OptiCon'98

Emerging Technology in Optimization

An Image Based Approach for CAE

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CAE at Present

An Introduction to Image Based CAE

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Current Approach in CAE

- Parametric (Geometry Based) CAD / CAE
  - Standard CAD Software is based on computational geometry by using parametric spline representation to define shape of a structure/domain
  - All of the existing CAD software are geometry based : Pro-E, UNIGRAPHICS, I-DEAS,CATIA, ...
  - In FEA, automatic mesh generation methods are also based on parametric representation of geometry

Lots of Sophistication
and
Big Success (2D,3D?)

Realization of importance and profitability of Parametric Geometry Based CAD and CAE

Industry Standard in CAD

- Automotive Industry
  - UNIGRAPHICS in GM
  - I-DEAS in FORD
  - CATIA in CHRYSLER

Paradigm Shift in 90s

- Leading companies have given up In-House CAD/CAE software

CAD/CAE Acceptance Not Yet

- 2D CAD is widely accepted, but 3D CAD is too sophisticated for majority of designers and manufacturers
- CAE becomes an accepted tool for single disciplinary analysis, but not sufficient to create new value except few areas (crash, forming, etc)

MCAE+FCAE=CAE

- MCAE(Mechanical CAE)
- FCAE(Fluid CAE)

- Two separated CAE, Two separated Preprocessing Software, Two separated CAE analysis specialists …..Difficulty of Integration for Design and Manufacturing

Trend in (M)CAE

- Major Software Houses
  - MSC/NASTRAN,PATRAN,ABAQUS (US,Europe,Japan)
  - ESI/PAMCRASH,PAMSTAMP,COMPOSIC (Europe,Japan,US)

Consolidation

Linear
Nonlinear
Impact
(Multi-Body)
Design Optimization

  - Others : Swanson/ANSYS, LS/DYNA, ALGOR, …..MDI/ADAMS,

Two Paths for Survival

- Total Consolidated MCAE/FCAE
  - Analysis(Linear,Nonlinear,Impact,Multi-body), Design Optimization, Simulation of Manufacturing Processes : ***Total CAE***
  - ESI is a typical example : European's Approach
  - MSC may follow : US for survival
- Integration with (Imbedding to) CAD
  - CAD software absorb linear CAE for ***Design***
  - MCAE is a part of major CAD software

CAD Imbedded MCAE

- CAD absorbs CAE software
- Simulation of Design Feasibility
  - Based on only Linear Analysis
  - users are Designers rather than Analysts
  - Less Accuracy but user oriented
  - possibly Design Optimization capability
  - ***DESIGN ORIENTED***
- Short Turn Around Time

Effort in MCAE

- For Shortening of Turn Around Time by Simplifying FE Modeling Methods
  - **CAD Linked Automatic Mesh Generation**
  - **Adaptive FE Methods (h and p elements)**
  - **Meshless FE Methods (ANALYSIS)**
- Integration with Design Optimization
  - **Design Sensitivity Analysis**
  - **Size,Shape, and Topology Optimization**

Importance

- Shortening of ***Modeling Time***
- Integration of MCAE and FCAE for
  - Design and Simulation of Manufacturing Process

PARADIGM CHANGE !

  - Automatic Mesh Generation ?   How?

Image Based CAE

Originated From/Based On OPTISHAPE

Topology Optimization

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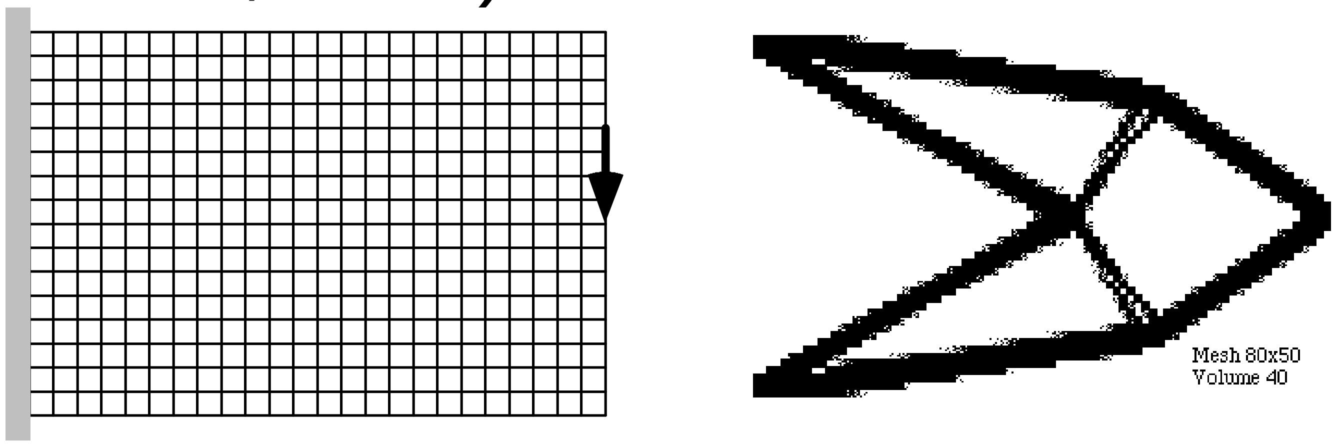
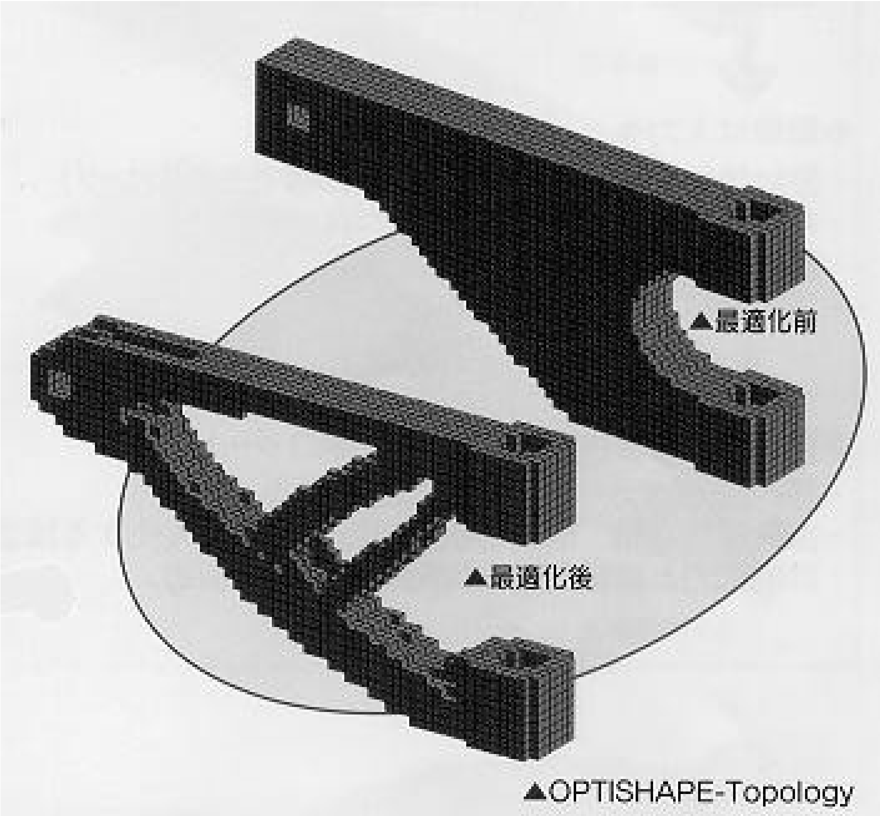
Topology Design Method

- Shape and Topology Design of Structures is transferred to Material Distribution Design (Bendsoe and Kikuchi, 1986)



TDM : 3D Shaping



Truly Three-dimensional shaping of a structure for optimum

Without parametric shape definition by splines

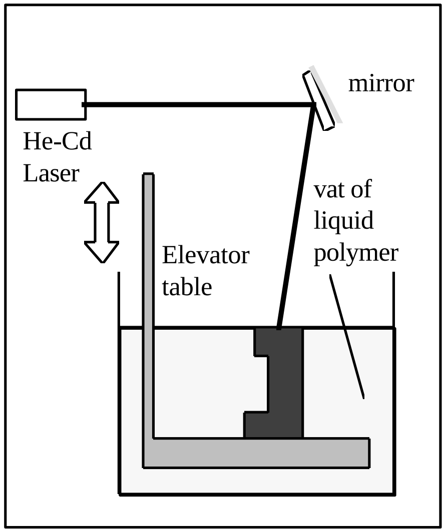
Closely Related to Rapid Prototype

Layer by Layer Operation

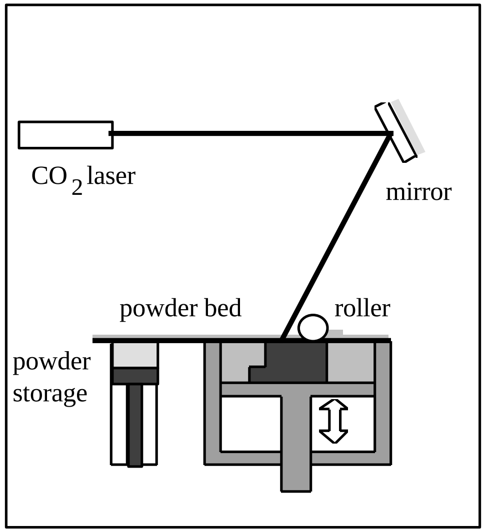
Link with CAD for pixel operation

Utility of STL (SLC) file

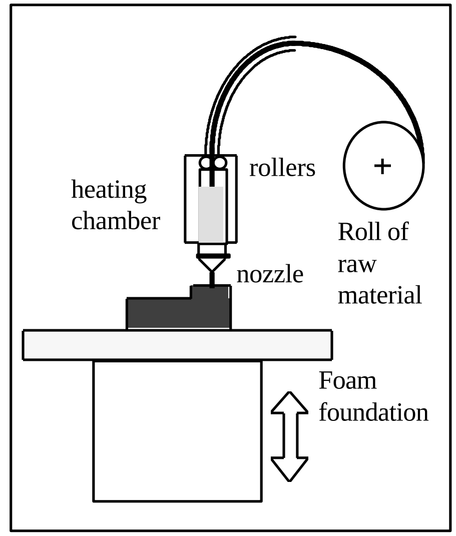
Typical Layerd Manufacturing Processes



Stereolithography



Selective Laser Sintering



Fused Deposition Modeling

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What we have done at University of Michigan in a DARPA Project ?

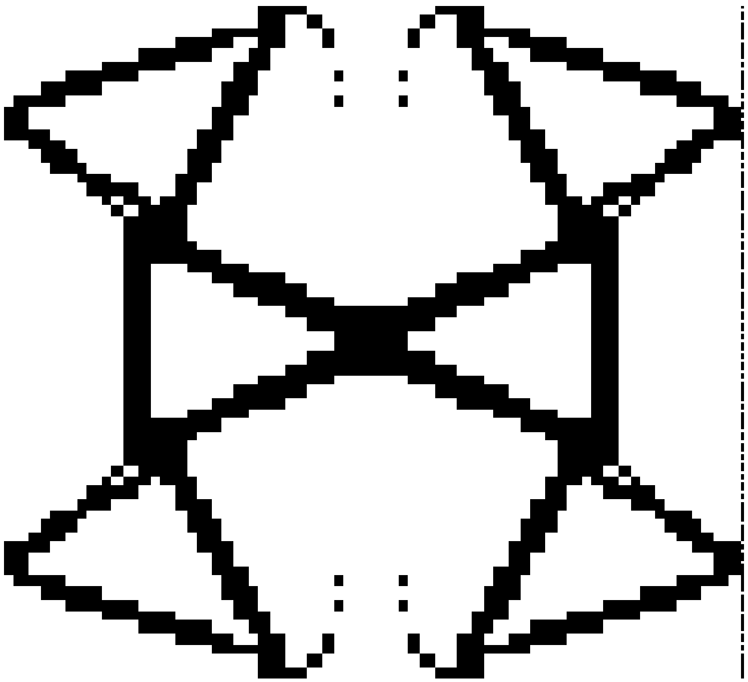
Project MAXWELL

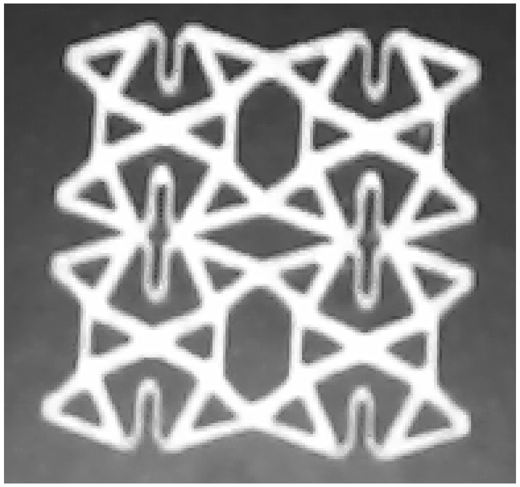
Two way communication between image and CAD data for Topology Optimization

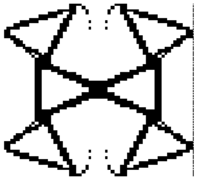
OPTISHAPE : *Material Design*

A Homogenization Design Method for
Topology of Structures and Materials

Poisson's
Ratio
- 0.5







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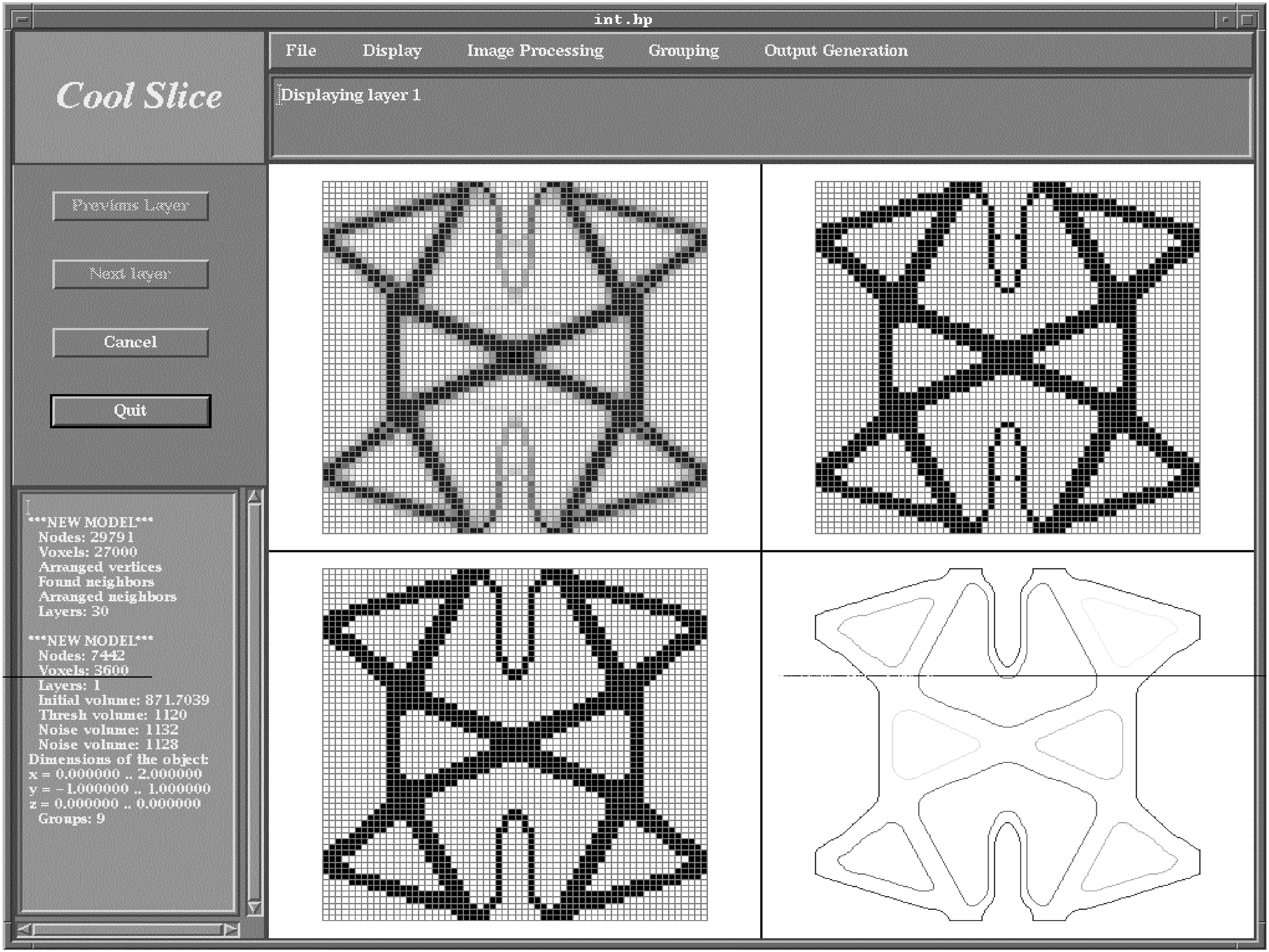


int.hp
File
Display
Image Processing
Grouping
Output Generation
Cool Slice
Displaying layer 1
Previous Layer
Next layer
Cancel
Quit
NEW MODEL
Nodes: 29791
Voxels: 27000
Arranged vertices
Found neighbors
Arranged neighbors
Layers: 30
NEW MODEL
Nodes: 7442
Voxels: 3600
Layers: 1
Initial volume: 871.7039
Thresh volume: 1120
Noise volume: 1132
Noise volume: 1128
Dimensions of the object:
x = 0.000000 .. 2.000000
y = -1.000000 .. 1.000000
z = 0.000000 .. 0.000000
Groups: 9

Image

Finite Element Modeling

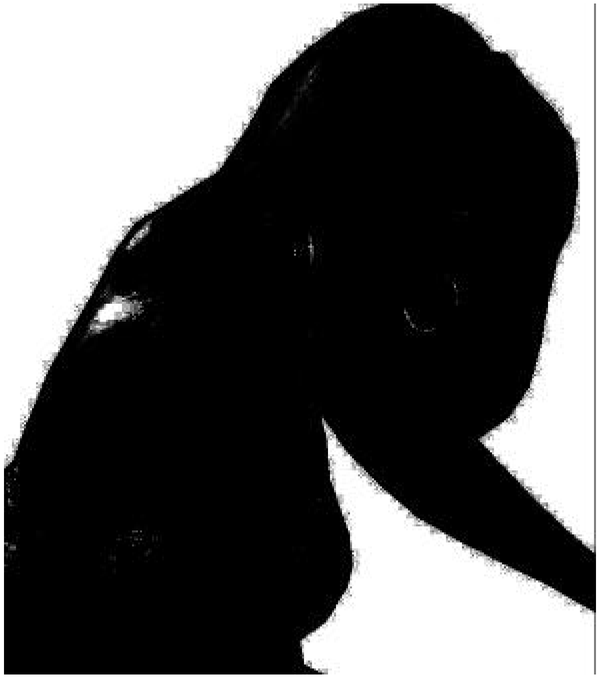
Finite Element Analysis

Design Optimization

Parametric Geometry

CAD & Rapid Prototype

Image Manipulation



Gray Scale Image

Adjust Level of Gray Scale

Mosaic Filtering

pixel/voxel mesh

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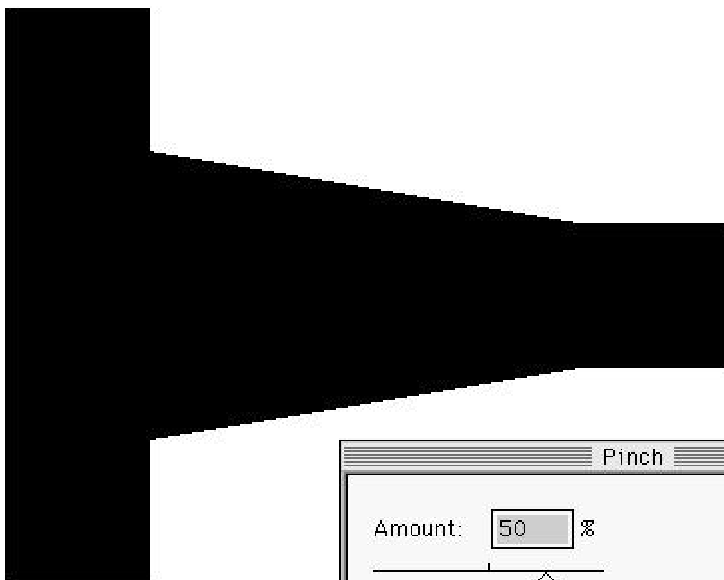
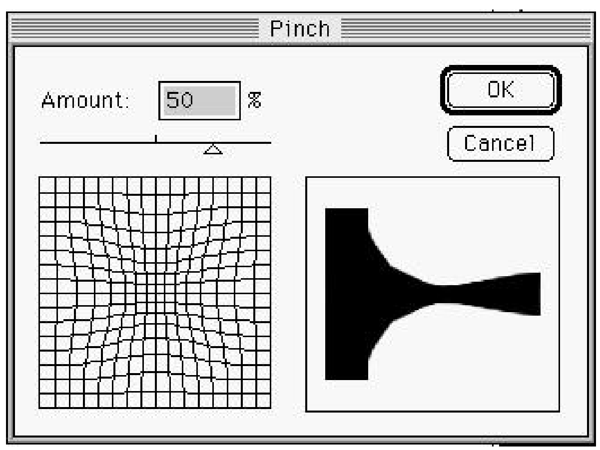
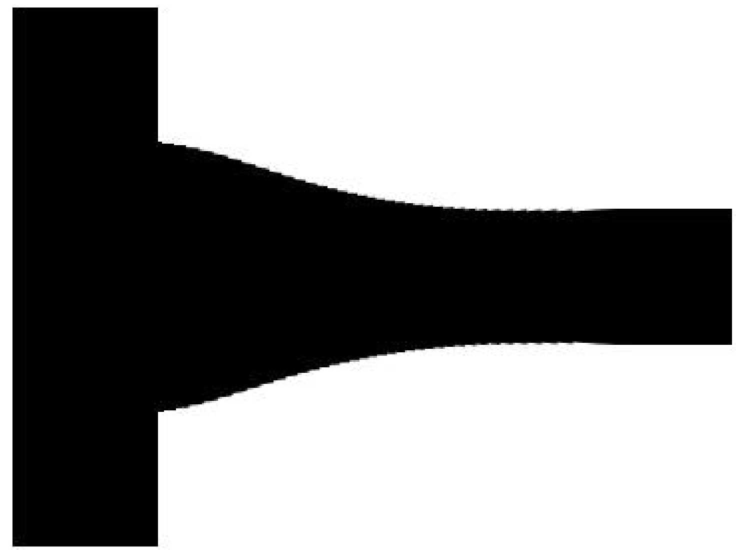
Pinching Filtering







Filtering Operation makes design change

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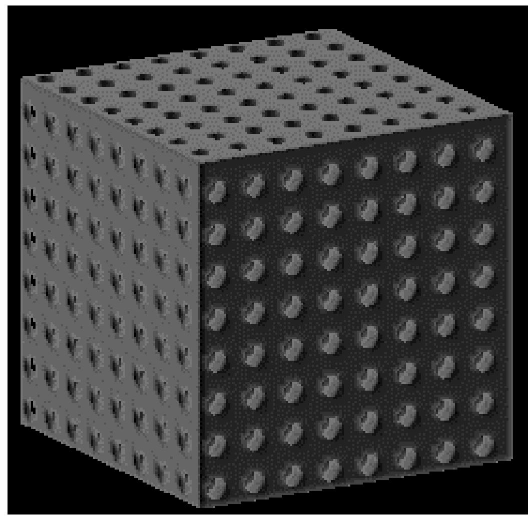
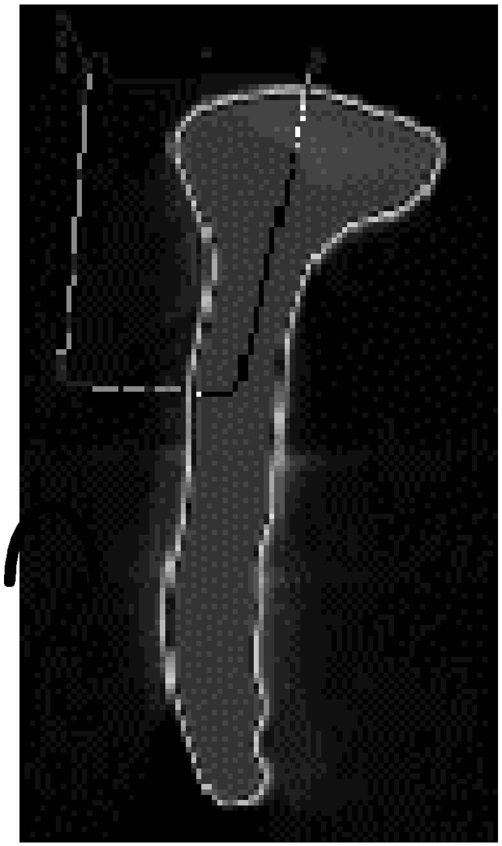
Image Algebra for Modeling

- $c^{isa} = 253$ or 252, $c^{TRR} = 255$, $0 < c^{anat} < 252$
- **Initial Scaffold defined by**
- **Accomplished in PV-Wave using *Where* mask**





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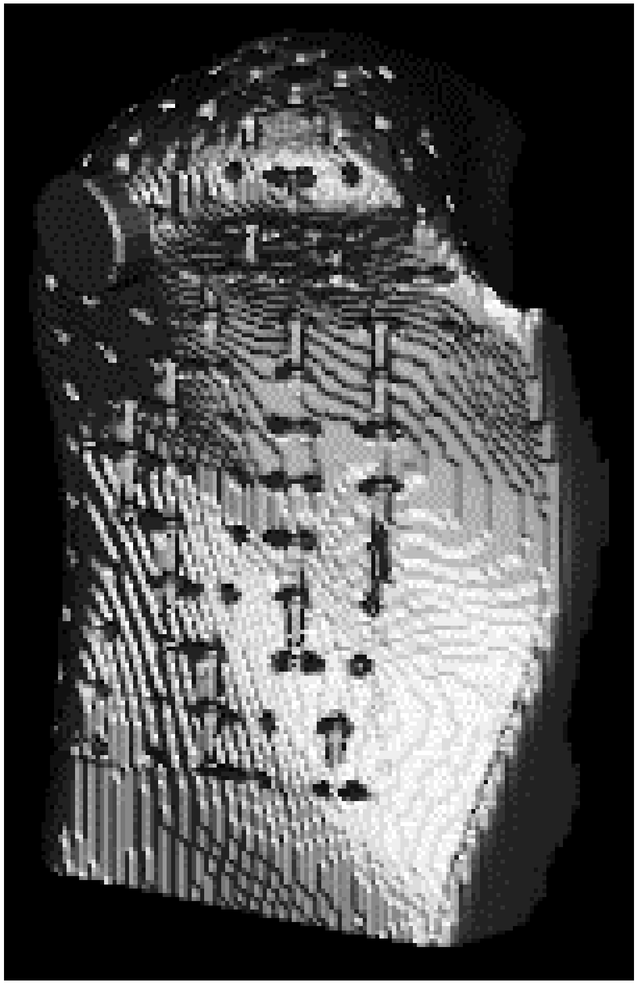
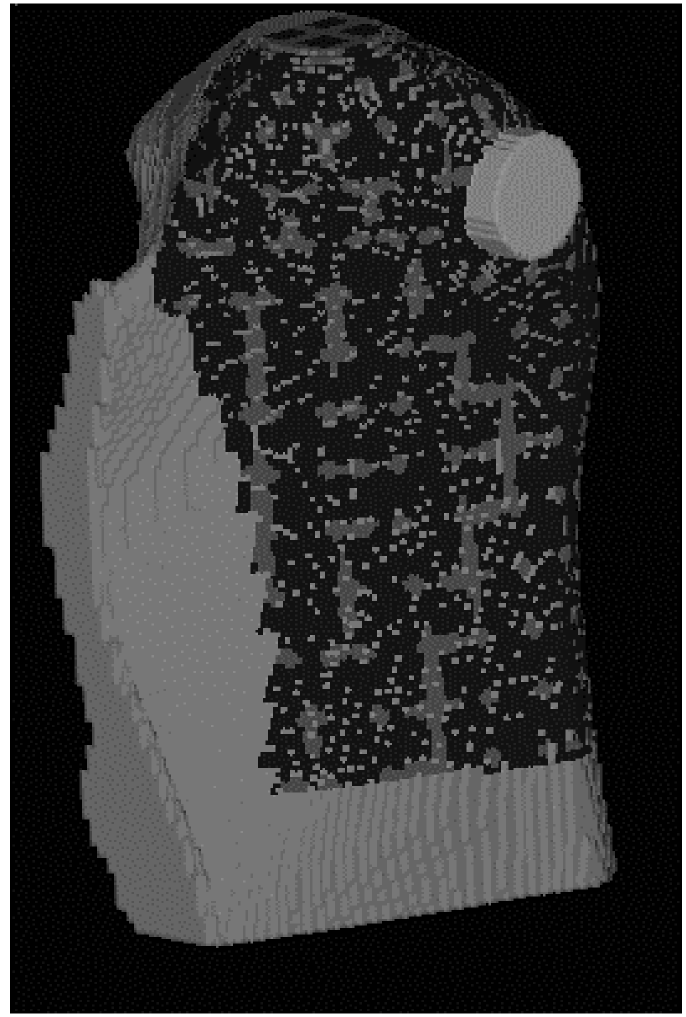
Resulted Finite Element Model



Scaffold/Bone Image



Scaffold/Bone Mesh

Done by Dr. Scott Hollister using Voxelcon2.0

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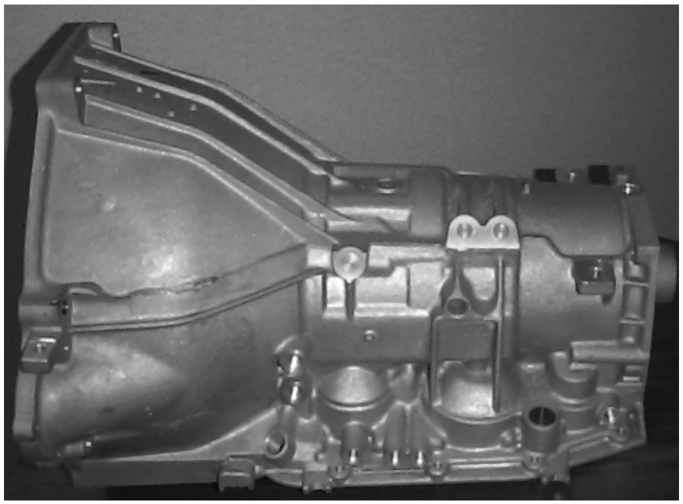
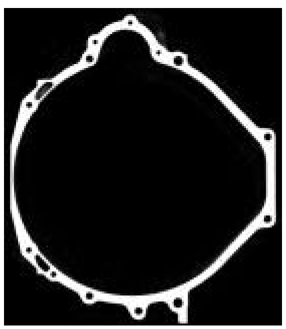
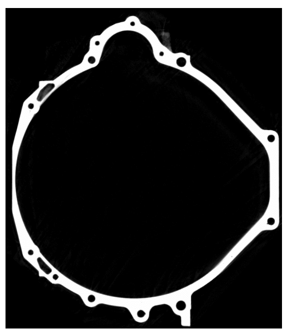
Image Based CAE

