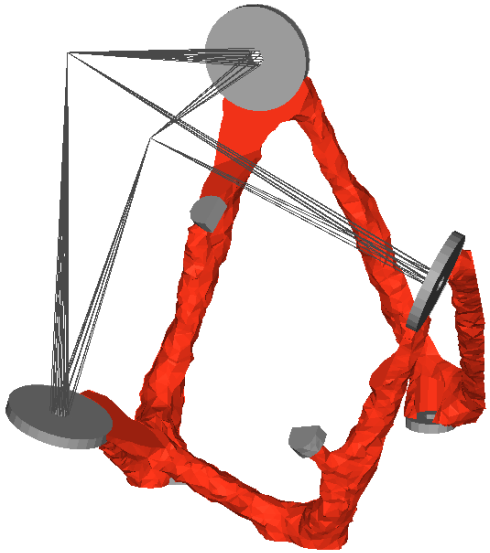
Topology optimization

A shift towards computational design



Ryan Watkins
Jet Propulsion Laboratory
California Institute of Technology

SLaMs YPF
8/30/2016

Most of the design problems at JPL are complex and challenge our intuition

It takes many years to gain intuition

There are only so many “grey beards”

Even with intuition, design is iterative in nature

Computers are built to iterate

Main costs are man-hours and mass

Topology optimization addresses both of these issues

I was tasked to jumpstart the integration of topology optimization at JPL

What are the fundamentals?

How does it work and how do we use it?

What are the available tools?

What are the best commercial implementations?

How should we use them at JPL?

Where will it be most effectively implemented?

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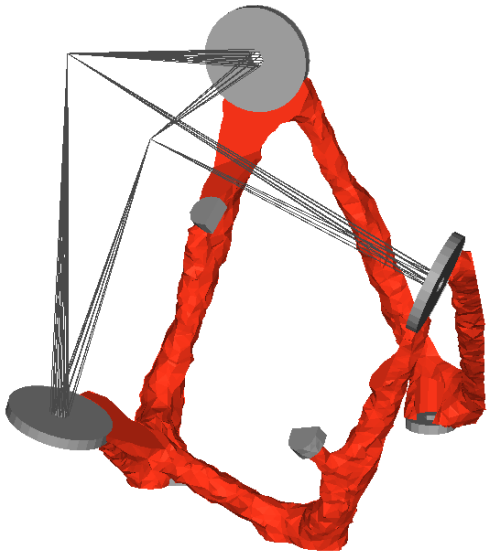

Background

General theory and framework

Available tools

Which to use

Case study

Designing a bracket for MSL

Topology optimization

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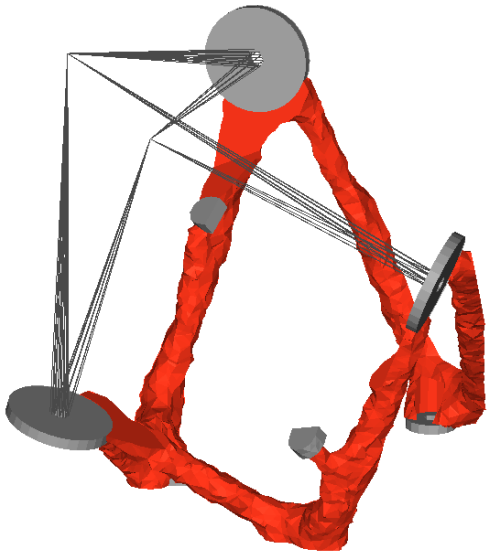

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Topology optimization is different than size and shape optimization

Size optimization

Optimum property definitions

Shape optimization

Optimum node positions

Topology optimization

Optimum design geometry

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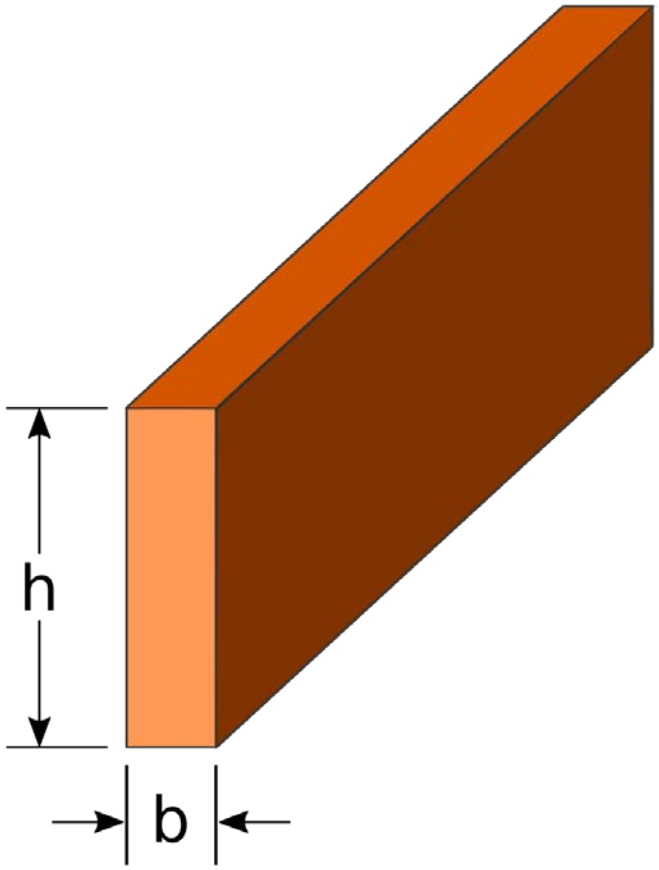

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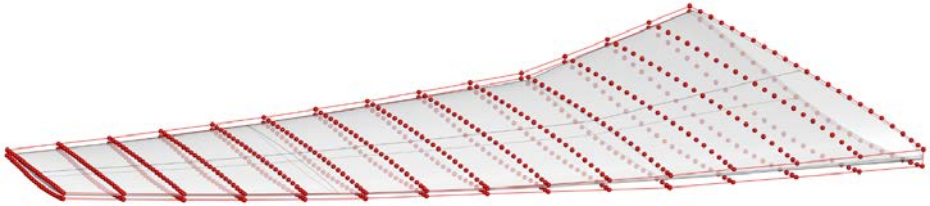

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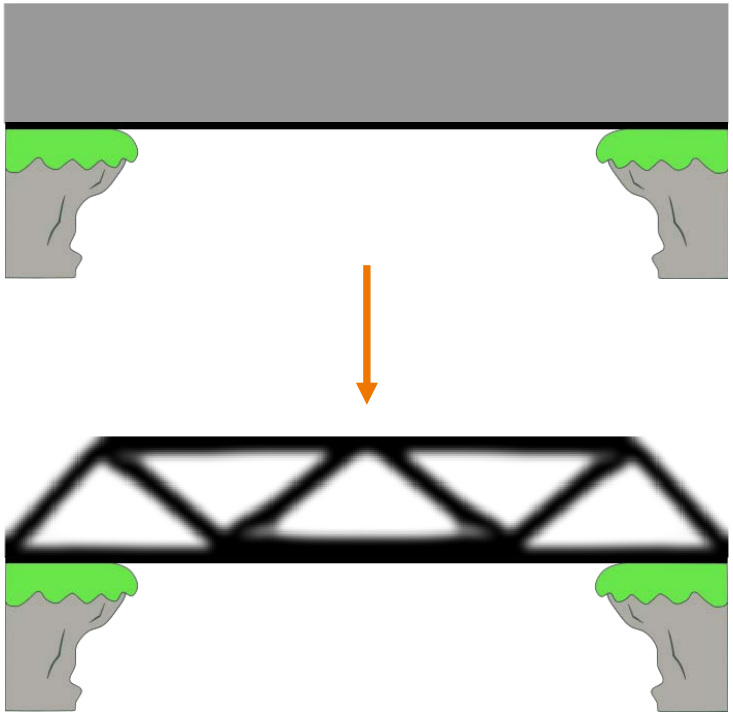


Size or shape optimization can further hone a topology optimized design

Size optimization

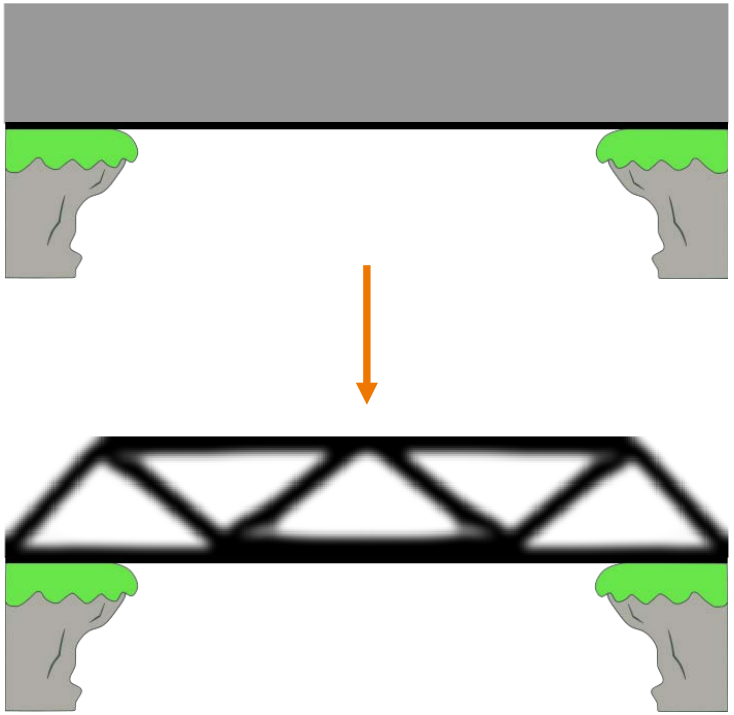
Optimum property definitions

Shape optimization

Optimum node positions

Topology optimization

Optimum design geometry



Topology optimization is usually implemented within the FE framework

Relevant domains

Design and non-design

Loading conditions

Load cases and constraints

Optimization objective

Max stiffness, min mass, etc.

Performance constraints

Max volume, max stress, etc.

The first step is to define the design and non-design spaces and mesh them

Relevant domains

Design and non-design

Loading conditions

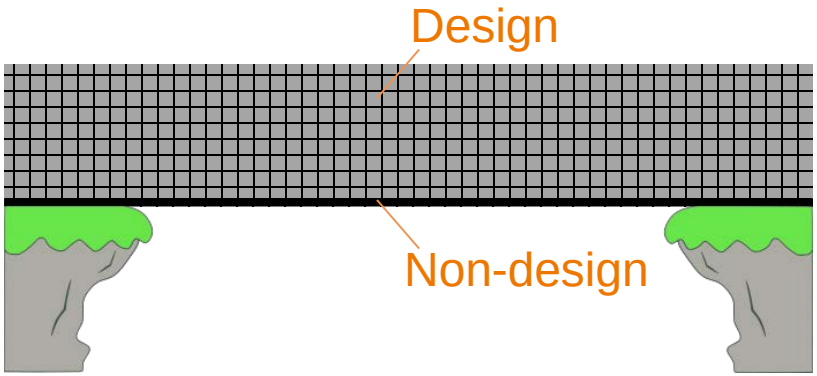
Load cases and constraints

Optimization objective

Max stiffness, min mass, etc.

Performance constraints

Max volume, max stress, etc.



The second step is to define the relevant boundary conditions

Relevant domains

Design and non-design

Loading conditions

Load cases and constraints

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Performance constraints

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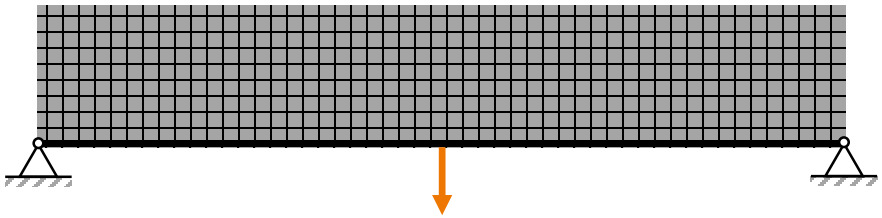

Third, define the ultimate goal of the optimization

Relevant domains

Design and non-design

Loading conditions

Load cases and constraints

Optimization objective

Max stiffness, min mass, etc.

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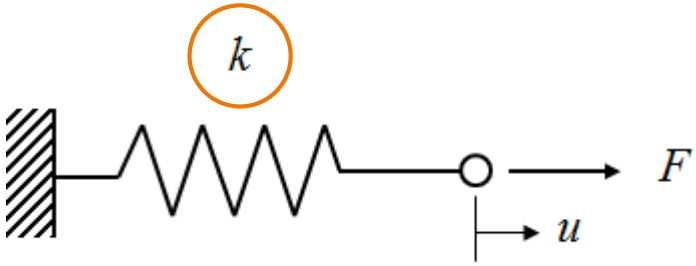
Max volume, max stress, etc.



