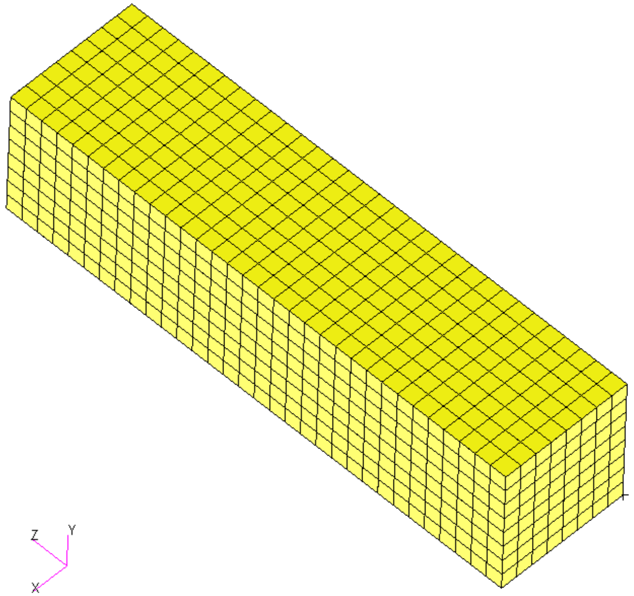
Workshop - MSC Nastran Topology Optimization
Manufacturing Constraints

AN MSC NASTRAN SOL 200 TUTORIAL

Goal: Use Nastran SOL 200 Optimization

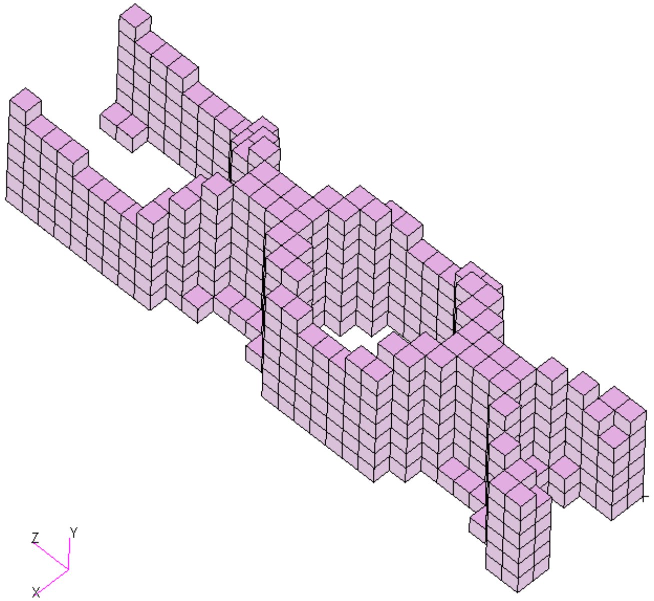
Before Optimization

- Mass: 25.6

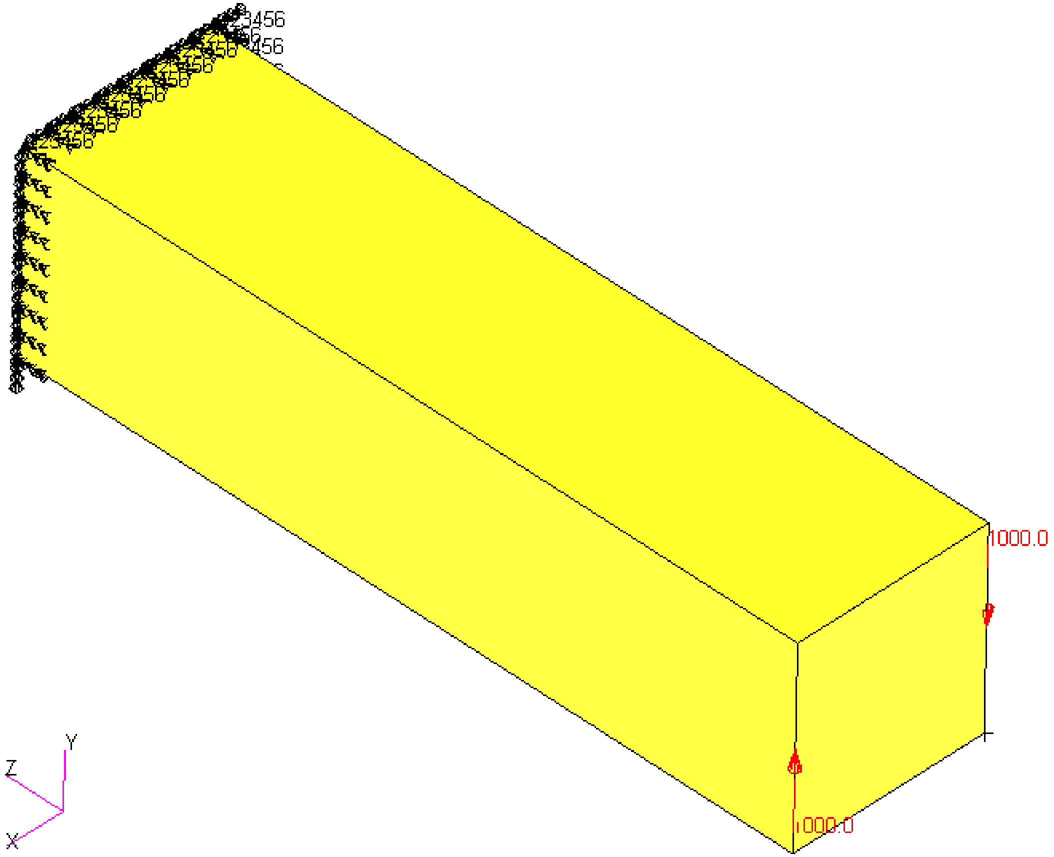


After Optimization

- Mass: 7.7 (~70% mass reduction)
- Mirror Symmetry Constraints
- Casting Constraints



Details of the structural model

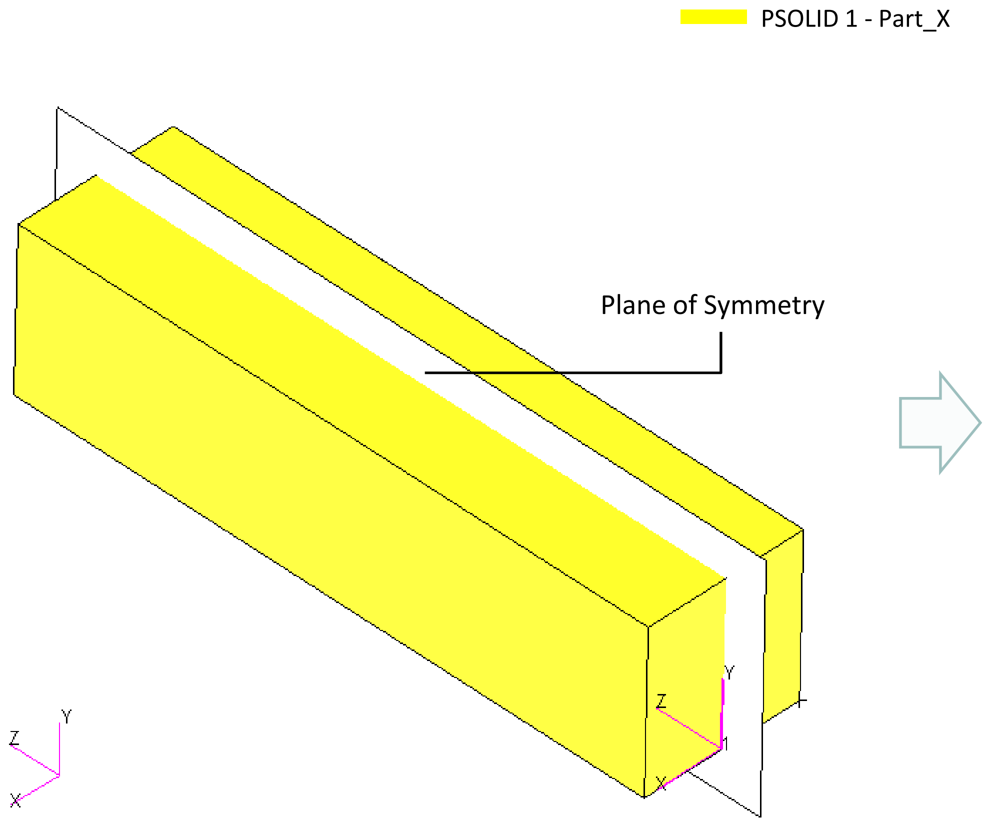


Optimization Problem Statement

Design Region/Variables

x1: PSOLID 1

Restrictions:
- Mirror Symmetry Constraints
    - Symmetry about the YZ plane of coordinate system 1
- Casting in Y direction of coordinate system 1, use 1 die



Design Objective

r0: Minimize compliance

Design Constraints

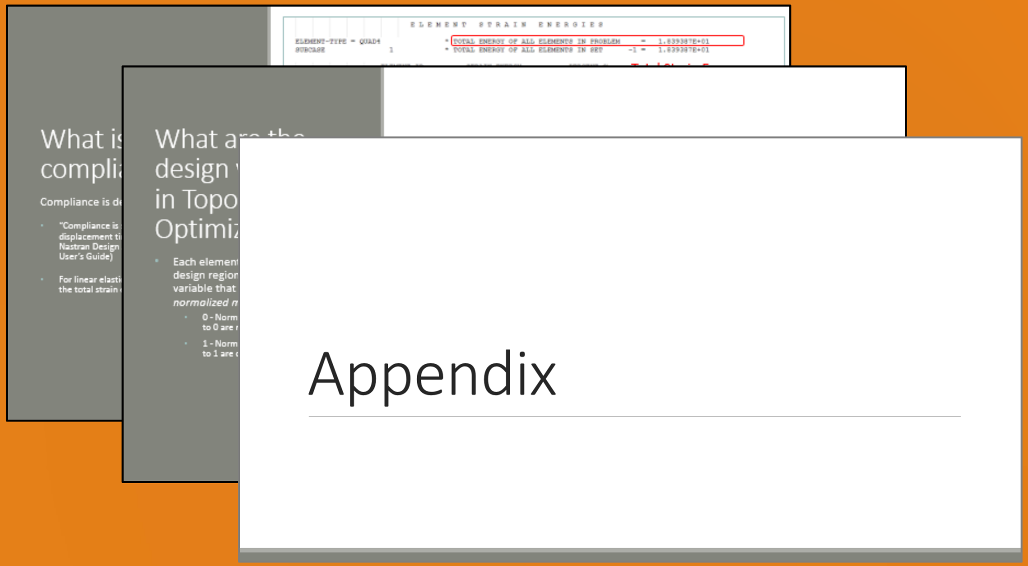
r1: Fractional mass

r1 < .3 (70% mass reduction)

More Information Available in the Appendix

The Appendix includes information regarding the following:

- 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?
- Topology Optimization Workflows
- Viewer Web App
  for Topology Optimization Post Processing



Contact me

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

christian@ the-engineering-lab.com

Tutorial

Tutorial Overview

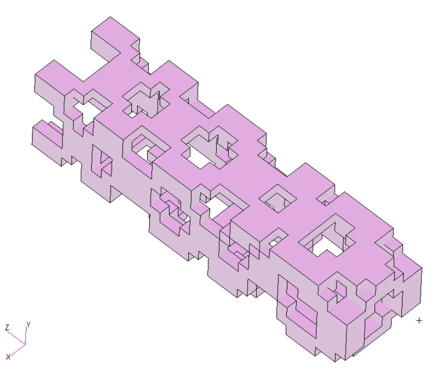
1. Start with a .bdf or .dat file
2. Use the SOL 200 Web App to:
   - Convert the .bdf file to SOL 200
     - Design Regions/Variables
     - Design Objective
     - Design Constraints
   - Perform optimization with Nastran SOL 200
3. Review optimization results
   - .f06
   - Topology Optimization and Structural Results

Special Topics Covered

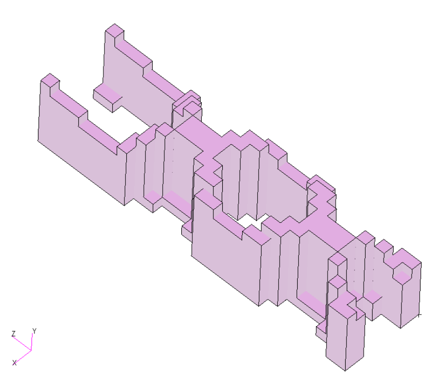
Mirror Symmetry Constraints - Fit the Topology Optimization solution must be symmetric, constraints may be imposed to achieve this.

Manufacturing Constraints - The manufacturability of Topology Optimization results is important. Options exist to produce results that can be manufactured.

Without Manufacturing Constraints, but with Symmetry



With Manufacturing Constraints and Symmetry

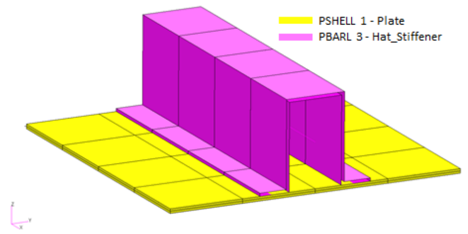


SOL 200 Web App Capabilities

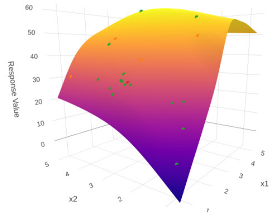
Benefits

- 200+ error validations (real time)
- Web browser accessible
- Automated creation of entries (real time)
- Automatic post-processing
- 76 tutorials

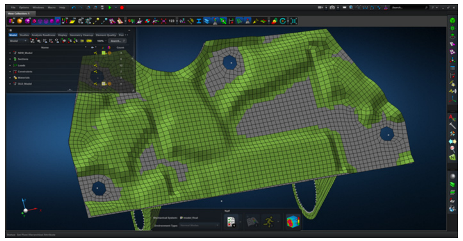
Capabilities



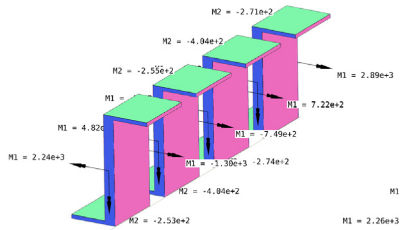
Web Apps for SOL 200
Pre/post for MSC Nastran SOL 200. Support for size, topology, topometry, topography and multi-model.



