MSC Nastran Topology Optimization Mirror Symmetry Constraints

PRESENTED BY CHRISTIAN APARICIO

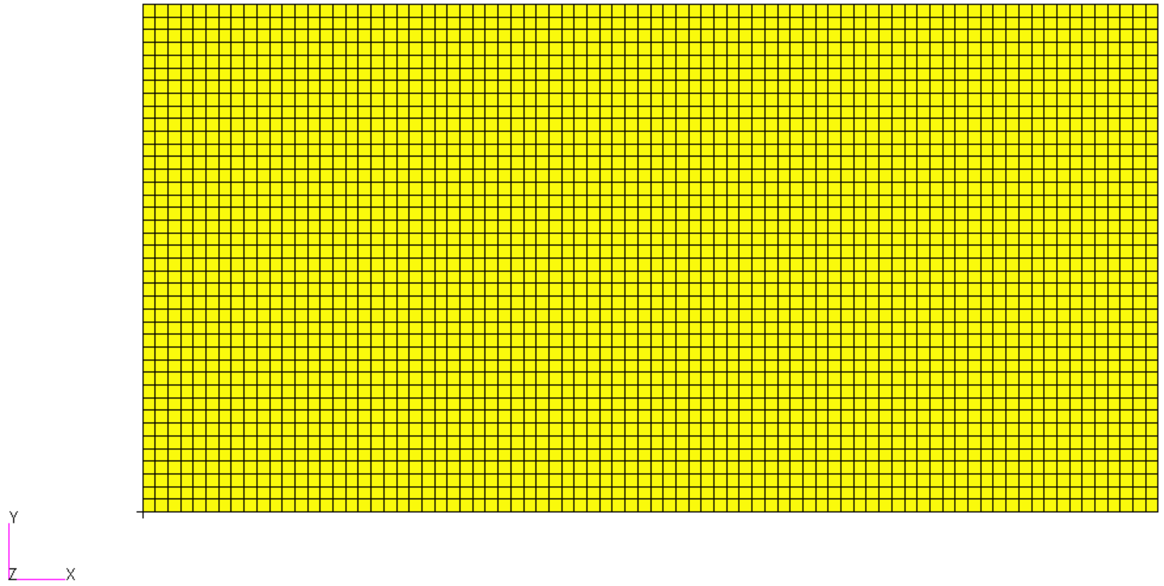
Goal: Use Nastran SOL 200 Optimization

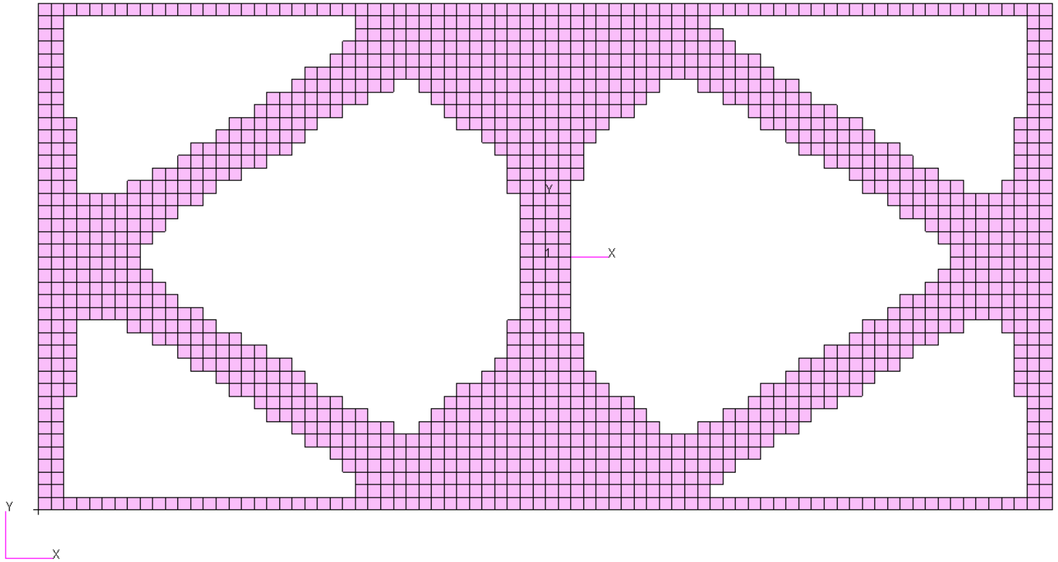
Before Optimization

- Mass: 67.

After Optimization

- Mass: 27.8 (~60% mass reduction)
- Mirror Symmetry Constraints





Agenda

Details of the structural model

Optimization Problem Statement

Steps to use Nastran SOL 200 (Optimization)

- Convert a .bdf file to SOL 200
- Create:
  - Design Regions/Variables
  - Design Objective
  - Design Constraints
- Perform optimization with Nastran SOL 200

View optimization results

- Online Plotter
- Topology Optimization and Structural Results

Contact me

- Nastran SOL 200 training
- Nastran SOL 200 questions
- Structural or mechanical optimization questions
- Access to the SOL 200 Web App

