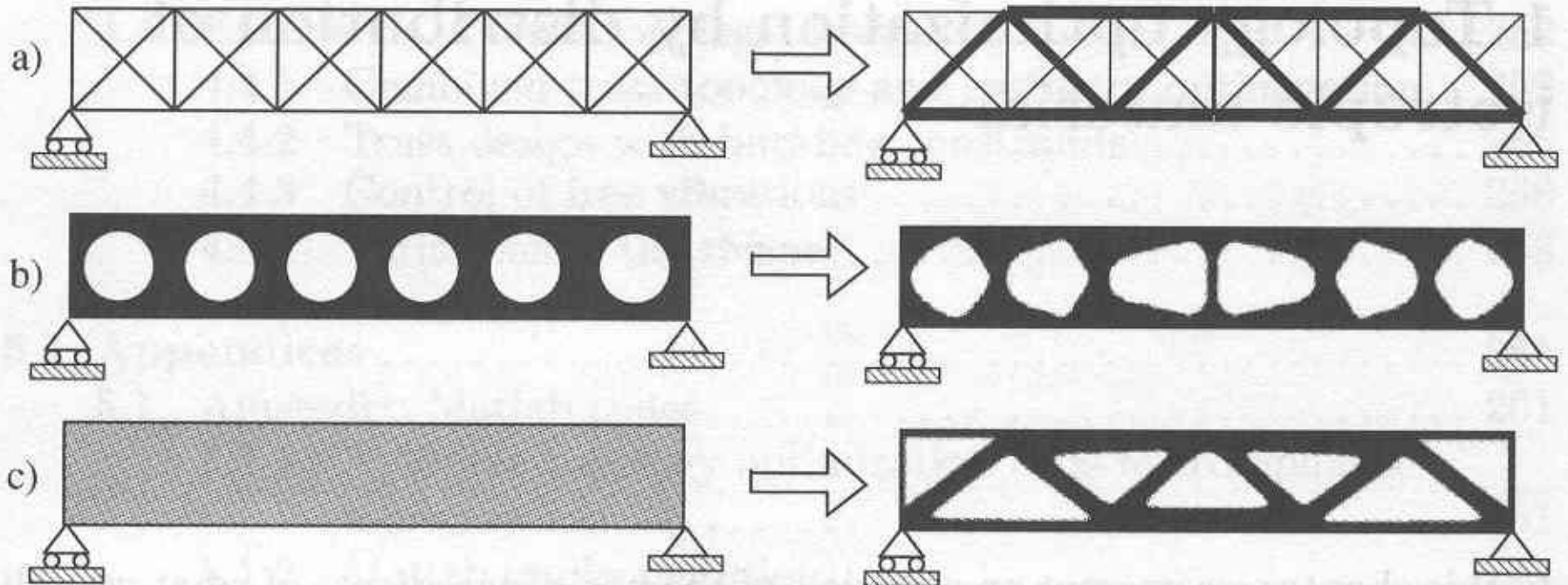
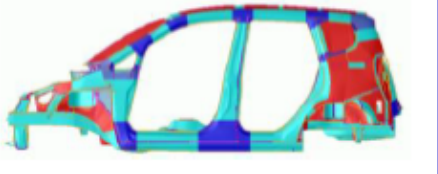

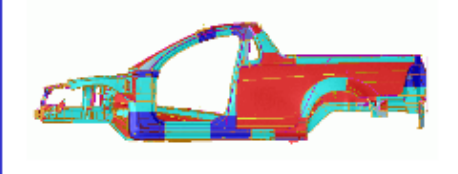
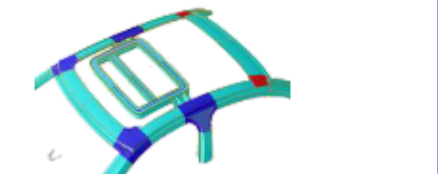
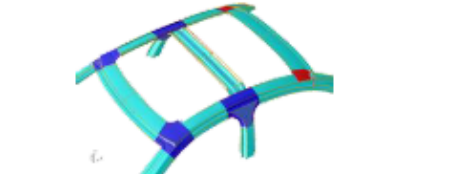
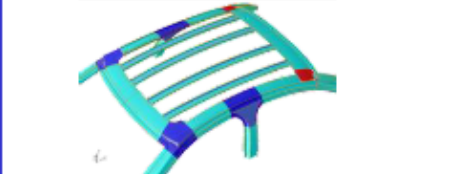
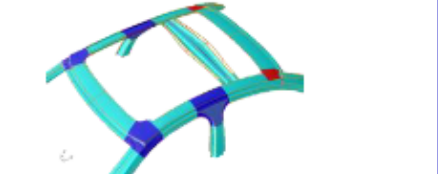
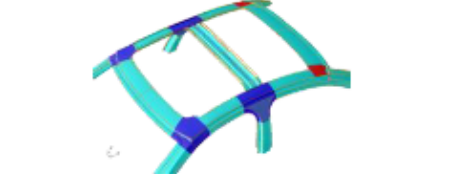
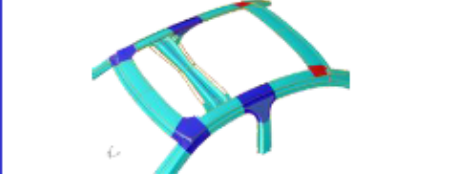

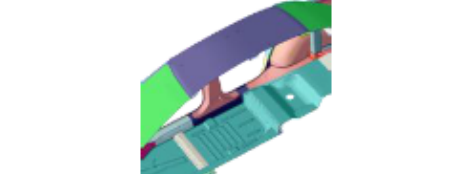
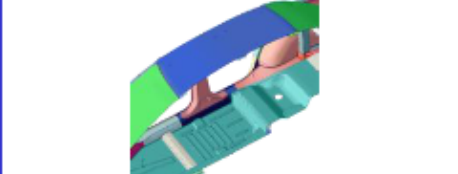


Categories of Structural Optimization

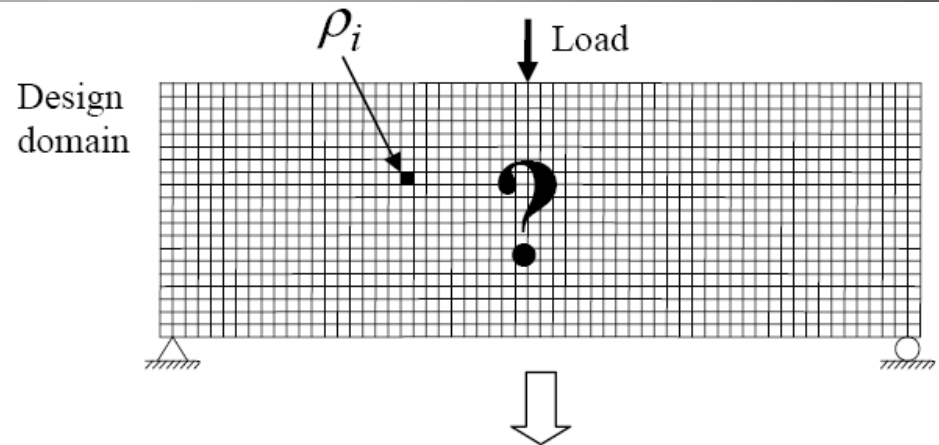
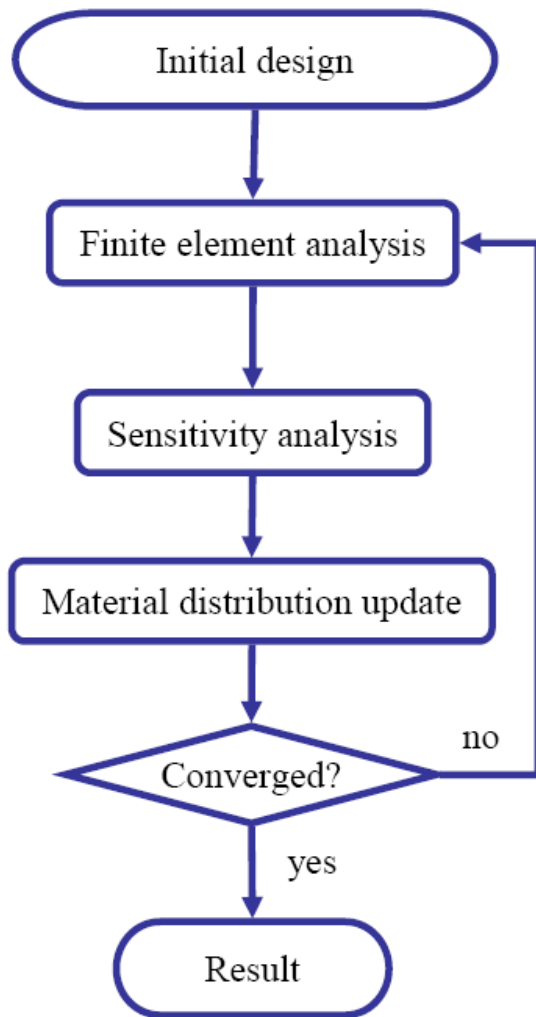


M.P.Bendsoe and O. Sigmund, Topology Optimization: Theory, Methods and Applications, Springer, 2003

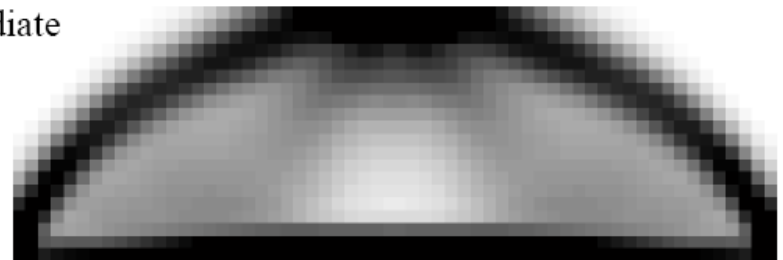
Shape and Topology Optimization for Crash

Concept			
Material	Steel	Aluminium	Composites
Topology			
Shape			
Size (thickness)			

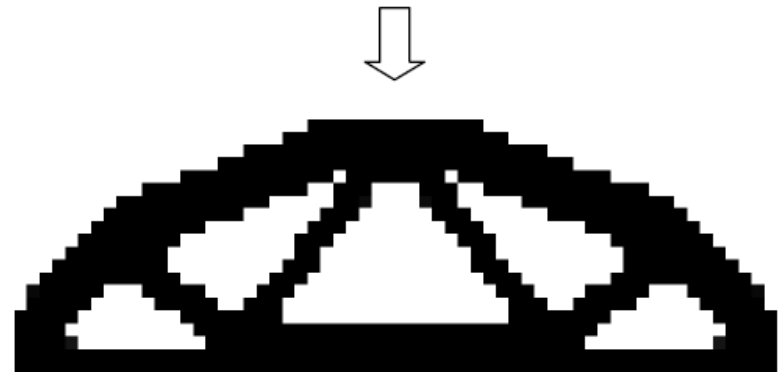
Topology Optimization Process



Intermediate result

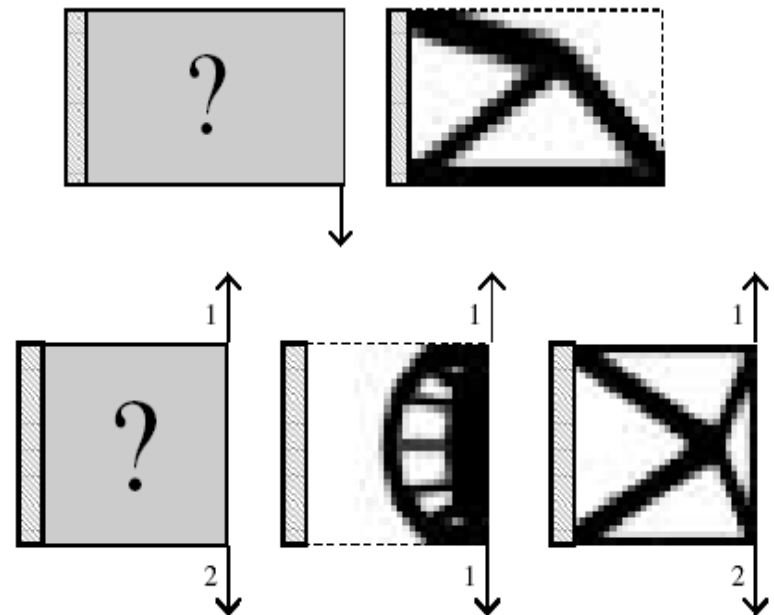
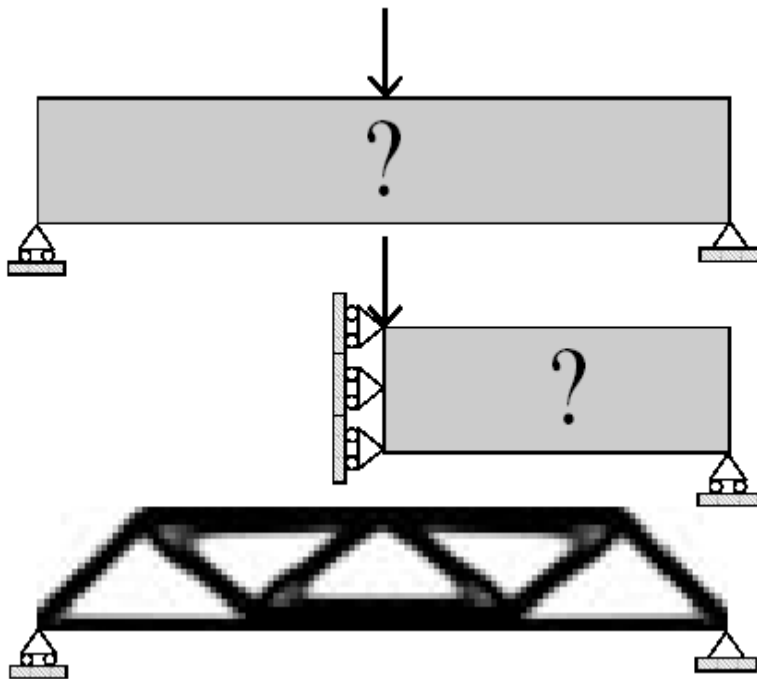


Final result



Educational Design Tool (1)

- TOPOPT (www.topopt.dtu.dk)
 - O. Sigmund, A 99 line topology optimization code written in Matlab, Struct Multidisc Optim 21, pp.120-127, 2001
 - D. Techerniak and O. Sigmund, A web-based topology optimization program, Struct Multidisc Optim 22, pp.179-187, 2001



Educational Design Tool (2)

The screenshot displays the 'Educational Design Tool' interface within a Netscape browser window. The main window is titled 'Try your own design!' and contains a design problem setup. It features a toolbar with various icons for design manipulation, a central design area showing a rectangular plate with a central square void and two upward-pointing arrows indicating loads, and a sidebar with controls for material properties and volume fraction. Three smaller windows, labeled 'Result 9', 'Result 10', and 'Result 12', are overlaid on the main window, each showing a different optimized design. Each result window displays a 'Densities' plot, a 'Show:' dropdown menu, and an 'Objective' value. The results are as follows:

Result	Status	Objective
Result 9	Stopped	28.21
Result 10	Finished	39.81
Result 12	Finished	66.74

The designs shown in the result windows are: Result 9 shows a simple truss structure; Result 10 shows a truss structure with a central cross-brace; Result 12 shows a truss structure with a central cross-brace and a central square void. The text 'Single loading' is positioned to the right of Result 9, and 'Multiple loading' is positioned to the right of Result 10. The text 'Multiple loading with void area' is positioned below Result 12.

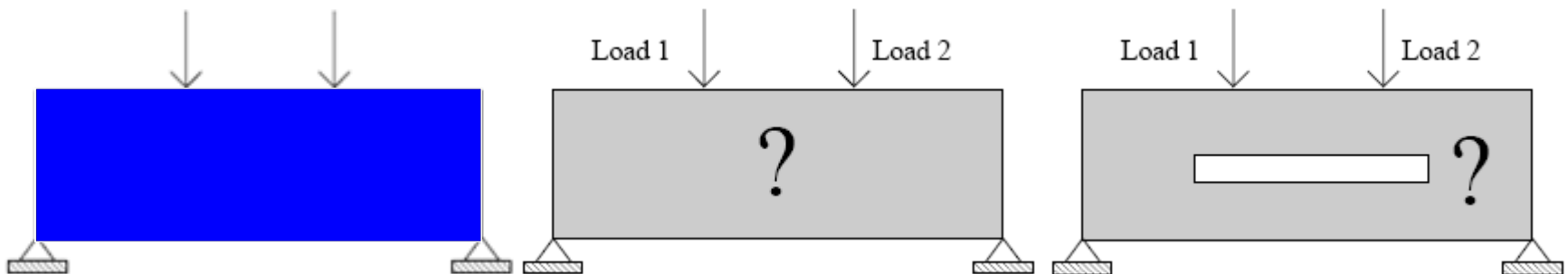
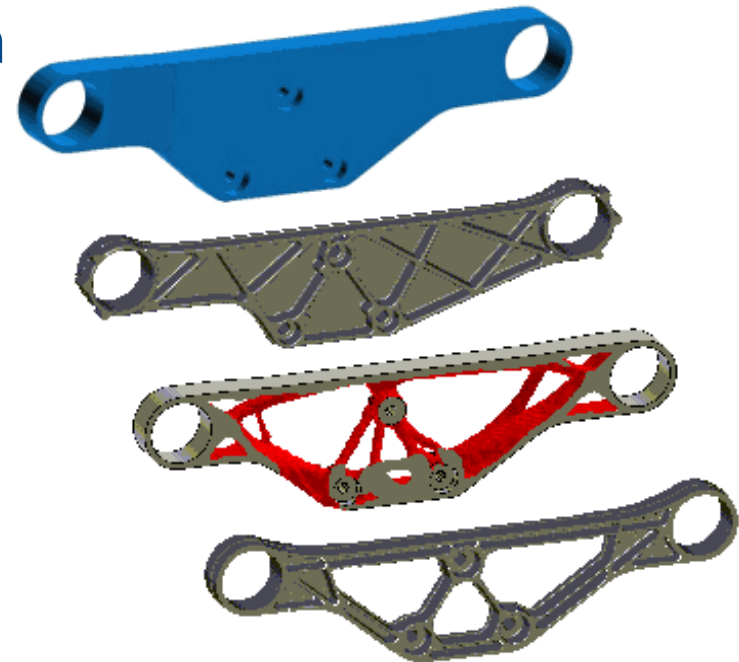
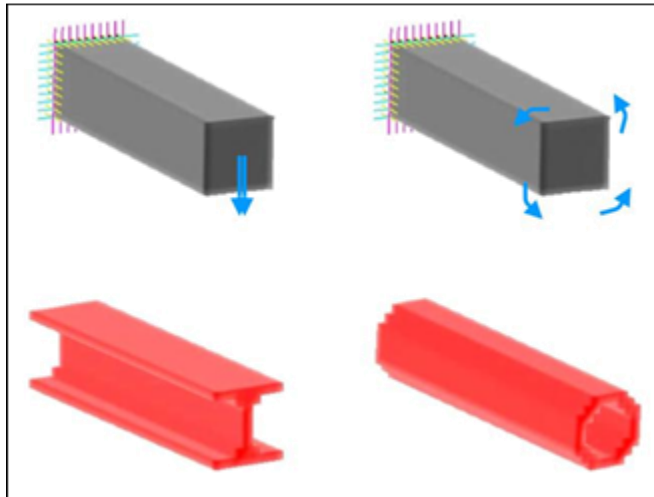
Single loading

Multiple loading

Multiple loading with void area

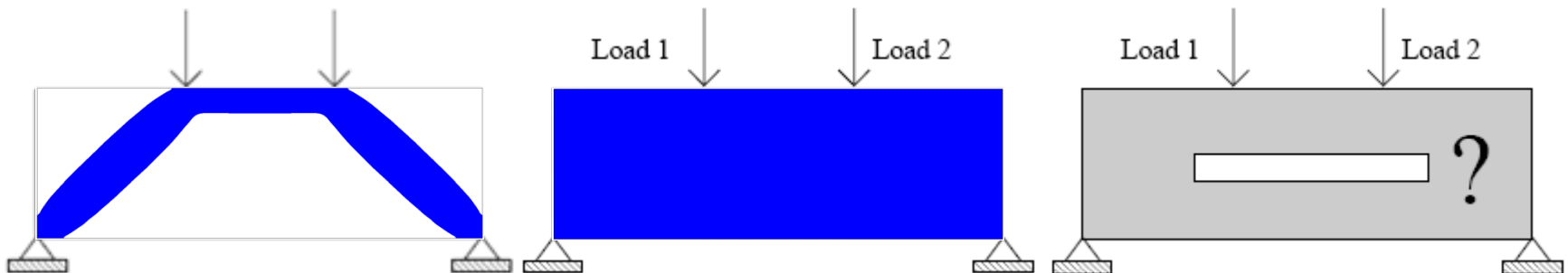
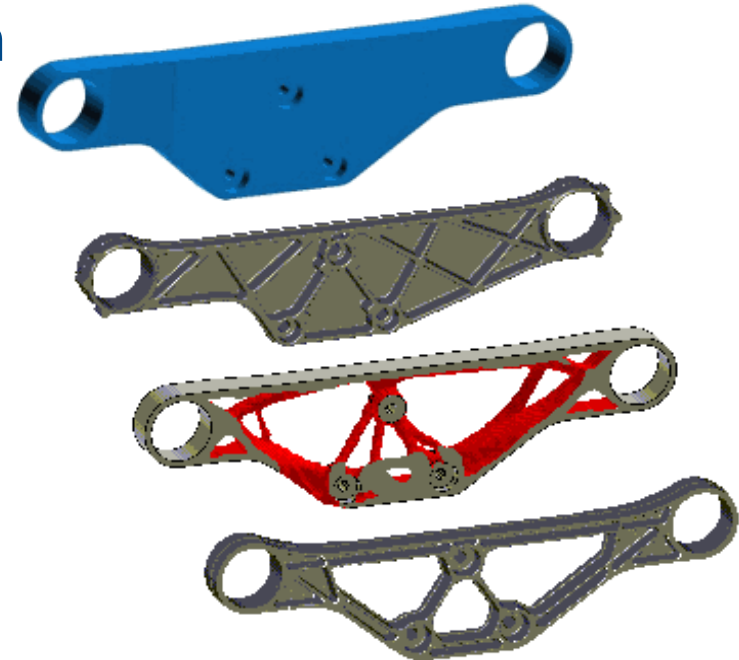
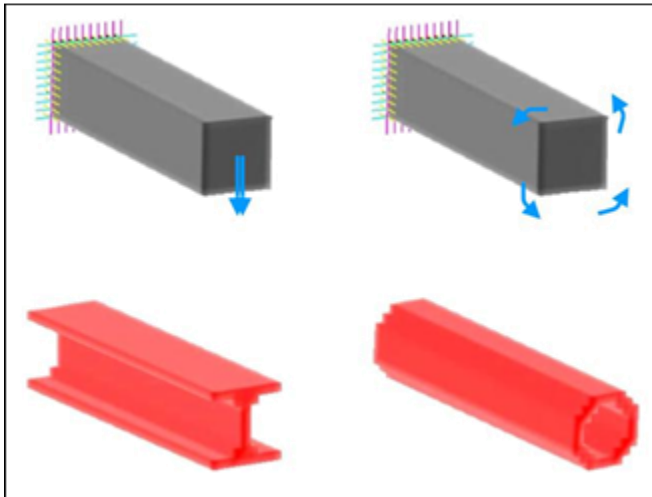
Linear Static Problem (1)

