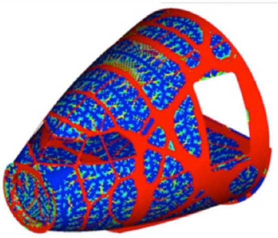
Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO

Structural and Multidisciplinary Design Optimization

TopOpt?

Prof. J. Morlier



1

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History

- Homogenization of Microstructures was introduced by mathematics in the 1970s.
- First paper by Martin Bendsoe (Technical University of Denmark) and Noboru Kikuchi (University of Michigan) in 1988

A topology optimisation problem can be written in the general form of an optimization problem as

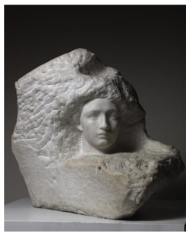
$$\min_{\rho} \ F = F(\mathbf{u}(\rho), \rho) = \int_{\Omega} f(\mathbf{u}(\rho), \rho)\mathrm{d}V$$

subject to

- $\rho \in \{0, 1\}$
- $G_0(\rho) = \int_{\Omega} \rho(\mathbf{u})\mathrm{d}V - V_0 \leq 0$
- $G_j(\mathbf{u}(\rho), \rho) \leq 0$ with $j = 1, \ldots, m$

TopOpt

Je choisis un bloc de marbre et j'enlève tout ce dont je n' ai pas besoin..
Auguste Rodin (1840-1917)



Define the design space (marble block, fixed mesh)

Apply charges & BCs

Start optimization with hyper parameters

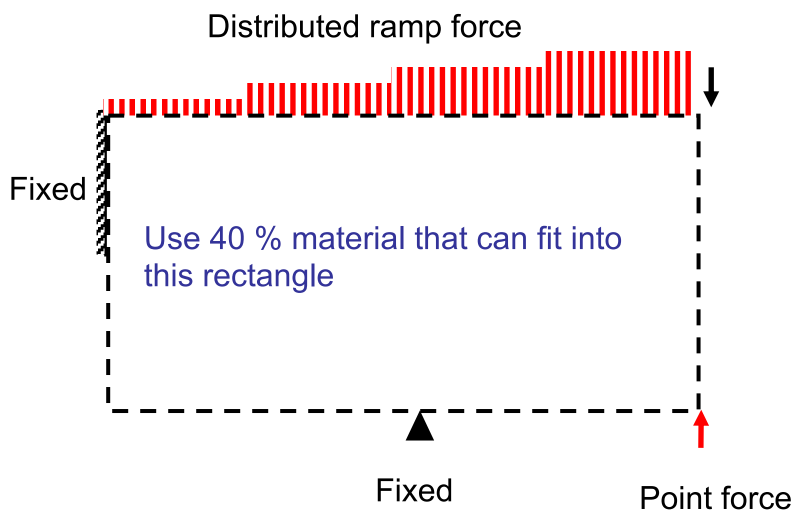
Interpreting the results

Optimal distribution of material (One can have an idea of the part to be reinforced, in addition to giving an excellent initial design ...)

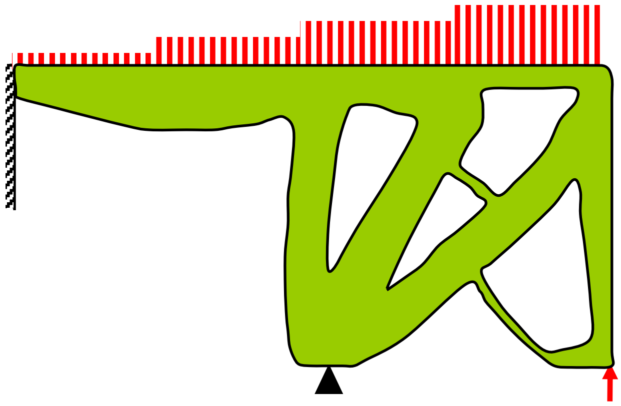
Why is it so powerful?

→There is a lot of possible redistribution of FORCES (internal)

Stiff structure for your specifications



Stiff structure for your specifications



Well-Known example

- Wing stiffening ribs of Airbus A380:

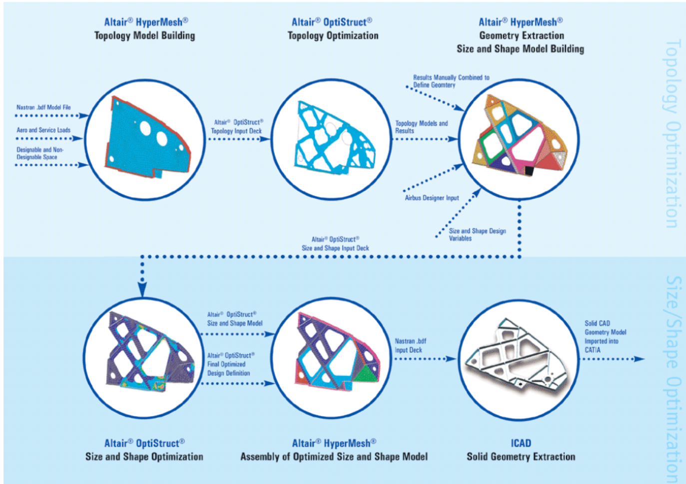
AIRBUS

- Objective: reduce weight
- Constraints: stress, buckling

Altair Engineering

6

Topology and shape optimization

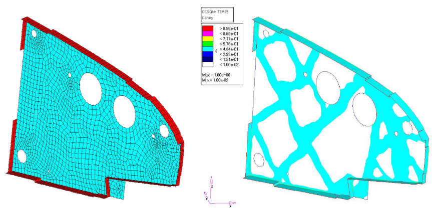


Schematic Representation of Enhanced Rib Design Process

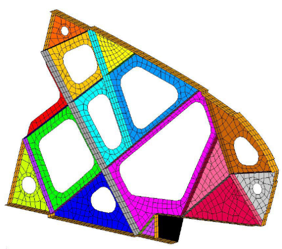
Altair Engineering

Airbus A380 example (cont.)