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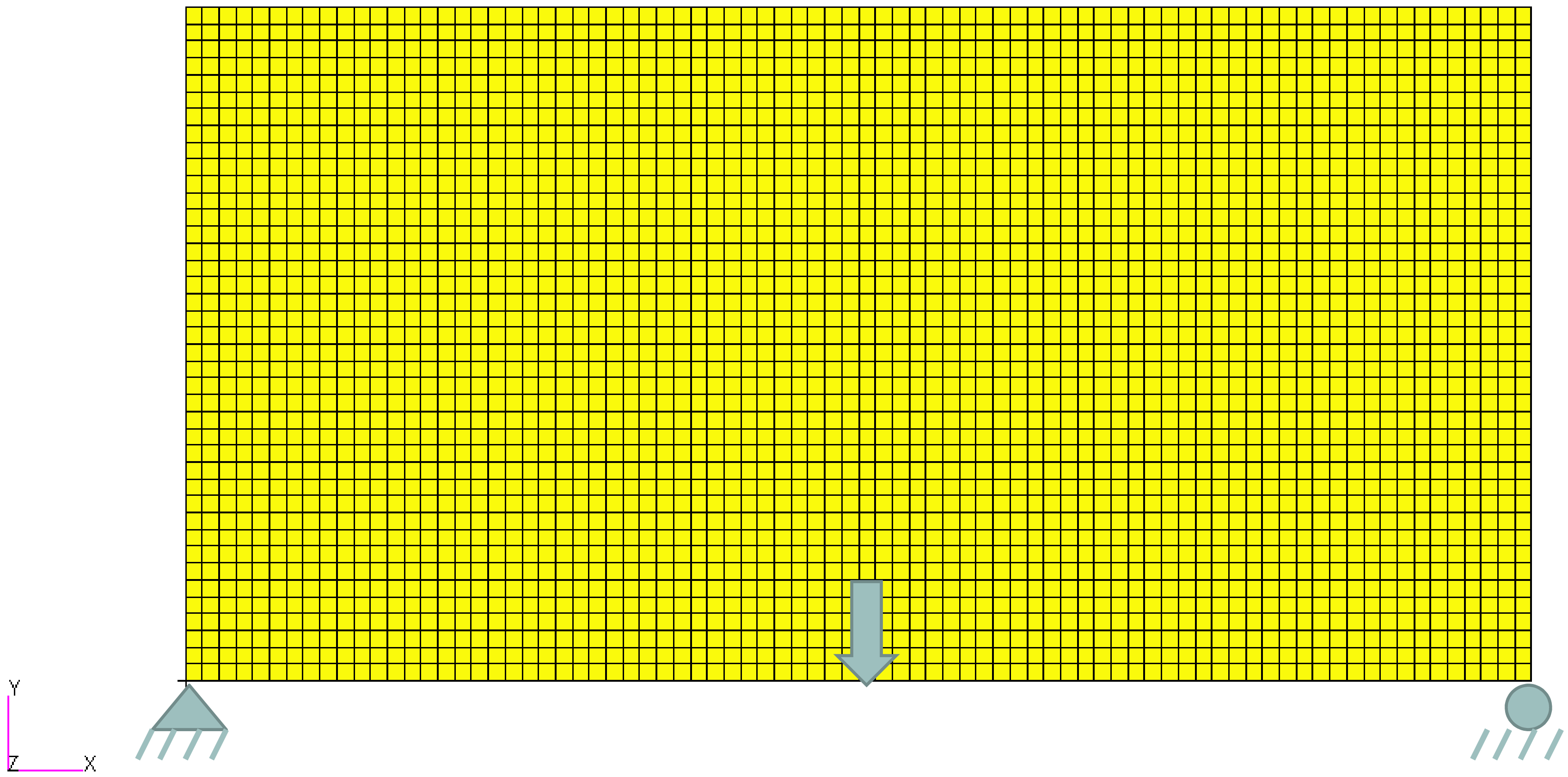
Details of the structural model



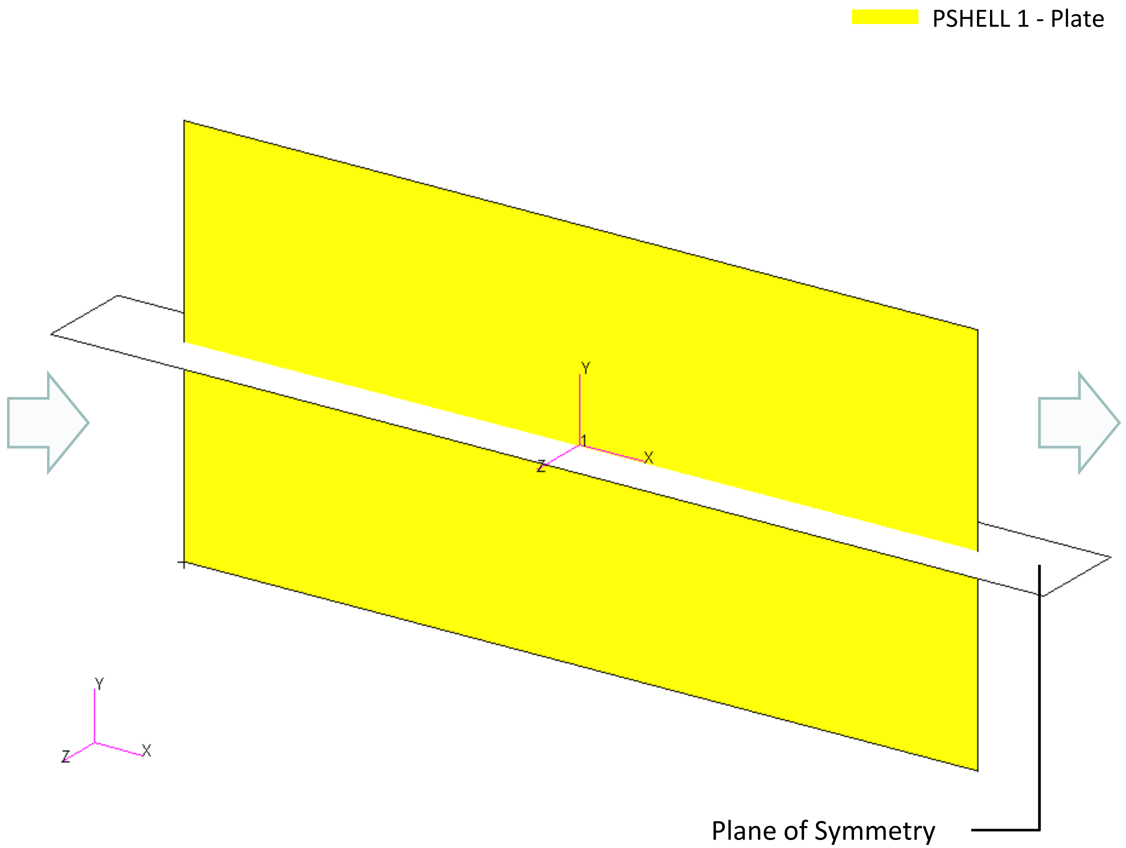
Optimization Problem Statement

Design Region/Variables

x1: PSHELL 1

Restrictions:

- Mirror Symmetry Constraints
  - Symmetry about the ZX plane of coordinate system 1