- Voxelcon : a Derivative of OPTISHAPE
  - CAD/CT/MRI Image Scan or Equivalent Ways
  - **Image Based** Automated **CAE**
    - Mesh Generation
    - Construction of Common Model for Multiple Analyses
    - Load/Support Condition
    - FE Analysis
  - **Image Based Design & Optimization**
    - **OPTISHAPE** for topology.layout design
  - Rapid Prototype by Layered Manufacturing
  - Simulation of Material Processing (Casting etc)

Database : Image

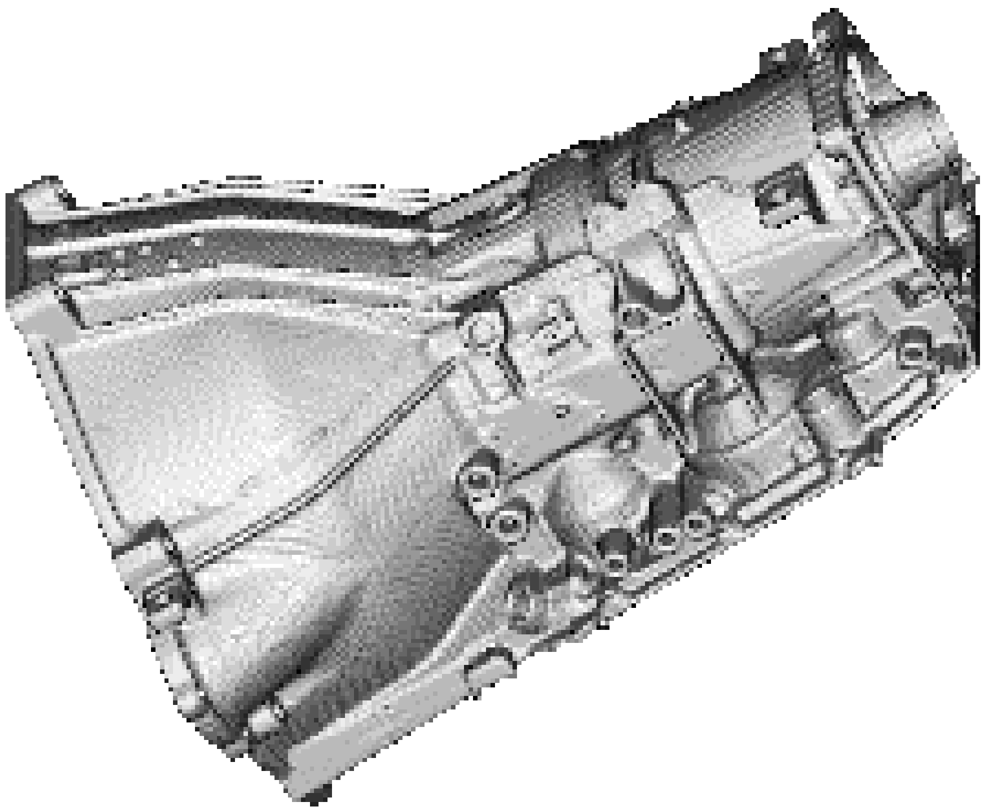






- Rather than STL files,SLC files are considered
- SLC files are stored as **IMAGES**
- images are then compressed
- 25K/slice x 500=7.5M

Image Regenerated



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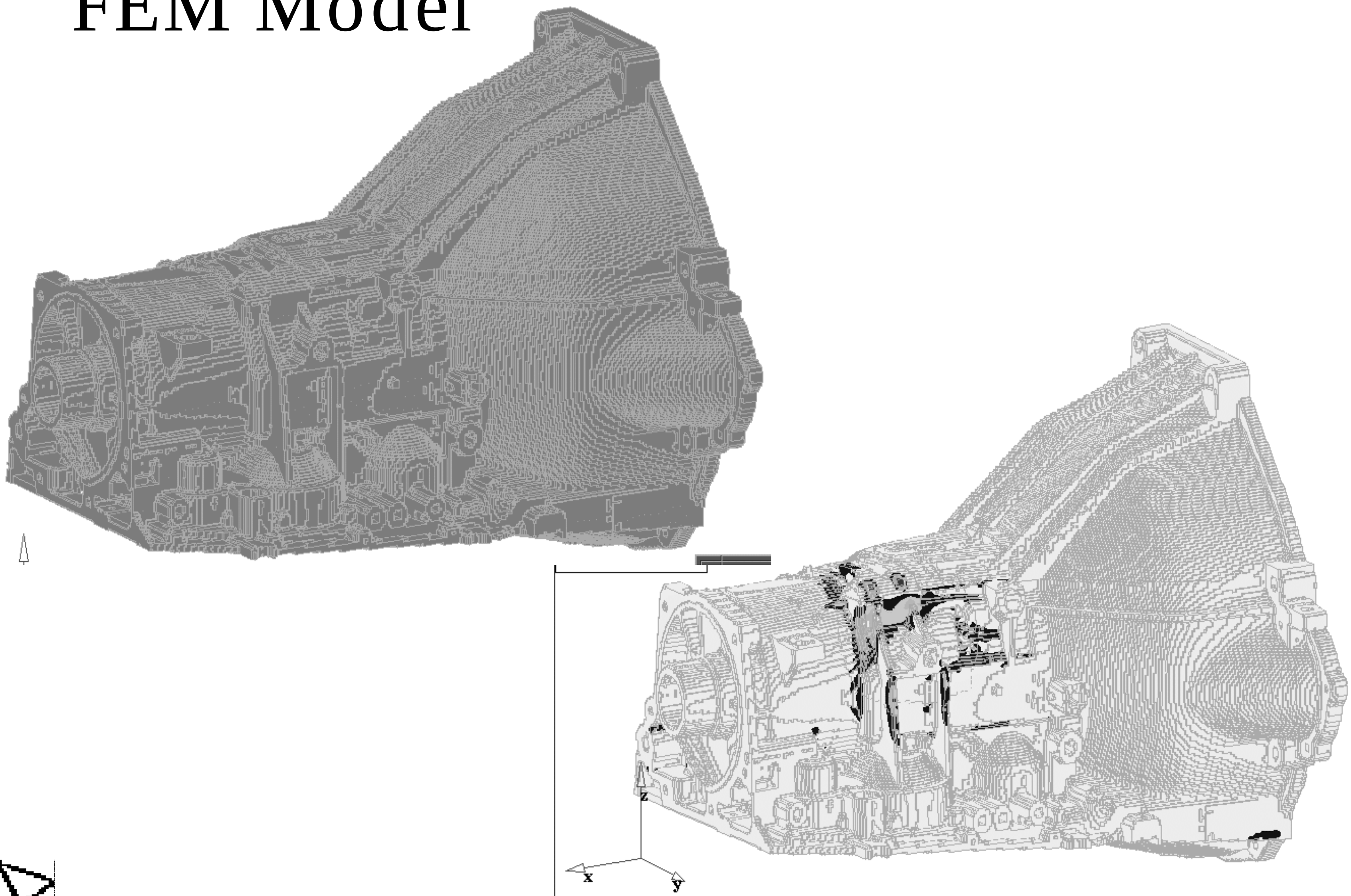
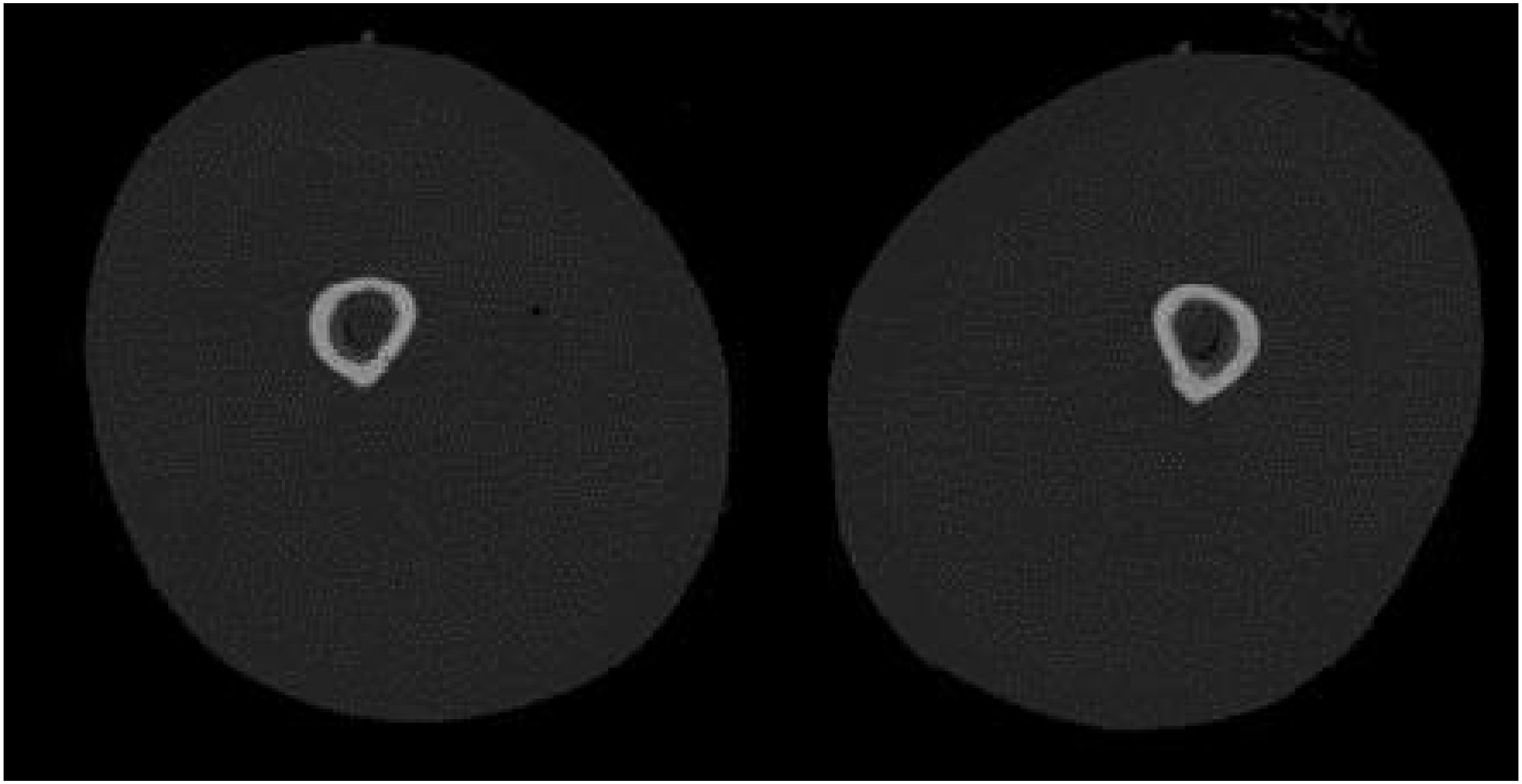
FEM Model



Femur CT from Visible Human Data



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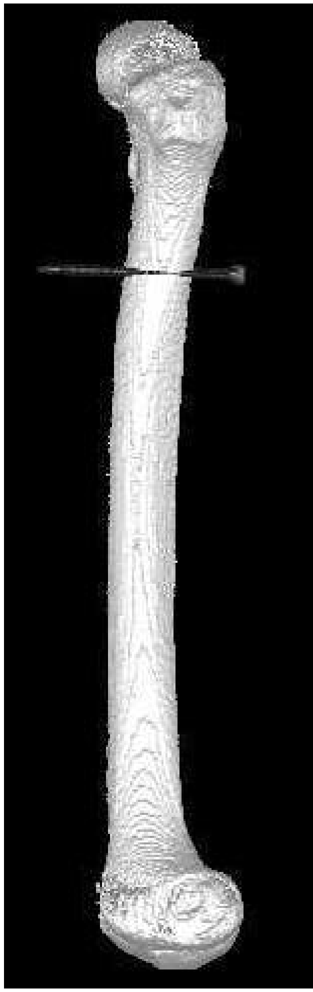
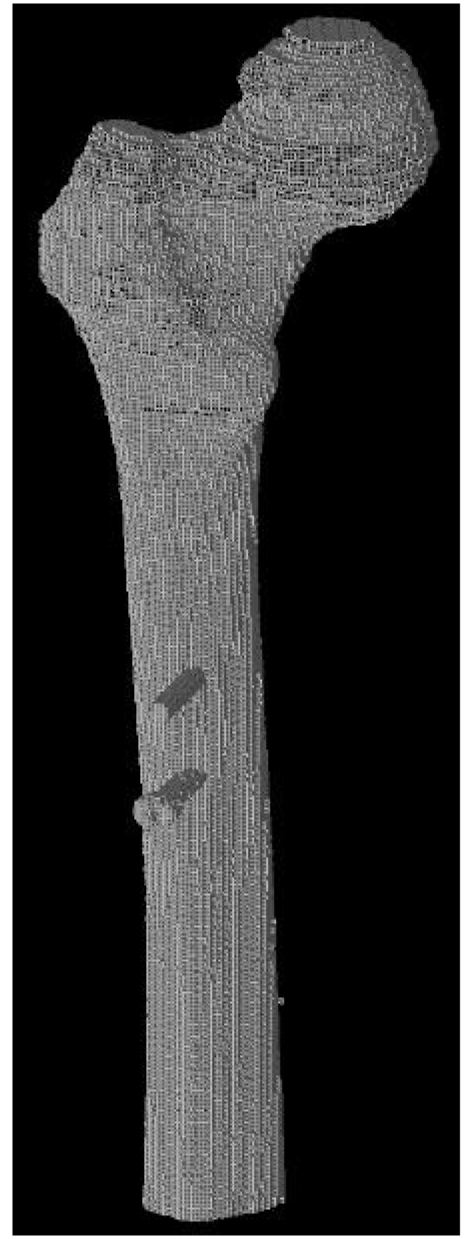
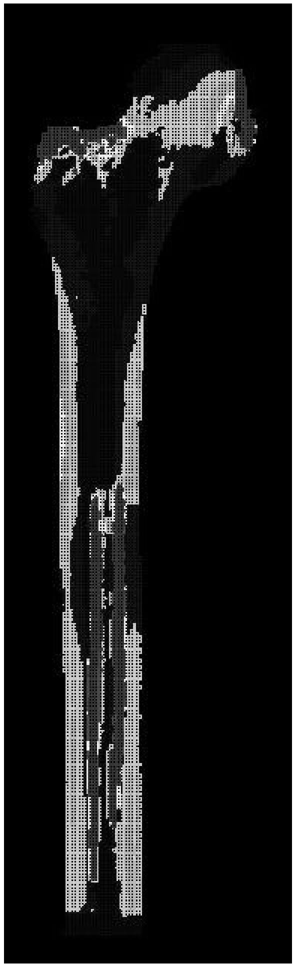
Virtual Femur with Nail - Rendering

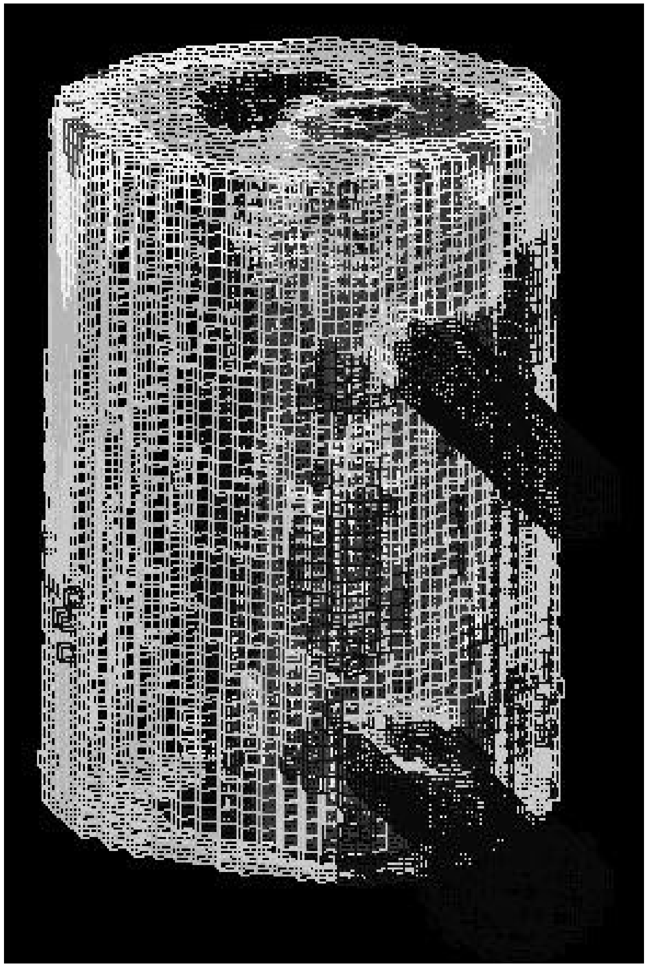


- **3D Surface Rendering of femur with nail**
- **Only screws show through femur**
- **Data ready for mesh generation**



VOXELCON byproduct of OPTISHAPE





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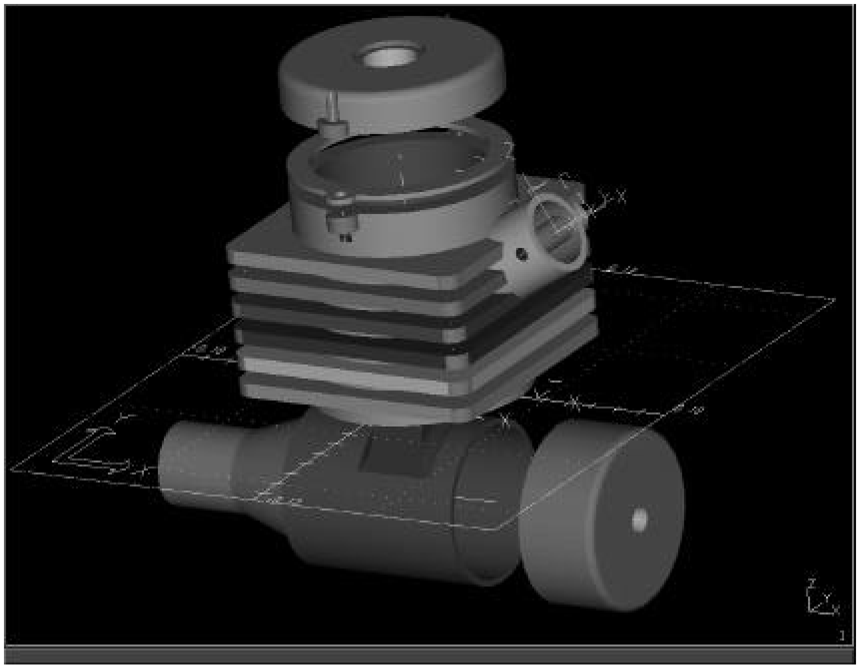
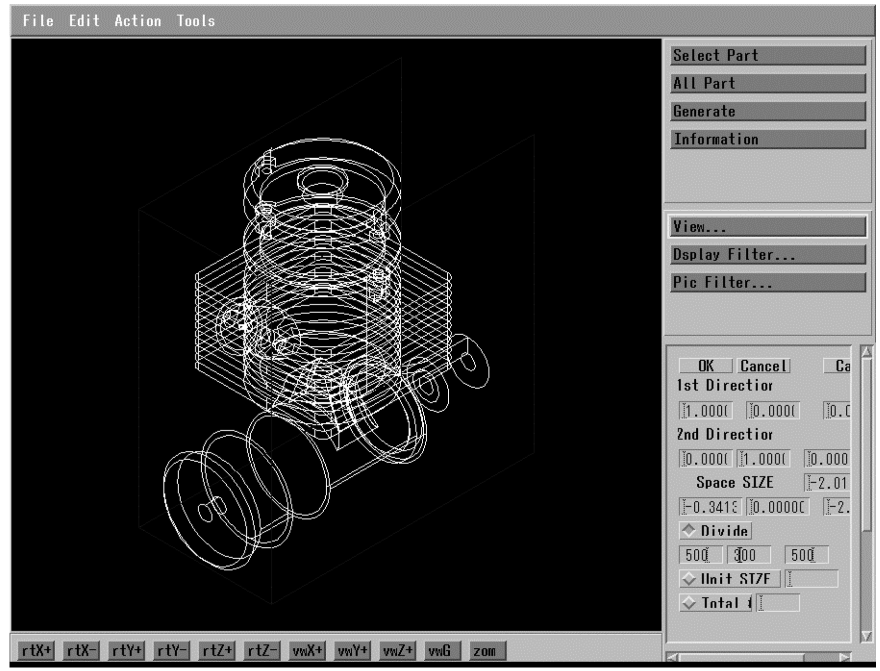
VOXELCON for I-DEAS

Quint Corporation





CAD Model by I-DEAS

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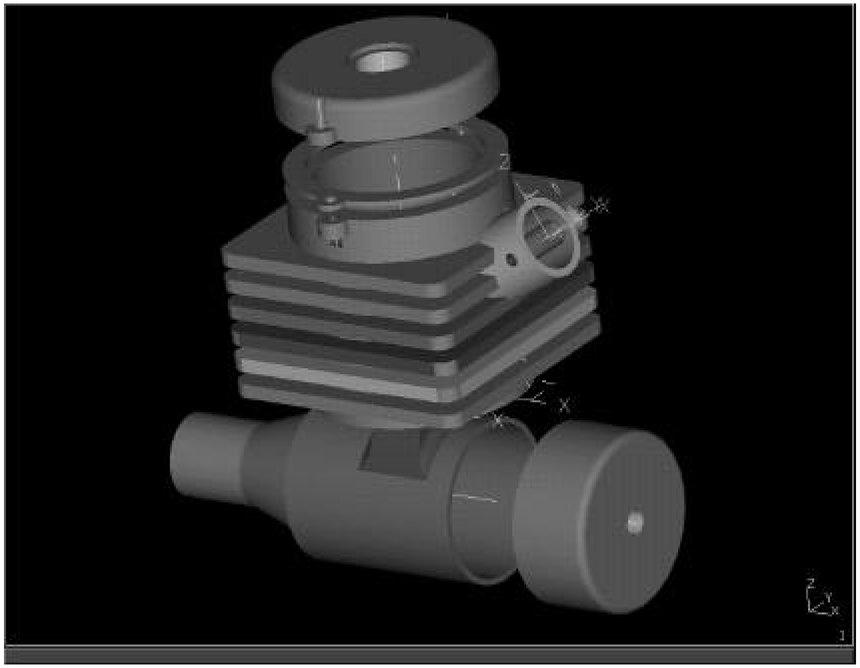
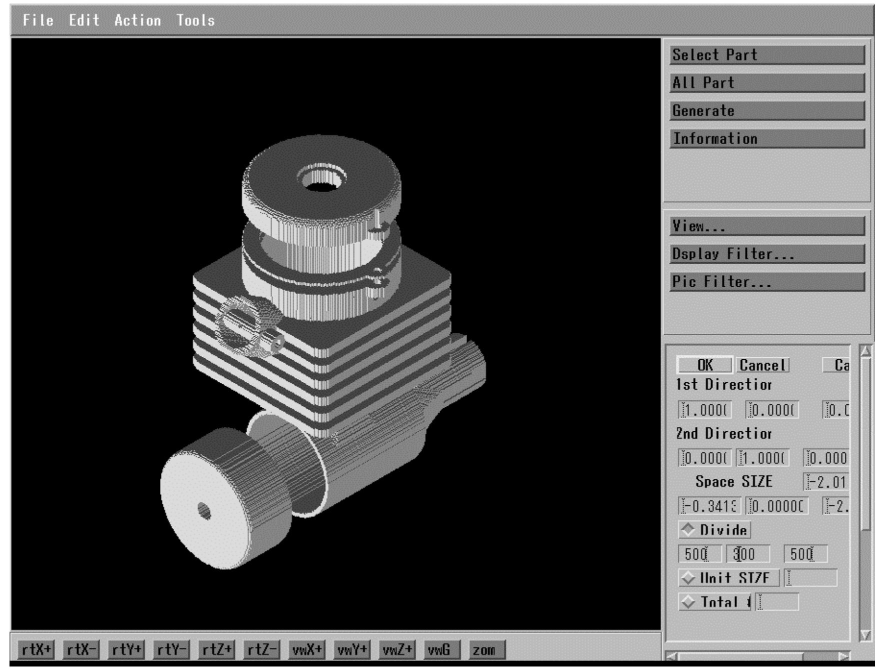
VOXELCON for I-DEAS (2)





75M Voxel Elements

9.4 M Voxel Elements

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OPTISHAPE

Quint Corporation

Topology (NK, A. Diaz)

Compliant Mechanisms (NK, S. Nishiwaki)

Shape (H. Azekami)

Size (H. Miura)

Extension of OPTISHAPE

- Structural Design
  - Static and Dynamic Stiffness Design
  - Control Eigen-Frequencies
  - Design Impact Loading
  - Elastic-Plastic Design
- Material Microstructure Design
  - Young's and Shear Moduli, Poisson's Ratios
  - Thermal Expansion Coefficients
- Flexible Body Design

New Extension of OPTISHAPE

Piezocomposite

and

Piezoelectric Actuator Design

For Creation of New Value

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Introduction

Force

Mechanical Energy ⟷ Piezoelectric Material ⟷ Electrical Energy

Displacement

Electric potential

Electric charge

Examples: Quartz (natural)
Ceramic (PZT5A, PMN, etc…)
Polymer (PVDF)

Applications

Pressure sensors
accelerometers
actuators,
acoustic wave generation
    ultrasonic transducers, sonar, hydrophones
etc...