■ Solid Mechanics: Load Path



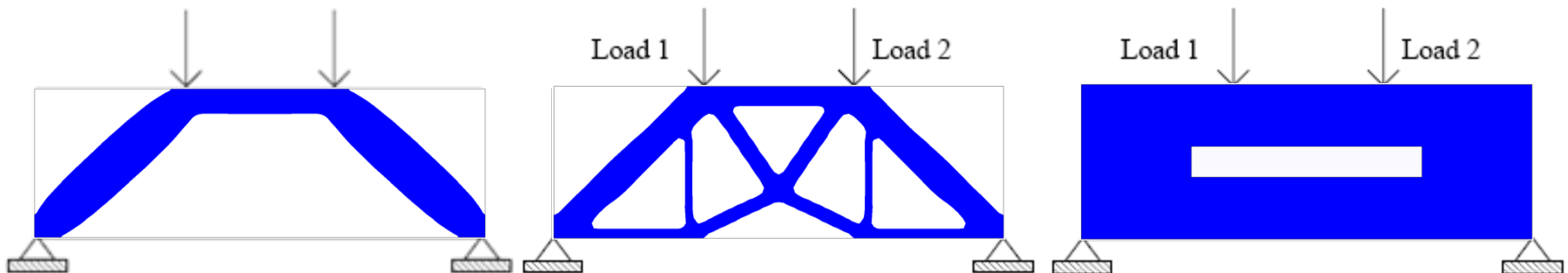
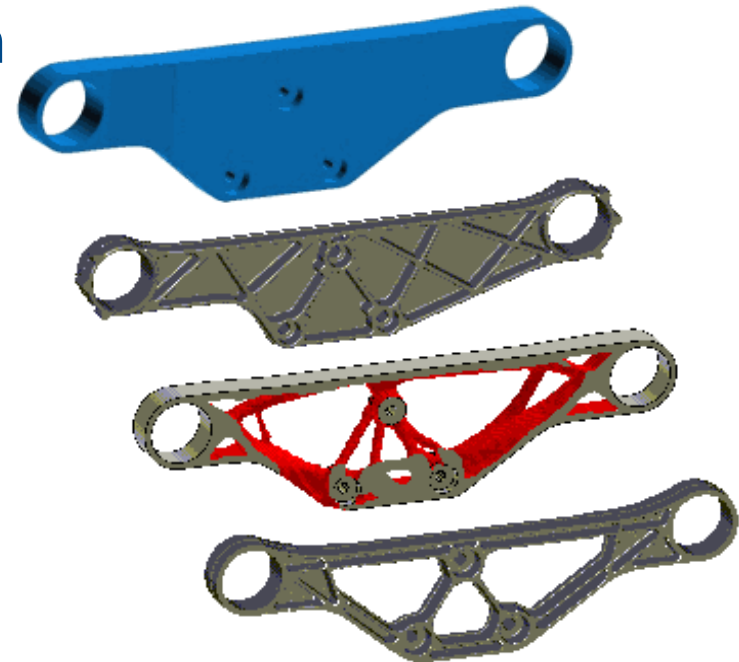
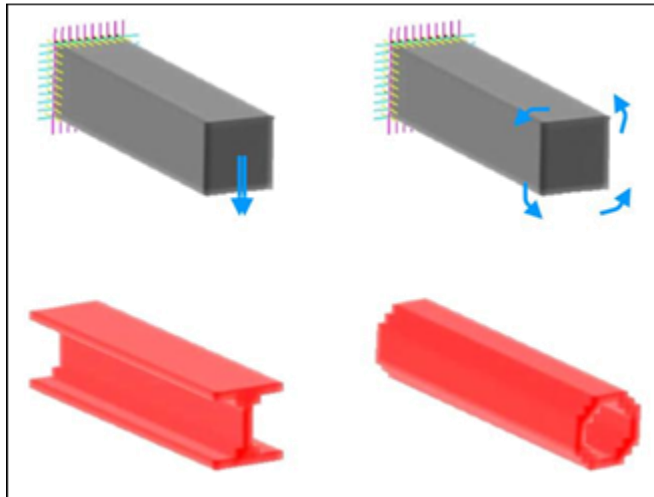
Linear Static Problem (2)

■ Solid Mechanics: Load Path



Linear Static Problem (3)

■ Solid Mechanics: Load Path

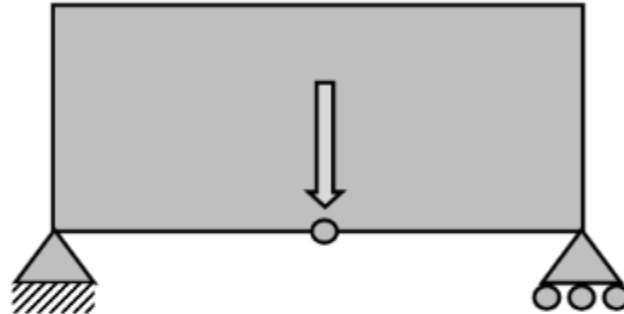


Test Your Intuition

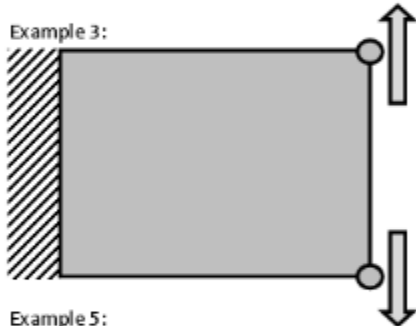
Example 1:



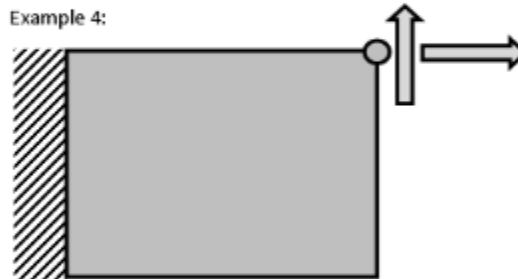
Example 2:



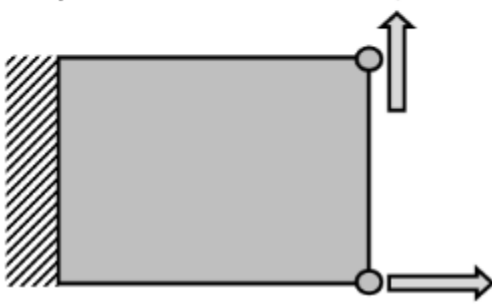
Example 3:



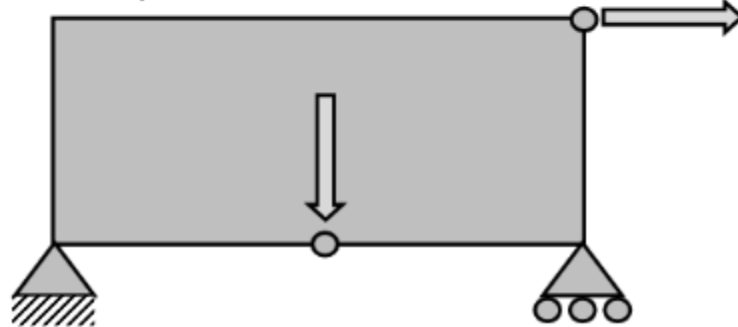
Example 4:





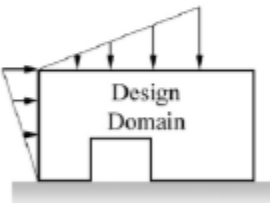
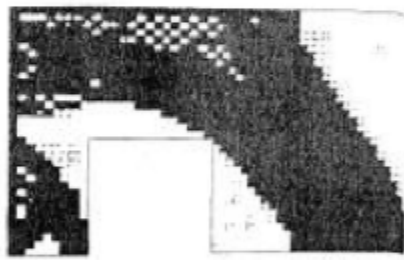
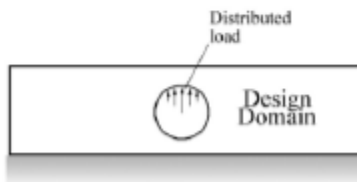



Example 5:



Comparison Bracket:



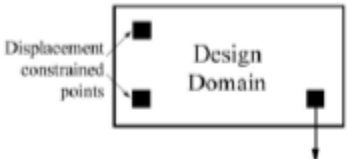



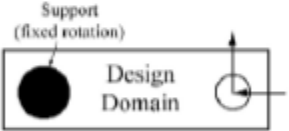



1		
2		
3		
4		

Bendsøe and Rodrigues (1991)

Bendsøe and Rodrigues (1991)

Bendsøe and Rodrigues (1991)

Olhoff *et al.* (1991)


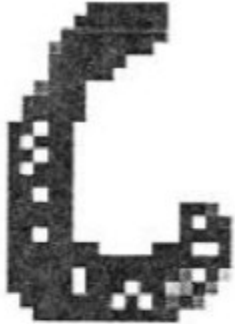
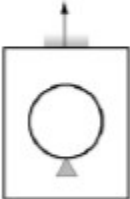
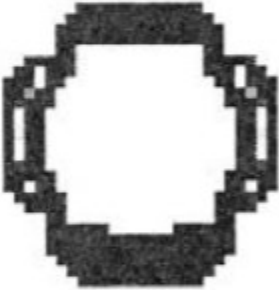

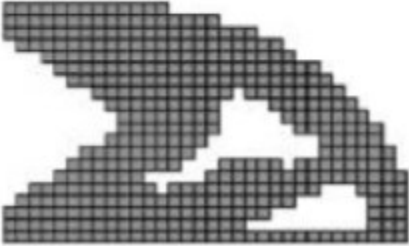
5		
6		
7		
8		

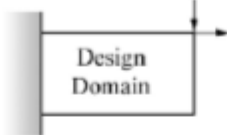


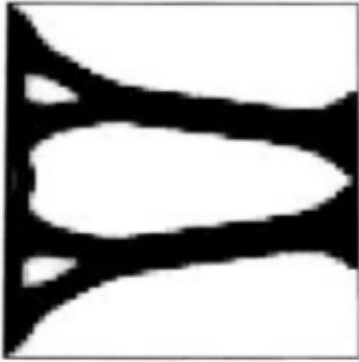
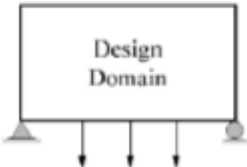

Bremicker *et al.* (1991)

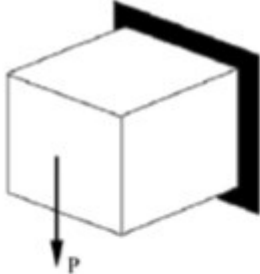
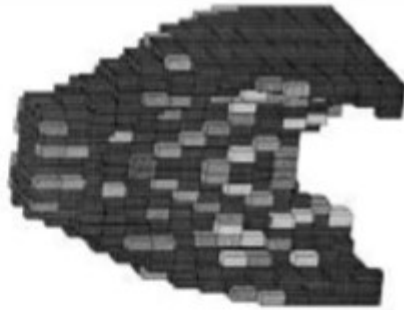
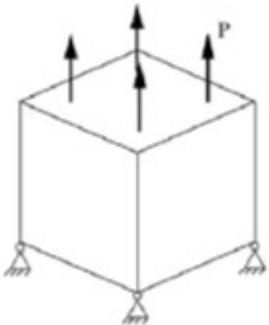

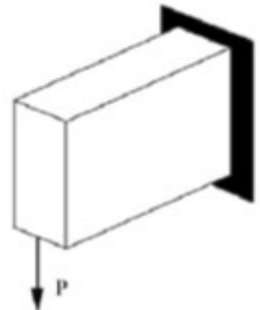
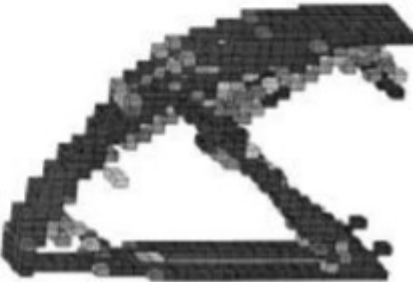
Bremicker *et al.* (1991)

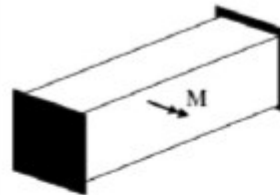
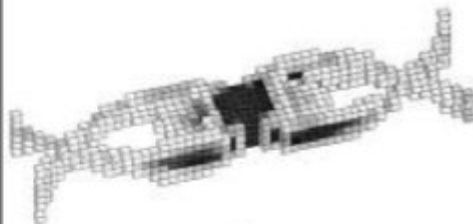

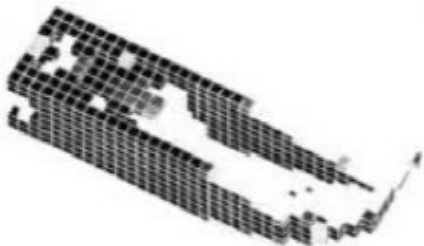
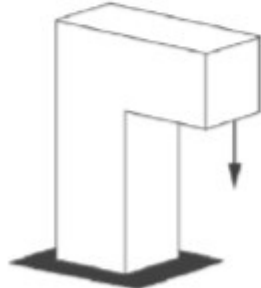

Bremicker *et al.* (1991)

Chirehdast *et al.* (1994)

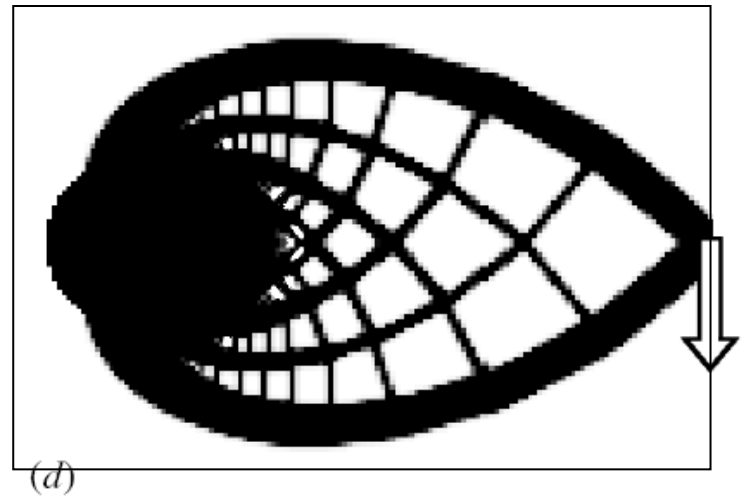
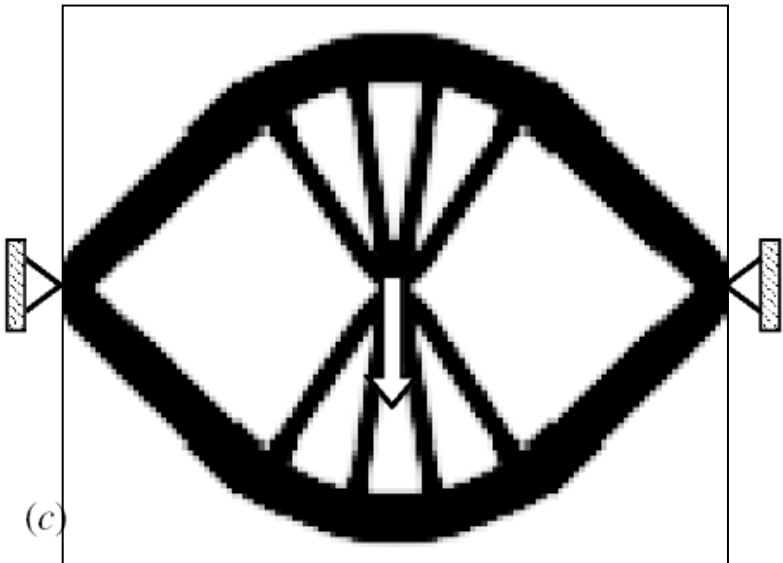
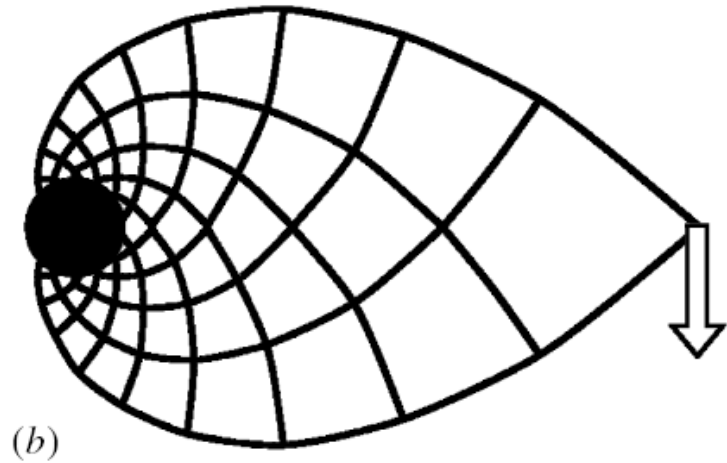
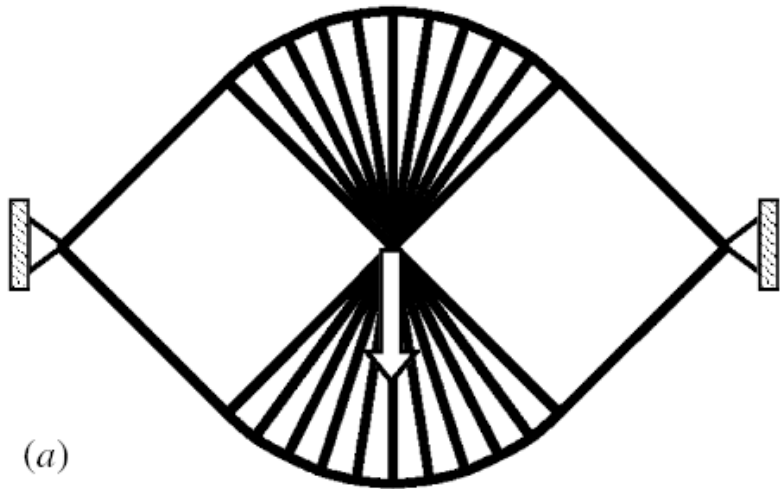
9		 <p>Chirehdast <i>et al.</i> (1994)</p>
10		 <p>Chirehdast <i>et al.</i> (1994)</p>
11		 <p>Tang and Chang (2001)</p>

12		 <p>Youn and Park (1997)</p>
13		 <p>Youn and Park (1997)</p>
14		 <p>Youn and Park (1997)</p>

1		 <p>Olhoff <i>et al.</i> (1998), Jacobsen <i>et al.</i> (1998), Beckers (1999)</p>
2		 <p>Olhoff <i>et al.</i> (1998), Jacobsen <i>et al.</i> (1998)</p>
3		 <p>Olhoff <i>et al.</i> (1998), Jacobsen <i>et al.</i> (1998)</p>

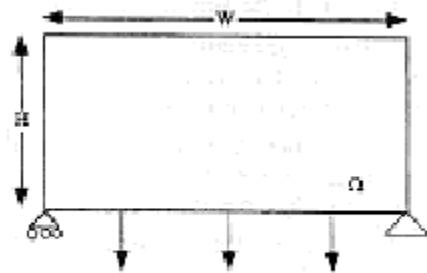
4		 <p>Olhoff <i>et al.</i> (1998), Jacobsen <i>et al.</i> (1998), Beckers (1999)</p>
5		 <p>Díaz and Lipton (1997)</p>
6		 <p>Díaz and Lipton (1997)</p>