Design Objective

r0: Minimize compliance

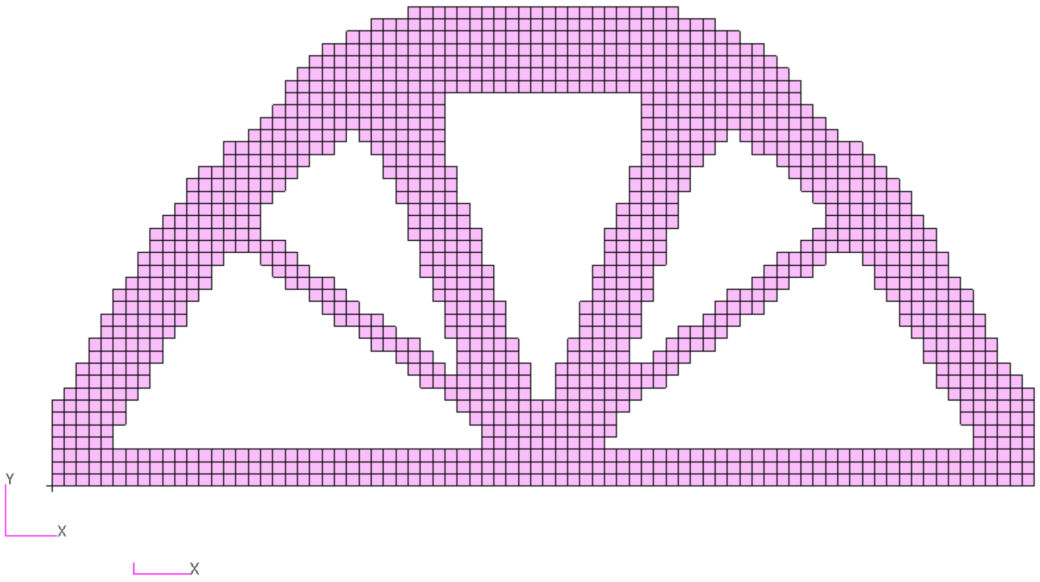
Design Constraints

r1: Fractional mass

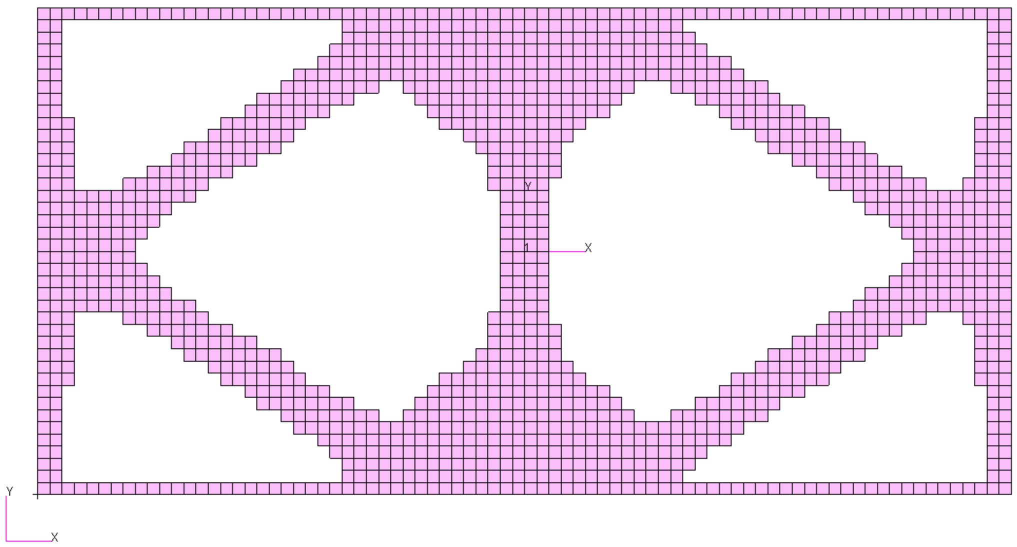
r1 < .4 (60% mass reduction)

Mirror Symmetry Constraints

Without Mirror Symmetry



With Mirror Symmetry



Steps to use Nastran SOL 200 (Optimization)

1. Start with a .bdf or .dat file
2. Use the SOL 200 Web App to:
   - Convert the .bdf file to SOL 200
     - Design Regions/Variables
     - Design Objective
     - Design Constraints
   - Perform optimization with Nastran SOL 200
3. Review optimization results
   - Online Plotter
   - Topology Optimization and Structural Results

SOL 200 Web App Capabilities

The Post-processor Web App and HDF5 Explorer are free to MSC Nastran users.

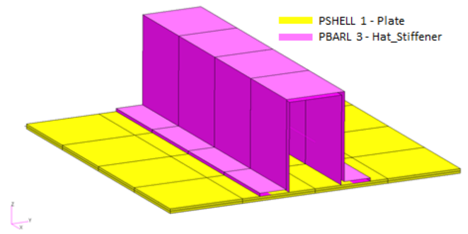
Compatibility

- Google Chrome, Mozilla Firefox or Microsoft Edge
- Windows and Red Hat Linux
- Installable on a company laptop, workstation or server. All data remains within your company.

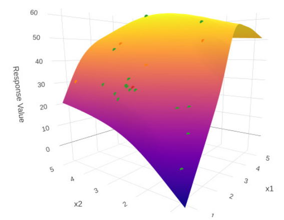
Benefits

- REAL TIME error detection. 200+ error validations.
- REALT TIME creation of bulk data entries.
- Web browser accessible
- Free Post-processor web apps
- +80 tutorials

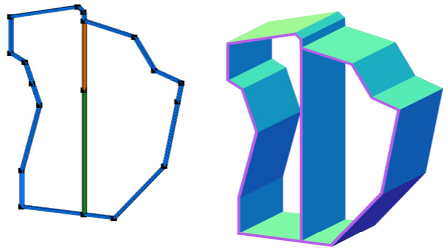
Web Apps



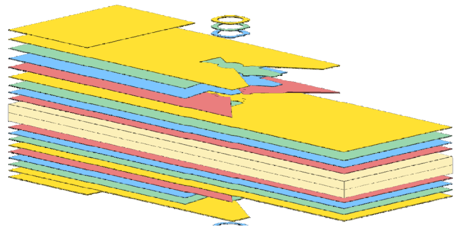
Web Apps for MSC Nastran SOL 200
Pre/post for MSC Nastran SOL 200. Support for size, topology, topometry, topography, multi-model optimization.