Constitutive Equations of Piezoelectric Medium

$$\begin{cases} T_{ij} = c^{E}_{ijkl} S_{kl} - e_{kij} E_k \\ D_i = \varepsilon^{S}_{ik} E_k + e_{ikl} S_{kl} \end{cases}$$

Elasticity equation

Electrostatic equation

T_{ij} - stress

S_{kl} - strain

E_k - electric field

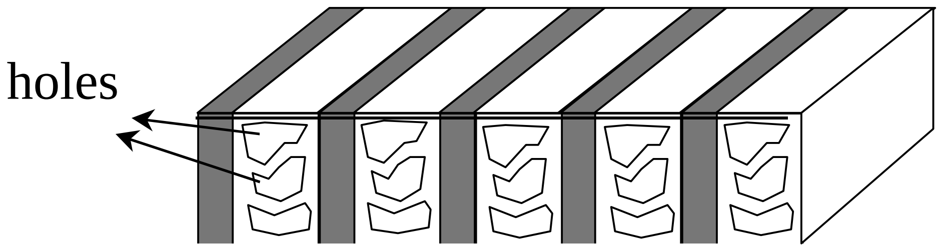
D_i - electric displacement

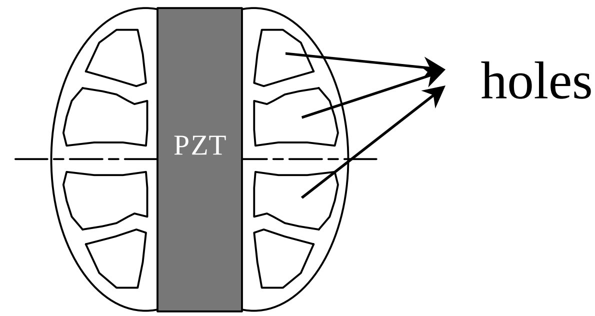
c^{E}_{ijkl} - stiffness property

e_{ikl} - piezoelectric strain property

ε^{S}_{ik} - dielectric property

Topology Design





Topology Optimization

Change the topology of microstructure (material) or structure (transducer)

Improvement in the performance of piezocomposite materials; design of new kinds of transducers for different applications

Many Approaches : MDM

Simple:
Density Method

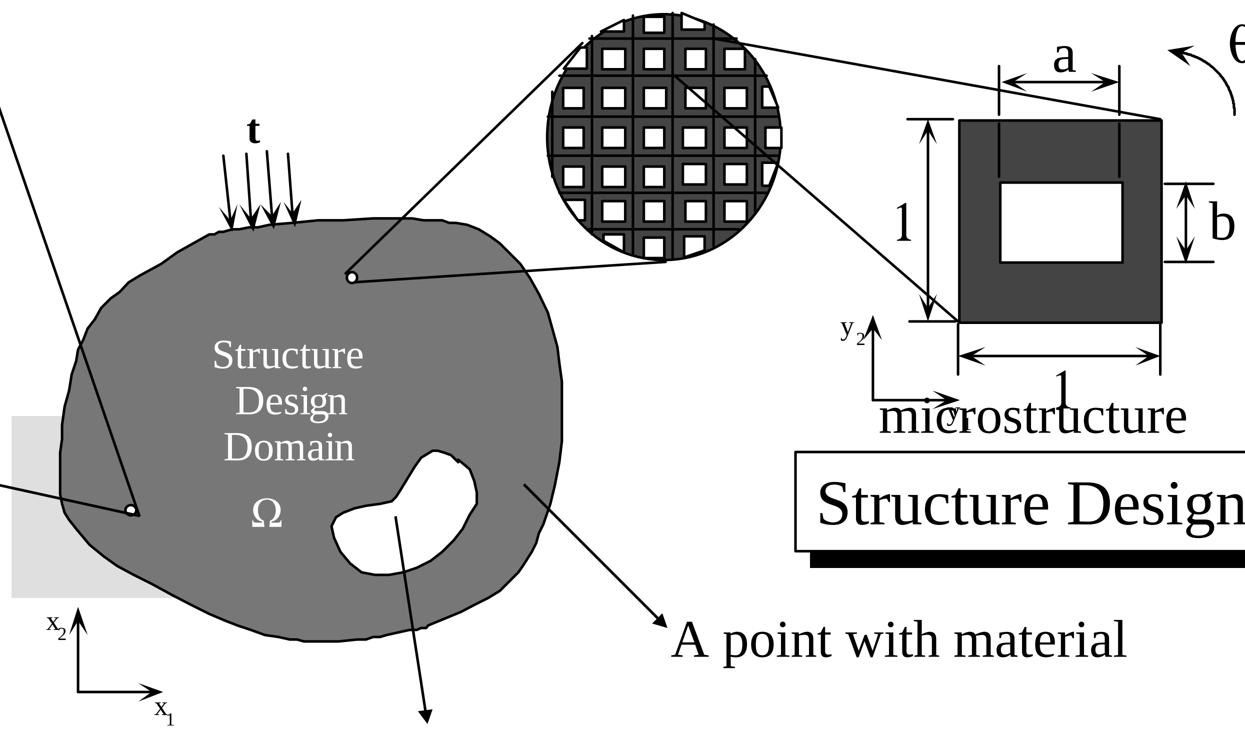
property

$$E_{ijkl} = x^{p} E^{0}_{ijkl}$$

fraction of material
in each point

Material Design

General:
Homogenization Method



Structure Design

Performance Characteristics 1

Hydrophones (Hydrostatic Mode)

- Hydrostatic Coupling Coefficient ($|d_h|$):

$$|d_h| = d_{13} + d_{23} + d_{33}$$

- Figure of Merit ($d_h g_h$):

$$d_h g_h = \frac{d_h^2}{\varepsilon_{33}^T}$$

- Hydrostatic Electromechanical Coupling Factor (k_h):

$$k_h = \sqrt{\frac{d_h^2}{\varepsilon_{33}^T s_h^E}}$$

Performance Characteristics 2

Ultrasonic Transducers (Thickness Mode)

- Electromechanical Coupling Factor (k_t):

$$k_t = \sqrt{\frac{e_{33}^2}{c_{33}^D \varepsilon_{33}^S}}$$

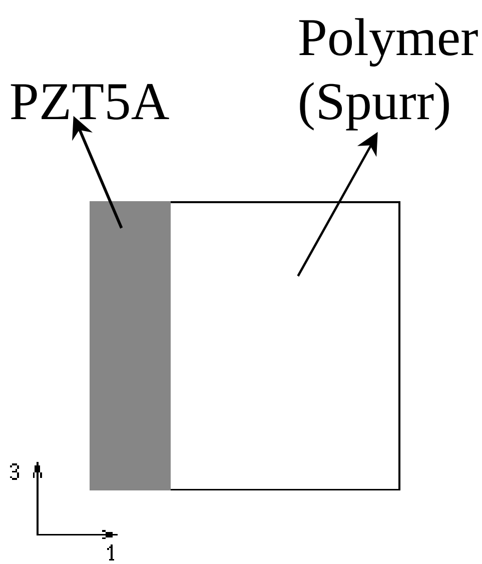
- Impedance (Z):

$$Z = \sqrt{\rho\, c_{33}^D}$$

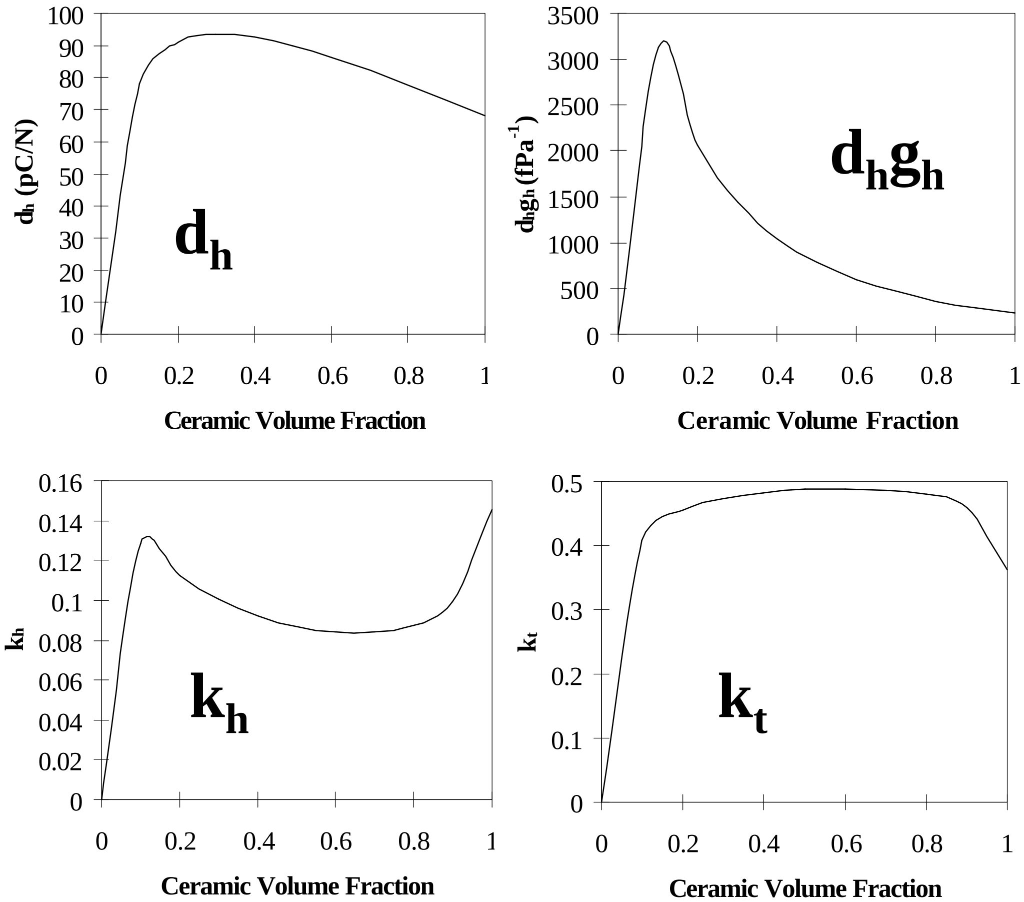
- Longitudinal Velocity (v_t):

$$v_t = \sqrt{\frac{c_{33}^D}{\rho}}$$

Reference unit cell for comparison: 2-2 piezocomposite

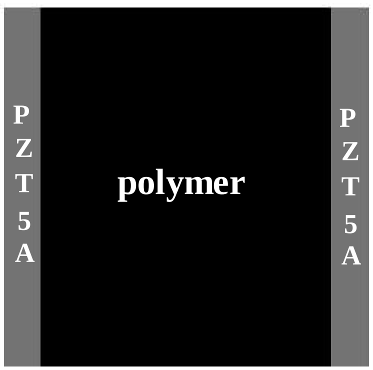


(Poled in the
3 direction)



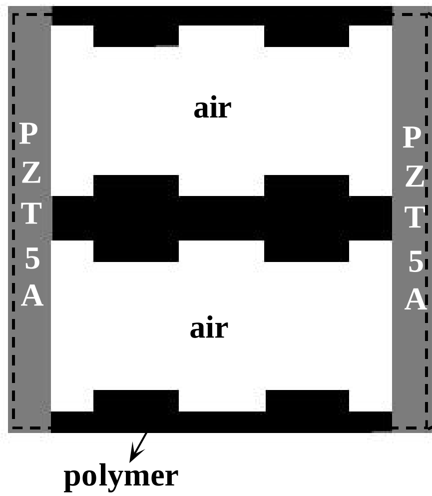
2D Piezocomposite Unit Cell
ultrasonic transducer

Initially

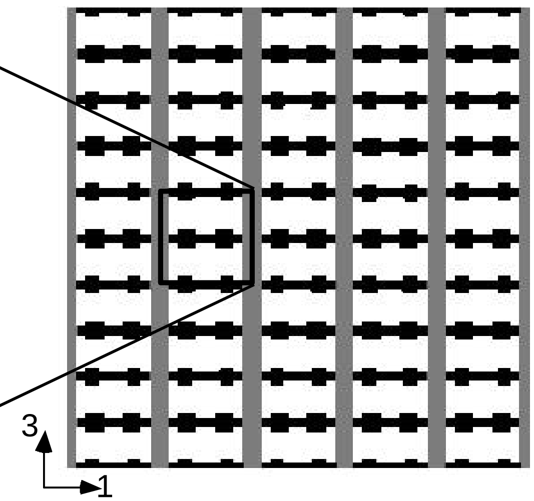


2-2 piezocomposite

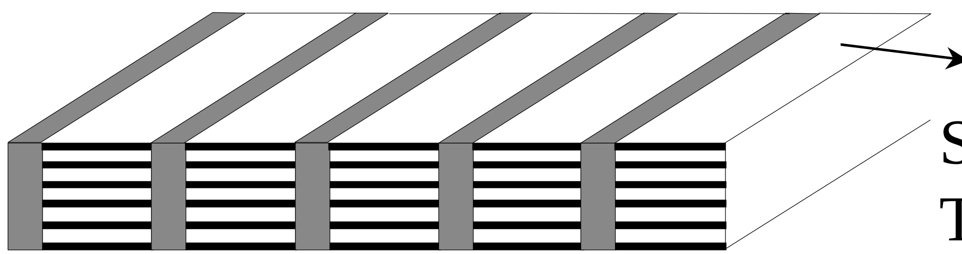
Optimized Microstructure



Piezocomposite



$$k_t = \sqrt{\frac{e_{33}^2}{c_{33}^D \varepsilon_{33}^S}}$$



Suggested Transducer

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Improvement

Improvement in relation to the 2-2 piezocomposite unit cell:

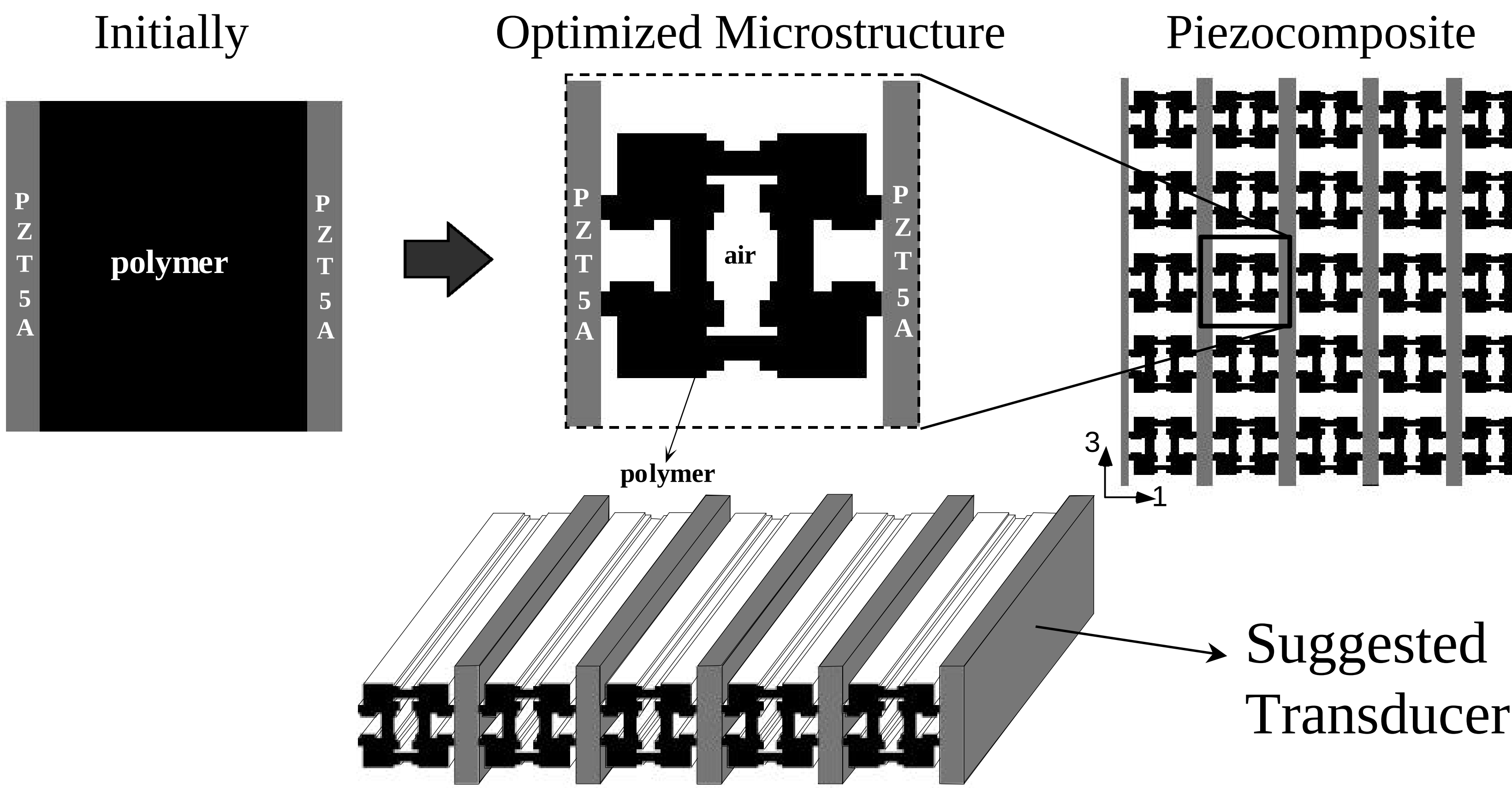
$|d_h|$: 2.5 times $\rho \Downarrow \;\Rightarrow\; Z \Downarrow$ v_t ($\cong$ same)

$d_h g_h$: 4.2 times

k_t: 1.13 times stiffness constraint: $c^E_{11} > 8.\,10^8$ N/m^2

2D Piezocomposite Unit Cell

hydrophone



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Improvement

Improvement in relation to the 2-2 piezocomposite unit cell:

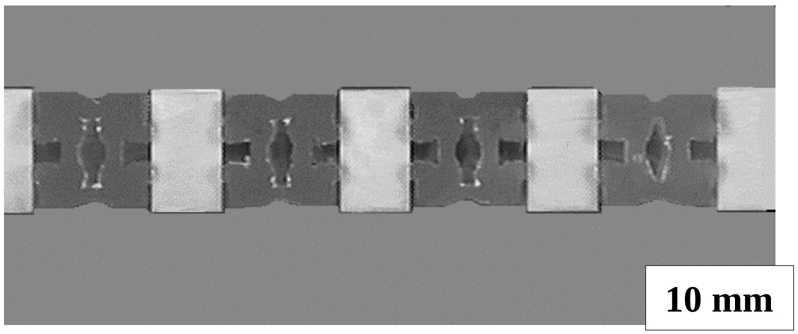
$|d_h|$: 2.8 times $\rho \Downarrow \Rightarrow Z \Downarrow$ v_t ($\cong$ same)

$d_h g_h$: 7.1 times

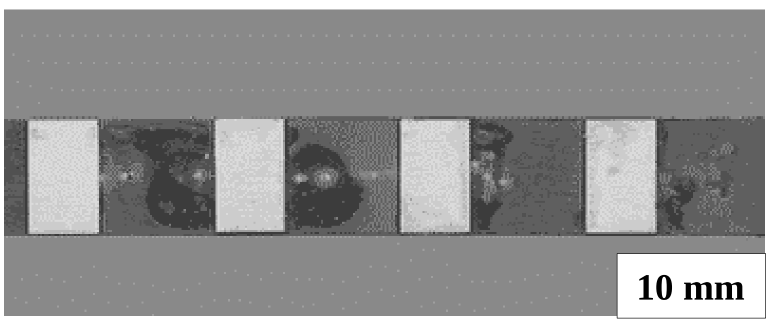
k_t: 1.13 times stiffness constraint: $c^E_{11} > 8.10^8 N/m^2$

Experimental Verification

• Rapid Prototyping: Stereolithography Technique

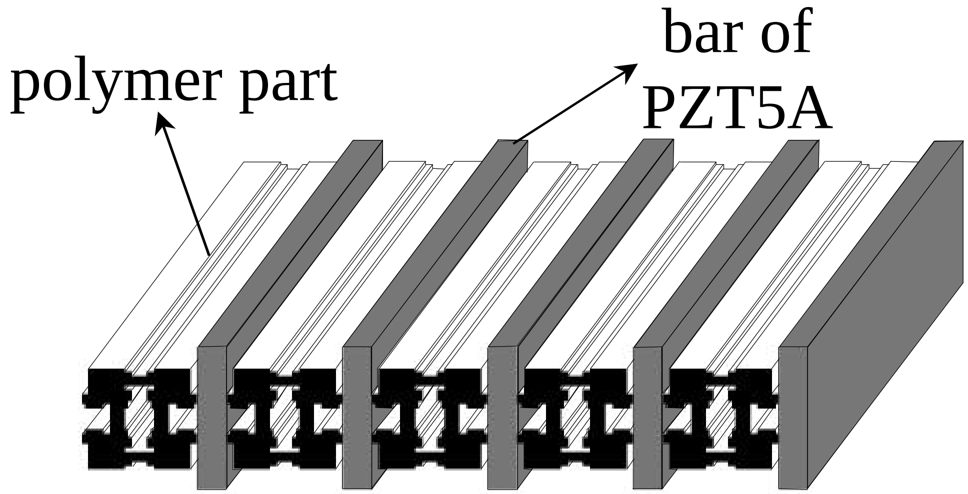


Optimized Transducer



Reference Transducer

Experimental Result

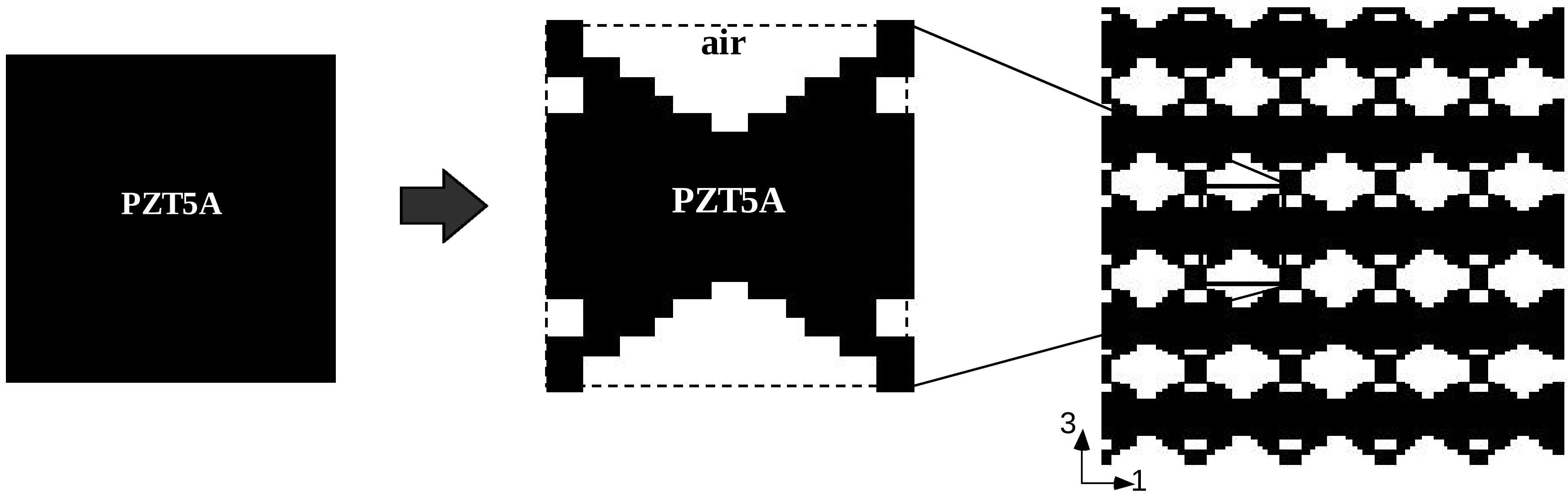


Measured Performances

	d_h(pC/N)	$d_h g_h$ (fPa^{-1})	k_t
Reference	9.1	13.2	0.69
Optimized (Simulation)	246. (229.)	10400. (10556.)	0.70 (0.66)

2D Piezocomposite Unit Cell
hydrophone

Initially | Optimized Microstructure | Piezocomposite



“optimized porous ceramic”

Improvement

Improvement in relation to the 2-2 piezocomposite unit cell:

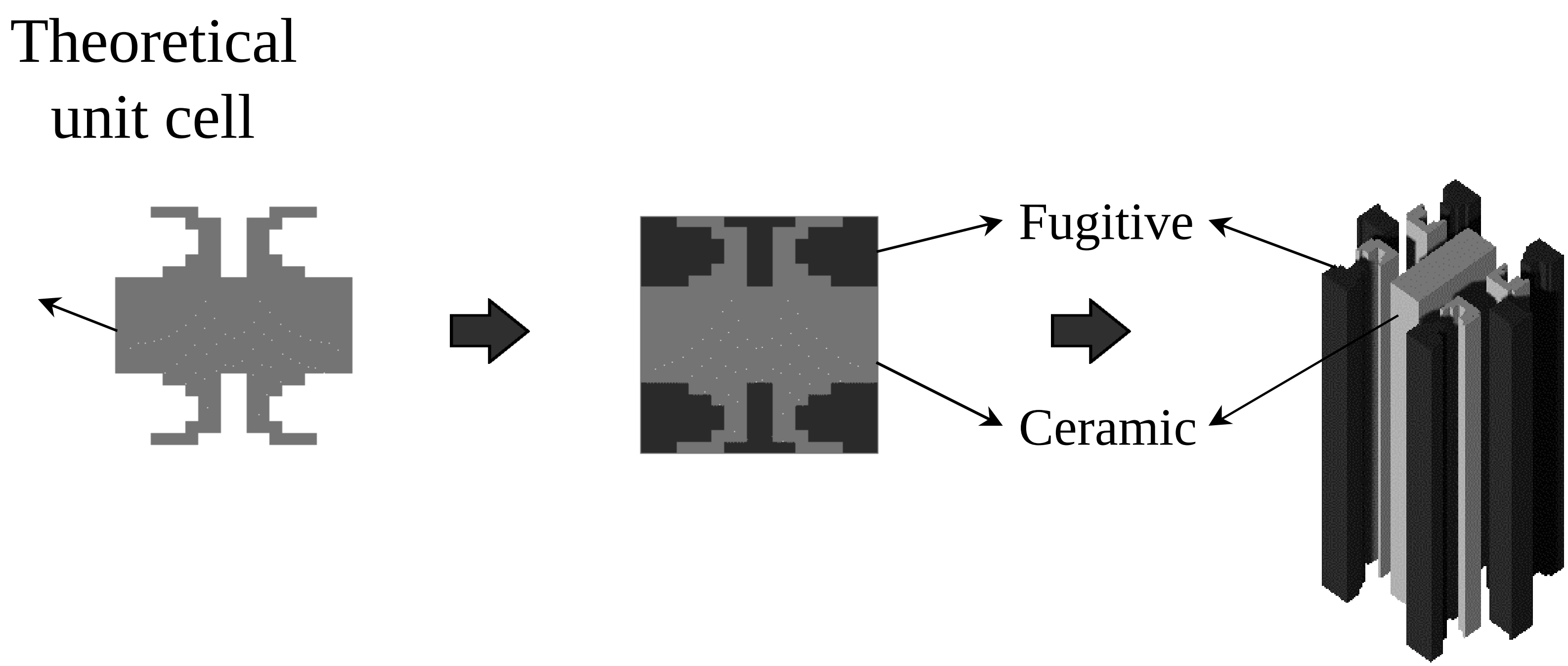
$|d_h|$: 3. times

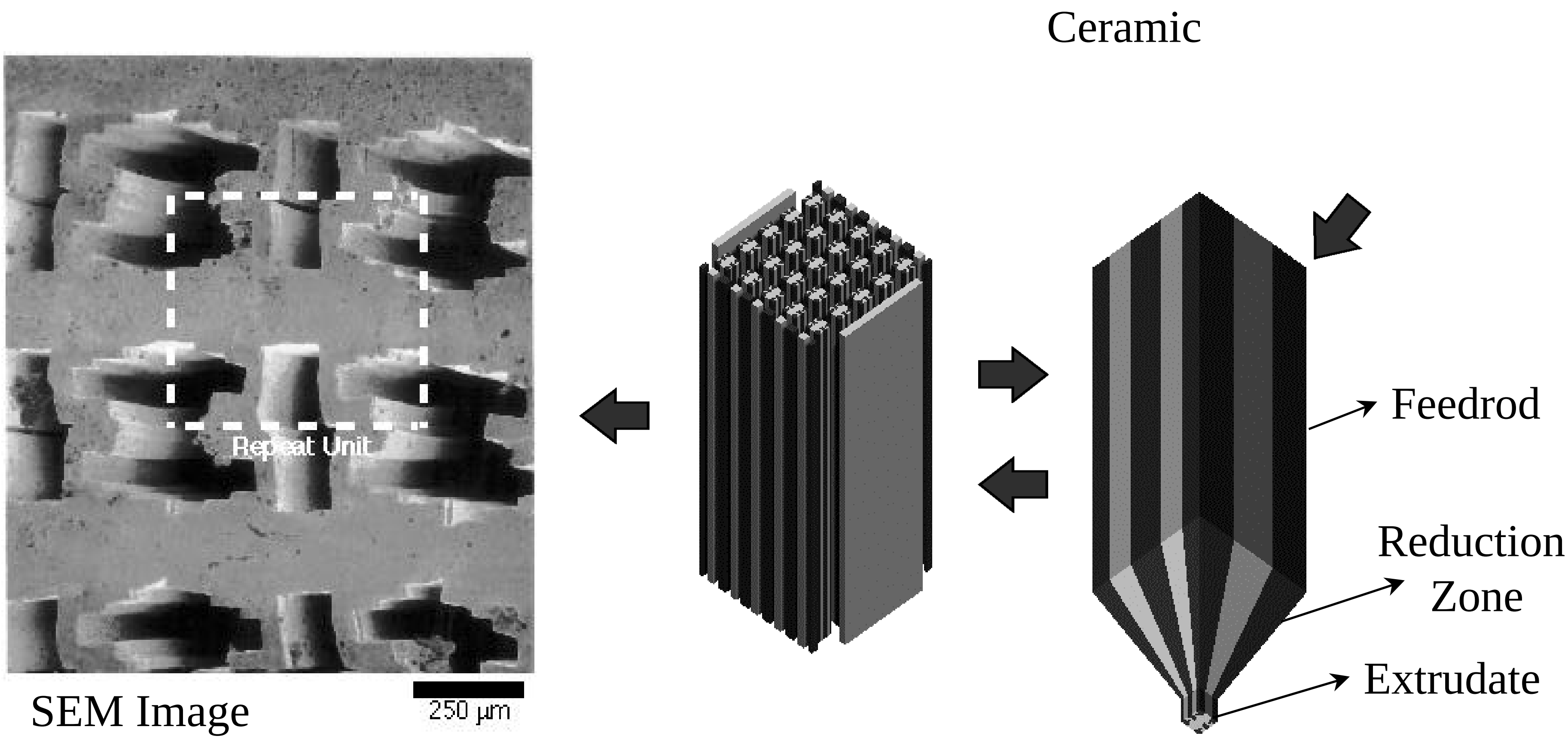
$d_h g_h$: 9.22 times

k_h: 3.6 times stiffness constraint: $c^E_{33} > 1.10^{10} N/m^2$

Piezocomposite Manufacturing

Microfabrication by coextrusion technique

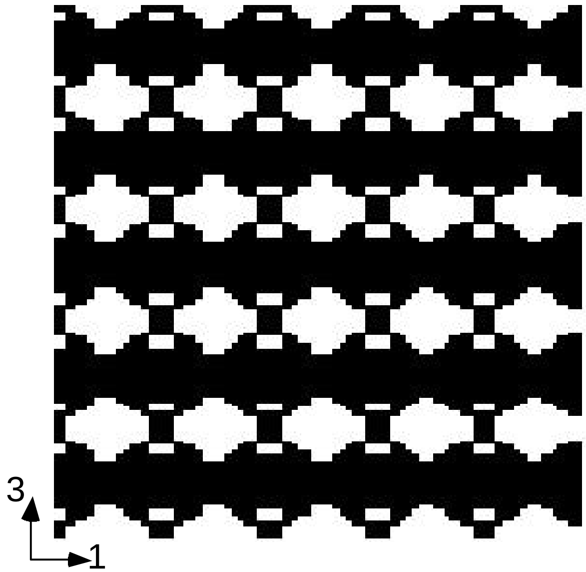


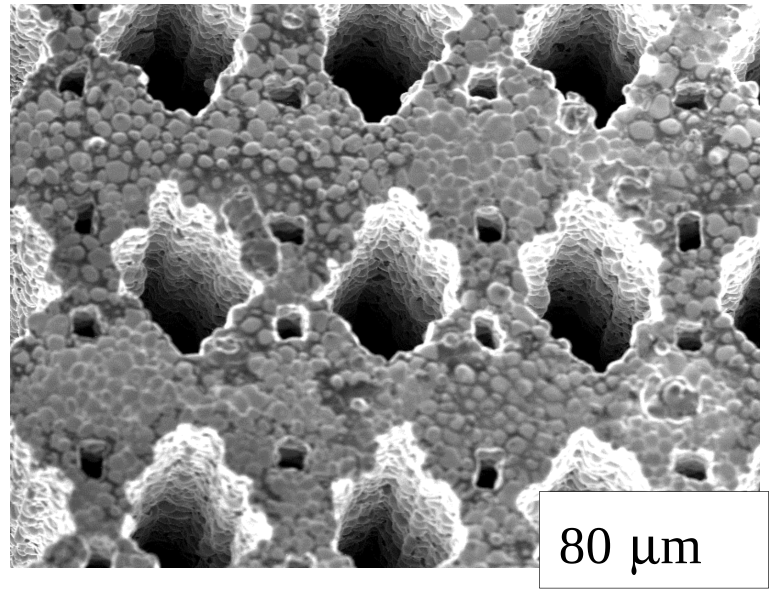


SEM Image

Crumm and Halloran (1997)

Theoretical	Prototype





Measured Performances

	d_h (pC/N)	$d_h g_h$ ($f\mathrm{Pa}^{-1}$)
Solid PZT	68.	220.
Optimized (Simulation)	308. (257.)	18400. (19000.)