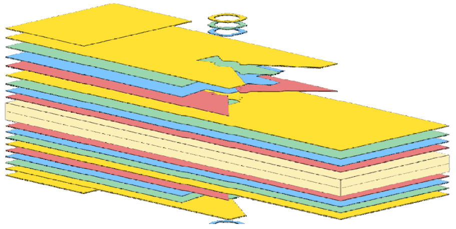
Machine Learning Web App
Bayesian Optimization for nonlinear response optimization (SOL 400)



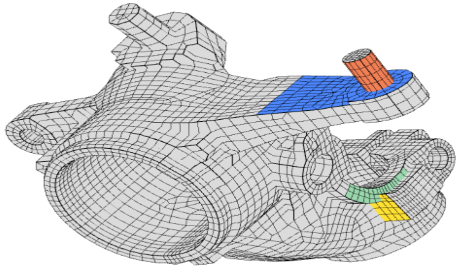
MSC Apex Post Processing Support
View the newly optimized model after an optimization



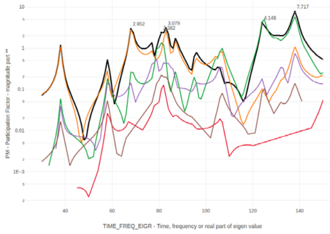
Beams Viewer Web App
Post process 1D element forces, including shear forces, moments, torque and axial forces



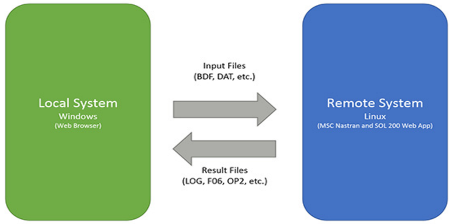
Ply Shape Optimization Web App
Spread plies optimally and generate new PCOMPG entries



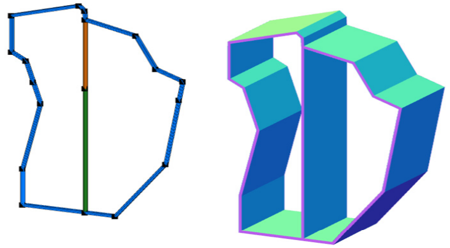
Shape Optimization Web App
Use a web application to configure and perform shape optimization.



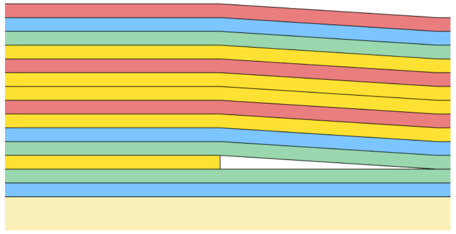
HDF5 Explorer Web App
Create XY plots using data from the H5 file



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



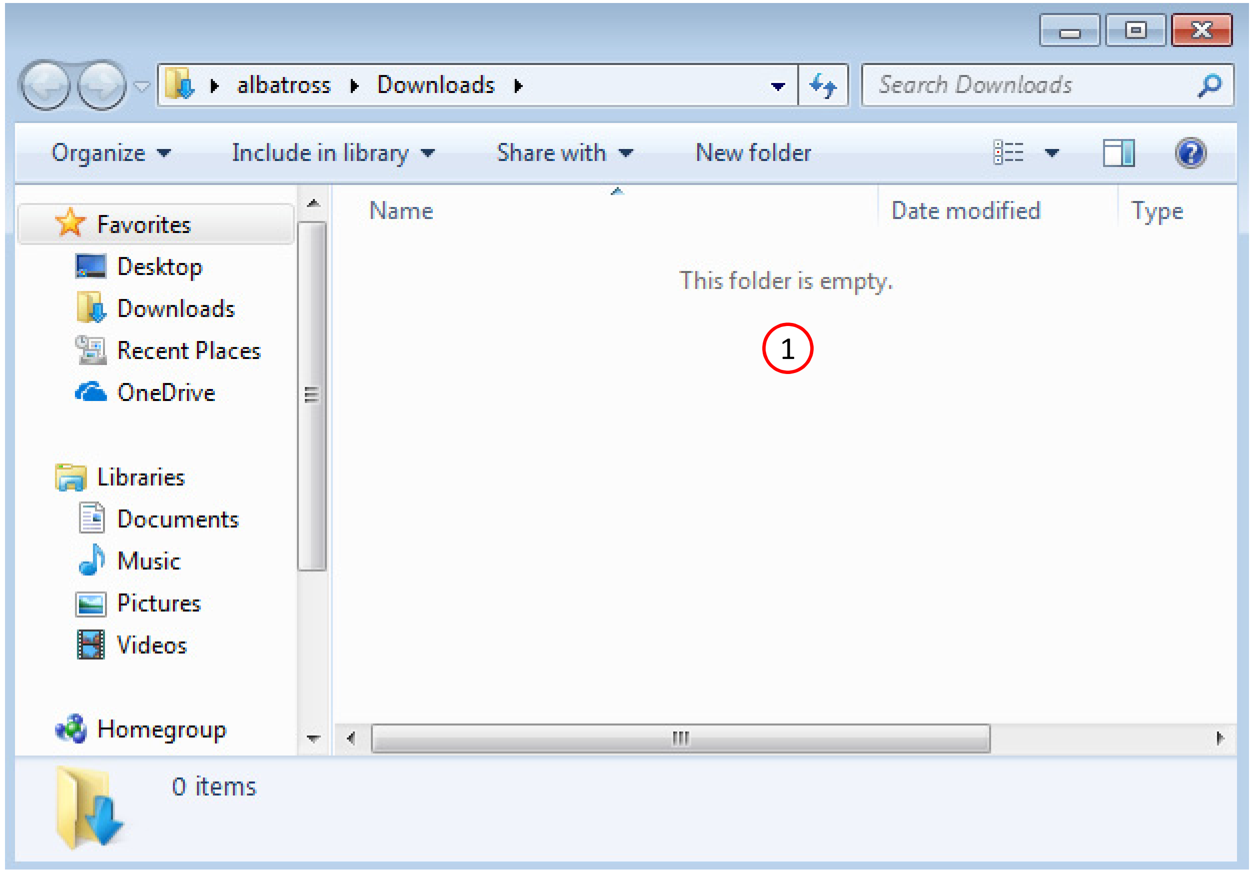
PBMSECT Web App
Generate PBMSECT and PBRSECT entries graphically



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

Before Starting

1. Ensure the Downloads directory is empty in order to prevent confusion with other files

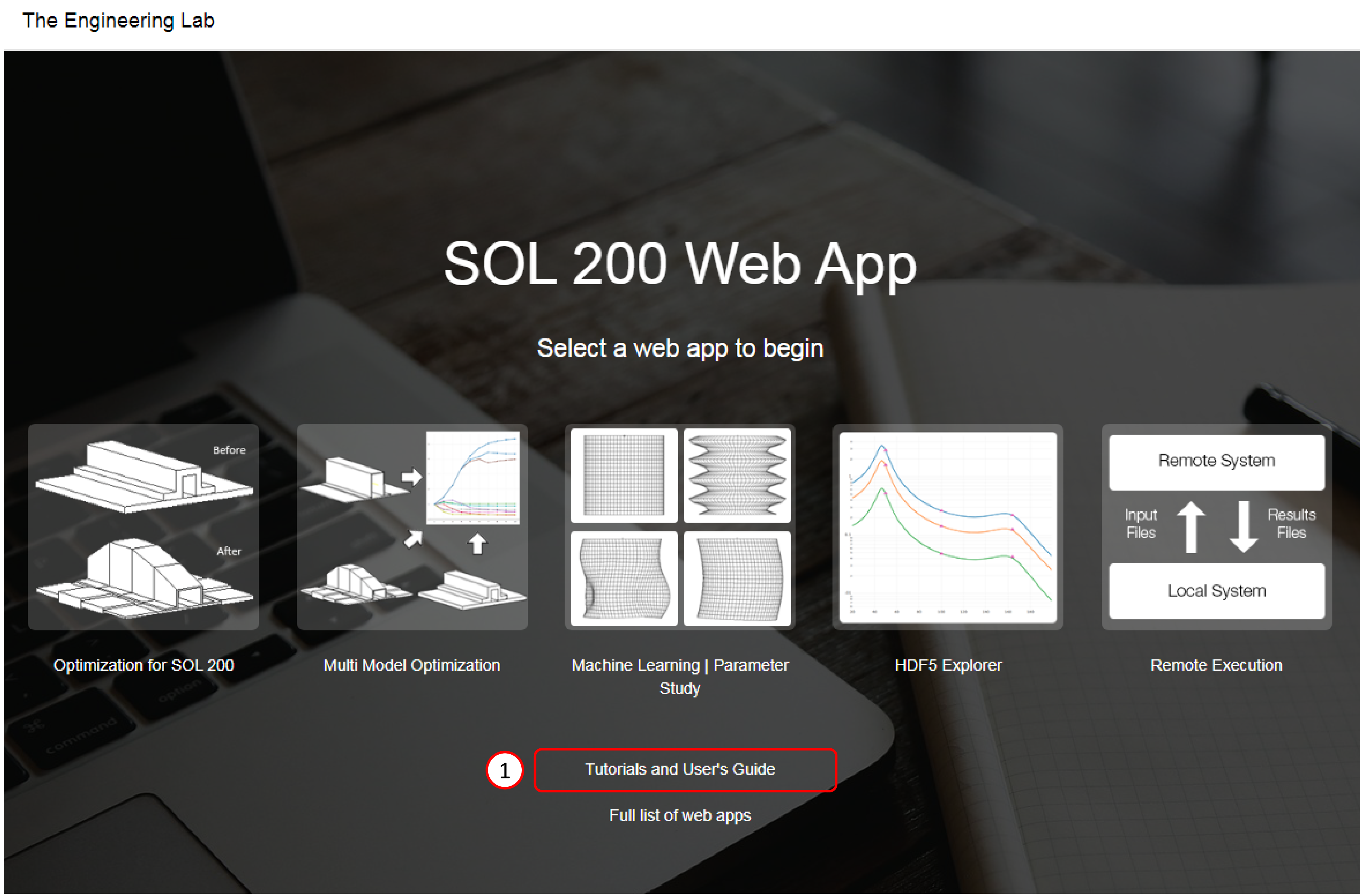


- Throughout this workshop, you will be working with multiple file types and directories such as:
  - .bdf/.dat
  - nastran_working_directory
  - .f06, .log, .pch, .h5, etc.
- To minimize confusion with files and folders, it is encouraged to start with a clean directory.

Go to the User's Guide

1. Click on the indicated link

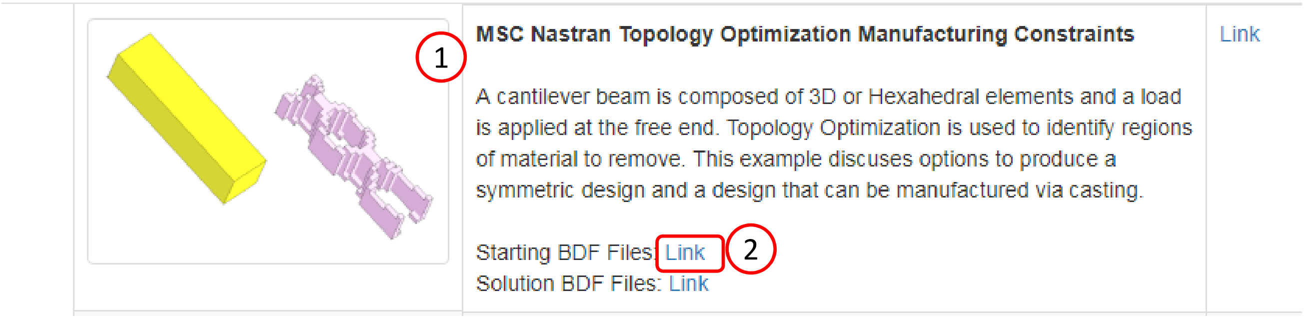
- The necessary BDF files for this tutorial are available in the Tutorials section of the User's Guide.

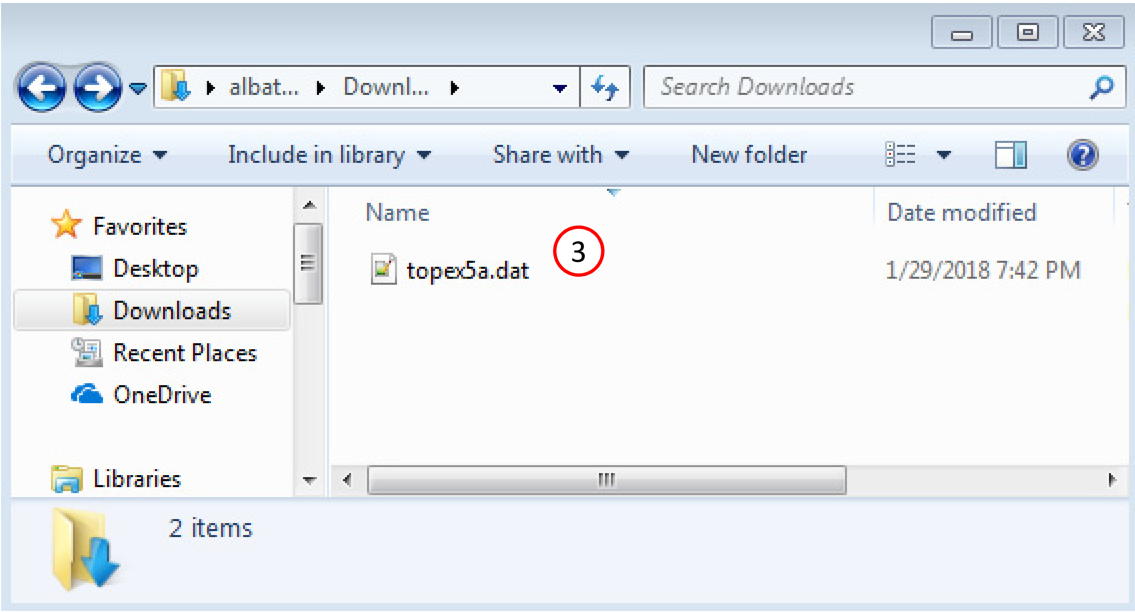


Obtain Starting Files

1. Find the indicated example
2. Click Link
3. The starting file has been downloaded

- When starting the procedure, all the necessary BDF files must be collected together.