- Topology optimization:



- Sizing / shape optimization:



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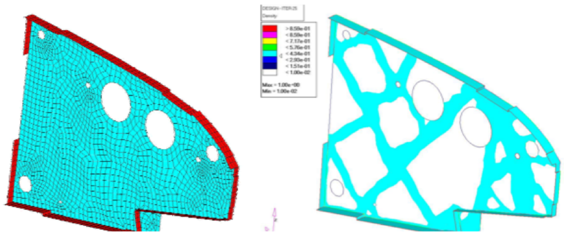
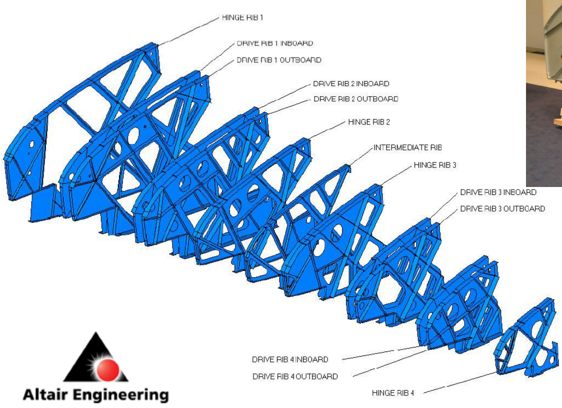
Finally…



9

Airbus A380 example (cont.)

- Result: 500 kg weight savings!



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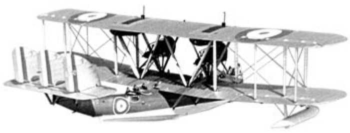
10

Wing rib designs

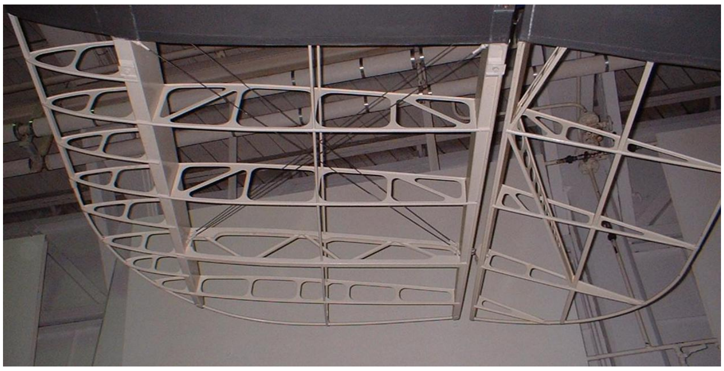
The perforated plates were replaced by reinforced lattice structures (think of the path of preferential intern foces)

Is this really a discovery?



11

Supermarine Southampton, 1925



System approach automates the process!

12

Industrial probems

TopOpt: Preliminary phases of a project

The idea is to find the best path of stiffening in a given volume of matter.

The mass is only found where it is needed, which is a good starting point for optimization of shape or dimensioning.

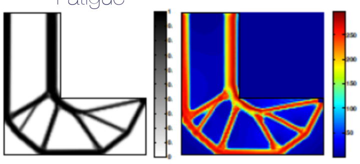
Adapted formulation:
To find the structure with the best static behavior.
The paths of internal forces identified are those which help to rigidify the structure as well as possible

→The structure will deform less, and stress levels will be possibly limited. But not only…

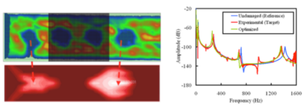
13

→Lots of Actuall Researches

Fatigue

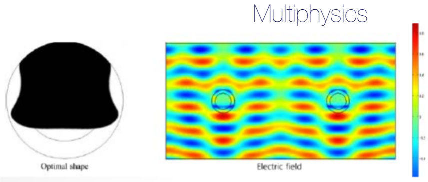


Global and clustered approaches for stress constrained topology optimization and deactivation of design variables. Erik Holmberg, Bo Torstenfelt, Anders Klarbring



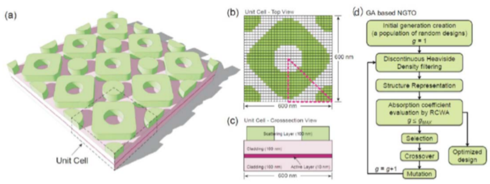
H. Niemann, J. Morlier, A. Shahdin and Y. Gourinat. Damage Localization using Experimental Modal Parameters and Topology Optimization. Mechanical Systems and Signal Processing. 24(3)636-652. 2010

Multiphysics



Topology Optimization of silver nano-particles in thin film solar cells Soohwan Byun, Jeonghoon Yoo

Microstructures

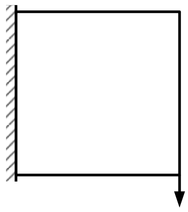


Topology Optimization for Highly-efficient Light-trapping Structure in Solar Cell Shuangcheng Yu, Chen Wang, Cheng Sun, Wei Chen*

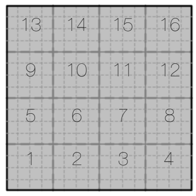
14

Discrete Material Optimization:
Prof. Pierre DUYSINX Université de Liège LTAS –
Automotive Engineering

- Maximum stiffness in the plane of a plate by selecting the best orientations of fibers



Loads and boundary conditions



Design model with 4 X4 patches

Table 4 Material properties

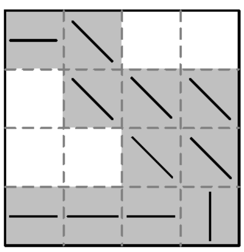
E_x	E_y	G_{xy}	ν_{xy}
146.86GPa	10.62GPa	5.45GPa	0.33

Table 3 Orientations

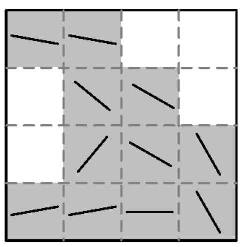
Number of material phases (m)	Number of design variables for each region (m_v)	Discrete orientation angle (°)
4	2	90/45/0/-45
9	4	80/60/40/20/0/-20/-40/-60/-80
12	4	90/75/60/45/30/15/0/-15/-30/-45/-60/-75

Discrete Material Optimization: exemple

- Topological optimization: vacuum + composite laminate
- Volume constraints: V <11/16