Optimal Michell Type Structures



Design Tool

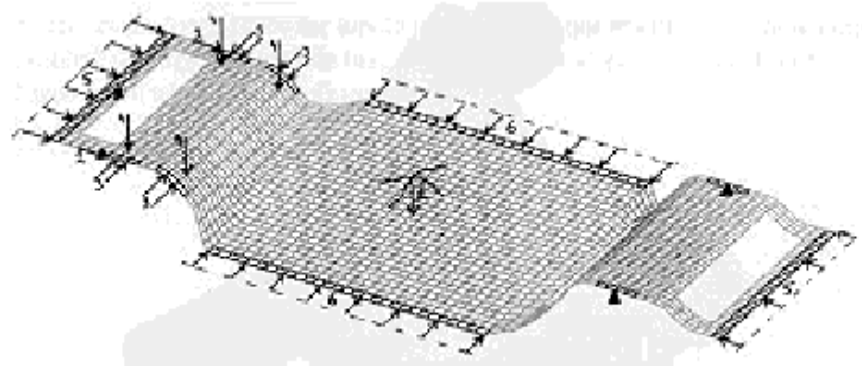
Conceptual Design



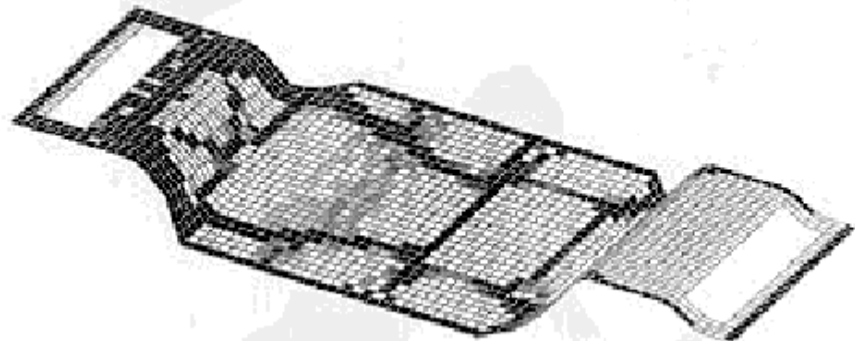
bridge design



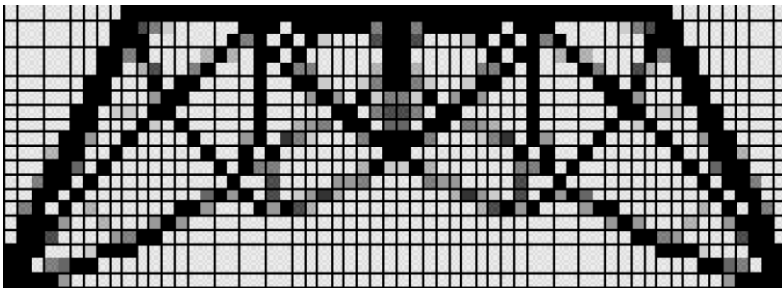
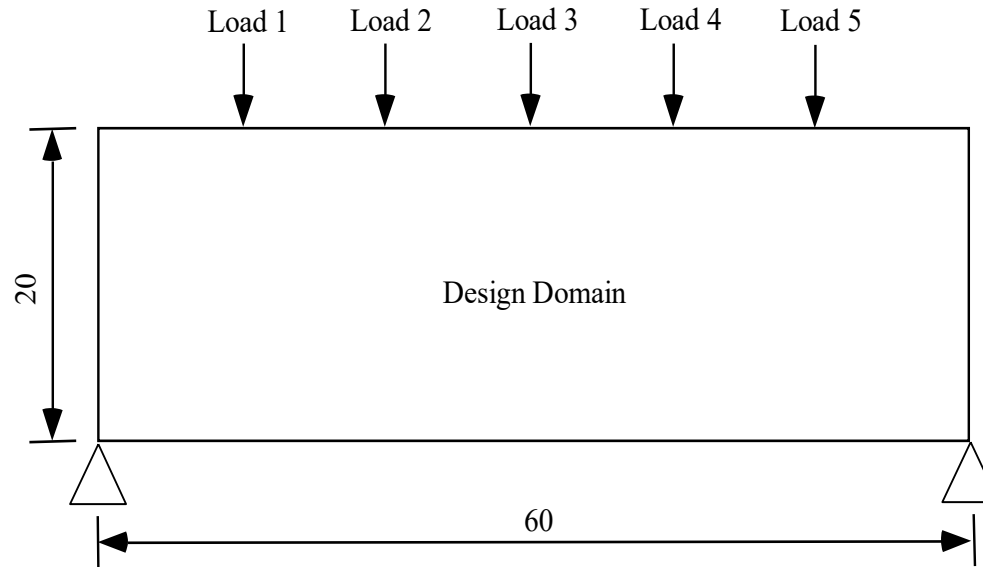
Reinforcement Design



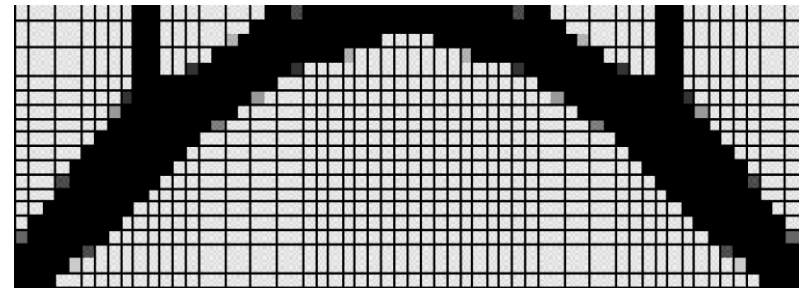
floor panel reinforcement



Bridge Structure

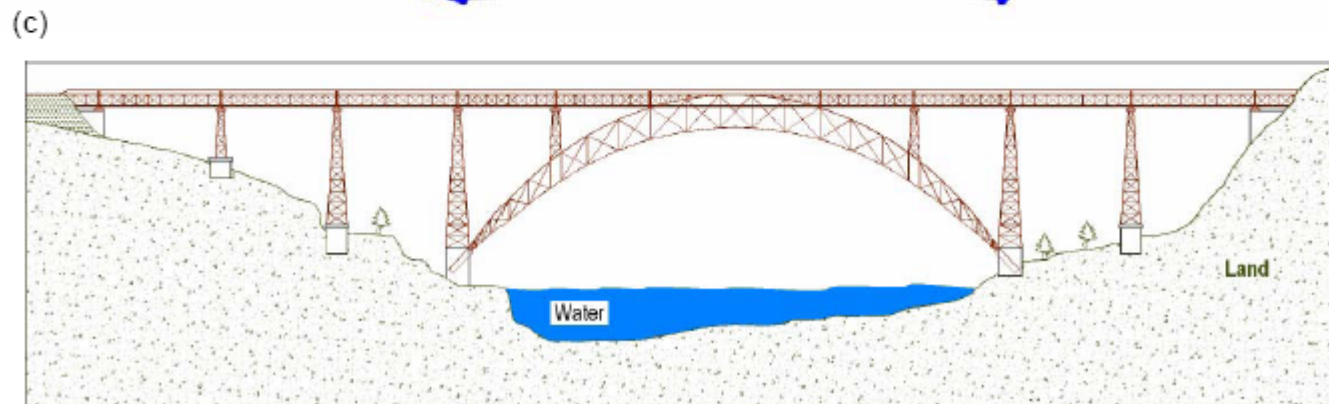
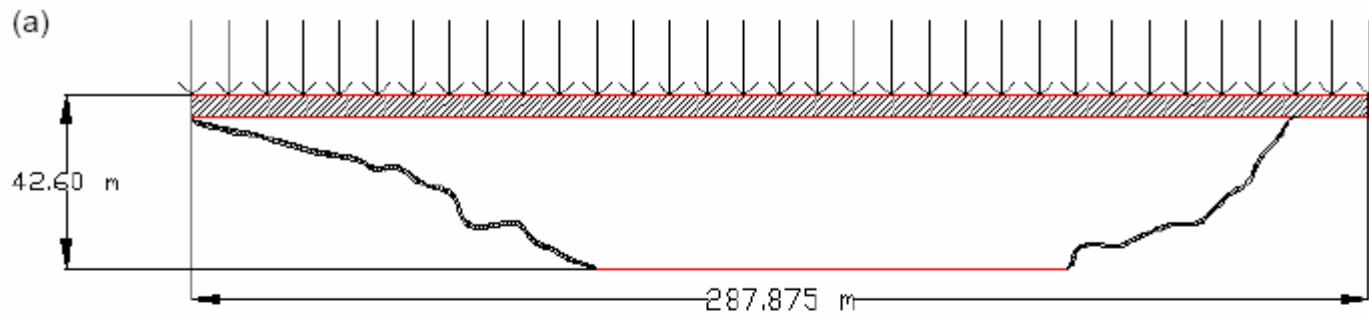


Multiple loadings



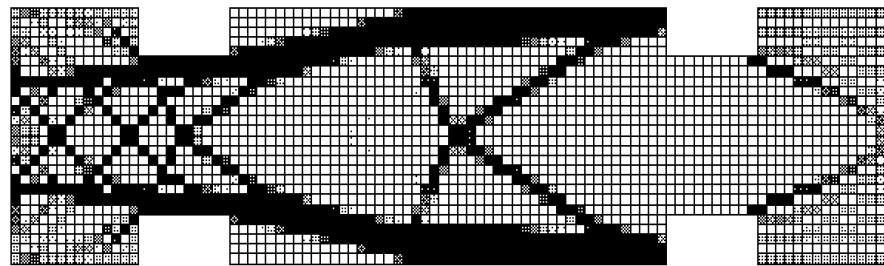
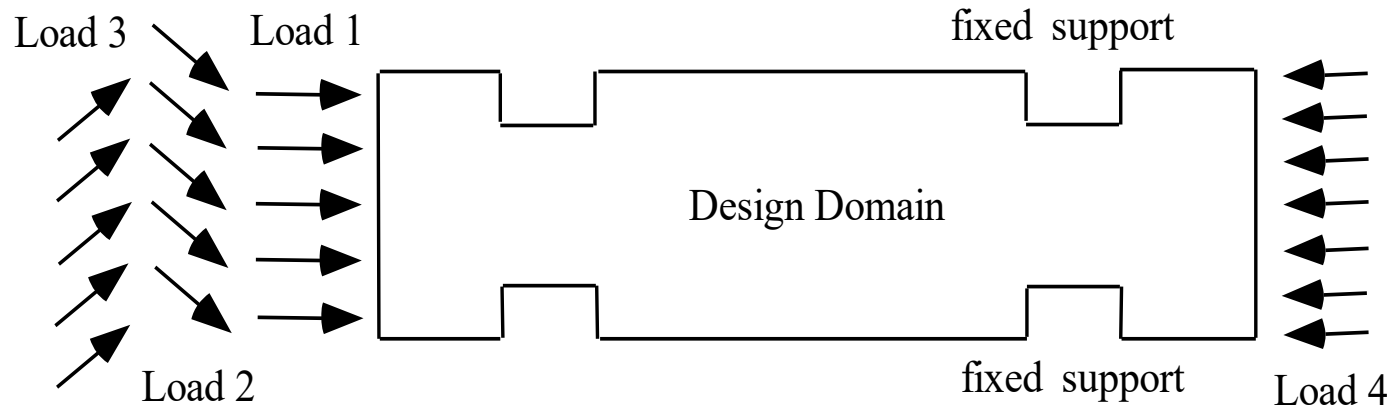
Single loading

Bridge

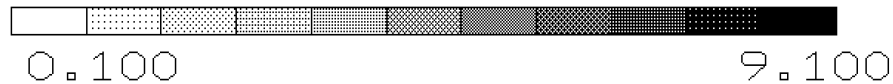


Maria Pia bridge

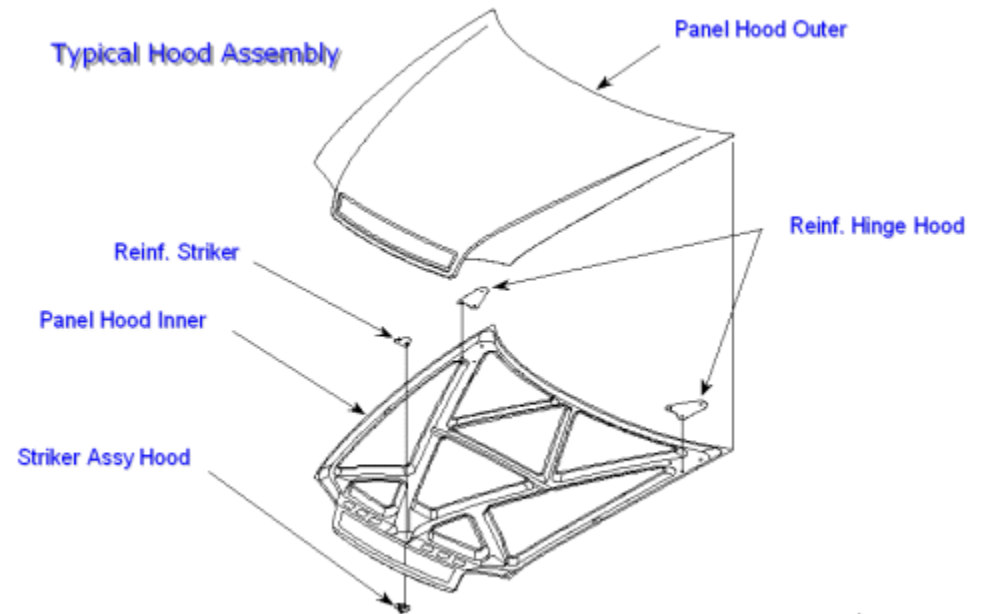
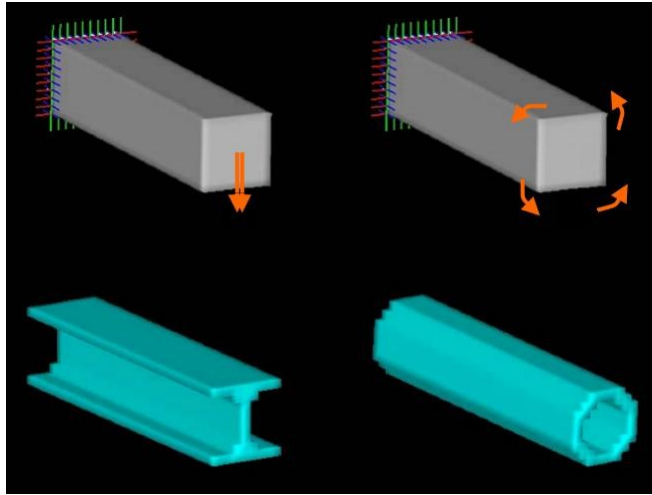
Floor Panel Reinforcement



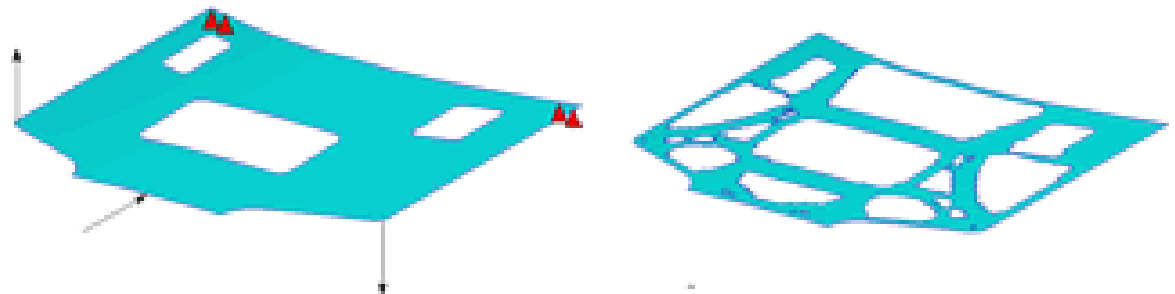
DENSITY



Hood Panel Reinforcement

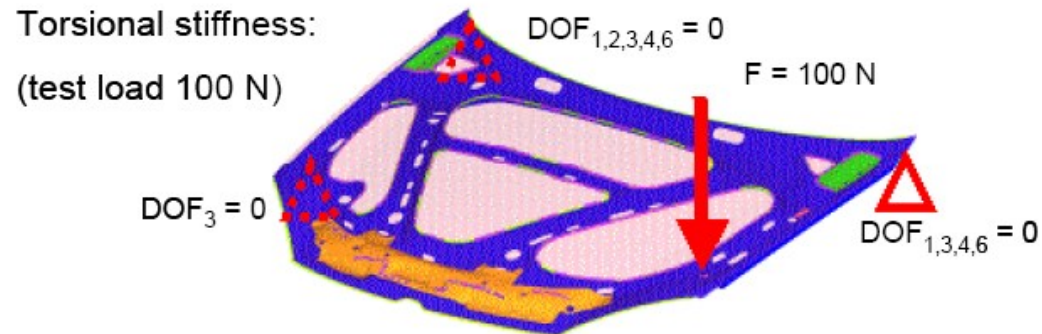
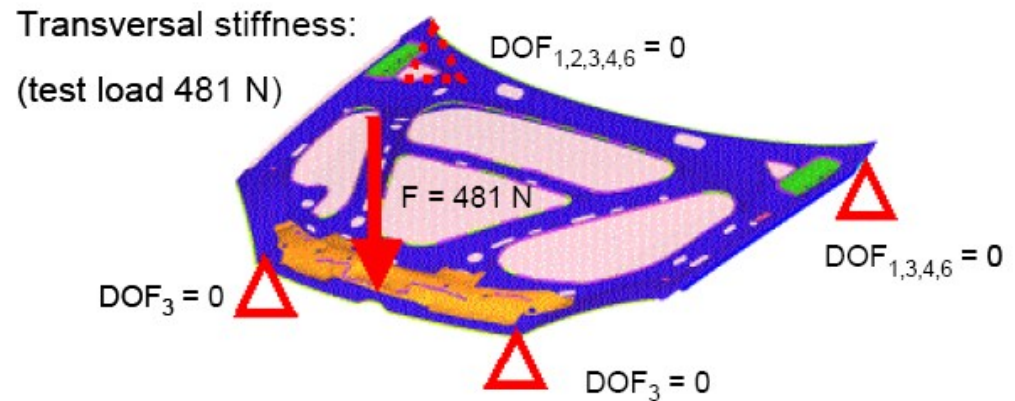
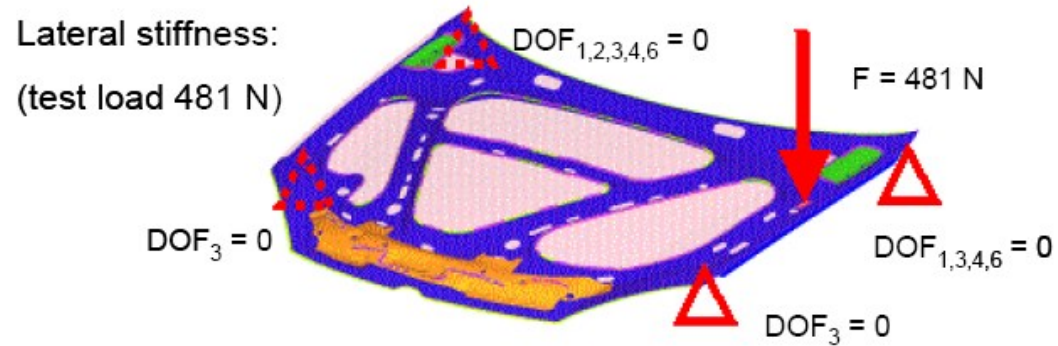


Source: Porsche Engineering

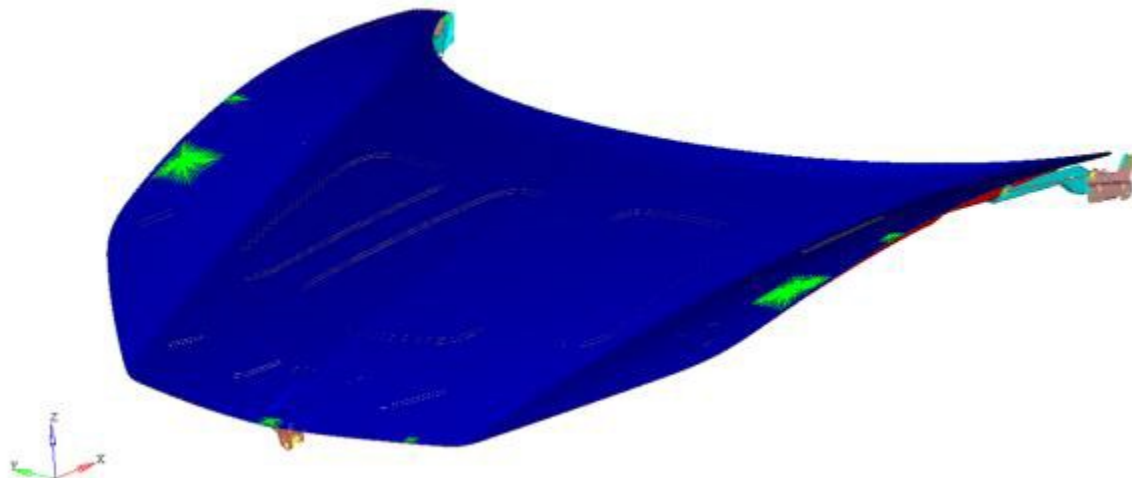


Load Cases for Hoods

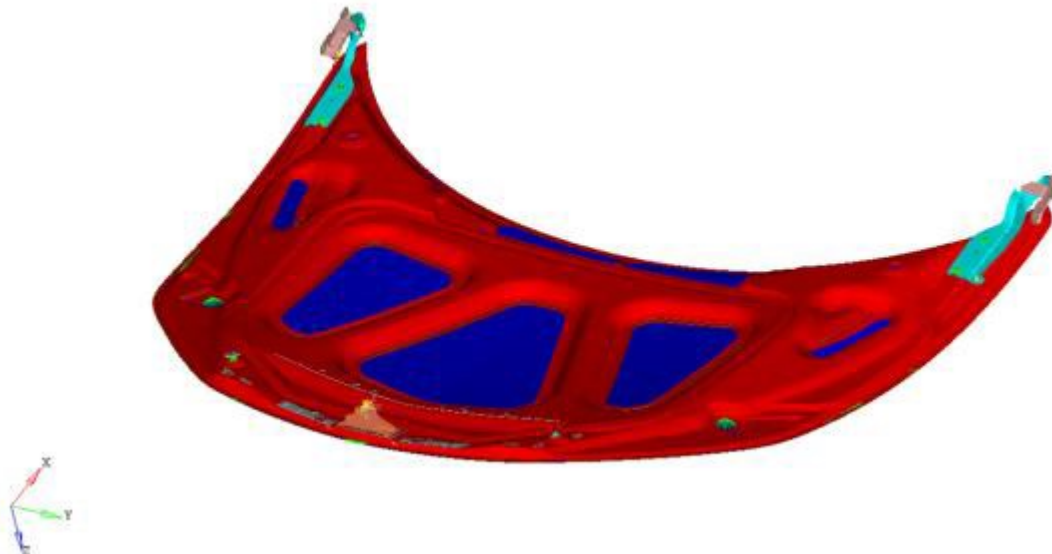
- Steel
 - 12.62 kg
 - 8.89 euro
- Aluminum
 - 8.10 kg (36% reduction)
 - 16.63 euro (87% increase)



