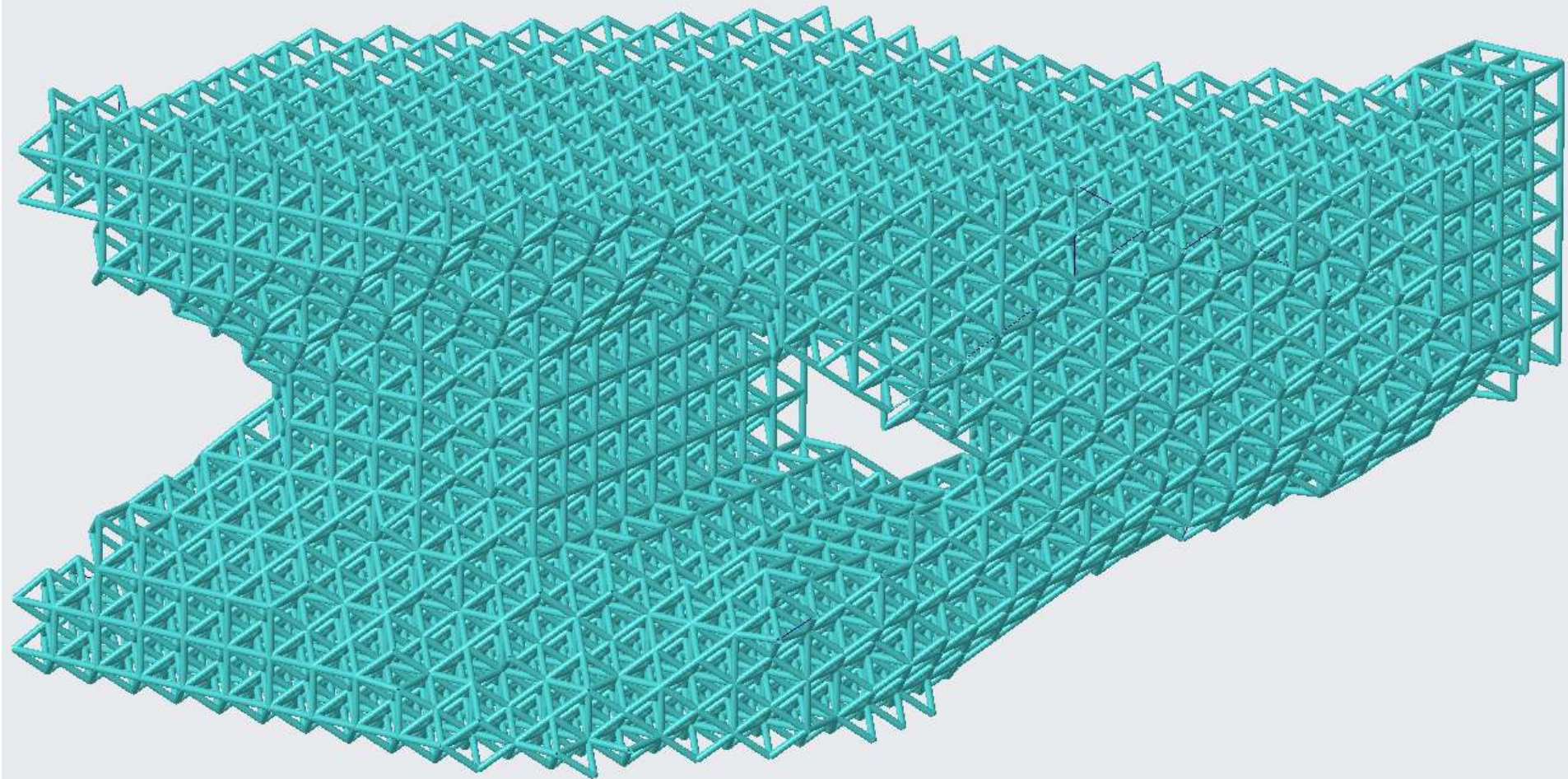


# Automatic Geometry Reconstruction with Free Style Feature



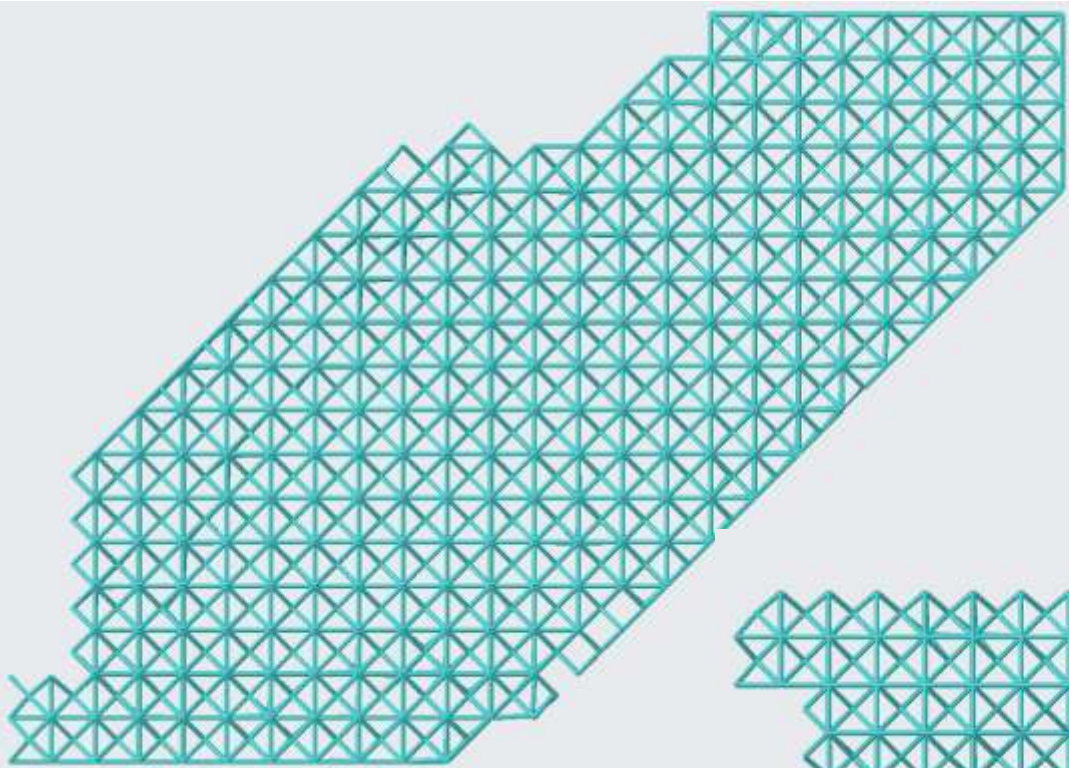
# Automatic Lattice Feature Generation with AM Extension

Lightweight structural panels, energy absorption devices, thermal insulation, porous implants