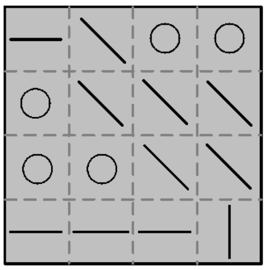
4 orientations
90/45/0/-45



18 orientations
90/80/70/60/50/40/30/20/10/0/
-10/-20/-30/-40/-50/-60/-70/-80

Discrete Material Optimization: exemple

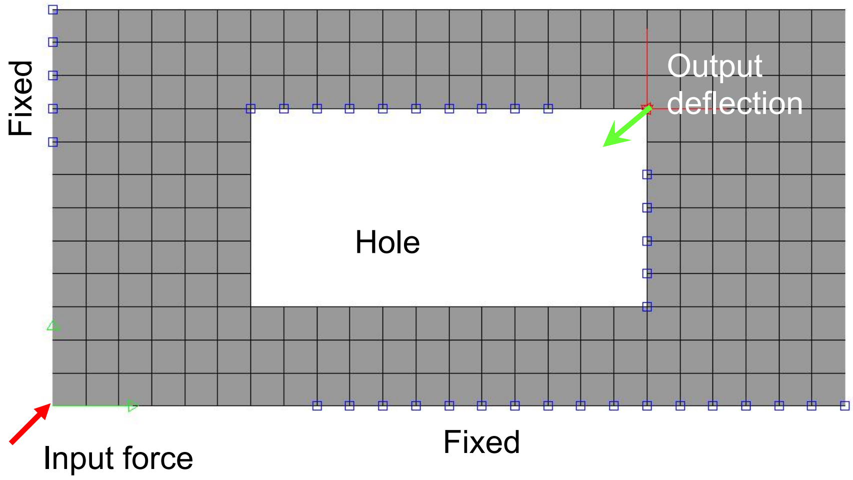
- Use of both glass fibers and foam
- Limitation of the number of domains occupied by the fiber of glass



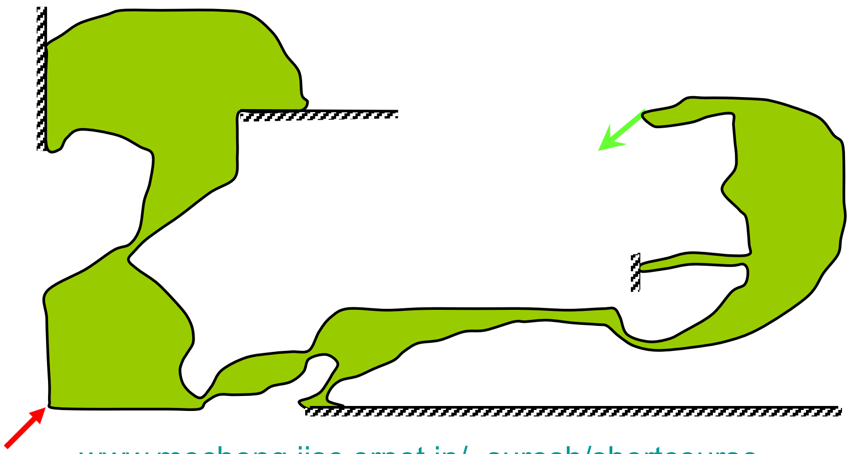
Optimization result of the square plate under vertical force with volume constraint
Glass-epoxy with 4 orientations (90/45/0/-45) and polymer-foam

Compliant mechanism to your specifications

Use 30 % material

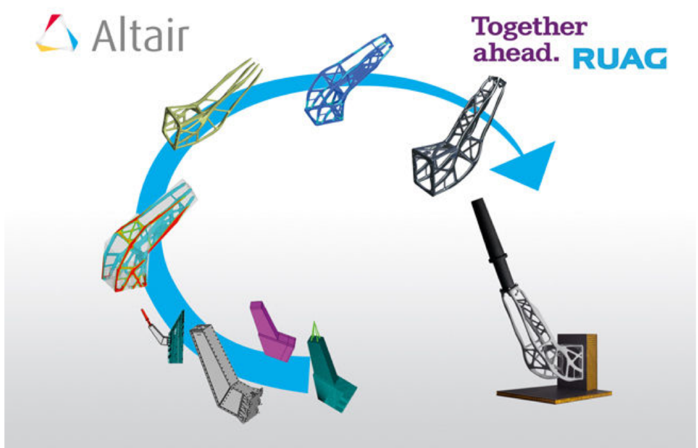


Compliant mechanism to your specifications



www.mecheng.iisc.ernet.in/~suresh/shortcourse

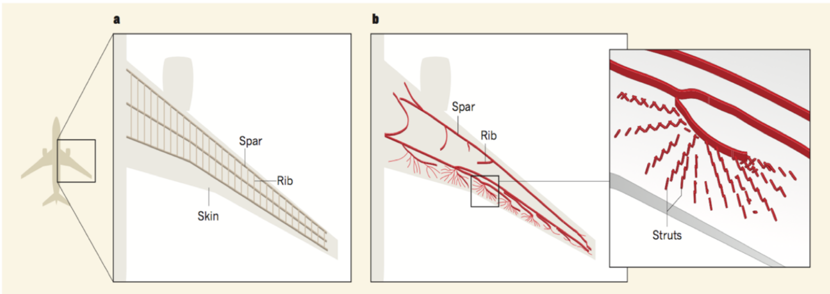
ALM



Processus de re-conception pour la fabrication additive par l'optimisation topologique

http://bcove.me/yg7pqkak

HPC

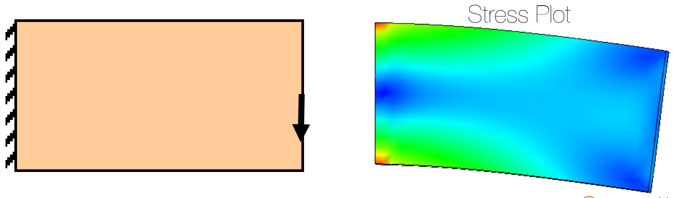


https://www.nature.com/articles/nature23911

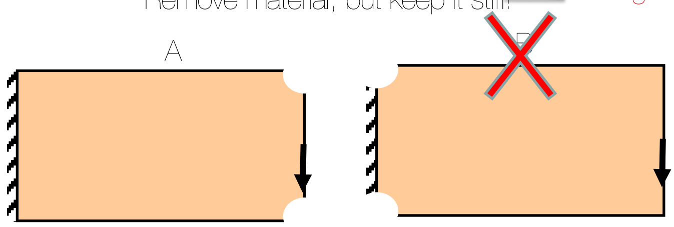
21

Intuition . . .