Lastly, define the restrictions that govern the performance of the design

Relevant domains

Design and non-design

Loading conditions

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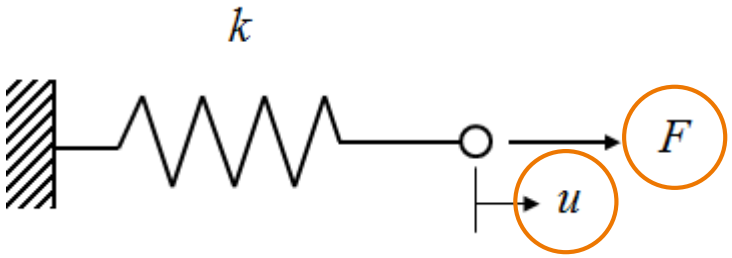

There are two common optimization formulations

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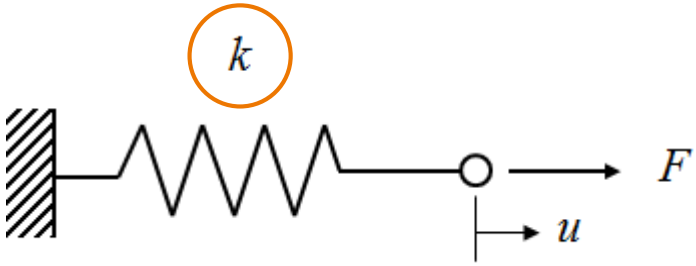

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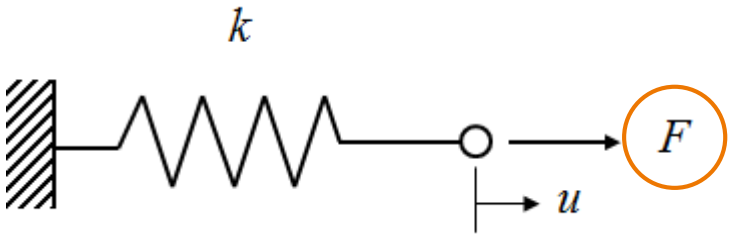


Most optimizers are based on a density formulation

Each element has a fictitious density

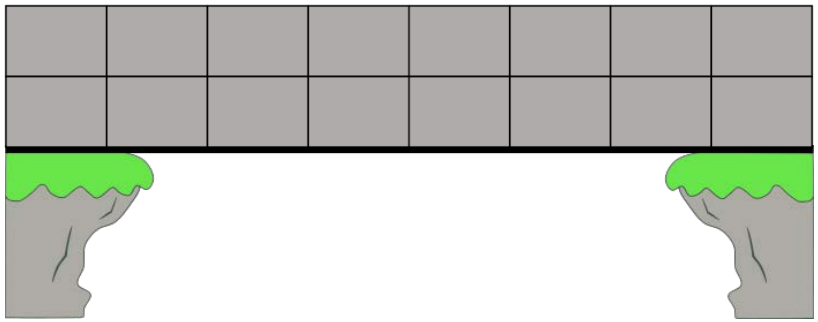
$\rho \in \{0, 1\}$

Element stiffness is scaled by this density

$E^* = \rho E$

Optimizer iteratively modifies density profile

Typically a gradient based algorithm



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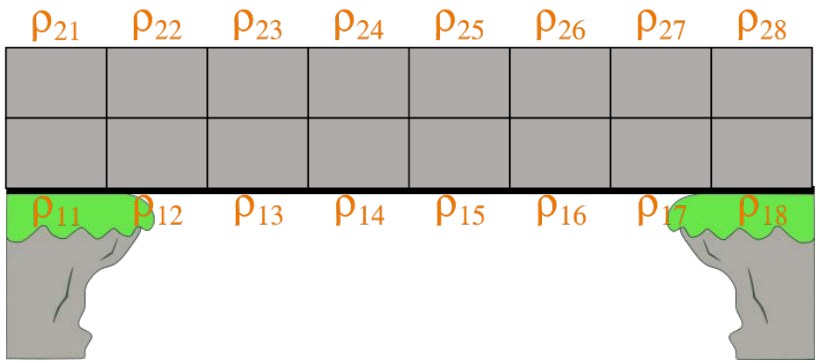

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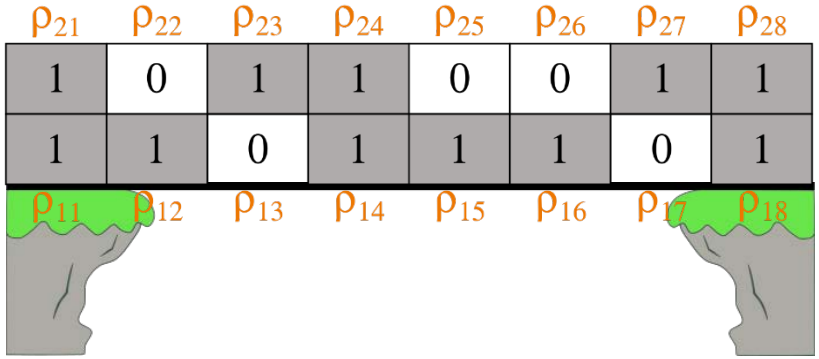


The SIMP method is the most common problem formulation

Fictitious density is a continuous variable

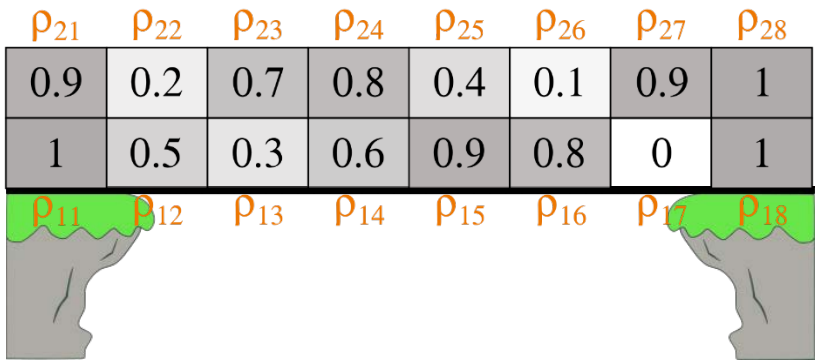
$0 \leq \rho \leq 1$

Intermediate densities are penalized

$E^* = \rho^n E$

Cutoff density defines retained material

$\rho > \rho_c$



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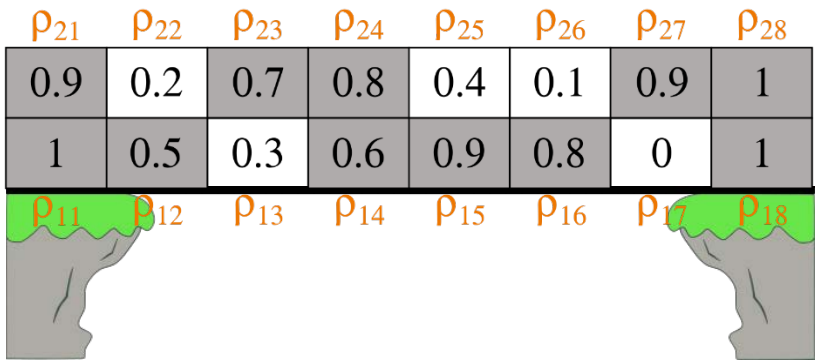

$\rho_c = 0.49$

Topology optimization

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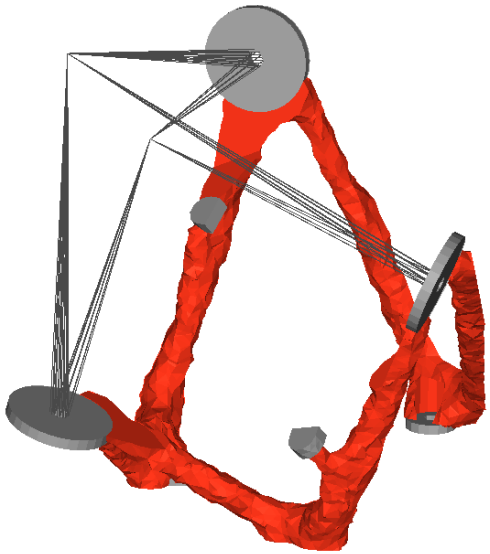

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Which to use

Case study

Designing a bracket for MSL

There are four main commercial tools

OptiStruct (Altair)
HyperMesh and Inspire

TOSCA (Dassault Systèmes)
ANSA, Abaqus, and ANSYS Workbench

GENESIS (Vanderplaats R&D)
Design Studio and ANSYS Workbench

MSC Nastran (MSC)
Patran

There are two new players on the market

OptiStruct (Altair)
HyperMesh and Inspire

TOSCA (Dassault Systèmes)
ANSA, Abaqus, and ANSYS Workbench

GENESIS (Vanderplaats R&D)
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MSC Nastran (MSC)
Patran

AutoDesk Nastran (AutoDesk)
Shape Generator

Plato (Sandia National Labs)
Integrated Analysis Workbench

I examined the capabilities of the four main commercial tools

Institutional (JPL)

Licensing and availability

Functionality

Response functions, manufacturing constraints

Speed

Finite element method and optimizer

Usability

Ease of setting up a design problem

I recommend using OptiStruct in conjunction with Inspire or HyperMesh

Institutional (JPL): OptiStruct

Licensing and availability

Functionality: OptiStruct

Response functions, manufacturing constraints

Speed: OptiStruct

Finite element method and optimizer

Usability: OptiStruct/Inspire

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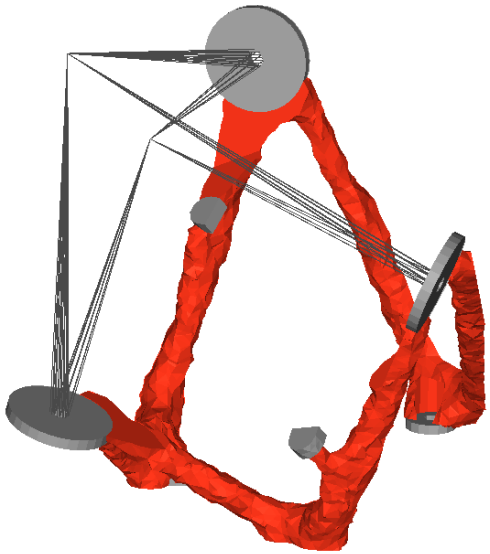

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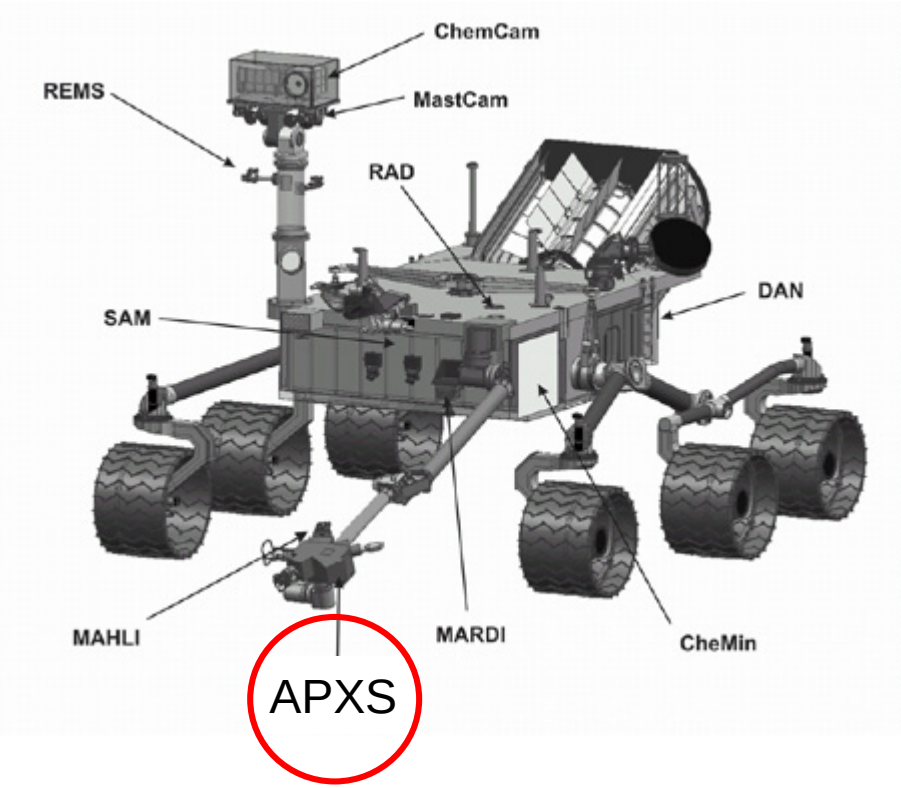
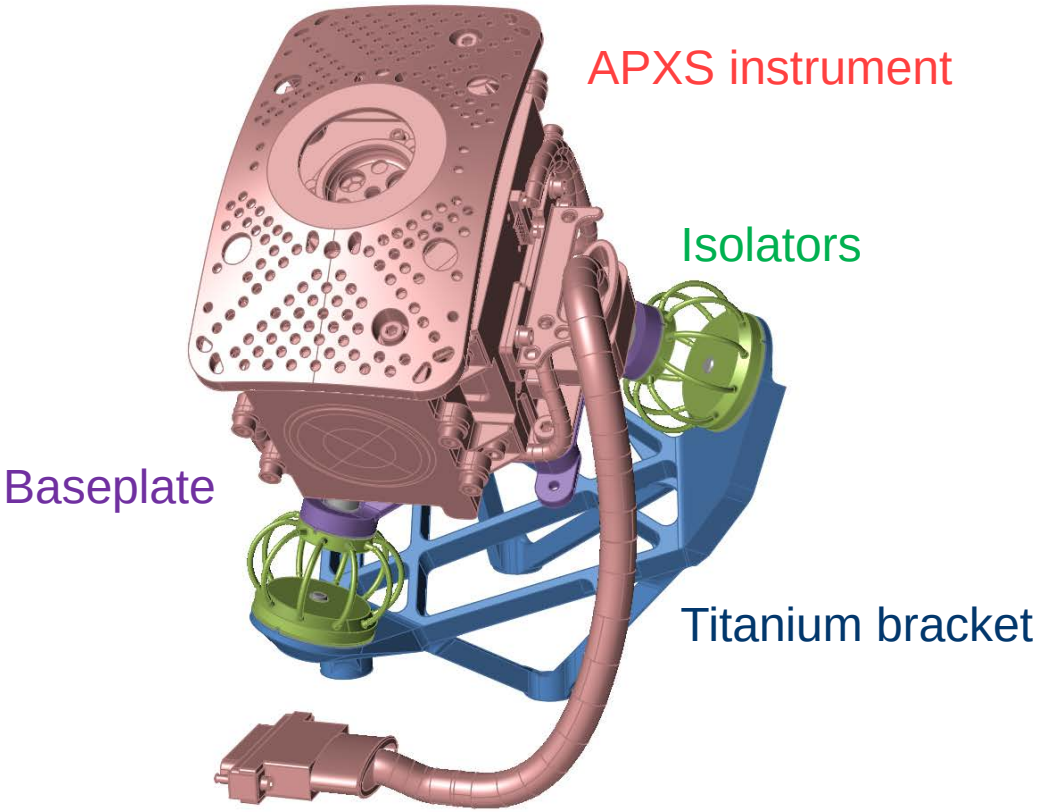
Designing a bracket for MSL