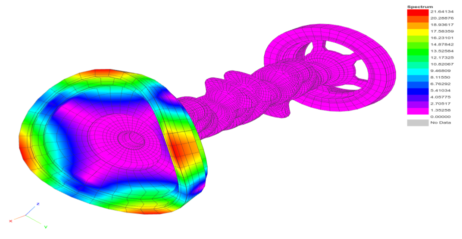
Machine Learning Web App
Bayesian Optimization for nonlinear response optimization (SOL 400)



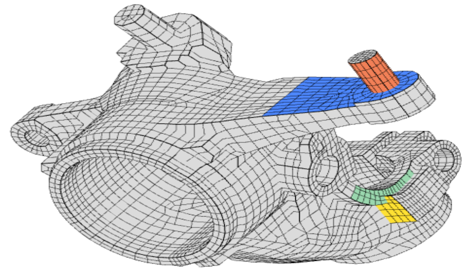
PBMSECT Web App
Generate PBMSECT and PBRSECT entries graphically



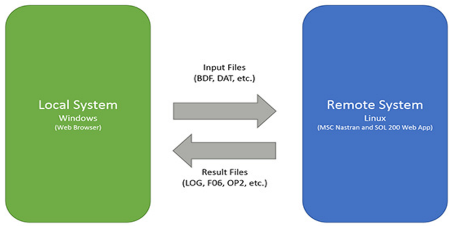
Ply Shape Optimization Web App
Optimize composite ply drop-off locations, and generate new PCOMPG entries



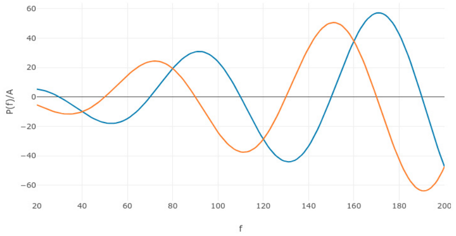
Post-processor Web App
View MSC Nastran results in a web browser on Windows and Linux



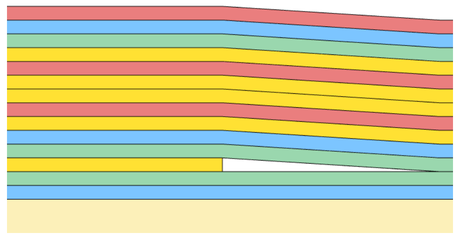
Shape Optimization Web App
Use a web application to configure and perform shape optimization.



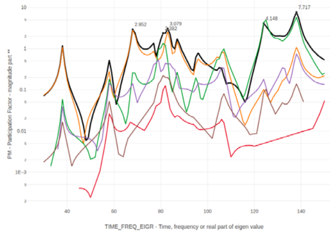
Remote Execution Web App
Run MSC Nastran jobs on remote Linux or Windows systems available on the local network



Dynamic Loads Web App
Generate RLOAD1, RLOAD2 and DLOAD entries graphically



Stacking Sequence Web App
Optimize the stacking sequence of composite laminate plies



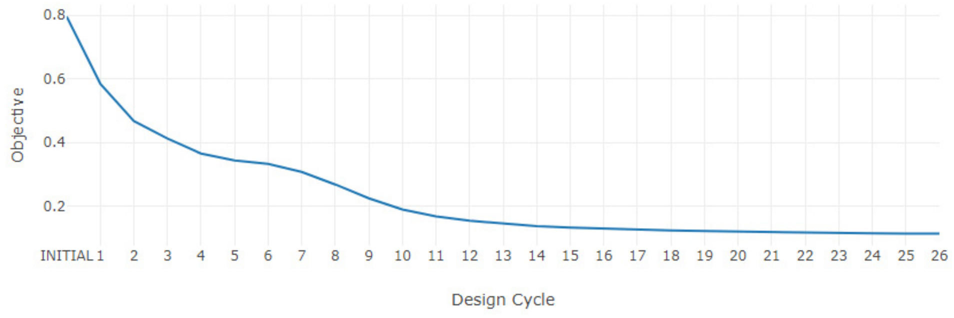
HDF5 Explorer Web App
Create graphs (XY plots) using data from the H5 file

View Optimization Results
Online Plotter

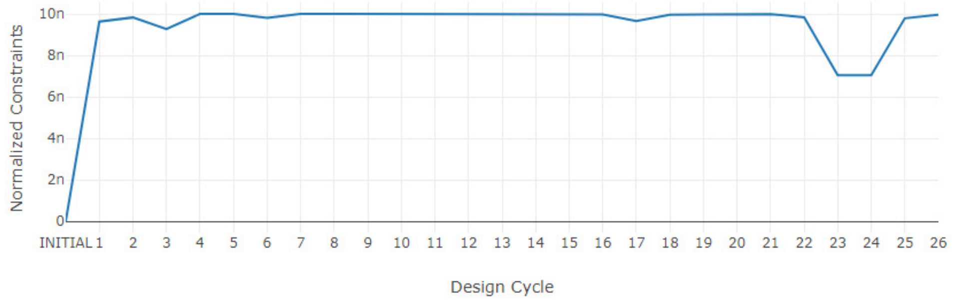
Final Message in .f06

```
RUN TERMINATED DUE TO HARD CONVERGENCE TO AN OPTIMUM AT CYCLE NUMBER =        26.
```

Objective



Normalized Constraints



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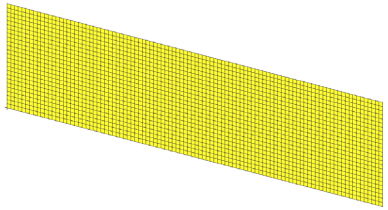
Topology Optimization Workflows

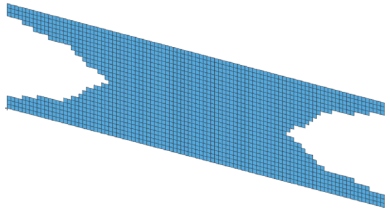
Traditional Topology Optimization

Objective: Minimize Compliance (Maximize Stiffness)
Constraint: Fractional Mass < .## (Target Mass)

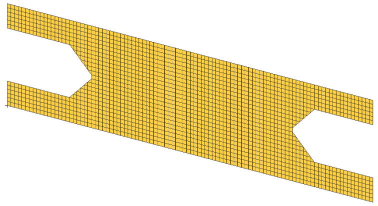
Original Design



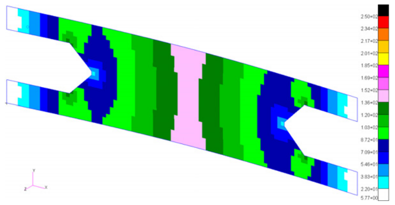
Mass: 9.737 grams



FRMASS < .75
Mass: 7.186 g
Optimization B



Mass: 7.739 g



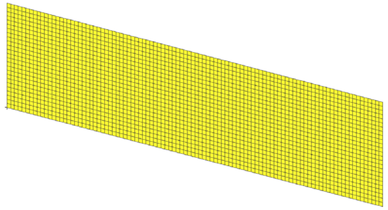
Max von Misses: 150 MPa
Max Displacement : 2.78 mm