*See Prof Suresh’s work:
https://dl.acm.org/citation.cfm?id=1861606



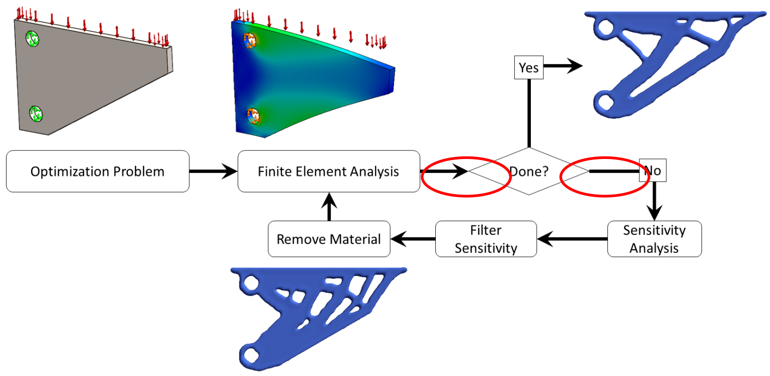
Remove material, but keep it ~~stiff~~ Strong*!



23

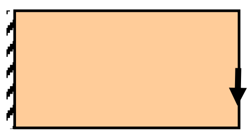
TopOpt relies on FEA

Online computation: http://www.cloudtopopt.com



24

TopOpt



$Ku = f$

Compliance $J = f^T u$

Compliance = 1/Stiffness

1. Objective?
2. Constraints?
3. Method?

Minimize Compliance

Volume Constraint

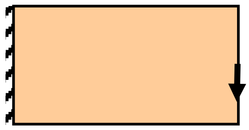
Minimize J

Vol.Frac ≤ 0.5

Method: Gradient based:
Need sensitivities…

25

Current TO Strategies



Minimize J

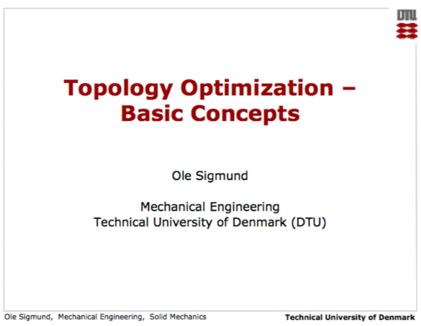
Vol.Frac ≤ 0.5

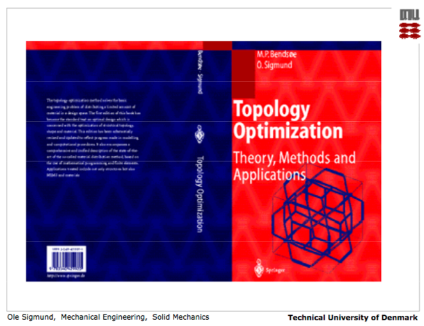
Ku = f

TO Strategies

- Homogenization
- SIMP
- Level-Set
- Evolutionary

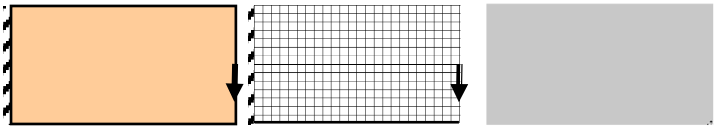
One pioneer, **SIMP** (Solid Isotropic Material with **Penalization**)





SIMP

SIMP: Solid Isotropic Material with Penalization



Min Compliance

$v = 0.5v_0$

Where do we add holes?

$0 < \rho_e \leq 1$: 'PseudoDensity'

$$\underset{\rho_e}{Min} \text{ Compliance}$$

$$\sum \rho_e v_e = 0.5 v_0$$

Intuitive Problem? Quadratic Form

- Objective function: Strain energy

$$\min c(\mathbf{x}) = \mathbf{U}^T\mathbf{F} = \mathbf{U}^T\mathbf{K}\mathbf{U} \qquad \text{with} \quad x_e = \frac{\rho_e}{\rho_0} \qquad (4)$$

with $\mathbf{K} = \mathbf{K}_0 \sum_{e=1}^{N} x_e^p$ one can write:

What is p, (simP)????????

$$\min c(\mathbf{x}) = \sum_{e=1}^{N} (x_e)^p \mathbf{u}_e^T \mathbf{k}_0 \mathbf{u}_e \qquad (5)$$

Scalar

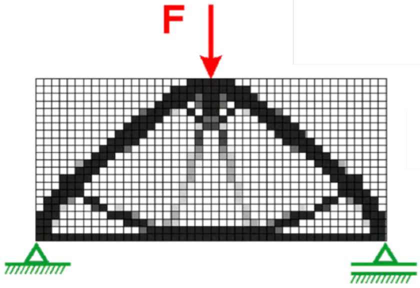
- Contraints: mass target

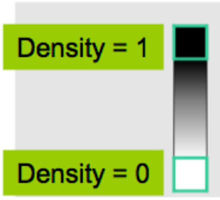
$$\frac{V(\mathbf{x})}{V_0} = f = const \iff \sum_{e=1}^{N} V_e x_e - V_0 f = 0 = h(\mathbf{x})$$

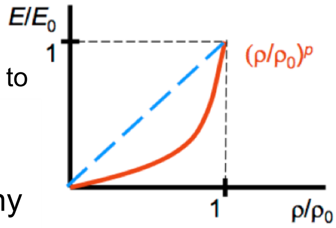
Scalar

$$0 < \rho_{\min} \leq \rho_e \leq 1$$

Penalization for altering stiffness localy







p is the penalty parameter to push densities to black (1) and white (0).

For optimization, there will be as many as the number of elements in the discretized model.

Rozvany, G.I.N. , Zhou, M., and Gollub, M. (1989). Continuum Type Optimality Criteria Methods for Large Finite Element Systems with a Displacement Connstraint, Part 1. *Structural Optimization* 1:47-72.