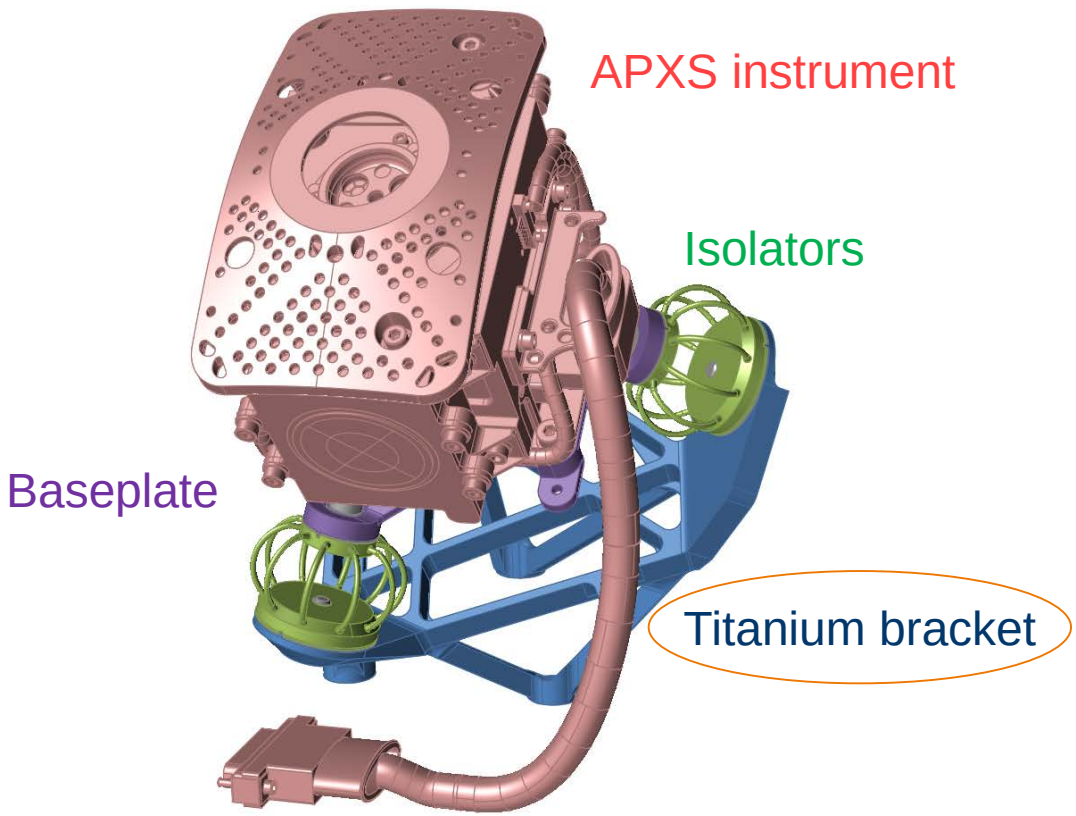
I looked at a case study of the design of MSL's APXS instrument



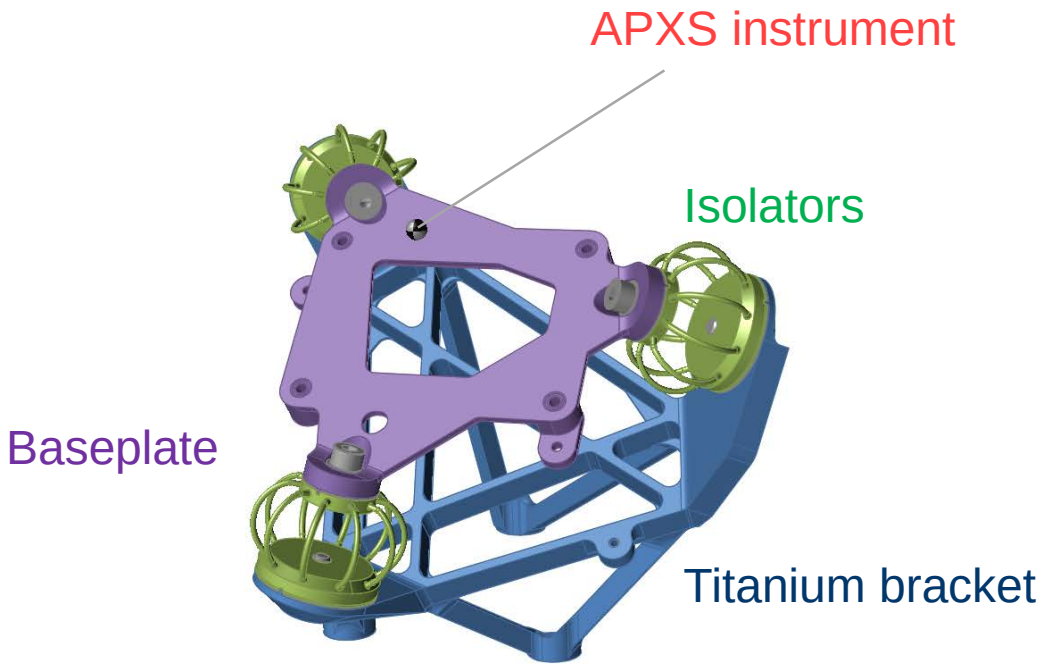
The APXS isolator assembly consists of four major components



This case study focuses on the optimization of the support bracket



For the purposes of the optimization, let's remove the non-essentials



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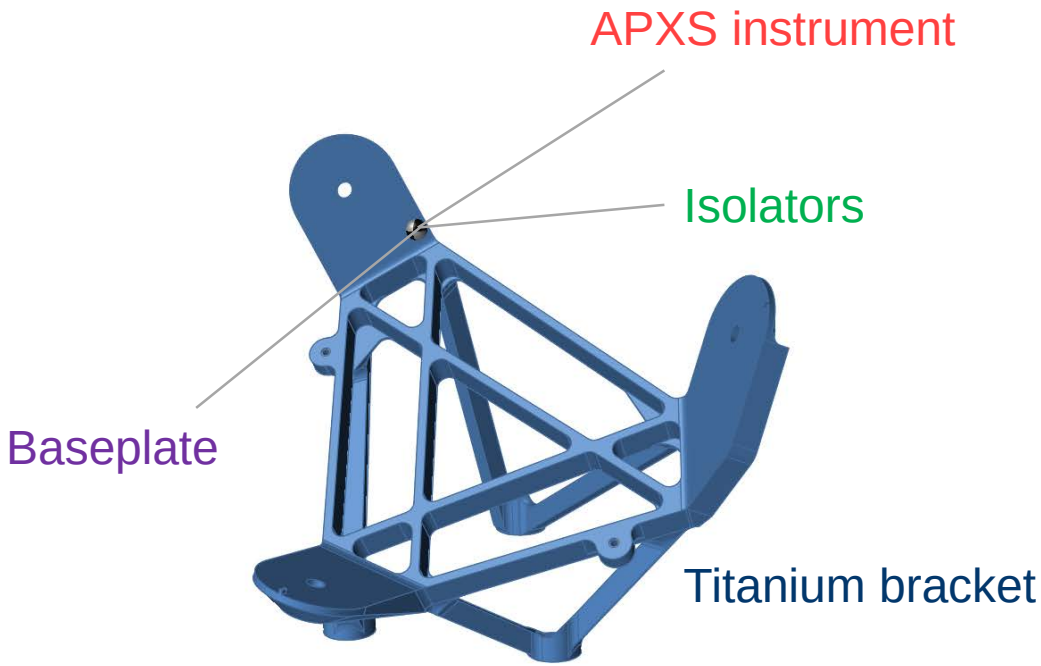

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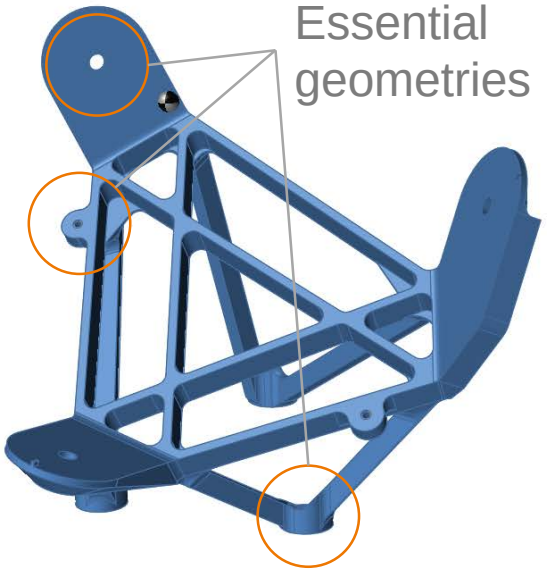

