... within Epsilon

Twin Cities
ANSYS® User Meeting

February 2019

Topology Optimization

... within Epsilon

Agenda

1. Epsilon FEA Introduction
2. Topological Optimization Overview
3. Topological Optimization Procedure
4. Topological Optimization Case Studies
5. Q&A

Intro to Epsilon

... within Epsilon

- Epsilon FEA provides engineering analysis (10 yrs!)
- Making Simulation Accurate
  - In-depth knowledge of the tools
    - ANSYS® Suite of Multi-Physics software
  - Experience with industry successes/failures
    - Aerospace, Rotating Machinery, Electronics, Manufacturing, Packaging, etc.
  - We validate with calibration runs and hand-calcs
    - Experienced Assessing Discretization Error

- Making Simulation Affordable
  - Low hourly rates and/or fixed-price estimates
  - We use specialized experienced engineers
  - Detailed statements of work, scope and budget tracking
  - Automation (APDL, ACT, Journaling)

Epsilon's Customers

... within Epsilon

- Our customers need load-leveling with:
  - Analyst is a team-member, not a black-box
    - Interface with same Epsilon analyst to leverage past experiences
  - Open and frequent communication
  - Any new FEA methods/lessons learned are well communicated
  - Schedule/budget fidelity with frequent status updates
    - Achieved by using the right person, tools, and technical approach

Critical!

- Our customers benefit from external expertise
  - We infuse up-to-date FEA methods/tools
    - Leverage other industries' FEA innovations
  - We are not a software reseller
    - Unbiased tool selection, infrastructure advice
  - We share our knowledge, files, and lessons learned!

Topology Optimization

- Optimizes parts for stiffness while reducing weight
- Faster, simpler compared to parameterized geometry studies/Design Assessment analyses
- Especially useful for additive manufacturing
  - Includes lattice optimization
- Allows validation of optimized part(s)
  - Requires simplification in CAD
- Limitations apply

Topology Optimization Features

- Added as a linked analysis
  - Works for all linear analysis types
  - Can optimize for multiple linked analyses simultaneously
  - Multiple criteria options
    - Maximum stress
      - Either within optimization region or outside of it
    - Pull-out/extrusion axis manufacturing constraints
    - Cyclic/planar symmetry
  - Mesh sensitive, but not overly limited by size
    - Can cut/form new elements rather than removing entire elements
    - Finer mesh still recommended
    - Different meshes can give different results

Topology Optimization: Limitations

… within Epsilon

- **<u>Element Types</u>**
  - All elements not Solid, Shell, or Plane will be ignored
    - Shell support new for R2019
- **<u>General Limitations</u>**
  - Composites
  - Cracks from a fracture analysis
  - Section planes
    - Resulting STL can be exported and viewed in CAD software
  - Pre-stressed or damped Modals
  - Thermal-Structural stresses (Beta only)
  - Joints other than Fixed or contact other than Bonded or No Separation
    - MPC contacts and Remote conditions allowed, nonlinear contact in Beta only
  - Nonlinear (NLGEOM, ON) analyses
  - Issues with HPC and RSM solvers

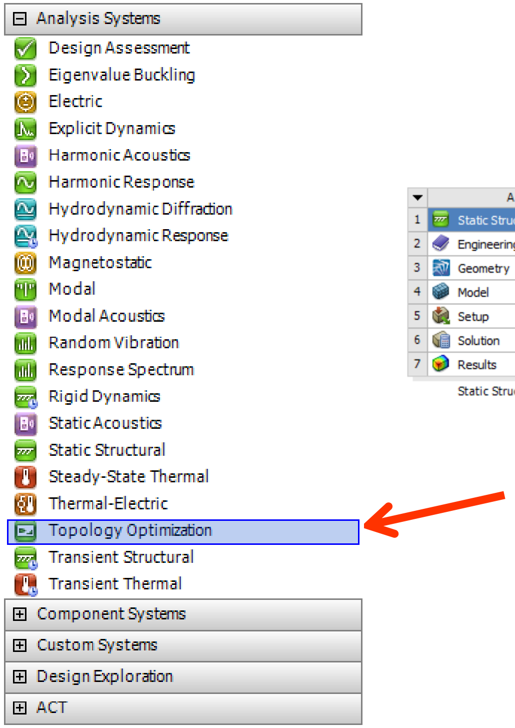
Topology Optimization: Limitations

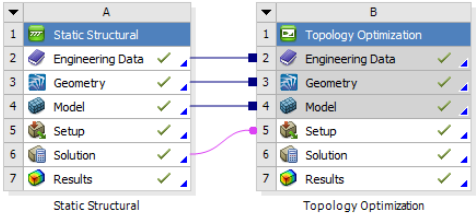
- **<u>Constraint/Objective Specific Limitations</u>**
  - Compliance Objective not compatible with both force-based and displacement-based loading
  - Extrusion constraint works for hex mesh only
    - Not one tet allowed in optimization region
  - Minimum Member Size requires mesh density to be 4x finer than specified member size
  - Stress constraints not allowed for axisymmetric models or with the Level Set method

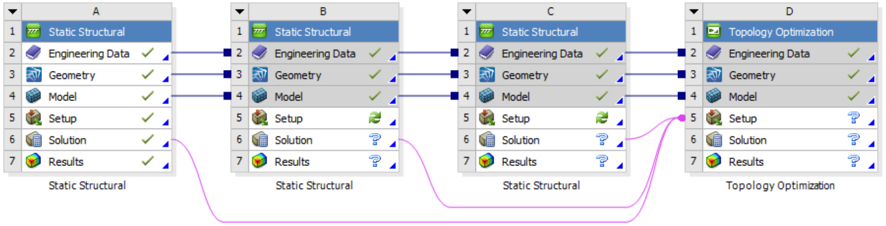
Topology Optimization: Procedure

... within Epsilon

- Drag the Topology Optimization module onto the analysis to optimize
- All linked analyses can be included (must be linked to Topology Optimization manually)



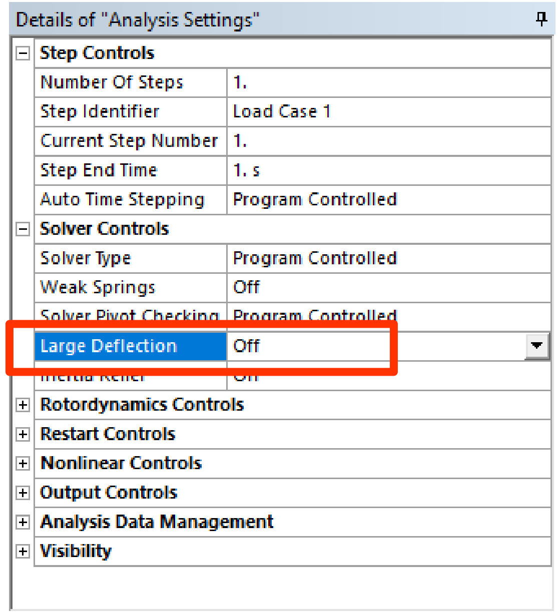


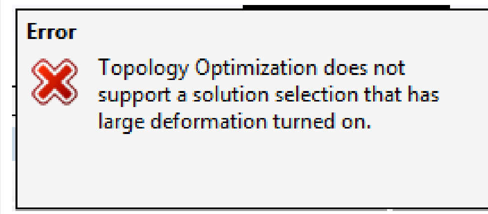


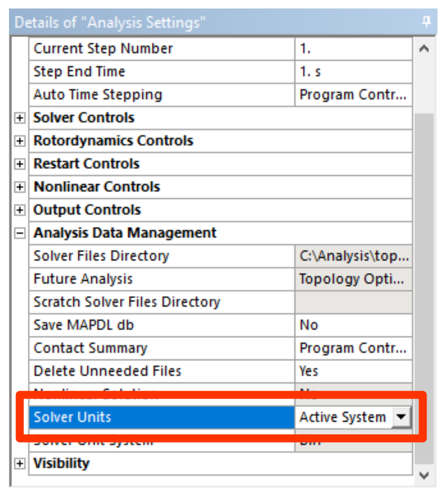
Topology Optimization: Procedure

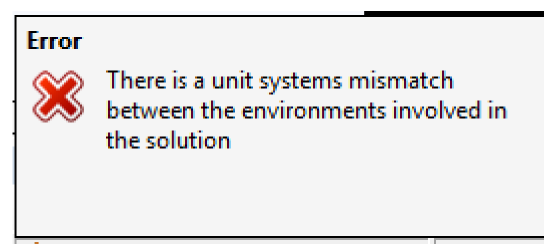
... within Epsilon

- Required Upstream Analysis/Mesh Settings:
  - Large Deflection must be off for all linked analyses
  - If Extrusion constraint is used, all elements in optimization region must be hexahedral
  - If Level Set method is used, all elements in optimization must be tetrahedral
  - Optimization and all linked analyses must be in the same unit system, may be beneficial to manually set solver units if switching often



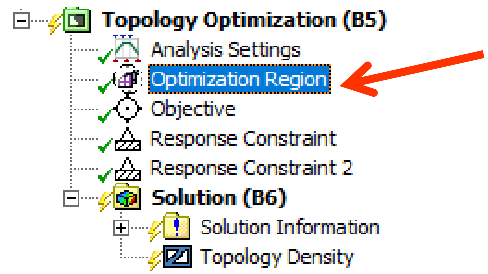


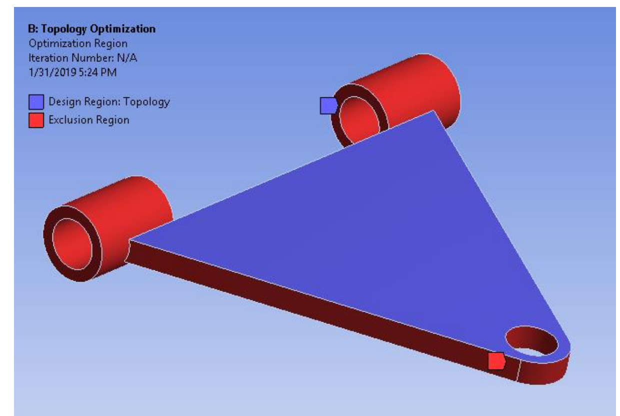




Topology Optimization: Procedure

- Optimization Region
  - Select which bodies are to be optimized
    - Can be multiple bodies regardless of connectivity, though only one Optimization Region can be made
  - Set exclusion regions for faces to remain unchanged
    - Defaults to faces scoped to boundary conditions over all linked analyses, may be manually set
    - Multiple sets of Exclusion Regions can be added
  - Set optimization type: Density-Based or Lattice Optimization
  - Density based is simple mass reduction
  - Lattice optimization allows one to set lattice structure, maximum density ratio, and cell size
  - Level Set (Beta feature in R2019) is similar to density based, also allows constraining exclusion region thickness





Details of "Optimization Region"

Design Region	
Scoping Method	Geometry Selection
Geometry	1 Body
Exclusion Region	
Define By	Geometry Selection
Geometry	12 Faces
Optimization Option	
Optimization Type	Topology Optimization - Density Bas...

Details of "Optimization Region"

Design Region	
Scoping Method	Geometry Selection
Geometry	1 Body
Exclusion Region	
Define By	Geometry Selection
Geometry	12 Faces
ExclusionThickness	5. mm
Optimization Option	
Optimization Type	Topology Optimization - Level Set Base...

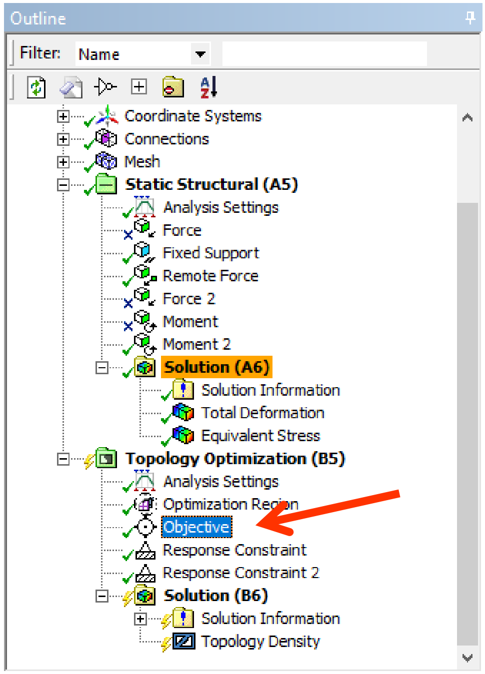
Details of "Optimization Region (Lattice)"

Design Region	
Scoping Method	Geometry Selection
Geometry	1 Body
Exclusion Region	
Define By	Geometry Selection
Geometry	12 Faces
Optimization Option	
Optimization Type	Lattice Optimization
Lattice Type	Cubic
Minimum Density	0.
Maximum Density	0.5
Lattice Cell Size	5. mm

Topology Optimization: Procedure

... within Epsilon

- Objective
  - Default Objective is Minimize Compliance (aka maximize stiffness/thermal conductivity)
  - Other Objectives include Minimize Mass and Minimize Volume
  - Multiple linked analyses will each need their own Objective
    - Analyses can be weighted over one another
  - Multiple Objectives may be used
  - Compliance Objective most useful
    - Mass/volume more easily controlled with response constraints



Worksheet

Objective

Right click on the grid to add, modify and delete a row.