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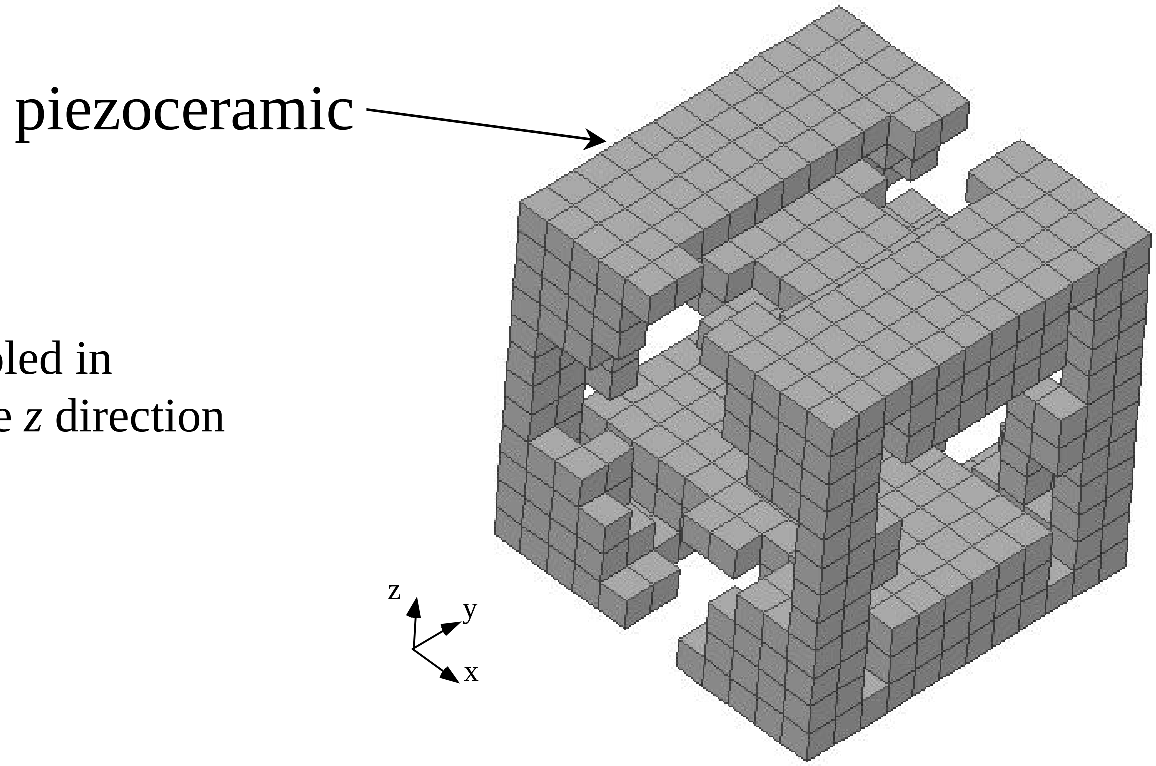
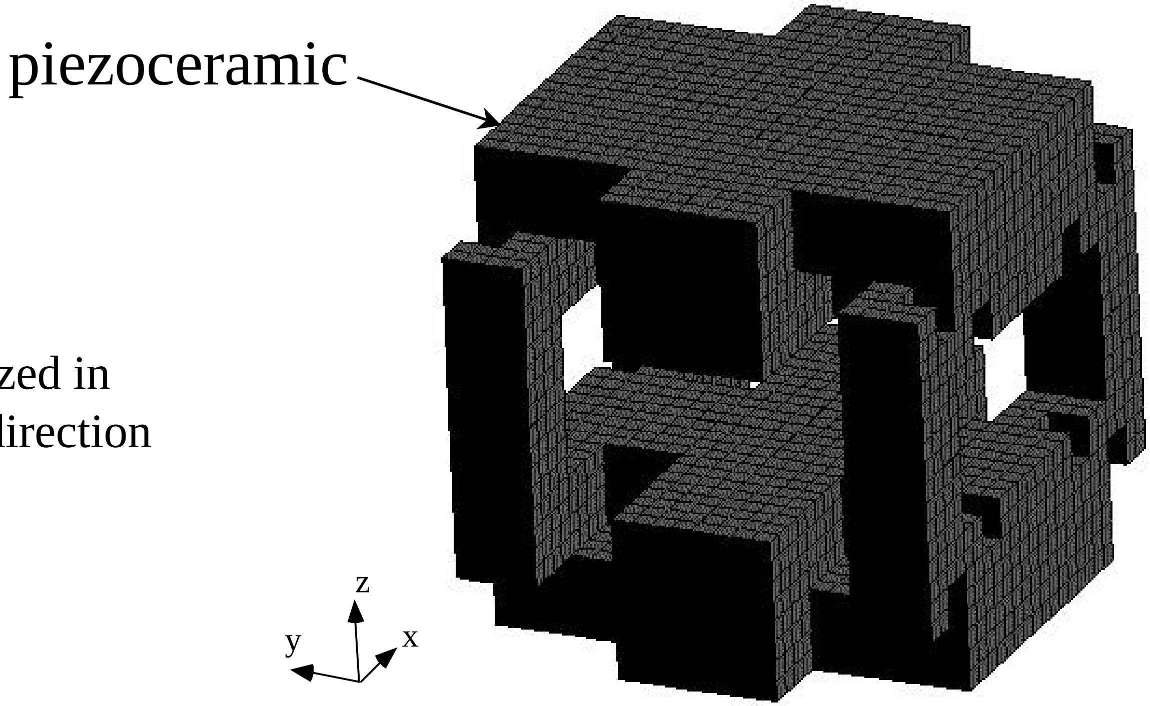
3D Piezocomposite Unit Cell
hydrophone



Poled in
the *z* direction

3D Piezocomposite Unit Cell
hydrophone



Polarized in
the *z* direction

OPTISHAPE

Compliant Mechanism Design

A New Release

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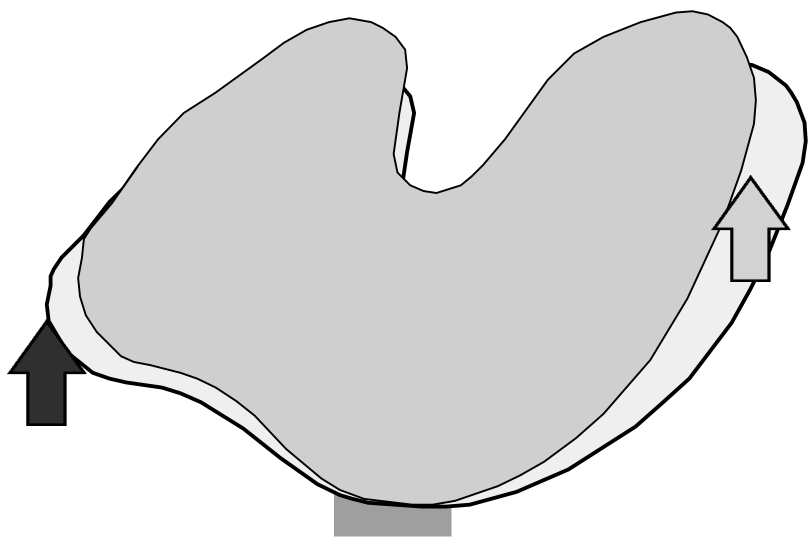
Structural Flexibility

Flexibility can provide
higher performance or additional function
If we can specify the flexible mode appropriately.

Applied force



Deformed
direction

Kinematic Synthesis

Lumped compliant mechanism

Based on traditional rigid body kinematics

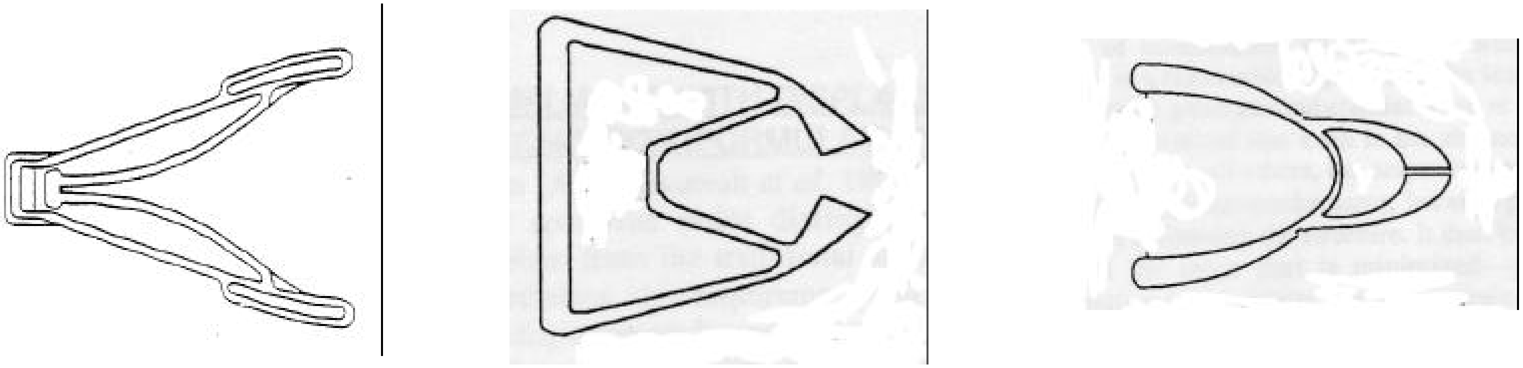
Lumped compliance (Pivot) ⇨ Stress concentration

Her and Midha (1986),
Howell and Midha (1994), (1996)

Continuum Synthesis

Distributed compliant mechanism

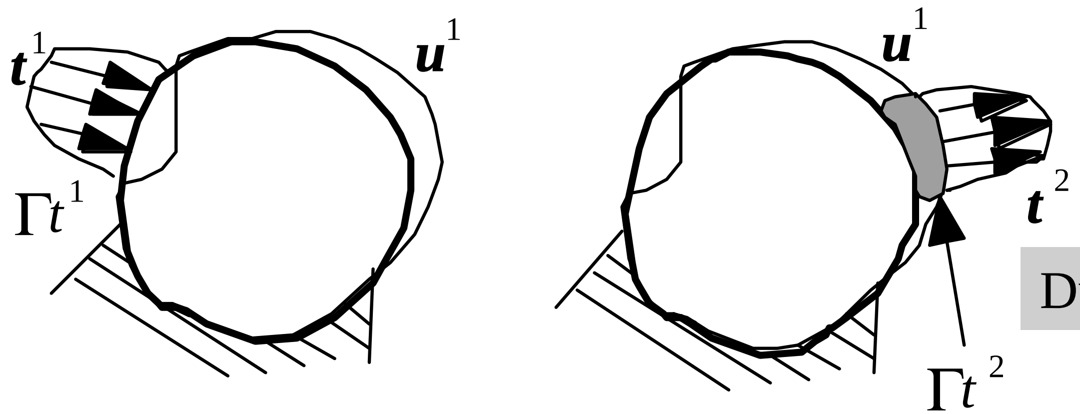
Based on the topology optimization method



Ananthasuresh et al. (1994, 1995), Frecker et al. (1997)
Sigmund (1995), (1996), Larsen et al. (1996)

Flexibility and Stiffness

Applied traction



Dummy traction

Maximize $L^2\left(\boldsymbol{u}^1\right)=\int_{\Gamma t^2} \boldsymbol{t}^2 \bullet \boldsymbol{u}^1 d\Gamma$ — Mutual Mean Compliance (MMC)

➡ Flexibility at Γ_{t^2}

Minimize $L^1\left(\boldsymbol{u}^1\right)=\int_{\Gamma t^1} \boldsymbol{t}^1 \bullet \boldsymbol{u}^1 d\Gamma$ — Mean Compliance (MC)

➡ Stiffness at Γ_{t^1}

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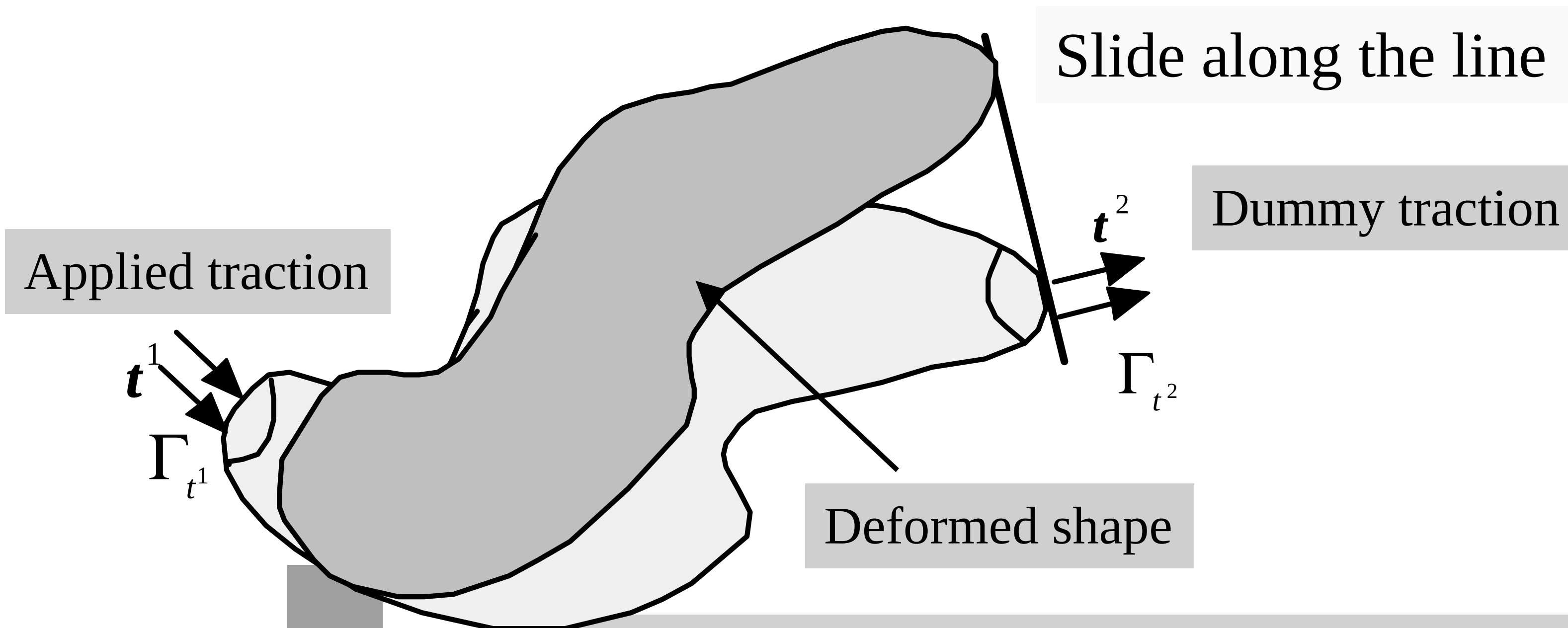
Formulation of Mutual Stiffness



Stiffness at Γ_{t^2} with respect to $\boldsymbol{t}^1$

Minimize $\left|L^2\left(\boldsymbol{u}^1\right)\right| = \left|\int_{\Gamma_{t^2}} \boldsymbol{t}^2 \bullet \boldsymbol{u}^1 \, d\Gamma\right|$

Compliant Mechanism Design

Kinematic function

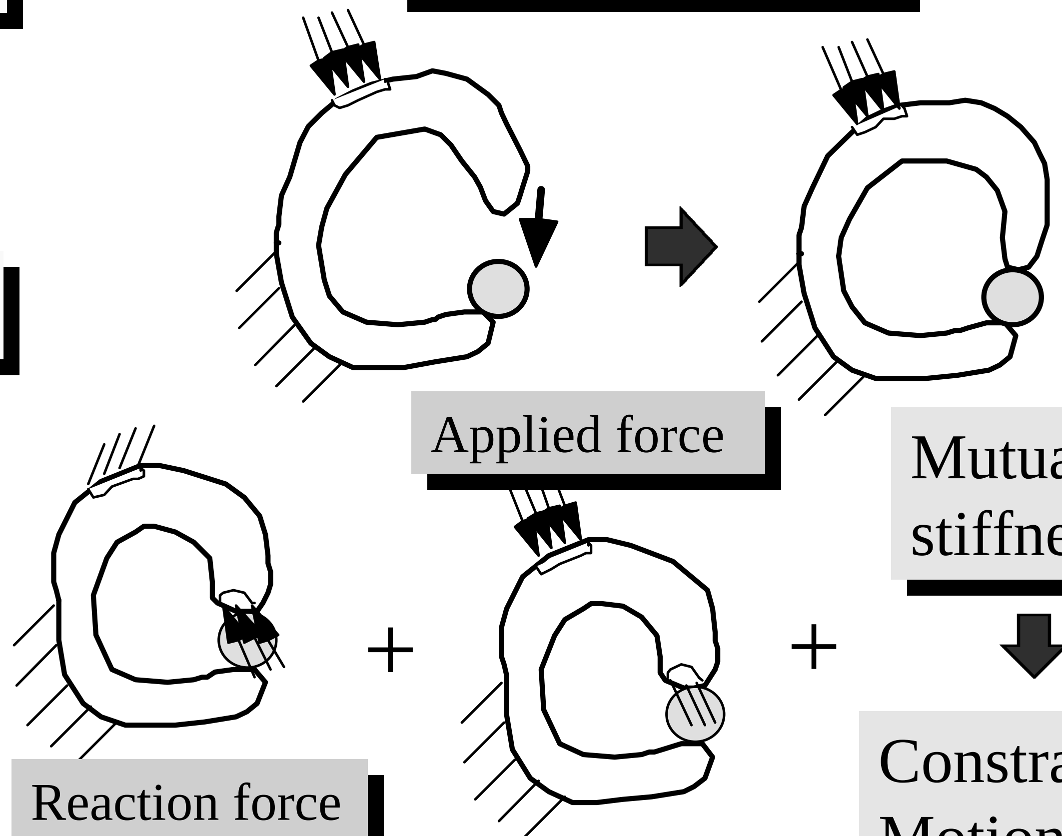
→ Flexibility

Structural function

→ Stiffness

Minimize ($\sum$ MC)

Maximize (MMC)



Constrained Motion

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Multicriteria Optimization

Flexibility → Maximize (MMC)

↕ Trade off

Stiffness → Minimize $\sum$ (MC)

Multi-objective Functions (1)

Typical methods to deal with multi-objective problems

- The weighting method
- The ε-constraint method
- The goal programming method

MMC ----> Infinite !

Nash’s Optimum

Multi-objective Functions (2)

(1) Single flexibility case

(a)

$$\text{Maximize } \frac{MMC}{\sum MC}$$

(b)

$$\text{Maximize } \begin{array}{l} w \,\mathrm{Log}(MMC) \\ -(1-w)\mathrm{Log}(\sum MC) \end{array}$$

$$\text{Variation} = w \frac{\mathrm{d}MMC}{MMC} - (1-w)\frac{\sum \mathrm{d}MC}{\sum MC}$$

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Multi-objective functions (3)

(2) Displacement single flexibility case

$$\text{Minimize} \sum \text{MC}$$

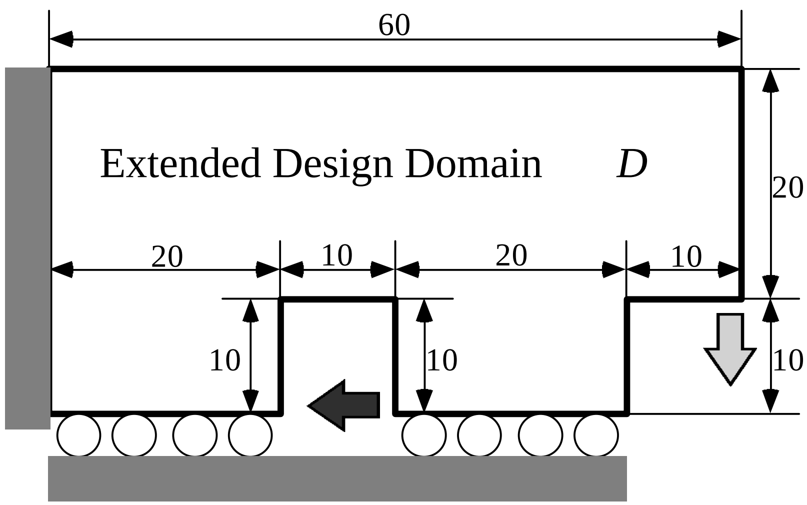
$$MMC \Rightarrow Constraint$$

(3) Multi-flexibility case

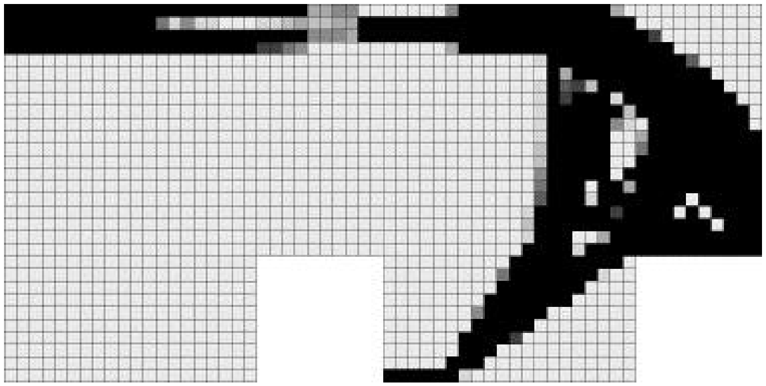
$$\text{Maximize} \ \frac{-1/C_f \ \text{Log}\left(\sum \text{Exp}(-C_f{}^i MMC) \right)}{1/C_s \ \text{Log}\left(\sum \text{Exp}(C_s{}^j MC) \right)}$$

Compliant Gripper (1)

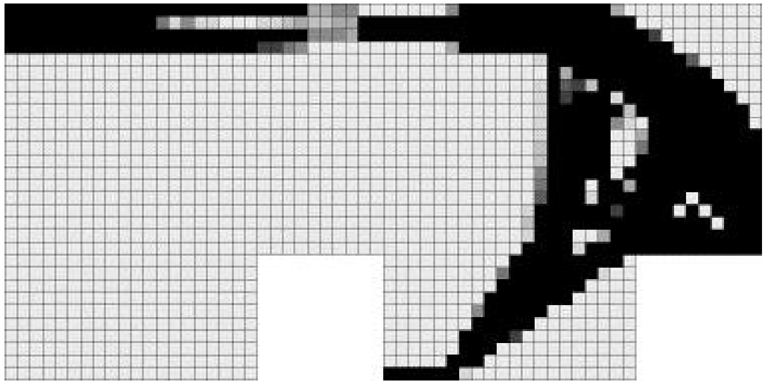
Unconstrained single flexibility



Design domain

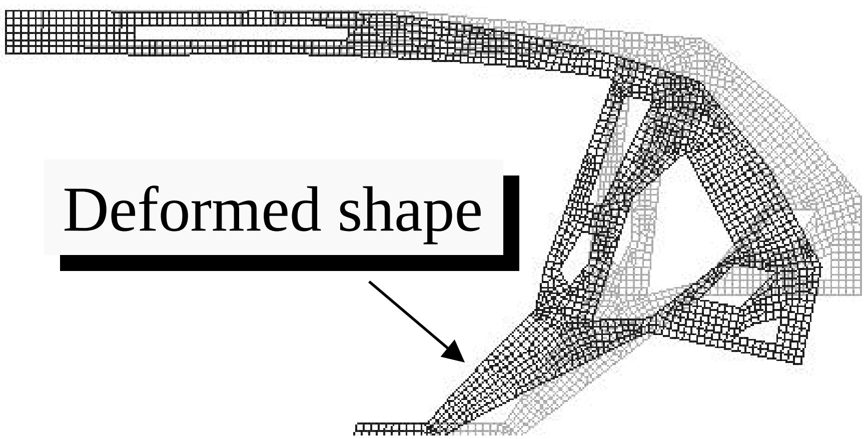


Ω_s=20%



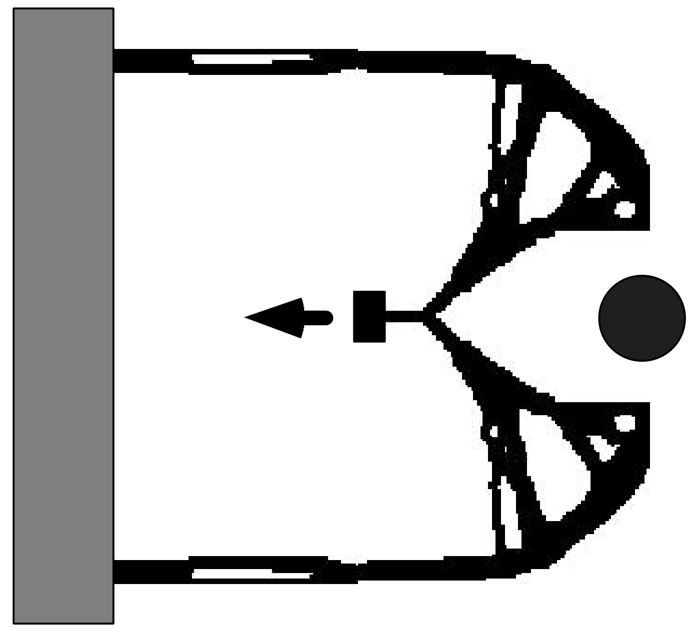
Ω_s=30%

Compliant Gripper (2)



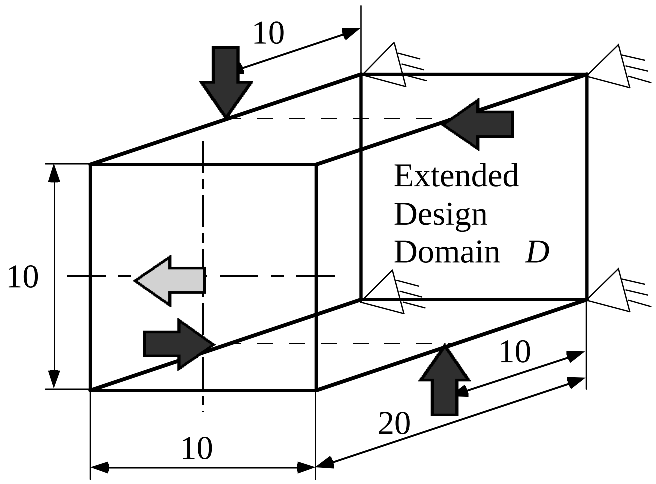
Deformed shape

Mises stress



Extracted image design

Torsional Compliant Mechanism

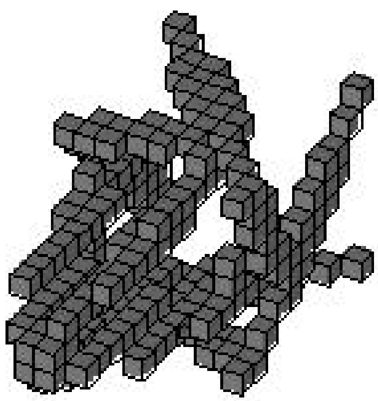


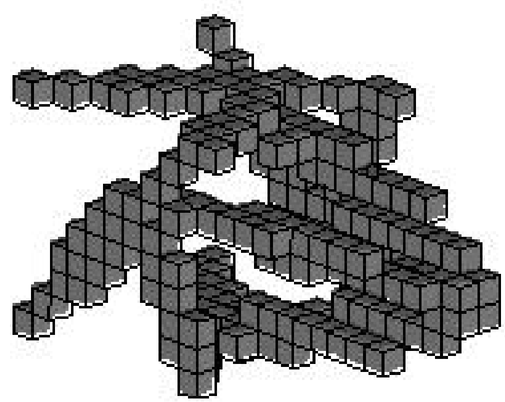
Unconstrained single flexibility

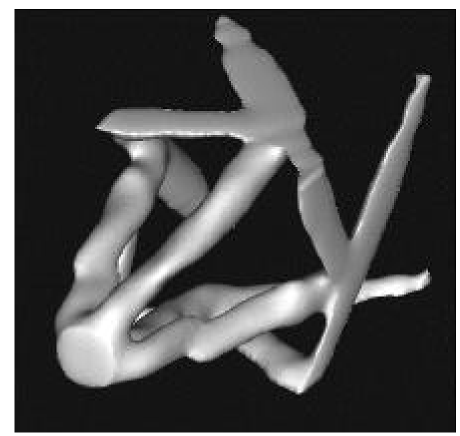
: Applied force

: Direction of deformation

Design domain



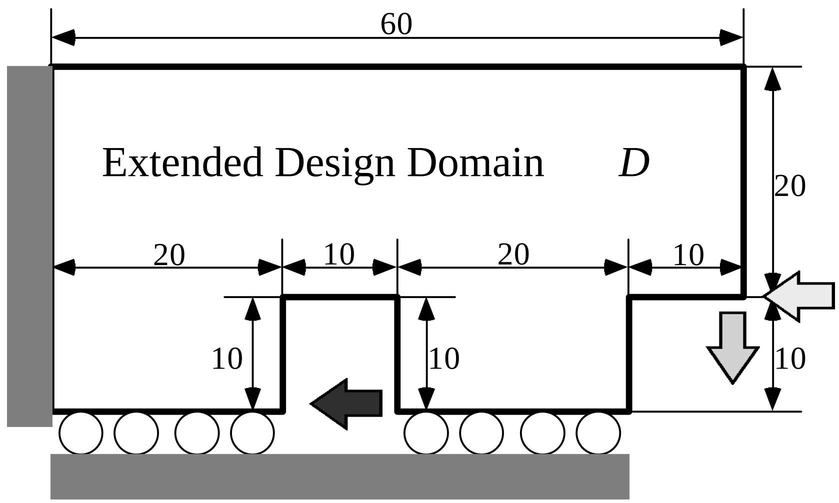




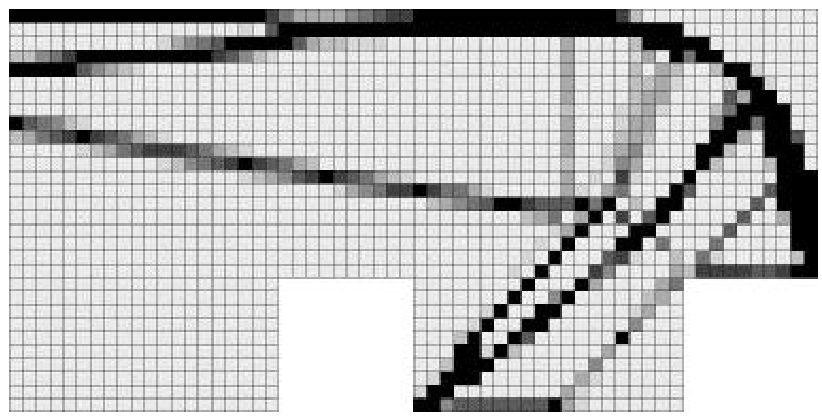
Extracted image design

Constrained Compliant Gripper

Constrained single flexibility



Design domain

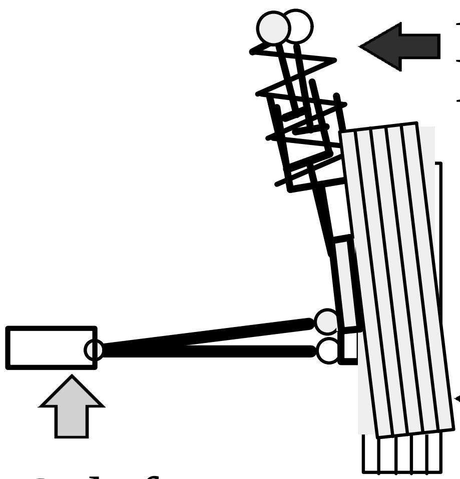


Constrained case

Optimal configurations (Ω_s=20%)