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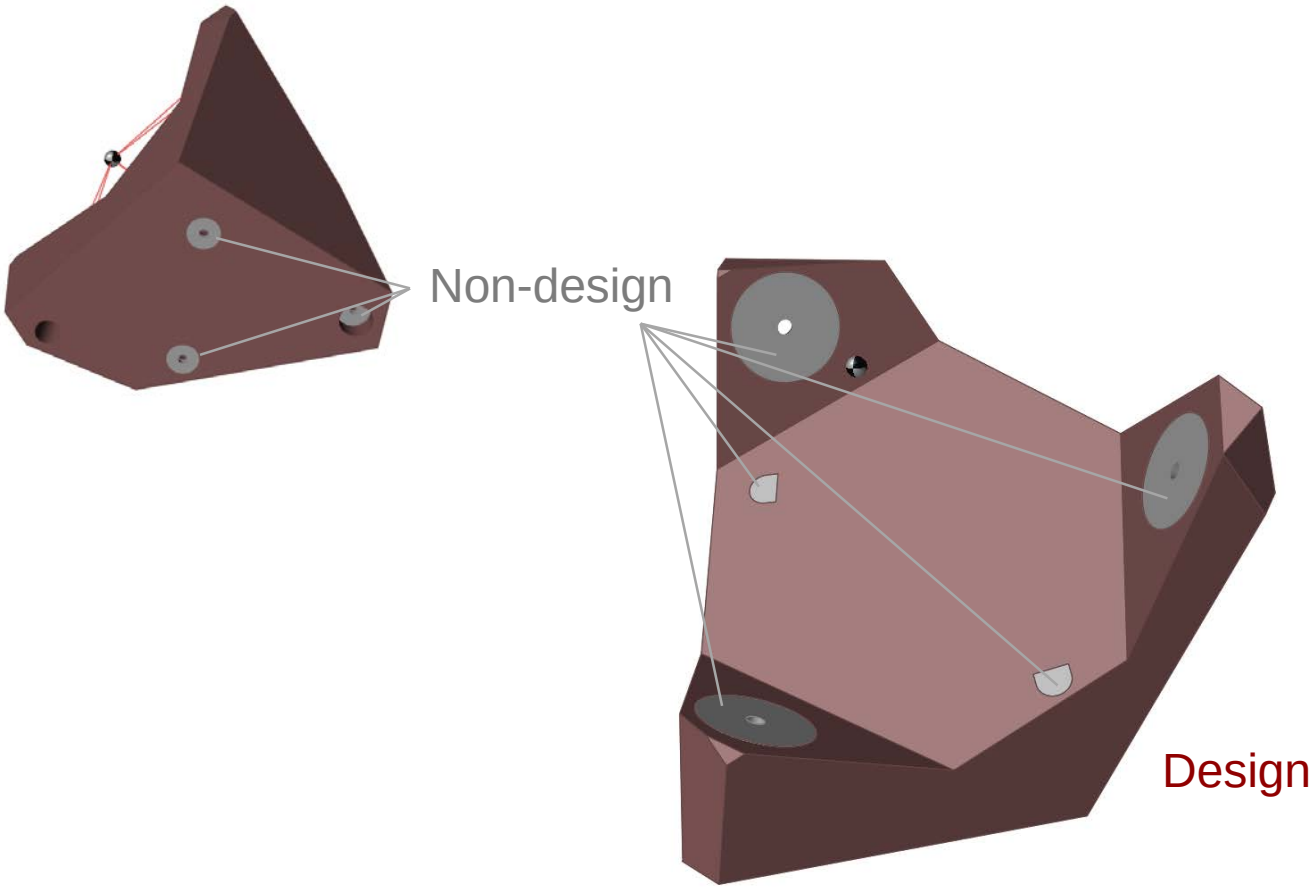
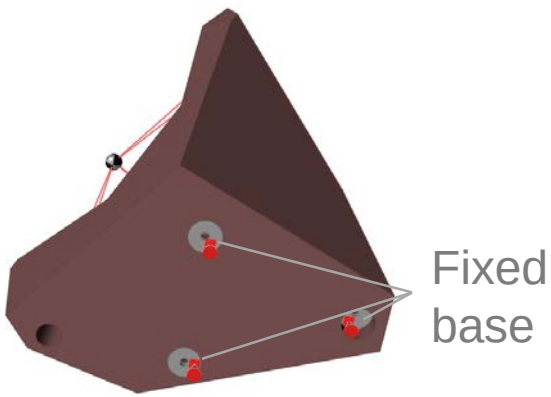
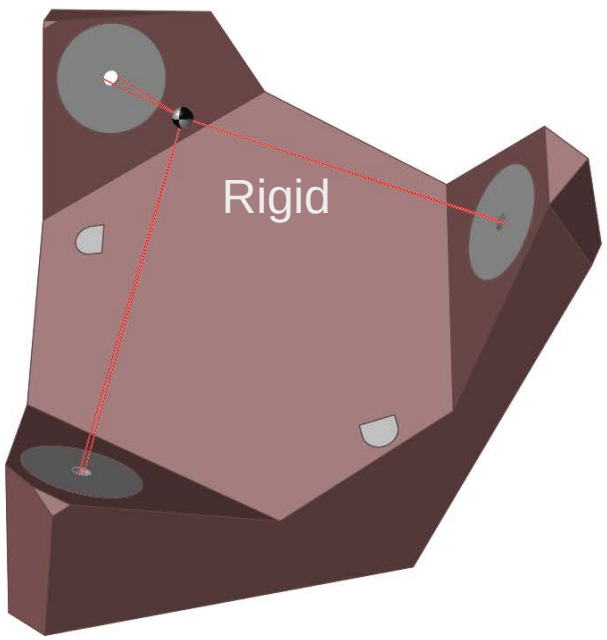
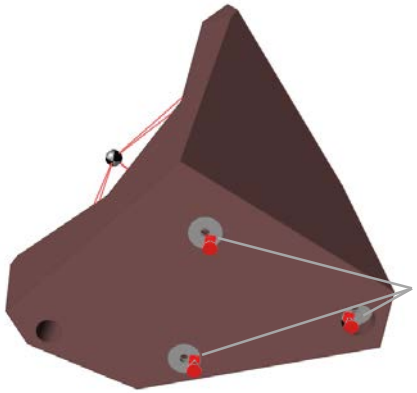


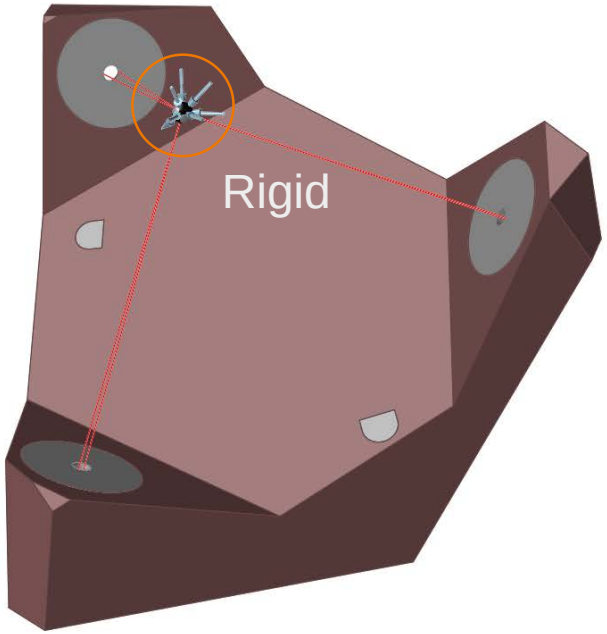
There are three relevant loading cases:





There are three relevant loading cases:
MAC launch loads (60 Gs)

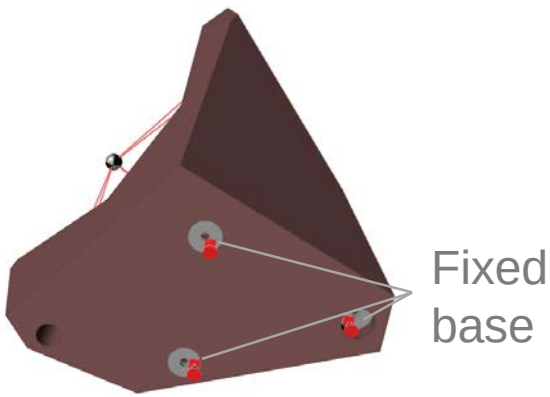


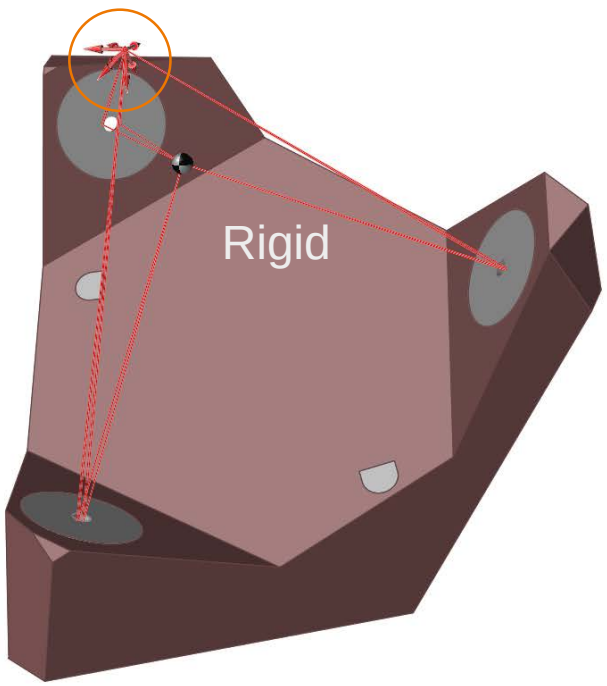


Subcases:

1. (X, 0, 0)
2. (0, Y, 0)
3. (0, 0, Z)
4. (X, Y, 0)
5. (X, 0, Z)
6. (0, Y, Z)
7. (X, Y, Z)

There are three relevant loading cases:
Inadvertent arm loading (200 N)





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4. (X, Y, 0)
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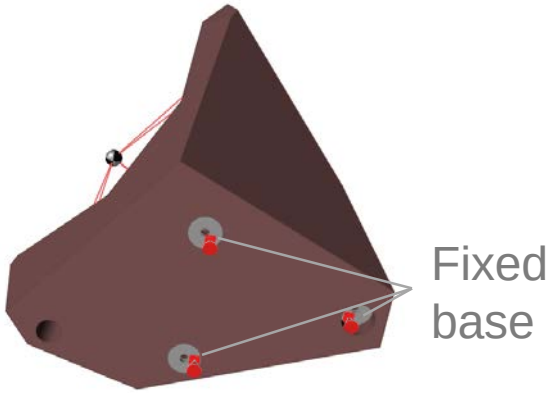
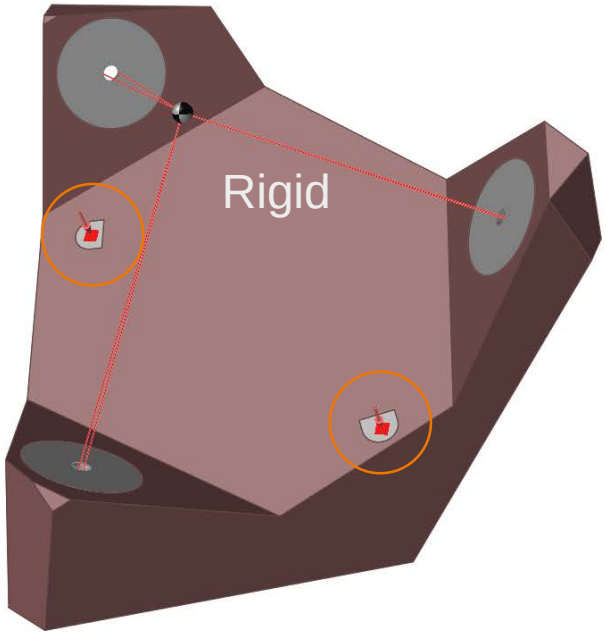
6. (0, Y, Z)
7. (X, Y, Z)

There are three relevant loading cases:
Installation loads (500 N)