Enabled	Response Type	Goal	Formulation	Environment Name	Weight	Multiple Sets	Start Step	End Step	Step	Start Mode	End Mode	Mode
☑	Compliance	Minimize	Program Controlled	Static Structural	1	Enabled	1	1	1	N/A	N/A	N/A

Topology Optimization: Procedure

- Response Constraints
  - Default Response Constraint is 50% Mass retention
    - Any value between 1% and 99% retention allowed
    - May be a constant retention or a range (will trend toward the upper end of the range to minimize compliance)
  - Volume Constraint
    - Works the same as Mass
  - Global/Local von-Mises Stress Constraint
    - Will optimize parts to meet a stress criteria over all or individual linked analyses
    - Stress constraints can be set for optimized regions or excluded regions
  - Displacement Constraint
    - Set maximum displacement for any selection in the model
  - Reaction Force Constraint
    - Set maximum reaction (nodal) force for any selection in the model

Details of "Response Constraint"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Response Constraint
Response	Mass
Define By	Range
Percent to Retain (Min)	30 %
Percent to Retain (Max)	50 %
Suppressed	No

Details of "Response Constraint 2"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Response Constraint
Response	Global von-Mises Stress
Maximum	27000 psi
Environment Selection	All Static Structural
Suppressed	No

Details of "Response Constraint 3"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Vertex
Definition	
Type	Response Constraint
Response	Displacement
Coordinate System	Nodal Coordinate System
X Component (Max)	Free
Y Component (Max)	0.25 in
Z Component (Max)	Free
Environment Selection	All Static Structural
Suppressed	No

Details of "Response Constraint 4"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Response Constraint
Response	Reaction Force
Coordinate System	Nodal Coordinate System
Axis Selection	All
X Component (Max)	500. lbf
Y Component (Max)	500. lbf
Z Component (Max)	100. lbf
Environment Selection	All Static Structural
Suppressed	No

Topology Optimization: Procedure

- Manufacturing Constraints
  - Member Size
    - Sets maximum and minimum member size
  - Pull Out Direction
    - Prevents undercutting, creates castable surfaces from one direction
  - Extrusion
    - Similar to Pull Out Direction, forces a constant cross-section along an axis
  - Cyclic
    - Forces cyclic symmetry along an axis
  - Symmetry
    - Forces planar symmetry
  - Symmetry constraints can be combined with Pull Out Direction/Extrusion
    - Pull Out axis must be coplanar with Symmetry plane or colinear with Cyclic symmetry axis
    - Extrusion axis must be colinear with Cyclic symmetry axis or normal to Symmetry plane
  - AM Overhang
    - Sets maximum overhang angle for additive manufacturing based on build direction

Details of "Manufacturing Constraint"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Manufacturing Constraint
Subtype	Member Size
Suppressed	No
Member Size	
Minimum	Manual
--Min Size	2. in
Maximum	Manual
--Max Size	Unspecified

Details of "Manufacturing Constraint 3"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Manufacturing Constraint
Subtype	Pull Out Direction
Suppressed	No
Location and Orientation	
Coordinate System	Coordinate System
Axis	X Axis
Direction	Along Axis

Details of "Manufacturing Constraint 4"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Manufacturing Constraint
Subtype	Extrusion
Suppressed	No
Location and Orientation	
Coordinate System	Coordinate System
Axis	Z Axis

Details of "Manufacturing Constraint 5"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Manufacturing Constraint
Subtype	Cyclic
Suppressed	No
Location and Orientation	
Number of Sectors	6
Coordinate System	Global Coordinate System
Axis	X Axis

Details of "Manufacturing Constraint 2"

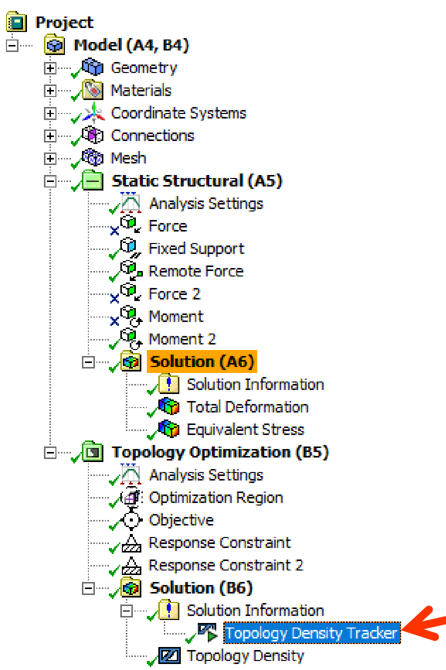
Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Manufacturing Constraint
Subtype	Symmetry
Suppressed	No
Location and Orientation	
Coordinate System	Coordinate System
Axis	Y Axis

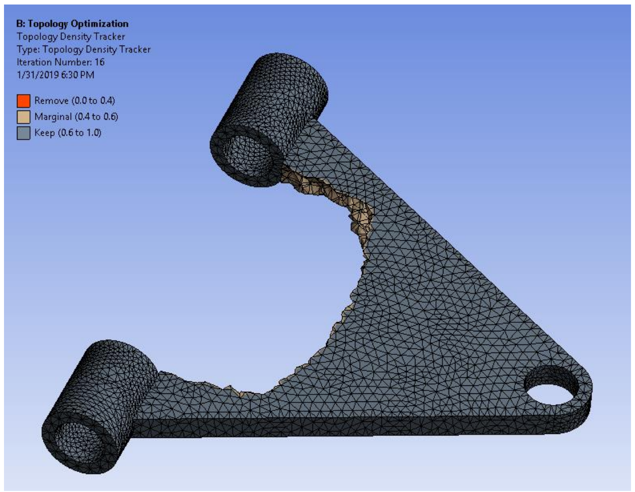
Details of "AM Overhang Constraint"

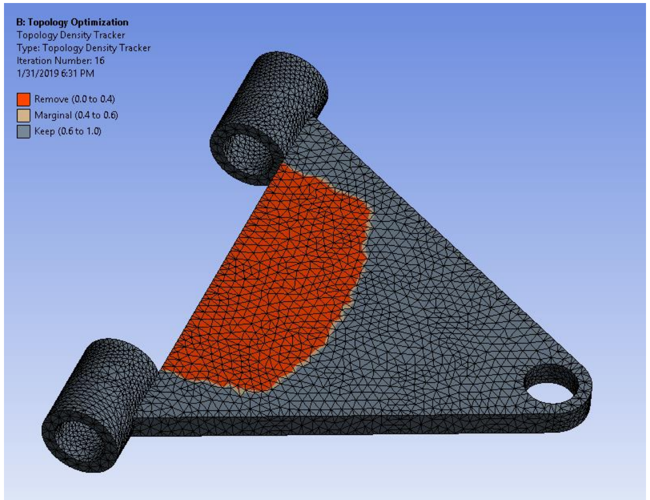
Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	AM Constraint
Subtype	Overhang Angle
Suppressed	No
Location and Orientation	
Coordinate System	Global Coordinate System
Build Direction	+Z Axis
Overhang Angle	45. °

Topology Optimization: Results

- Topology Density Tracker can be used to watch optimization in real time
- Removed material visibility can be turned on or off







Details of "Topology Density Tracker"

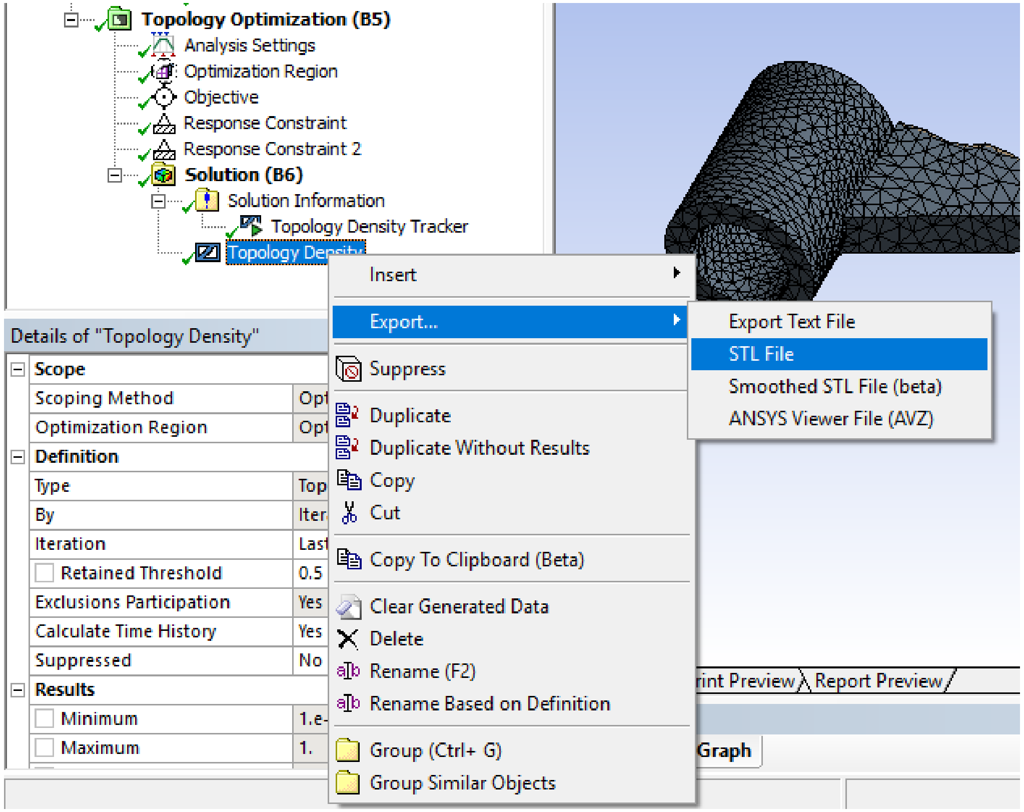
Definition	
Type	Topology Density Tracker
By	Iteration
Iteration	Last
Retained Threshold	0.5
Suppressed	No
Results	
Minimum	1.e-003
Maximum	1.
Average	0.79905
Visibility	
Show Optimized Region	Retained Region
Information	
Iteration Number	16

Details of "Topology Density Tracker"

Definition	
Type	Topology Density Tracker
By	Iteration
Iteration	Last
Retained Threshold	0.5
Suppressed	No
Results	
Minimum	1.e-003
Maximum	1.
Average	0.79905
Visibility	
Show Optimized Region	All Regions
Information	
Iteration Number	16

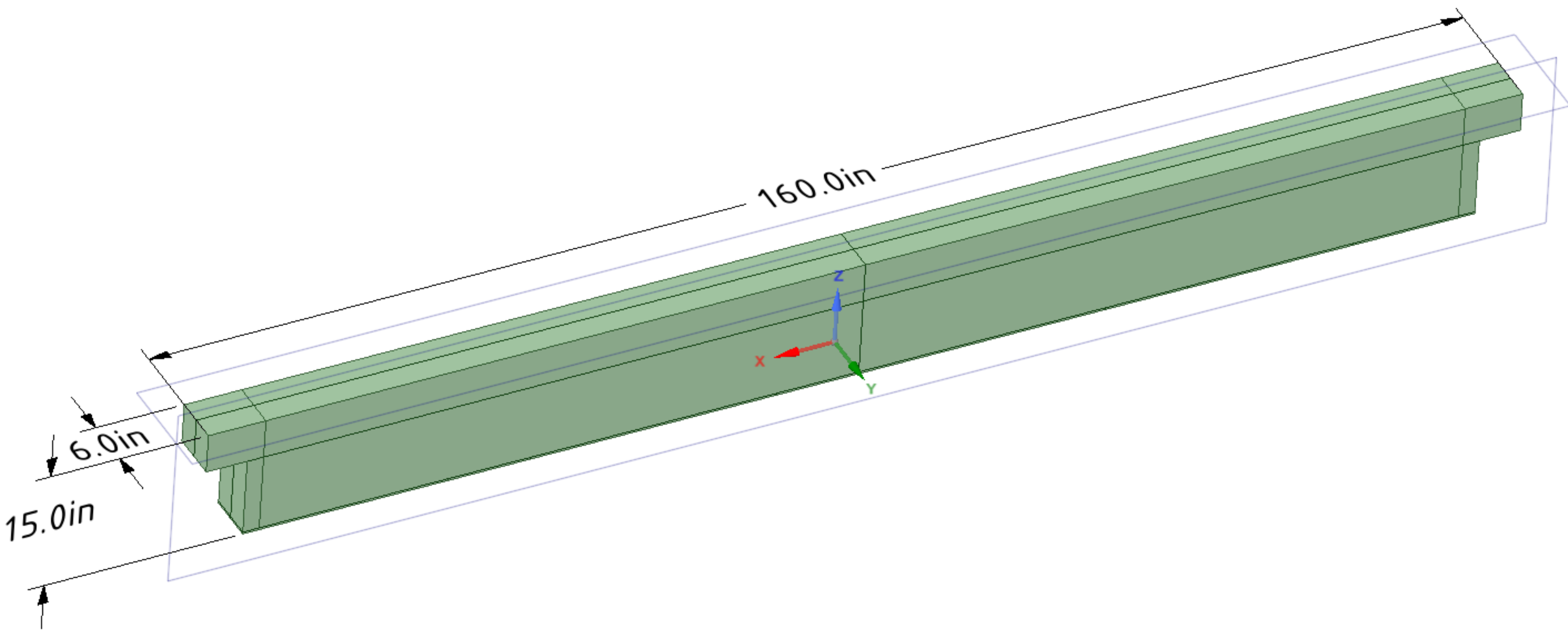
Topology Optimization: Results

- Resulting STL file can be exported for CAD manipulation, reverse engineering, and validation



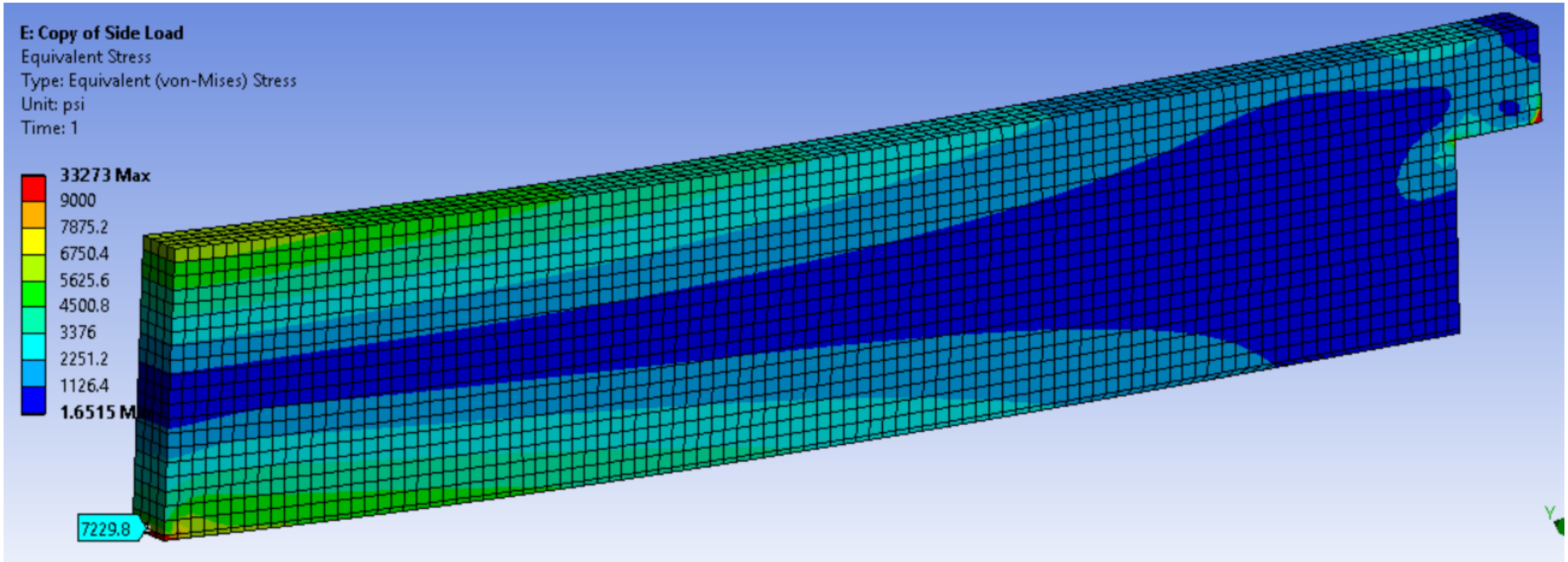
Case Study 1: Box Beams

- Gain some trust in the tool by having it make something we already know the solution to
- Simply supported beam with centered point load