Penalty parameter in the SIMP method: some justification

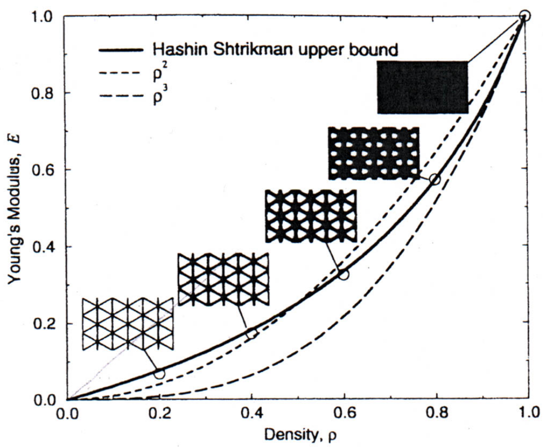
Hashin-Shtrikman bounds

$$0 \le E \le \frac{\rho E^0}{3-2\rho}$$

Therefore,

$$\rho^p E^0 \le \frac{\rho E^0}{3-2\rho}$$

$$\Rightarrow p \ge 3$$



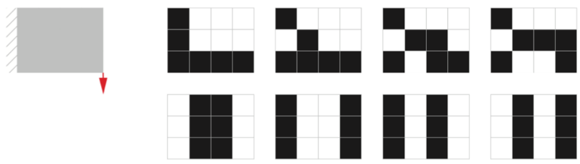
Bendsøe, M.P. and Sigmund, O., “Material Interpolation Schemes in Topology Optimization,” *Archives in Applied Mechanics*, Vol. 69, (9-10), 1999, pp. 635-654.

Pixels?

36

Pixels

- Finding a solution by checking all the possible combinations IS impossible since the number of topologies nT increases exponentially with the number of finite elements n
- nT = 2^n,



The legal (top) and some illegal (bottom) topologies with 4 by 3 elements

Division into elements (pixels or voxels) and binary decision for each
or example 10,000 elements --> 210,000 possible configurations!

37

Nice idea !

1. Transform discrete variables continuously (TO USE gradient-based algorithms)
2. Find an objective function with "cheap" derivatives (we will see this later)

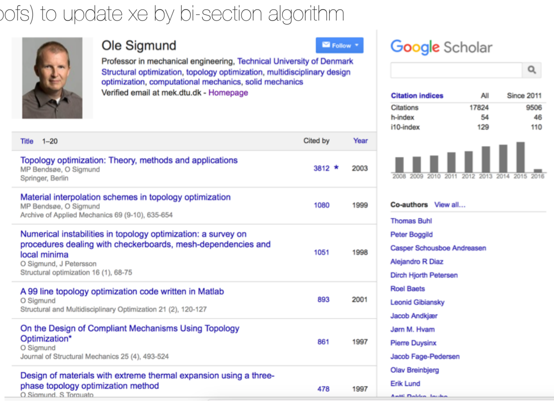
38

BUT …IN PRACTICE?

Educational article:

O. Sigmund , A 99 line topology optimization code written in Matlab Struct Multidisc Optim 21, 120–127 Springer-Verlag 2001

Heuristic formulation (intuitiive method of optimisation, but with no convergency proofs) to update xe by bi-section algorithm



39

History (1988, Bendsoe)

A topology optimization problem based on the power-law approach, where the objective is to minimize compliance can be written as

$$\left.\begin{aligned} \min_{\mathbf{x}}: &\quad c(\mathbf{x}) = \mathbf{U}^T\mathbf{K}\mathbf{U} = \sum_{e=1}^{N}(x_e)^p\, \mathbf{u}_e^T\, \mathbf{k}_0\, \mathbf{u}_e \\ \text{subject to}: &\quad \frac{V(\mathbf{x})}{V_0} = f \\ : &\quad \mathbf{K}\mathbf{U} = \mathbf{F} \\ : &\quad \mathbf{0} < \mathbf{x}_{\min} \leq \mathbf{x} \leq \mathbf{1} \end{aligned}\right\}, \tag{1}$$

where $\mathbf{U}$ and $\mathbf{F}$ are the global displacement and force vectors, respectively, $\mathbf{K}$ is the global stiffness matrix, $\mathbf{u}_e$ and $\mathbf{k}_e$ are the element displacement vector and stiffness matrix, respectively, $\mathbf{x}$ is the vector of design variables, $\mathbf{x}_{\min}$ is a vector of minimum relative densities (non-zero to avoid singularity), N ($=$ `nelx` $\times$ `nely`) is the number of elements used to discretize the design domain, p is the penalization power (typically $p = 3$), $V(\mathbf{x})$ and V_0 is the material volume and design domain volume, respectively and f (`volfrac`) is the prescribed volume fraction.

40

Compliance minimization

- Compliance is the opposite of stiffness

$$C = \mathbf{f}^T\mathbf{u} = \mathbf{u}^T K\mathbf{u}$$

- Inexpensive derivatives (use chain rule)

$$\frac{dC}{dx} = 2\mathbf{u}^T K \frac{d\mathbf{u}}{dx} + \mathbf{u}^T \frac{dK}{dx}\mathbf{u}$$

But since $K\mathbf{u} = \mathbf{f}$ if $\mathbf{f}$ does not depend on x

$$K\frac{d\mathbf{u}}{dx} = -\frac{dK}{dx}\mathbf{u}$$

$$\frac{dC}{dx} = -\mathbf{u}^T\frac{dK}{dx}\mathbf{u}$$

Density design variables

Need a DEMO ?

- Recall $$\frac{dC}{dx} = -\mathbf{u}^T \frac{dK}{dx}\mathbf{u}$$
- For density variables
$$\frac{dC}{d\rho^e} \propto -\mathbf{u}^T \rho^{p-1} K^e \mathbf{u}$$
- Want to increase density of elements with high strain energy and vice versa
- To minimize compliance for given weight can use an optimality criterion method.