Automotive Hood Substructure (Inner Panel)



Ferrari F458 Italia front hood

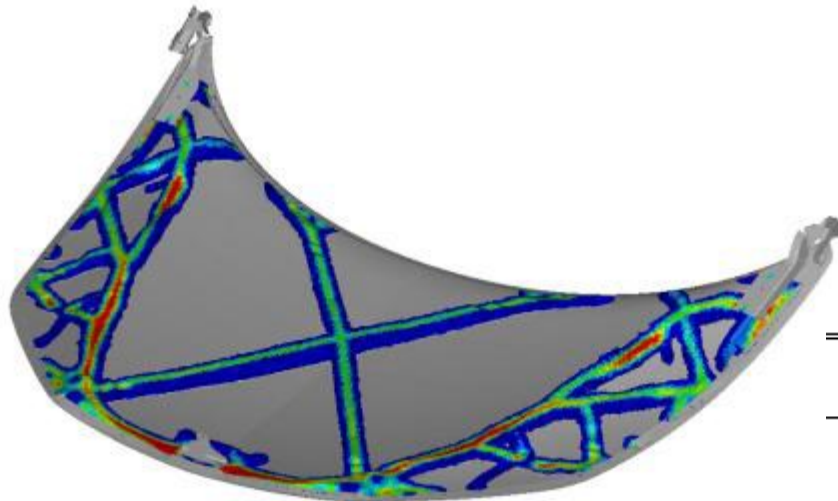


Results

Contour Plot
Element Density(Density)

1.000E+00
8.890E-01
7.700E-01
6.670E-01
5.560E-01
4.400E-01
3.340E-01
2.230E-01
1.120E-01
1.000E-03

Max = 1.000E+00
3D 304083
Min = 1.000E-03
3D 411026

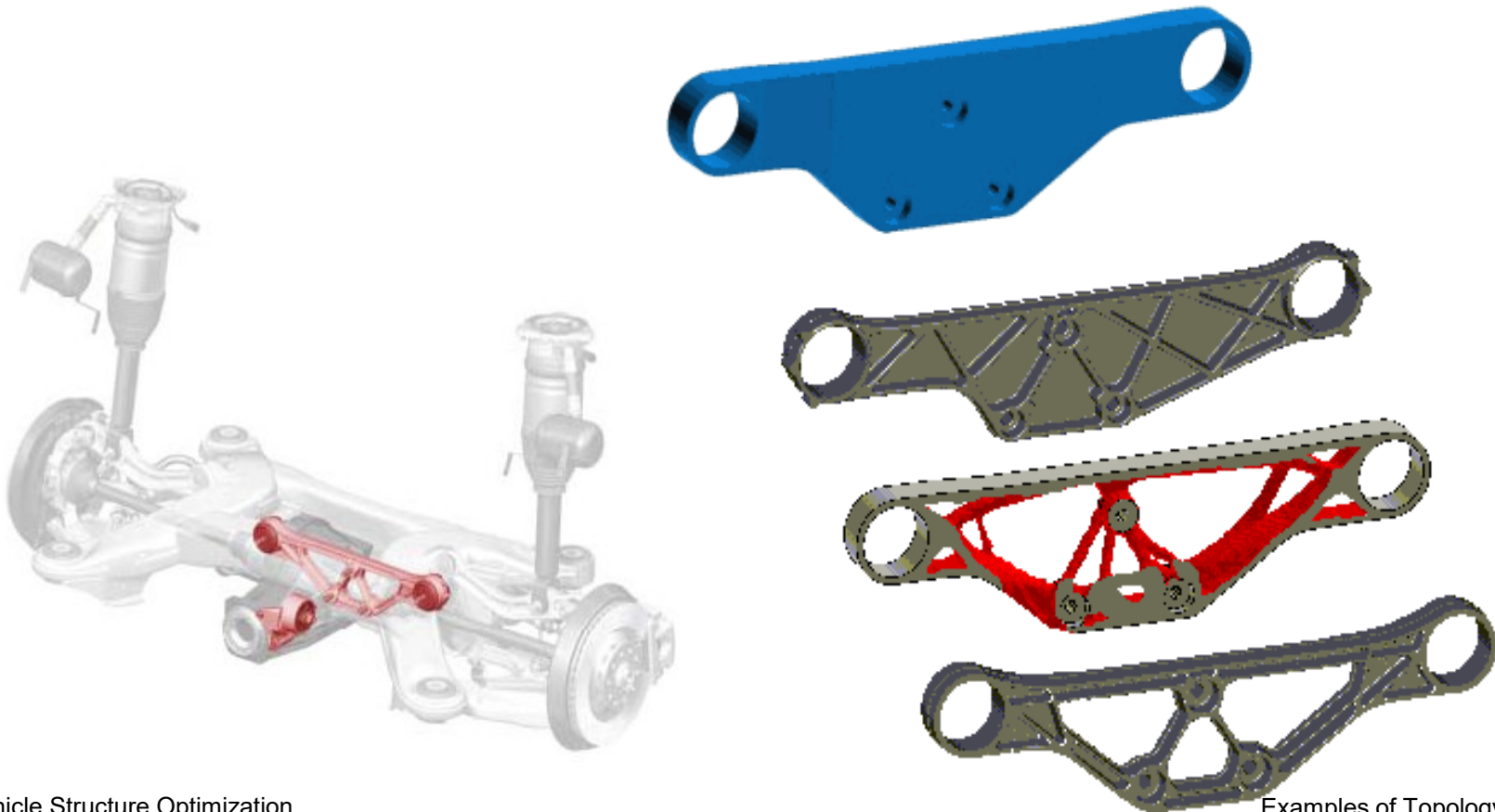


STIFFNESS OF THE MODEL IN EACH LOADCASE

Loadstep	Initial Model ^a	Final Model ^a
Torsion	100.00%	99.78%
Bending	100.00%	102.45%
Flap's Bending	100.00%	101.21%
Closure hand STD	100.00%	101.23%
Closure hand Central	100.00%	105.47%
Closure hand Lateral	100.00%	110.88%
Total Mass	100.00%	87.56%

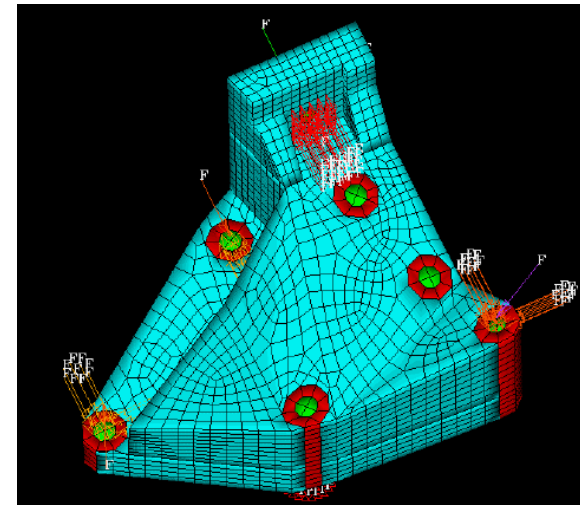
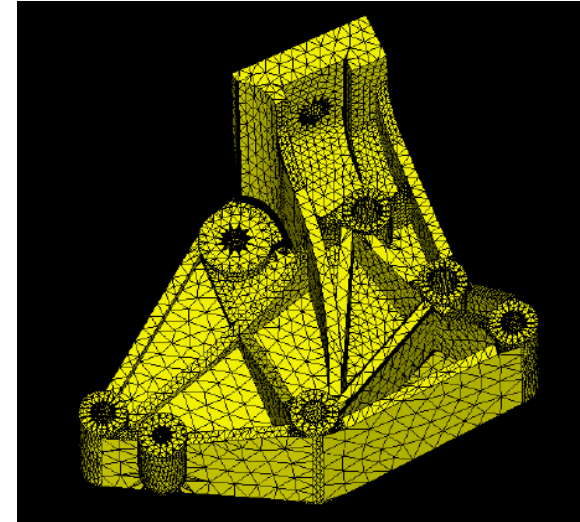
Transverse Link of Audi A8

- 45% stress reduction
- 10% weight reduction
- 1st prototype passed all mechanical tests !



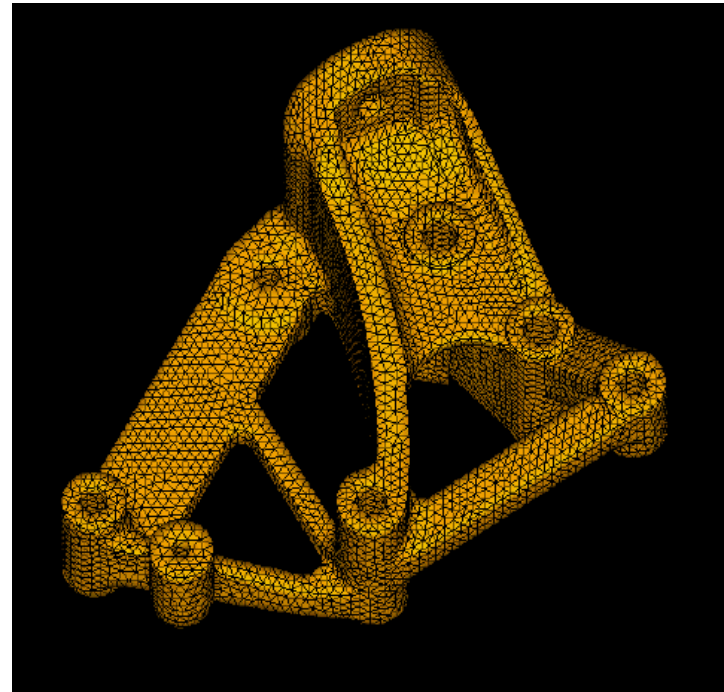
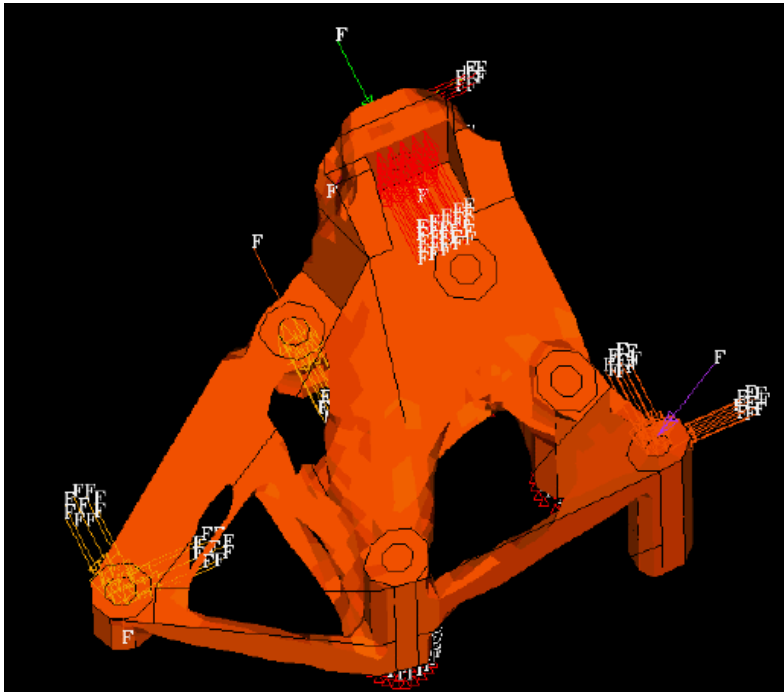
Engine Mounting Bracket (1)

- Minimize mass of engine bracket
 - Subject to stiffness/frequency constraint
- (a) Initial mass = 950 g
- (b) 20,000 solid elements, 30% material
 - Bolted joints: non-design domain
 - Loading conditions
 - Drive-off forward
 - Drive-off backwards
 - Driving into a pot hole
 - Driving out of a pot hole
 - Transmission loads
 - Assembly

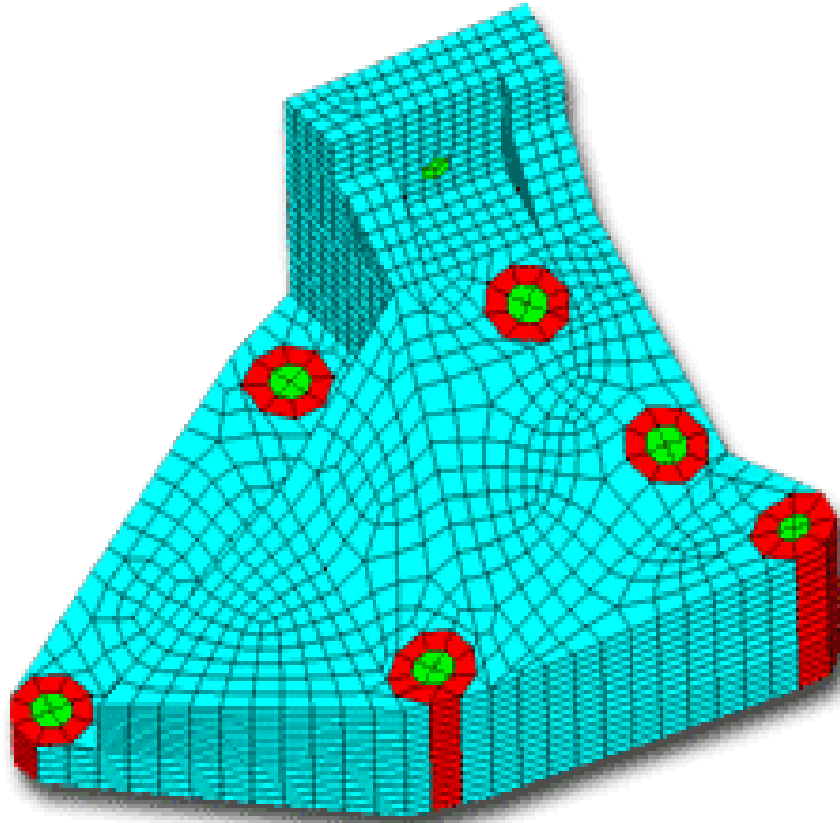


Engine Mounting Bracket (2)

- (c) 3D features of the optimal configuration
- (d) isodensity surface (density > 0.4)
 - Starting point for developing a production-ready engine bracket
- (e) shape optimization, final mass = 730 g (23%↓)



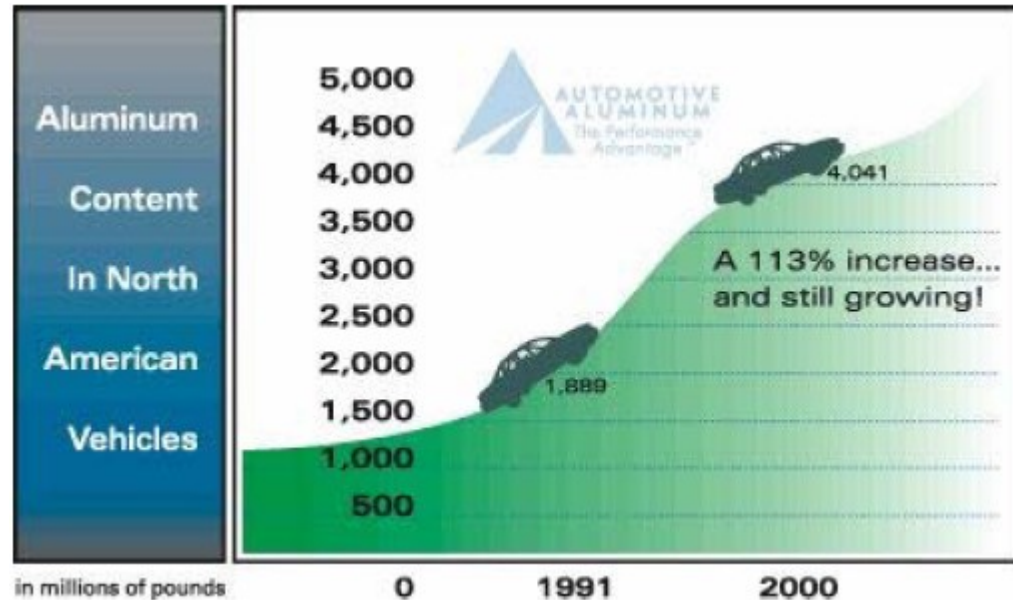
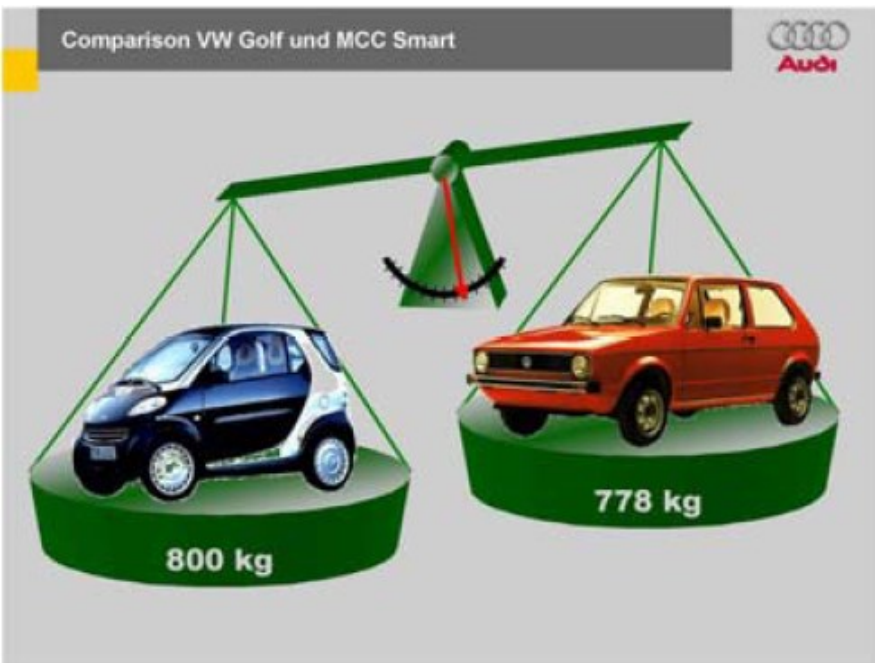
Engine Mounting Bracket (3)



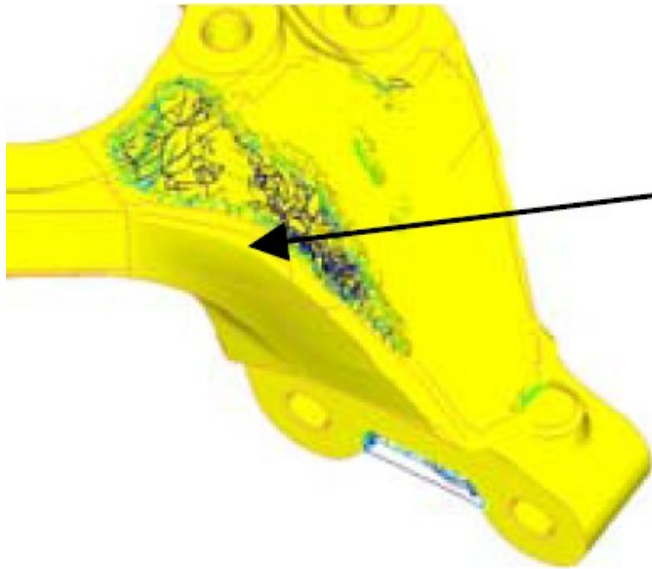
Courtesy of Volkswagen AG, Wolfsburg via Altair Engineering

Vehicle Weight Trend

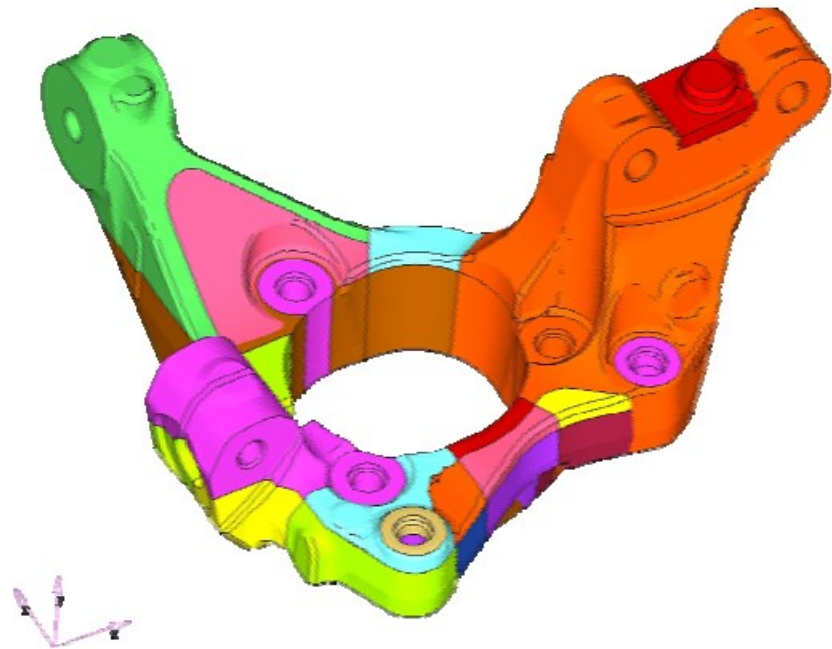
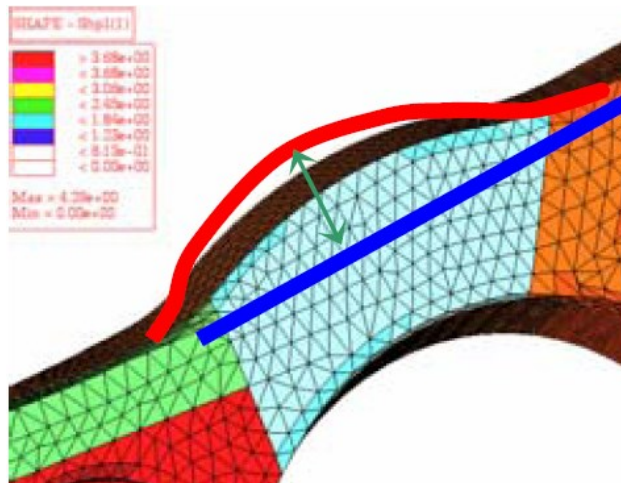
- VW GTI: 1804 lb (1976) → 2939 lb (2004)
- Aluminum casting component: 92.3 lb (1978) → 240 lb (2002)