The design is optimized with respect to stiffness

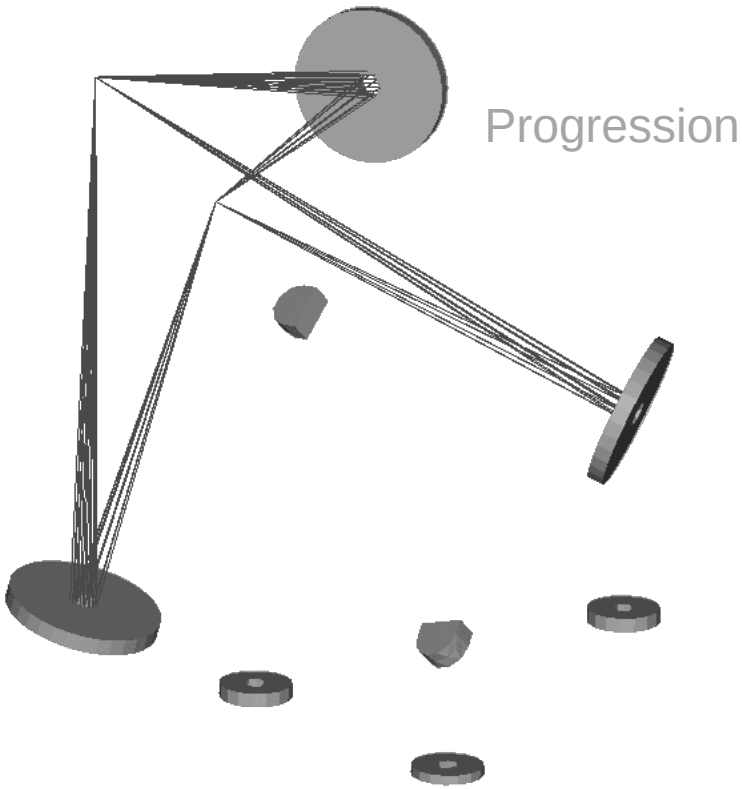
Objective: weighted compliance

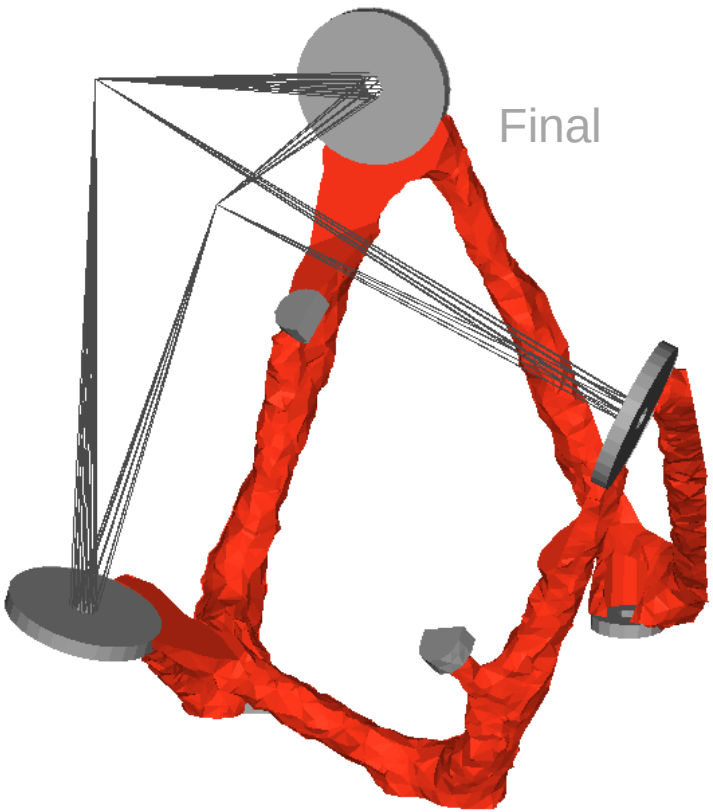
Fifteen equally weighted cases

Constraint: maximum volume

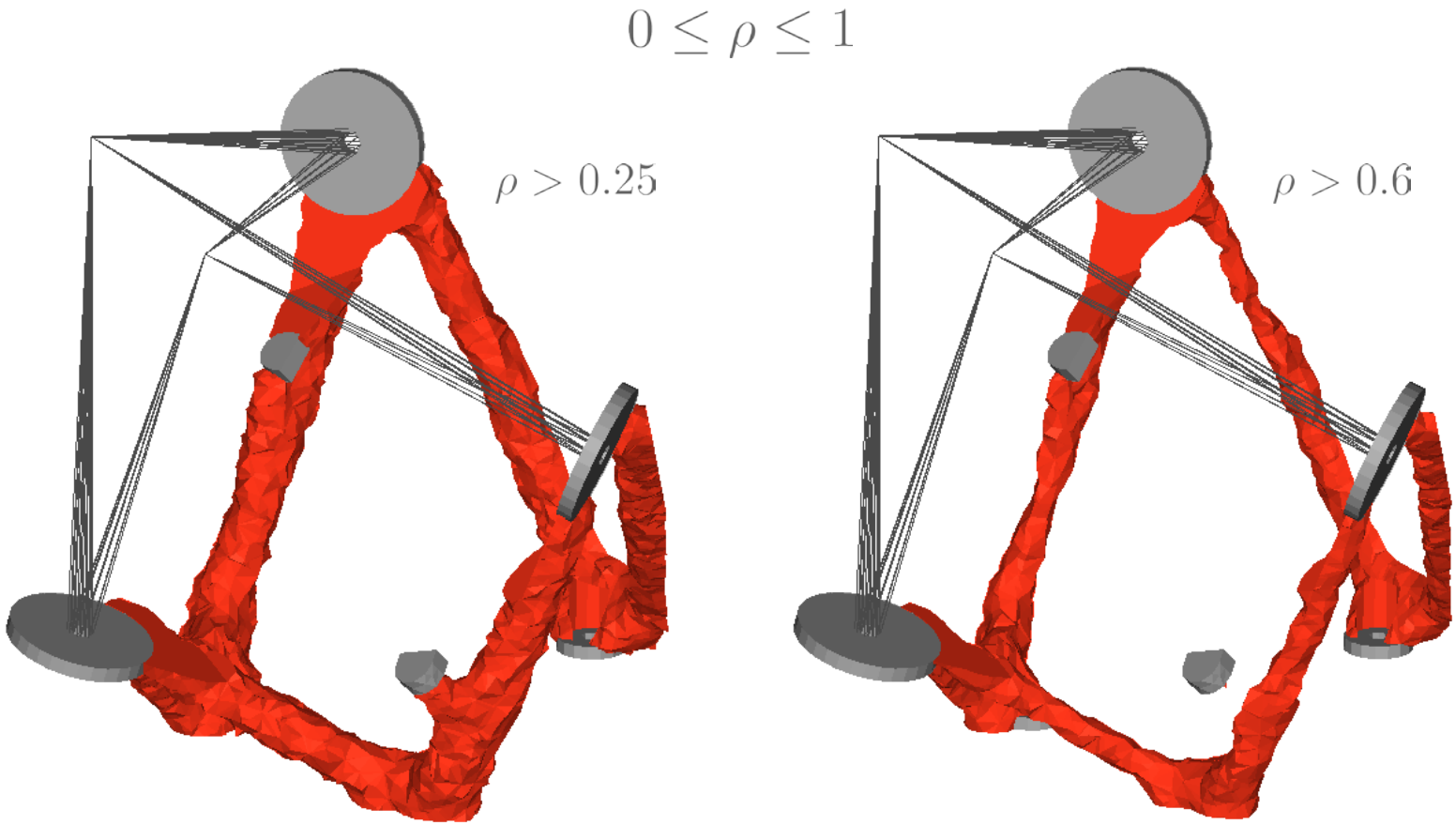
Target volume of 5% of original design space

The optimized design consists of struts connecting the base with the isolators





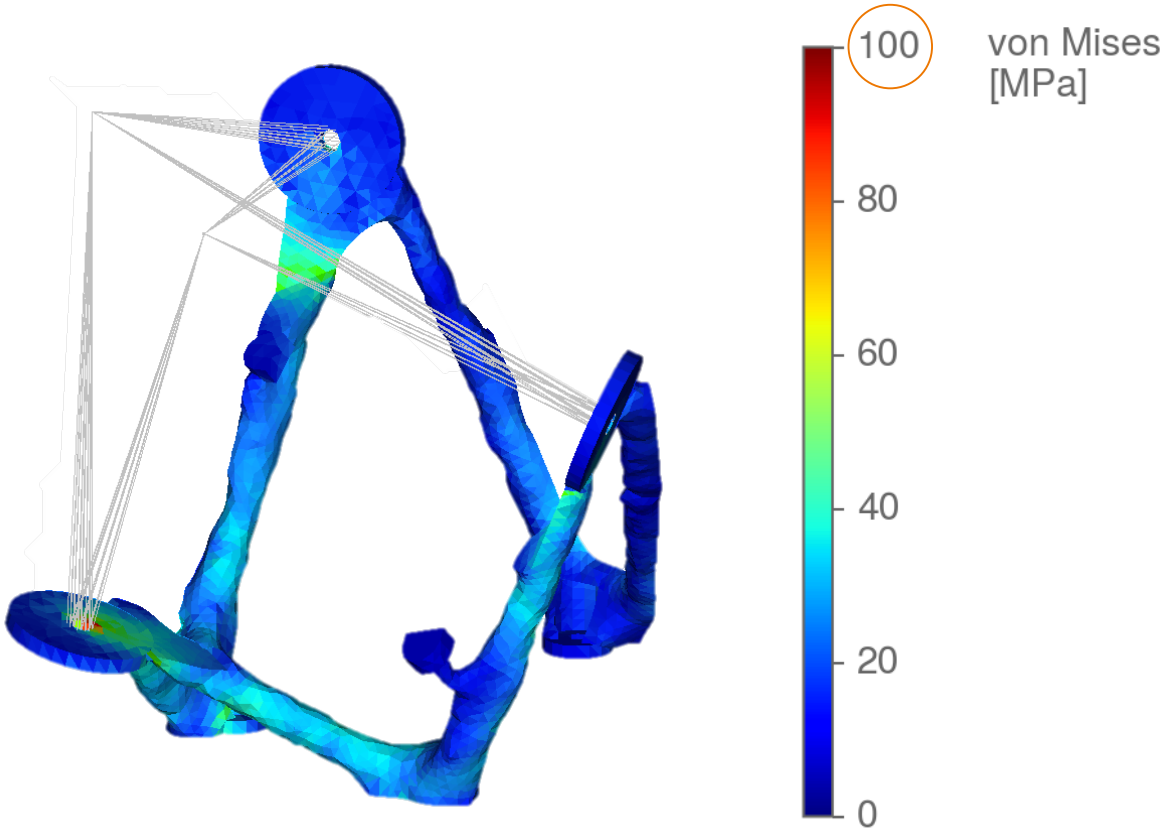
Your choice of the cutoff density dictates the retained material for the design



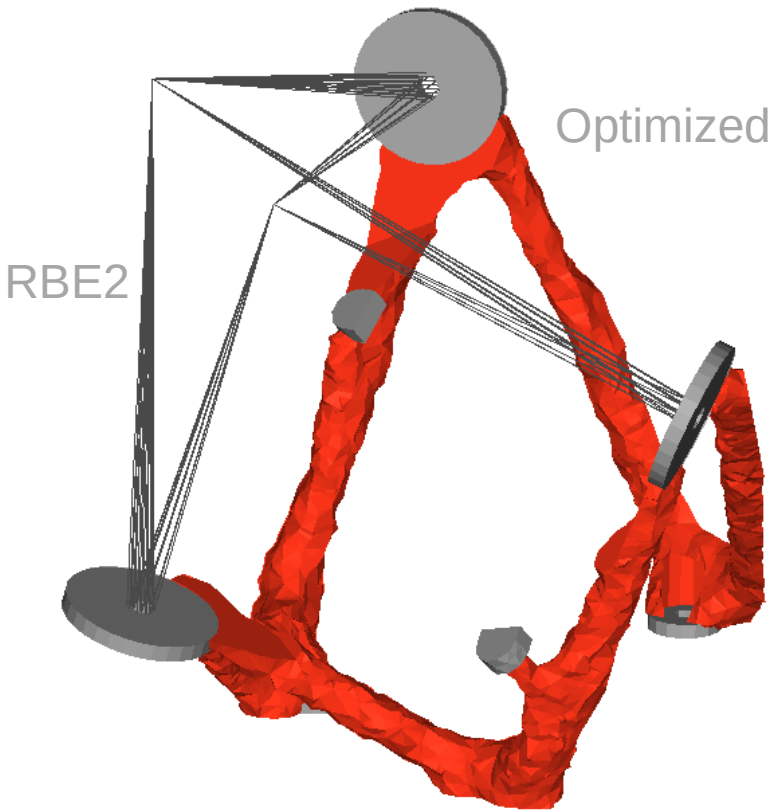
Optimizing for stiffness doesn’t prevent over-design (or under-design)

Worst case loading

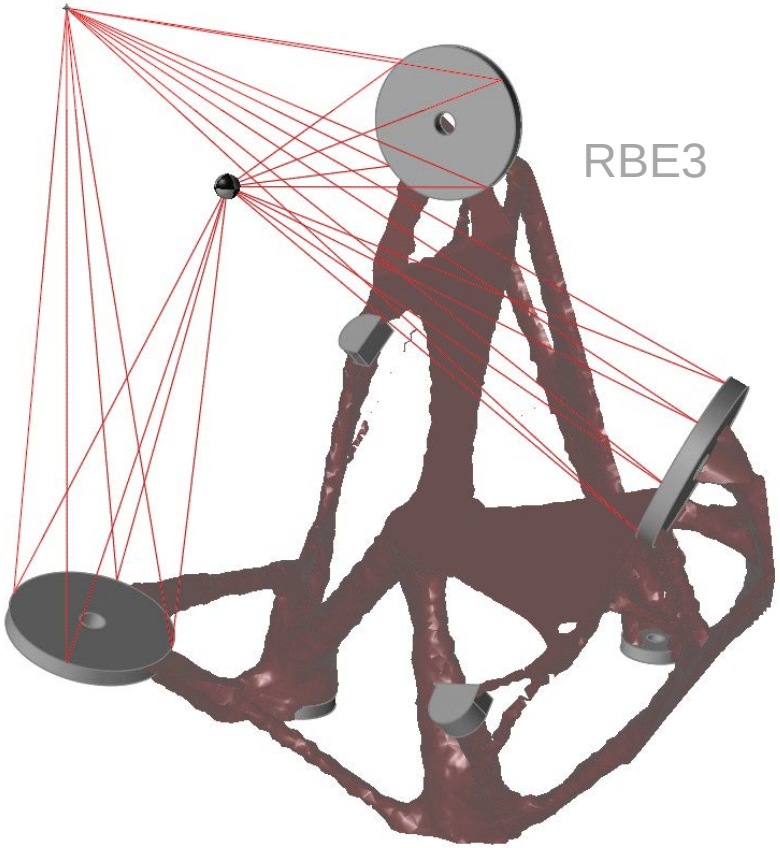
Yield stress: 965 MPa

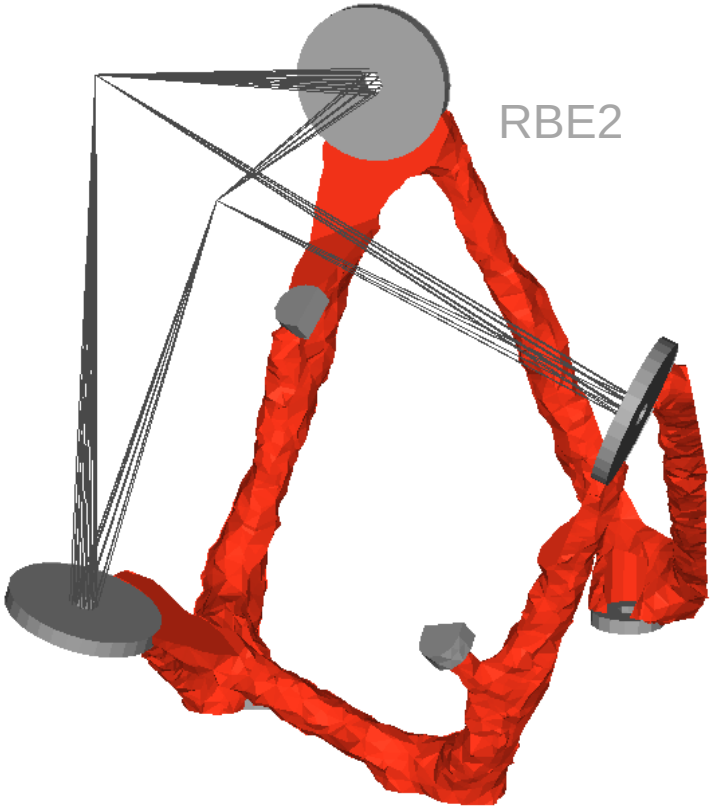


The optimized structure is similar to the original with one main exception



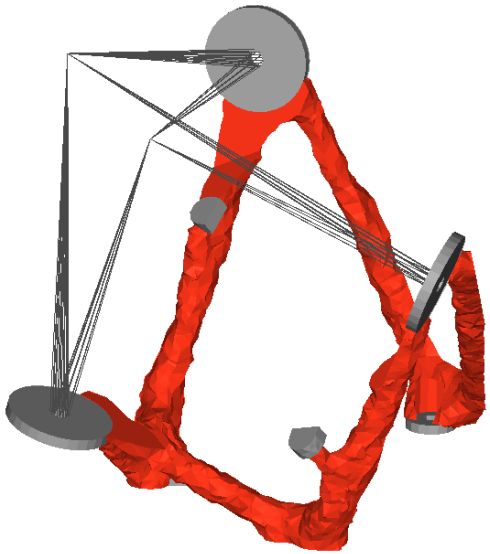
Switching from RBE2s to RBE3s has a significant effect on the design