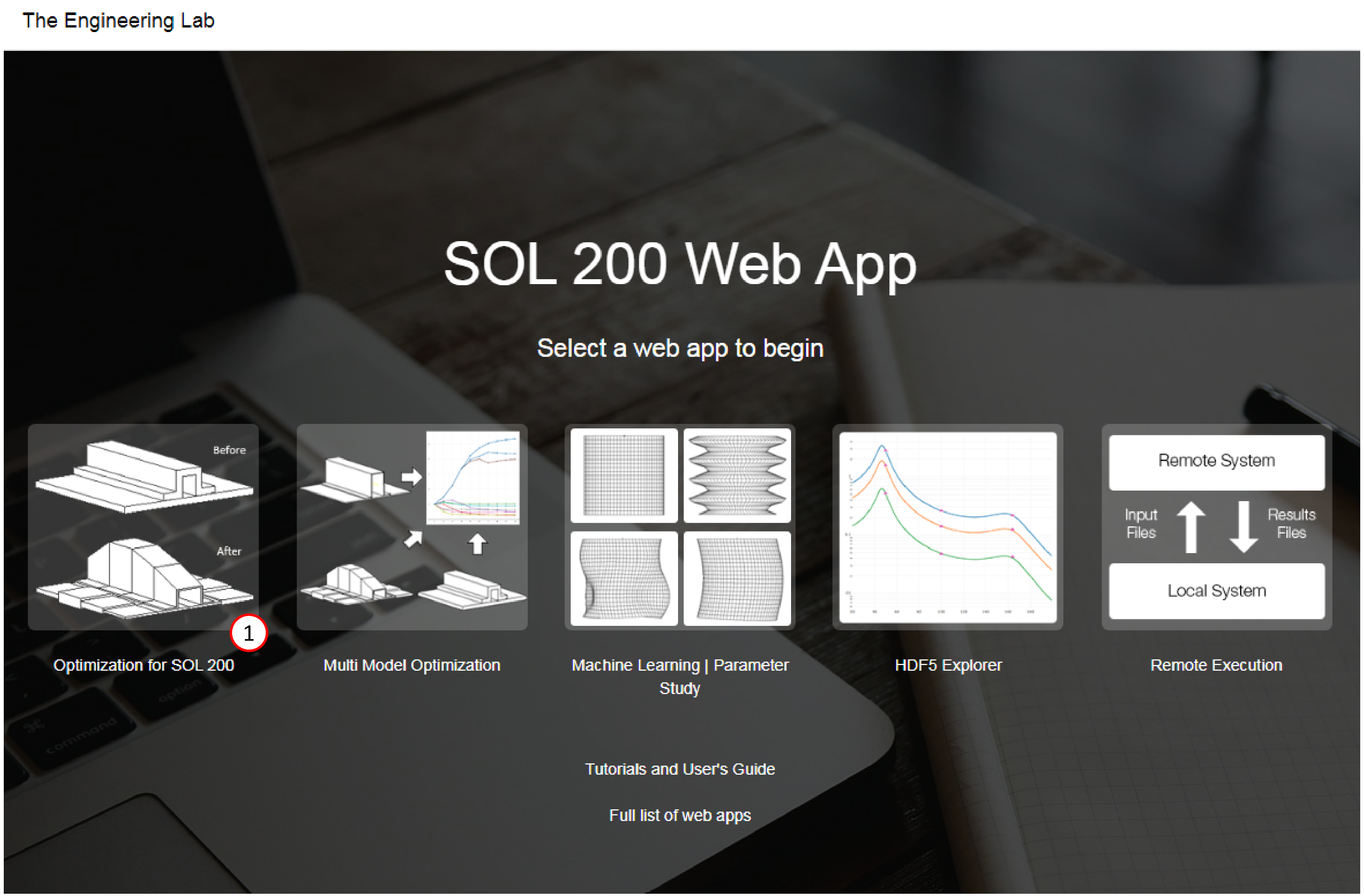




Open the Correct Page

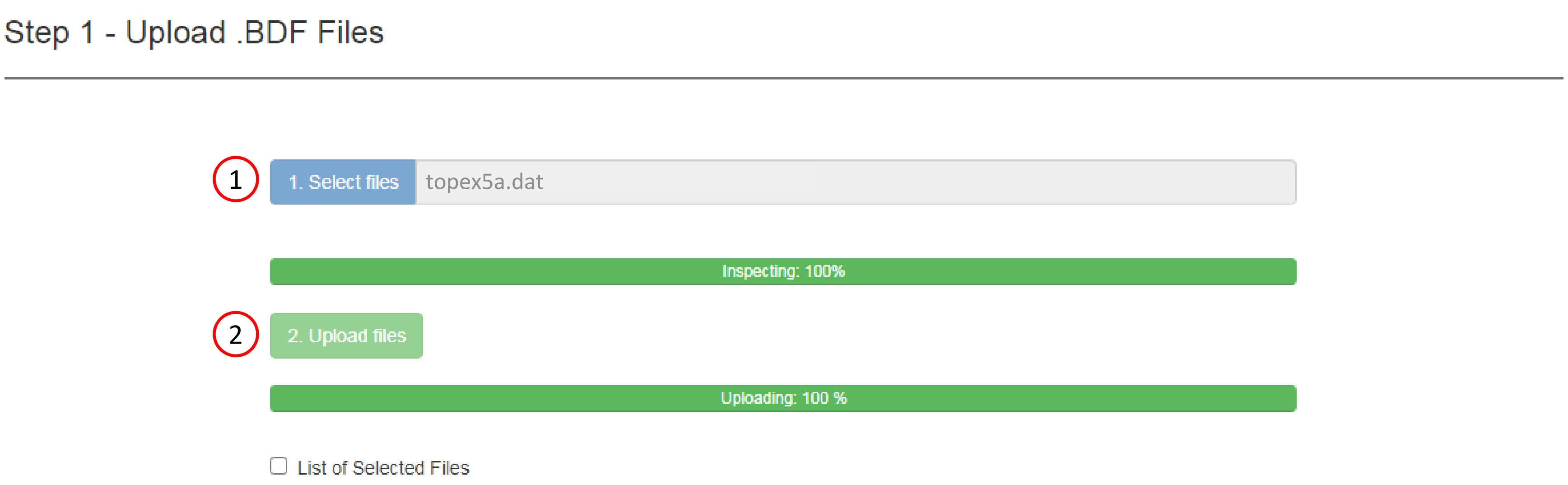
1. Click on the indicated link

- MSC Nastran can perform many optimization types. The SOL 200 Web App includes dedicated web apps for the following:
    - Optimization for SOL 200 (Size, Topology, Topometry, Topography, Local Optimization, Sensitivity Analysis and Global Optimization)
    - Multi Model Optimization
    - Machine Learning
- The web app also features the HDF5 Explorer, a web application to extract results from the H5 file type.



Upload BDF Files

1. Click 1. Select Files and select topex5a.dat
2. Click Upload Files

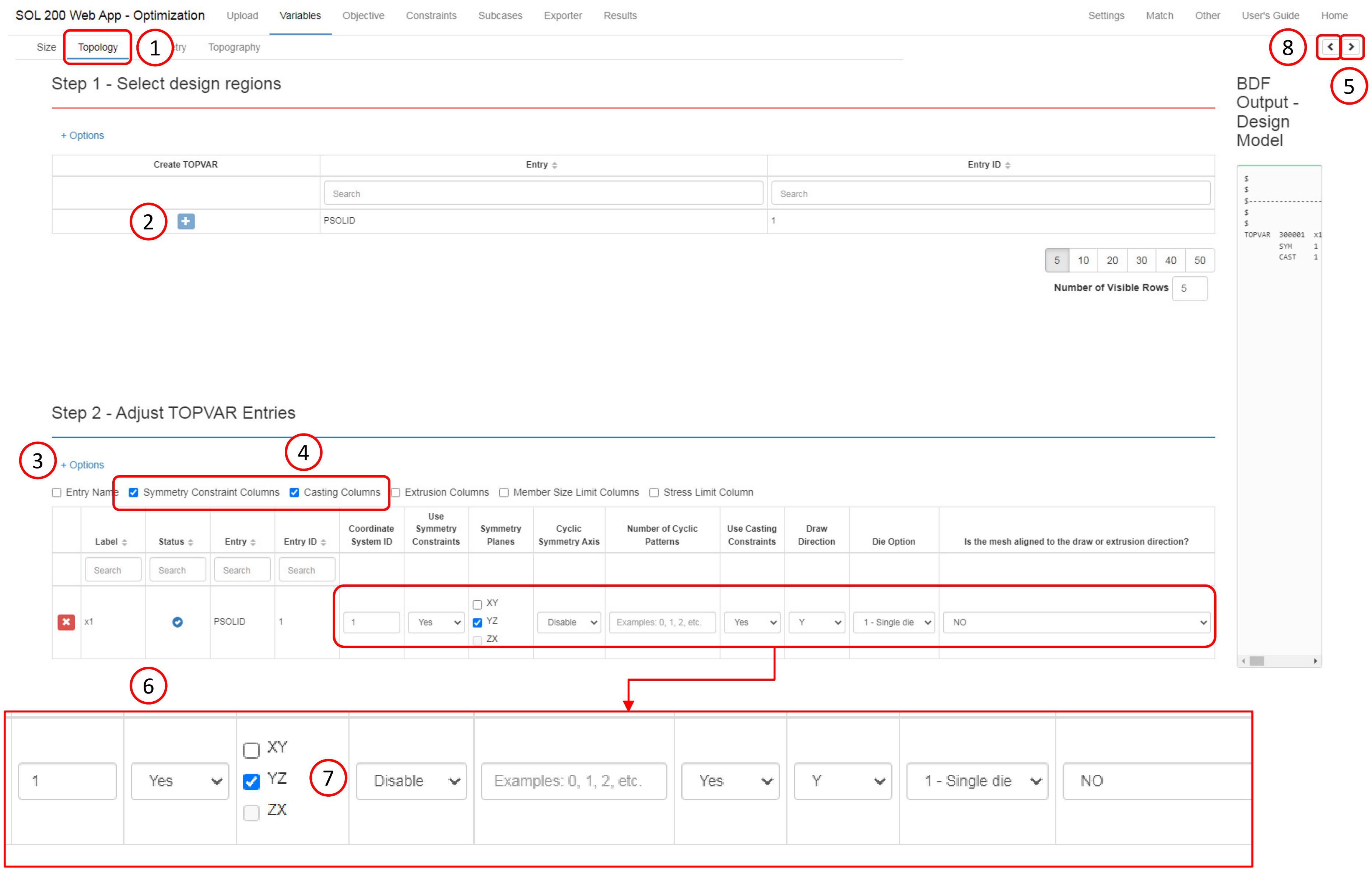


- The process starts by uploading all the necessary BDF files. The BDF files can be files of your own or files found in the Tutorials section of the User's Guide.

Create Design Region

1. Click Topology
2. Click on the plus (+) icons to set PSOLID 1 as a Design Region
3. Click + Options
4. Mark the checkboxes for the following:
    1. Symmetry Constraint Columns
    2. Casting Columns
5. Click the Right Arrow to expand the width of the table
6. Set the following for the design region
    - Use Symmetry Constraints: Yes
    - Coordinate System ID: 1
    - Symmetry Planes: YZ
    - Use Casting Constraints: Yes
    - Draw Direction: Y
    - Die Option: 1 - Single
    - Is the mesh aligned to …: NO
7. Confirm the Symmetry Plane is set to YZ
8. Click the Left Arrow to restore the width of the table

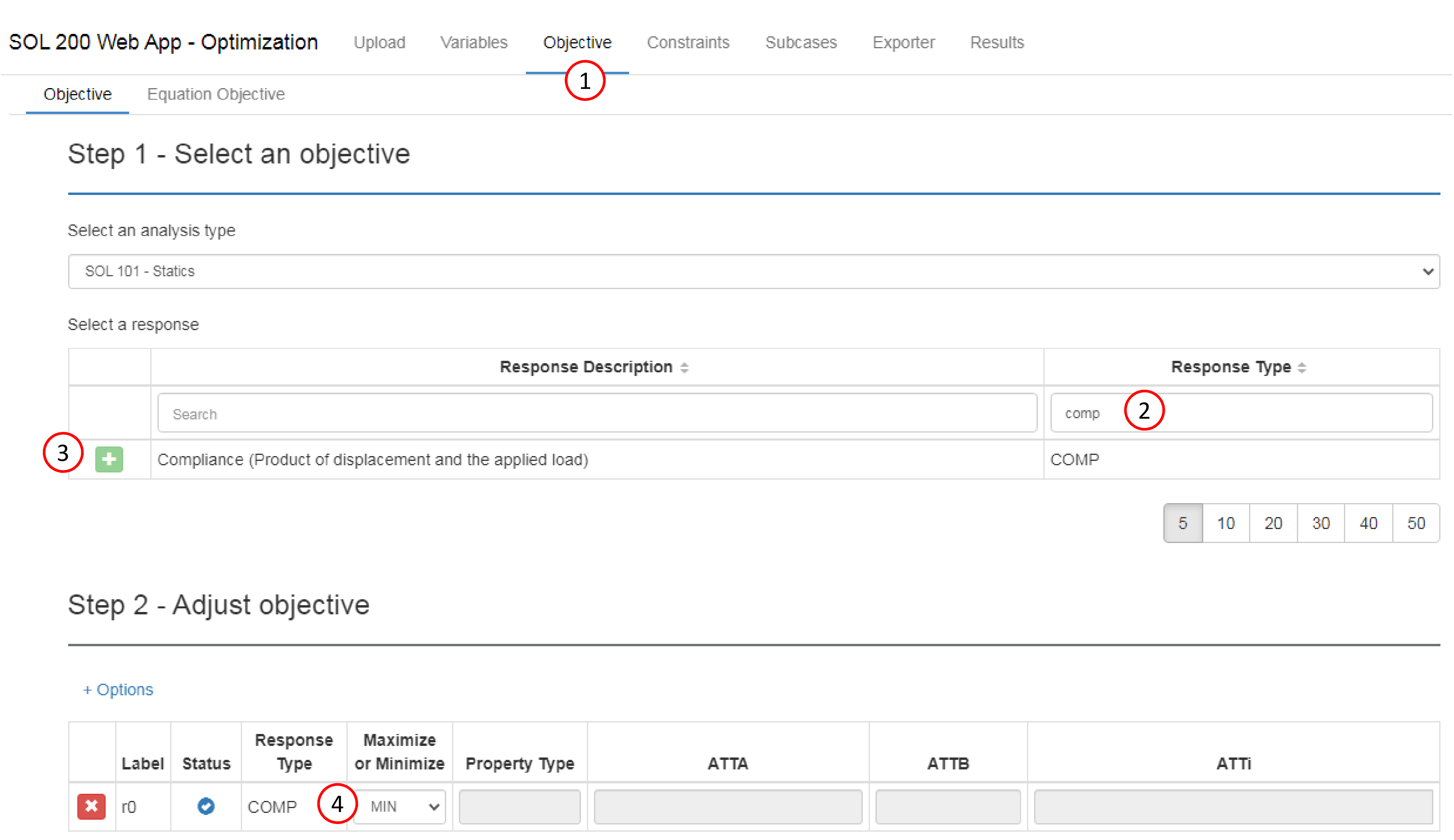
- When a topology design region is set, one design variable is created for each element in the design region. Each design variable corresponds to the Normalized Material Density of that element, see the appendix for additional details.
- If PSOLID 1 has 500 elements associated and is configured as a design region, then there will be 500 design variables created.