Aluminum Front Knuckle Design (1)

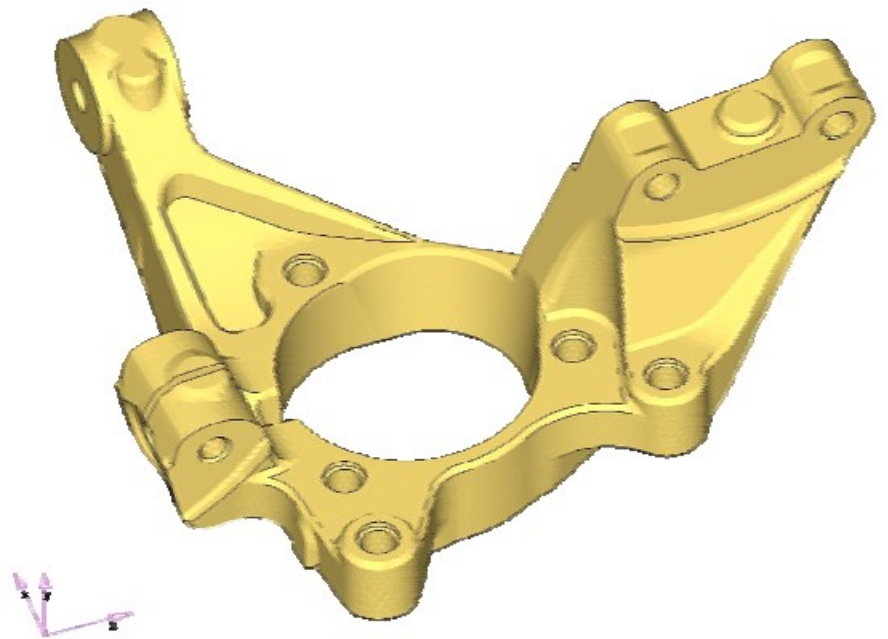
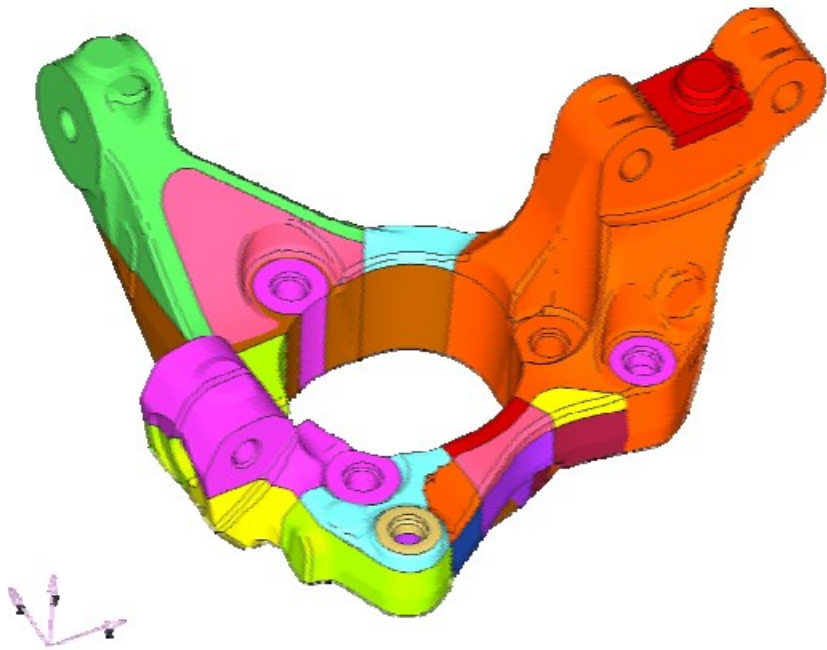


Example of results in a topology optimization zone

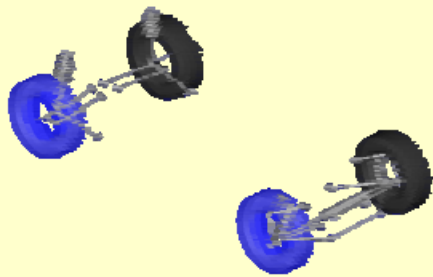


Example of a shape optimization zone:
shape function allows FE mesh to “morph”
between red and blue lines

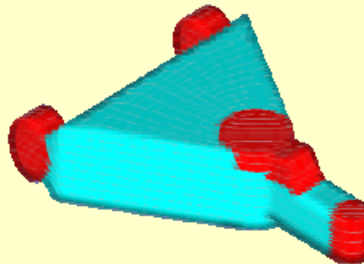
Aluminum Front Knuckle Design (2)



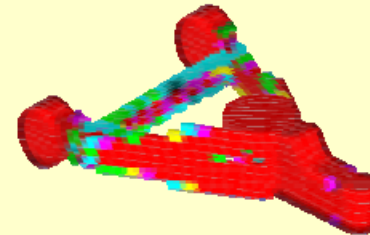
Concept Design Environment



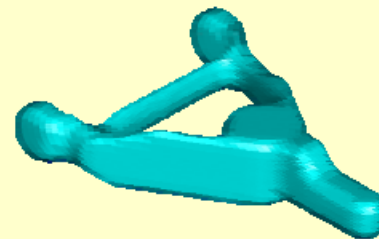
System Level Requirements



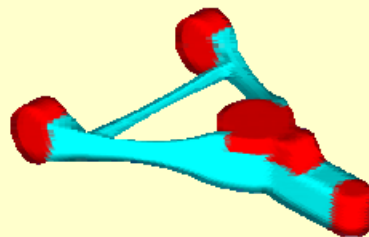
Package Space



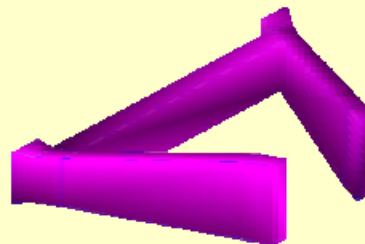
Topology Optimization



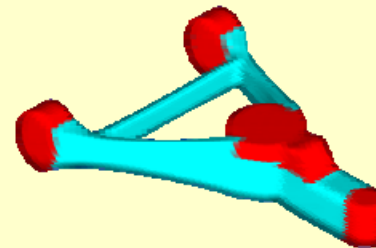
Surface Geometry Generation



Size and Shape Optimization



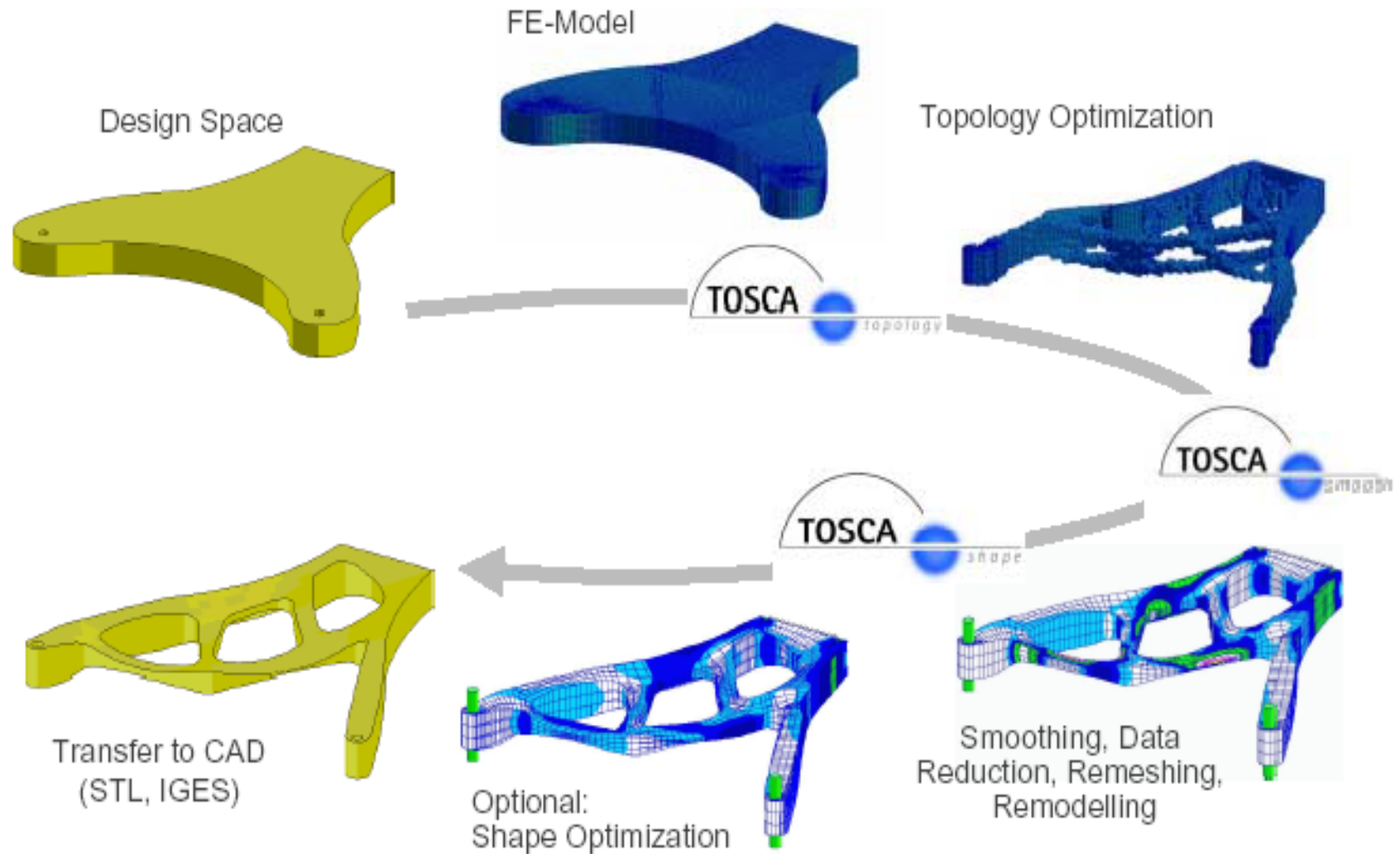
Parametric Shape Vectors



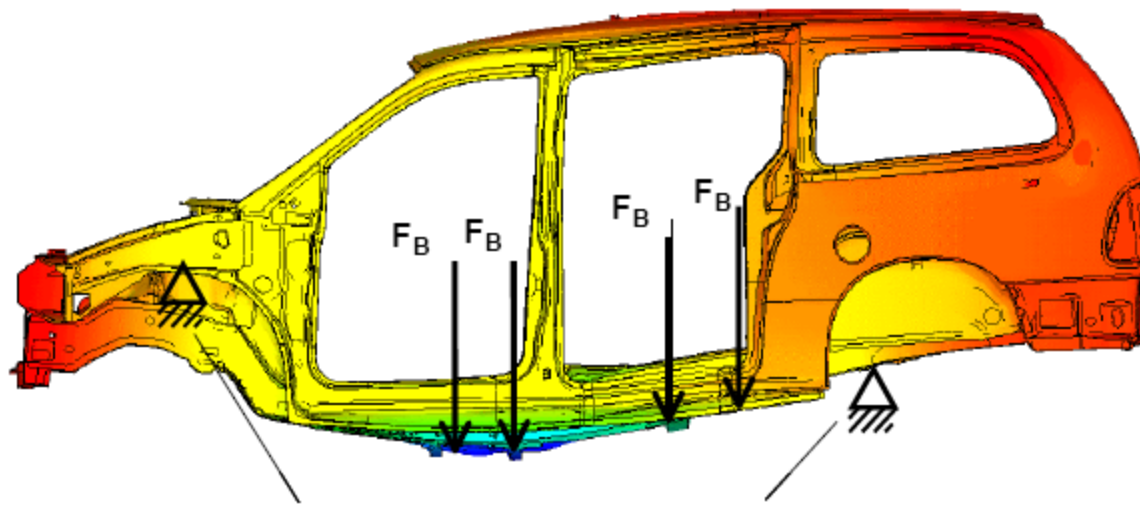
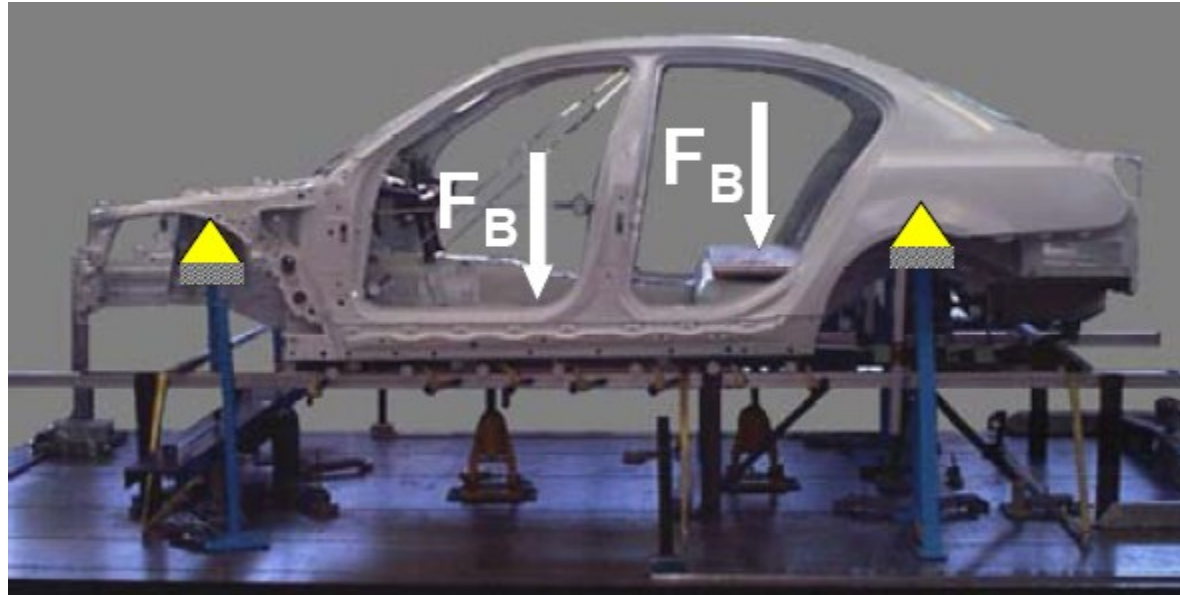
Finite Element Modeling

Control Arm Development Example

Integrated Topology and Shape Optimization into Product Development Process

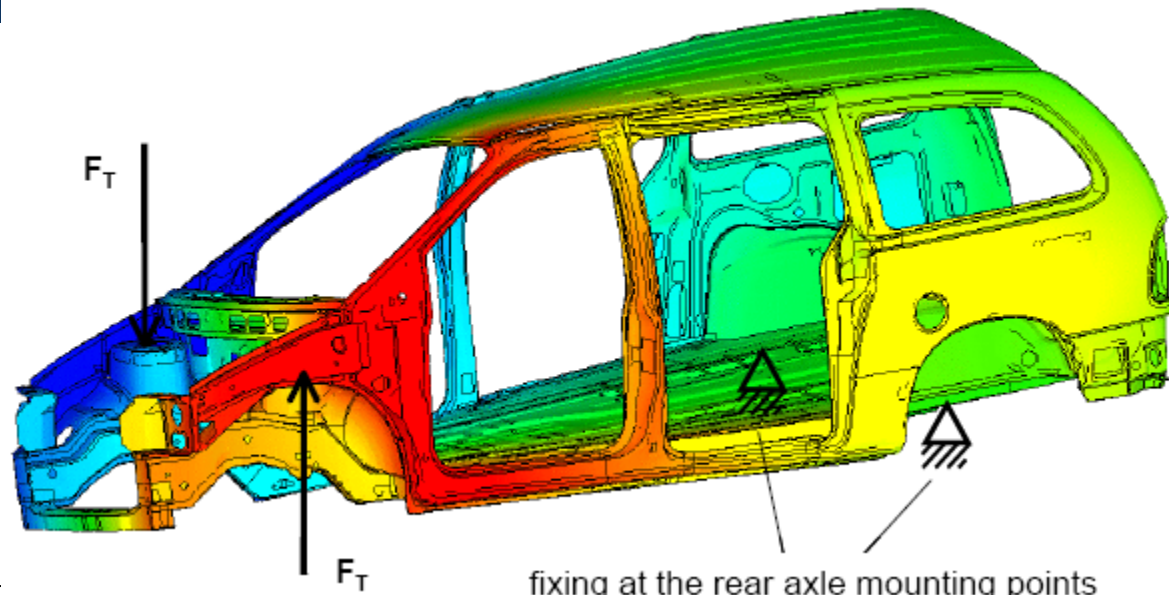


Bending Test



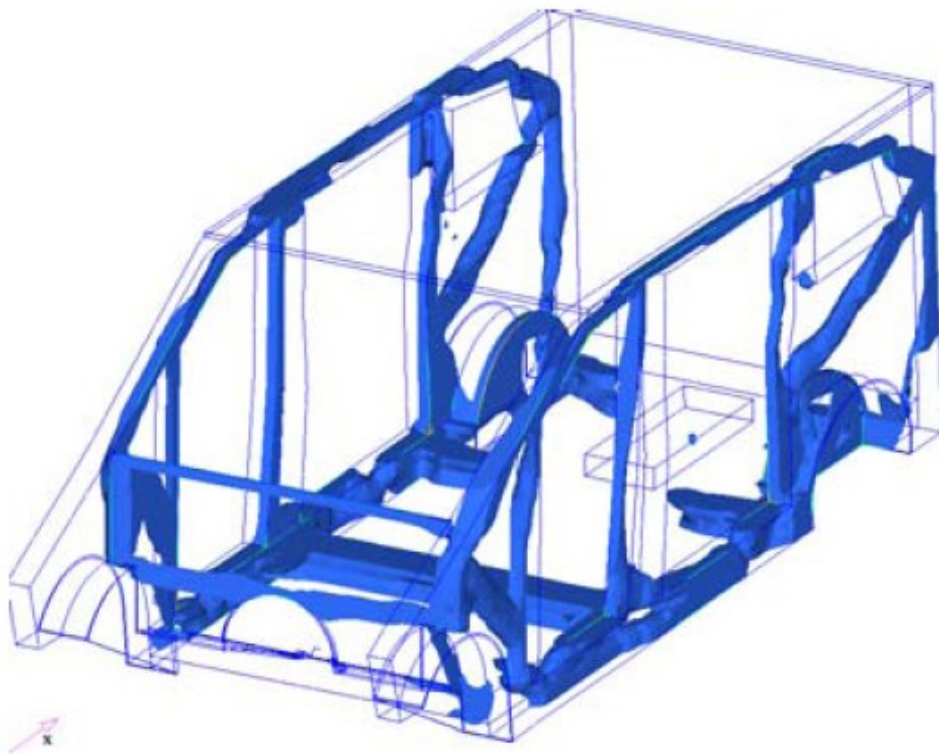
fixing at the axle mounting points

Torsional Test

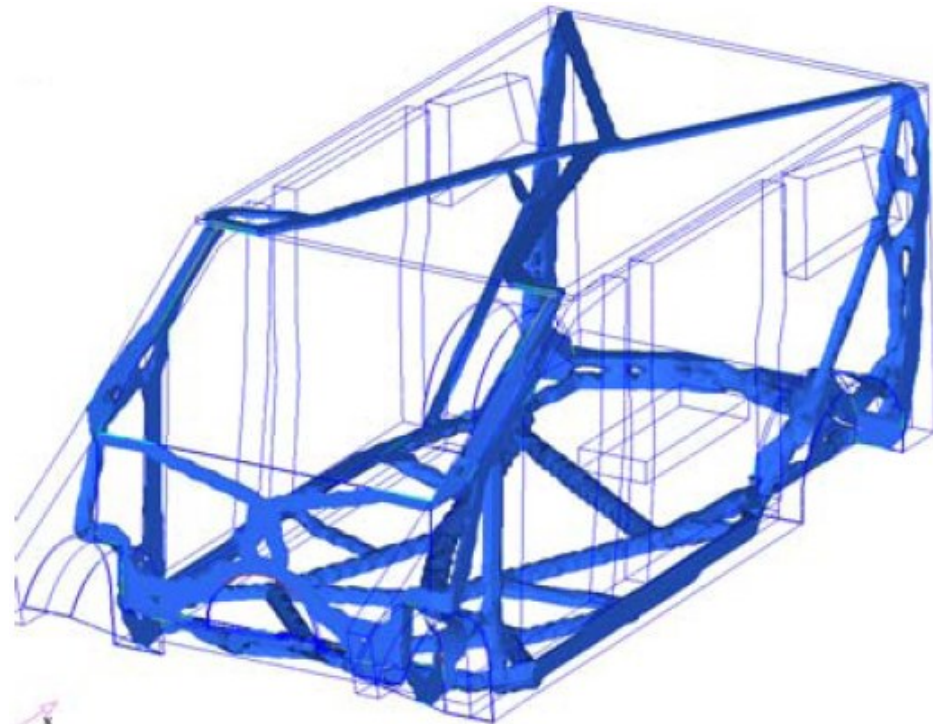


Result of Topology Optimization (1)