Topology optimization

A shift towards computational design



Background

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Which to use

Case study

Designing a bracket for MSL

Topology optimization will not supplant designers in the immediate future

Restricted response functions

Ex: stress constraints, buckling, dynamics

Uncertainty quantification and robustness

Ex: loading eccentricities

Problem formulation and computation time

Big problems require big computing

Organic designs and manufacturing

Need for additive manufacturing capabilities

There are some niche areas for topology optimization

Bracket design

Ex: optics

Design inspiration

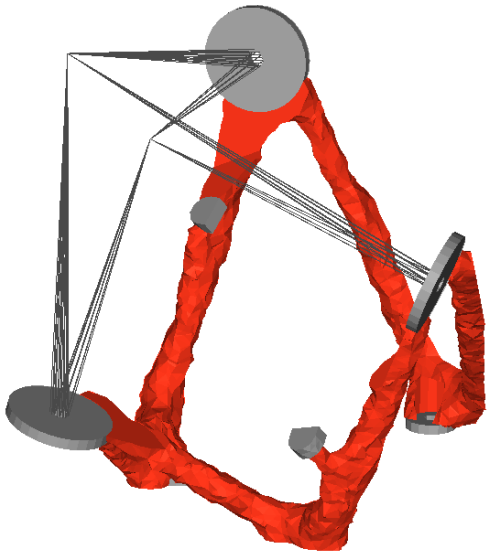
Fixing a “broken” design

Improving an existing design

Ex: slimming down on mass

Topology optimization

A shift towards computational design



Ryan Watkins
ryan.t.watkins@jpl.nasa.gov

Software comparison

Wired article

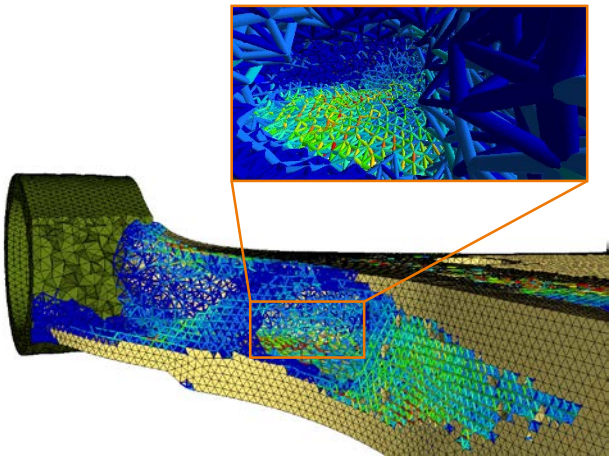
MSL case study

Wired article to come

There are new functionalities on the horizon

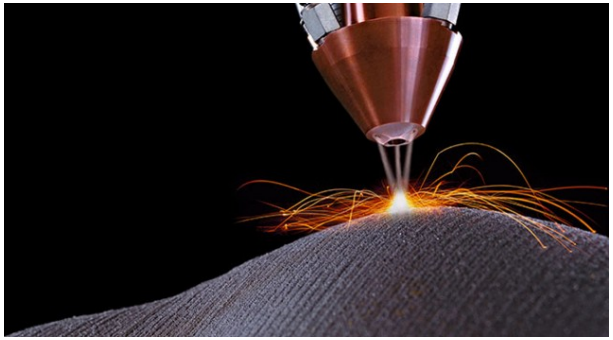
Cellular meso-structure

Designing sparse structures



Additive manufacturing

Printing with metals



Licensing works differently for each software package

Institutional (JPL)

Licensing and availability

Functionality

Response functions, manufacturing constraints

Speed

Finite element method and optimizer

Usability

Ease of setting up a design problem

To compare functionality, speed and usability, I looked at a case study

Institutional (JPL)

Licensing and availability

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A software functionalities were compared side-by-side

Institutional

Licensing and availability through MCAE

Functionality

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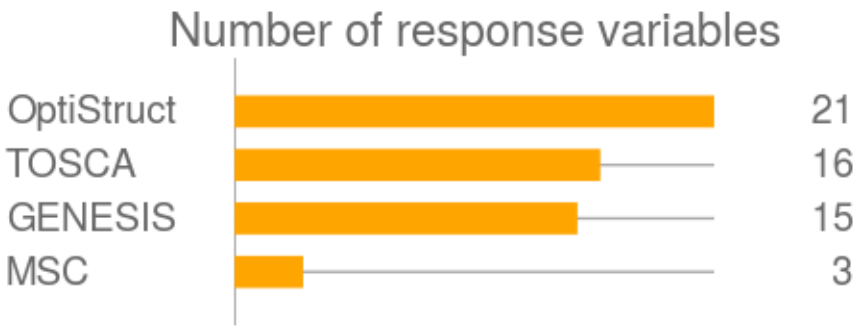
OptiStruct has the greatest variety of response variables

Response variable: quantifiable output that can be used as an objective or constraint

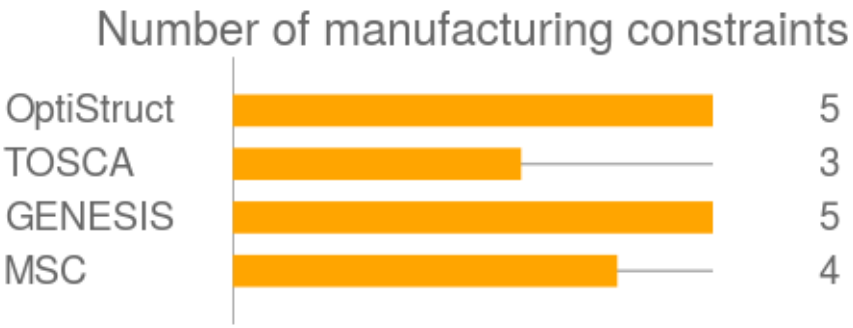
Examples: mass, displacement, stress, …



OptiStruct and GENESIS have the most manufacturing constraints

Manufacturing constraint: imposes constraints on the design to allow for manufacturability

Examples: extrusion, casting, symmetry, …



To get a better sense of optimizer speed and usability, I looked at a case study

Institutional

Licensing and availability through MCAE

Functionality

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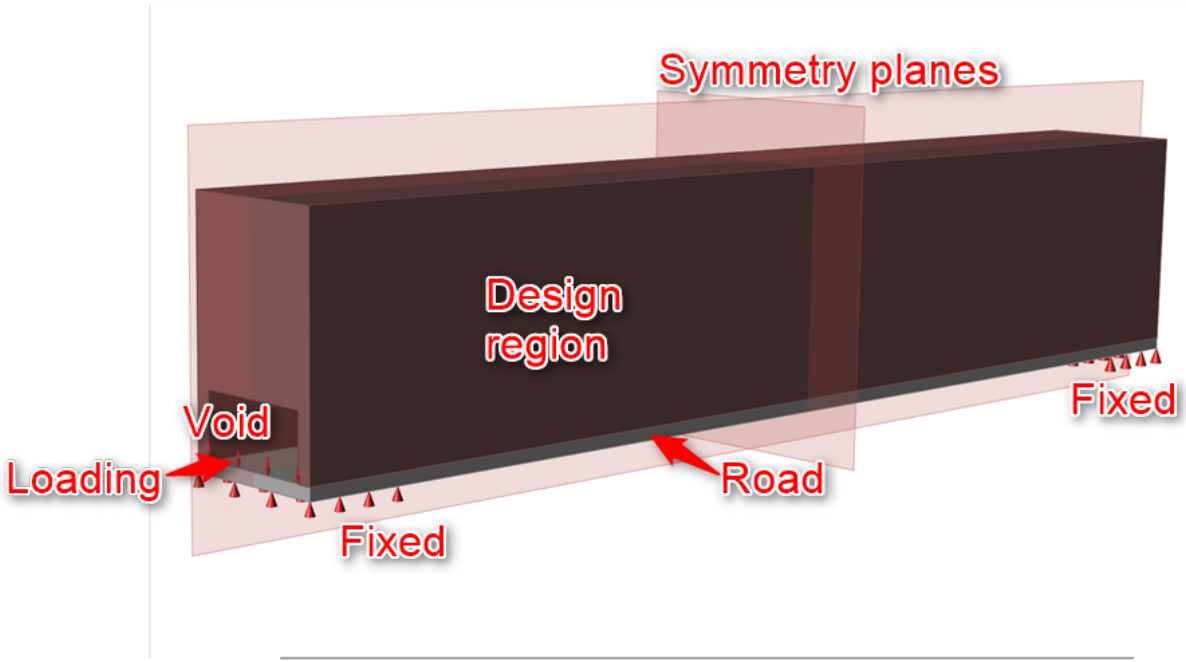
The case study looked at the optimization of a bridge design

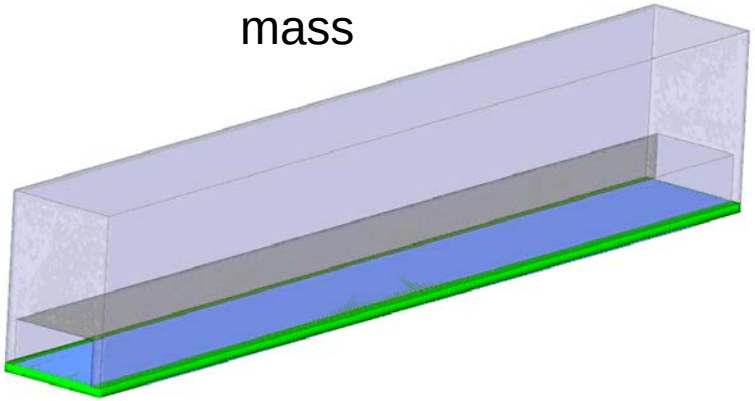


Case	Objective	Constraint
1	Minimize mass	Yield stress
2	Maximize stiffness	Maximum volume

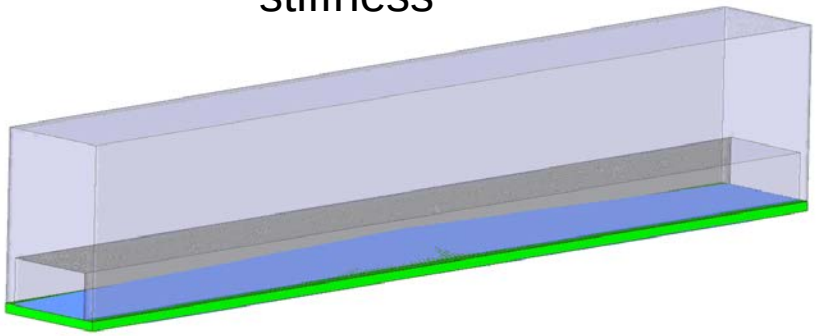
All of the optimizers produced truss-like geometries