Create Design Objective

1. Click on Objective
2. Type ‘comp’ in the search box
3. Select the plus(+) icon for Compliance
4. The objective with label r0 is created. The objective is to minimize (MIN)

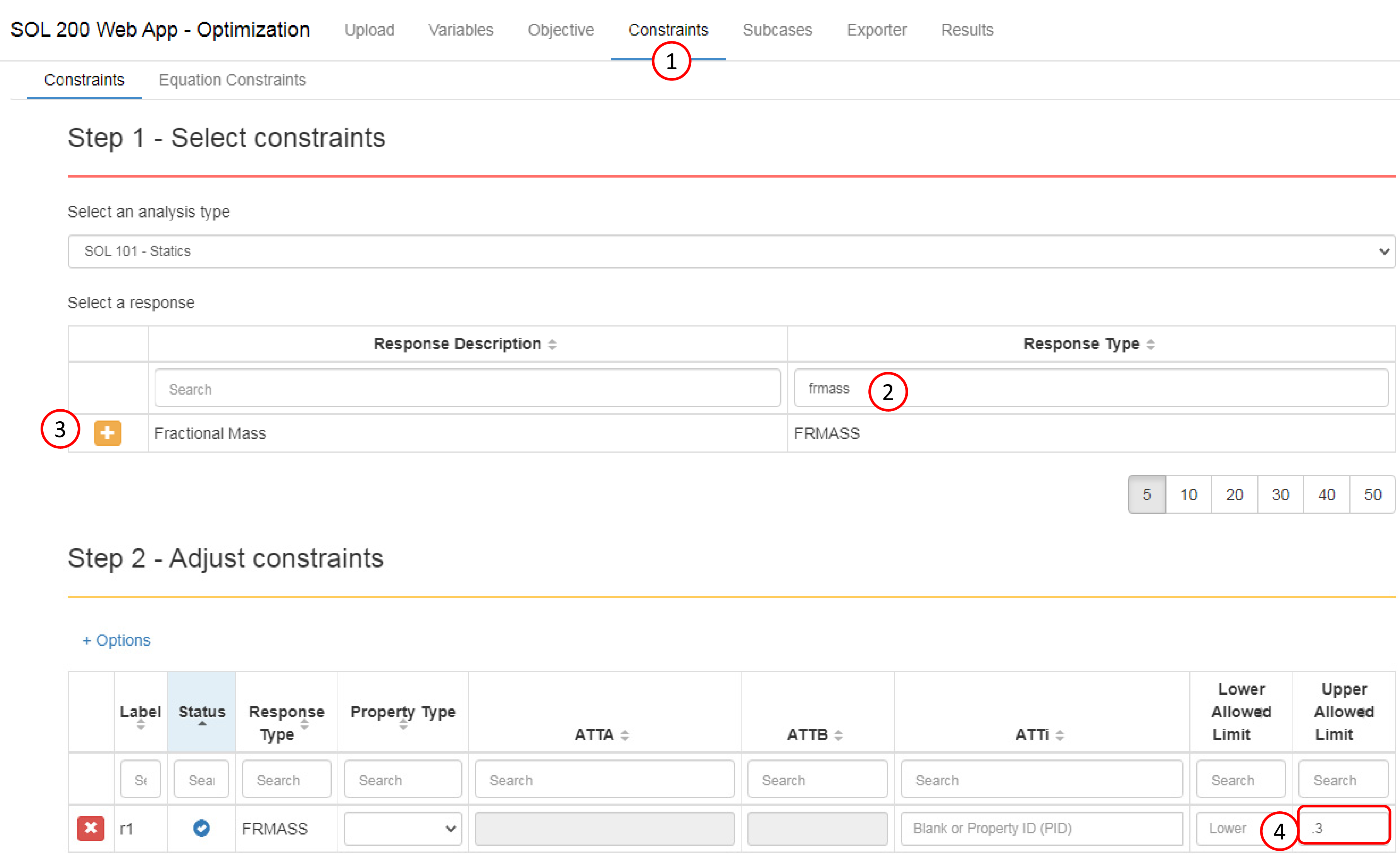
- Compliance is equal to twice the total strain energy. By minimizing the compliance/strain energy, the stiffness of the model is being maximized. See the appendix for additional details regarding compliance.



Create Design Constraints

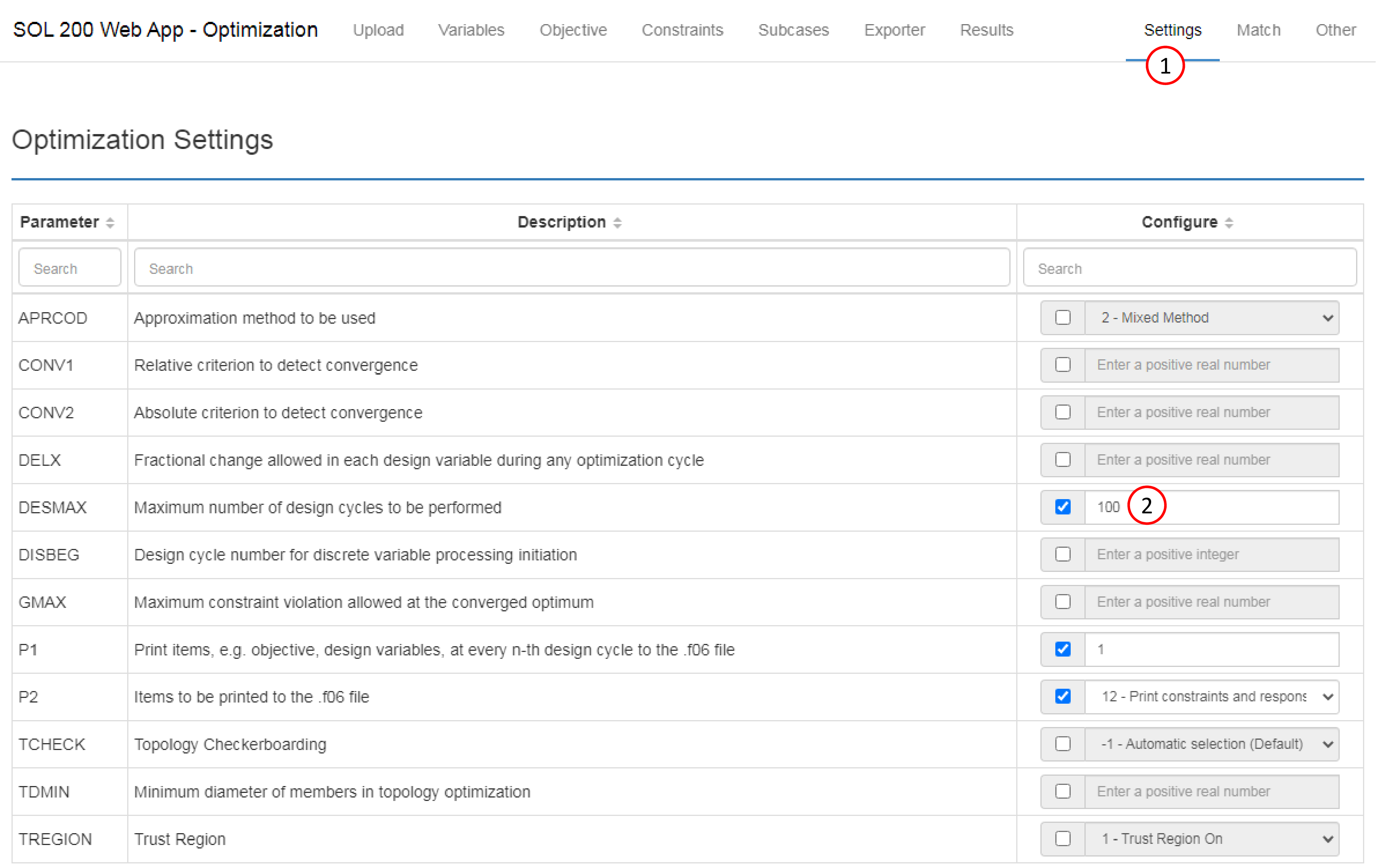
1. Click Constraints
2. Type ‘frmass’ in the search box
3. Select the plus(+) icon for Fractional Mass
4. Configure the following for r1
    - Upper Allowed Limit: .3
        - (Retain 30% of the material / 70% mass reduction)

- The fractional mass constraint r1 is set for a target of .3. The optimizer will vary the design variables, normalized material densities, to produce a design that is less than or equal to 30% of the original mass.



Configure Optimization Settings

1. Click Settings
2. Set DESMAX to 100



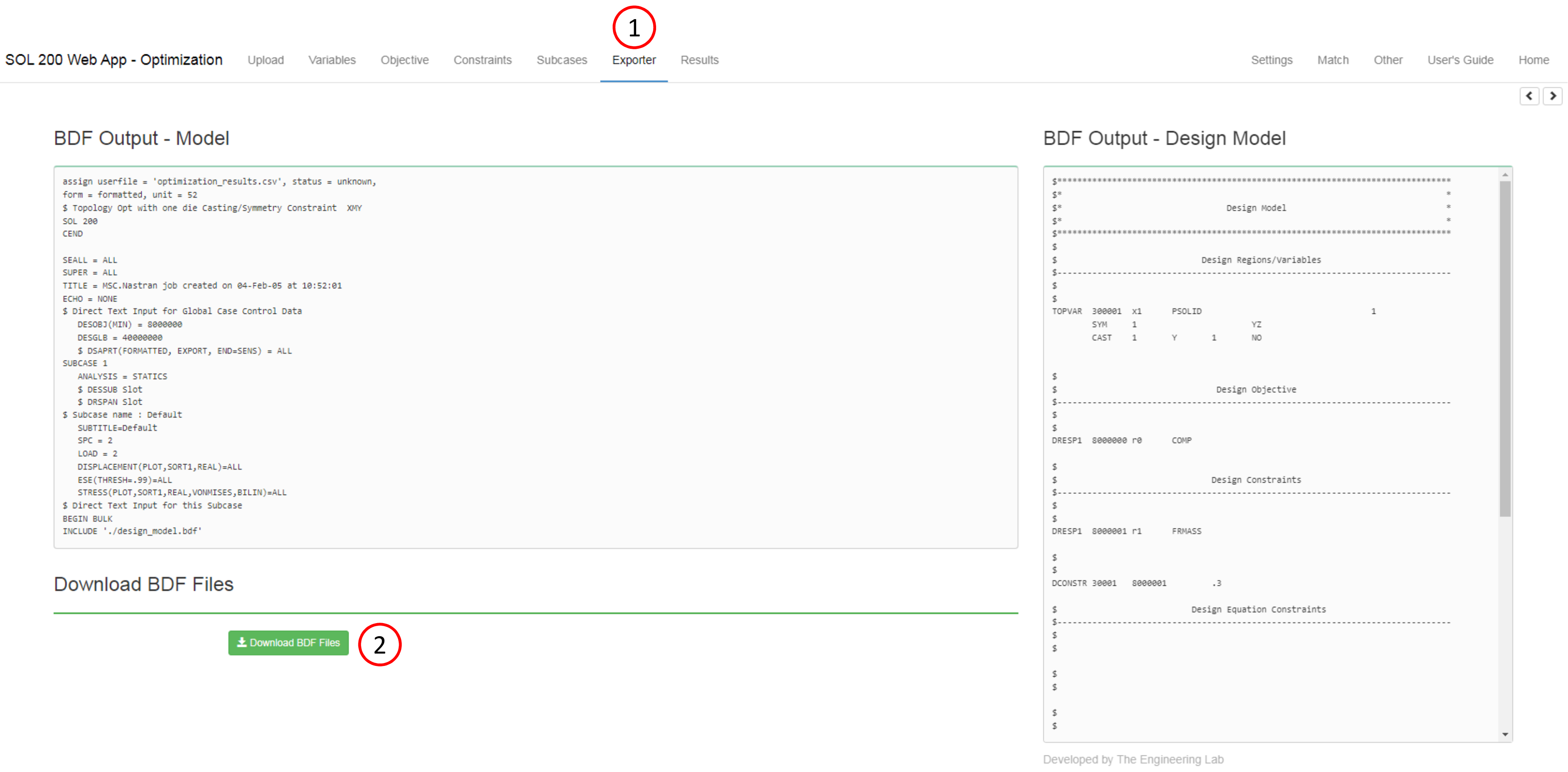
Parameter	Description	Configure
APRCOD	Approximation method to be used	2 - Mixed Method
CONV1	Relative criterion to detect convergence	Enter a positive real number
CONV2	Absolute criterion to detect convergence	Enter a positive real number
DELX	Fractional change allowed in each design variable during any optimization cycle	Enter a positive real number
DESMAX	Maximum number of design cycles to be performed	100
DISBEG	Design cycle number for discrete variable processing initiation	Enter a positive integer
GMAX	Maximum constraint violation allowed at the converged optimum	Enter a positive real number
P1	Print items, e.g. objective, design variables, at every n-th design cycle to the .f06 file	1
P2	Items to be printed to the .f06 file	12 - Print constraints and respons
TCHECK	Topology Checkerboarding	-1 - Automatic selection (Default)
TDMIN	Minimum diameter of members in topology optimization	Enter a positive real number
TREGION	Trust Region	1 - Trust Region On

- This example has been previously performed with a DESMAX value of 50, but the optimization ended with RUN TERMINATED DUE TO MAXIMUM NUMBER OF DESIGN CYCLES.
- A DESMAX value of 100 is used instead to allow for additional design cycles with the goal of obtaining convergence.

Export New BDF Files

1. Click on Exporter
2. Click on Download BDF Files

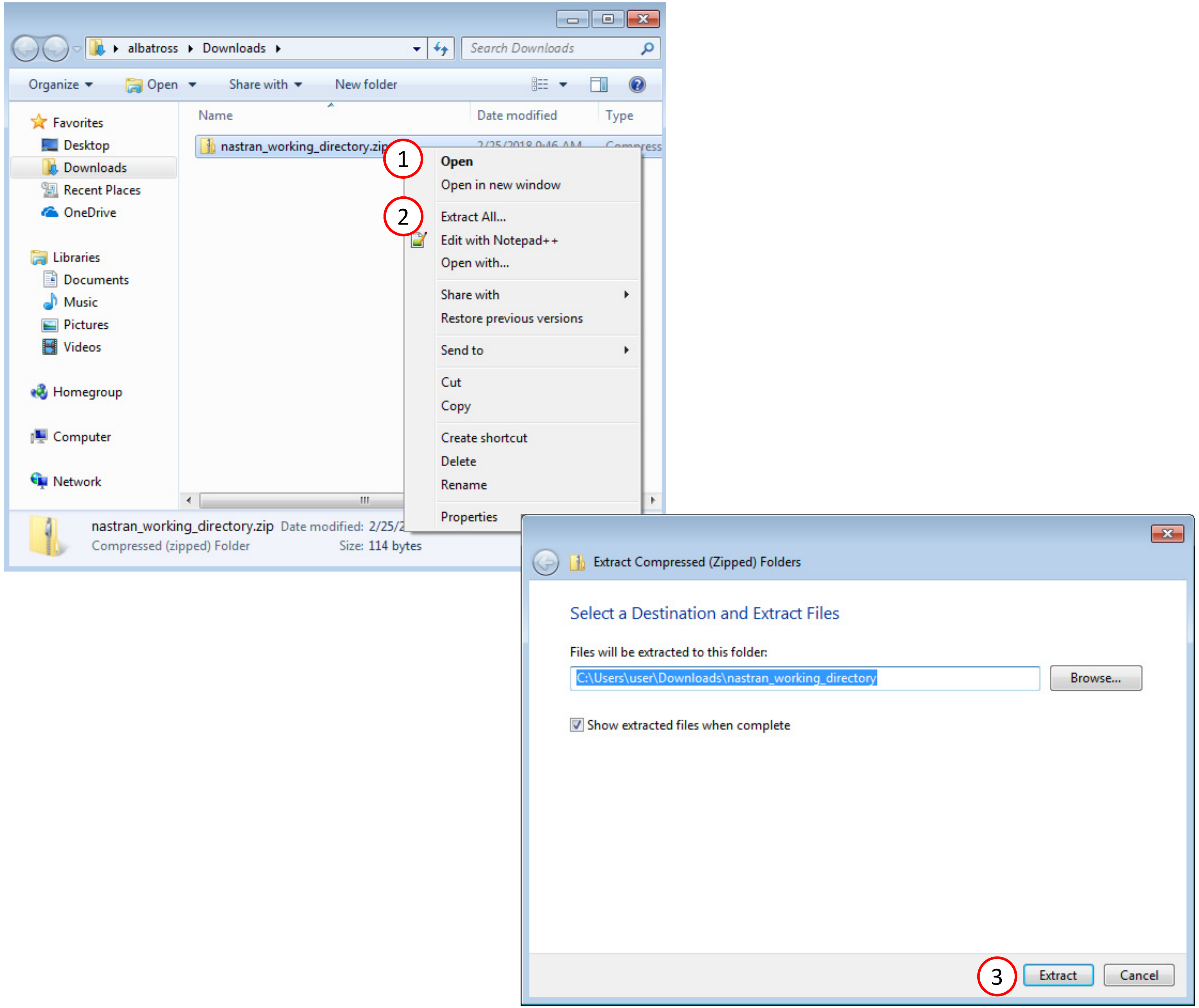
- When the download button is clicked a new file named “nastran_working_directory” is downloaded. If the file already exists in your local folder, the folder name is appended with a number, e.g. “nastran_working_directory (1).zip”



Perform the Optimization with Nastran SOL 200

1. A new .zip file has been downloaded
2. Right click on the file
3. Click Extract All
4. Click Extract on the following window

- Always extract the contents of the ZIP file to a new, empty folder.