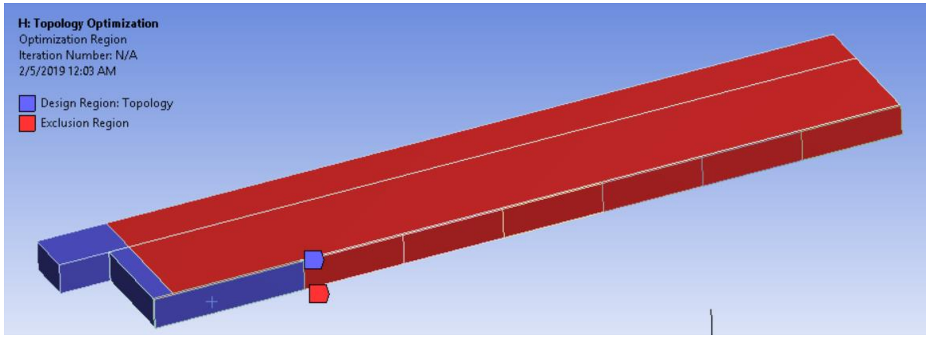
Case Study 1: Box Beams

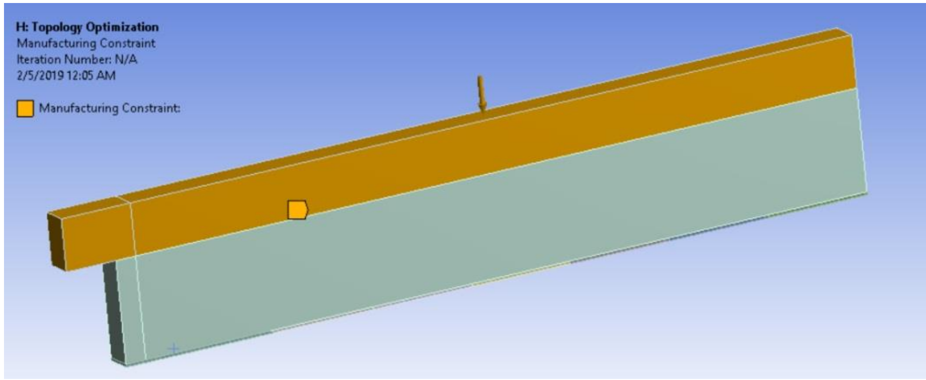
- Point load of 36,000 lbf
- Static structural model using ¼ symmetry (frictionless supports)
- Displacement of 0 for support



Case Study 1: Box Beams

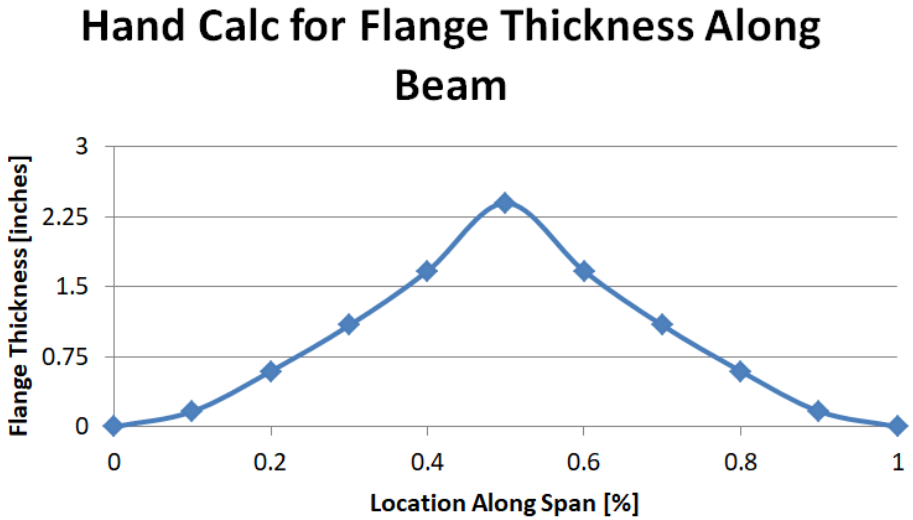
- Symmetry Constraints
  - Along XZ and YZ planes
- Entire body is optimization zone
  - Exclusion zone of bottom and outside face
  - Removes constraint/load based stress concentrations
  - Helps enforces the 'box' beam
- 2 Pull out direction constraints
  - This enforces hollowness
- Stress limit of 9,000
  - 4X SF on A36
- Mass optimization weight of 8x





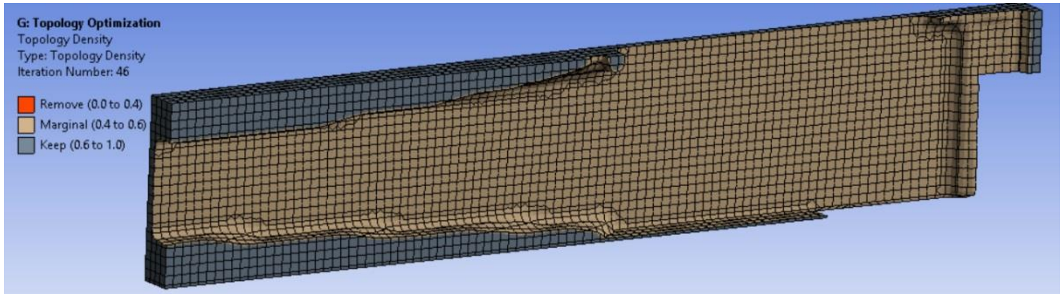
Case Study 1: Box Beams

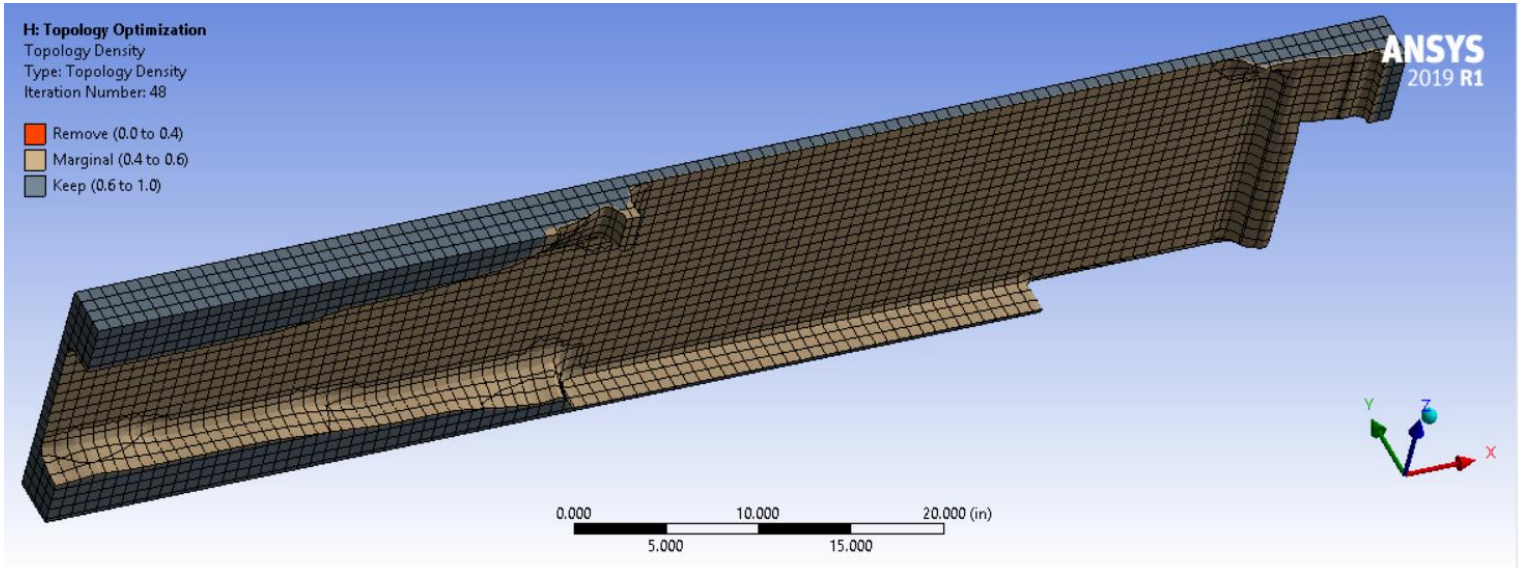
- Mesh size is 0.75”
  - Means the webs will be 0.75” thick because of exclusion zone
- Optimal flange thickness is computed down length of beam by hand. Optimal thickness is about 2.25”
  - This is about 3 elements thick



Case Study 1: Box Beams

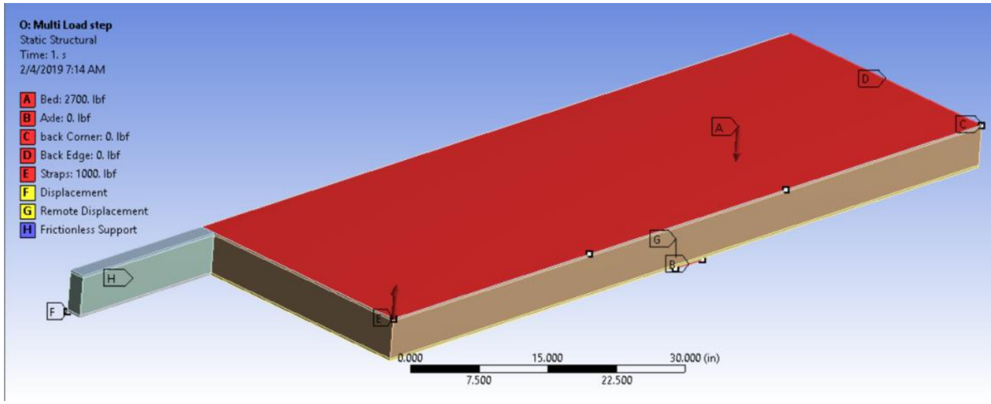
- Mass minimization objective weight of 8x
  - 3.5” flange
- Mass minimization objective weight of 15x
  - 3.0” flange

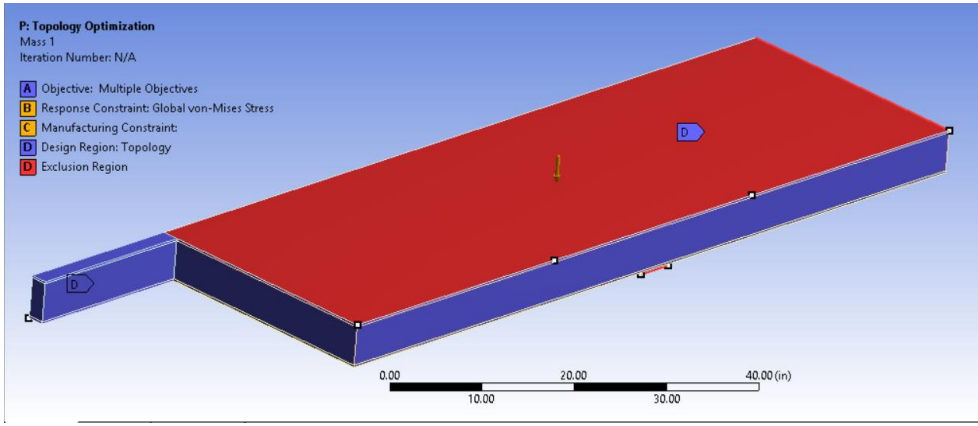




Case Study 2: Trailer Weldment

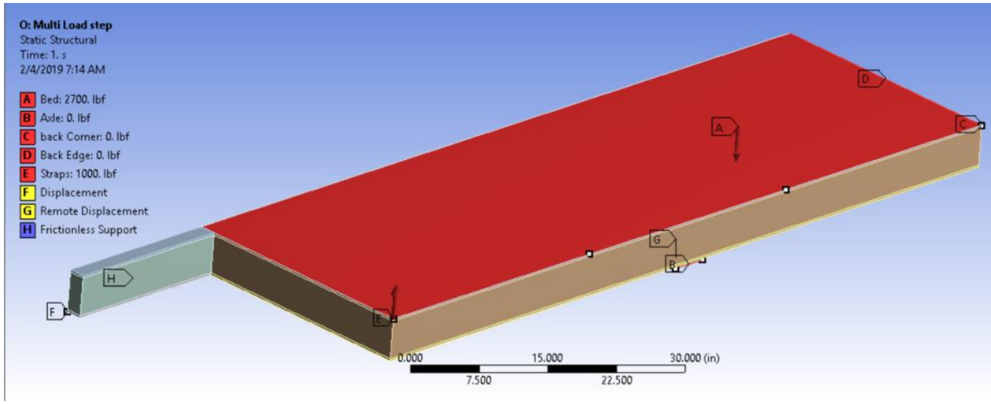
- Can the optimizer find a suitable design for a weldment given only a bounding box to work with?
- How do multi load step models behave?
- What affect does the weight option have in the Objective window?

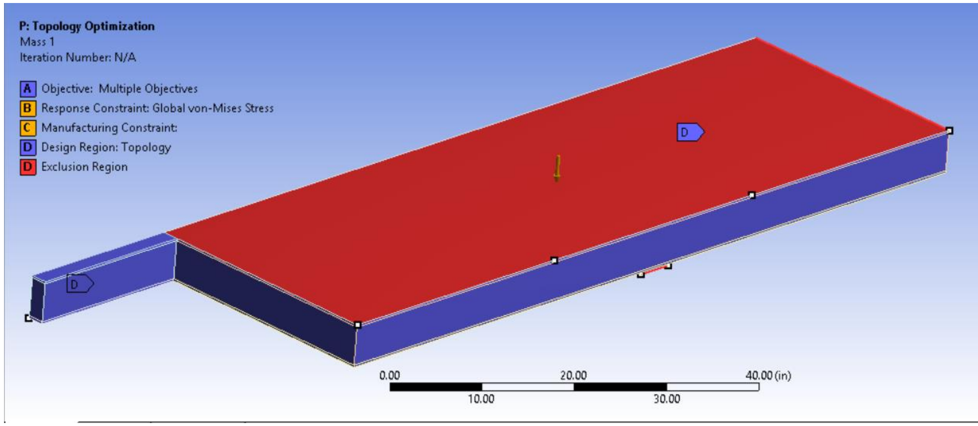




Case Study 2: Trailer Weldment

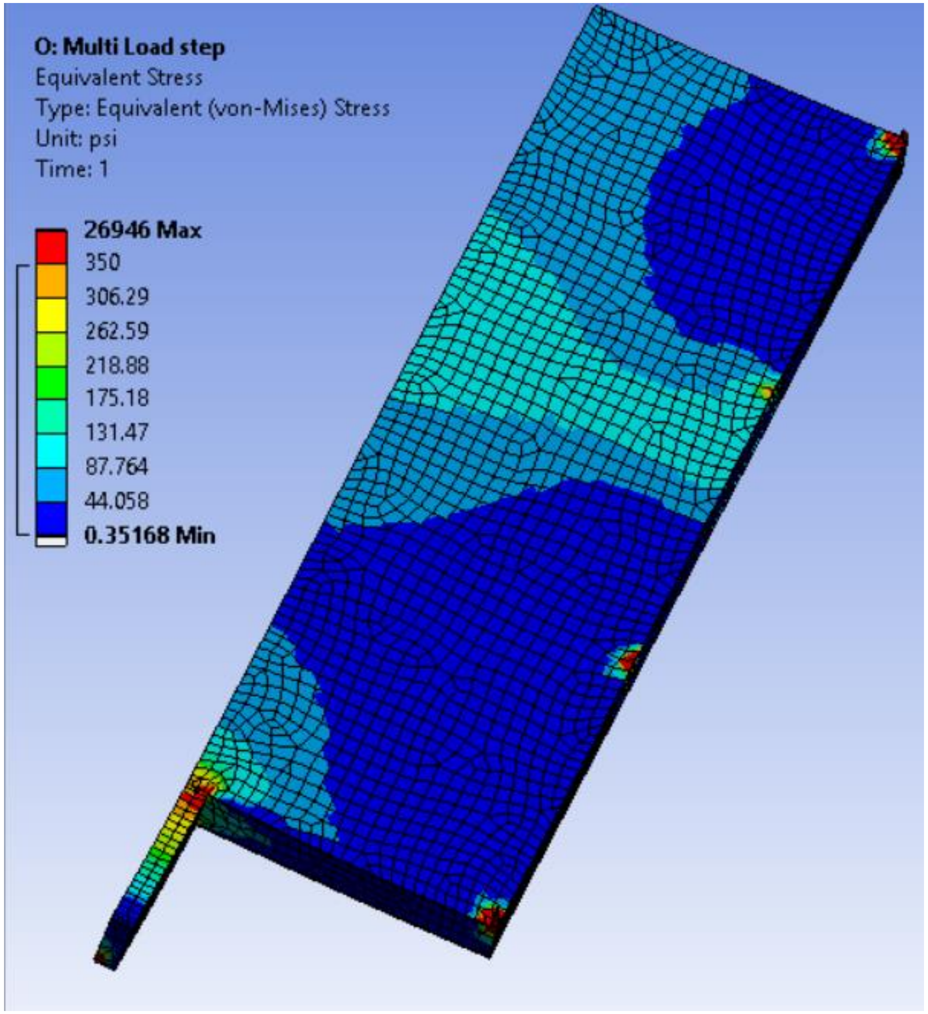
- Use of symmetry
  - Frictionless applied in Static Structural
- Set Pull Out direction manufacturing constraint to get constant sections
  - CS set to top surface, pointing down
- Global constraint of 50ksi
- Changing optimization weights
  - Objective weight on mass objective is varied