GENSIS results

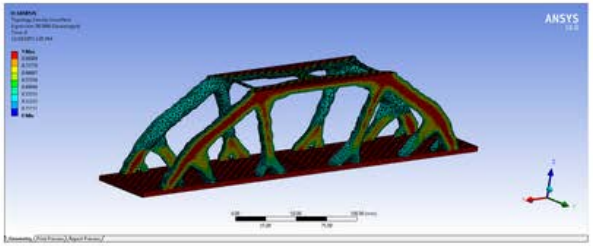
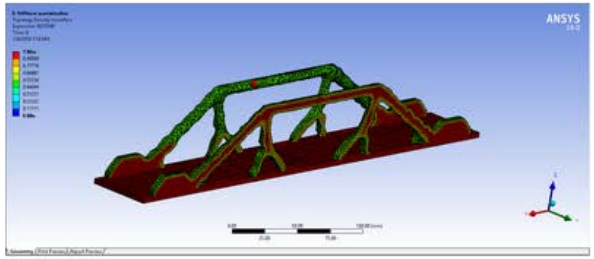
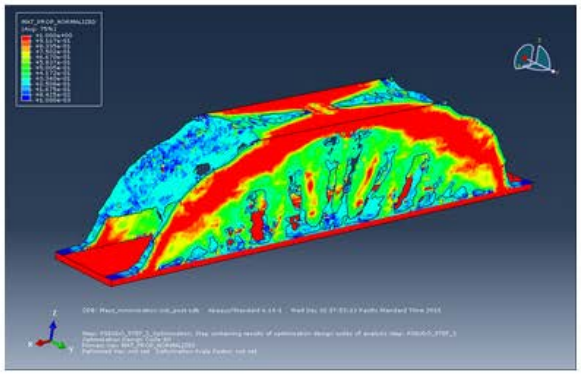
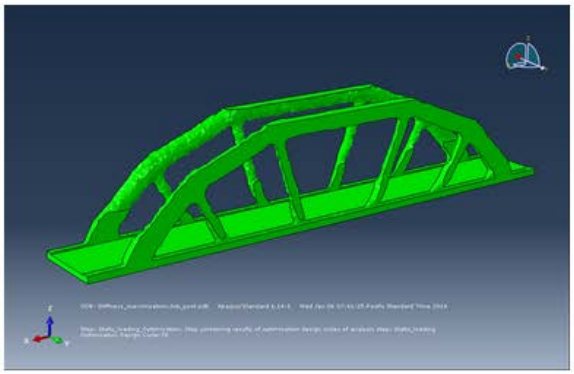
Minimize mass



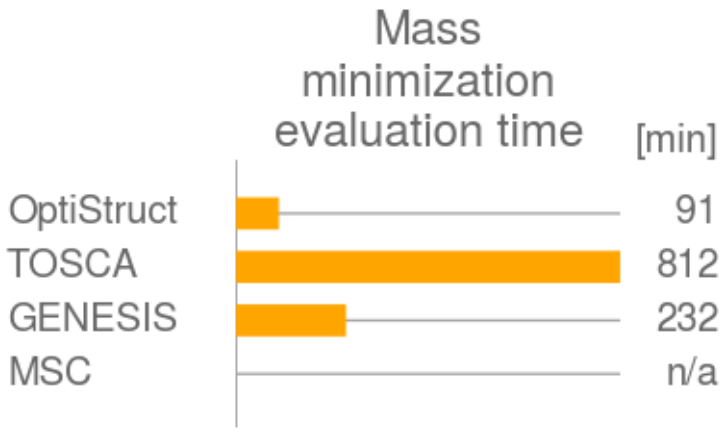
Maximize stiffness

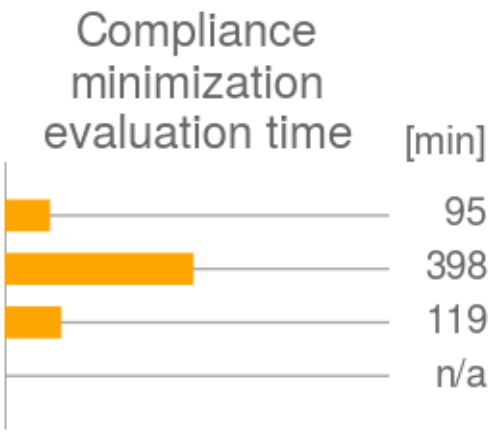


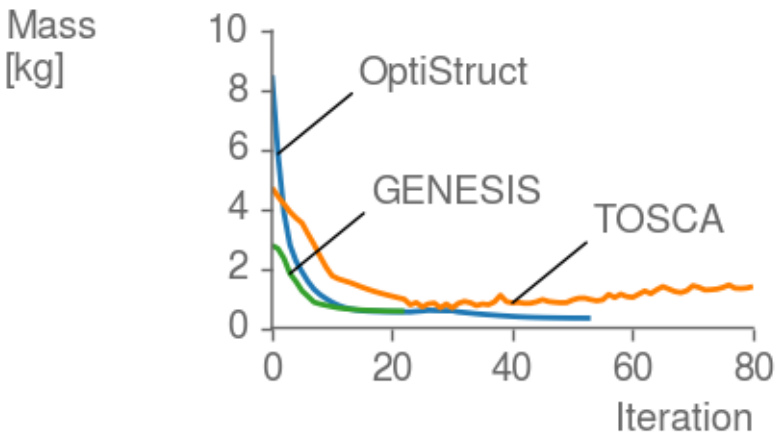
Comparing between the different optimizers, you get different results

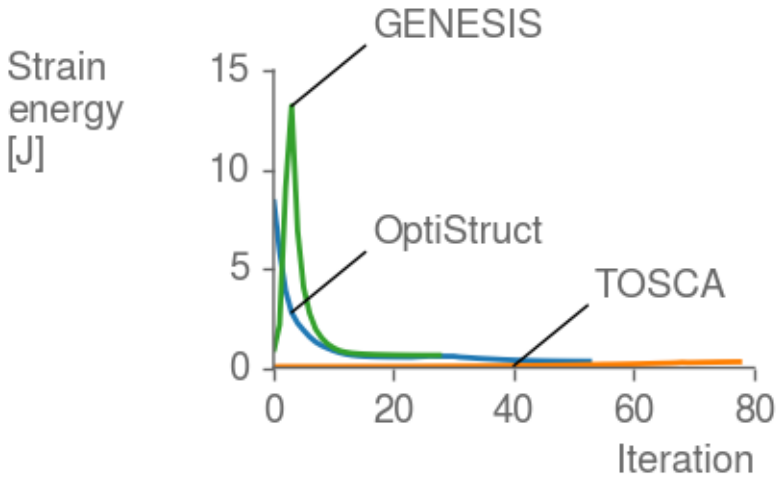
	Mass minimization	Compliance minimization
OptiStruct		
GENESIS		
TOSCA		

OptiStruct was the fastest and most efficient optimizer





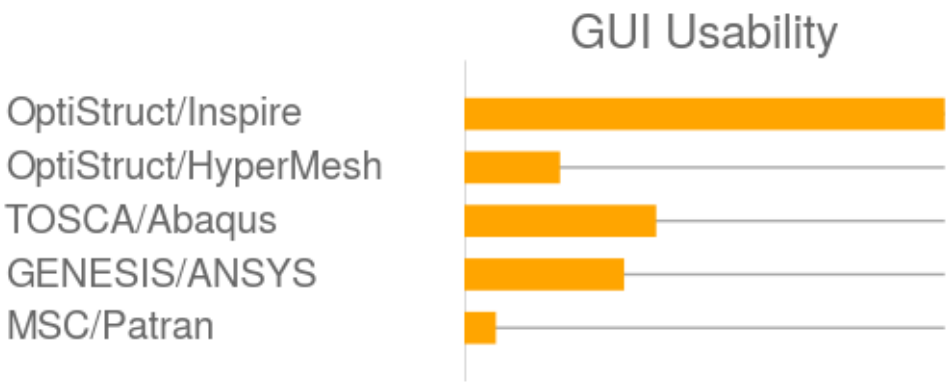




The OptiStruct/Inspire GUI interface was the easiest and fastest to use

Usability: integration with GUI interface

Examples: ease of problem setup,
time to setup problem

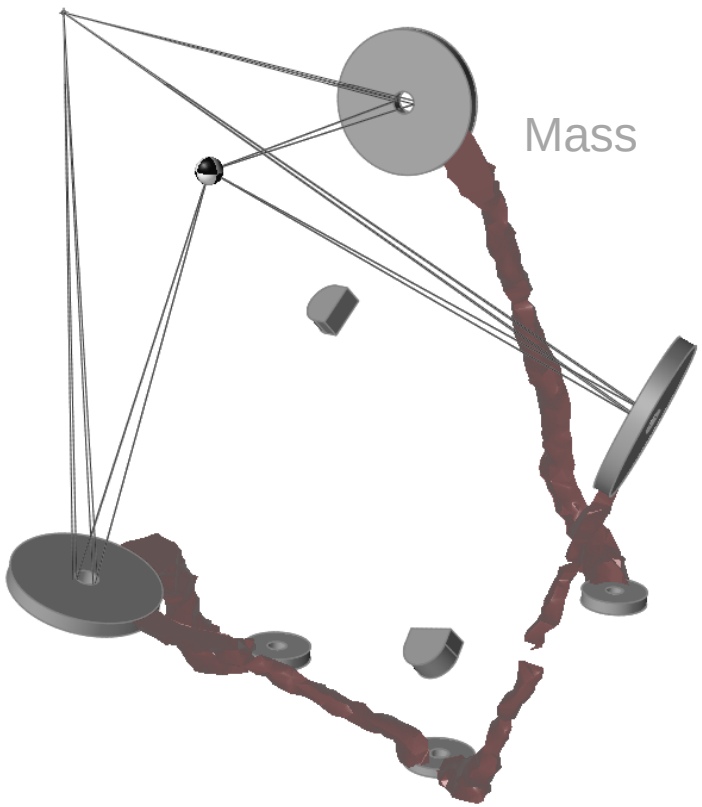


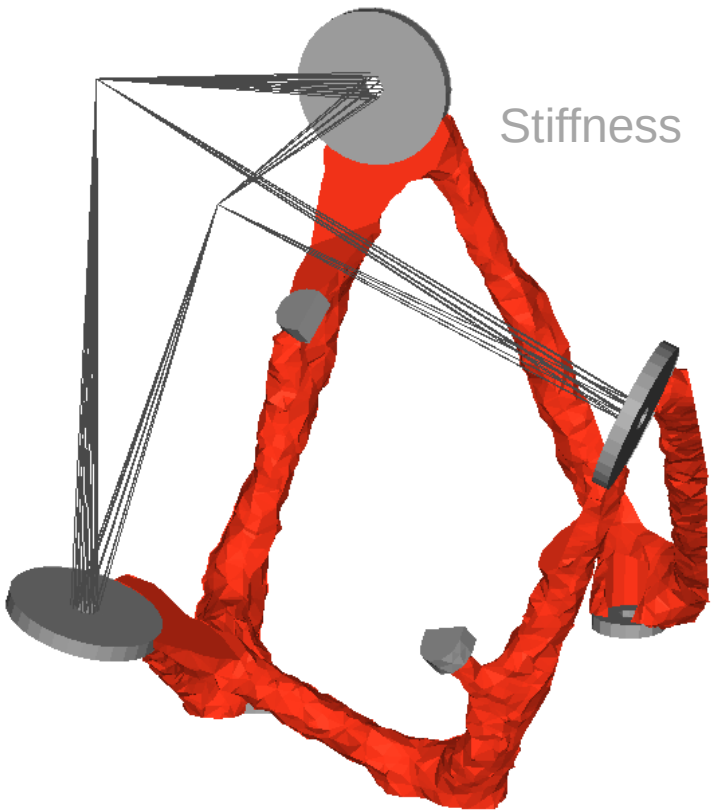
Tools that transition from an optimized result to an actual design are limited

OptiStruct/Inspire

Fit NURBS surfaces

An equivalent mass minimization fails to converge due to sensitivity issues

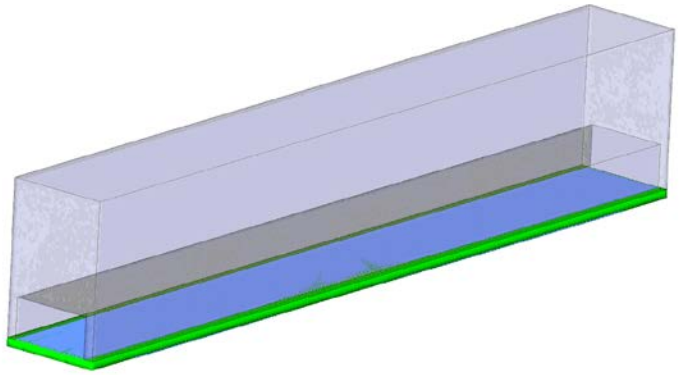




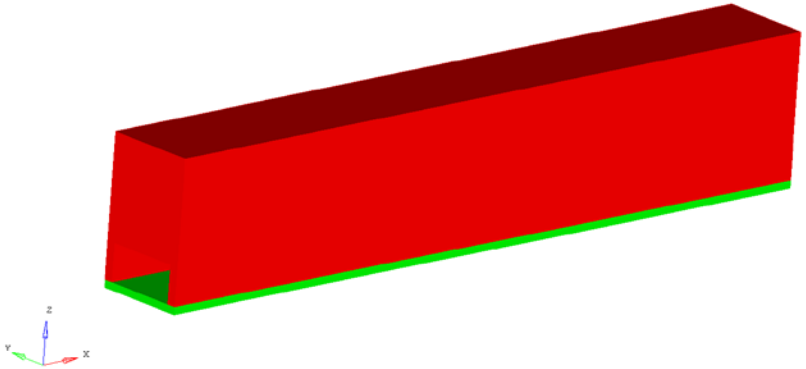
GENESIS

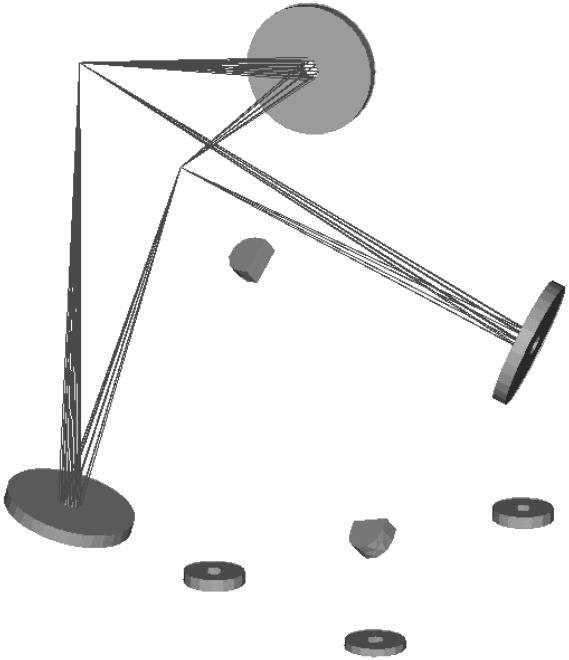
TOPOLOGY DESIGN ELEMENT DENSITY, DESIGN CYCLE NUMBER = 0
Isosurface enclosing 0% of topology region