1st natural Frequency: 111 Hz

Traditional Topology Optimization

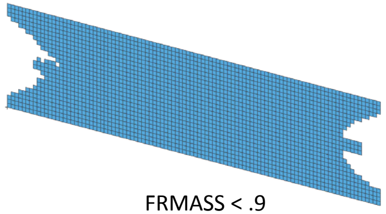
Objective: Minimize Compliance (Maximize Stiffness)
Constraint: Fractional Mass < .## (Target Mass)

Original Design

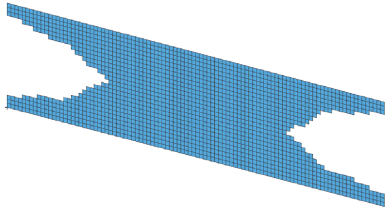


Mass: 9.737 grams

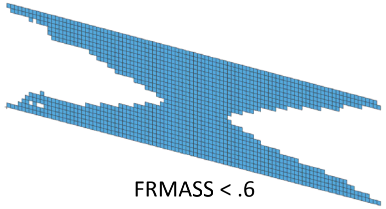
Topology Solution



FRMASS < .9
Mass: 8.756 g
Optimization A

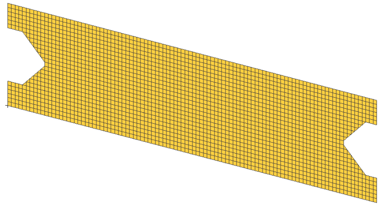


FRMASS < .75
Mass: 7.186 g
Optimization B

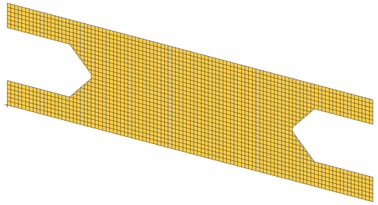


FRMASS < .6
Mass: 5.718 g
Optimization C

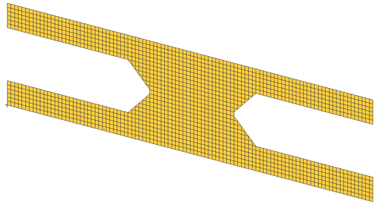
Refined Design



Mass: 9.094 g

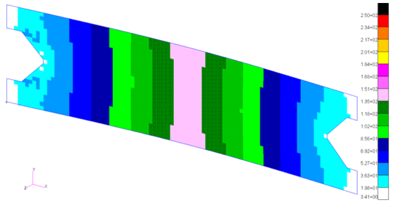


Mass: 7.739 g



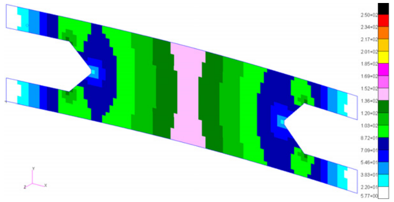
Mass: 6.119 g

Verification



Max von Misses: 150 MPa
Max Displacement: 2.52 mm

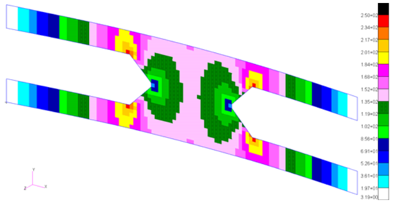
1st natural Frequency: 114 Hz



Max von Misses: 150 MPa
Max Displacement : 2.78 mm

1st natural Frequency: 111 Hz

Optimization B led to a valid and light weight design



Max von Misses: 250 MPa
Max Displacement : 3.57 mm

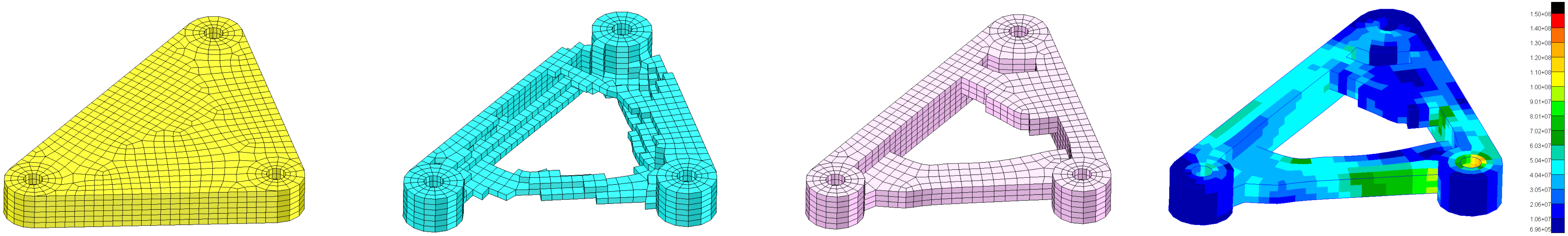
1st natural Frequency: 109 Hz

Latest Topology Optimization

Objective: Minimize Fractional Mass (Minimize Mass)

Constraint: Stress Constraint

Original Design → Topology Solution → Refined Design → Verification



Appendix

Appendix Contents

- Frequently Asked Questions
  - What are the design variables in Topology Optimization?
  - What is FRMASS or Fractional Mass?
  - What is compliance?
  - How can non-critical elements be removed from the design?

What are the design variables in Topology Optimization?

Consider the following topology optimization workflow.