Matlab Code

```
x(1:nely,1:nelx) = volfrac;                          % INITIALIZE

loop = 0; change = 1.;
while change > 0.01                                  % START ITERATION While Xk+1>>Xk
        loop = loop + 1;
        xold = x;
        [U]=FE(nelx,nely,x,penal);       % FE-ANALYSIS
        [KE] = lk;
        c = 0.;

for ely = 1:nely
  for elx = 1:nelx
    n1 = (nely+1)*(elx-1)+ely;
    n2 = (nely+1)* elx +ely;
    Ue = U([2*n1-1;2*n1; 2*n2-1;2*n2; 2*n2+1;2*n2+2; 2*n1+1;2*n1+2],1);
    c = c + x(ely,elx)^penal*Ue'*KE*Ue;                % OBJECTIVE FUNCTION
    dc(ely,elx) = -penal*x(ely,elx)^(penal-1)*Ue'*KE*Ue; % SENSITIVITY ANALYSIS
end
```

Sensitivity

$$\frac{\partial c}{\partial x_e} = -p(x_e)^{p-1}\, \mathbf{u}_e^T\, \mathbf{k}_0\, \mathbf{u}_e$$

Update rule

- OPTIMALITY CRITERIA METHOD

$$\begin{cases} \max(x_{\min}, x_e - m) \\ \quad \text{if} \quad x_e B_e^\eta \leq \max(x_{\min}, x_e - m)\,, \\ x_e B_e^\eta \\ \quad \text{if} \quad \max(x_{\min}, x_e - m) < x_e B_e^\eta < \min(1, x_e + m) \\ \min(1, x_e + m) \\ \quad \text{if} \quad \min(1, x_e + m) \leq x_e B_e^\eta\,, \end{cases} \qquad B_e = \frac{-\dfrac{\partial c}{\partial x_e}}{\lambda \dfrac{\partial V}{\partial x_e}}$$

44

Element Stiffness Matrix

```
function [KE]=lk
%Element Stiffness Matrix

E = 1.;
nu =1/3.;
k=[ 1/2-nu/6 1/8+nu/8 -1/4+nu/12 -1/8-nu/8
-1/4-nu/12 -1/8+3*nu/8 ... nu/6 1/8-3*nu/8];
KE = E/(1-nu^2)* ...
[ k(1) k(2) k(3) k(4) k(5) k(6) k(7) k(8)
k(2) k(1) k(8) k(7) k(6) k(5) k(4) k(3) k(3) k(8) k(1) k(6)
k(7) k(4) k(5) k(2) k(4) k(7) k(6) k(1) k(8) k(3) k(2) k(5)
k(5) k(6) k(7) k(8) k(1) k(2) k(3) k(4) k(6) k(5) k(4) k(3)
k(2) k(1) k(8) k(7) k(7) k(4) k(5) k(2) k(3) k(8) k(1) k(6)

k(8) k(3) k(2) k(5) k(4) k(7) k(6) k(1)];
```


FEM Analysis

```
function [U]=FE(nelx,nely,x,penal)
[KE] = lk;
K = sparse(2*(nelx+1)*(nely+1), 2*(nelx+1)*(nely+1));
F = sparse(2*(nely+1)*(nelx+1),1); U = zeros(2*(nely+1)*(nelx+1),1);
for elx = 1:nelx
 for ely = 1:nely
  n1 = (nely+1)*(elx-1)+ely;
  n2 = (nely+1)* elx +ely;
  edof = [2*n1-1; 2*n1; 2*n2-1; 2*n2; 2*n2+1; 2*n2+2; 2*n1+1; 2*n1+2];
  K(edof,edof) = K(edof,edof) + x(ely,elx)^penal*KE;
end
 end
F(2*(nelx+1)*(nely+1),1)=-1;
fixeddofs=union([1,2],[2*nely+1:2*(nely+1)]);
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
% SOLVING
U(freedofs,:) = K(freedofs,freedofs) \ F(freedofs,:);
U(fixeddofs,:)= 0;
```

OPTIMALITY CRITERIA

```
function [xnew]=OC(nelx,nely,x,volfrac,dc)
l1 = 0; l2 = 100000; move = 0.2;
while (l2-l1 > 1e-4)
 lmid = 0.5*(l2+l1);
 xnew = max(0.001,max(x-move,min(1.,min(x+move,x.*sqrt(-dc./lmid)))));
 if sum(sum(xnew)) - volfrac*nelx*nely > 0;
   l1 = lmid;
 else
   l2 = lmid;
 end
end
```

lmid: 50.0000	l1: 0.0000	l2: 50.0000
lmid: 25.0000	l1: 0.0000	l2: 25.0000
lmid: 12.5000	l1: 0.0000	l2: 12.5000
lmid: 6.2500	l1: 6.2500	l2: 12.5000
lmid: 9.3750	l1: 6.2500	l2: 9.3750
lmid: 7.8125	l1: 6.2500	l2: 7.8125
lmid: 7.0313	l1: 7.0313	l2: 7.8125
lmid: 7.4219	l1: 7.0313	l2: 7.4219
lmid: 7.2266	l1: 7.2266	l2: 7.4219
lmid: 7.3242	l1: 7.3242	l2: 7.4219
lmid: 7.3730	l1: 7.3242	l2: 7.3730
lmid: 7.3486	l1: 7.3242	l2: 7.3486
lmid: 7.3364	l1: 7.3364	l2: 7.3486
lmid: 7.3425	l1: 7.3425	l2: 7.3486
lmid: 7.3456	l1: 7.3425	l2: 7.3456
lmid: 7.3441	l1: 7.3441	l2: 7.3456
lmid: 7.3448	l1: 7.3448	l2: 7.3456
lmid: 7.3452	l1: 7.3448	l2: 7.3452
lmid: 7.3450	l1: 7.3450	l2: 7.3452
lmid: 7.3451	l1: 7.3450	l2: 7.3451

47

Can also use:

- fmincon
- MMA…

The MMA approach, which was initially proposed by Svanberg (see Mini Project) is based on the first-order Taylor series expansion of the objective and constraint functions.

With this method, an explicit convex subproblem is generated to approximate the implicit nonlinear problem.

48

Matlab code command

top(nelx, nely, volfrac, penal, rmin)

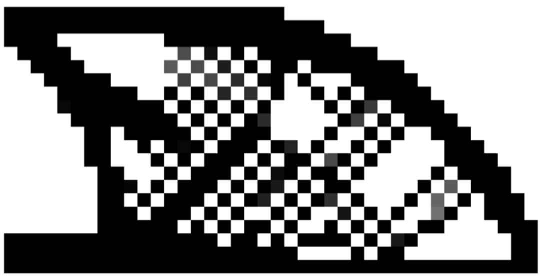
- nelx and nely: number of elements in the horizontal and vertical directions,
- volfrac: volume fraction,
- penal: penalization power,
- rmin: filter size (divided by element size).