- Bending

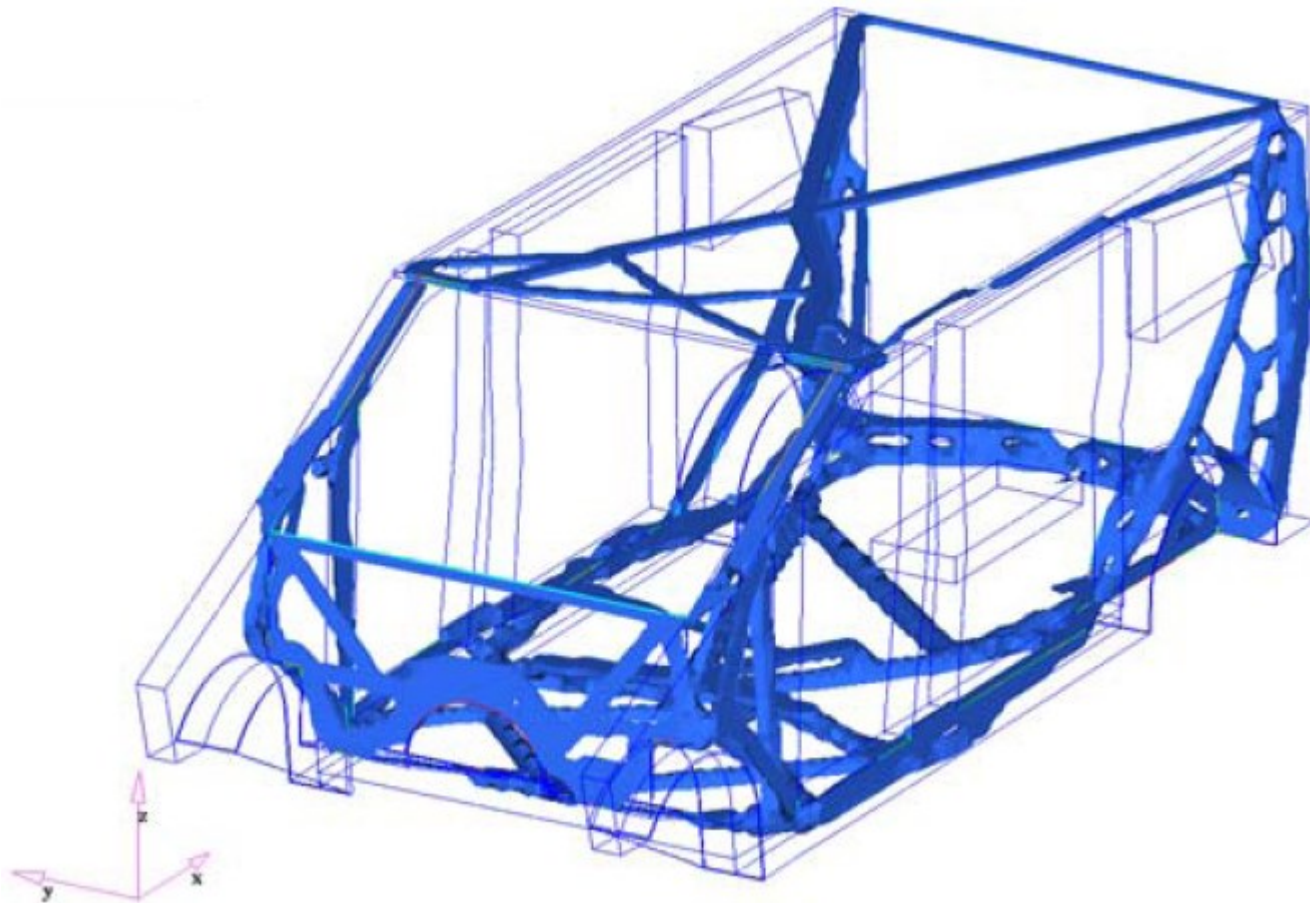


- Torsion



Result of Topology Optimization (2)

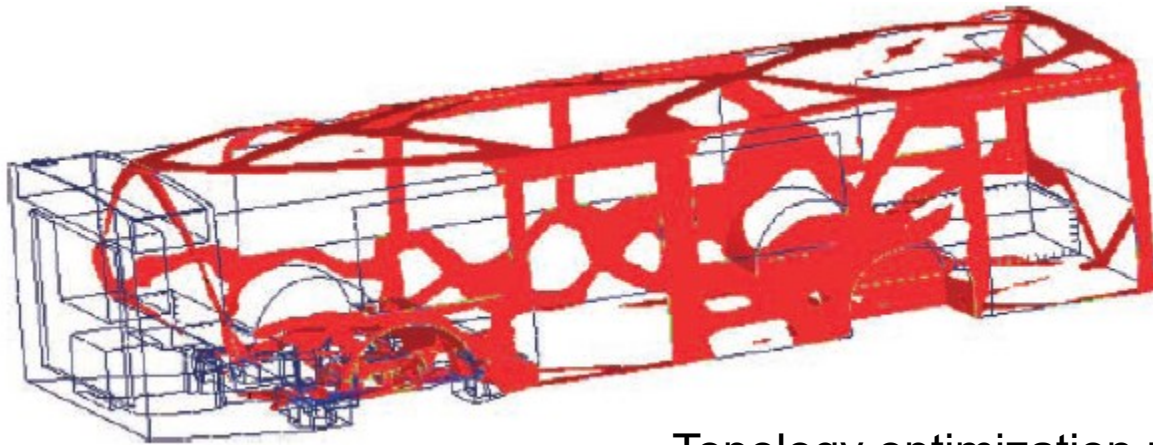
- Combination of bending and torsion



Lightweight City Bus (1)

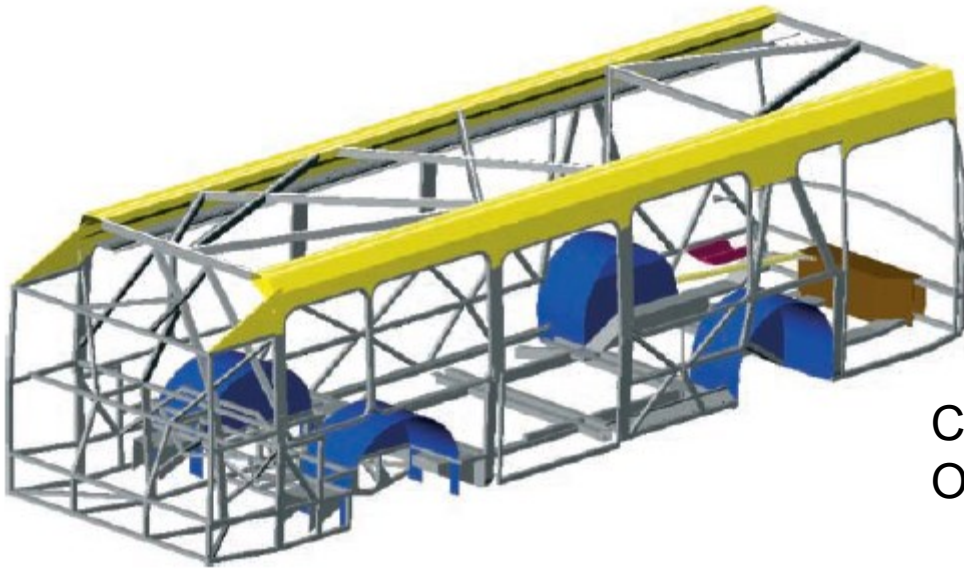


Bus design package space (in gray)

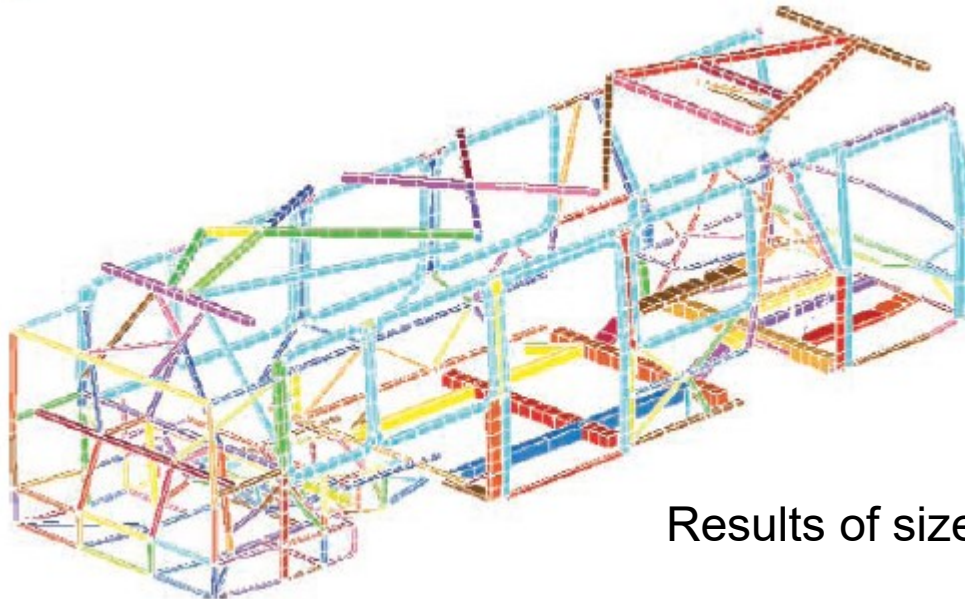


Topology optimization result

Lightweight City Bus (2)



CAD model interpretation of topology
Optimization design proposal



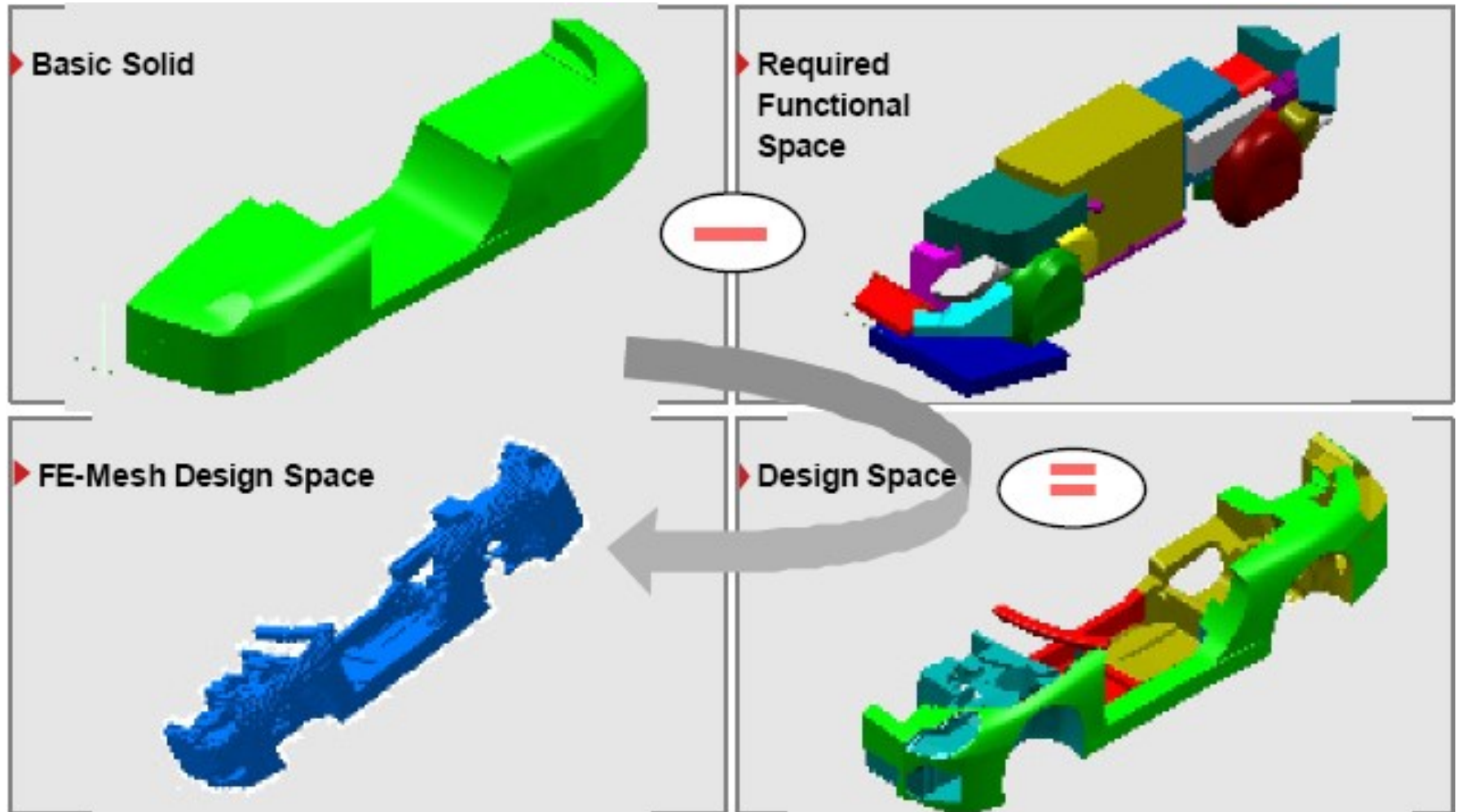
Results of size optimization

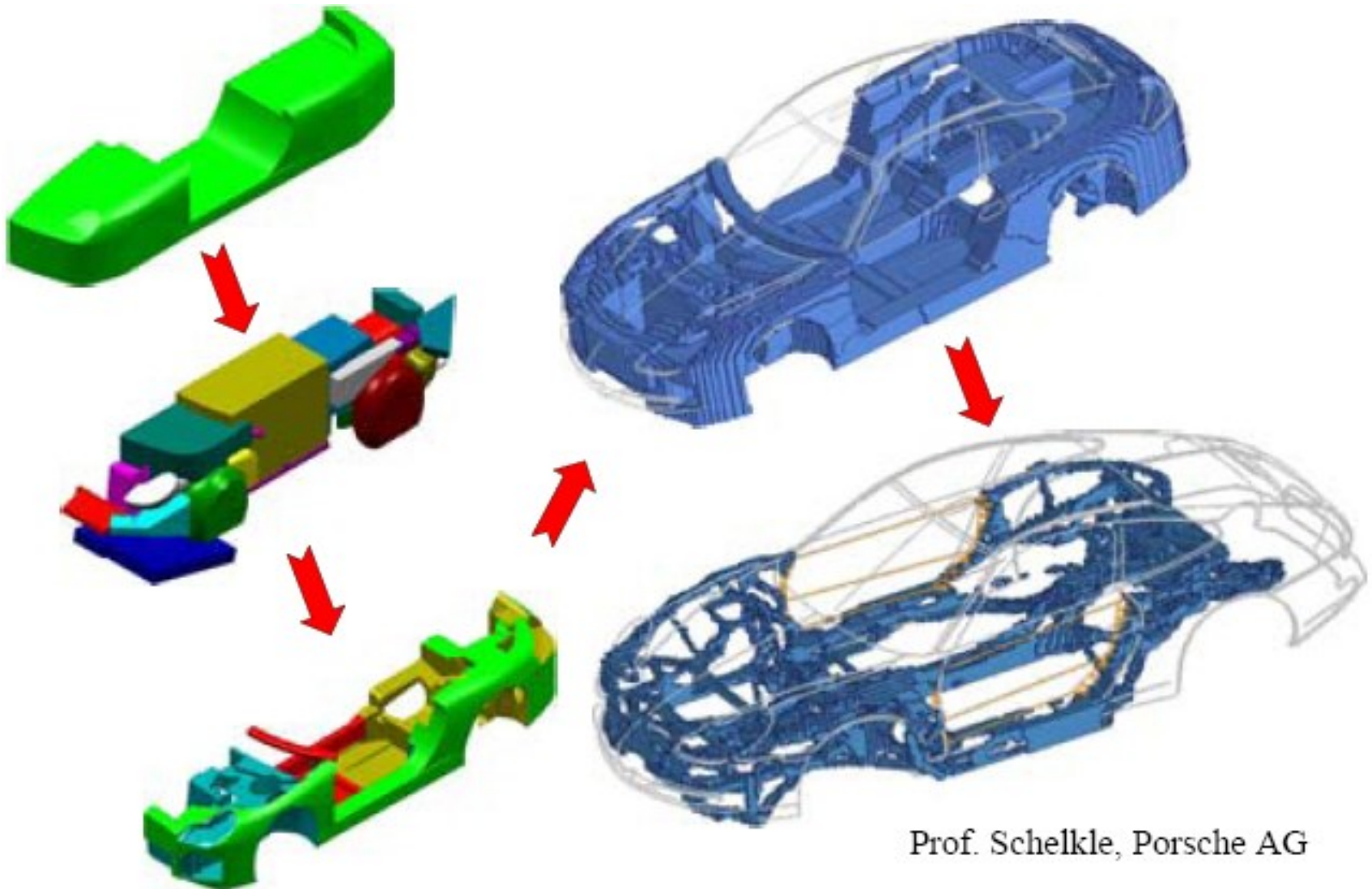
Lightweight City Bus (3)