1. A topology design region is selected.
   - 1 material
   - 2048 elements

2. At the start of an optimization, each element is assigned its own material (stiffness and density).
   - 2048 materials
   - 2048 elements

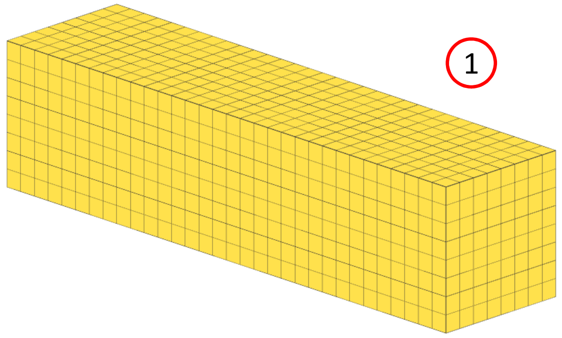
3. During the optimization, each element is given a topology variable x_i, where i is the element ID.
   - 2048 topology variables

   The topology variable x_i controls the material density and stiffness of element i via these expressions.
   - $p_i = p_0 \cdot x_i$
   - $E_i = E_0 \cdot x_i^{Penalty}$

   The penalty term ranges between 2-5 and is 3 by default. The topology variable varies between 0 and 1.

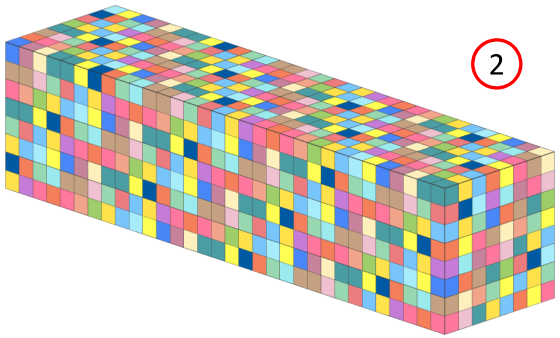
4. After the topology optimization, the user must decide which elements to keep.
   - During the topology optimization, elements are not automatically removed. It is up to the user to decide which elements to keep after the optimization.

Topology Design Region

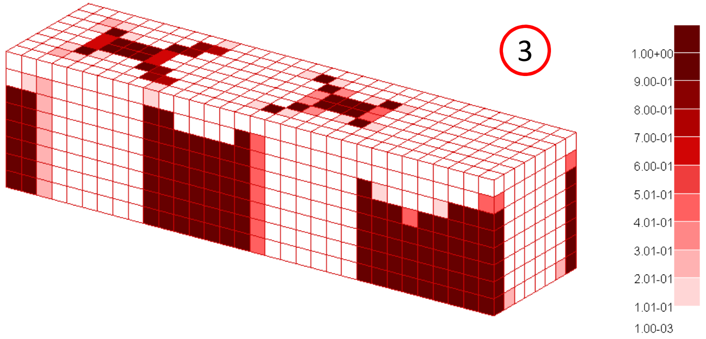


1

Topology Optimization



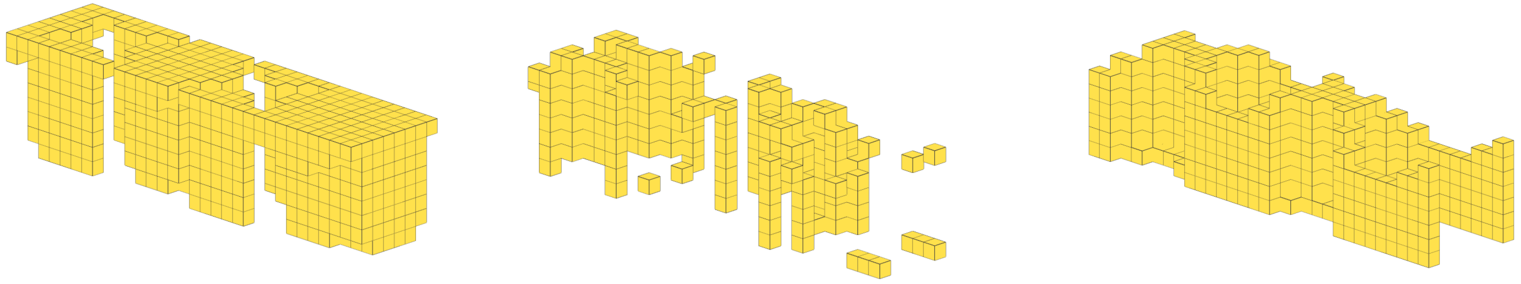
2



3

Results Post-processing

4



What are the design variables in Topology Optimization?

Many practitioners suggest keeping elements whose topology variable is in the range of 0.3 and 1.0, but do not explain the reasoning behind this suggestion.

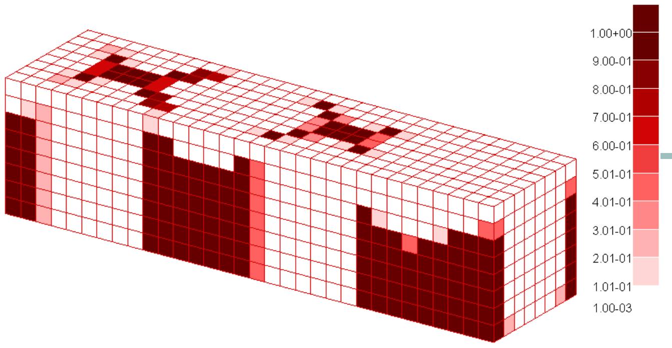
The following is an attempt to explain the suggestion.

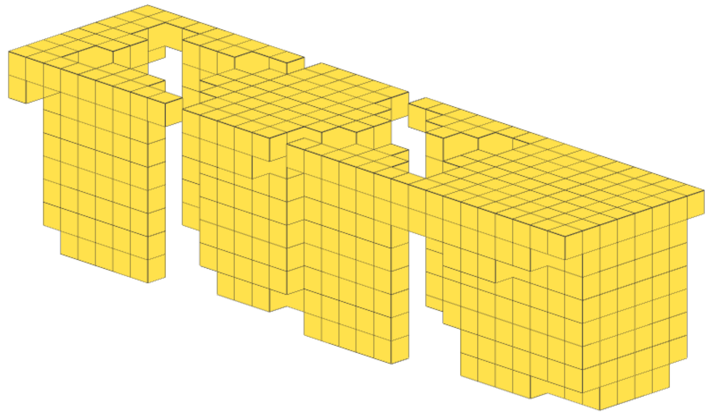
Suppose the original stiffness of the material is $E_0 = 200E9\ Pa$.

- If x_i=0.3, then
  - E_i = 200E9 Pa * 0.3^3 = 5.4E9 Pa (5.4 GPa)
  - A topology variable value of x_i=0.3 yields a stiffness on the range of wood.
- If x_i=.0056, then
  - E_i = 200E9 Pa * .0056^3 = 3.5123E4 Pa (35.123 kPa)
  - A topology variable value of x_i=.0056 yields a stiffness on the range of gelatin dessert, such as Jello.