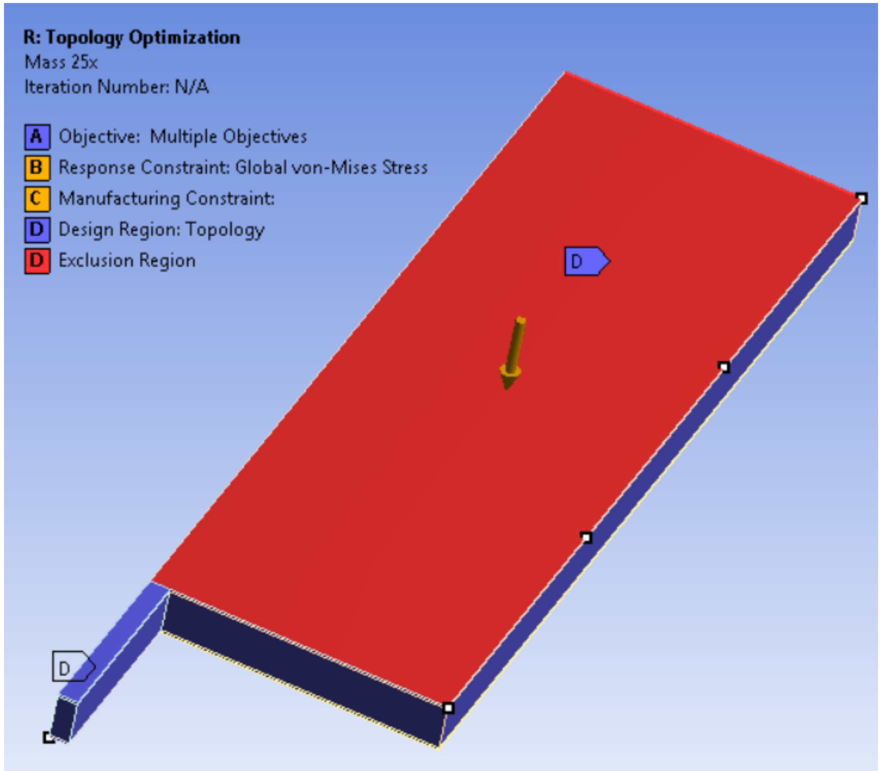
Case Study 2: Trailer Weldment

- 5 Load steps set up modeling:
  - 2G bounce with tie downs
  - Trailer braking with tie downs
  - Hard cornering with tie downs
  - Loading
  - Backing into post
- Tongue and deck set to 0 density to exclude from optimization



Case Study 2: Trailer Weldment

- Using Objective function to control mass and compliance
- Ran multiple iterations at different objective weights for mass minimization
- Response constraint of 50ksi
- Pull out direction set to get constant cross section



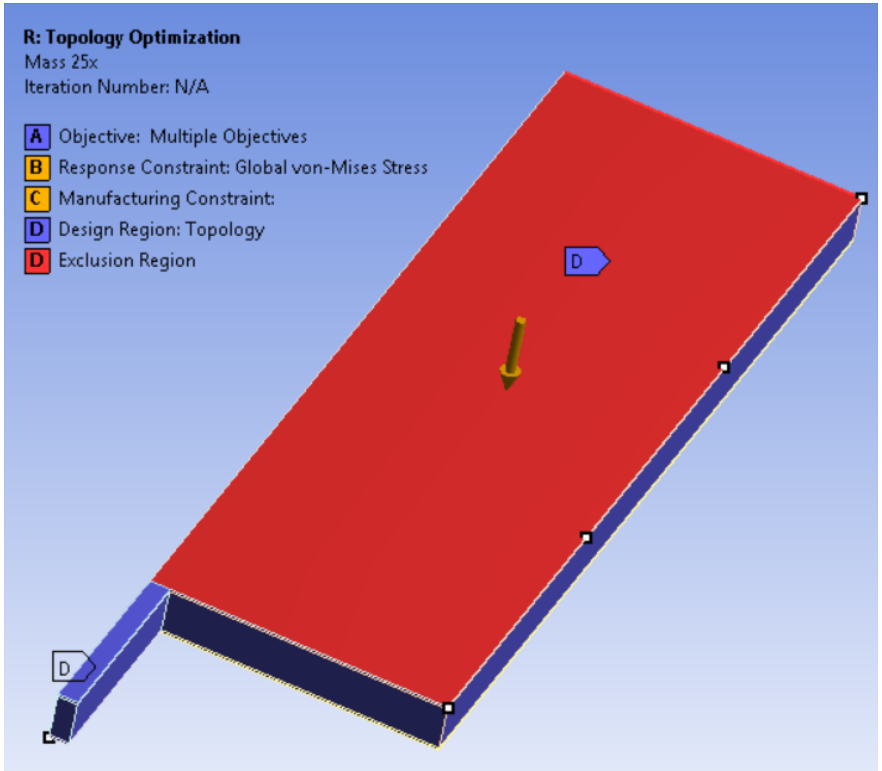
Objective

Right click on the grid to add, modify and delete a row.

Enabled	Response Type	Goal	Formulation	Environment Name	Weight	Multiple Sets	Start Step	End Step	Step	Start Mode	End Mode	Mode
☑	Compliance	Minimize	Program Controlled	Static Structural	1	Enabled	1	5	All	N/A	N/A	N/A
☑	Mass	Minimize	N/A	N/A	25	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Case Study 2: Trailer Weldment

- Compliance weight is cumulative on multi-load step problems is cumulative
  - 5 load steps with compliance weight of 1 and mass weight of 1 means 83% of objective is to minimize compliance
- Run 5 load step models with mass minimization objective weight of 1,10,25, and 50
  - Mass minimization effort of 17%, 67%, 83%, and 91% respectively



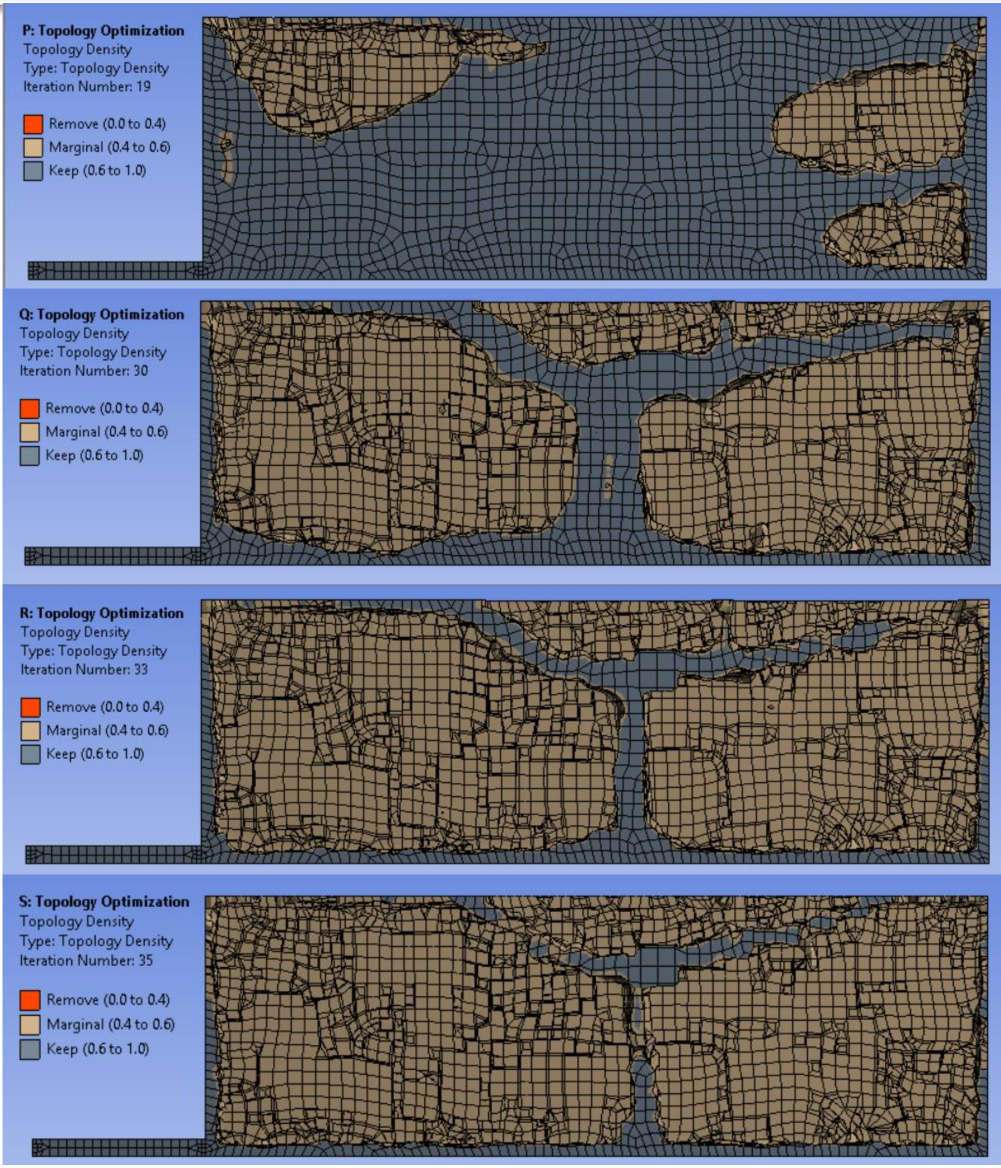
Objective

Right click on the grid to add, modify and delete a row.

Enabled	Response Type	Goal	Formulation	Environment Name	Weight	Multiple Sets	Start Step	End Step	Step	Start Mode	End Mode	Mode
☑	Compliance	Minimize	Program Controlled	Static Structural	1	Enabled	1	5	All	N/A	N/A	N/A
☑	Mass	Minimize	N/A	N/A	25	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Case Study 2: Trailer Weldment

- Mass objective weight of 1x
  - 2770lb (76% of solid mass)
  - 19 iterations
  - 20 minute solve
- Mass objective weight of 10x
  - 925lb (25.5% of solid mass)
  - 30 iterations
  - 50 minute solve
- Mass objective weight of 25x
  - 600lb (16.5% of solid mass)
  - 33 iterations
  - 62 minute solve
- Mass objective weight of 50x
  - 484lb (13.3% of solid mass)
  - 35 iterations
  - 76 minute solve



Case Study 2: Trailer Weldment

… within Epsilon

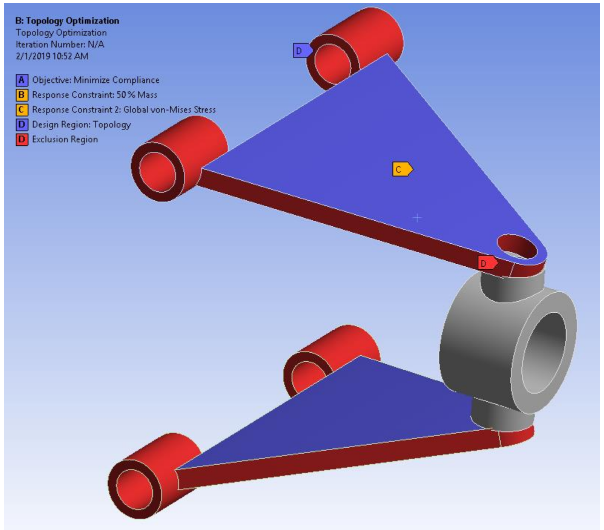
- Each iteration of the optimization has to solve all of the load steps in the Static Structural model
- There is a time consuming task of solving the solution using the optimization solver as well.
- The time to solve consecutive iterations grew each step in this model
- The result is qualitatively what is expected
- Half of a real trailer as modeled here should weight around 150lb not 450

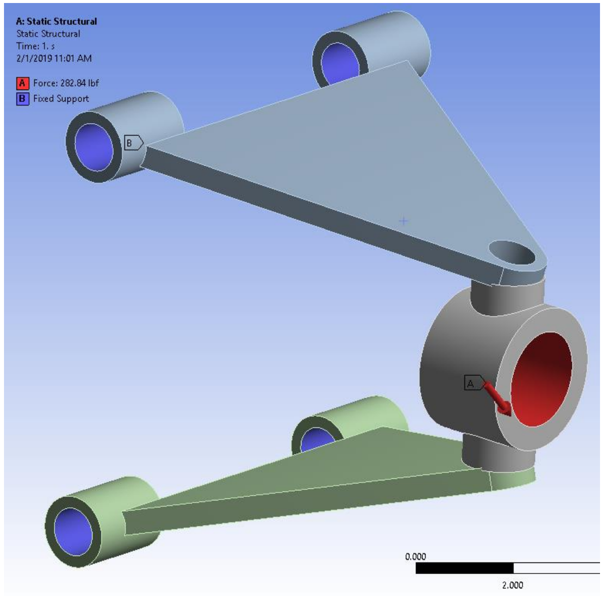
Case Studies 1 & 2 Findings

- It is incredibly important to have an idea of targets. The model will fail to solve or give underwhelming solution if you do not give it proper inputs.
- Topology optimization will NOT solve your problem for you. It MAY give you insight to an optimal solution.
- This tool has not reached a point where it is useful for weldments.