Model info: 1
Result: C:/Users/rwatkin/Documents/TopologyOptimization/Bridge/HyperMesh/Bridge6_des.h3d
Design : Iteration 0
Frame 1

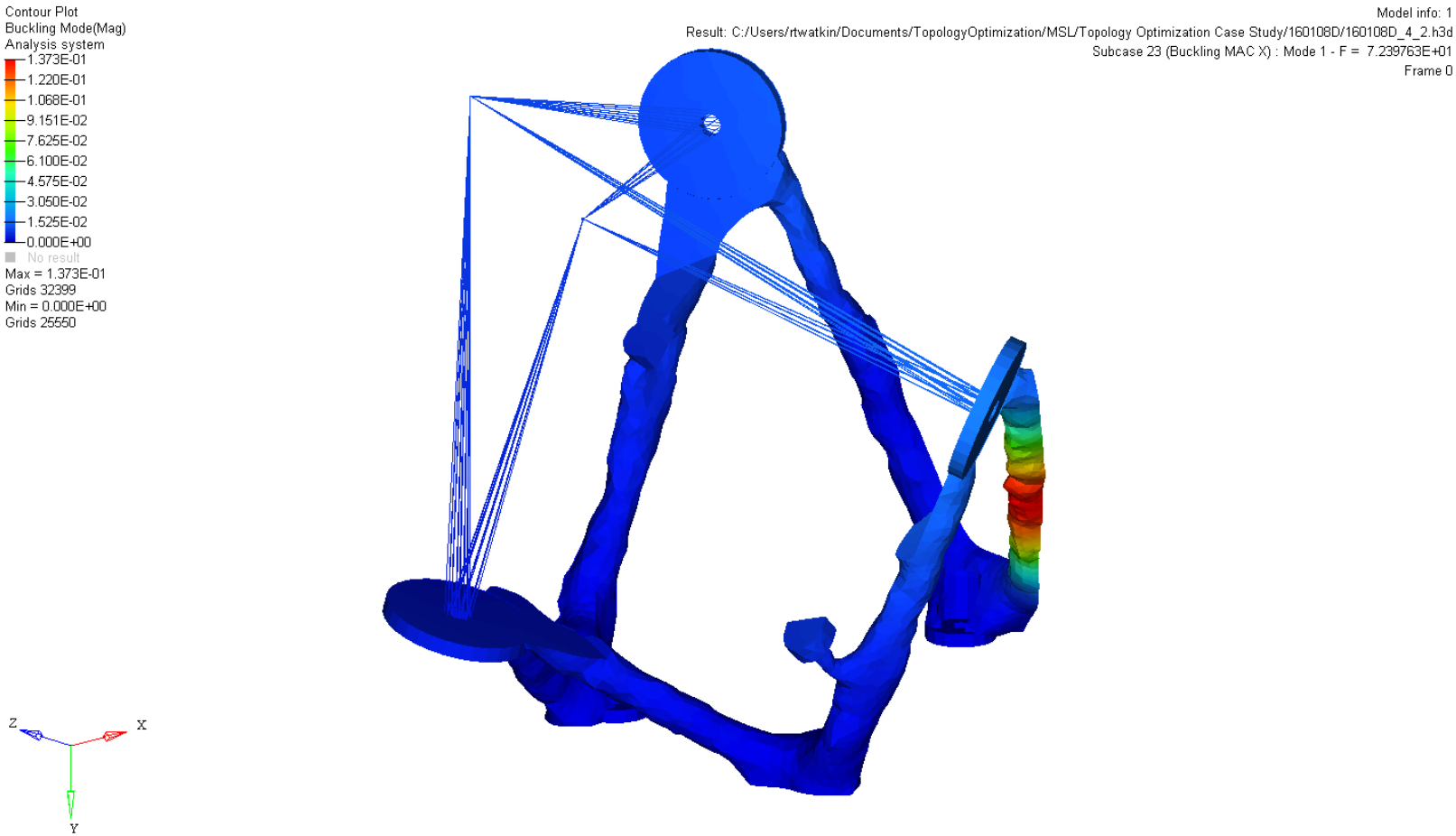


1 / 23

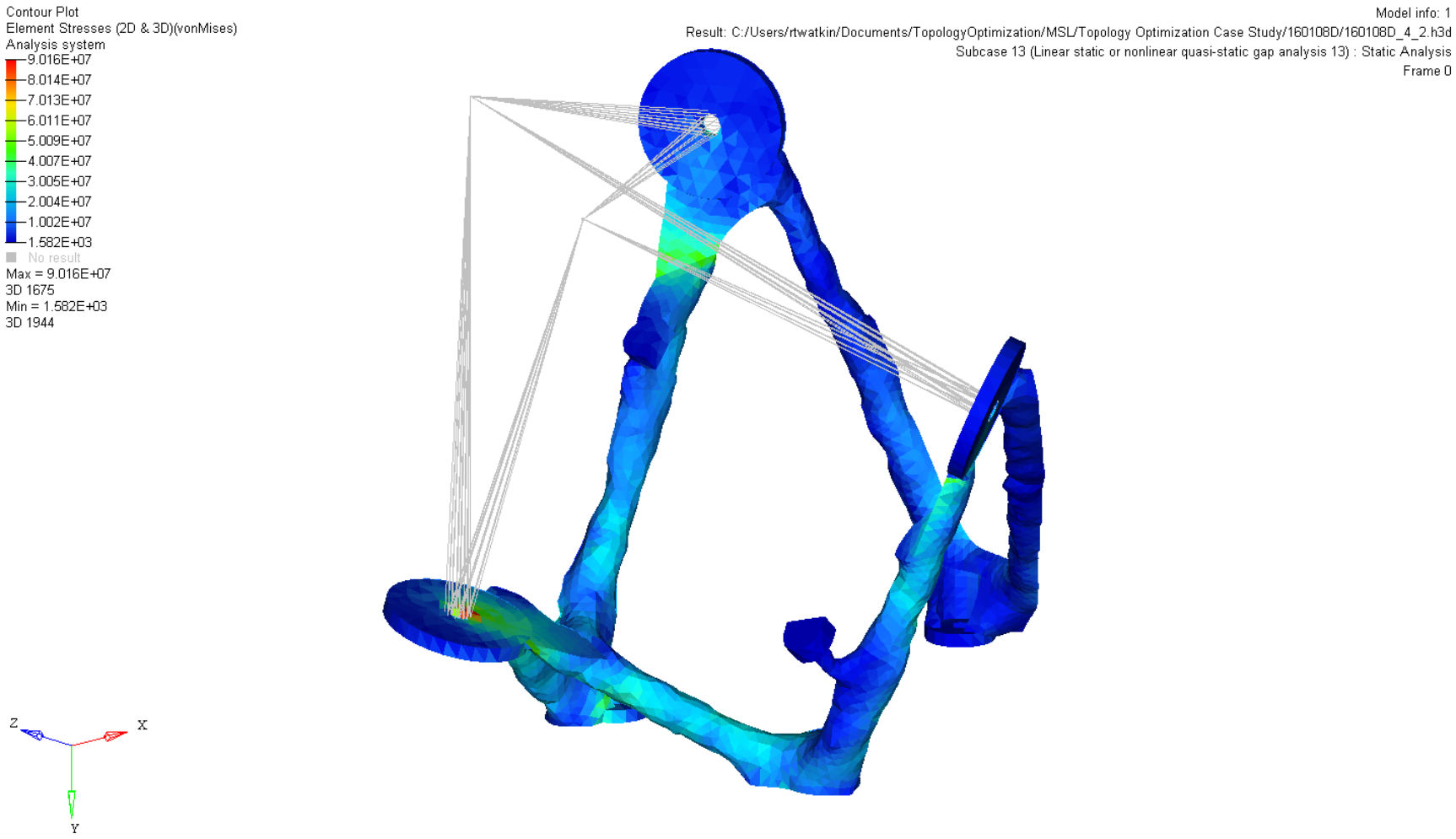
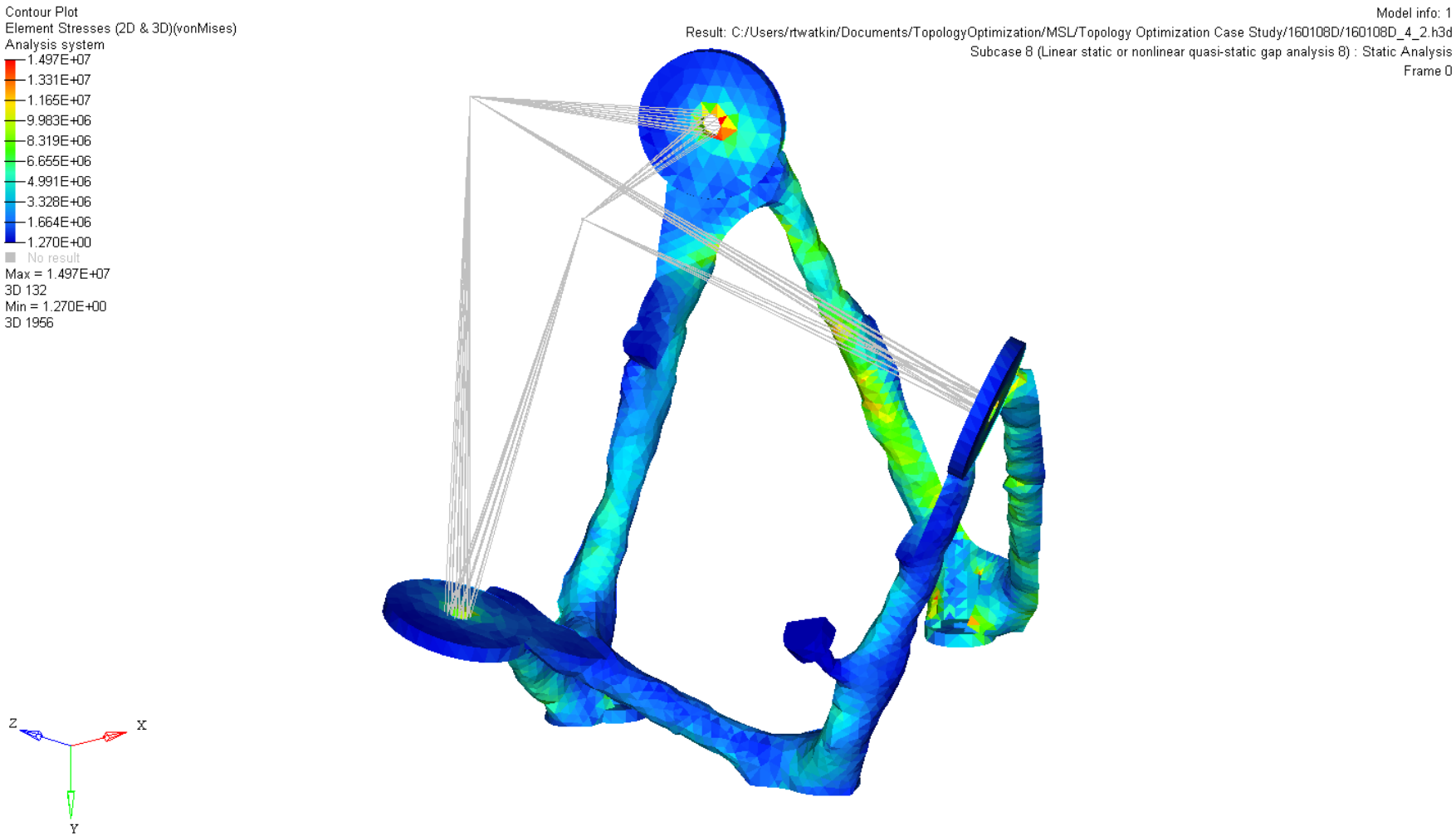




MSL case study: worst case buckling



MSL case study: worst case MAC



MSL case study: worst case tip loading