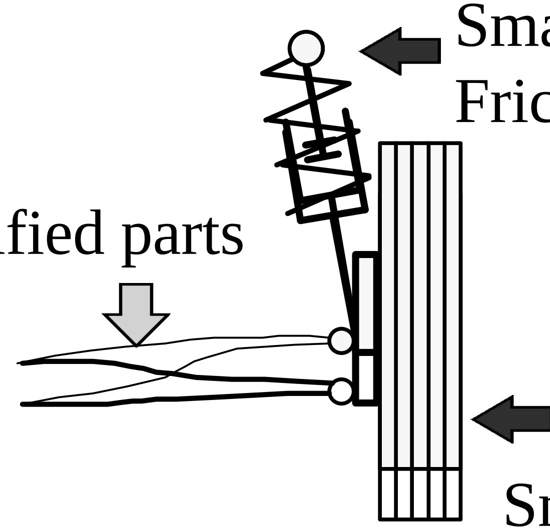
Unified Design of Structures and Mechanisms

Current design approach



Unified design approach

Strut-type suspension



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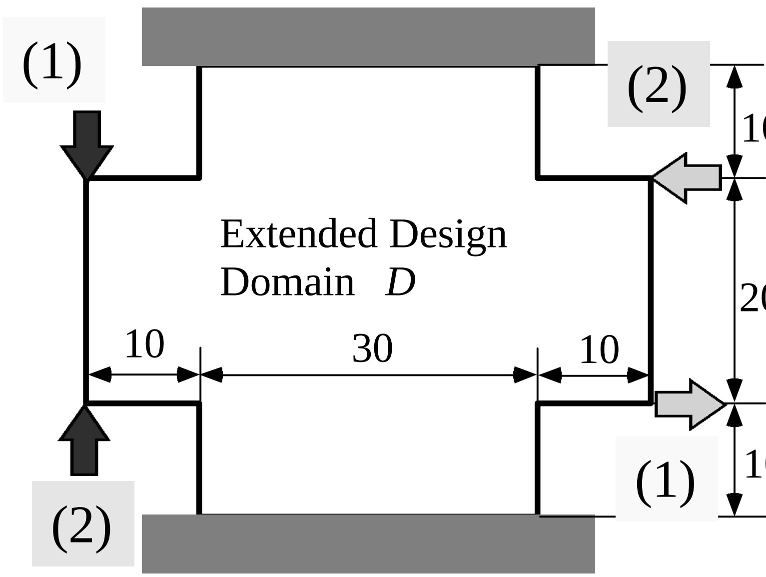
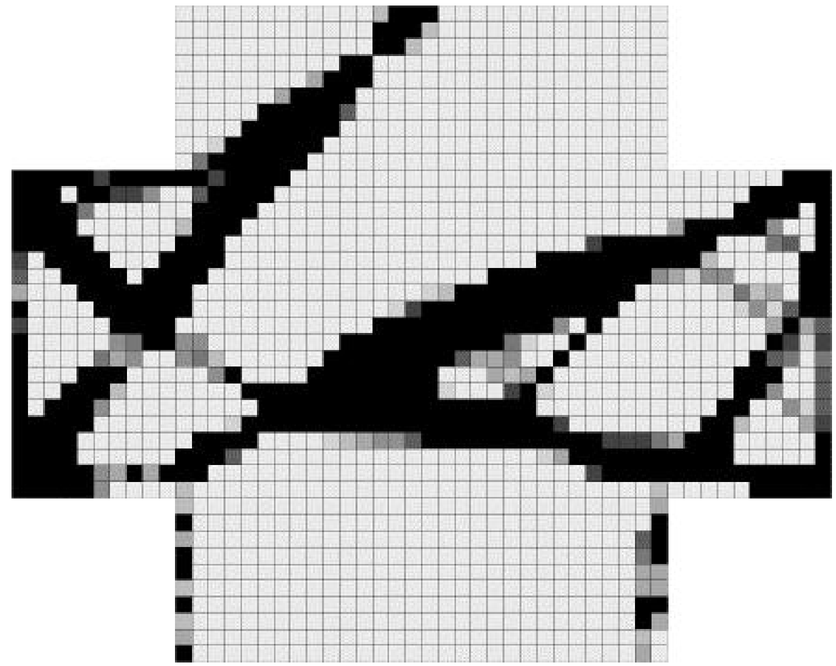
Multi-flexibility Compliant Mechanism (1)

Multi-flexibility



Design domain

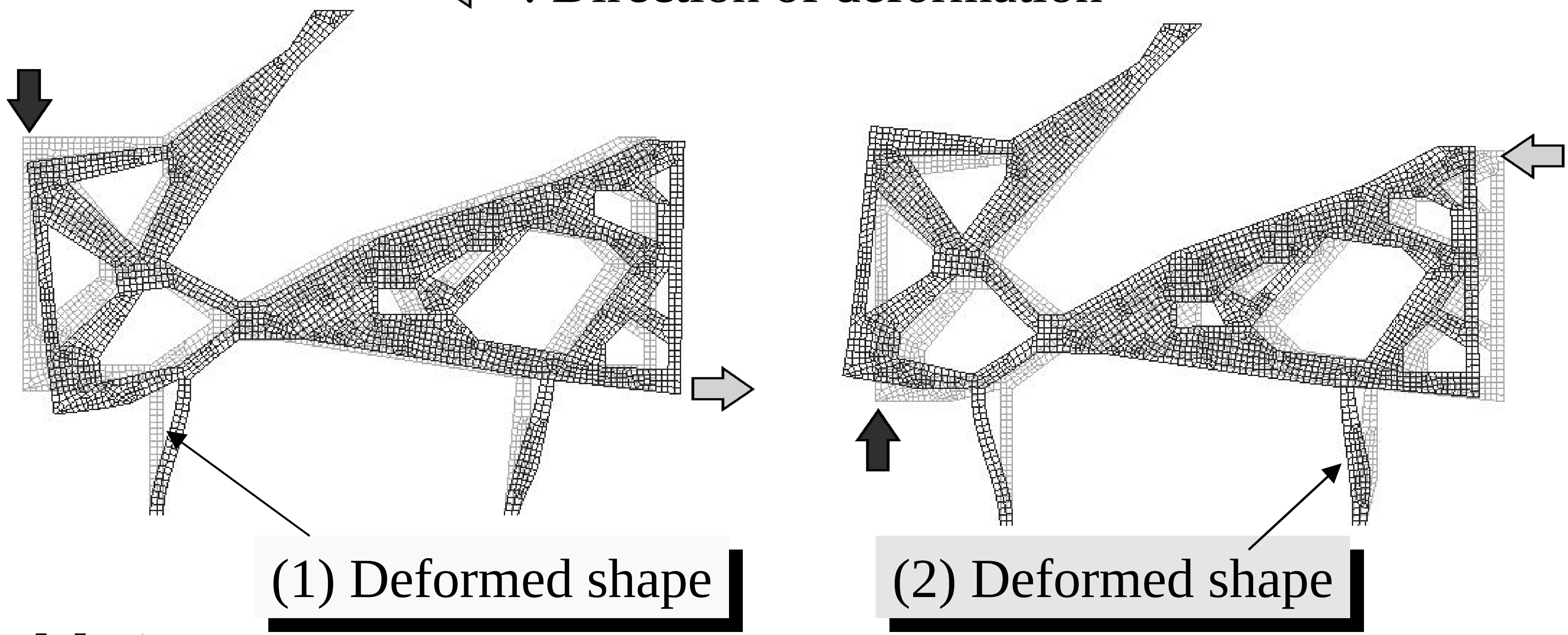


Optimal configurations (Ω_s=30%)

Multi-flexibility Compliant Mechanism (2)

: Applied force

: Direction of deformation



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Flextensional Actuator Design

Piezoceramic + Flexible coupling structure

Coupling Structure → Mechanical Transform

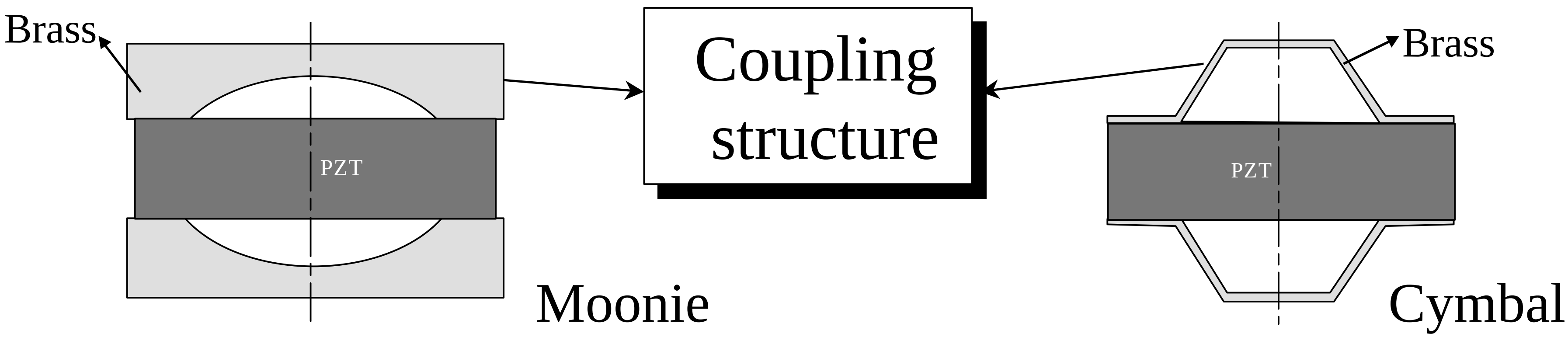
- Amplify output displacement
- Change displacement direction
- Provide stiffness

OPTISHAPE

Actuator Design

A New Capability
to be Implemented

Examples of Flextensional Actuators:



Low-frequency applications are considered
(inertia effect is neglected)

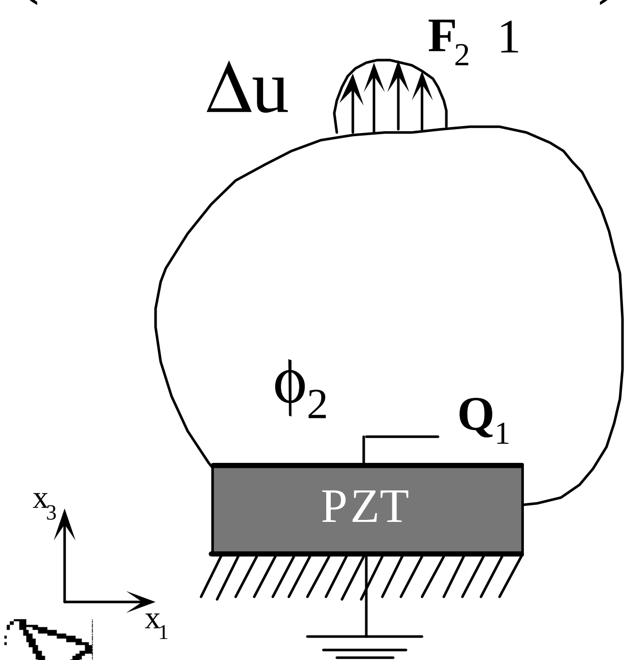
Maximize output displacement (Δu) (⬅ trade-off ➡) Maximize blocking force

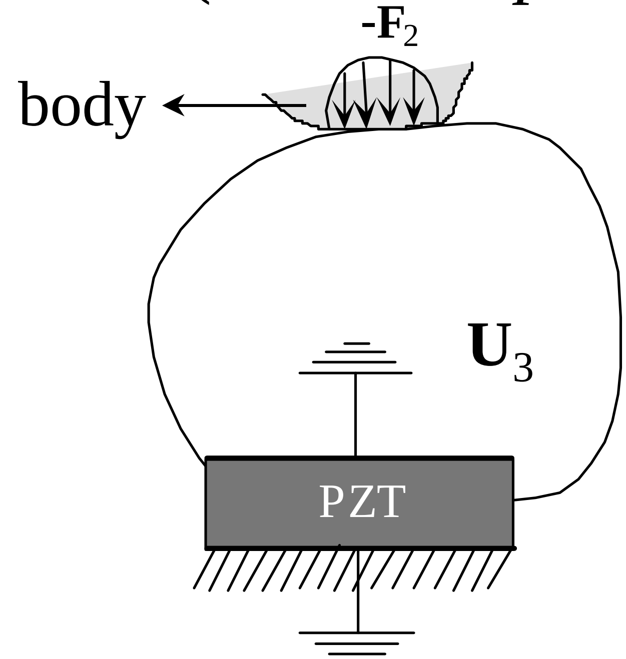
$$\text{Max} \quad \{f_2\}^t\{\mathbf{Q}_1\}$$

(*mean transduction*)

$$\text{Min} \quad \{\mathbf{U}_3\}^t\{-\mathbf{F}_2\}$$

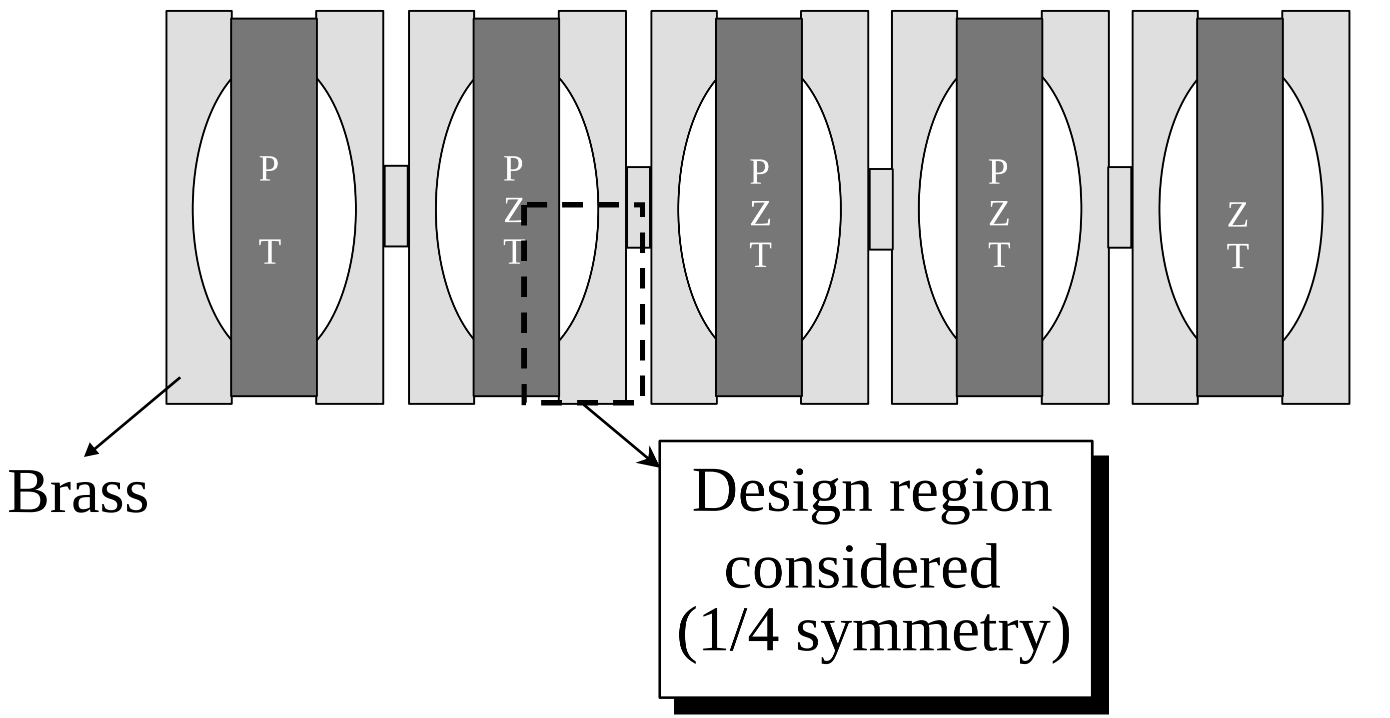
(*mean compliance*)



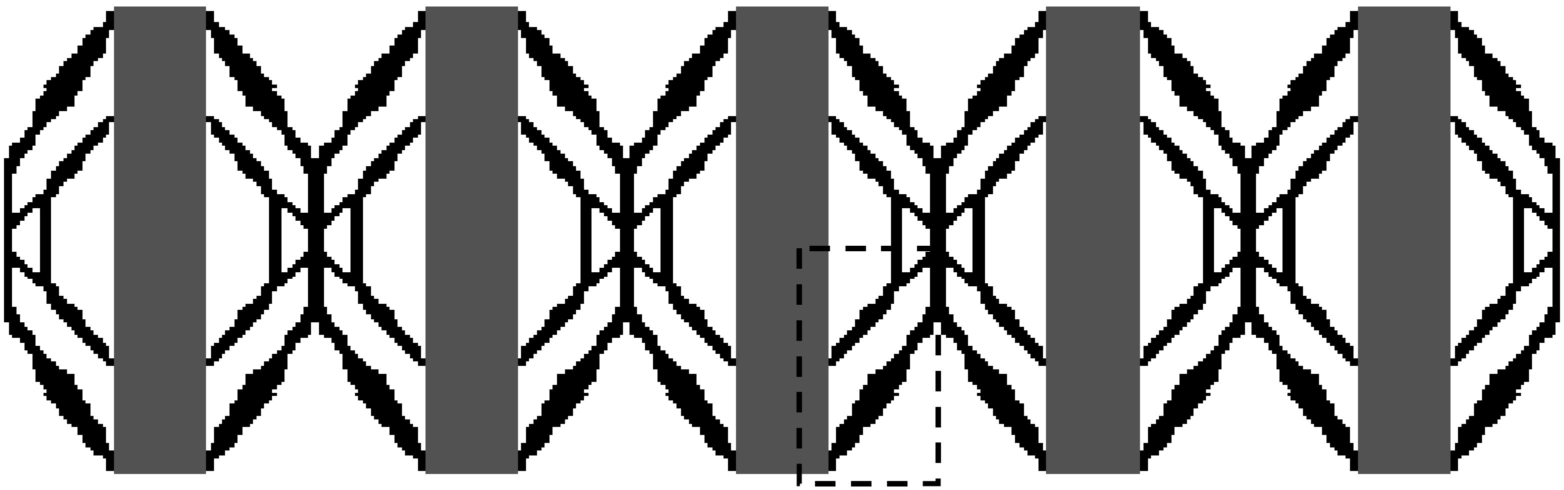


Example 1

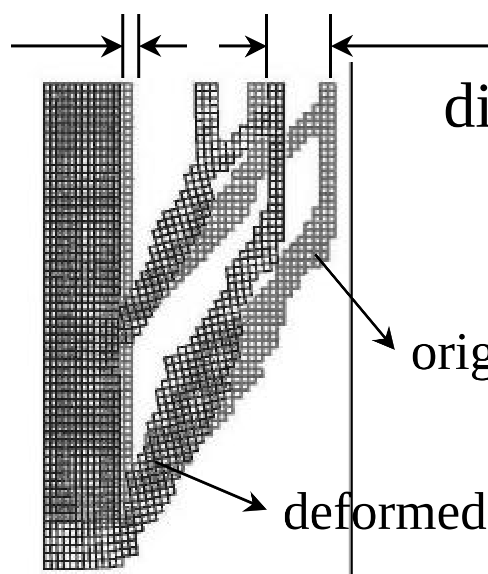
Multilayer actuator (common design)



Multilayer Configuration

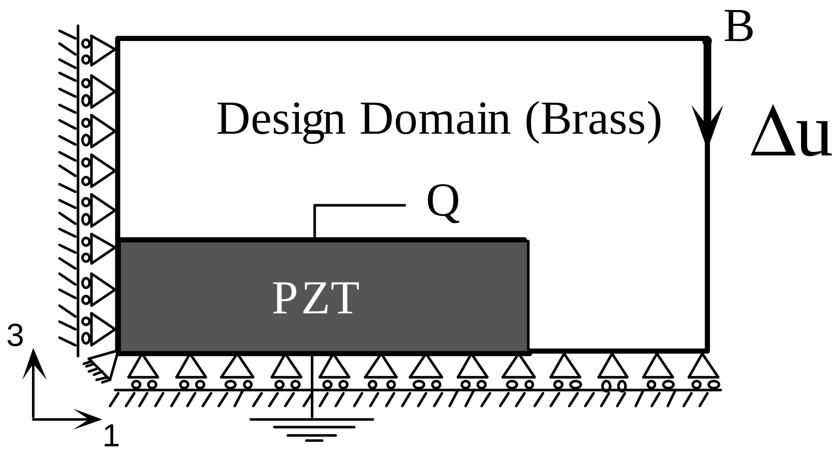


FEM verification:

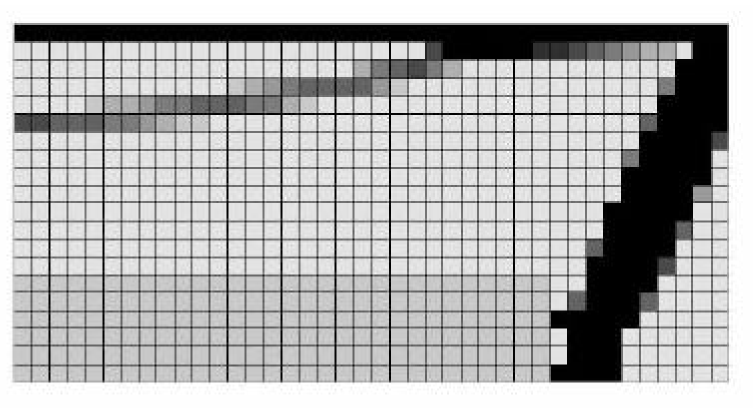


Example 2

(1/4 symmetry)

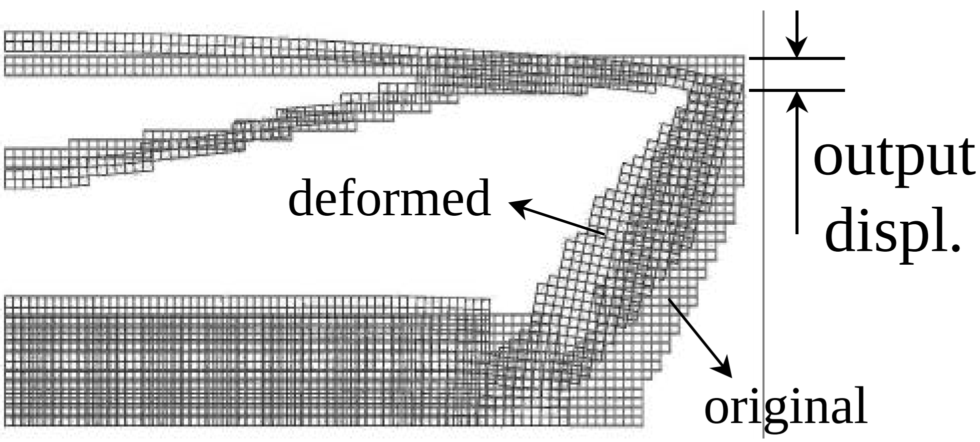


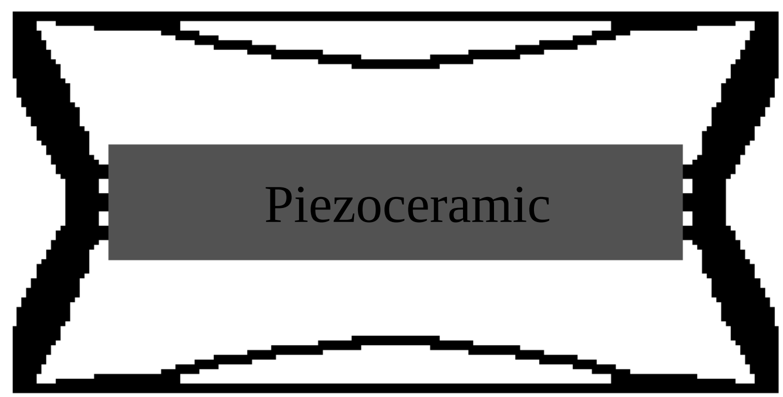
w=0.5



Optimal topology

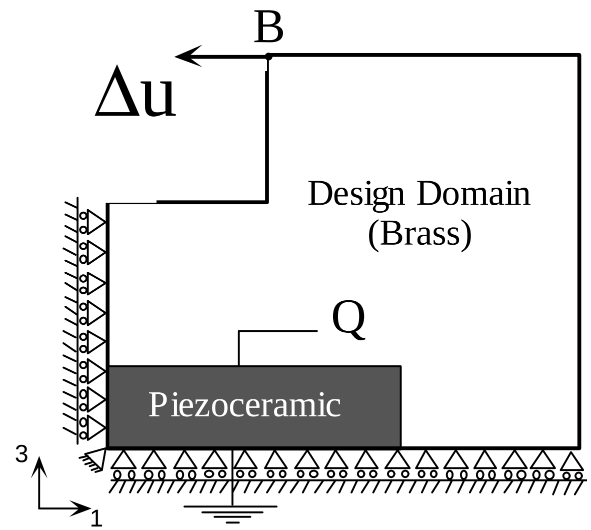
FEM verification:



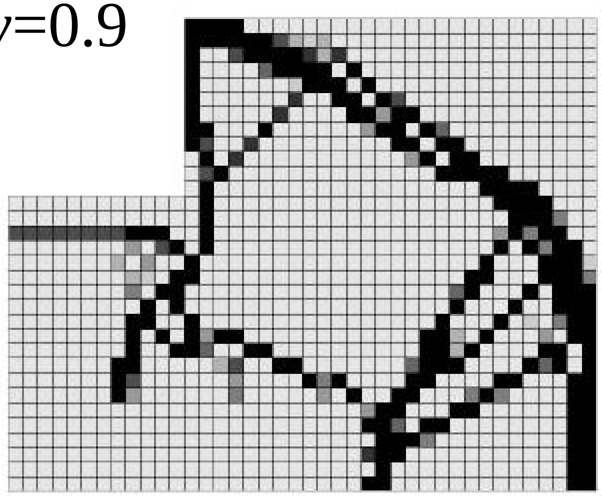


Example 3

(1/2 symmetry)



w=0.9



Optimal topology ($\Omega_s = 25\%$)

Image interpretation

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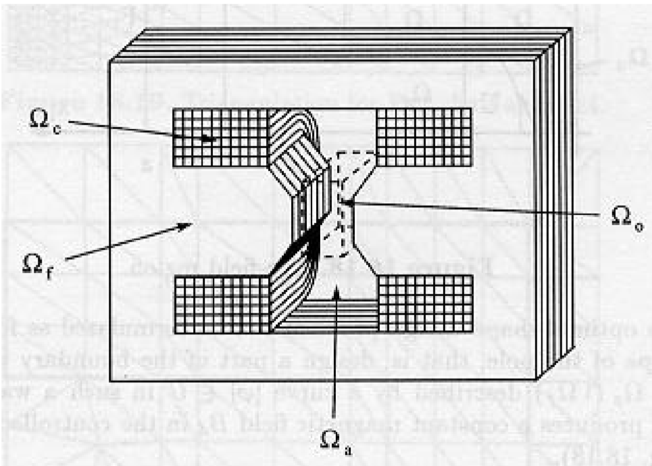
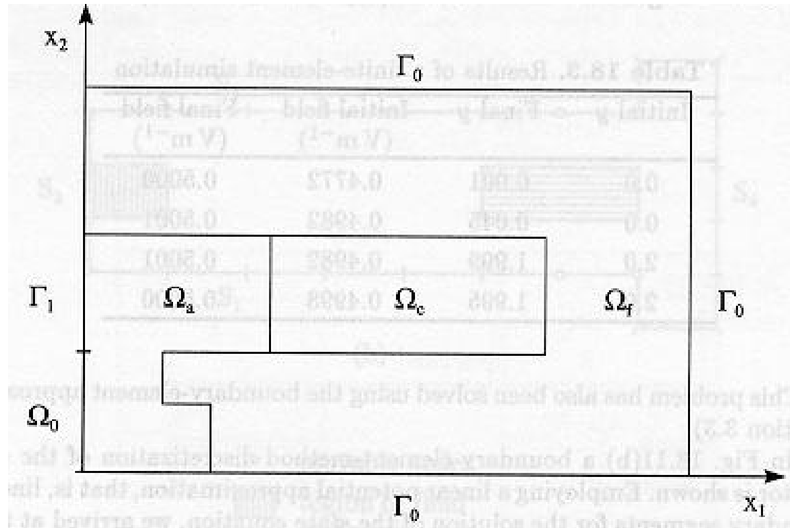
Structural Optimization in Magnetic Fields

Future OPTISHAPE Capability

Shape of H-magnet

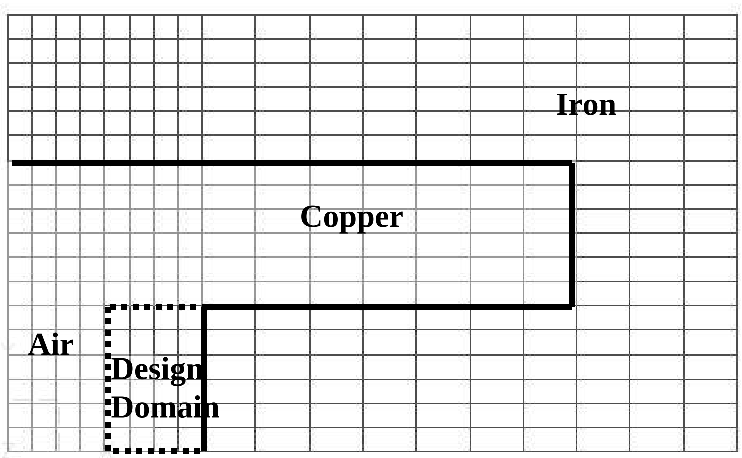


Cross Sectional View

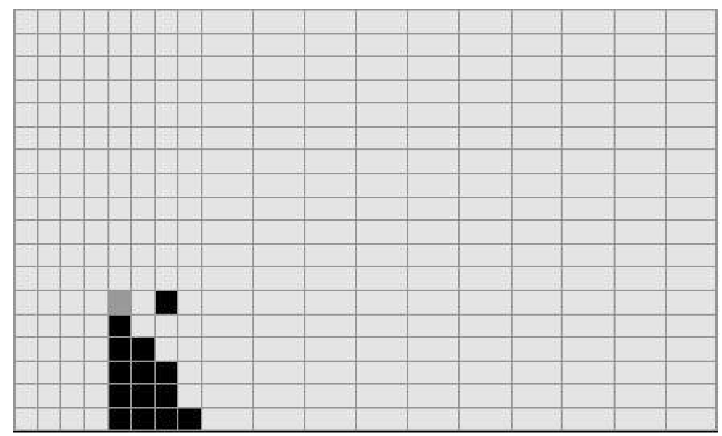


A quarter Model for Analysis

Optimal Shape for Maximizing Total Potential Energy

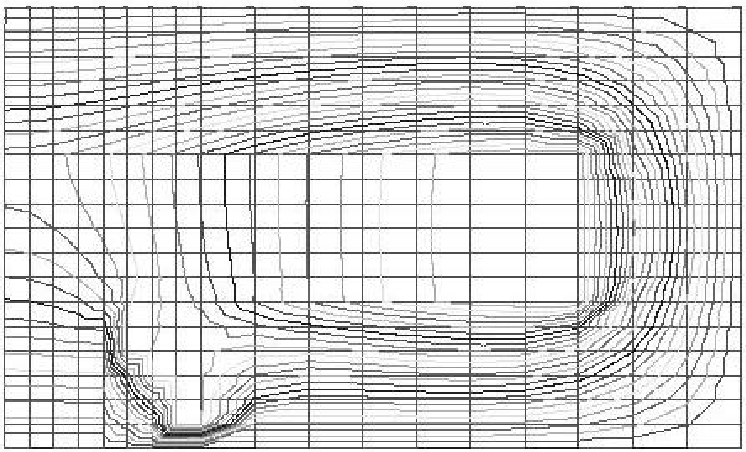


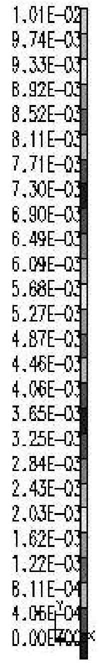
Design Domain for Optimization (324 elements)