Case Study 3: Control Arms

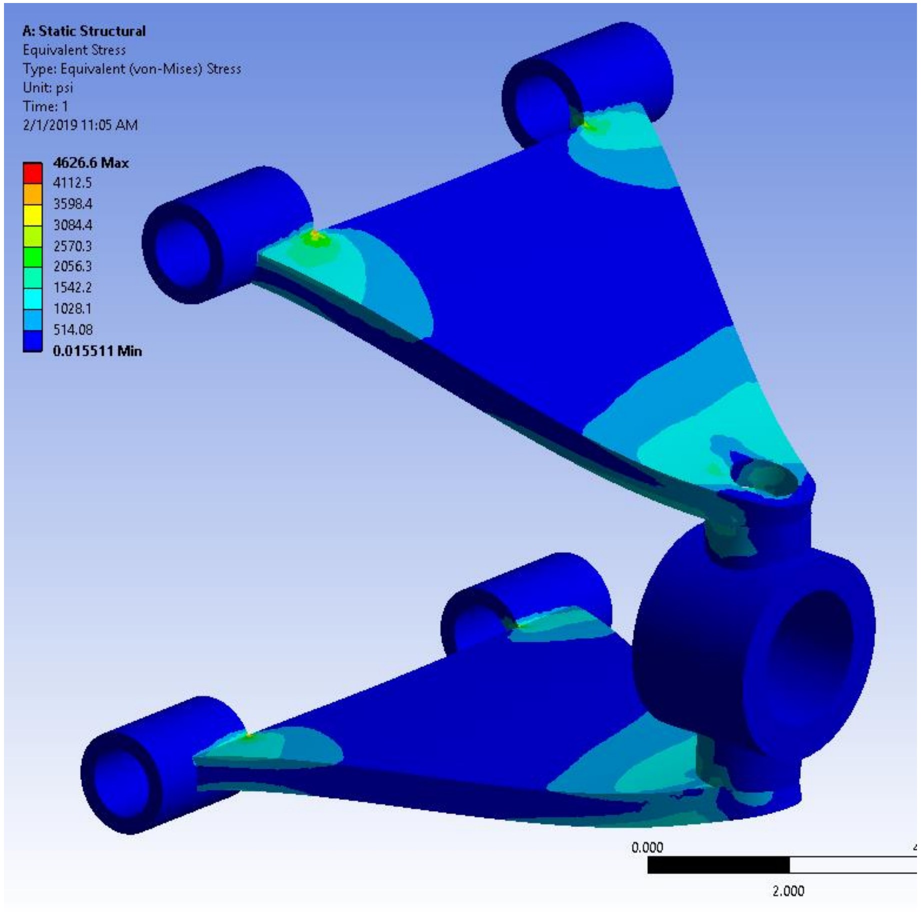
- Tests multiple optimization bodies in a single analysis
- Tests robustness for unconnected parts out of orthogonal alignment/symmetry
- Many exclusion regions
- Uses contact





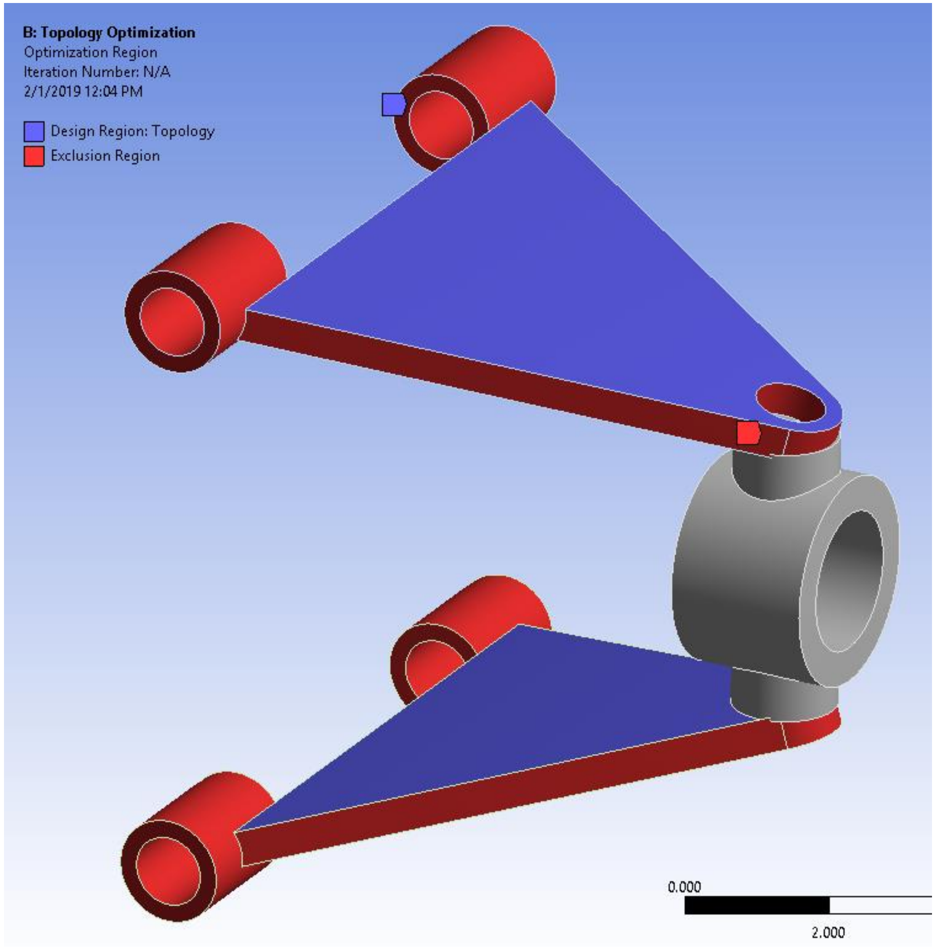
Case Study 3: Control Arms

- Check Static Structural run for max stresses, adjust loading/contact to avoid hotspots if using maximum stress constraint
- If hotspots are unavoidable due to sharp corners/contact formulation, maximum stress constraints can be scoped to groups of elements away from the hotspot region
- Prevents hotspots from driving the optimization



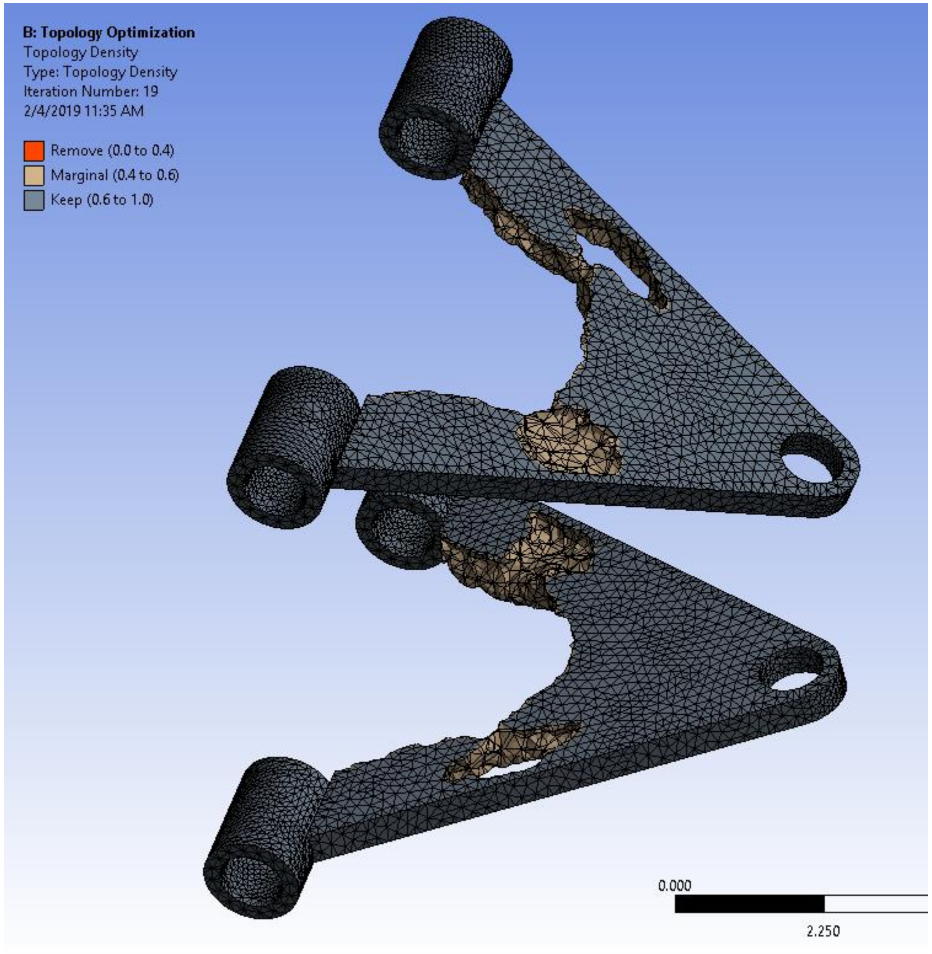
Case Study 3: Control Arms

- Set Response/ Manufacturing Constraints
- Mass retention: 50%
- Maximum global stress: 5 ksi
  - Maximum from Static Structural
- Manufacturing constraints not easily used with multiple bodies
  - Apply to entire optimization region, cannot be scoped to individual bodies

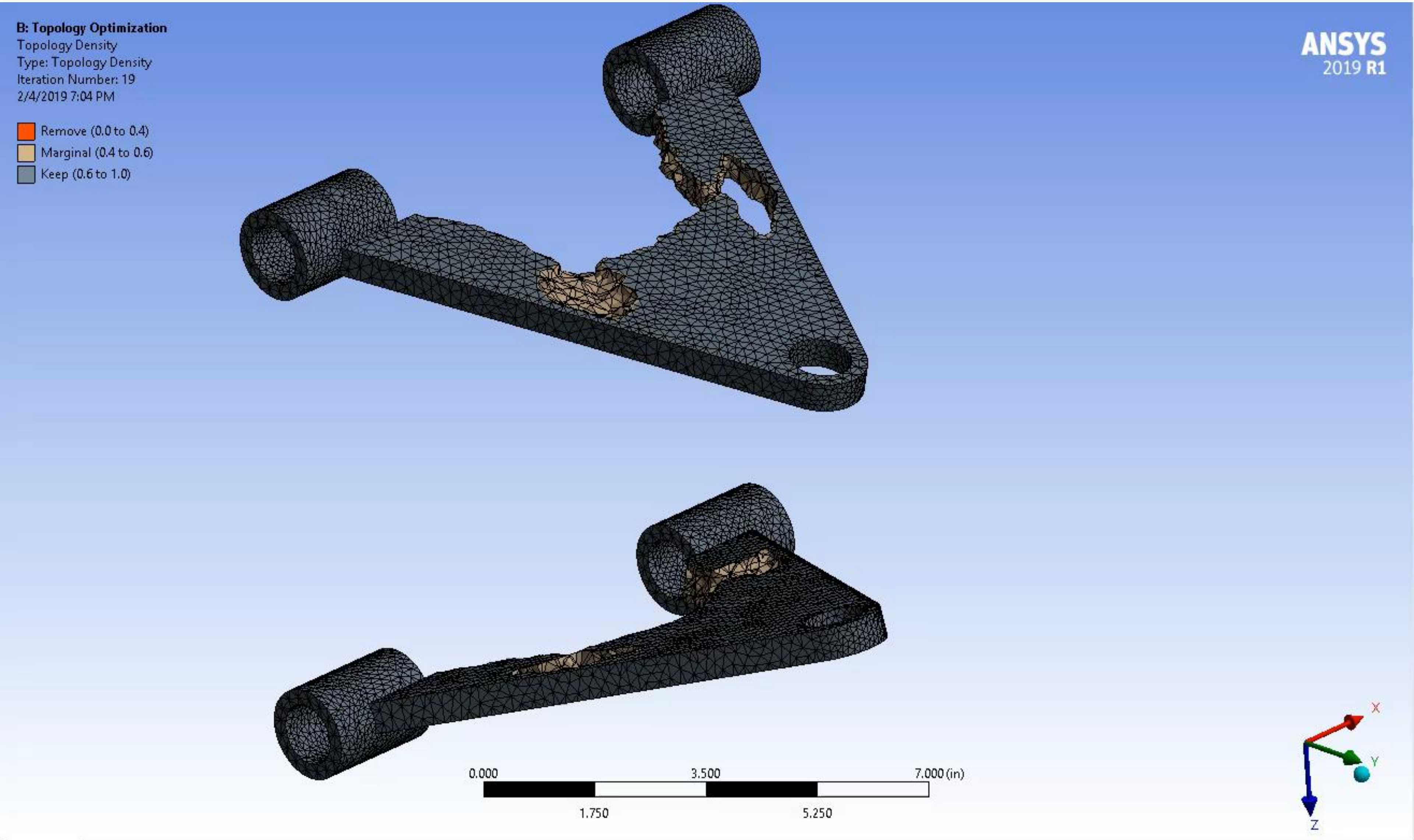


Case Study 3: Control Arms

- Converged fairly quickly – 19 iterations
- Actual mass retention: 64.5%
  - Common occurrence, need to iterate on target mass if critical
- Benefit in parts being optimized together rather than one at a time
- Not an ideal shape for manufacturing
  - Scalloping, hollowing out, etc.