Elements with a stiffness equivalent to Jello are negligible and may be removed from the design. Elements with a stiffness equivalent to wood are also candidates for removal. Those who use topology optimization long enough will find the suggestion of keeping elements between 0.3 and 1.0 is not absolute. With trial and error, some will find that ranges of 0.5 to 1.0 or 0.4 to 1.0 will also sometimes work. Given that the best range is often unknown, this makes topology optimization a *black art*.

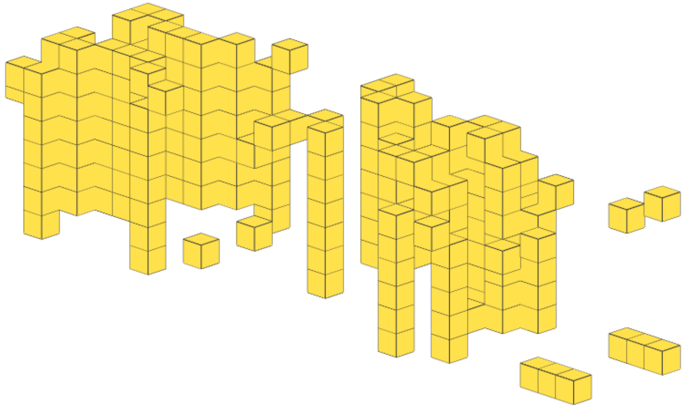
Topology Optimization Results





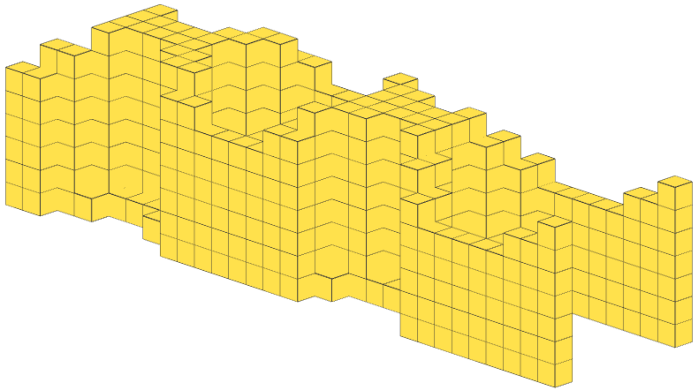
Elements in range:
0 < x_i <= .0056
0 < E_i <= 3.5123E4 Pa
Range: Jello

Do not keep



Elements in range:
.0056 < x_i <= 0.3
3.5123E4 < E_i <= 5.4E9 Pa
Range: Wood

Do not keep



Elements in range:
0.3 < x_i <= 1.0
5.4E9 Pa < E_i <= 200E9 Pa

Keep

What is FRMASS or Fractional Mass?

Since the topology variables can range between 0 and 1, the final mass will be some fraction of the original mass. This is known as the fractional mass or FRMASS.

$$\text{FRMASS} = \frac{\Sigma\, p_i \cdot v_i}{\Sigma\, p_0 \cdot v_i}$$

p_0 : The original material density

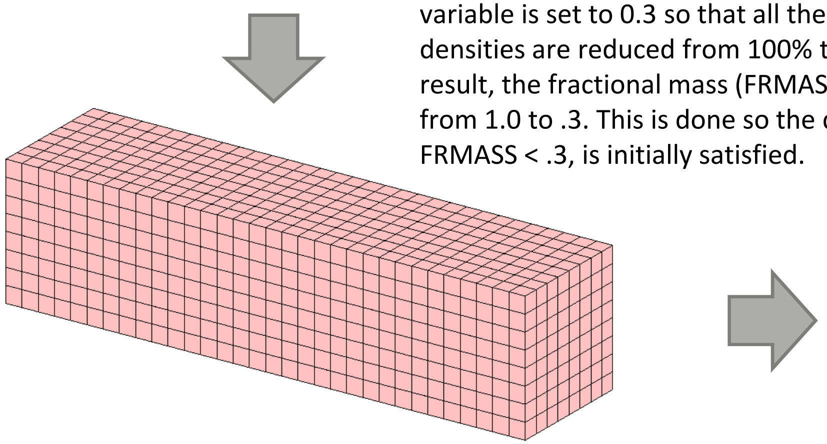
p_i : The optimized material density of the element ($p_i = p_0 \cdot x_i$)

v_i : Volume of element

0) Suppose this is the optimization problem statement:

- Objective: Minimize compliance
- Constraint: FRMASS < .3

1) Prior to the optimization start, each topology variable is set to 0.3 so that all the material densities are reduced from 100% to 30% of p_0. As a result, the fractional mass (FRMASS) is reduced from 1.0 to .3. This is done so the design constraint, FRMASS < .3, is initially satisfied.



2) During the optimization, each topology variable is allowed to range between 0 and 1.0, but the constraint on fractional mass (FRMASS < .3) should ultimately be satisfied.

What is compliance?

Compliance is defined in many ways

- “Compliance is simply the product of the displacement times the applied load” (MSC Nastran Design Sensitivity and Optimization User’s Guide)
- For linear elastic solids, the work is twice the total strain energy

```
                    E L E M E N T   S T R A I N   E N E R G I E S

ELEMENT-TYPE = HEXA             * TOTAL ENERGY OF ALL ELEMENTS IN PROBLEM     =    9.111034E+03
SUBCASE              1          * TOTAL ENERGY OF ALL ELEMENTS IN SET      -1 =    9.111034E+03

                     ELEMENT-ID          STRAIN-ENERGY           PERCENT OF TO
                             25          8.059148E+02                 8.8455
                             32          8.059148E+02                 8.8455                    6.447318E+03
                             33          8.059148E+02                 8.8455                    6.447318E+03
                             40          8.059148E+02                 8.8455                    6.447318E+03

          TYPE = HEXA      SUBTOTAL          9.111034E+03               100.0000
```