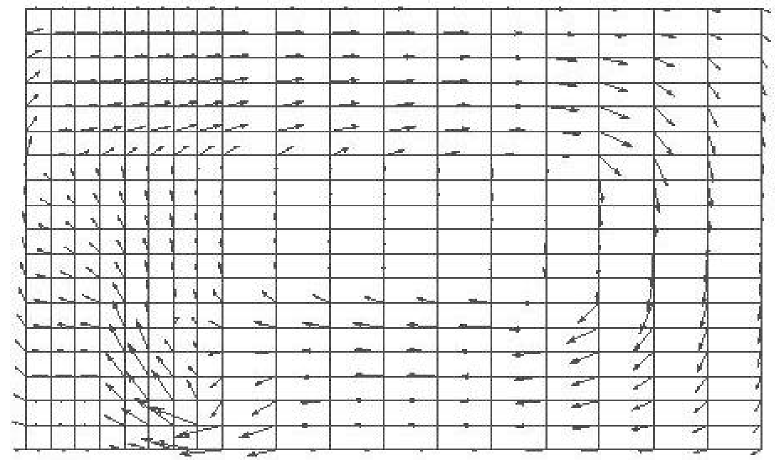
Optimal Shape with 60% Volume Constraint

Analysis of the Optimal Shape





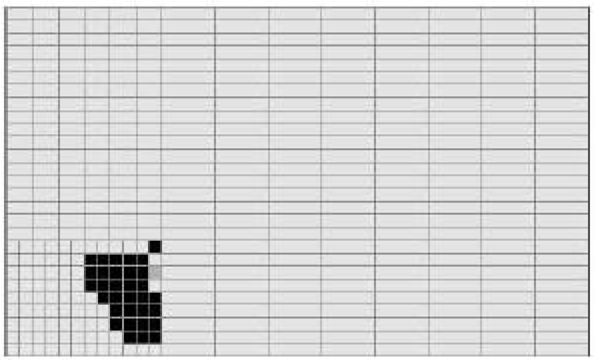
Vector Potential



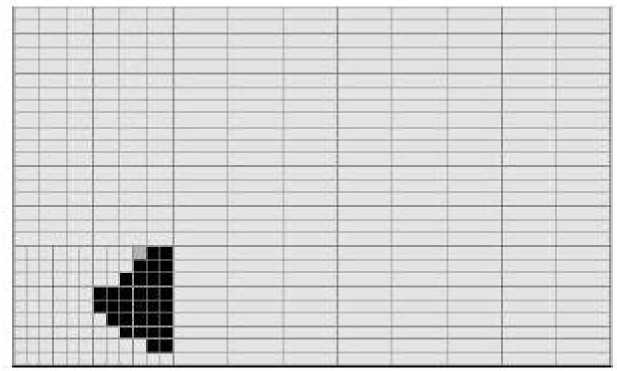
Flux Density

⇨ Increase the value of Flux Densities in Design Domain
(25 - 40%)
Stabilize the Flux Densities

Optimal Shape for Prescribed Uniform Fields (432 element model)



Prescribed **Bx** = -0.18

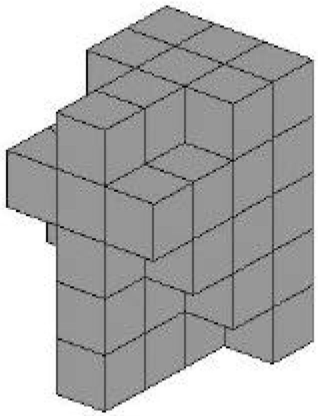


Prescribed **Bx** = -0.18, **By** = 0.05

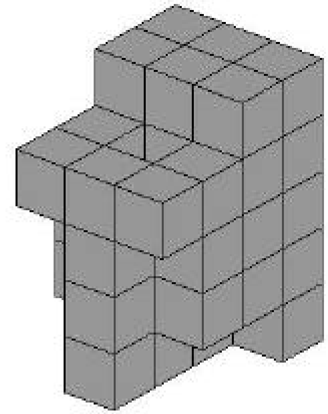
	Prescribed Bx = -0.18	Prescribed Bx = -0.18 By = 0.05
Ave. of x components	-0.18298E+00	-0.16645E+00
Ave. of y components	0.69363E-01	0.38788E-01
Stand. Dev. of x components	0.62515E-01	0.57342E-01
Stand. Dev. of y components	0.68198E-01	0.46641E-01

Optimal Shape of the Design Domain for Prescribed Uniform Fields

(3-layer, 432 element model)



Prescribed **Bx** = -0.20



Prescribed **Bx** = -0.20, **By** = 0.05

	Prescribed Bx = -0.18	Prescribed Bx = -0.18 By = 0.05
Ave. of x components	-0.20712E+00	-0.20706E+00
Ave. of y components	-	0.44251E-01
Stand. Dev. of x components	0.87911E-01	0.69931E-01
Stand. Dev. of y components	-	0.57347E-01

Research Issue in OPTISHAPE

Material Design Optimization

Young's & Shear Moduli

Poisson's Ratios

Thermal Exapansion Coefficients

Electro-magnetic Properties

Following To
Dr. O. Sigmund

Technical University of Denmark

Jun Ono Fonseca

and

Bing-Chung Chen

The University of Michigan, Department of Mechanical Engineering
Computational Mechanics Laboratory

Three-Phrase Material Design

- Artificial material mixing rule

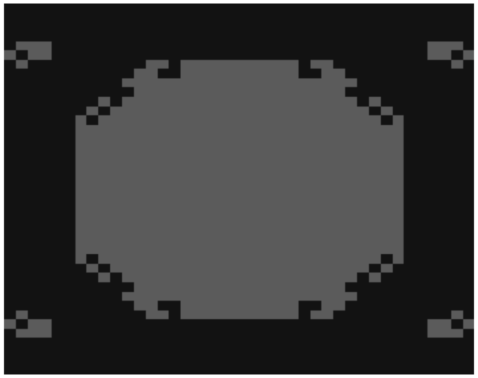
$$E = \mathrm{r}\left[mE^{(1)} + (1-m)E^{(2)}\right]$$

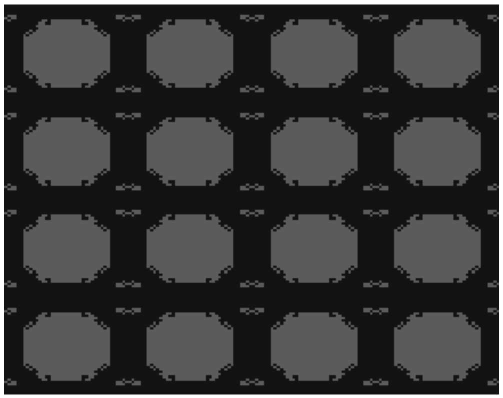
$$\mathrm{a} = \left[m\mathrm{a}^{(1)} + (1-m)\mathrm{a}^{(2)}\right]$$

- Design layout of two solid phases and void simultaneously
- Possible overlap between two phases when $m \neq 1 \; or \; m \neq 0$

Benchmarking

with existing 2-phase bound





- $E^{(1)} = 10, \nu^{(1)} = 0.3, \alpha^{(1)} = 1.0, V = 50\%$
- $E^{(2)} = 1.0, \nu^{(2)} = 0.3, \alpha^{(2)} = 10.0, V = 50\%$

- "Good" expansion material surrounded by "Bad" expansion material results in the "Worst" expansion composite

$$\alpha^{H} = \begin{bmatrix} 6.5 & 0 \\ 0 & 6.48 \end{bmatrix}$$

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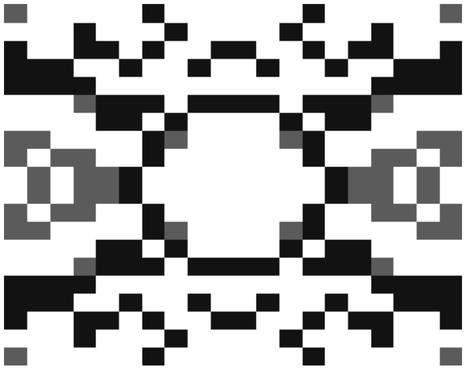
Negative Expansion

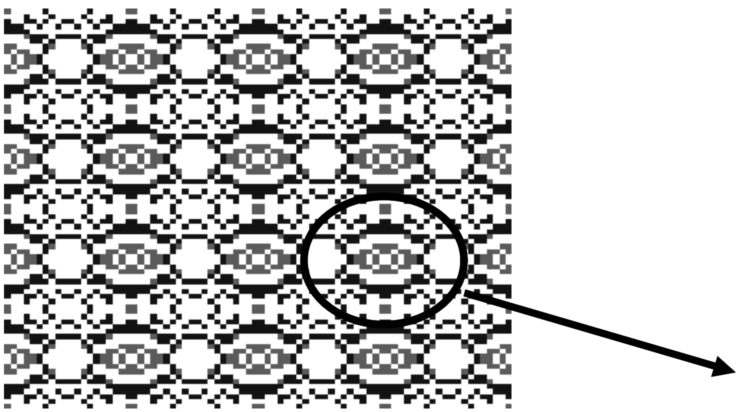
in the vertical direction



$E^{(1)} = 10, \nu^{(1)} = 0.3, \alpha^{(1)} = 1.0, V = 25\%$

$E^{(2)} = 1.0, \nu^{(2)} = 0.3, \alpha^{(2)} = 10.0, V = 10\%$

Void



$$\alpha^H = \begin{pmatrix} 2.0 & 0 \\ 0 & -1.1 \end{pmatrix}$$

Re-entrant structure

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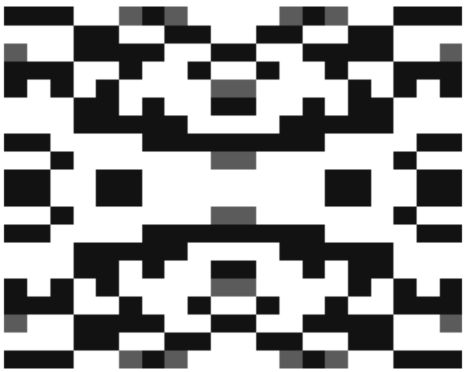
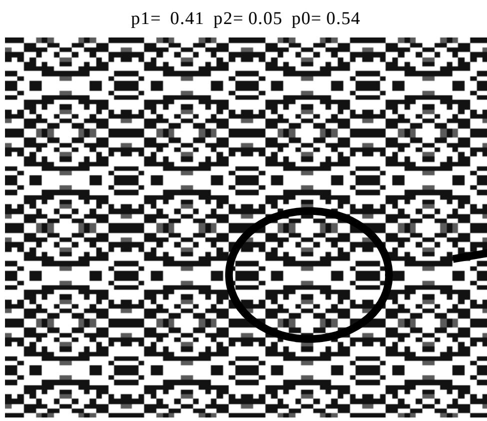
Near Zero Expansion

in the Horizontal Direction



- Almost disconnected in the y
- Again, very complicated structure in terms of manufacturing



$$E^H = 0.6\begin{pmatrix} 1.0 & 0.0008 & 0 \\ 0.0008 & 0.0011 & 0 \\ 0 & 0 & 0.0005 \end{pmatrix}$$

$$\alpha^H = \begin{pmatrix} 0.08 & 0 \\ 0 & 1.6 \end{pmatrix}$$

Construction of three-phase material by two stage design

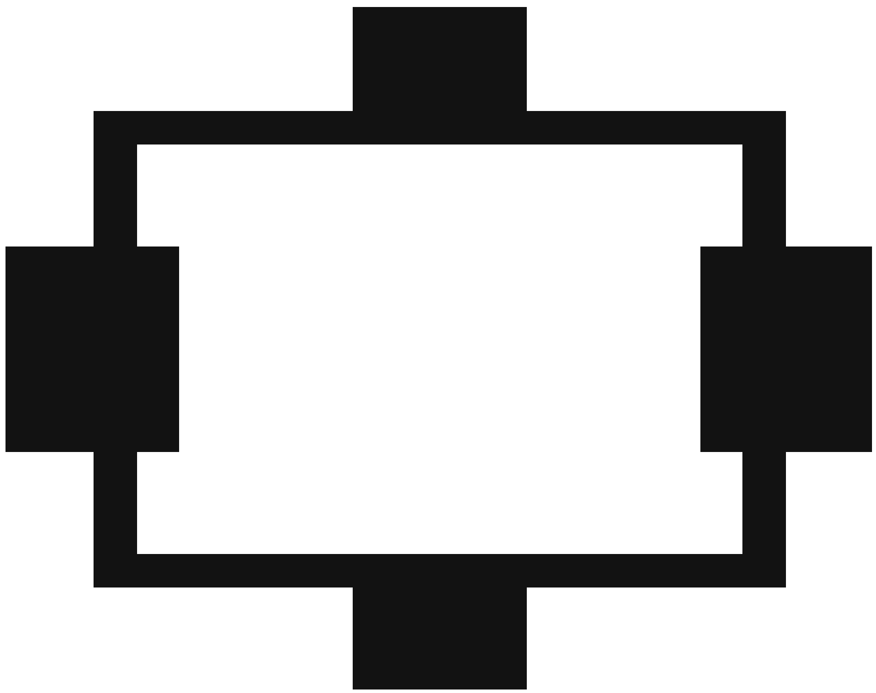
- Given distribution of phase 1, design phase 2 distribution, excluding the domain occupied by phase 1
- Mark phase 2 as exclusion, design phase 1
- The final micro-structure should be non-complex and easy to manufacture.

Design phase 2
Mark phase 1
as excluded

Design phase 2
Mark phase 1
as excluded

Example: Reinforcement Design

distribution of phase 1

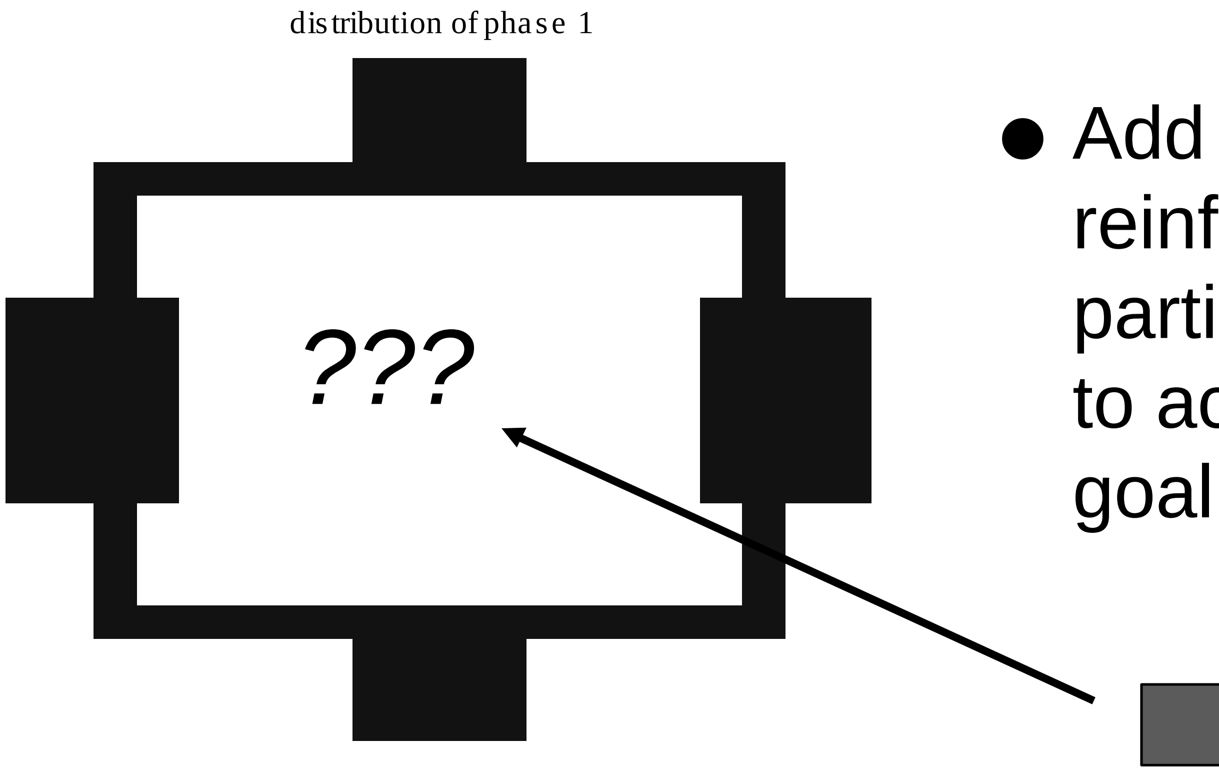


- Given a material with properties to be improved

$$E^H = \begin{pmatrix} 0.9 & 0.32 & 0 \\ 0.32 & 0.6 & 0 \\ 0 & 0 & 0.324 \end{pmatrix}$$

$E_1 = 10, n = 0.3$

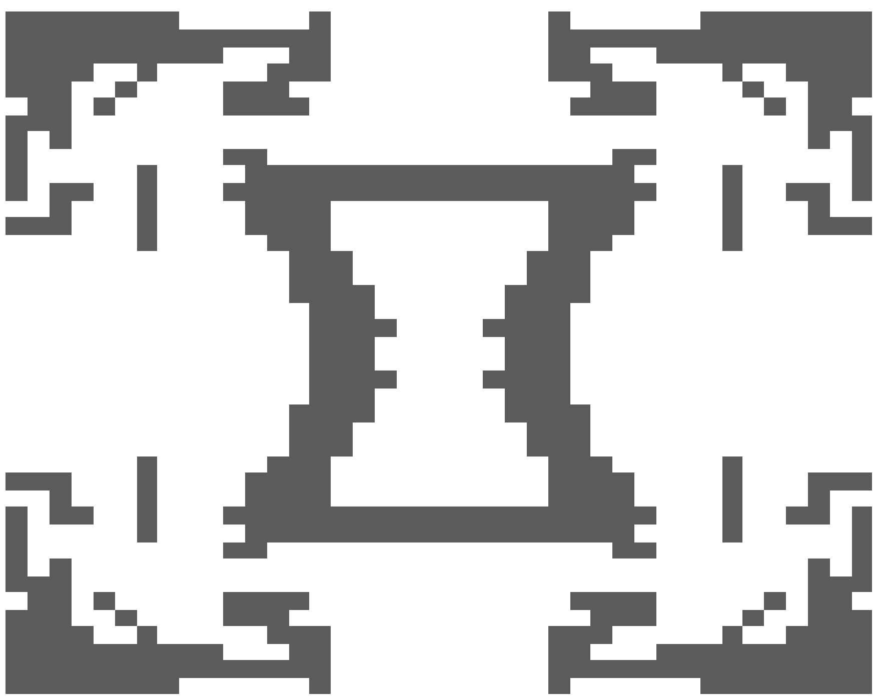
Find the Optimal Distribution of Reinforcement. Phase 2



- Add the reinforcement in a particular pattern to achieved design goal

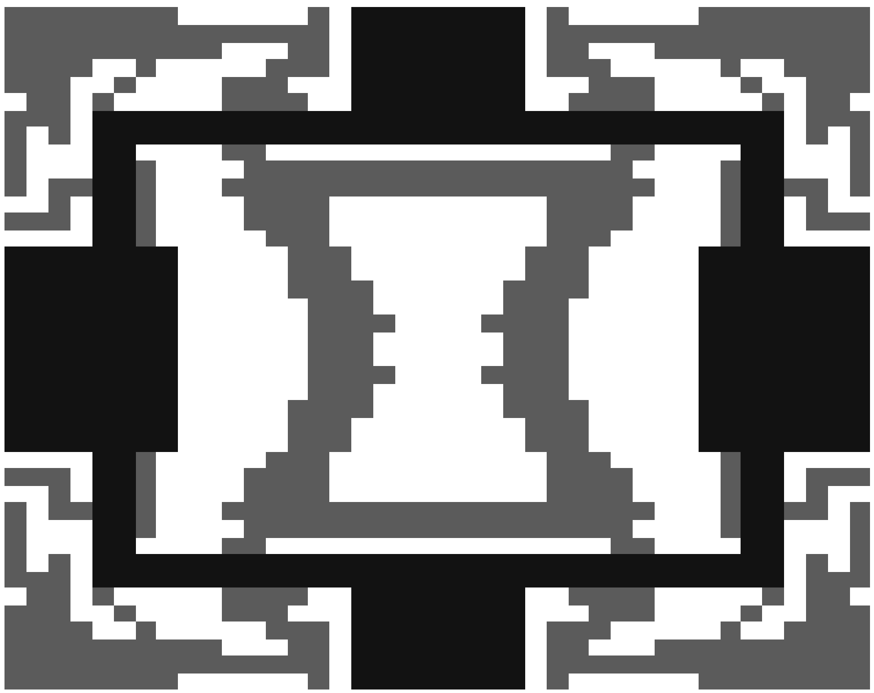
$E_2 = 5, n = 0.3$

The Optimal Distribution of Reinforcement



- The reinforcement phase is non-overlapping with the original phase

Superimpose the two non-overlapping phases



- Super-impose the two phases to achieve the design goal (increased rigidity and negative Poisson's ratio)

$$E^H = \begin{bmatrix} 1.0 & -0.27 & 0 \\ -0.27 & 1.0 & 0 \\ 0 & 0 & 0.32 \end{bmatrix}$$

■ $E_1 = 10, \nu = 0.3$ ■ $E_2 = 5, \nu = 0.3$

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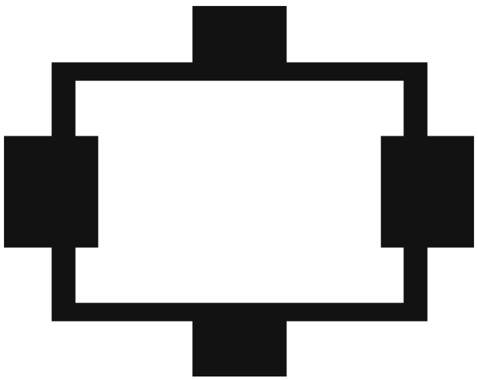
Negative expansion in the horizontal direction

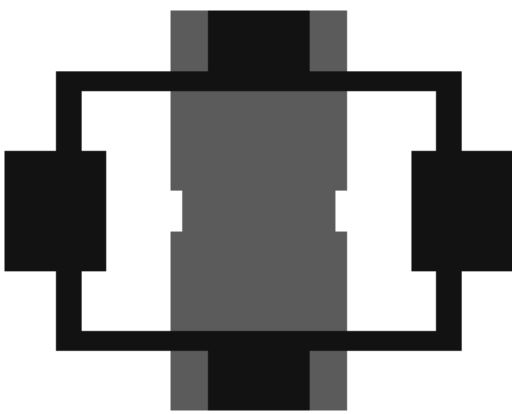
distribution of phase 1



$E^{(1)} = 10, \nu^{(1)} = 0.3, \alpha^{(1)} = 1.0, V = 30\%$

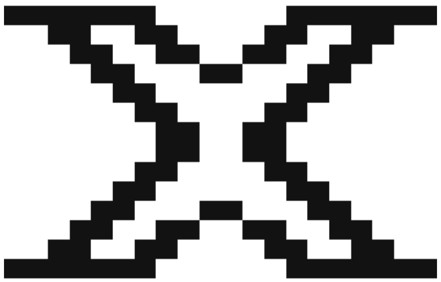
$E^{(2)} = 10, \nu^{(2)} = 0.3, \alpha^{(2)} = 10.0, V = 25\%$

Void



- Stretch in the y due to temperature rise
- Shrink in the x due to Poisson’s effect
- Unusual CTE material must encompass structure-like mechanism

Negative expansion in the vertical direction



Initial phase 1 distribution
(inverted honeycomb)

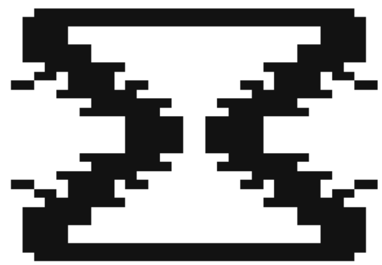
$$\alpha^{H} = \begin{bmatrix} 0.8 & 0 \\ 0 & -0.5 \end{bmatrix}$$

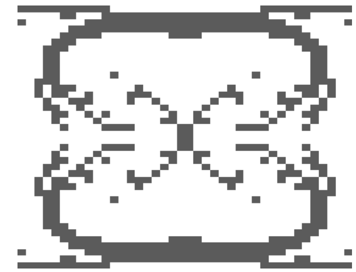
$E^{(1)} = 5, \nu^{(1)} = 0.3, \alpha^{(1)} = 10, V = 35\%$

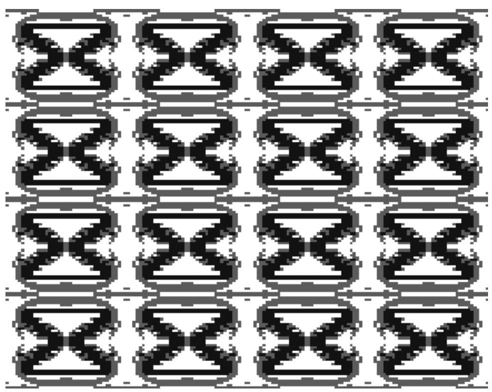
$E^{(2)} = 10, \nu^{(2)} = 0.3, \alpha^{(2)} = 5, V = 25\%$

Void

Near zero Thermal Expansion







Phase 1

Phase 2

$$\alpha^{H} = \begin{bmatrix} 0.22 & 0 \\ 0 & 0.21 \end{bmatrix}$$

■ $E^{(1)} = 5, \nu^{(1)} = 0.3, \alpha^{(1)} = 10, V = 25\%$

■ $E^{(2)} = 10, \nu^{(2)} = 0.3, \alpha^{(2)} = 5, V = 30\%$

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Topology Optimization Algorithm Examination / Research

Various Filtering Schemes

Proposed

using SLP

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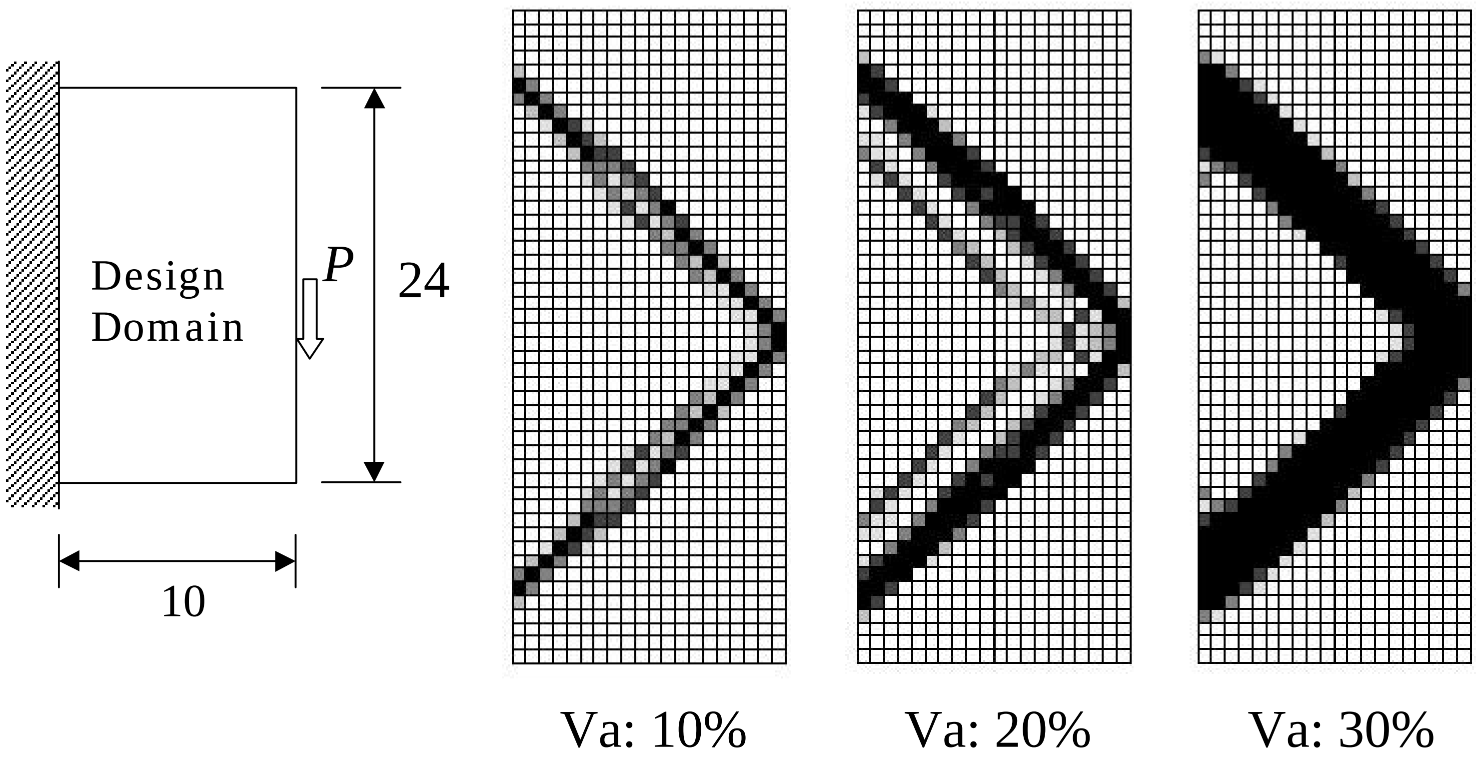
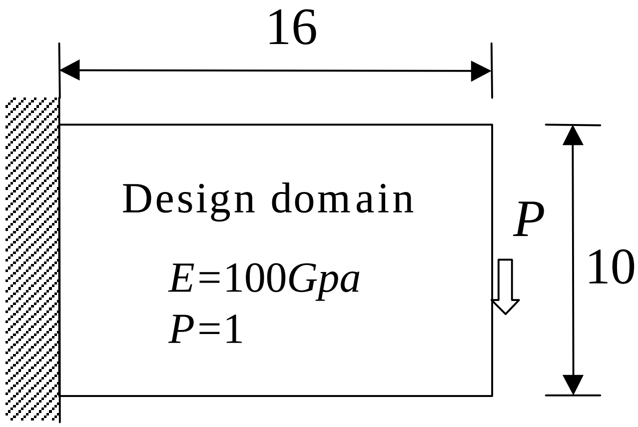
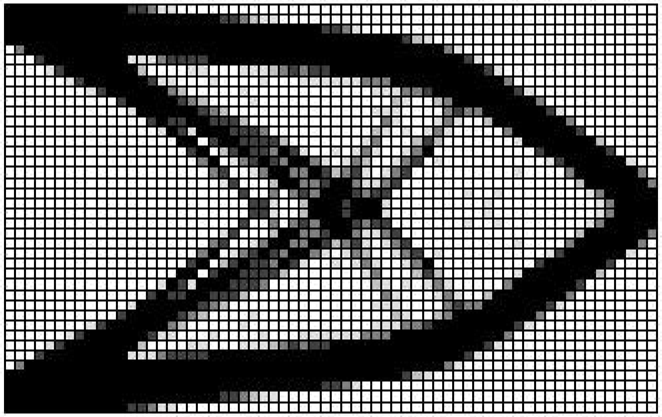
Example 1