Perform the Optimization with Nastran SOL 200

1. Inside of the new folder, double click on Start MSC Nastran

2. Click Open, Run or Allow Access on any subsequent windows

3. MSC Nastran will now start

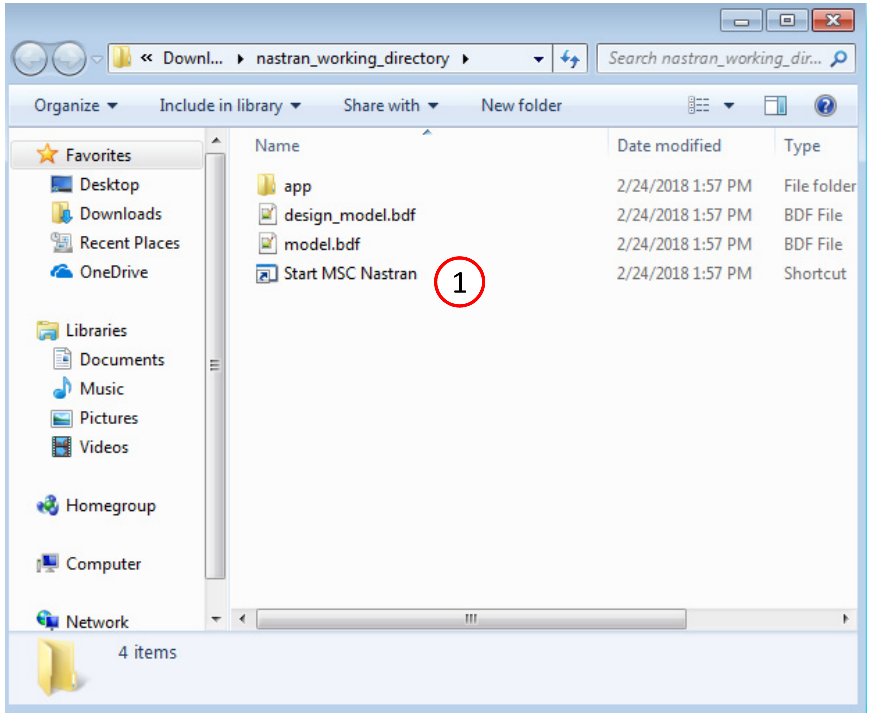
- After a successful optimization, the results will be automatically displayed as long as the following files are present: BDF, F06 and LOG.
- One can run the Nastran job on a remote machine as follows:
  1) Copy the BDF files and the INCLUDE files to a remote machine. 2) Run the MSC Nastran job on the remote machine. 3) After completion, copy the BDF, F06, LOG, H5 files to the local machine. 4) Click “Start MSC Nastran” to display the results.

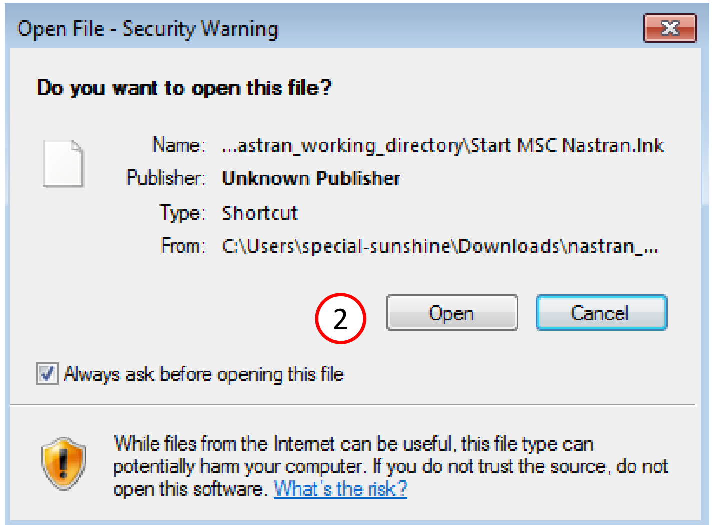
Using Linux?

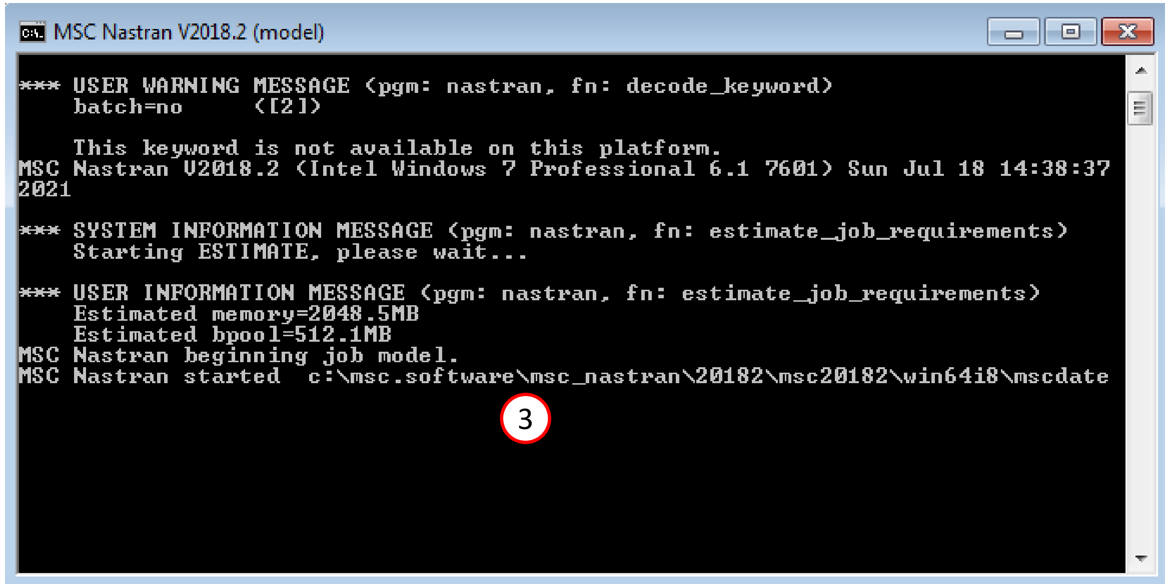
Follow these instructions:
1) Open Terminal
2) Navigate to the nastran_working_directory
cd ./nastran_working_directory
3) Use this command to start the process
./Start_MSC_Nastran.sh

In some instances, execute permission must be granted to the directory. Use this command. This command assumes you are one folder level up.

sudo chmod -R u+x ./nastran_working_directory







Status

1. While MSC Nastran is running, a status page will show the current state of MSC Nastran

- The status of the MSC Nastran job is reported on the Status page. Note that Windows 7 users will experience a delay in the status updates. All other users of Windows 10 and Red Hat Linux will see immediate status updates.

SOL 200 Web App - Status

Python MSC Nastran

Status

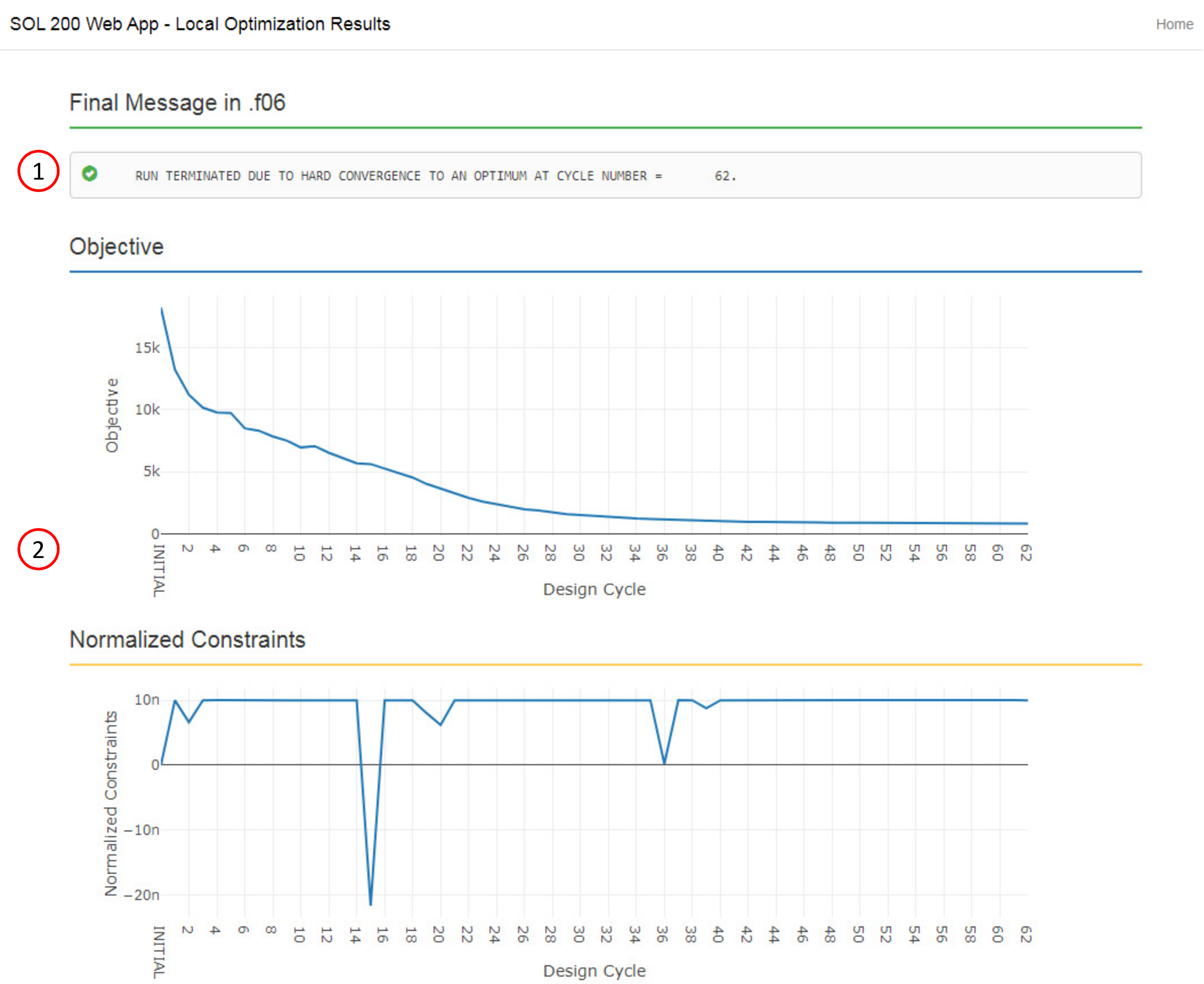
Name	Status of Job	Design Cycle	RUN TERMINATED DUE TO
model.bdf	Running	None	

Review Optimization Results

After MSC Nastran is finished, the results will be automatically uploaded.

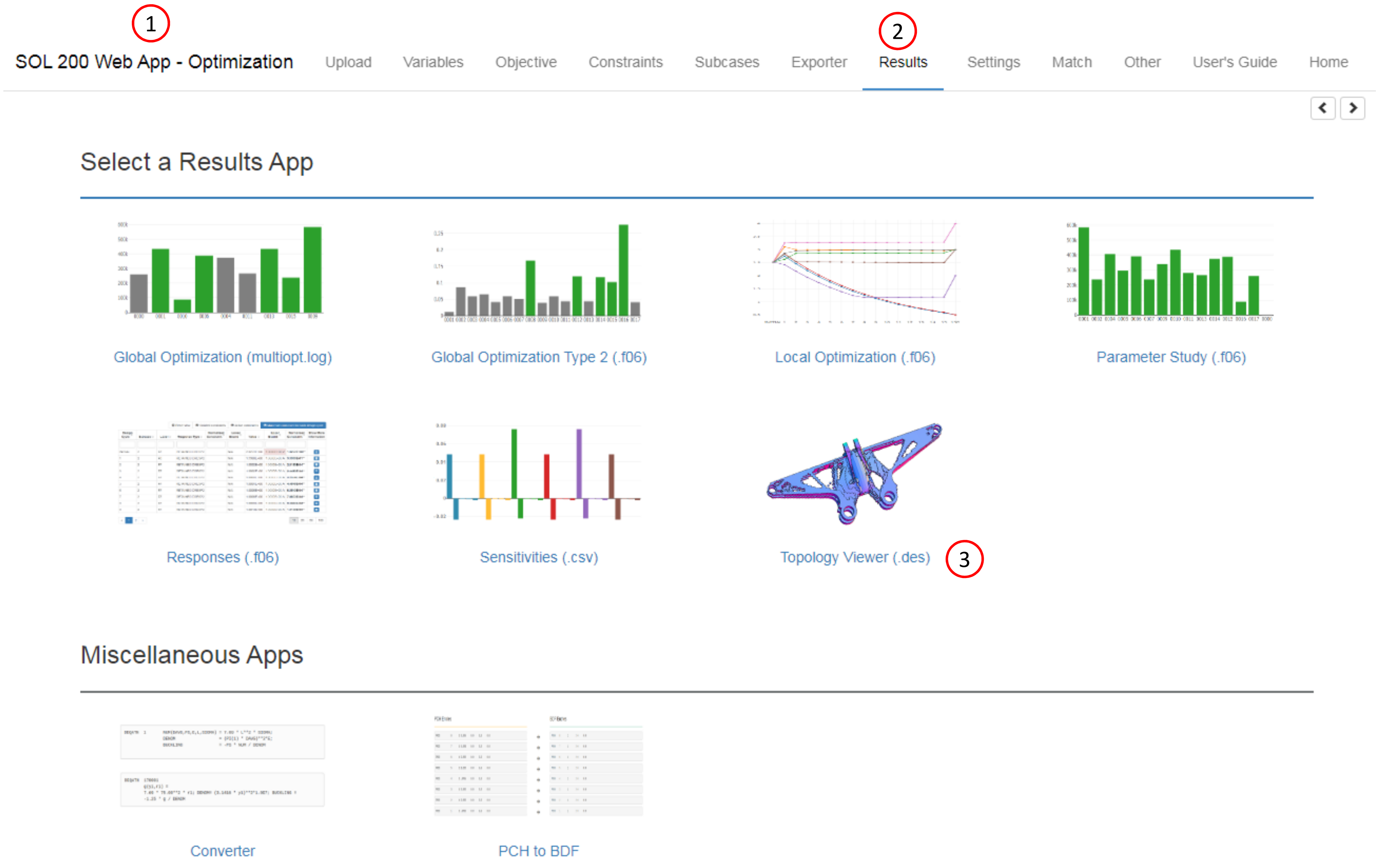
1. Ensure the messages shown have green checkmarks. This is indication of success. Any red icons indicate challenges.
2. The final value of objective and normalized constraints can be reviewed.