49

Example 1

Numerical instability

- top(40, 20, 0.5, 3, 1.0)



effect→ Checkerboard Pattern

50

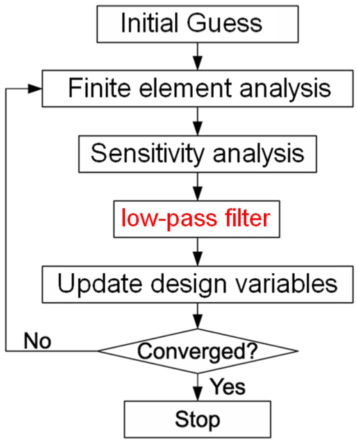
Example 1 -- Checkerboard Pattern Problem

→ Solution: LOW PASS Filter

$$\widehat{\frac{\partial c}{\partial x_e}} = \frac{1}{x_e \sum_{f=1}^{N} \hat{H}_f} \sum_{f=1}^{N} \hat{H}_f \, x_f \, \frac{\partial c}{\partial x_f}.$$

$$\hat{H}_f = r_{\min} - \mathrm{dist}(e,f),$$

$$\{f \in N \mid \mathrm{dist}(e,f) \le r_{\min}\}, \quad e = 1, \ldots, N$$



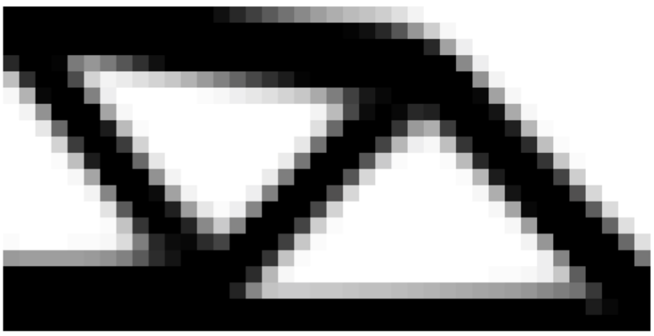
[dc] = check(nelx, nely, rmin, x, dc);

% FILTERING OF SENSITIVITIES

51

Example 2

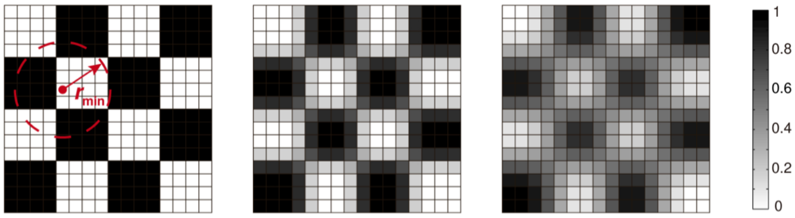
- top(40, 20, 0.5, 3, 1.5)



- top(40, 20, 0.5, 3, 3) effect?

52

Filter



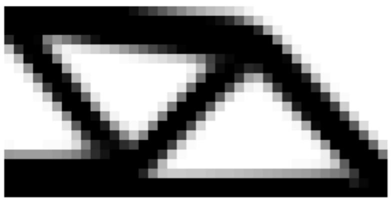
A checkerboard field and filtered fields ($r_{\min} = 1.5l_e$ and $3l_e$)

Example 2

→ Size of the filter makes it possible to obtain a more physical representation (Unblur?)

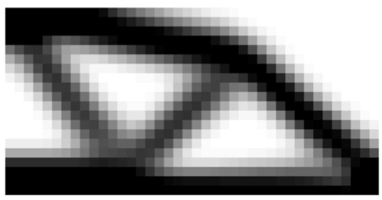
- rmin=1.5

Obj=82.7562;



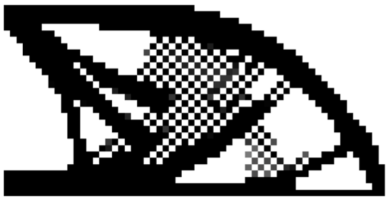
- rmin=3

Obj=99.1929;



Example 3: Change mesh !

- top(60, 30, 0.5, 3, 1.0)
Obj: 83.0834



- top(40, 20, 0.5, 3, 1.0)
Obj: 80.4086;

Example 3: mixing

- top(60, 30, 0.5, 3, 1.5)
Obj: 81.3491

→ Filter size

- top(60, 30, 0.5, 3, 2.25)
Obj: 83.5963

→ +mesh dependency, combined eddect It's complicated

- top(40, 20, 0.5, 3, 1.5)
Obj=82.7562;

NanoProject

Optimisation topologique avec Matlab
Ce n'est pas noté !
J. Morlier*[1]

Le maillage EF est composé de quadrangle de taille 1*1. La densité appelée x, est définie tq $0.001 \leq x \leq 1$. (la borne inf est non nulle, pour que K ne soit pas singulière). La correspondance entre les éléments de la matrice des densités et le modèle EF est donnée sur la figure 1.1.

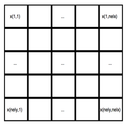


Figure 1: Index de la matrice densité

Nous allons dans cette exercice essayer (en lisant l'article associée au code top.m) d'optimiser la conception d'un cadre de bicyclette.

Le domaine de conception est donnée ci dessous (figure 3)

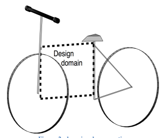
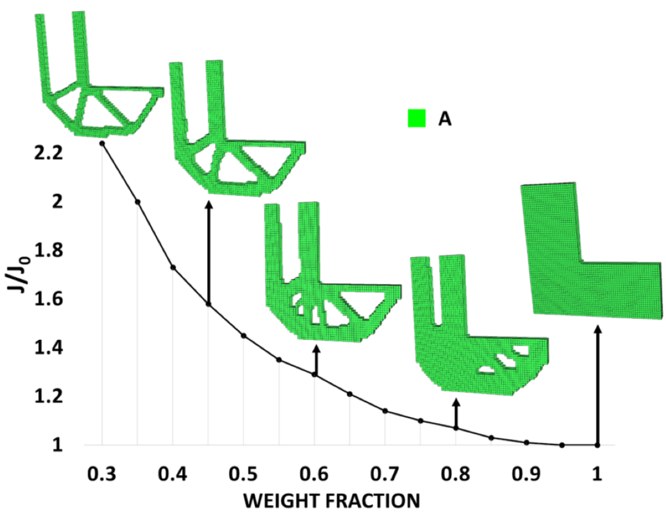


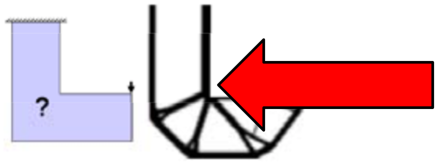
Figure 2: domaine de conception

[1] *d'apres le site:
http://www.topopt.dtu.dk

The engineer's way: Pareto



At this time the structure is rigid… but feasible?