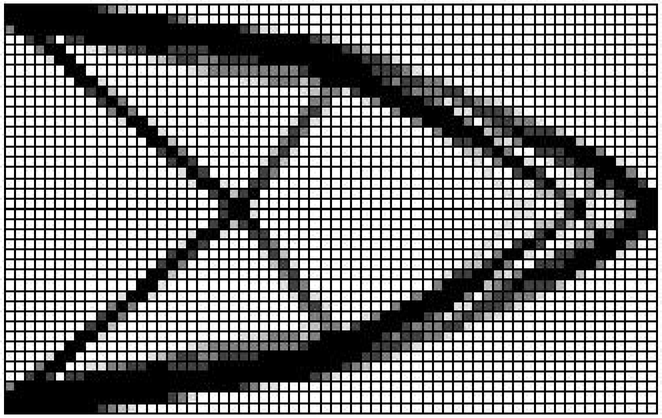


Example 2

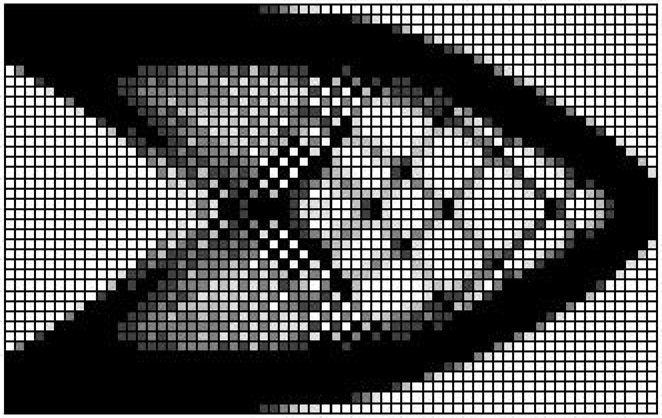




Va:37.5% CE: 0.9454



Va:25% CE: 1.422



Va:50% CE: 0.7157

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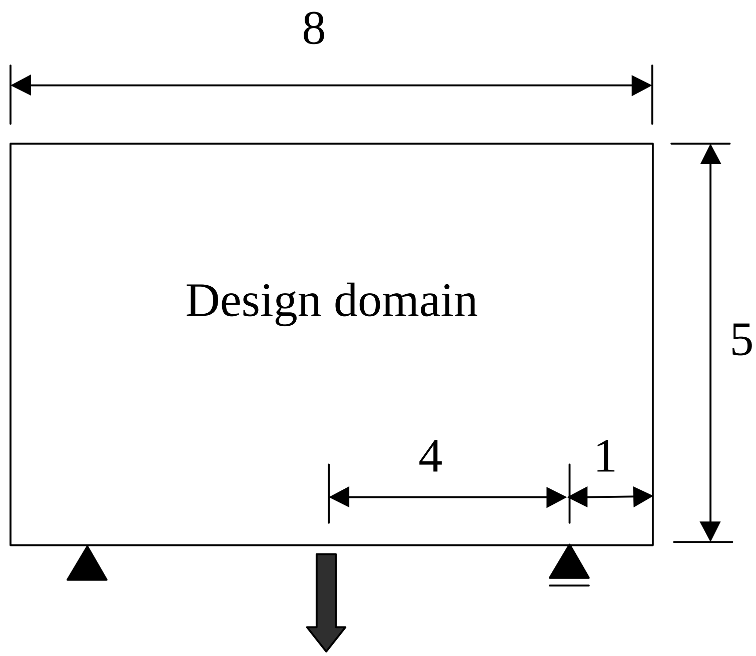
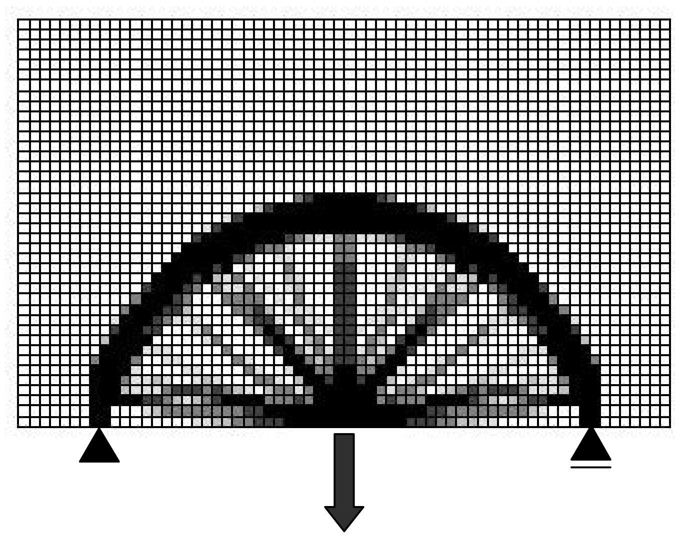
Example 3





Maximization of Attractive Force

$$g = \sum_{i=1}^{N} \sum_{k=1}^{4} \frac{\mathrm{r}_i \mathrm{r}_k}{r_{ik}^{2}} \rightarrow \mathbf{max}$$

	r_2	
r_1	r_i	r_3
	r_4	

$\mathrm{r}_i = 1 - \mathrm{a}_i \mathrm{b}_i$

r_{ik} :distance

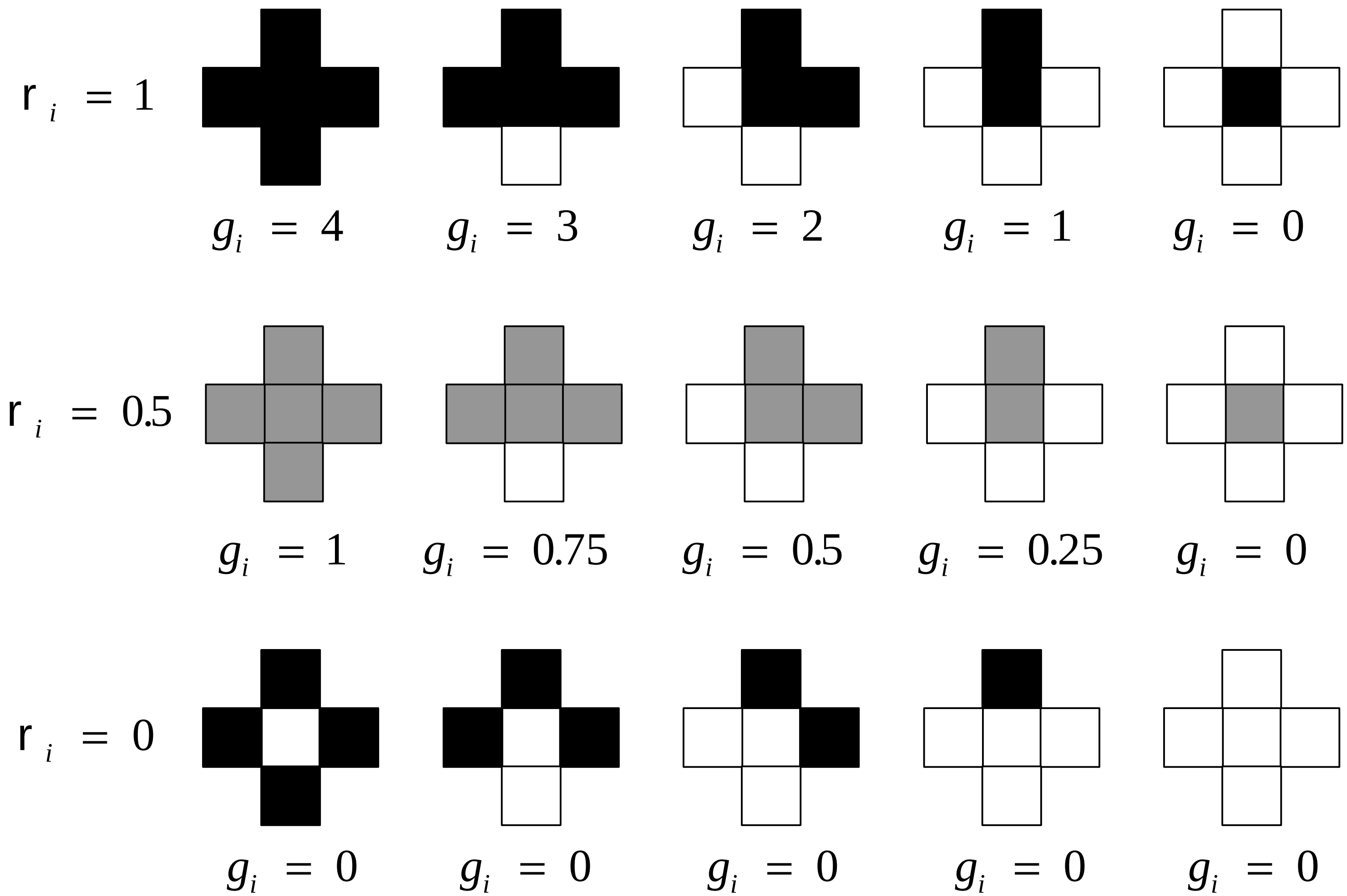
N : number of element

w_g: *weight* $\quad \bar{g} = g \,/\, g_{ini}$

$$\text{Objective} \quad f = C\sqrt{1 - (w_g \bar{g})^2}$$

Attractive Forces

$r_{ik} = 1$



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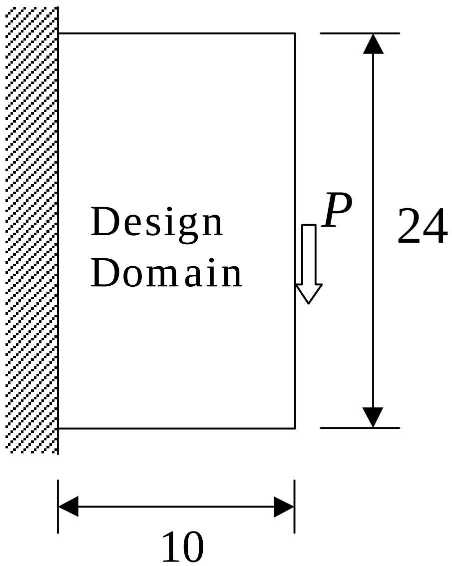
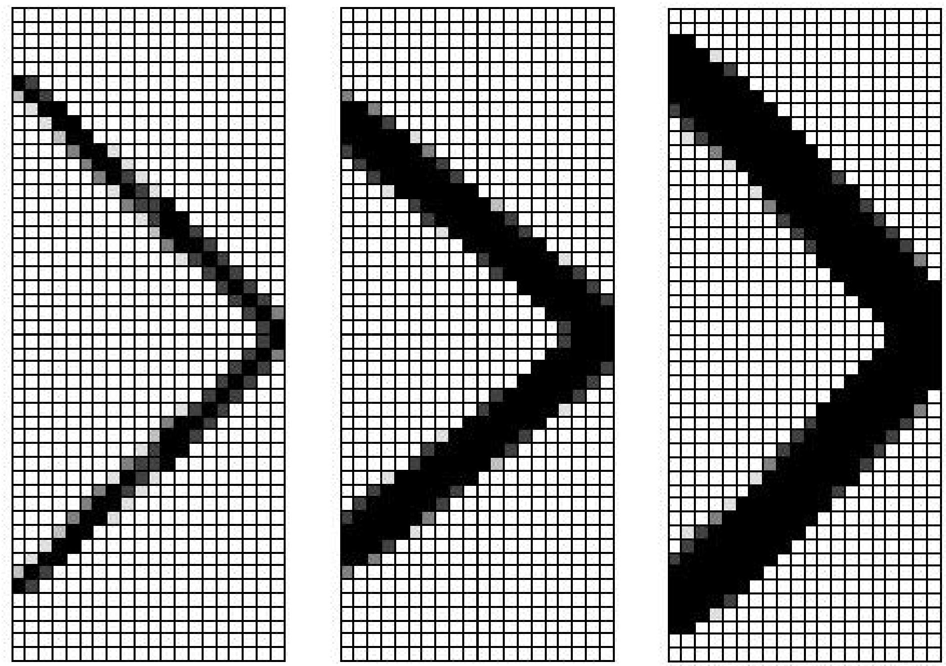
Example 1A

$w_g = 0.1$

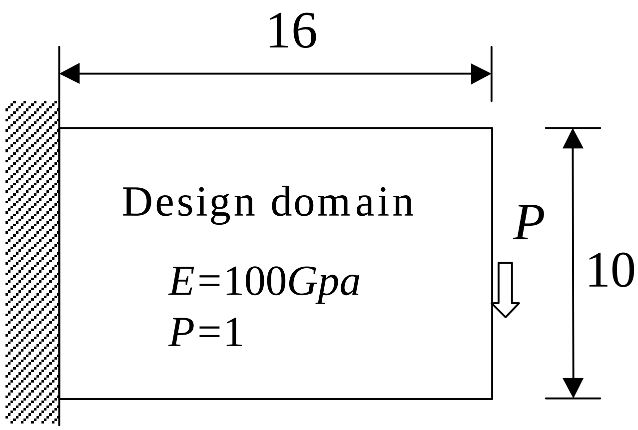


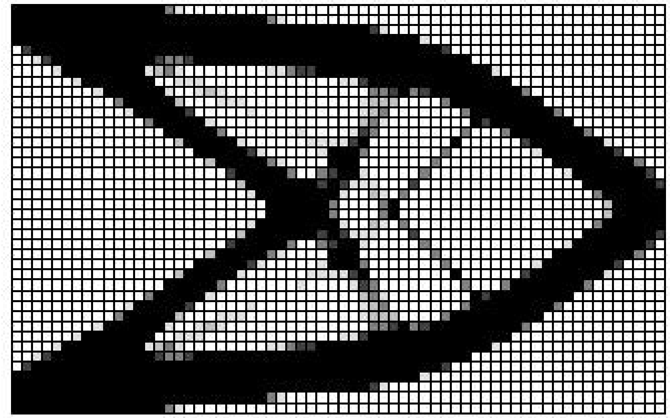


Va: 10%   Va: 20%   Va: 30%

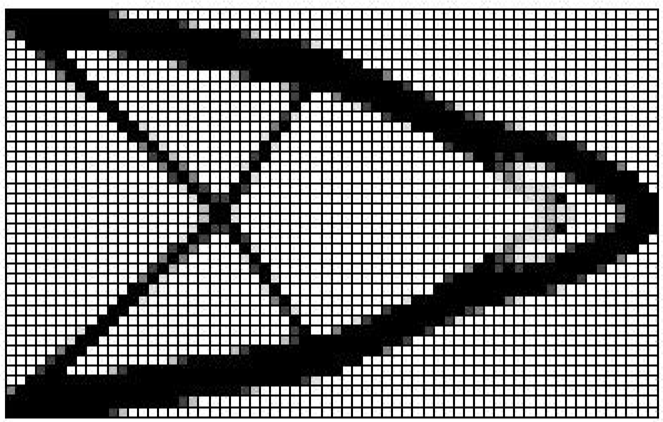
Example 2A

$w_g = 0.1$

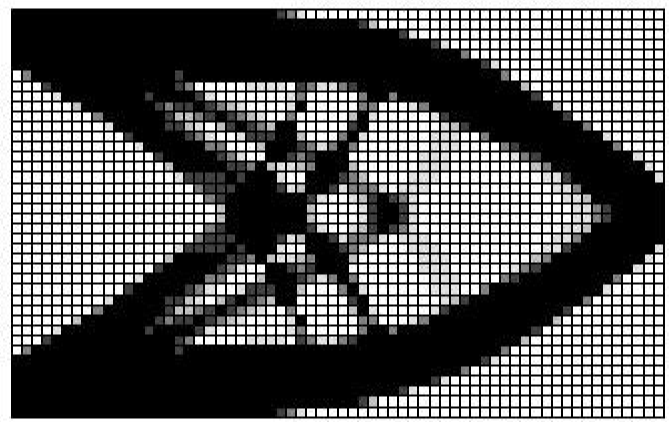




Va:37.5% CE: 0.9576



Va:25% CE: 1.499



Va:50% CE: 0.7275

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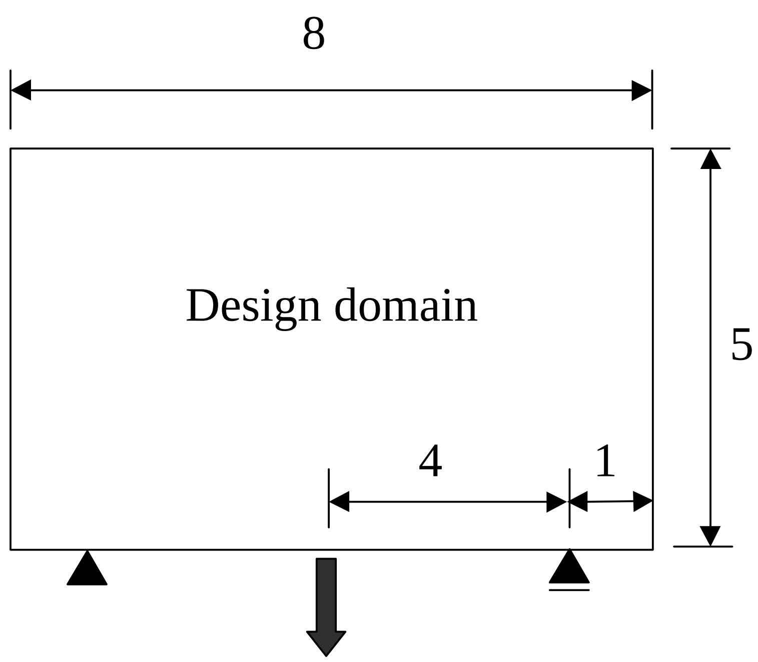
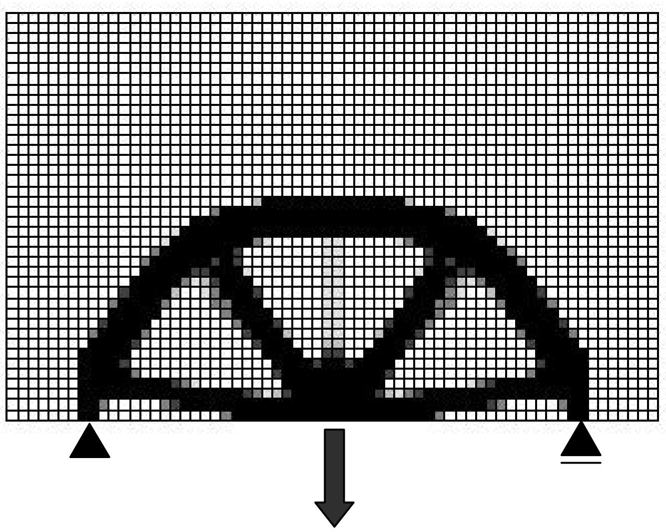
Example 3A

$\boxed{w_g = 0.1}$





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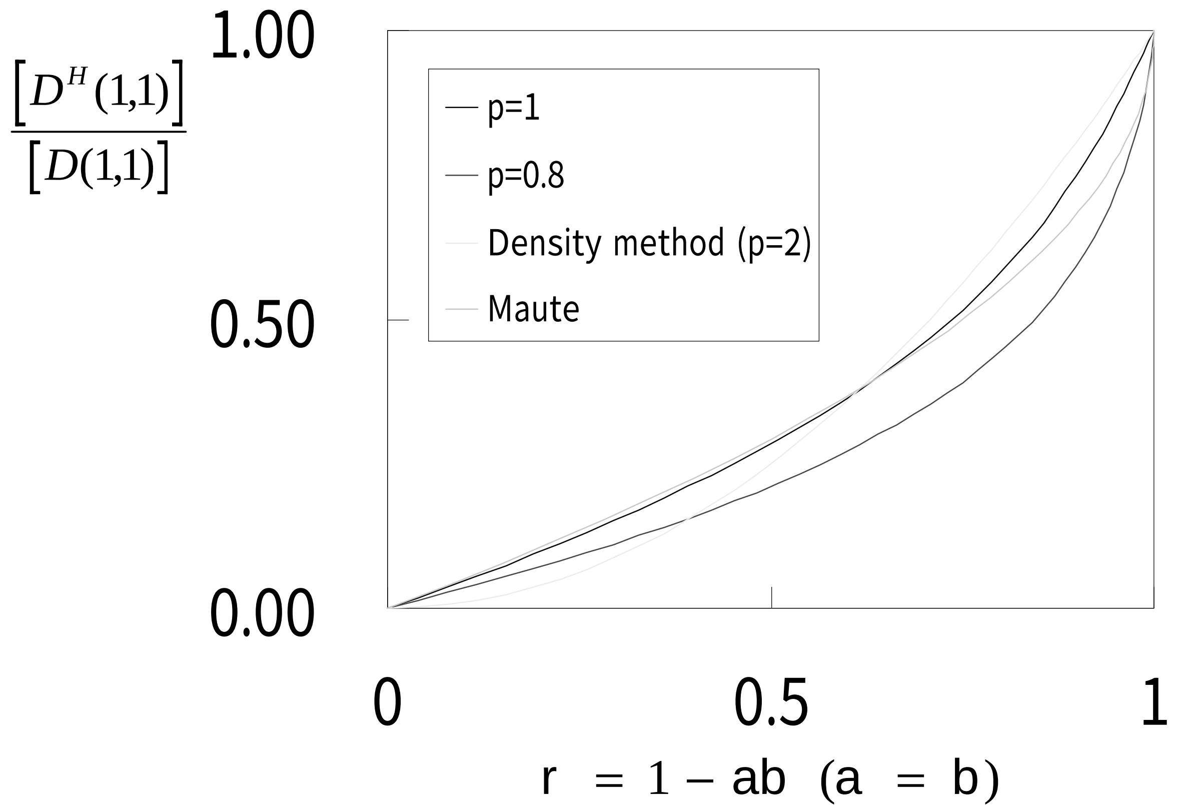
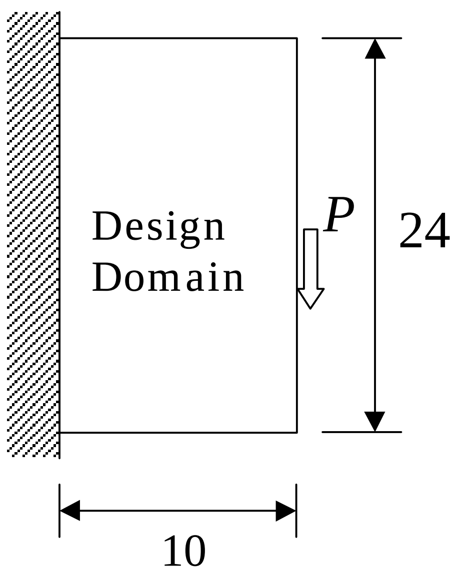
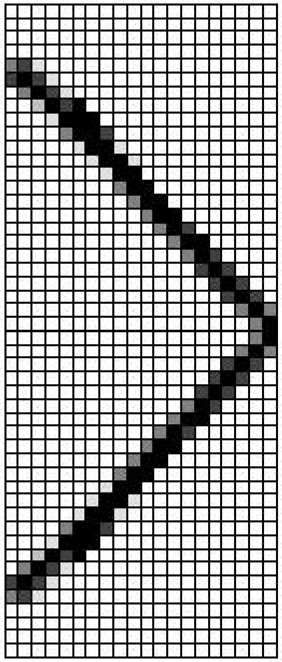
Gray Scale Penalty



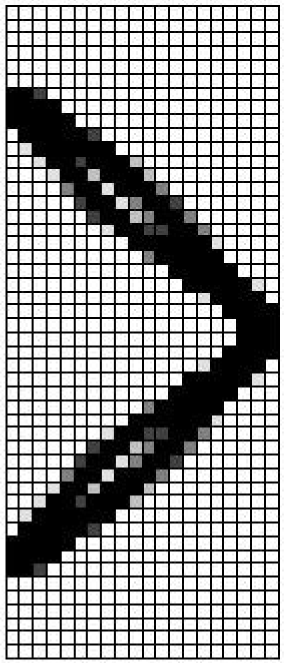
Example 1B

$$\boxed{w_g = 0.1, \; p = 0.8}$$

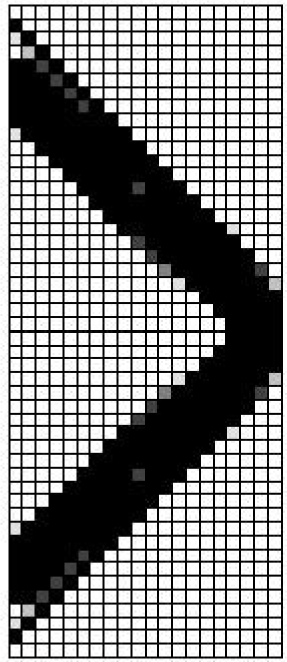




Va: 10%



Va: 20%



Va: 30%

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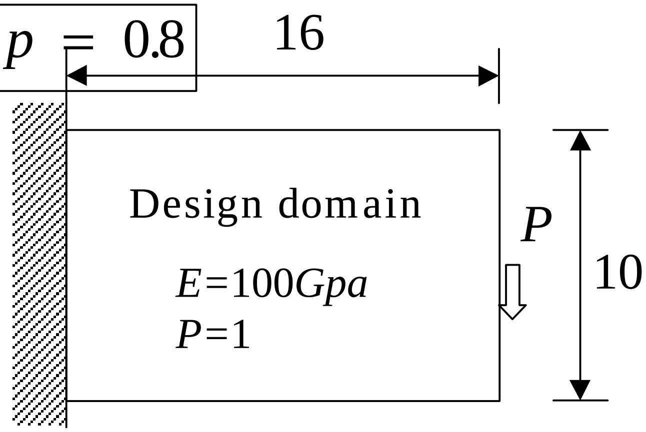
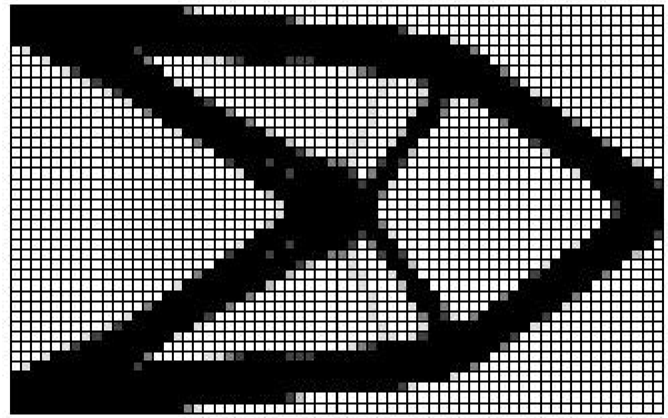
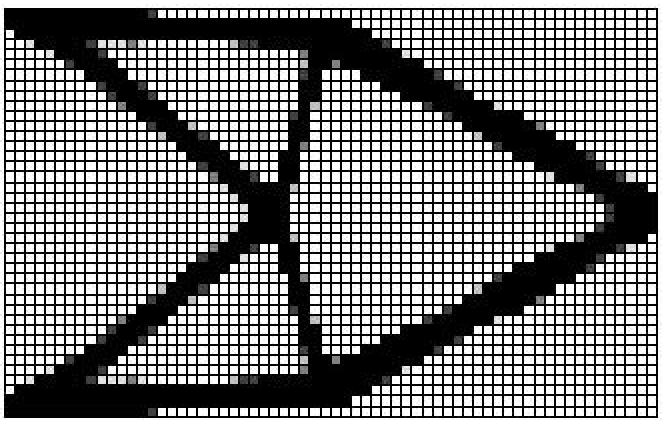
Example 2B