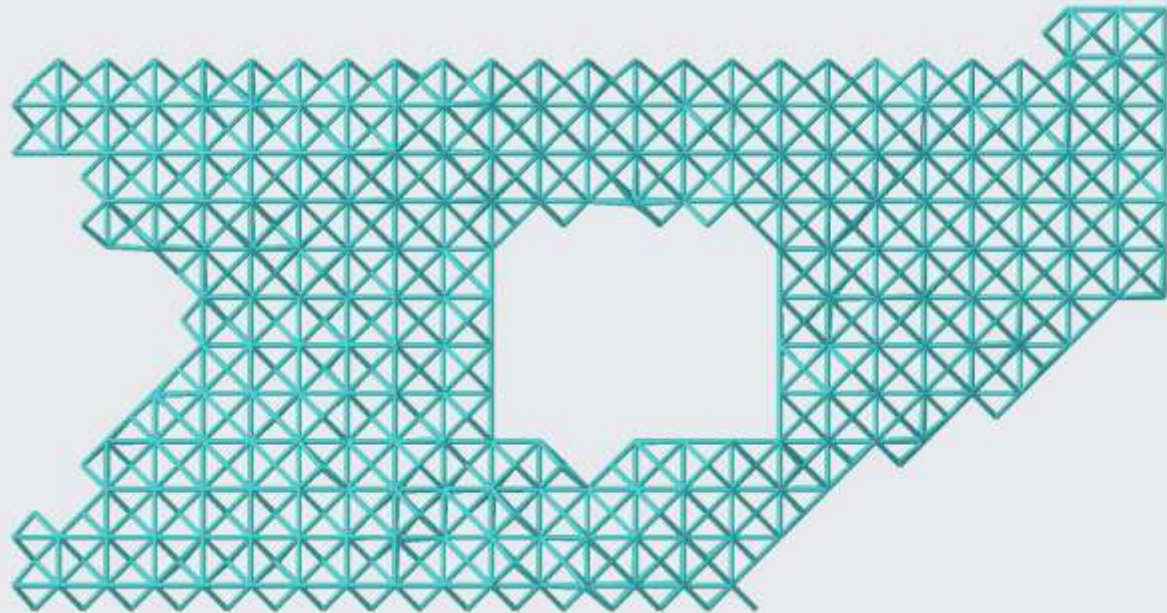


# Top and Side views of the internal lattice structure



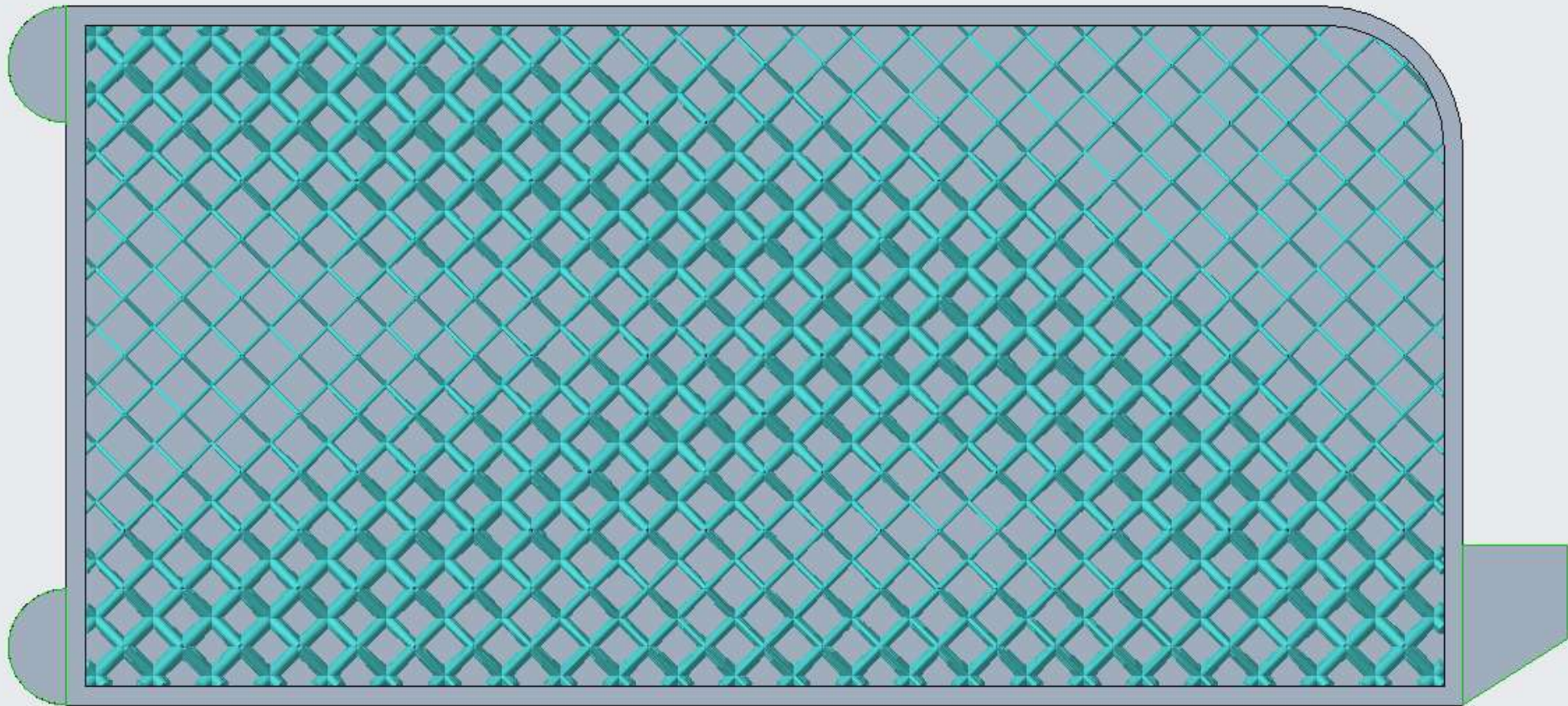
Lattice structure can be modeled with

- Solids if small number  $< 2,000$
- Beams if less than 20,000
- Homogenized material if more than 20,000 elements





# Lattice element size based on the Topology Optimization





# Modeling Lattices - Complexity versus size

Full Geometry Simulation

Simplified Geometry Simulation - Homogenization

Metallic Foams

Surface lattices  
minimal Surfaces

Stochastic  
i.e. Voronoi

Beams &  
Shells

Homogenization  
with  
uncertainty

Simplified  
Rep Ex, Ey, Ez

Full Geometry Rep

1000

10,000

1,000,00

100,000,000

Number of Cells

# Short Course by AES on:

## *Design Optimization Process for 3D Printed Designs*

- Is your organization ready to unleash the full potential of Additive Manufacturing?
- A two day course on *Design Optimization Process for 3D Printed Designs*
- Learn how to:
  - Create in CREO parametric 2 ½ D and 3D Lattice Features
  - Learn how to size and generate Lattice Structures
  - Optimize Lattice Structures using Behavioral Modeling
  - Use topology optimization to find the best distribution of material for stiffness or compliance with *homogenization techniques*
  - How to reconstruct the CAD geometry from the optimization results (*Nurbification*)
  - Design for additive manufacturing and practice the validation and verification steps required for Aerospace & Defense applications
  - Use topology optimization for light weight heat exchangers
  - Synthesize *Metamaterials* using Topology Optimization & Lattices

For more information contact Andreas at [andreas@aes.nu](mailto:andreas@aes.nu)