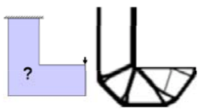


Check the stress?

60

Stress based TOPOPT

That's the subject of the marked miniproject…Just after the pause

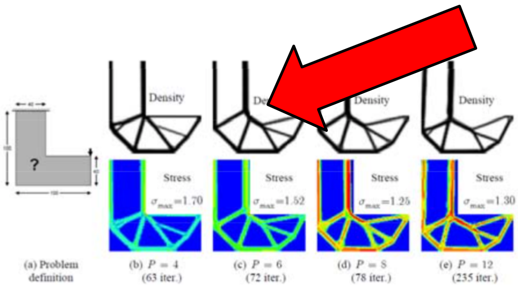


$$
\begin{aligned}
\min_{\rho} &: \max_{e}(\sigma_e)_{VM} \\
s.t. &: \sum_{e=1}^{N} v_e \rho_e \le V^* \\
&: \mathbf{0} \le \boldsymbol{\rho} \le \mathbf{1} \\
&: \mathbf{K}(\boldsymbol{\rho})\mathbf{U} = \mathbf{F}
\end{aligned}
$$

$$
\begin{aligned}
\min_{\rho} &: \sum_{e=1}^{N} v_e \rho_e \\
s.t. &: (\sigma_e)_{VM} \le \rho_e^p \sigma^*, \quad \text{if } \rho_e > 0, \quad e = 1, \dots, N \\
&: \mathbf{0} \le \boldsymbol{\rho} \le \mathbf{1} \\
&: \mathbf{K}(\boldsymbol{\rho})\mathbf{U} = \mathbf{F}
\end{aligned}
$$

61

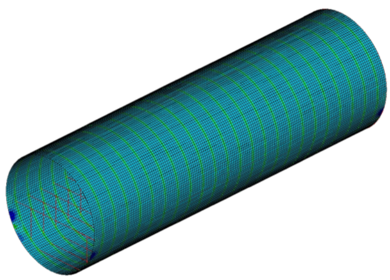
Results

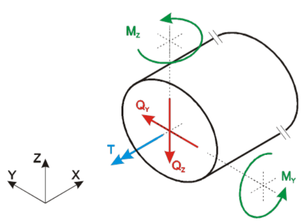


Le *et al.*, *SMO* (2010)

Its it better?

Topopt on barrel (Fuselage) using Optistruct





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Structural topology optimization for multiple load cases using a dynamic aggregation technique

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(*Received 1 December 2008; final version received 16 March 2009*)

A series of techniques is presented for overcoming some of the numerical instabilities associated with SIMP materials. These techniques are combined to create a robust topology optimization algorithm designed to be able to accommodate a large suite of problems that more closely resemble those found in industry applications. A variant of the Kreisselmeier–Steinhauser (KS) function in which the aggregation parameter is dynamically increased over the course of the optimization is used to handle multi-load problems. Results from this method are compared with those obtained using the bound formulation. It is shown that the KS aggregation method produces results superior to those of the bound formulation, which can be highly susceptible to local minima. Adaptive mesh-refinement is presented as a means of addressing the mesh-dependency problem. It is shown that successive mesh-refinement cycles can generate smooth, well-defined structures, and when used in combination with nine-node elements, virtually eliminate checkerboarding and flexural hinges.

Keywords: topology optimization; Kreisselmeier–Steinhauser function; adaptive mesh refinement; multiple load cases

1. Introduction

Since the its inception more than two decades ago (Bendsøe and Kikuchi 1988), topology optimization has undergone significant growth both in terms of its number of practitioners as well as the types of problems to which it is applied. Researchers from a wide range of disciplines and industries have adopted the method due to its ability to produce highly efficient, light-weight structures. A salient example of this trend is the Airbus A380 aircraft (Krog *et al*. 2004), in which topology optimization was used in the preliminary structural layout design of the leading edge and wingbox ribs. Examples such as this highlight the need for increased robustness in topology optimization algorithms. The desire to generate optimized topologies for feasible real-world structures demands that these frameworks come equipped with features and capabilities that take into account factors such as multiple load cases, material failure constraints, and buckling effects.

These considerations often give rise to optimization constraints that are difficult to implement due to numerical instabilities inherent in most topology optimization procedures. This article

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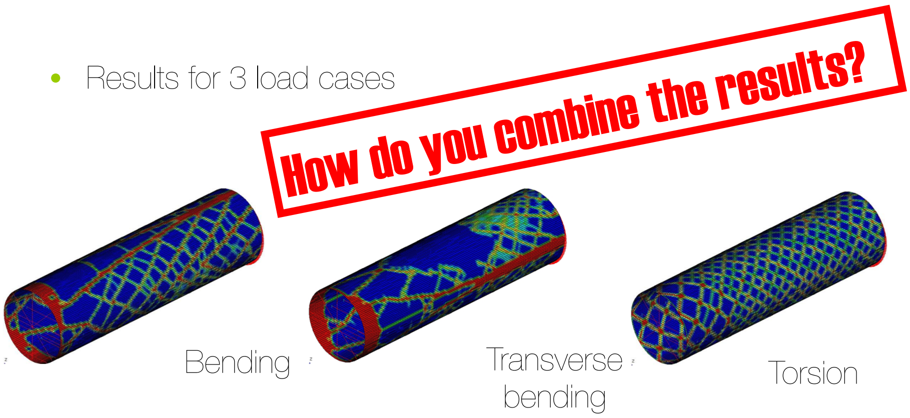
http://www.informaworld.com

Topology Optimisation –Altair Optistruct

- Results for 3 load cases

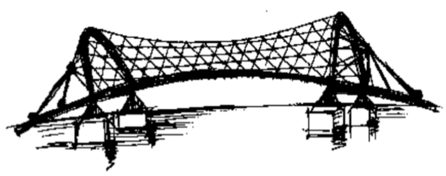


64

Conclusion

"The art of structure is where to put the holes"

Robert Le Ricolais
French-American engineer and philosopher
(1894-1977)



68