- After an optimization, the results will be automatically displayed as long as the following files are present: BDF, F06 and LOG.



Review Optimization Results

1. Return to the Optimization web app
2. Go to the Results section
3. Click Topology Viewer

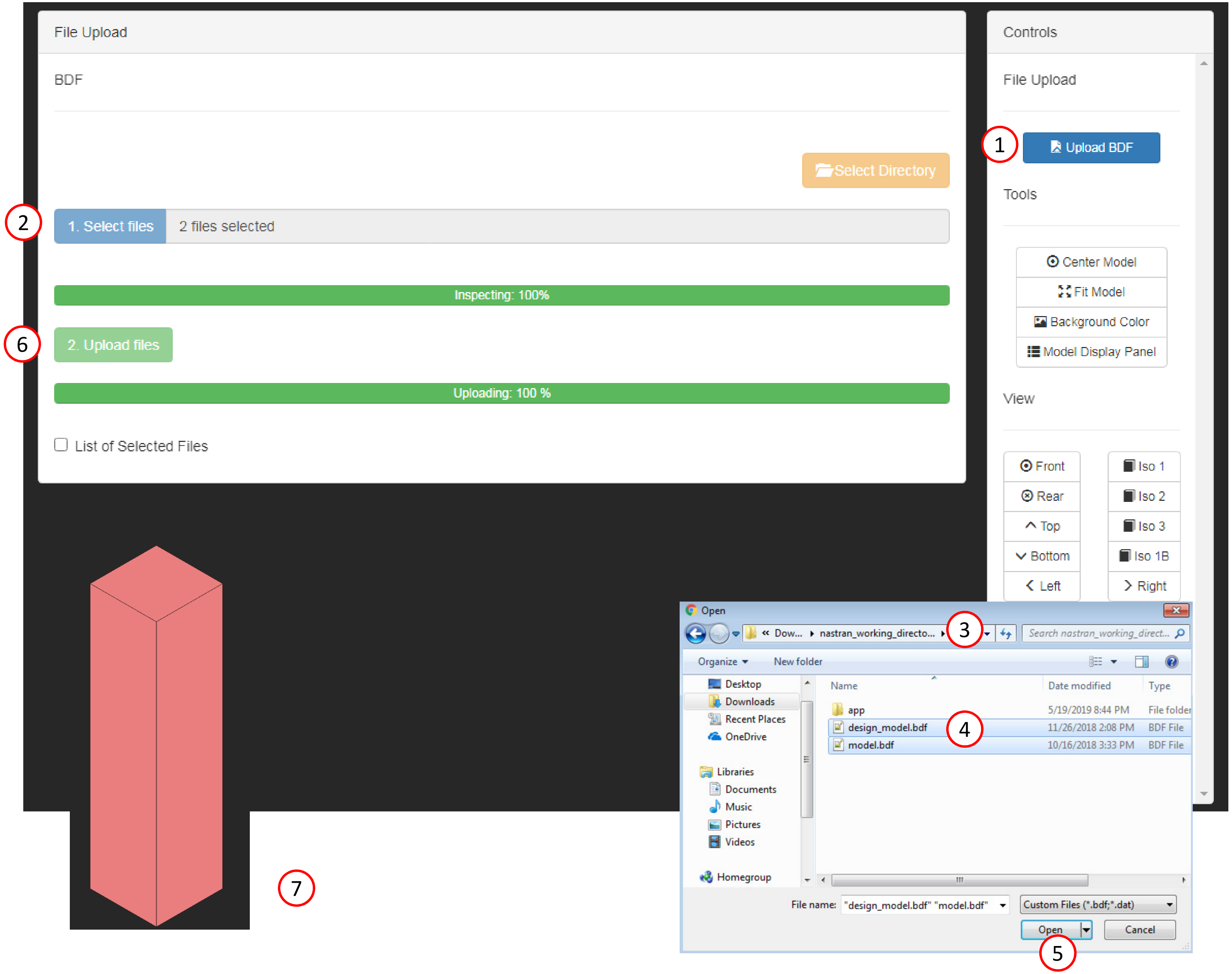


- The Topology Viewer is capable of displaying topology results and is accessed from the Results section of the Optimization web app. The appendix has additional information regarding capabilities of the Topology Viewer.

Review Optimization Results

1. Click Upload BDF
2. Click 1. Select files
3. Navigate to directory nastran_working_directory
4. Select the model.bdf and design_model.bdf files.
5. Click Open
6. Click 2. Upload files
7. The model is displayed

- During file upload, reading and parsing process, the web app does not report the reading progress for large files. Know that the web app parses files at a rate of 10MB every 25 seconds.

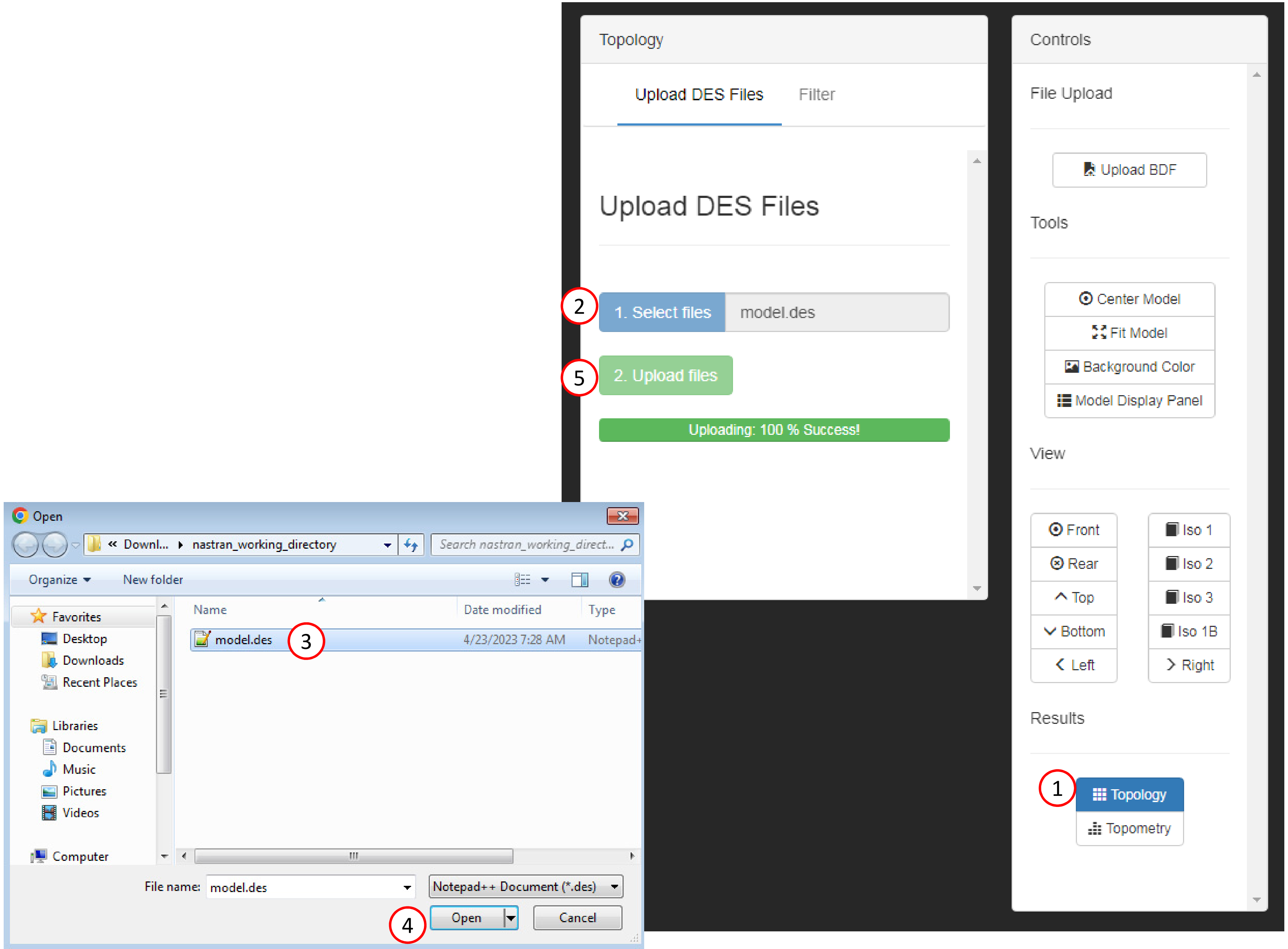


Review Optimization Results

1. Click Topology
2. Click 1. Select files
3. Select the model.des file
4. Click Open
5. Click 2. Upload files

The results of the topology optimization are now accessible within the Viewer web app.

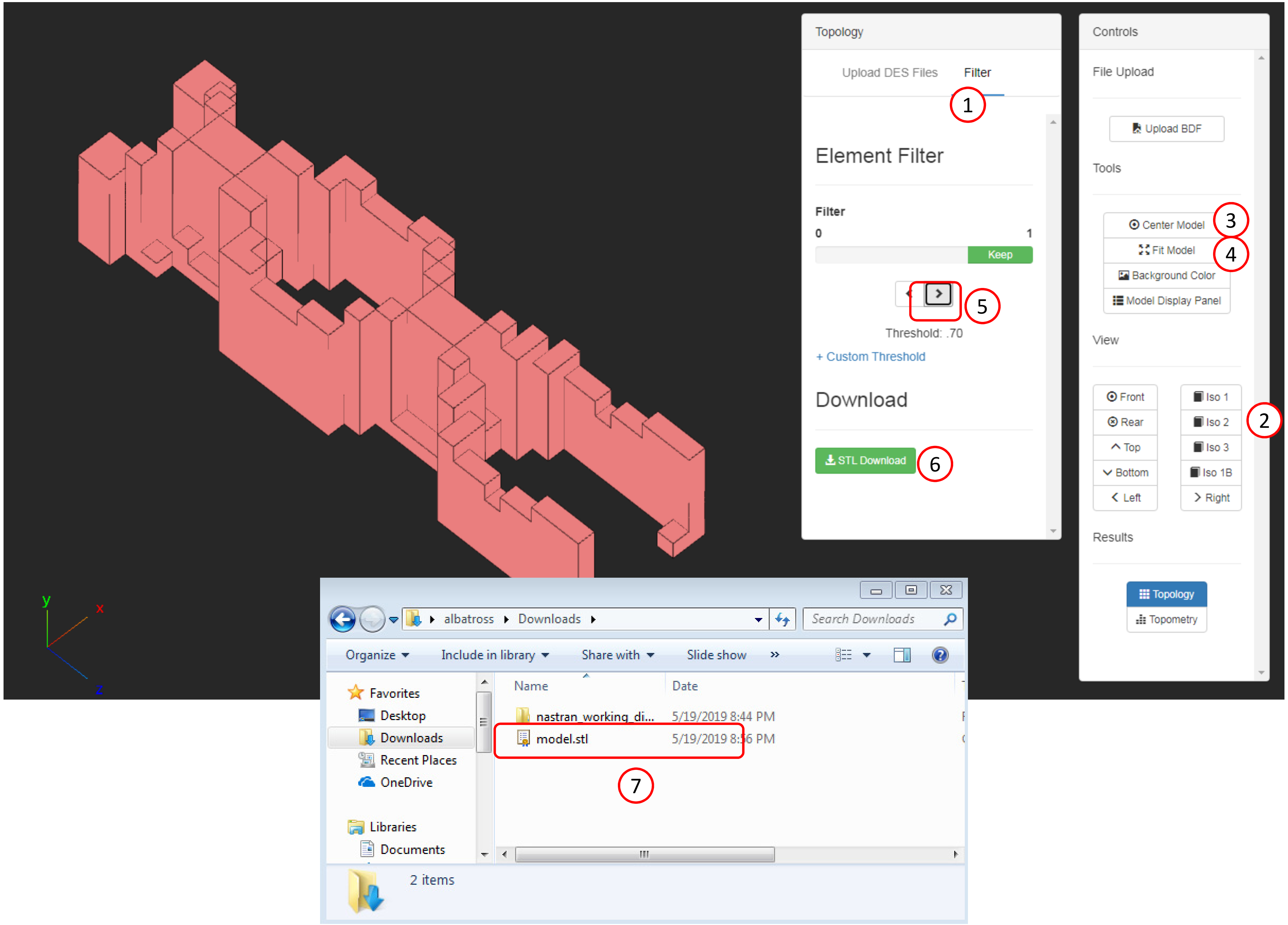
- When the DES file is uploaded, the topology results are automatically displayed. By default, elements with a normalized material density greater than a threshold of .3 are displayed. The threshold can be modified.