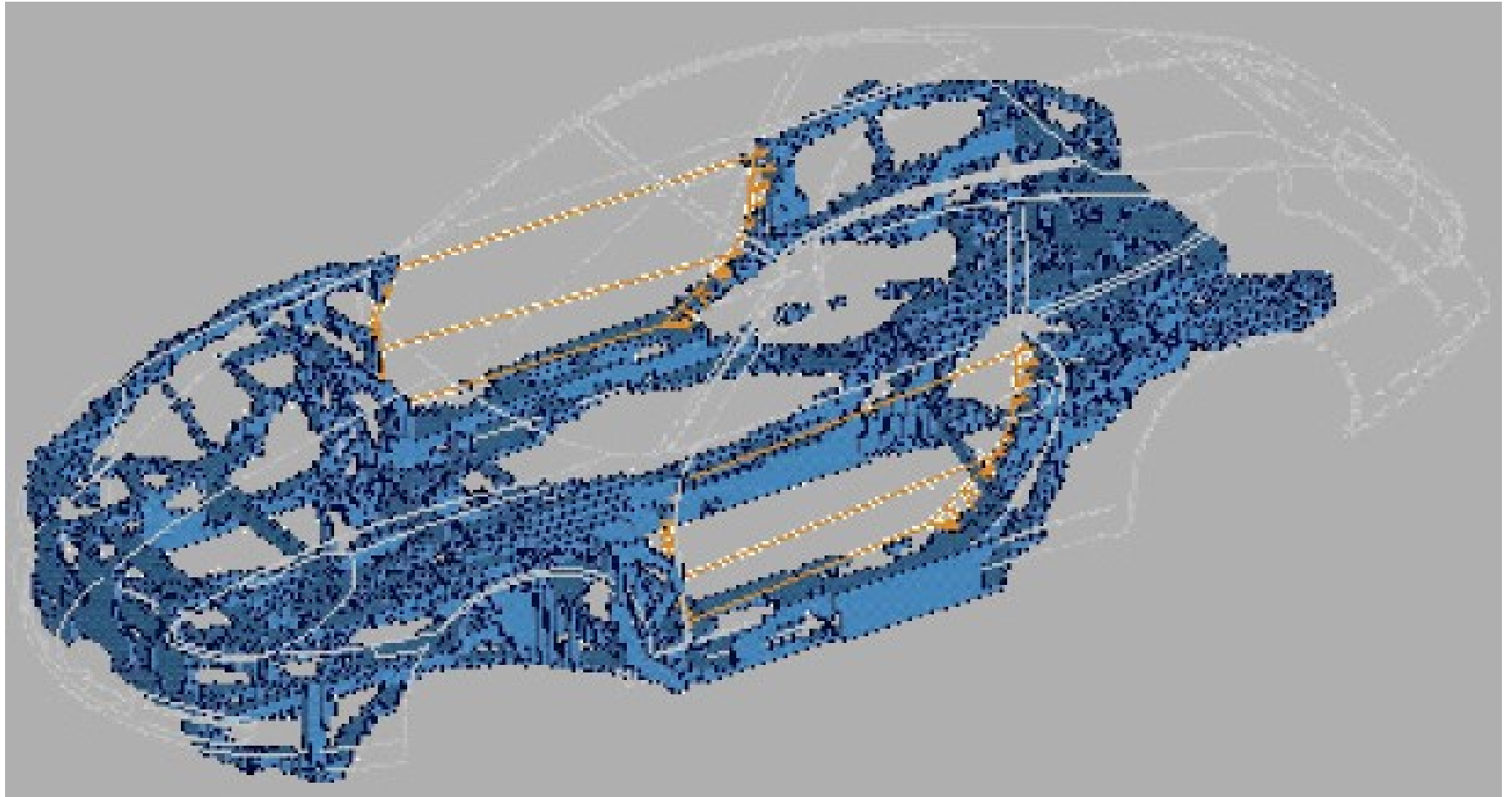
Final bus design

Load Path Analysis Sequence

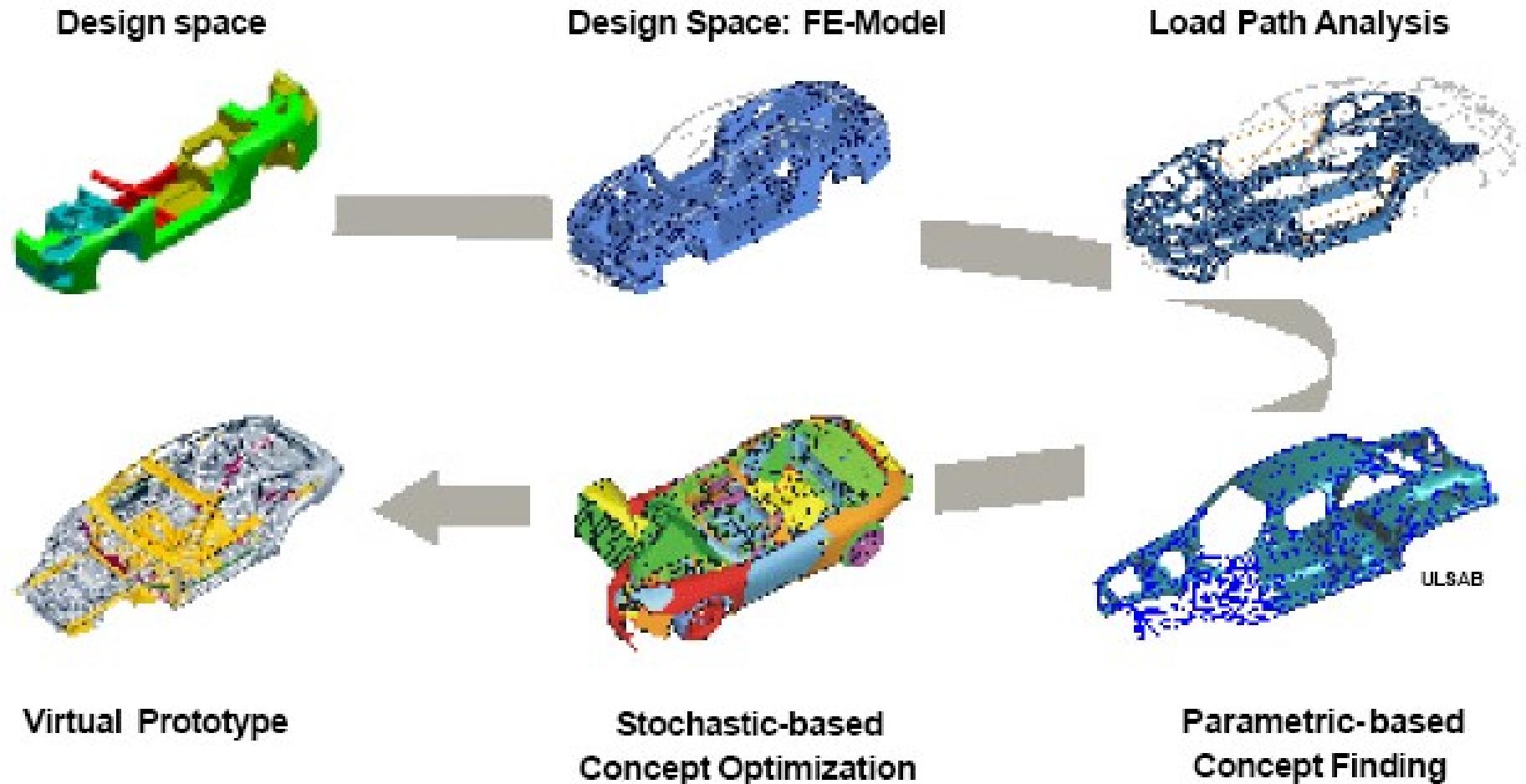




Prof. Schelkle, Porsche AG

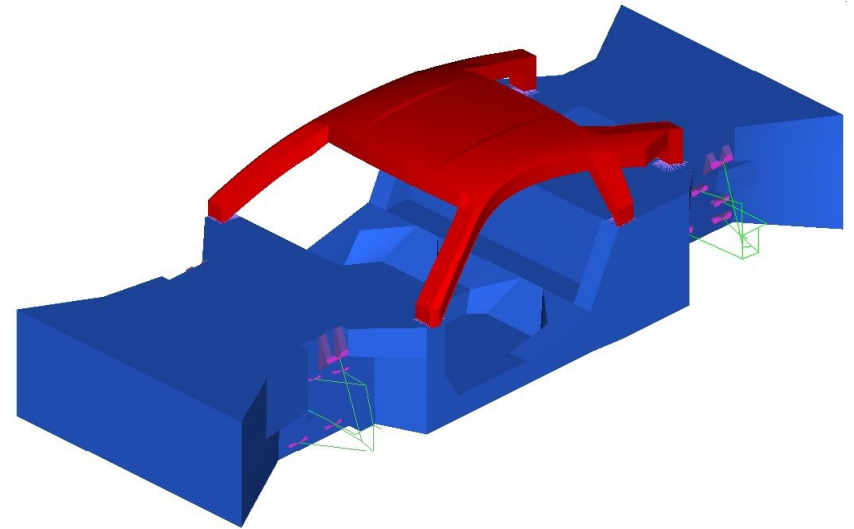
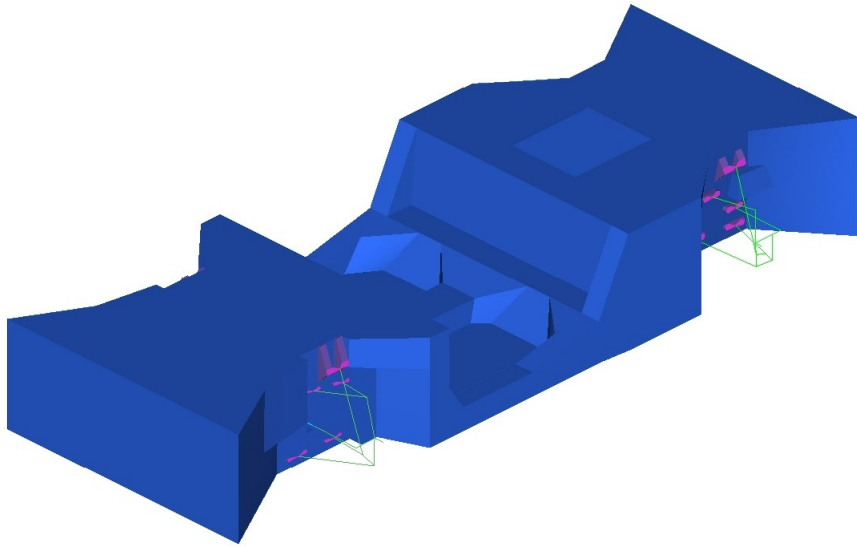


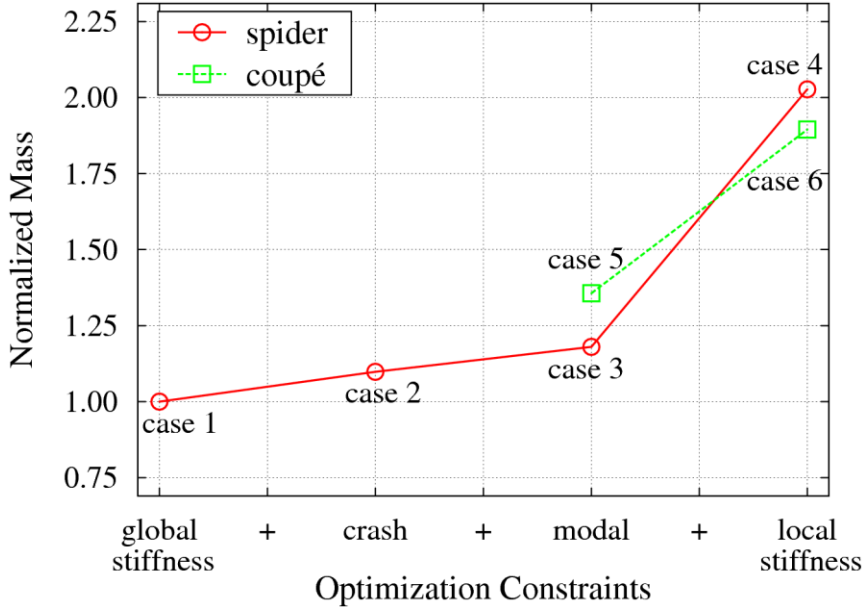
Concept Stage of Vehicle Development



Automotive Chassis

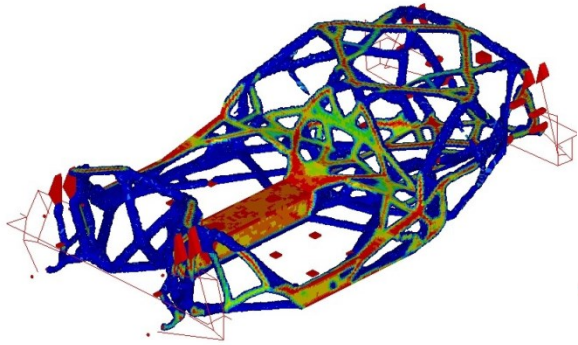
- Comparison Between Spider and Coup'e Designs



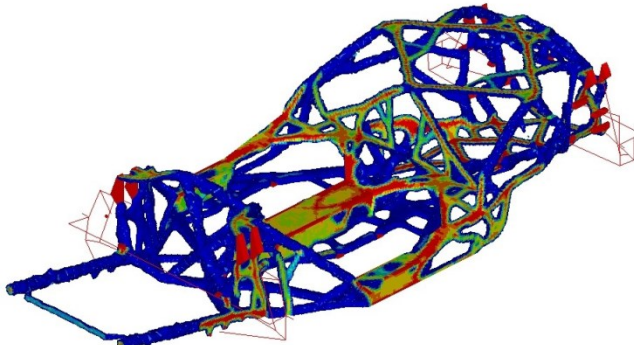


Active Optimization Constraints	Cases					
	Spider				Coupé	
	1	2	3	4	5	6
Global bending stiffness	✓	✗	✓	✓	✓	✓
Global torsion stiffness	✓	✓	✓	✓	✓	✗
Crash seat joints displacement	–	✗	✗	✗	✓	✗
Crash engine joints displacement	–	✓	✓	✗	✓	✓
Crash A-pillar displacement	–	✓	✓	✓	✓	✓
Crash pedal displacement	–	✗	✓	✗	✗	✗
Crash flame shield displacement	–	✓	✓	✗	✗	✗
Crash dashboard joints displacement	–	✗	✗	✗	✗	✓
Crash compliance	–	✓	✓	✓	✓	✓
First natural mode	–	–	✓	✓	✓	✓
Local front wheel stiffness along x	–	–	–	✓	–	✓
Local front wheel stiffness along y	–	–	–	✓	–	✓
Local front wheel stiffness along z	–	–	–	✓	–	✓
Local rear wheel stiffness along x	–	–	–	✓	–	✓
Local rear wheel stiffness along y	–	–	–	✓	–	✓
Local rear wheel stiffness along z	–	–	–	✗	–	✗
Local engine joint stiffness along z	–	–	–	✓	–	✓
Local gearbox joint stiffness along z	–	–	–	✓	–	✗
Total	$\frac{2}{2}$	$\frac{5}{9}$	$\frac{8}{10}$	$\frac{12}{18}$	$\frac{7}{10}$	$\frac{12}{18}$

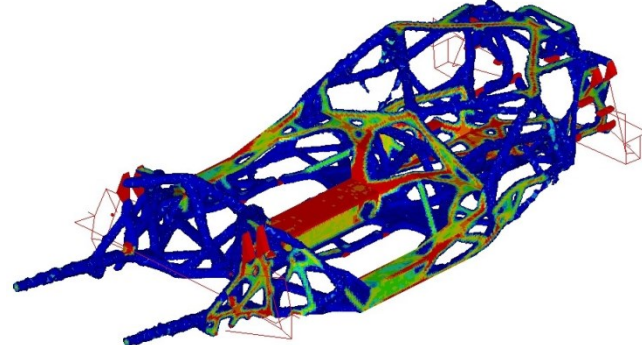
Results (1)



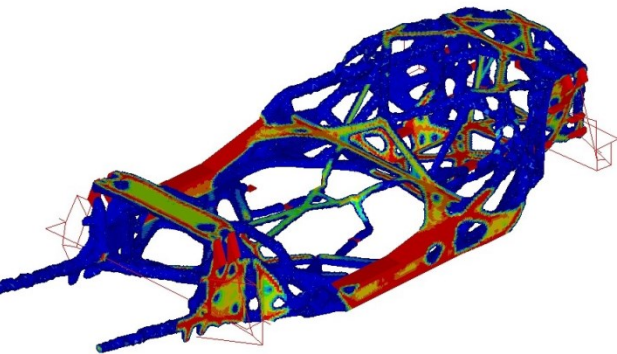
Case 1



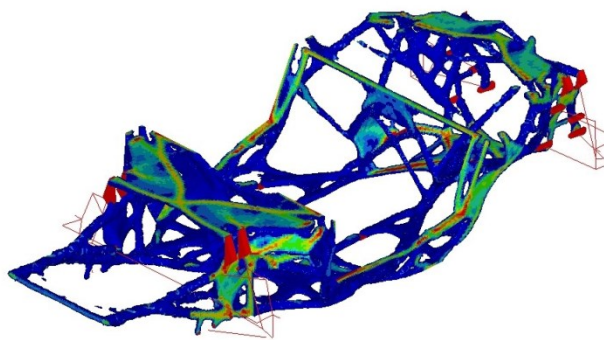
Case 2



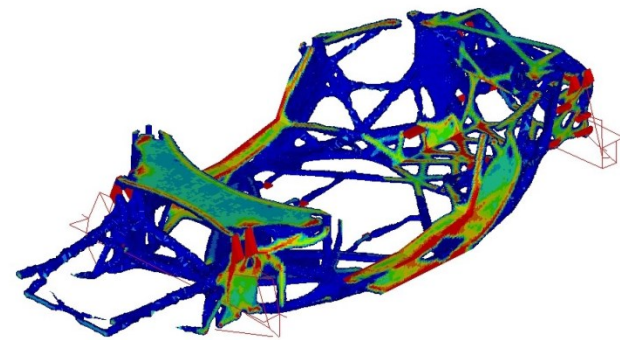
Case 3



Case 4

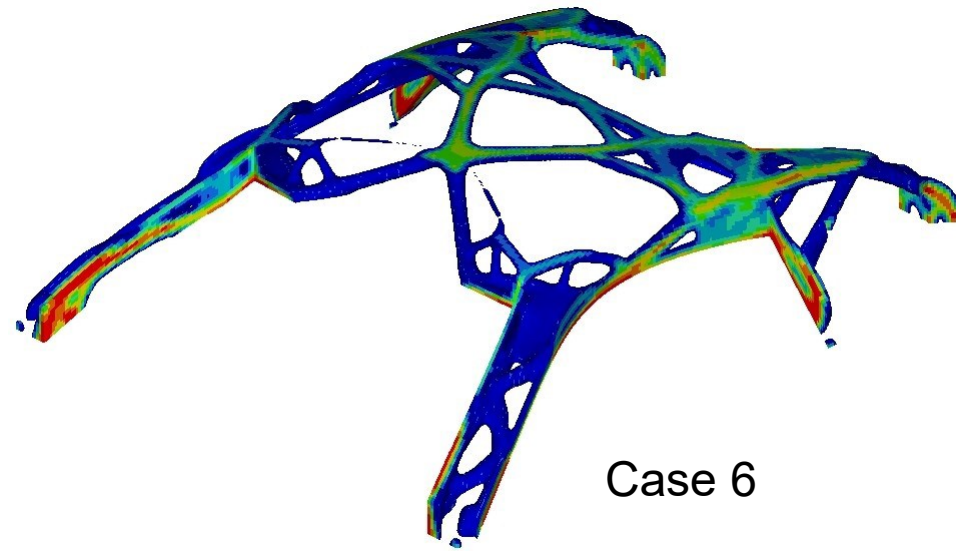
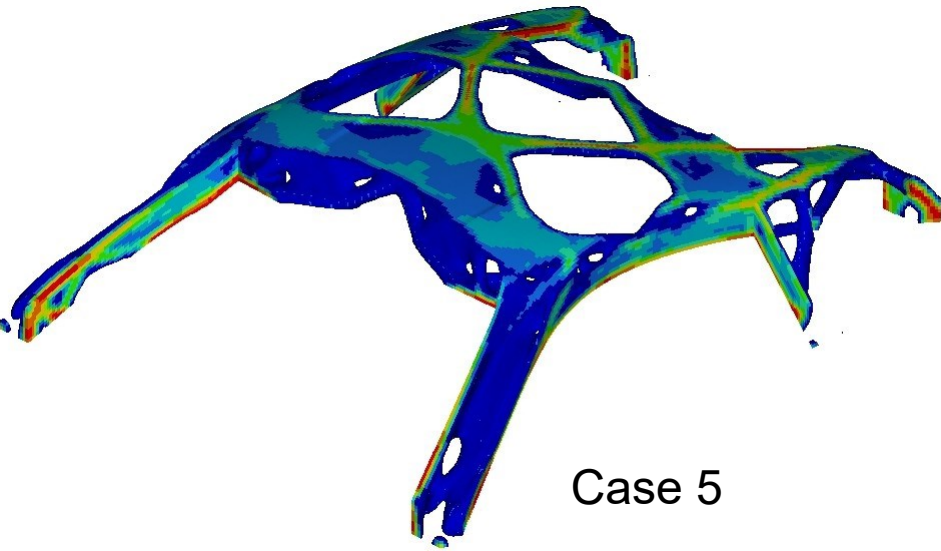


Case 5

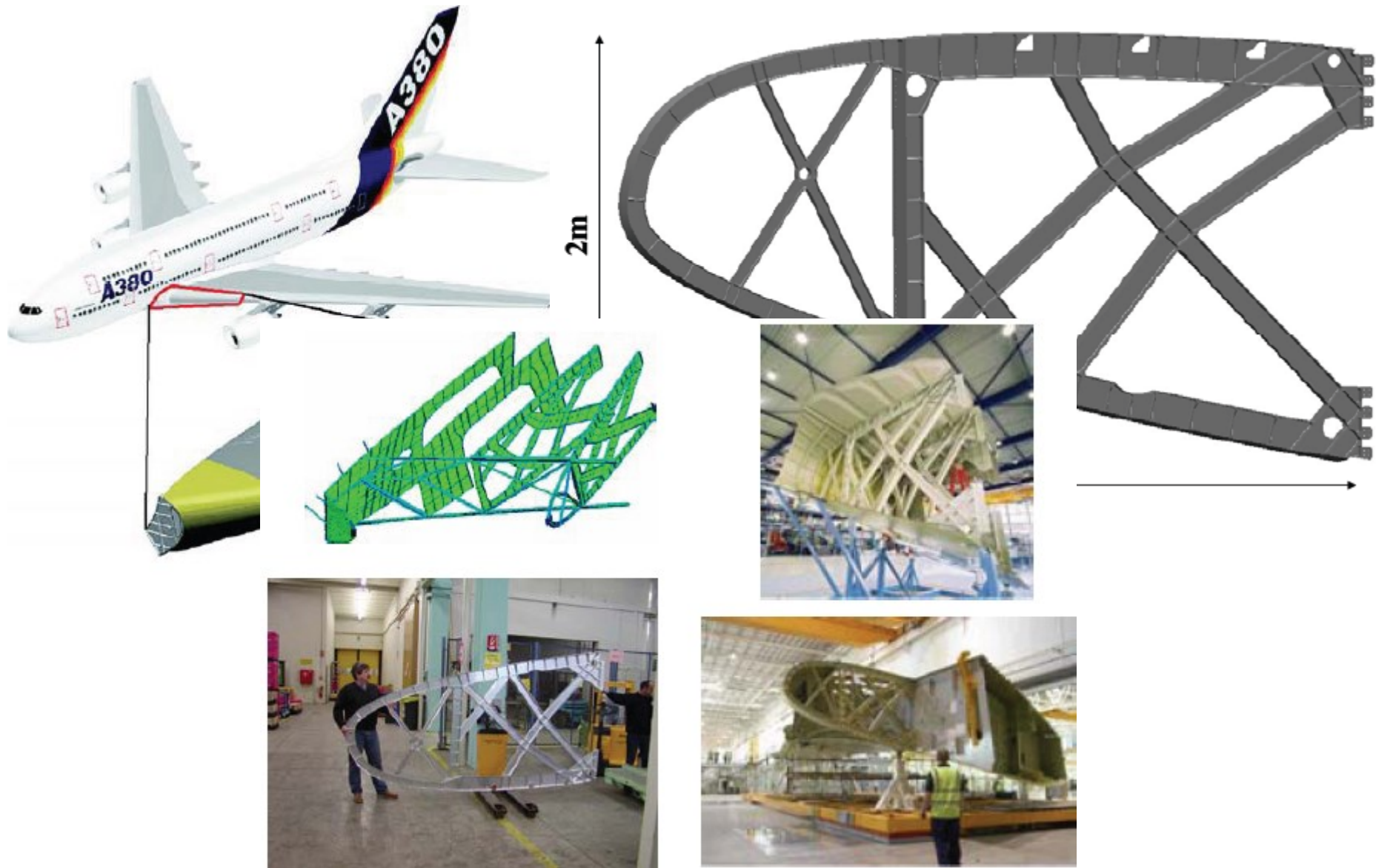


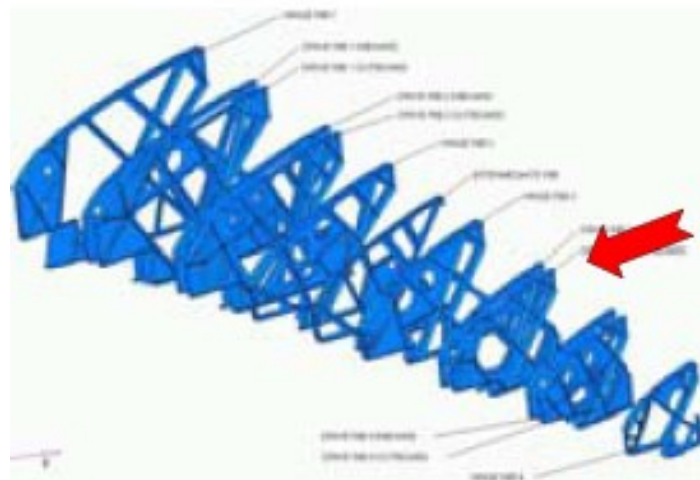
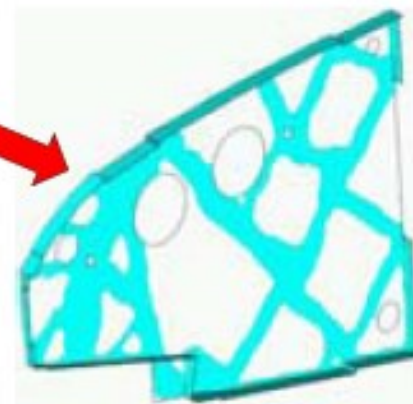
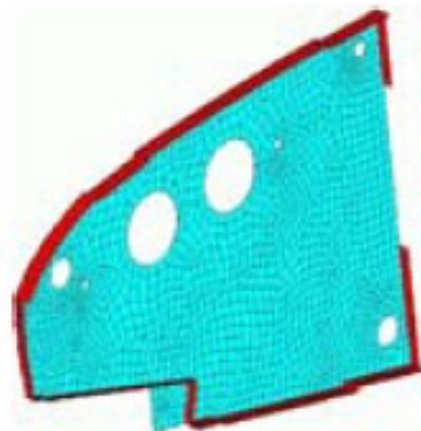
Case 6