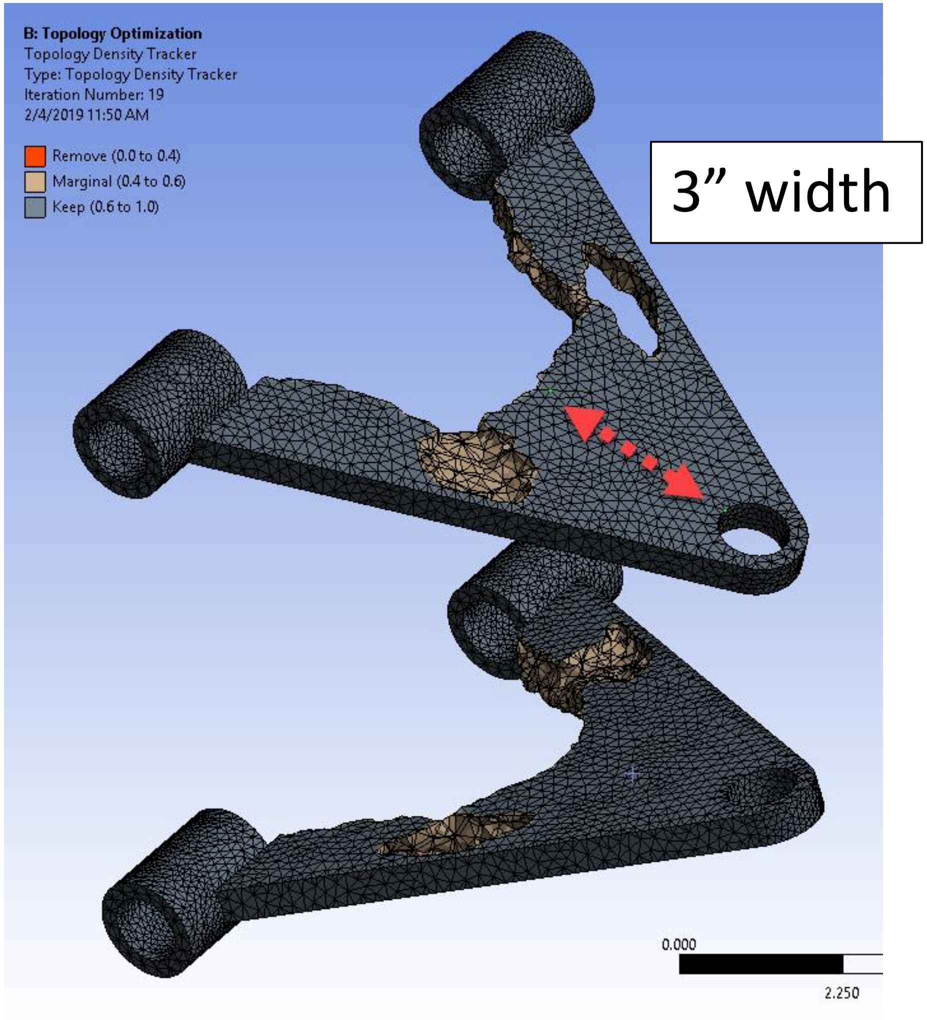


Case Study 3: Control Arms



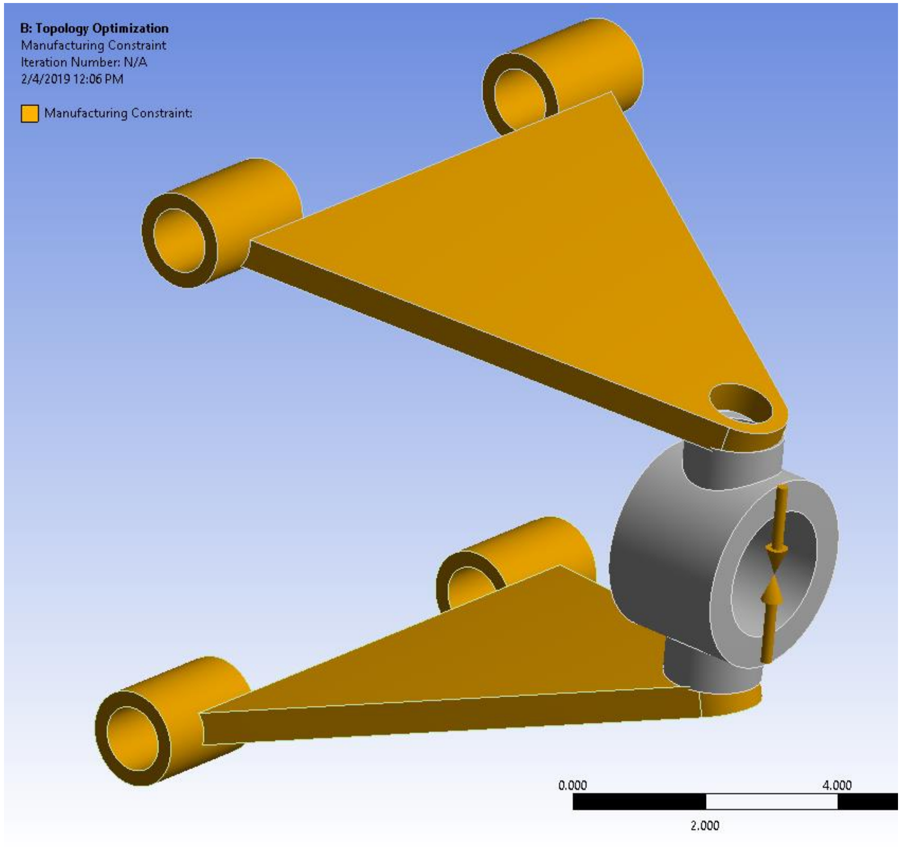
Case Study 3b: Member Sizing

- Try adding max member size manufacturing constraint
  - 1.5”
- Dependent on mesh sizing
  - Maximum member size must be at least 4.4x mesh density
  - Would require 1.2M nodes between these two parts in order to have a max member size under 0.5” (plate thickness)
- Exact same results
- Member size constraint larger than original thickness
  - Only needs to be satisfied in one direction



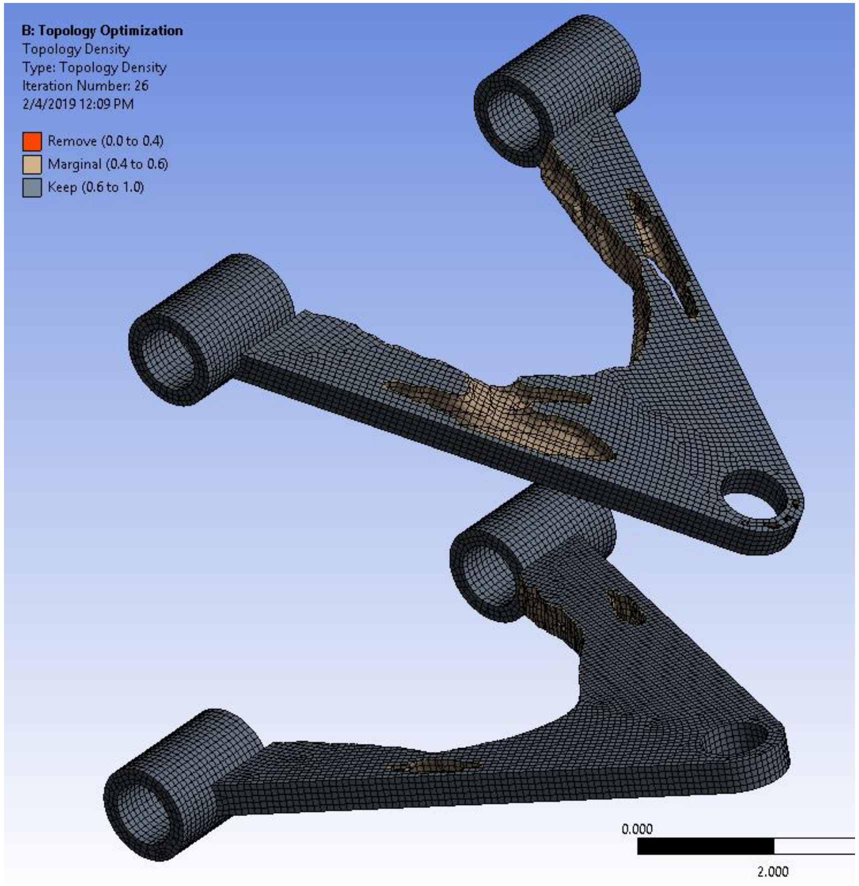
Case Study 3b: Extrusion/Pull-out

- Extrusion not viable due to two parts at angle
  - Must both be on same extrusion axis
  - Hex only mesh also requires additional model prep/consideration
- Add pull-out direction centered at hub
- Location of coordinate system as well as direction play a factor
  - Only parts "downstream" of an arrow are affected
  - In this case, enforces both parts to be castable from their exterior surfaces (one side)

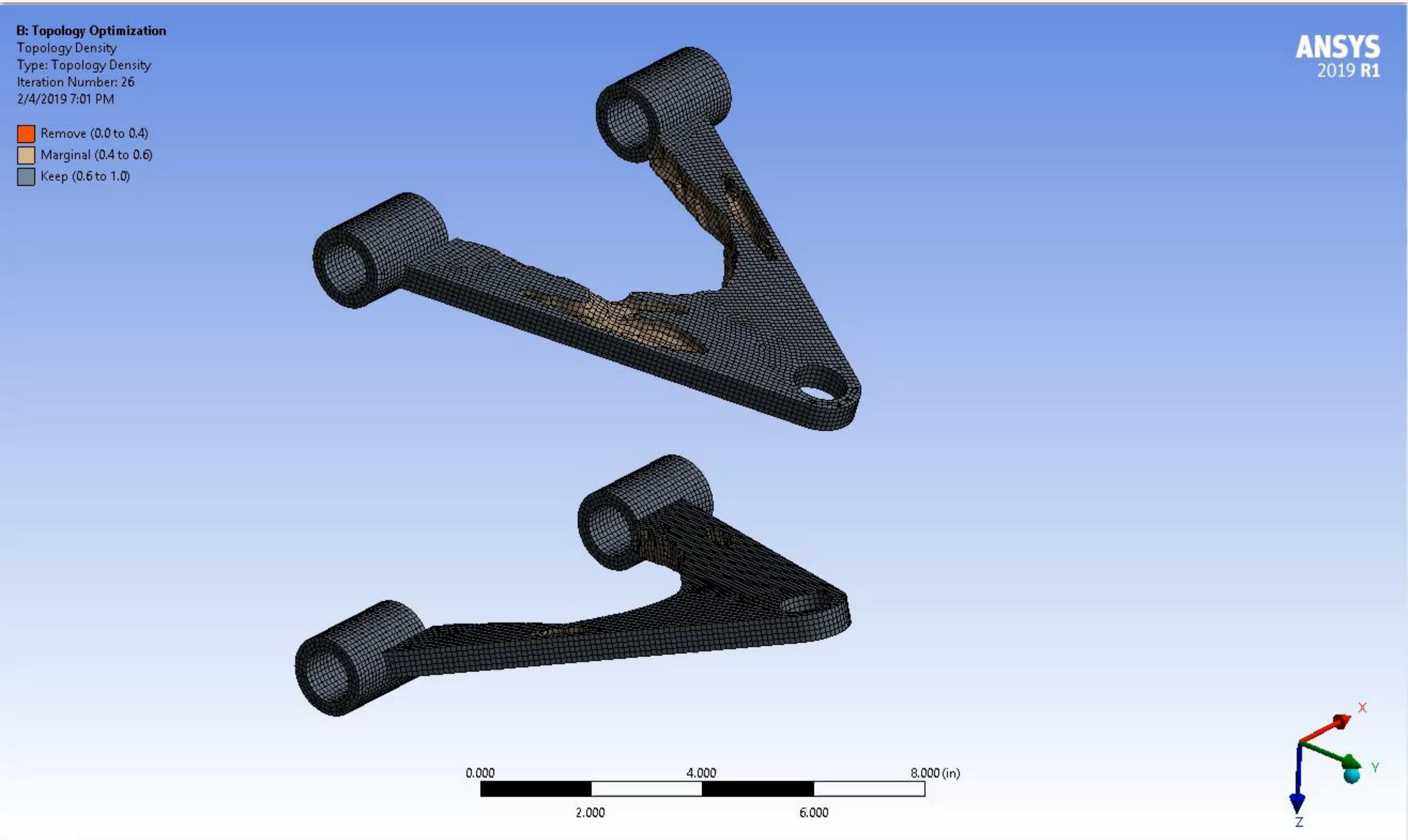


Case Study 3b: Extrusion/Pull-out

- Notable improvement
- Scalloping only from one direction, still allows through-holes
- Very little hollowing of plate interior



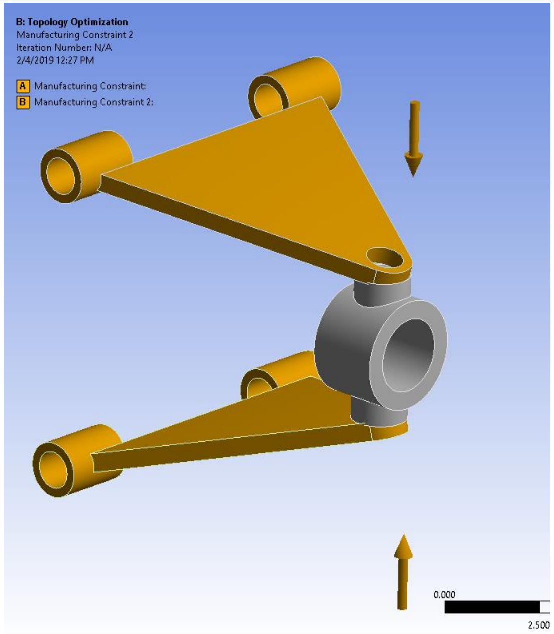
Case Study 3b: Extrusion/Pull-out

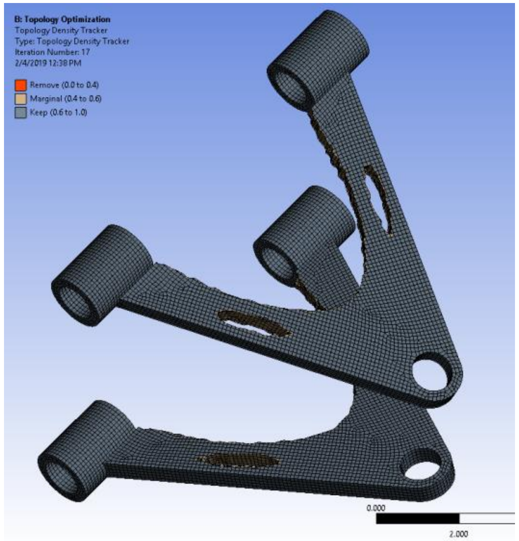


… within Epsilon

Case Study 3b: Extrusion/Pull-out

- Can set pull-out direction as two opposing axes rather than both sides of one axes
- Enforces pull-out direction on both top and bottom surfaces of plates
- Functions very similar to extrusion control, makes only cuts through the full thickness
- Also indirectly enforces symmetry

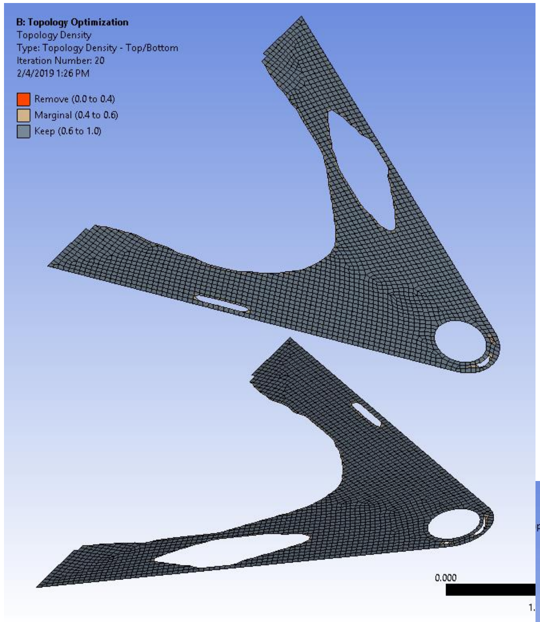


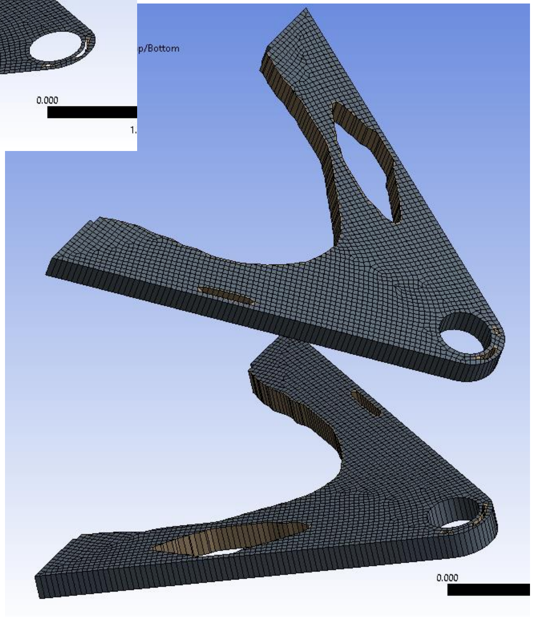


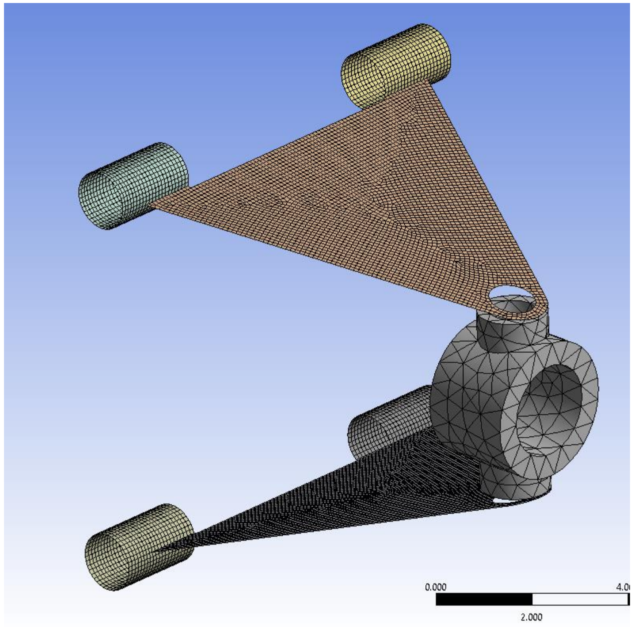
… within Epsilon

Case Study 3c: Shells

- Test geometry is prime candidate for using shell bodies
- Greatly simplifies necessary response constraints
- All cuts go through full shell thickness