Review Optimization Results

1. Click Filter
2. Click Iso 2
3. Click Center Model
4. Click Fit Model
5. Click the right arrow to remove elements below the threshold value
6. Click STL Download
7. The displayed model has been downloaded to an STL file and may be imported to separate CAD package or FEA pre processor

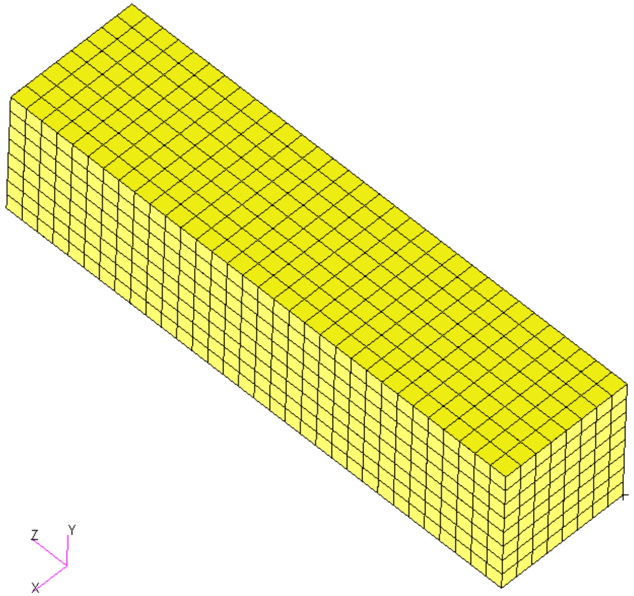
- A normalized material density (NMD) close to 1 indicates the element is very important and should be kept in the design. It is not recommended to go beyond a threshold of .7 since very critical elements would be removed. Elements with an NMD close to 0 are not critical and can be removed.
- Common thresholds to use are typically in the range of .3 to .7



Results

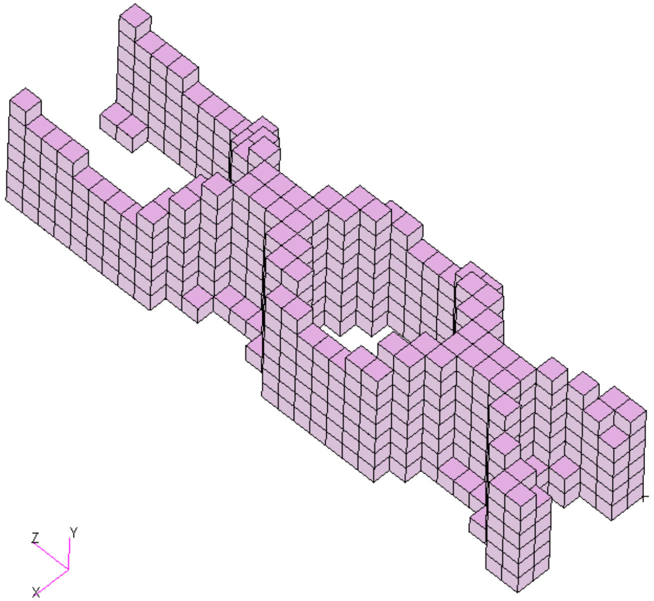
Before Optimization

- Mass: 25.6



After Optimization

- Mass: 7.7 (~70% mass reduction)
- Mirror Symmetry Constraints
- Casting



End of Tutorial

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?
- Topology Optimization Workflows
- Viewer Web App for Topology Optimization Post Processing

What are the design variables in Topology Optimization?

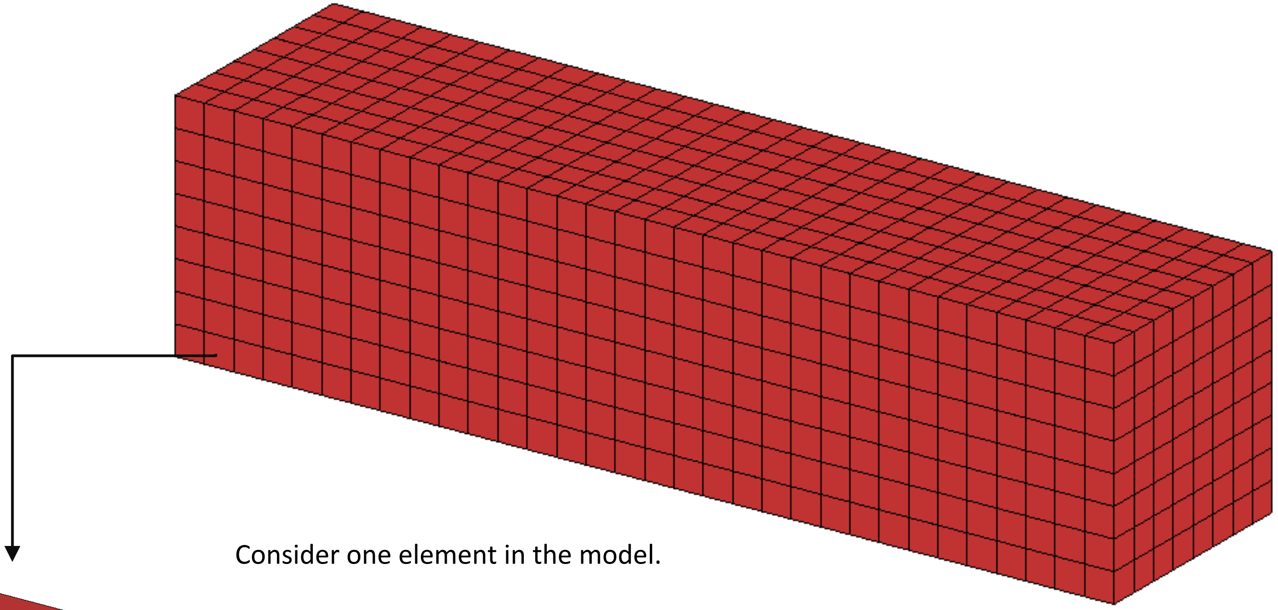
The design variables in a topology optimization are normalized material densities (p_i) of each element.

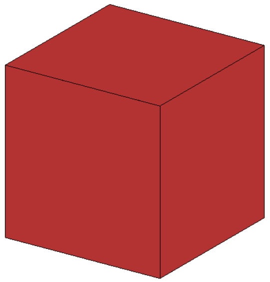
$$p_i = \frac{p_{ci}}{p_0}$$

p_{ci} : The current material density of element i

p_0 : The original material density

p_i : The normalized material density of element i



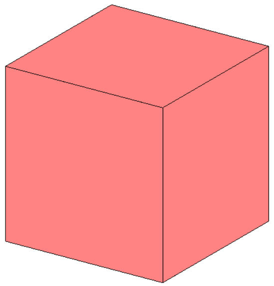


Consider one element in the model.

Suppose the original material density is 8000 kg/m^3.

If during the optimization, the normalized material density of the element is 1.0, then the current material density is

$$p_{ci} = p_i \cdot p_0$$
= 1.0 * 8000
= 8000



If during the optimization, the normalized material density is .5, then the current material density is

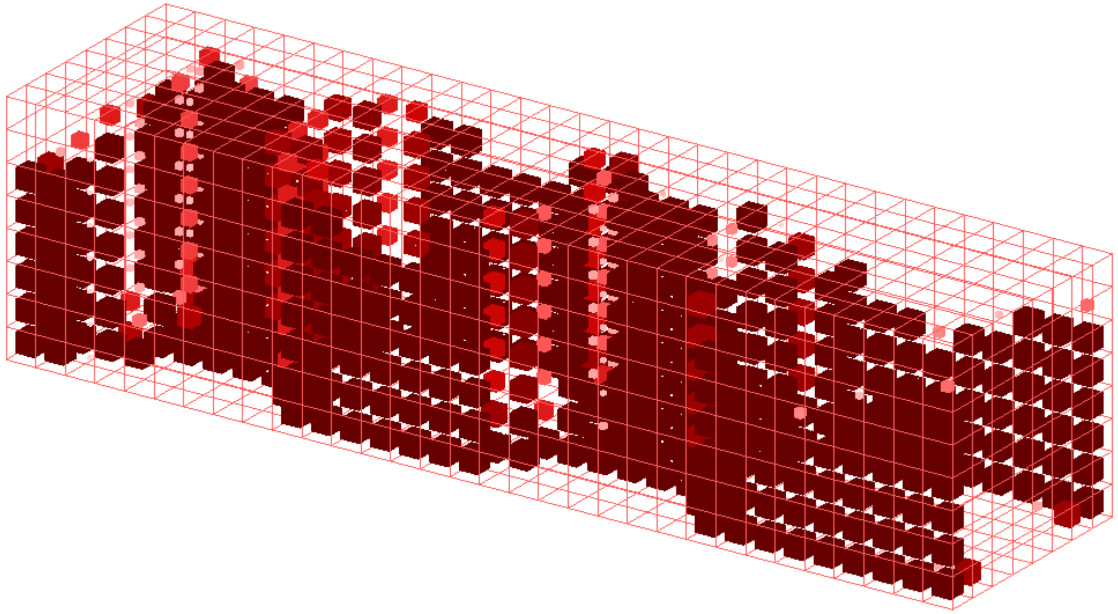
$$p_{ci} = p_i \cdot p_0$$
= .5 * 8000
= 4000

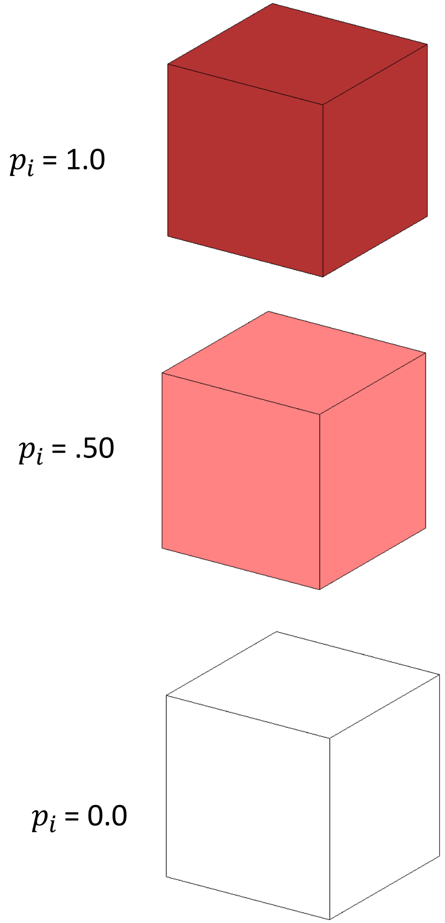
What are the design variables in Topology Optimization?

The design variables or normalized material densities can vary between 0 and 1.

- 1 - Normalized density values close to 1 are critical to the design
- 0 - Normalized density values close to 0 are not critical to the design

It should be noted that during the optimization, elements are never removed. Instead, the normalized material density values are used to determine which elements should be kept or removed.





During the optimization, the normalized material density of each element is allowed to vary between 0 and 1 ($0 < p_i \leq 1$)

What is FRMASS or Fractional Mass?

Since the design variables or normalized material densities 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.

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

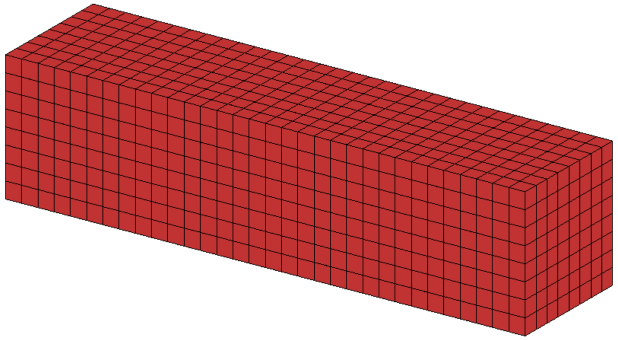
p_0 : The original material density

p_i : The normalized material density of the element

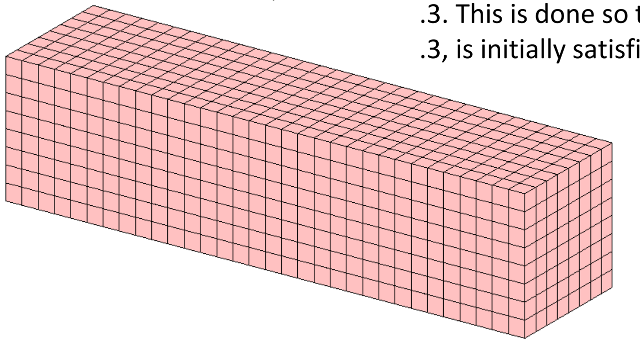
v_i : Volume of element

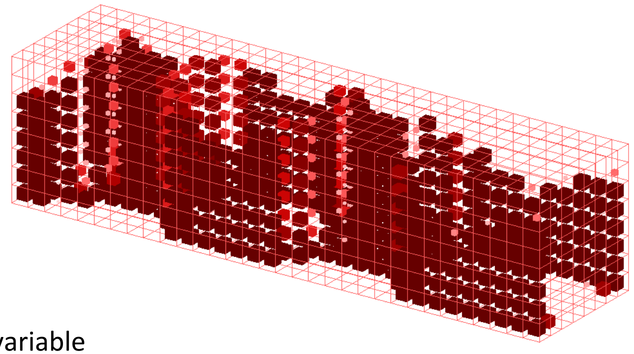
0) Suppose this is the optimization problem statement:

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



1) Prior to the optimization start, each material density is reduced from 1.0 to .3, and 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 variable (normalized material density) is allowed to range between 0 and 1.0, but the constraint that the 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
```

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	1.32	6.163140E-01	9.999972E-09
2	5.721454E+03	1.12	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

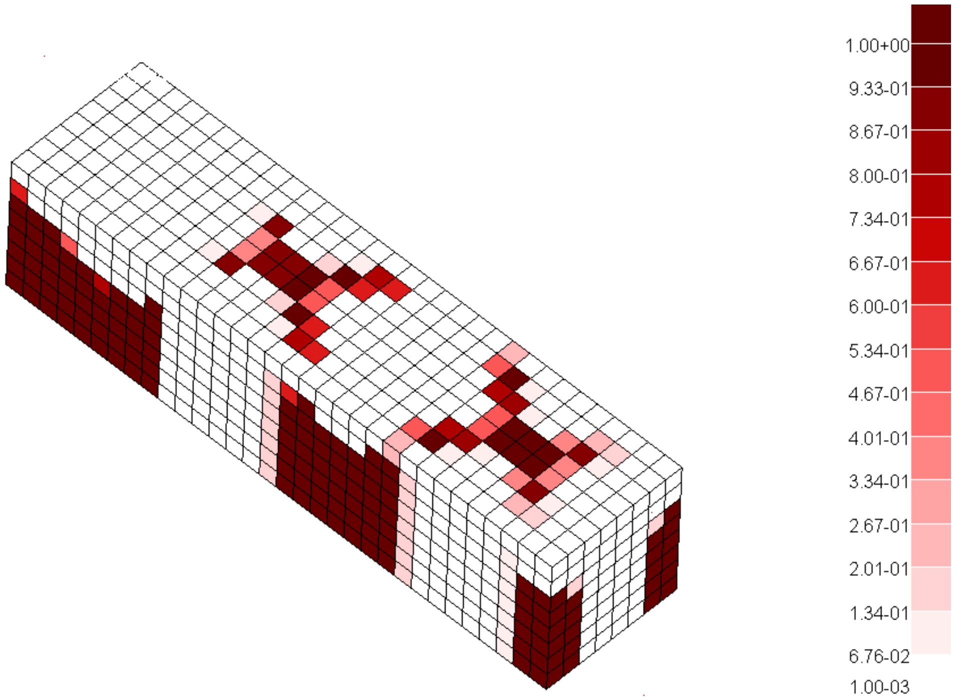
6. The Compliance of 1.8222E4 is twice the TOTAL STRAIN ENERGY of 9.11E3.