Total Strain Energy

```
                    ***************************************************************
                    S U M M A R Y   O F   D E S I G N   C Y C L E   H I S T O R Y
                    ***************************************************************

                                    (HARD CONVERGENCE ACHIEVED)

                        NUMBER OF FINITE ELEMENT ANALYSES COMPLETED          56
                        NUMBER OF OPTIMIZATIONS W.R.T. APPROXIMATE MODELS    55

                             OBJECTIVE AND MAXIMUM CONSTRAINT HISTORY
---------------------------------------------------------------------------------------------------------------
                  OBJECTIVE FROM        OBJECTIVE FROM        FRACTIONAL ERROR        MAXIMUM VALUE
CYCLE              APPROXIMATE              EXACT                    OF                     OF
NUMBER            OPTIMIZATION            ANALYSIS             APPROXIMATION            CONSTRAINT
---------------------------------------------------------------------------------------------------------------

INITIAL                                   1.822207E+04                                   -4.625929E-15

     1             5.076533E+03           1.32[illegible]             6.163140E-01            9.999972E-09

     2             5.721454E+03           1.12[illegible]             4.893855E-01            6.604279E-09

     3             4.220301E+03           1.016538E+04            -5.848357E-01            1.000032E-08

     4             3.996396E+03           9.769504E+03            -5.909315E-01            9.983010E-09
```

Compliance

What is compliance? Continued

The .f06 file reports the value of compliance and strain energy. **The following applies if and only if minimizing the compliance is the design objective.**

1. Make sure this statement is in the Case Control Section of the .bdf file.

   ESE(THRESH=.99)=ALL

2. Search the .f06 file for the initial design's

   E L E M E N T S T R A I N E N E R G I E S

3. *Note the value of TOTAL ENERGY OF ALL ELEMENTS IN PROBLEM*

4. *Search the .f06 for the*

   S U M M A R Y O F D E S I G N C Y C L E H I S T O R Y

5. Note the value for OBJECTIVE FROM EXACT ANALYSIS for the INITIAL cycle number

6. The Compliance of 1.8222E4 is twice the TOTAL STRAIN ENERGY of 9.11E3.

```
                                 E L E M E N T   S T R A I N   E N E R G I E S

ELEMENT-TYPE = HEXA                * TOTAL ENERGY OF ALL ELEMENTS IN PROBLEM     =   9.111034E+03
SUBCASE               1            * TOTAL ENERGY OF ALL ELEMENTS IN SET      -1 =   9.111034E+03

                       ELEMENT-ID          STRAIN-ENERGY          PERCENT OF TOTAL    STRAIN-ENERGY-DENSITY
                               25          8.059148E+02                8.8455              6.447318E+03
                               32          8.059148E+02                8.8455              6.447318E+03
                               33          8.059148E+02                8.8455              6.447318E+03
                               40          8.059148E+02                8.8455              6.447318E+03

          TYPE = HEXA     SUBTOTAL         9.111034E+03              100.0000
```

```
                     ***************************************************************
                     S U M M A R Y   O F   D E S I G N   C Y C L E   H I S T O R Y
                     ***************************************************************

                                    (HARD CONVERGENCE ACHIEVED)

                         NUMBER OF FINITE ELEMENT ANALYSES COMPLETED          56
                         NUMBER OF OPTIMIZATIONS W.R.T. APPROXIMATE MODELS    55

                              OBJECTIVE AND MAXIMUM CONSTRAINT HISTORY
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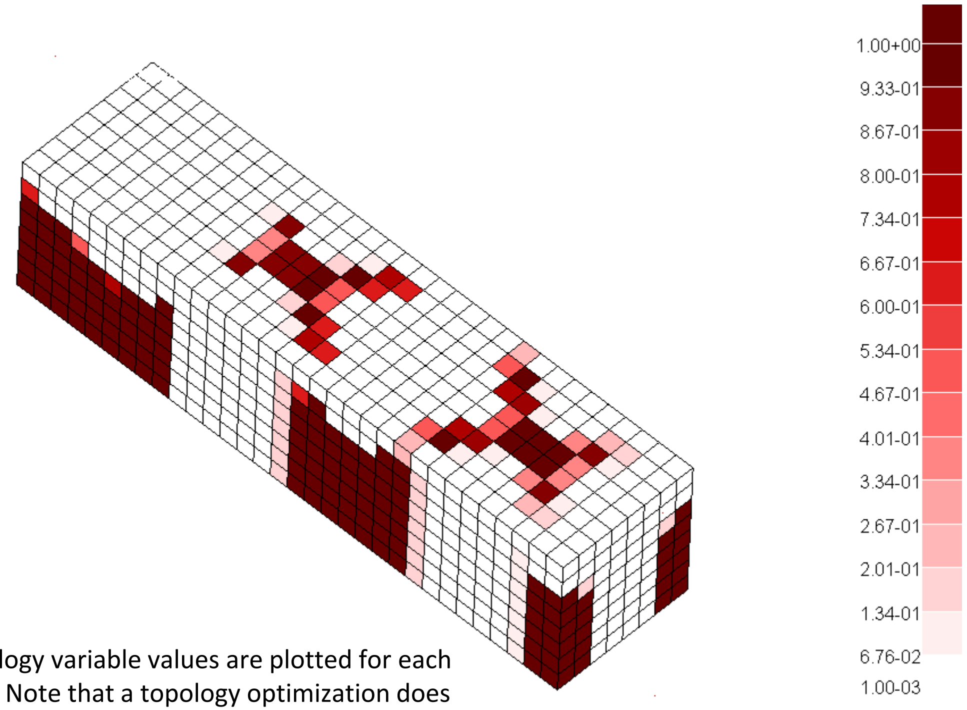
CYCLE NUMBER	OBJECTIVE FROM APPROXIMATE OPTIMIZATION	OBJECTIVE FROM EXACT ANALYSIS	FRACTIONAL ERROR OF APPROXIMATION	MAXIMUM VALUE OF CONSTRAINT
INITIAL		1.822207E+04		-4.625929E-15
1	5.076533E+03	1.323096E+04	-6.163140E-01	9.999972E-09
2	5.721454E+03	1.120504E+04	-4.893855E-01	6.604279E-09
3	4.220301E+03	1.016538E+04	-5.848357E-01	1.000032E-08
4	3.996396E+03	9.769504E+03	-5.909315E-01	9.983010E-09

How can non-critical elements be removed from the design?

- Use the threshold to suppress non-critical elements
- The threshold means: *'Keep every element that has a topology variable value greater than the threshold'*
- Recall from before:
  - 0 - Topology variable values close to 0 are not critical to the design
  - 1 - Topology variable values close to 1 are critical to the design



The topology variable values are plotted for each element. Note that a topology optimization does not automatically remove elements. It is up to the user to manually decide which elements to keep.