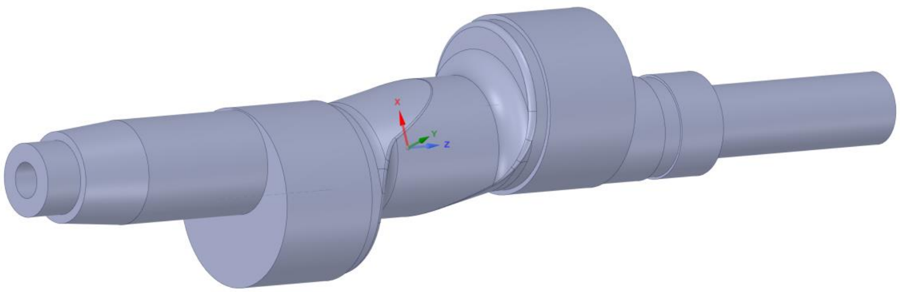


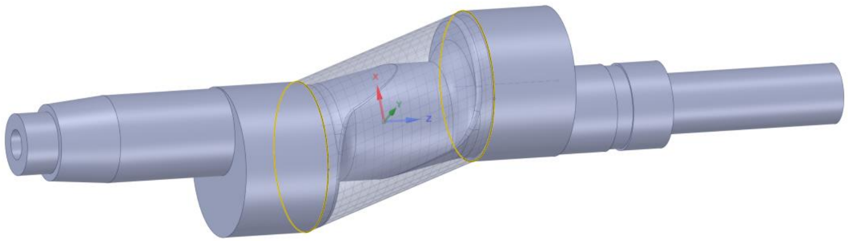




Case Study 4: Crankshaft

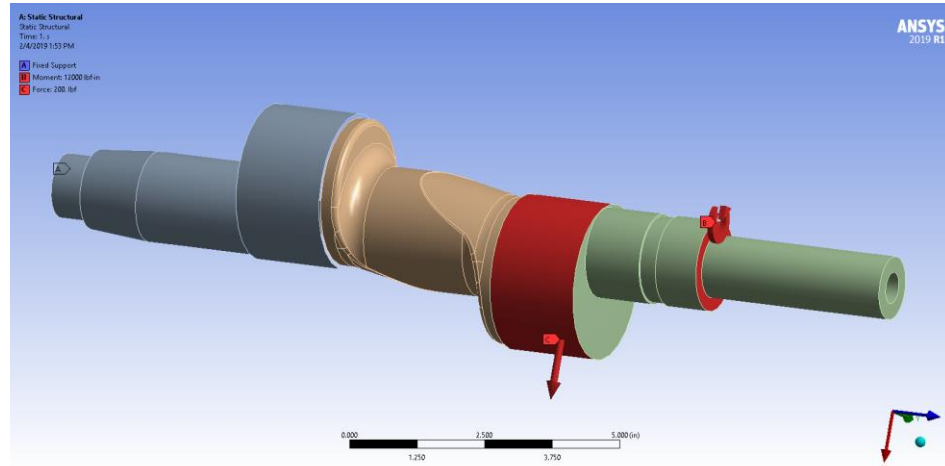
- Begin with existing crankshaft model from a rotary engine
- Model is easily manufactured by casting, milling, turning, etc.
- Reduced area was filled with material and set as the optimization region
- Try to gage Topology Optimization’s ability to replicate the original part’s manufacturability

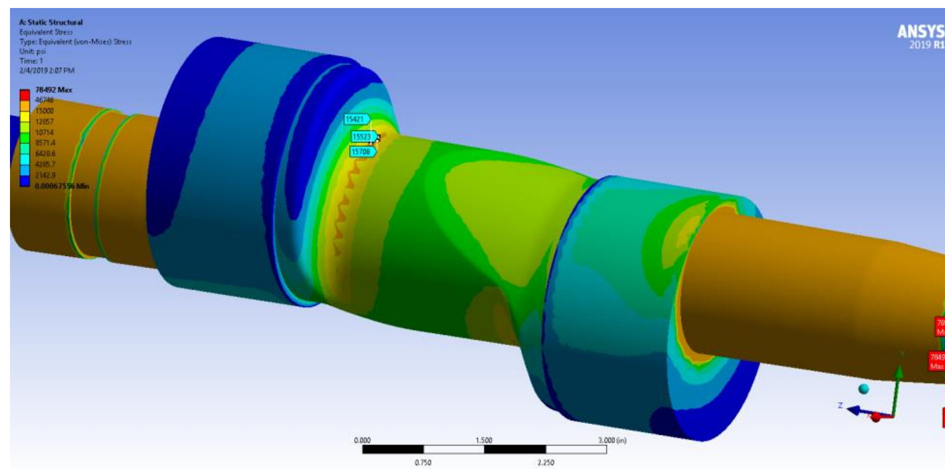


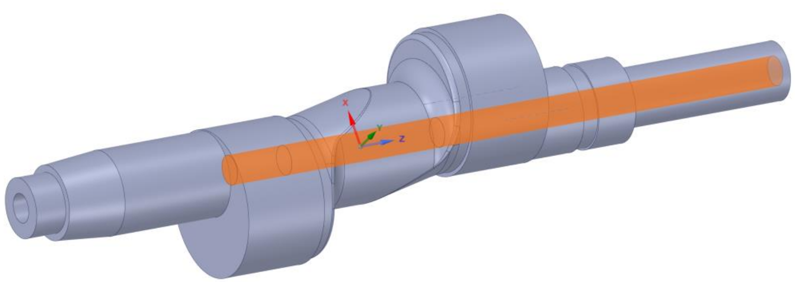


Case Study 4: Crankshaft

- Force and moment loading
- Find maximum stress in original model to use as constraint in Topology Optimization
  - 16 ksi
- Shaft is hollow, enforced for all optimization runs

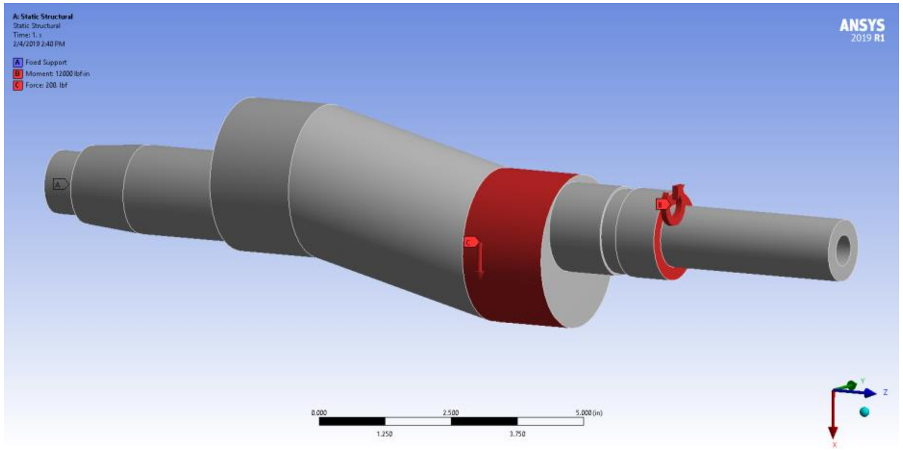


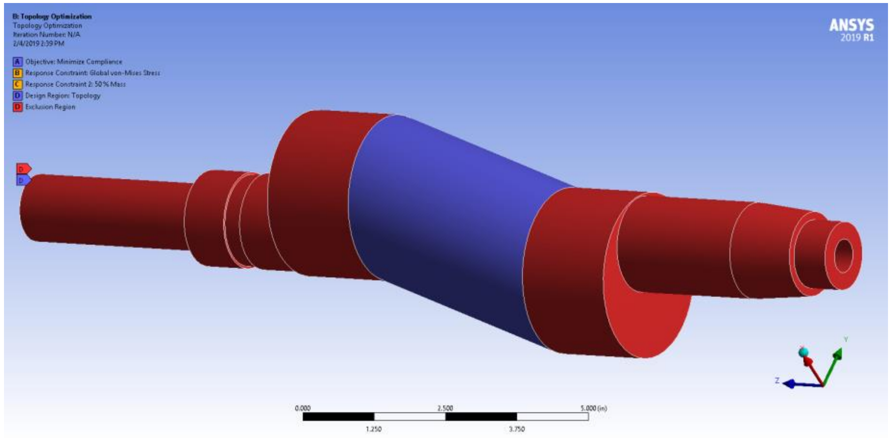




Case Study 4: Crankshaft

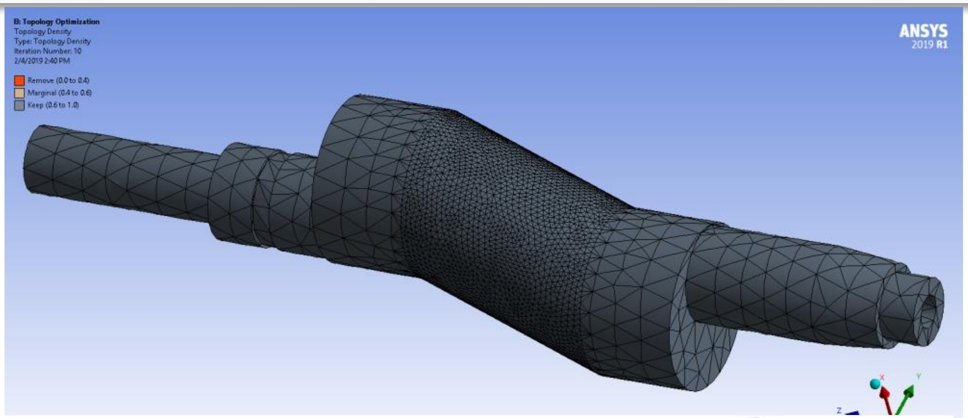
- Apply same loads to defeatured geometry
- Hold 16 ksi max stress constraint and 50% mass retention
- Entire body is optimization region, all faces except center section set as exclusion region
  - Includes inner hollow shaft

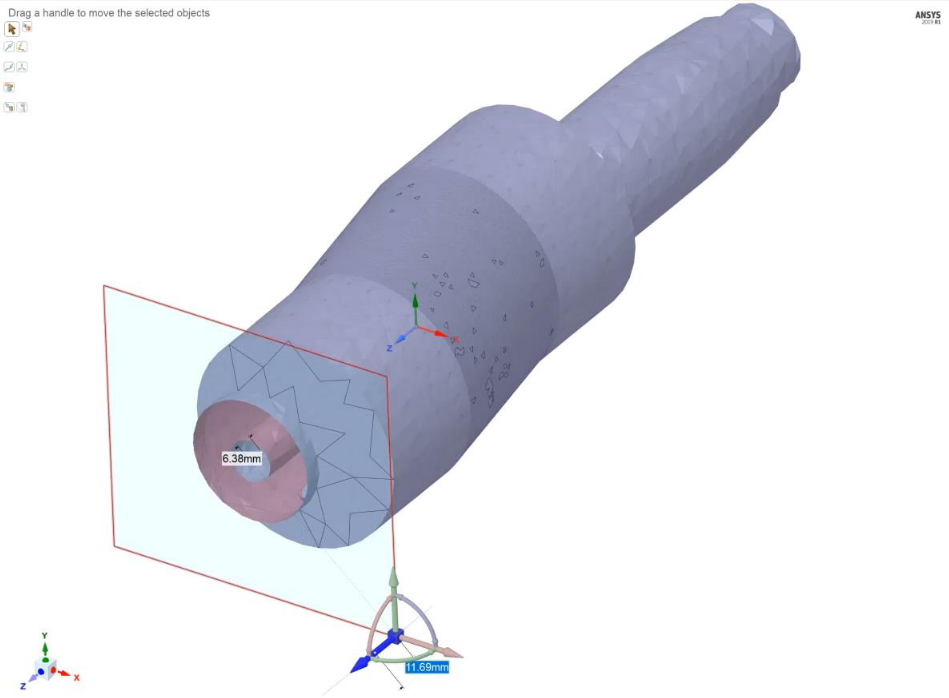


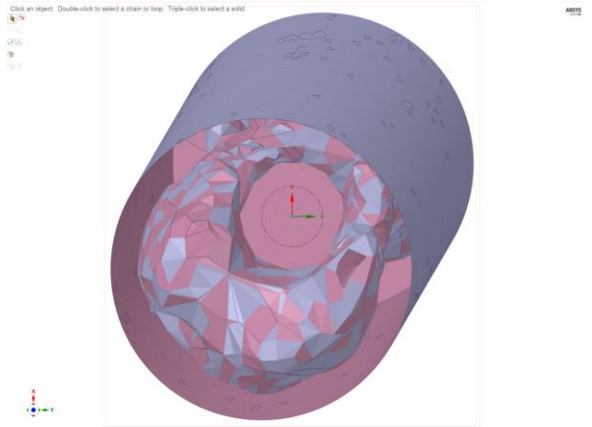


Case Study 4: Crankshaft

- Solution converges at 80% original mass… but where is the missing material?
- Export as STL and open in SCDM
- All material was hollowed out internally, maintaining interior and exterior shaft faces
- May not be an issue for additive manufacturing, but adjustments must be made to allow conventional manufacturing