```
                         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
```

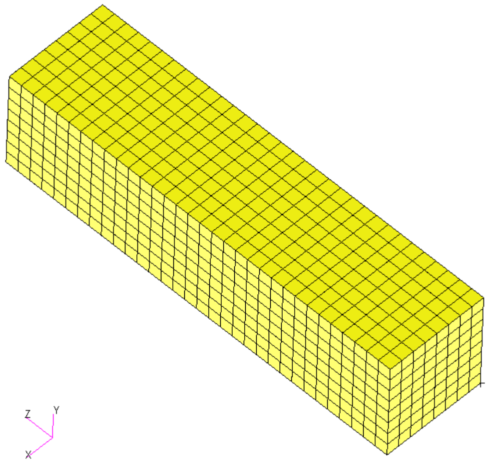
```
                   ***************************************************************
                   S U M M A R Y   O F   D E S I G N   C Y C L E   H I S T O R Y
                   ***************************************************************

                                     (HARD CONVERGENCE ACHIEVED)

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

                               OBJECTIVE AND MAXIMUM CONSTRAINT HISTORY
---------------------------------------------------------------------------------------------------------------
                      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           1.323096E+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
```

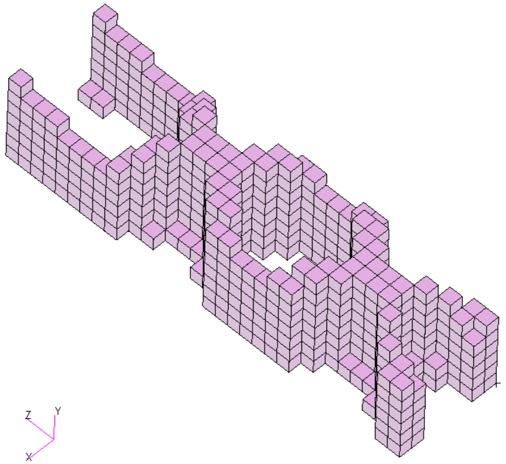
How can non-critical elements be removed from the design?

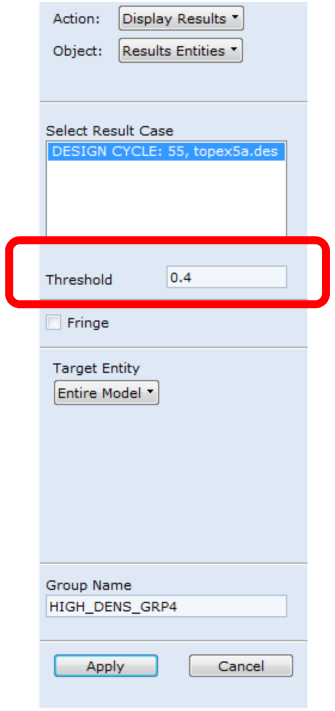
- Use the threshold to suppress non-critical elements
- The threshold means: *'Keep every element that has a normalized density greater than the threshold'*
- Recall from before:
  - 0 - Normalized density values close to 0 are not critical to the design
  - 1 - Normalized density values close to 1 are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



The normalized densities are plotted for each element. Note that all the elements are present.







Topology Optimization Workflows

There are 2 common optimization problem statements for topology optimization

METHOD A

Objective:

- Minimize Compliance

Constraint:

- FRMASS < Upper Bound

Comments:

- Multiple optimizations at different bounds for FRMASS are necessary. The best solution is selected from the multiple optimizations.

METHOD B

Objective:

- Minimize FRMASS

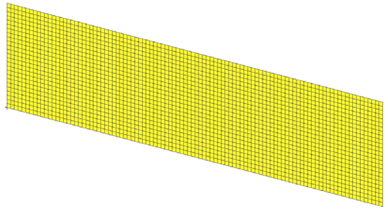
Constraint:

- Von Mises Stress < Upper Bound

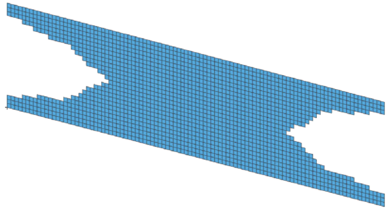
Traditional Topology Optimization

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

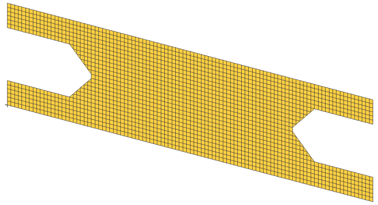
Original Design



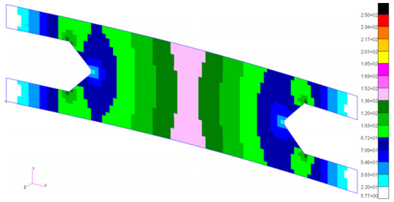
Mass: 9.737 grams



FRMASS < .75
Mass: 7.186 g
Optimization B



Mass: 7.739 g



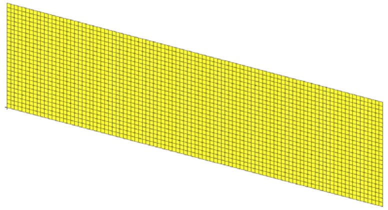
Max von Misses: 150 MPa
Max Displacement : 2.78 mm

1st natural Frequency: 111 Hz

Traditional Topology Optimization

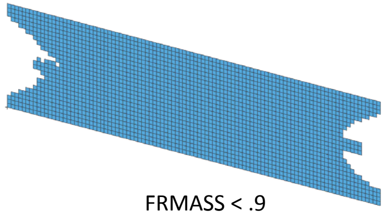
Objective: Minimize Compliance (Maximize Stiffness)
Constraint: Fractional Mass < .## (Target Mass)

Original Design

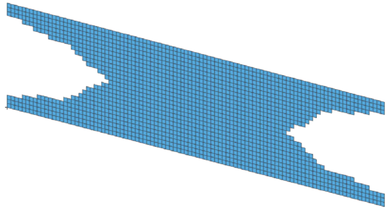


Mass: 9.737 grams

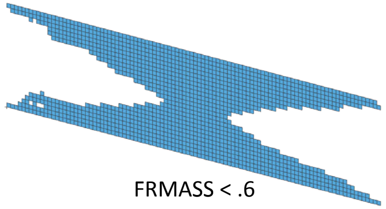
Topology Solution



FRMASS < .9
Mass: 8.756 g
Optimization A

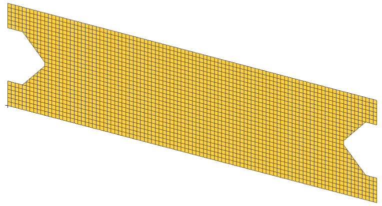


FRMASS < .75
Mass: 7.186 g
Optimization B

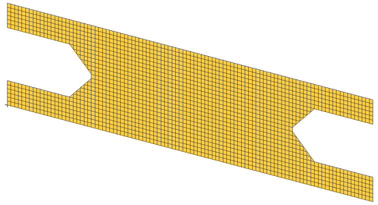


FRMASS < .6
Mass: 5.718 g
Optimization C

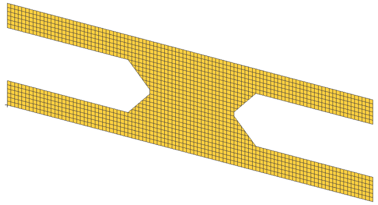
Refined Design



Mass: 9.094 g

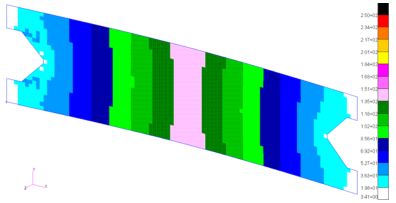


Mass: 7.739 g



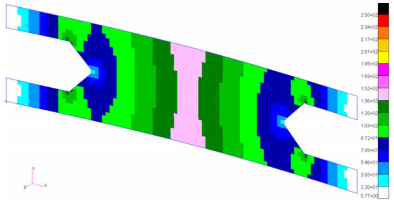
Mass: 6.119 g

Verification



Max von Misses: 150 MPa
Max Displacement: 2.52 mm

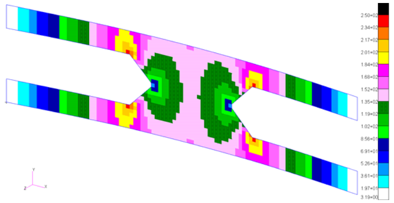
1st natural Frequency: 114 Hz



Max von Misses: 150 MPa
Max Displacement : 2.78 mm

1st natural Frequency: 111 Hz

Best Solution: Optimization B led to a valid and light weight design



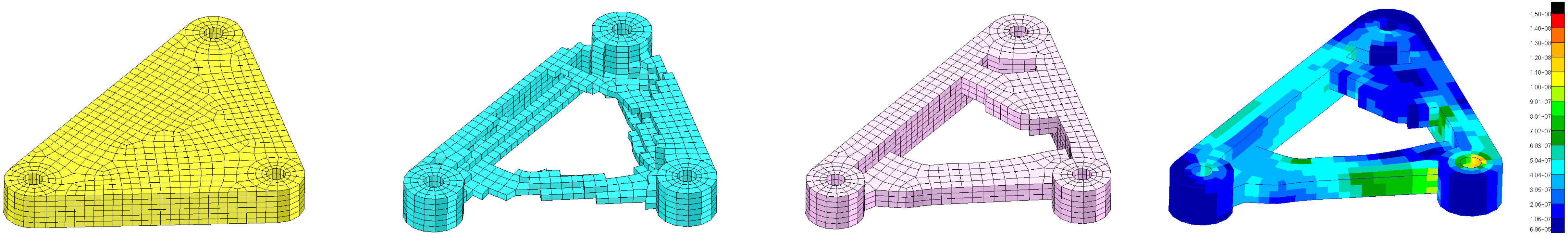
Max von Misses: 250 MPa
Max Displacement : 3.57 mm

1st natural Frequency: 109 Hz

Latest Topology Optimization

Objective: Minimize Fractional Mass (Minimize Mass)
Constraint: Stress Constraint

Original Design → Topology Solution → Refined Design → Verification



Viewer Web App for Topology Optimization Post Processing

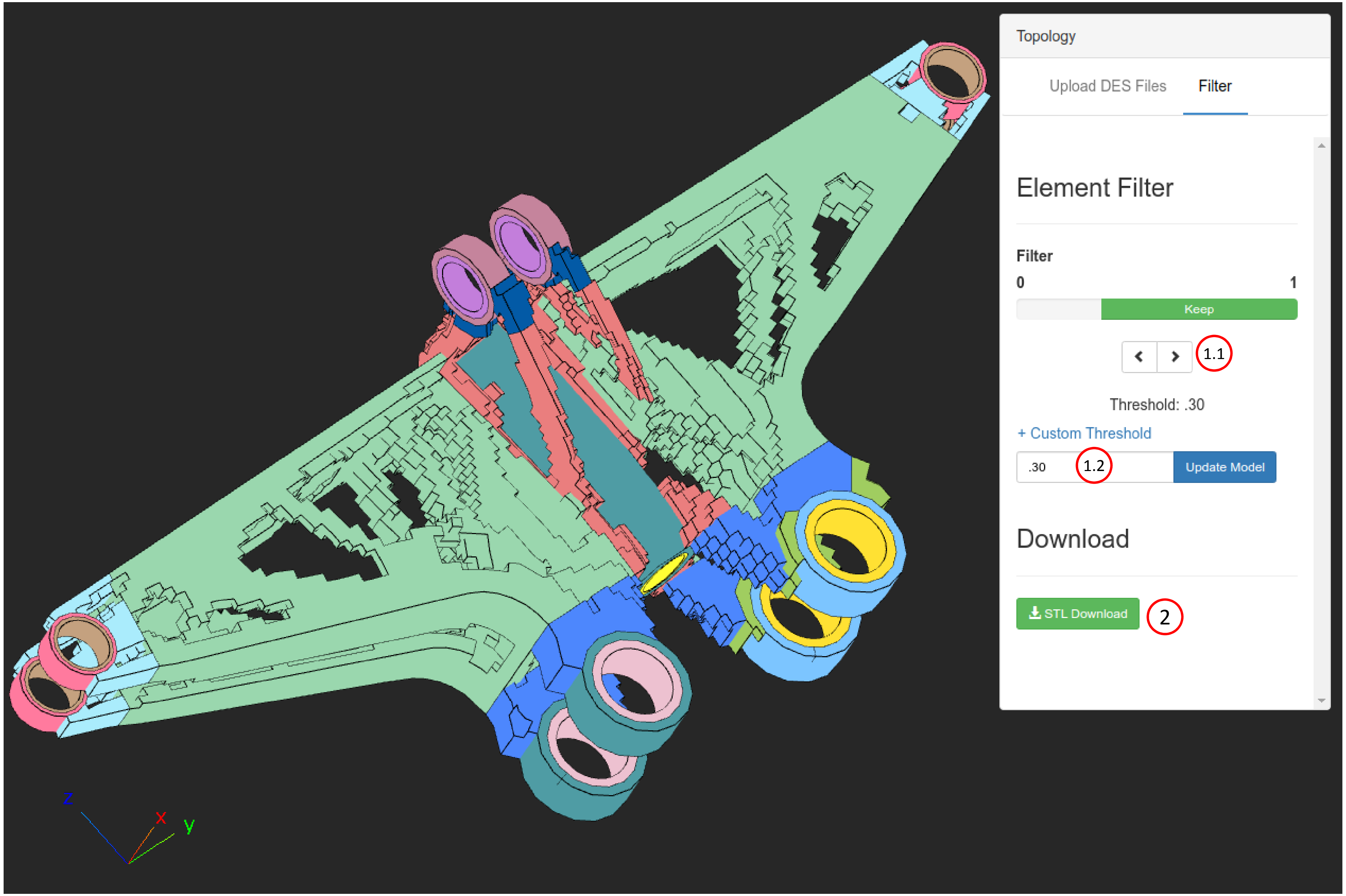
Review Optimization Results

The Viewer web app supports post processing topology optimization results.

Filtering of topology optimization results is controlled by one of 2 different ways:

1. The arrows can be used to move the threshold to values of 1.0, .3, .4, .5, .6 and .7
2. If a specific threshold is necessary, do the following:
    1. Click Custom Threshold
    2. Supply the custom threshold
    3. Click Update Model

1. STL Download – This downloads an STL file containing the model as displayed. This is useful for moving the topology results to a CAD package or FEA pre processor



Viewer
Supported Capabilities

Supported Element Types

- CTRIA3
- CTRIA6
- CTRIAR
- CQUAD4
- CQUAD8
- CQUADR
- CQUAD4
- CQUAD8
- CQUADR
- CHEXA
- CTETRA
- CPENTA
- All other elements are <u>not</u> supported

Coordinate Systems Supported

- Only the basic coordinate system (CID=0) is supported for GRIDs. This is a rectangular Cartesian system and is also known as the default coordinate system.
- All other coordinate systems are <u>not</u> supported. This includes cylindrical, spherical and other cartesian systems (CID=1, 2, 3…).

STL Download/Export is Supported

Performance

- When uploading BDF or DES files, there are many operations performed, e.g. reading, parsing, and displaying data. This is the first release of the Topology Viewer and future improvements to performance will be made. At the time of writing this, the viewer is capable of fully parsing and displaying 10MB of BDF files every 25 seconds. The viewer does not provide a progress bar regarding the parsing process, so it was best to document here the expected parsing rate.