Results (2)

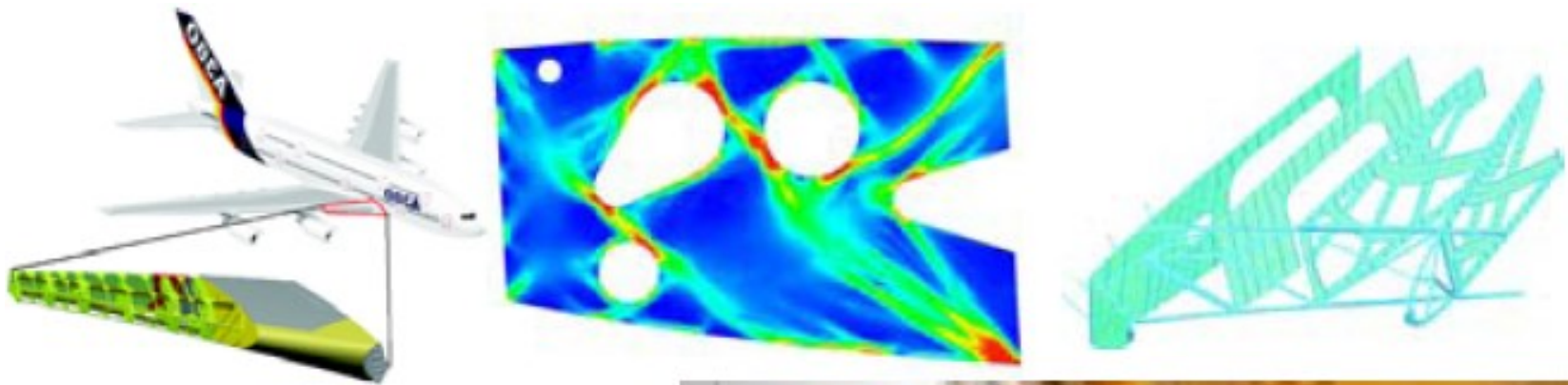


A380 Leading Edge Droop Nose Ribs





Airbus/Altair



Kochvara/Airbus



Ultra-lightweight Hub-Bearing

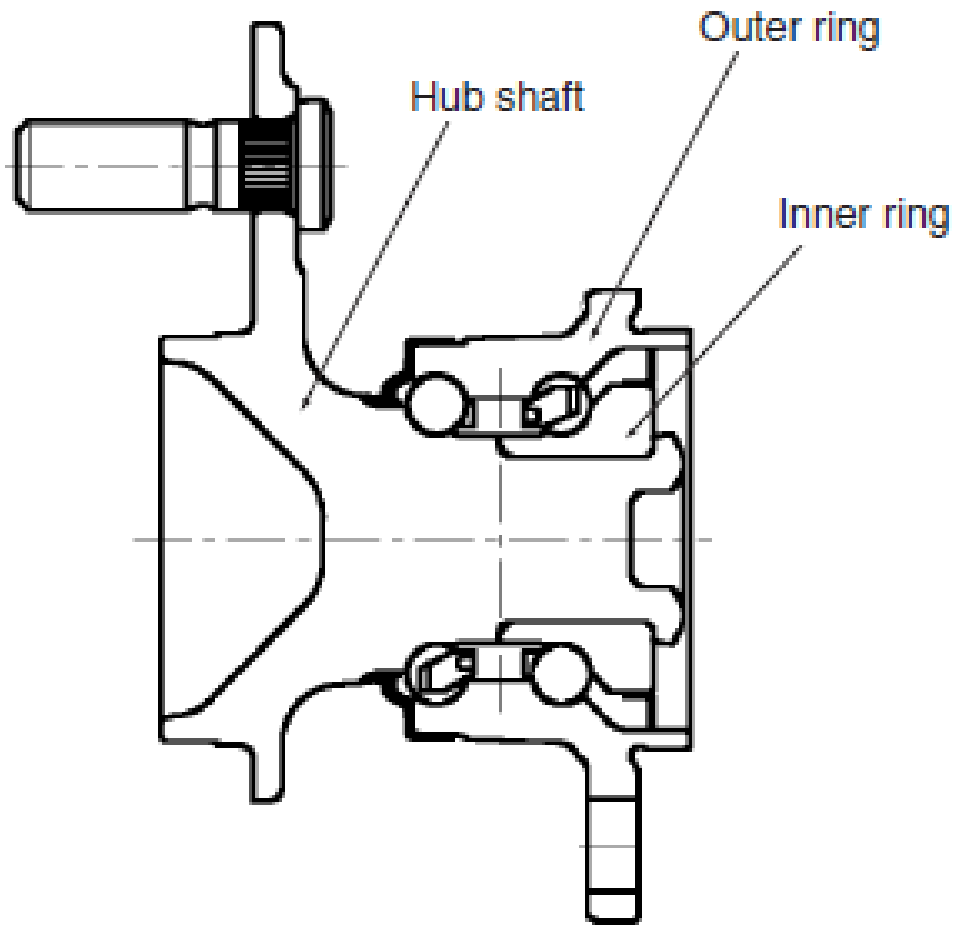
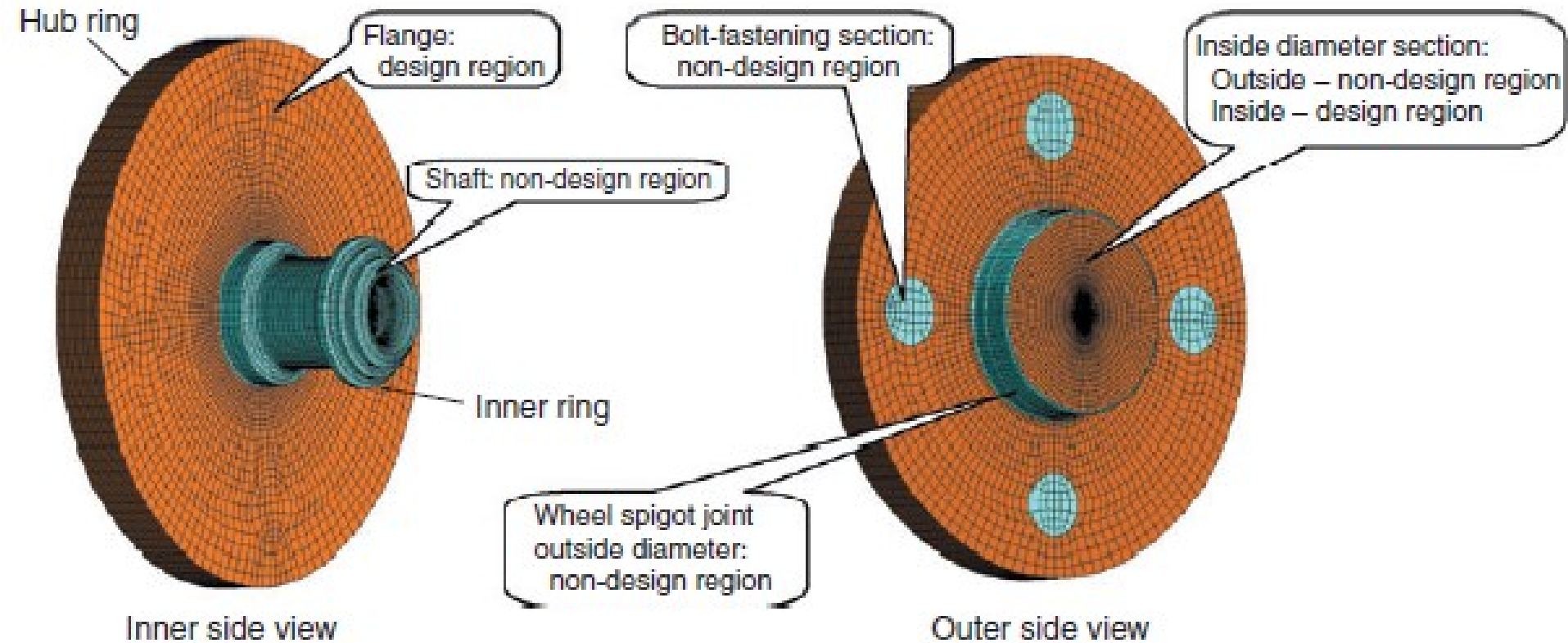


Fig.1 Hub-Bearing original design

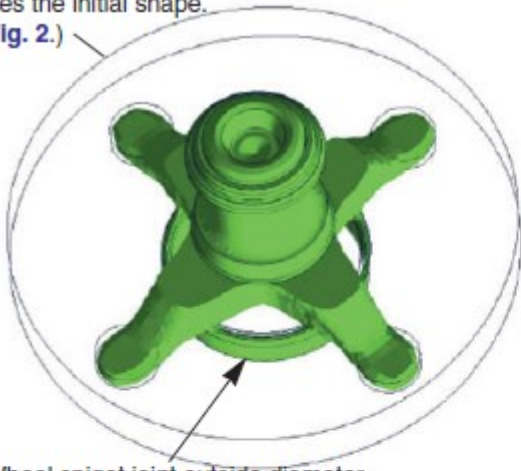
1.4 kg \rightarrow 1.0 kg
(strength, durability, rigidity)

Topology Optimization Model



Result of Topology Optimization

Indicates the initial shape.
(See Fig. 2.)



Wheel spigot joint outside diameter
(non-design region)

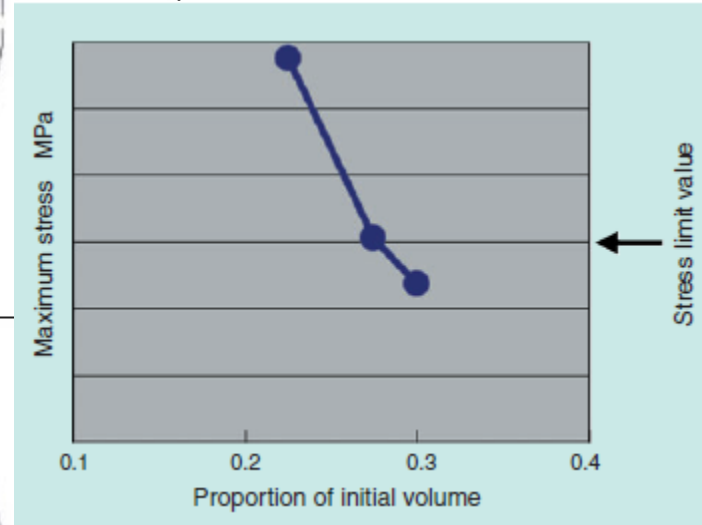
30% the initial volume



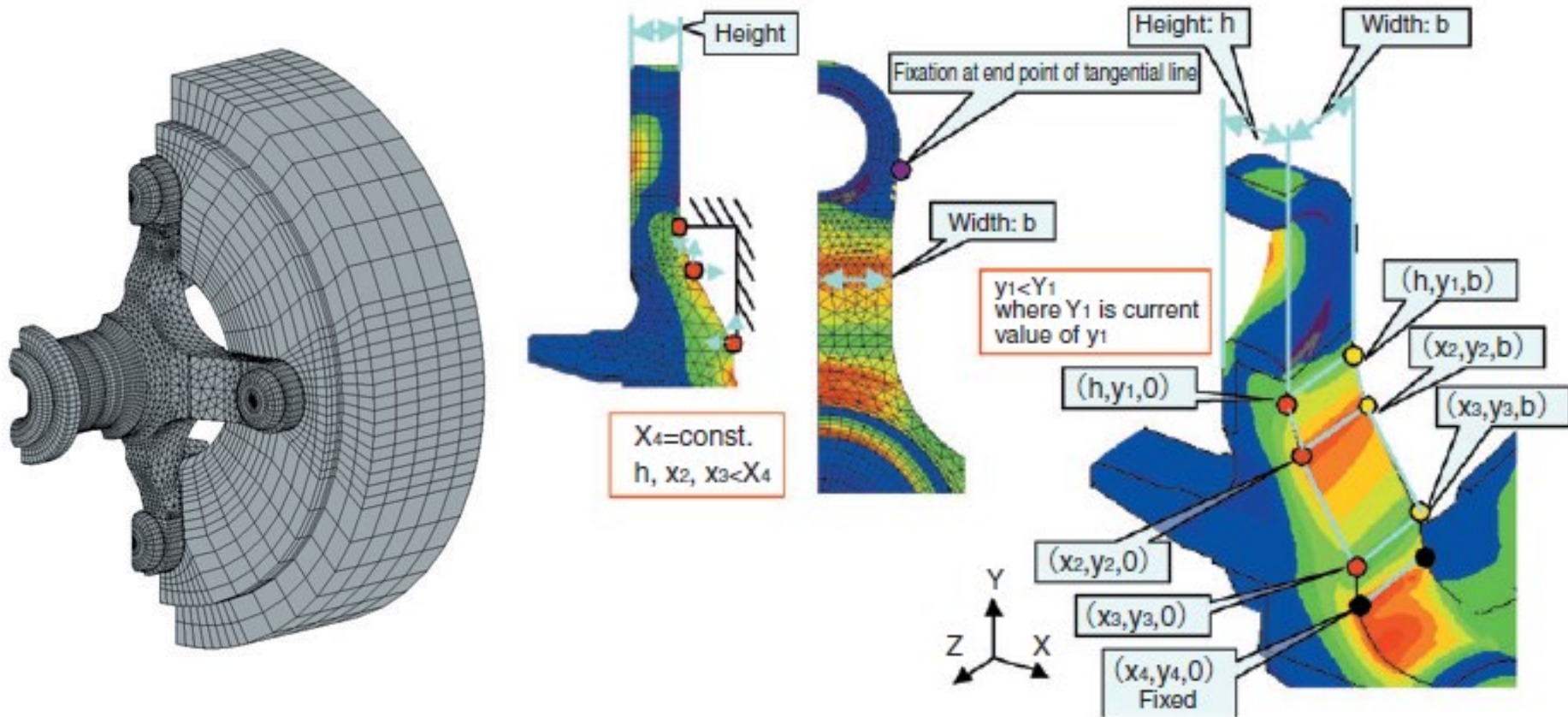
27.5% the initial volume



22.5% the initial volume

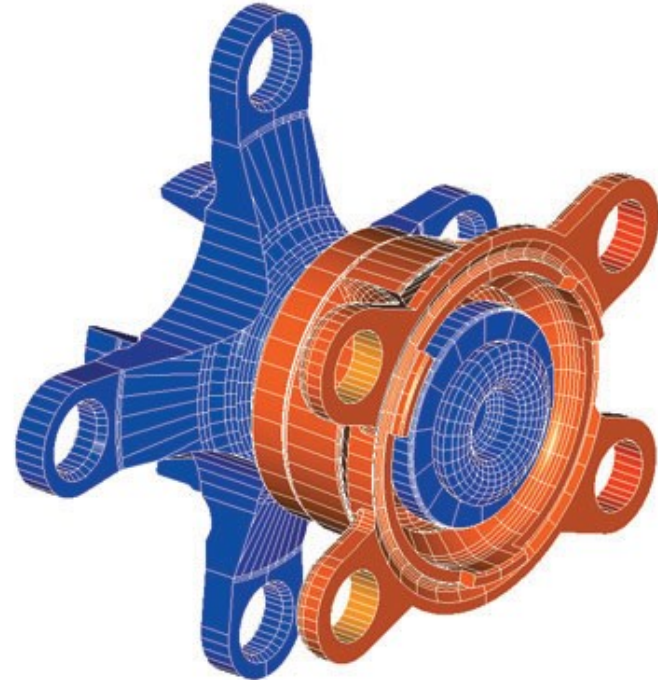
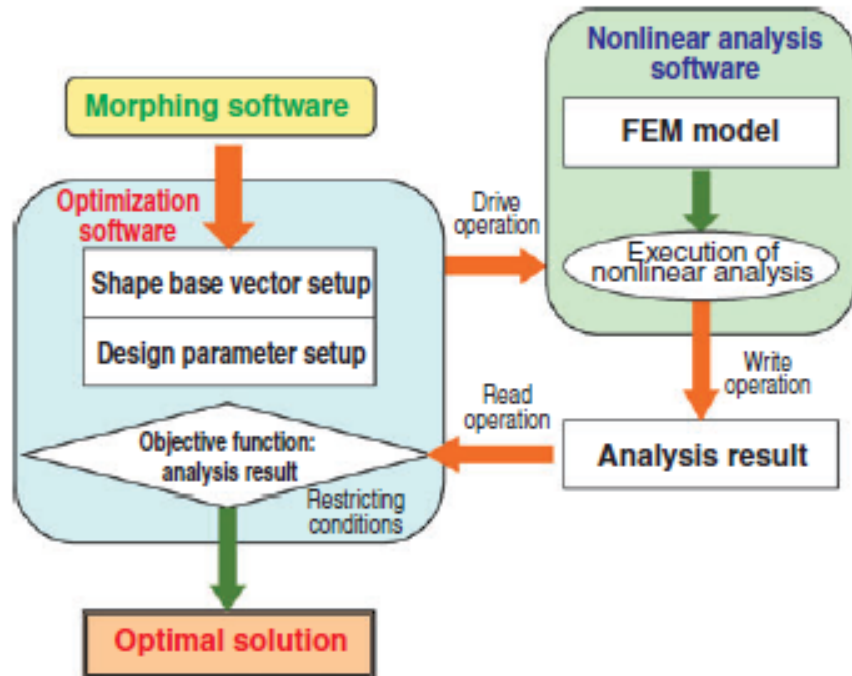


Shape Optimization



$(h, b, y_1, x_2, y_2, x_3, y_3)$

Result of Shape Optimization

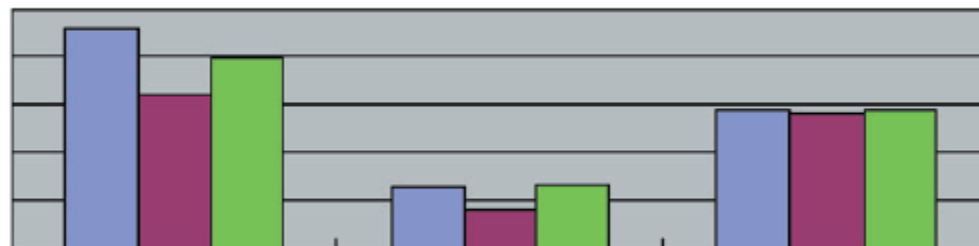


Legend: ■ L₂₇ best solution ■ Optimization



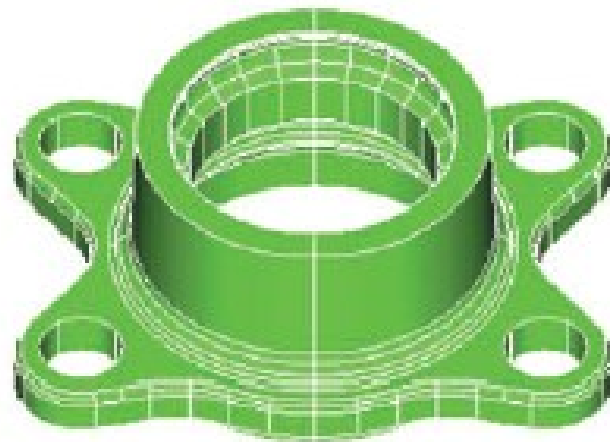
(a) Volume

Legend: ■ Initial value ■ L₂₇ best solution ■ Optimization

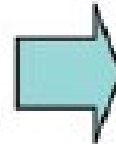


(b) Stress value

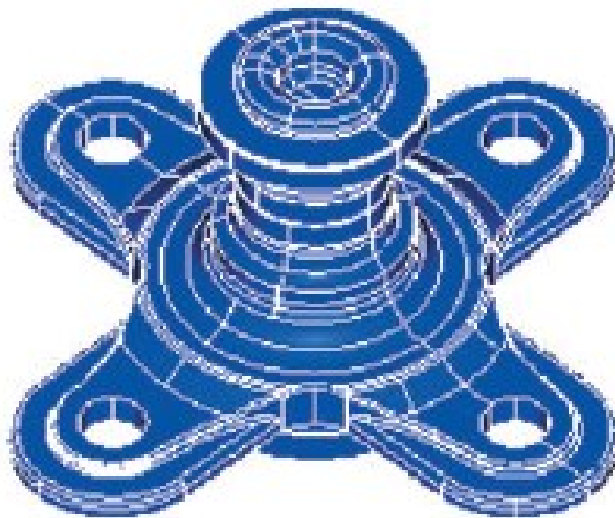
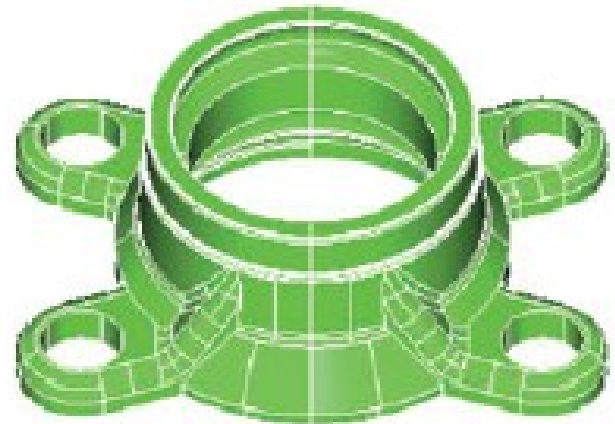
Final Design



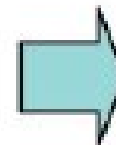
Outer ring



– 100g



Hub ring



– 240g