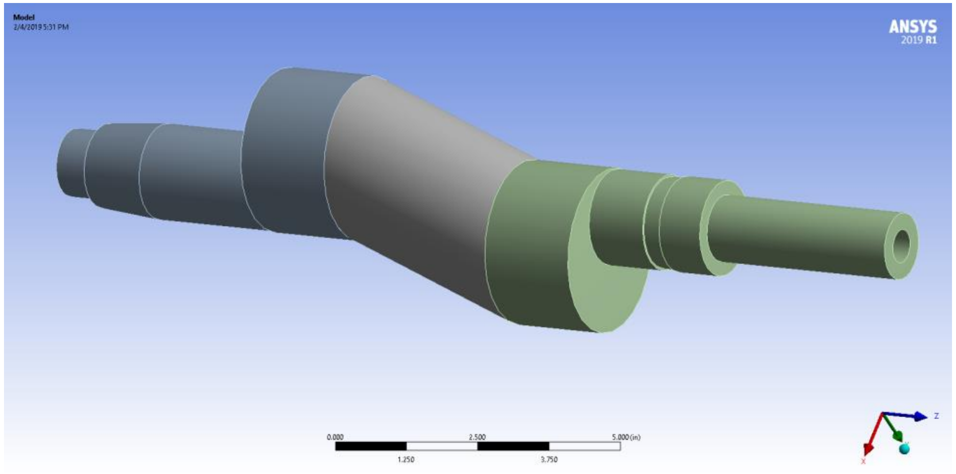


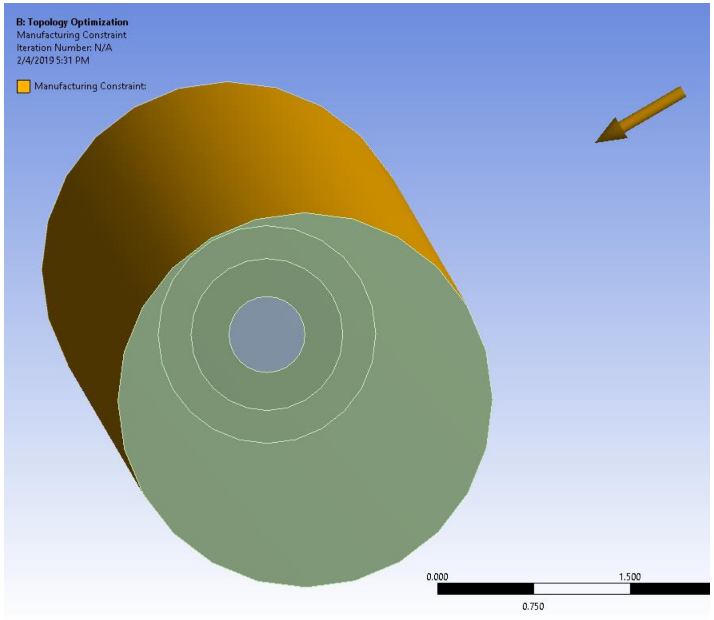




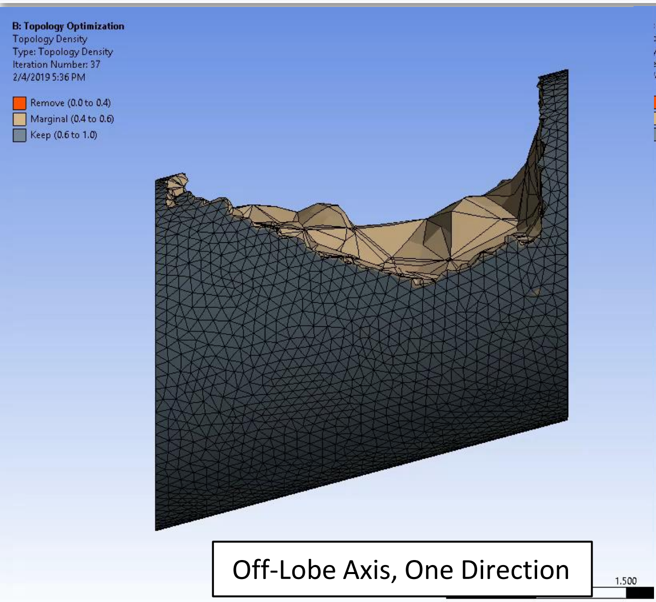
Case Study 4: Crankshaft

- Use three bodies with shared topology
  - Node to node connectivity, no contact
  - Allows much easier scoping/exclusion for optimization
  - Restricts all material removal to center section
- Apply pull-out direction manufacturing constraint
  - Removes material from the outside in
  - No undercutting/hollowing
  - Try both along lobe axis and perpendicular
  - Try from single direction and both directions
  - Try combining with planar symmetry

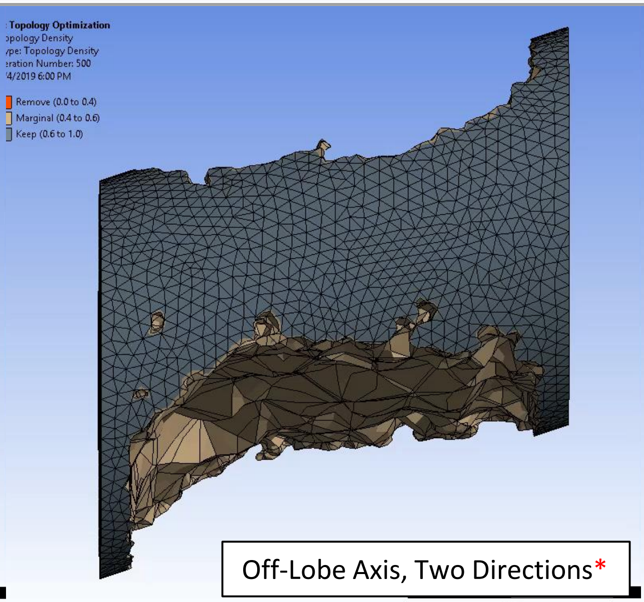




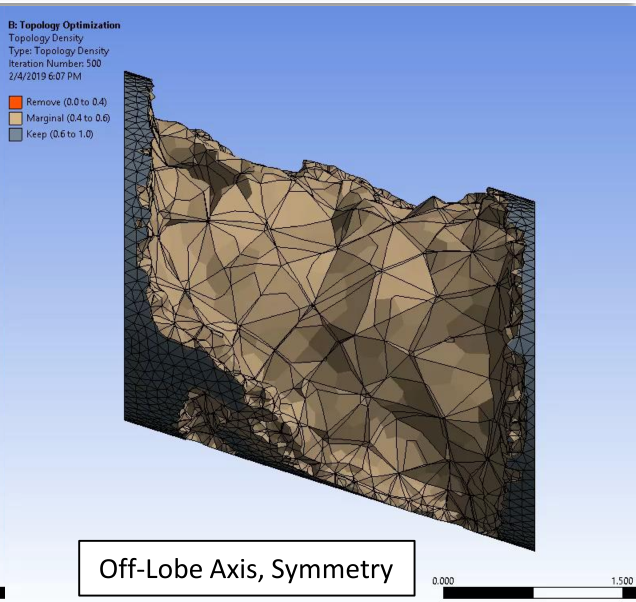
Case Study 4: Crankshaft



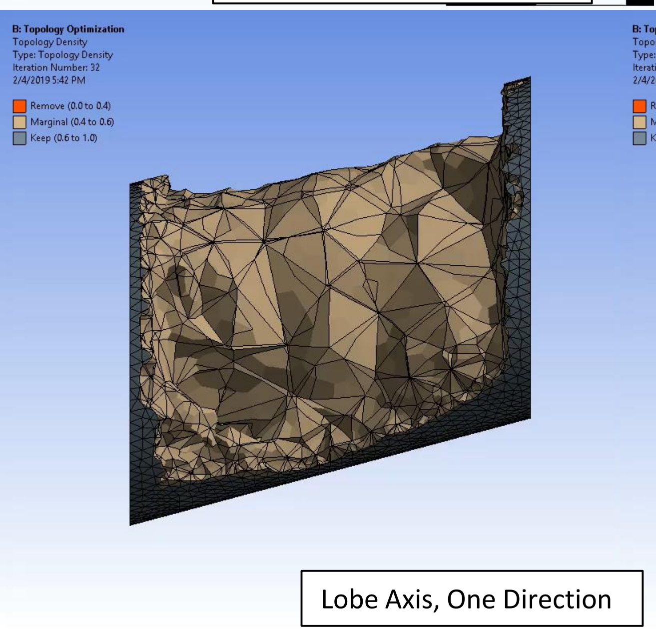
Off-Lobe Axis, One Direction



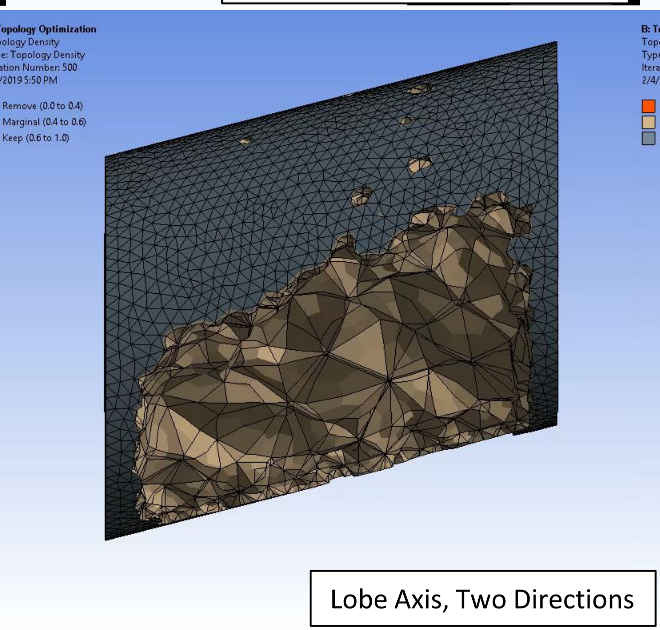
Off-Lobe Axis, Two Directions*



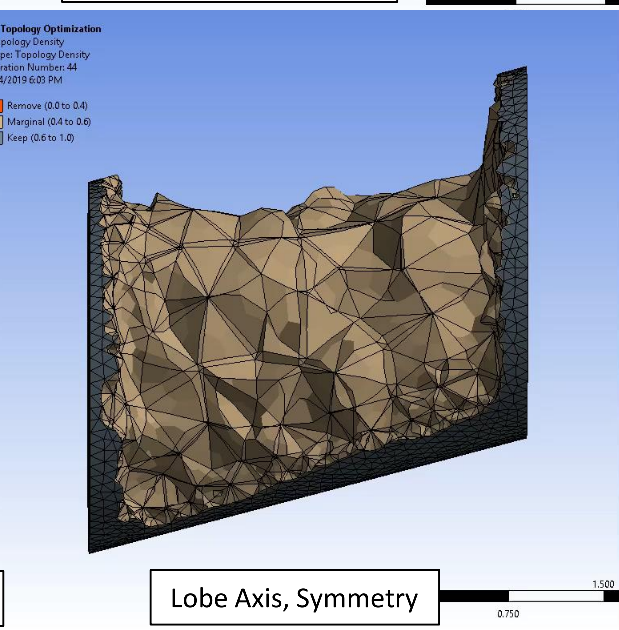
Off-Lobe Axis, Symmetry



Lobe Axis, One Direction



Lobe Axis, Two Directions

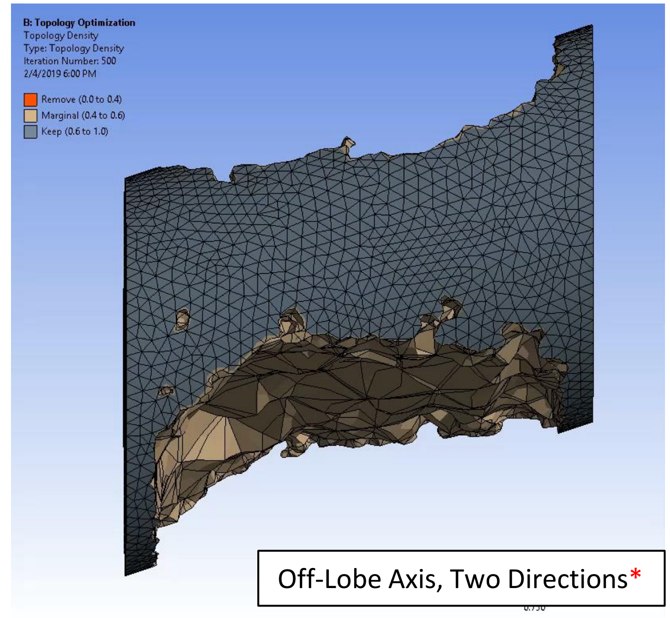


Lobe Axis, Symmetry

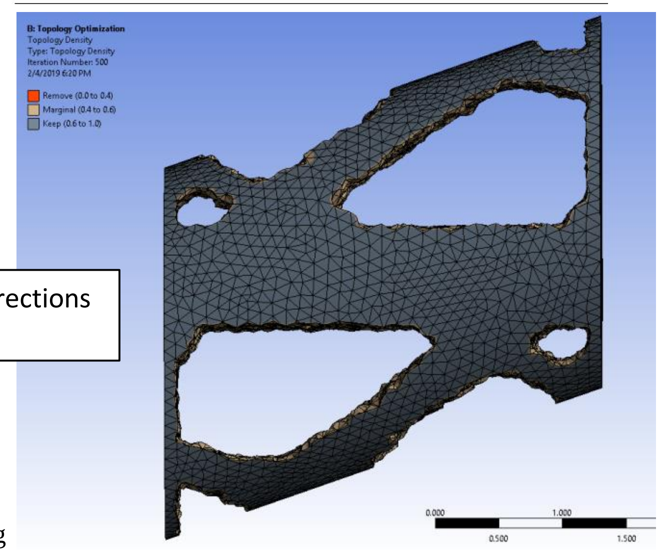
Case Study 4: Crankshaft

... within Epsilon

- Off-Lobe Axis, two direction case most closely resembles original part
- Refine mesh to aim for smoother result
  - Entirely different shape results
  - Goes from bulk solid to a truss framework



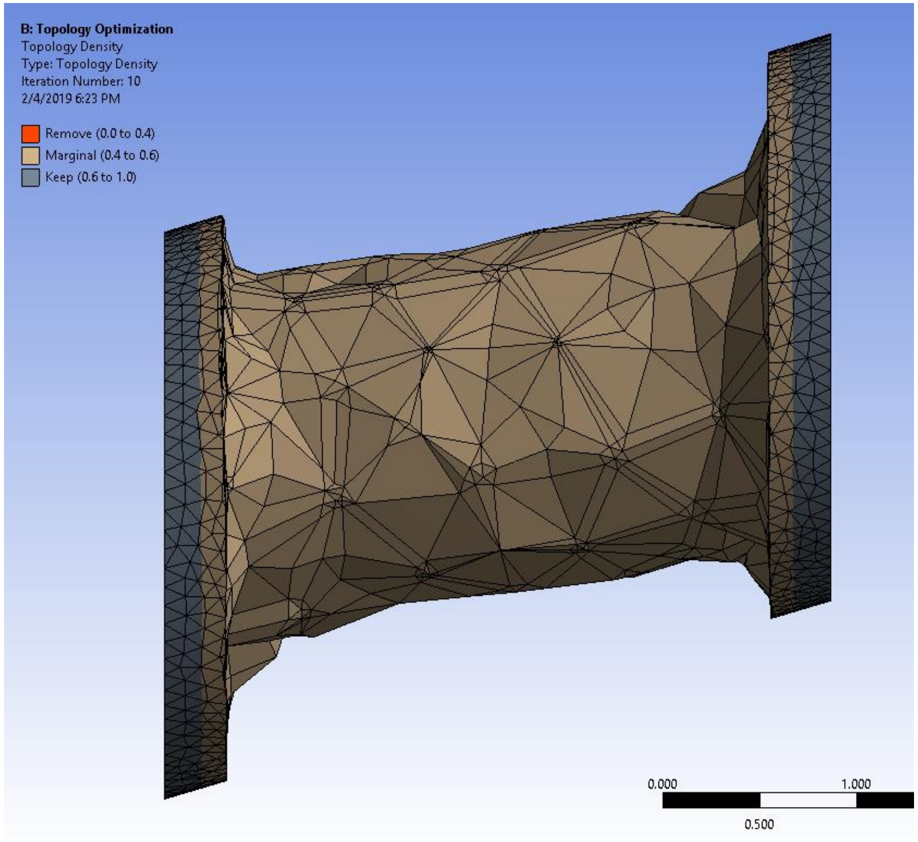
Off-Lobe Axis, Two Directions*



Off-Lobe Axis, Two Directions
Refined Mesh

Case Study 4: Crankshaft

- Beta Feature: Level Set Method
- Results in very smooth, organic shapes
- Not significantly affected by mesh sizing
- Cannot be used in combination with stress constraints
- Ignores most other constraints i.e. pull-out direction
- Promising future if controls can be added



Level Set

... within Epsilon

Conclusions

1. Plate/Shell based topology has high ease-of-use
2. Must have good handle on design envelope, targets, expected outcome
3. Large rectangular solids with few exclusion regions are ideal starting point for optimization
4. Still primarily built around additive manufacturing
   - Manufacturability issues are ignored unless expressly constrained
5. Many design constraints can be ignored or cheesed without warning
6. Enforcing manufacturability is possible but increased complexity cannot be overcome
   - May be possible in the future with increased number of optimization regions
7. A coarse and fine mesh should be considered whenever possible
   - Also tets vs. hex

Input / Questions