$w_g = 0.1, \; p = 0.8$

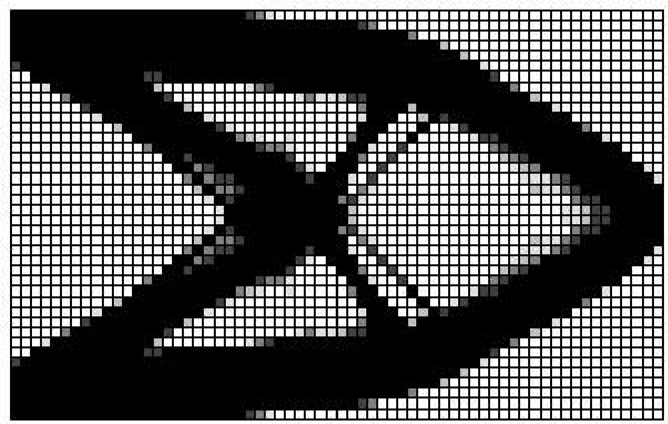




Va:37.5% CE: 1.011



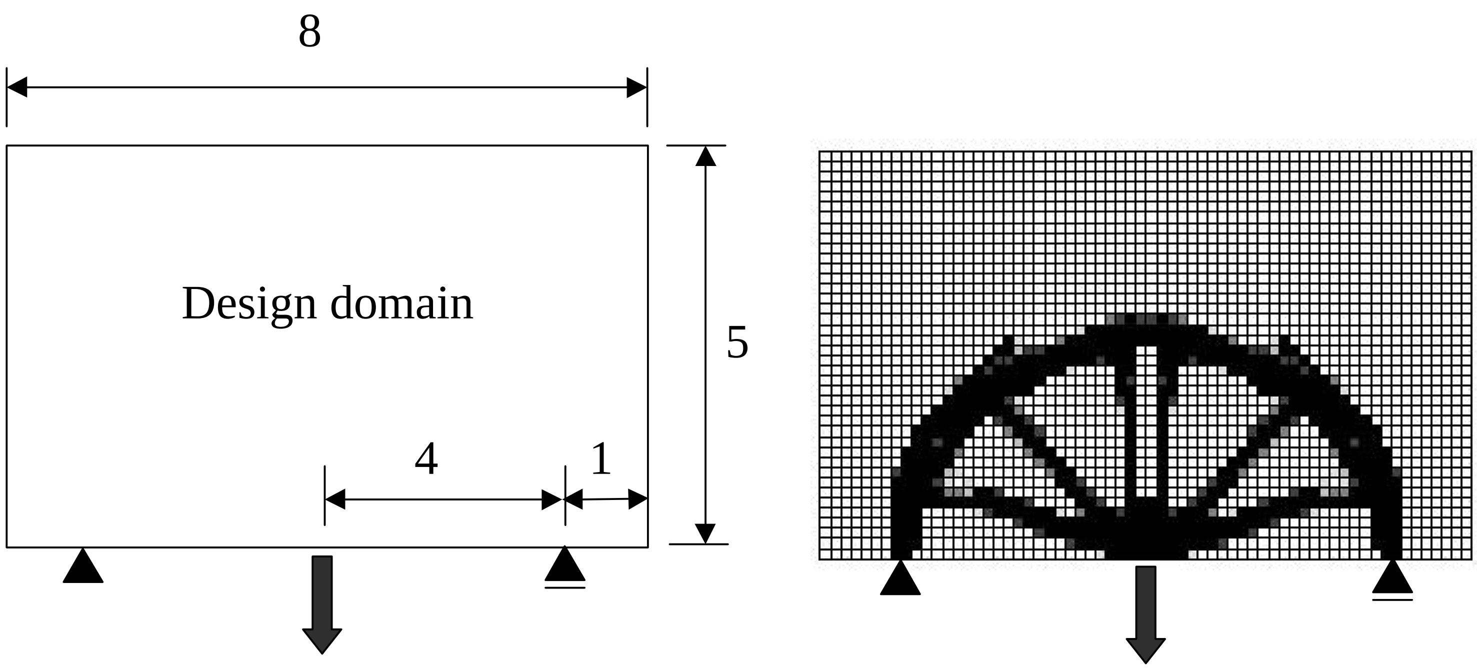
Va:25% CE: 1.642



Va:50% CE: 0.7530

Example 3B

$\boxed{w_g = 0.1, \; p = 0.8}$



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Perimeter Control
(Muriel BECKERS, 1997)

$$p_r = \sum_{i=1}^{N} \sum_{k=1}^{4} l_{ik} \left| r_i - r_k \right| \rightarrow \textbf{min}$$

	r_2	
r_1	r_i	r_3
	r_4	

$r_i = 1 - a_i b_i$

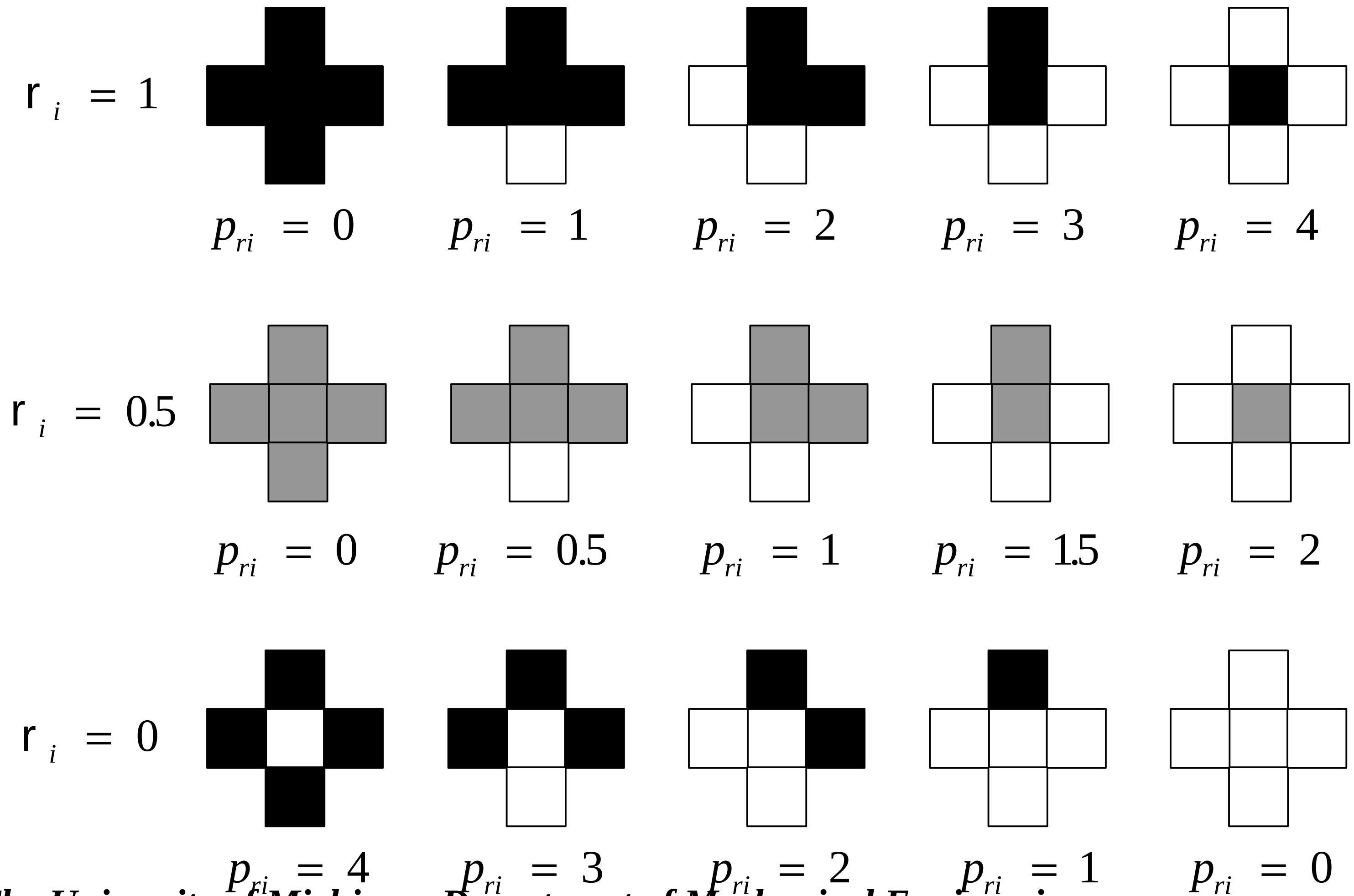
l_{ik} :Length of Common Boundary

N : number of element

$w_g:\ weight(g),\ w_p:\ weight(p_r),\ \bar{g} = g / g_{ini},\ \bar{p}_r = p_r / L$

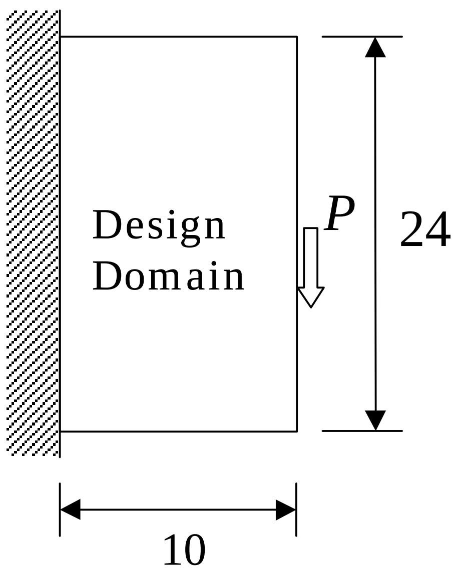
Objective $\quad f = C\sqrt{1 - (w_g \bar{g})^2 + (w_p \bar{p}_r)^2}$

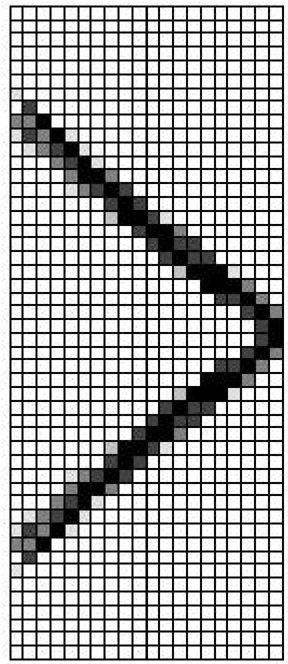
Perimeter Length



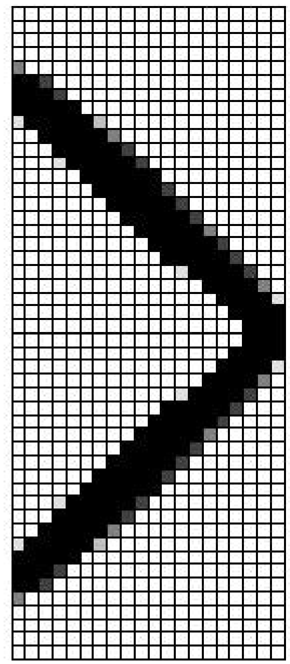
Example 1C

$$\boxed{w_g = 0.1,\ p = 0.8,\ w_p = 0.01}$$

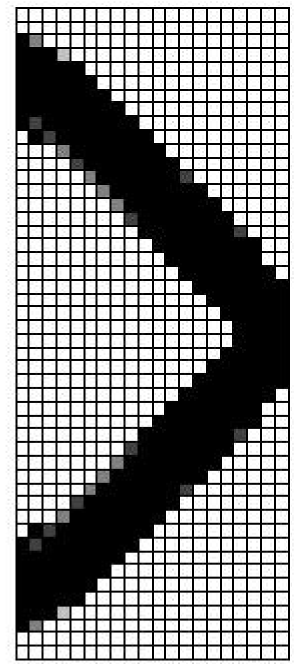




Va: 10%



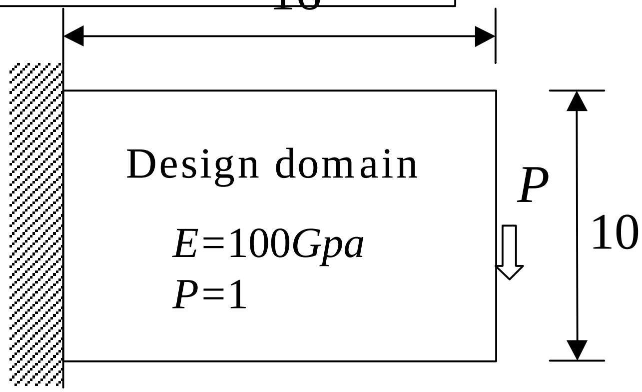
Va: 20%

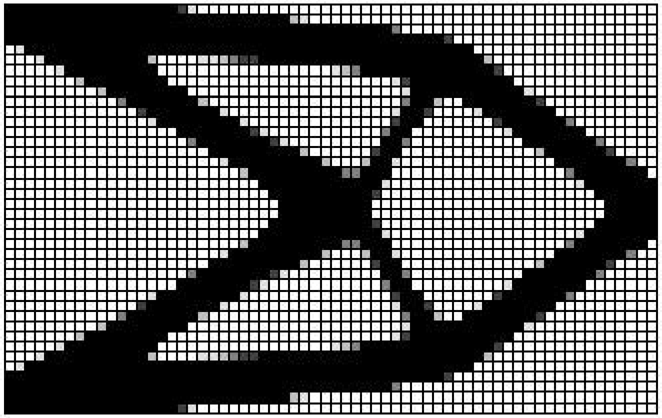


Va: 30%

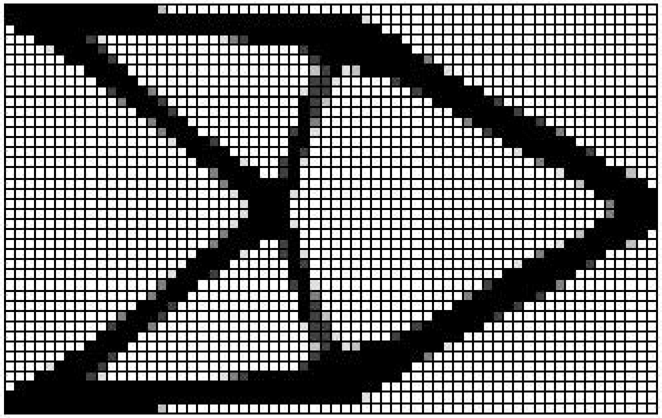
Example 2C

$w_g = 0.1,\ p = 0.8,\ w_p = 0.01$

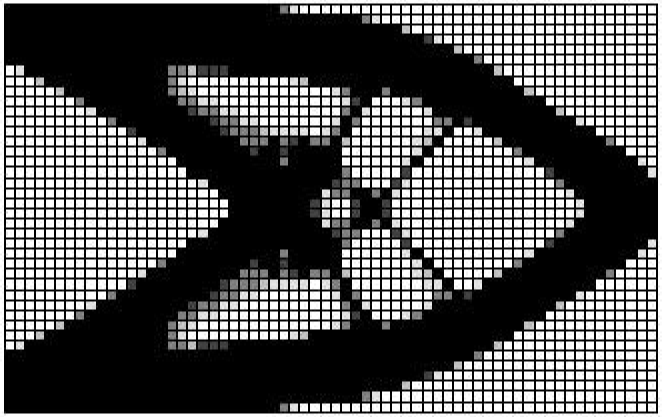




Va:37.5% CE: 1.009

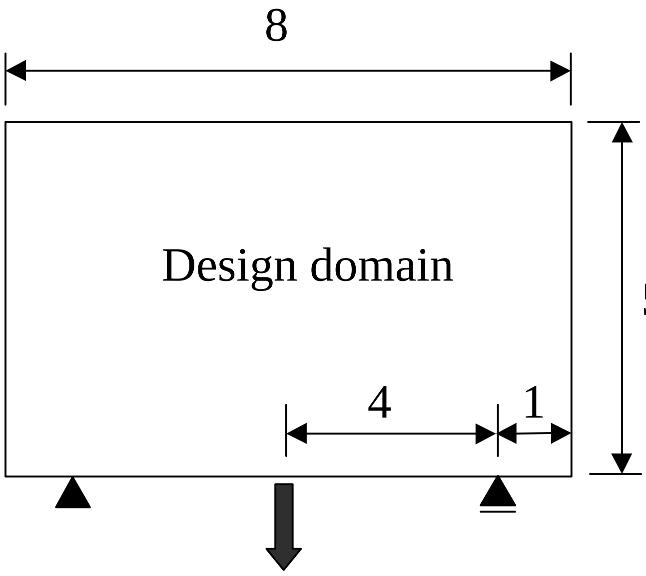


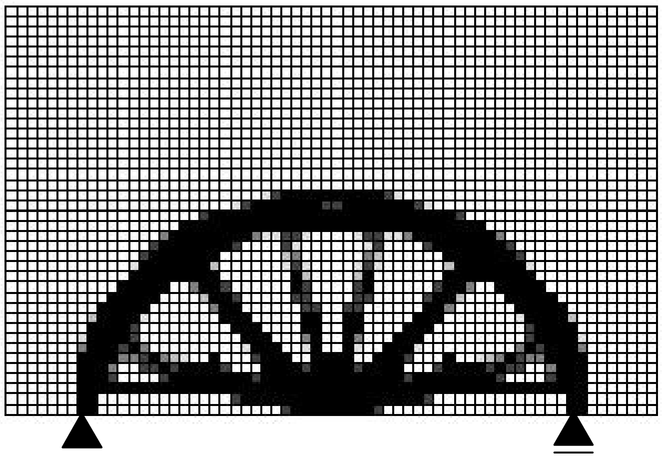
Va:25% CE: 1.632



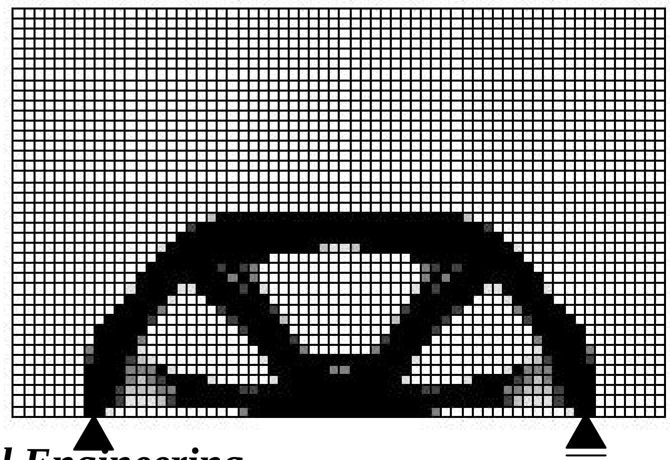
Va:50% CE: 0.7545

Example 3C





$$w_g = 0.1, \; p = 0.8, \; w_p = 0.005$$



$$w_g = 0.1, \; p = 0.8, \; w_p = 0.01$$

Post Processing
of
OPTISHAPE

Smooth Surface Extruction

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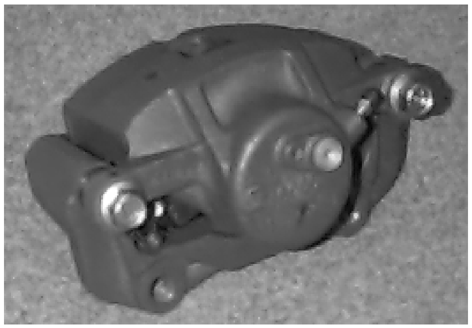
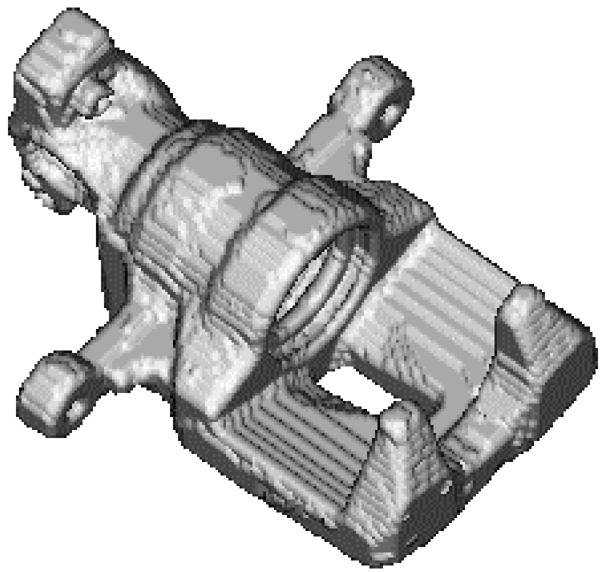
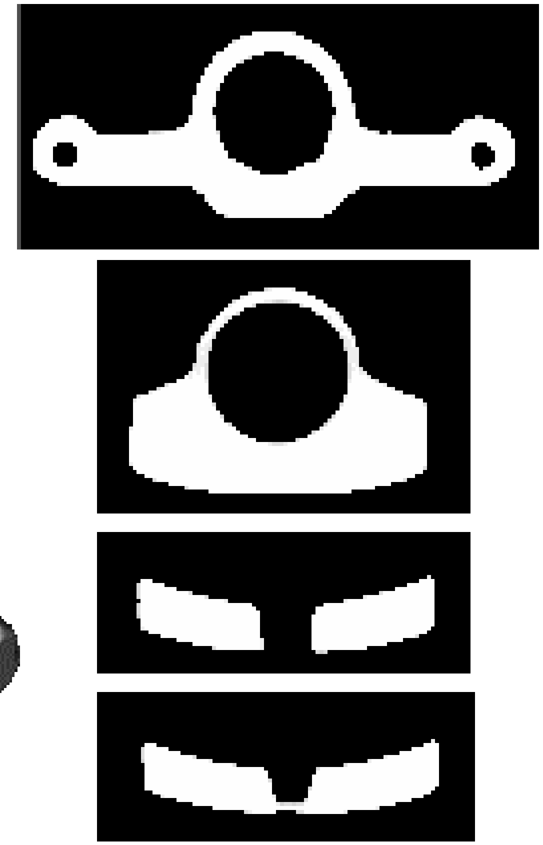
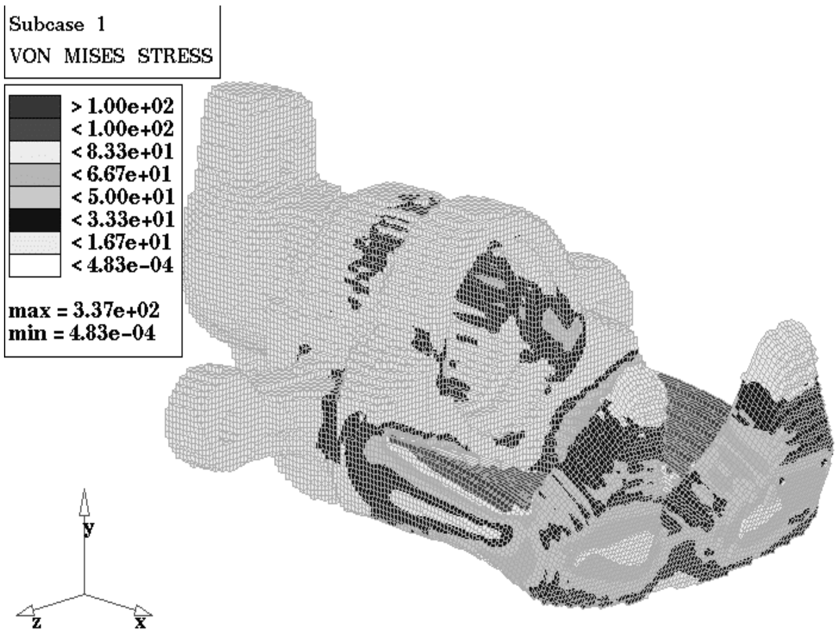
Example : Caliper

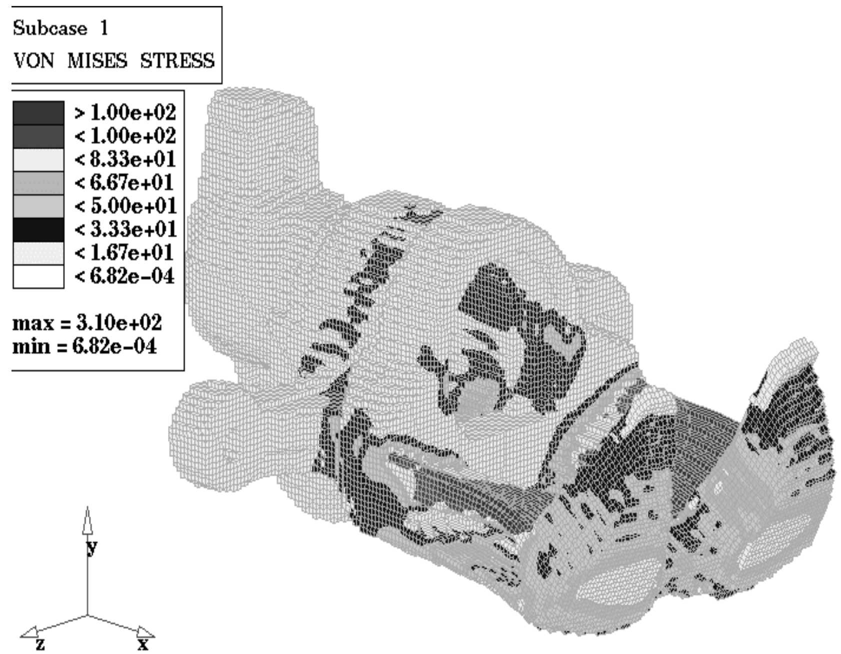






OPTISHAPE





Mesh From CT Scan
150,000 3-D Elements

9% Weight Reduction

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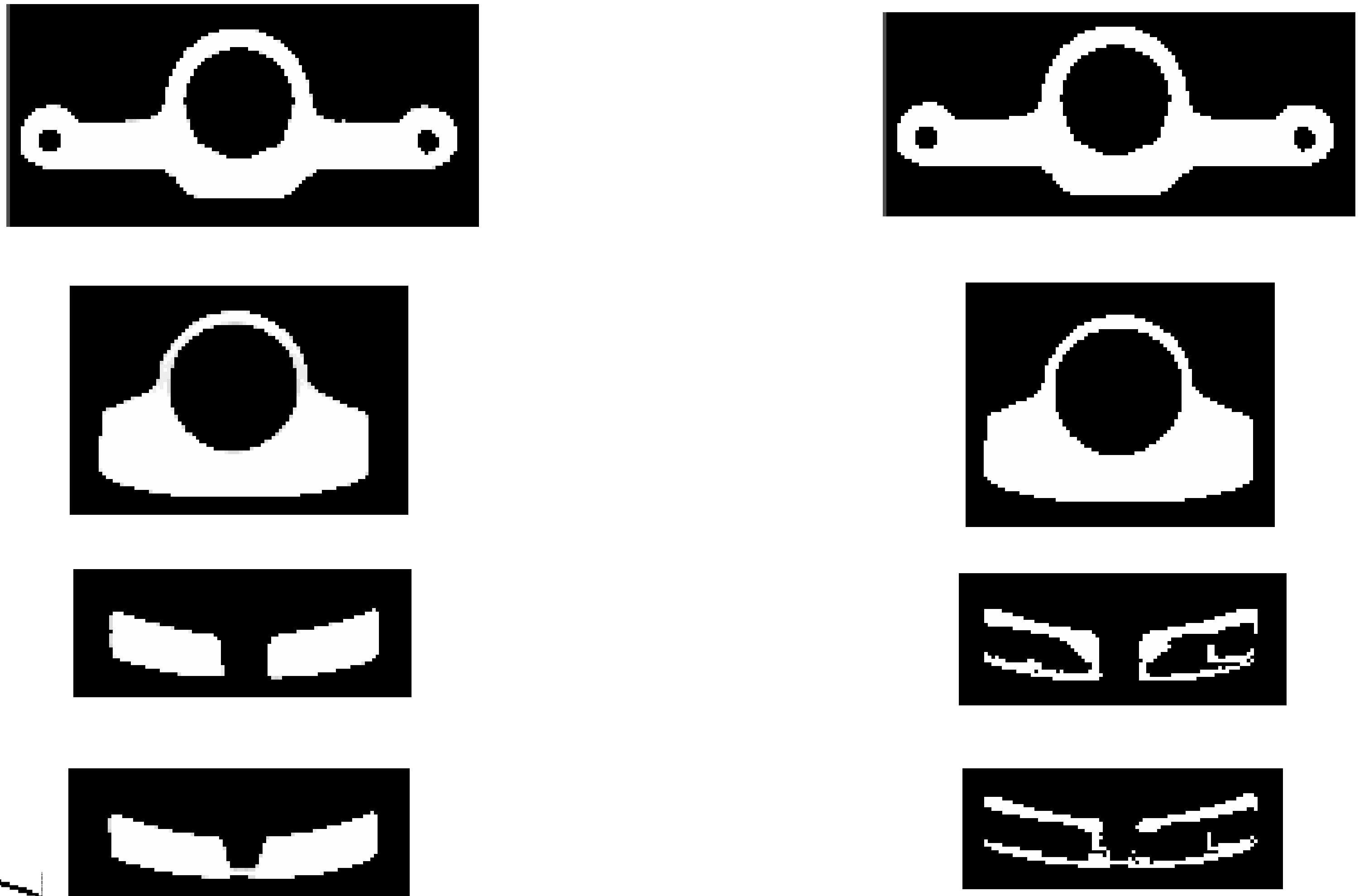
Comparison by Sections



Interpolation Functions

Meshless Approach

$$f(x) = \sum_{j=1}^{n} c_j \Phi_j(x) \qquad \text{where} \quad c_j = f(x_j)$$

$\Phi_j(x)$ is defined with non-polynomial function:

$$\Phi_j(x) = a_o(x) w_j(x)$$

where $w_j(x) = w(x - x_j)$ and $w(x) = \exp(-\alpha x^2)$

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Approximation Functions (2)

$$f(x) = \sum_{j=1}^{n} c_j \Phi_j(x)$$

To Determine $\Phi_j(x)$ which yield *k*-th degree polynomial, let's assume:

$$\Phi_j(x) = \left\{ a_o(x) + x_j a_1(x) + \; \dots \; + x_j^k a_k(x) \right\} w_j(x)$$

$$= \left\{ 1 \;\; \dots \;\; x_j^k \right\} \begin{Bmatrix} a_o(x) \\ \vdots \\ a_k(x) \end{Bmatrix} w_j(x)$$

$$f(x) = f_o + f_1 x + \; \dots \; + f_k x^k$$

Solve for $\left\{ a_o(x) \;\; \dots \;\; a_k(x) \right\}$

Approximation Functions (3)

$$\begin{Bmatrix} a_o(x) \\ \vdots \\ a_k(x) \end{Bmatrix} = \begin{bmatrix} \sum_{j=1}^{n} w_j(x) & \cdots & \sum_{j=1}^{n} x_j^k w_j(x) \\ \vdots & \ddots & \vdots \\ \sum_{j=1}^{n} x_j^k w_j(x) & \cdots & \sum_{j=1}^{n} x_j^{2k} w_j(x) \end{bmatrix}^{-1} \begin{Bmatrix} 1 \\ \vdots \\ x^k \end{Bmatrix}$$

Recall: $\Phi_j(x) = a_o(x) w_j(x)$

$$\Phi_j(x) = \begin{Bmatrix} 1 & \dots & x_j^k \end{Bmatrix} \begin{bmatrix} \sum_{j=1}^{n} w_j(x) & \cdots & \sum_{j=1}^{n} x_j^k w_j(x) \\ \vdots & \ddots & \vdots \\ \sum_{j=1}^{n} x_j^k w_j(x) & \cdots & \sum_{j=1}^{n} x_j^{2k} w_j(x) \end{bmatrix}^{-1} \begin{Bmatrix} 1 \\ \vdots \\ x^k \end{Bmatrix} w_j(x)$$

Reconstruction of a 3-D Model

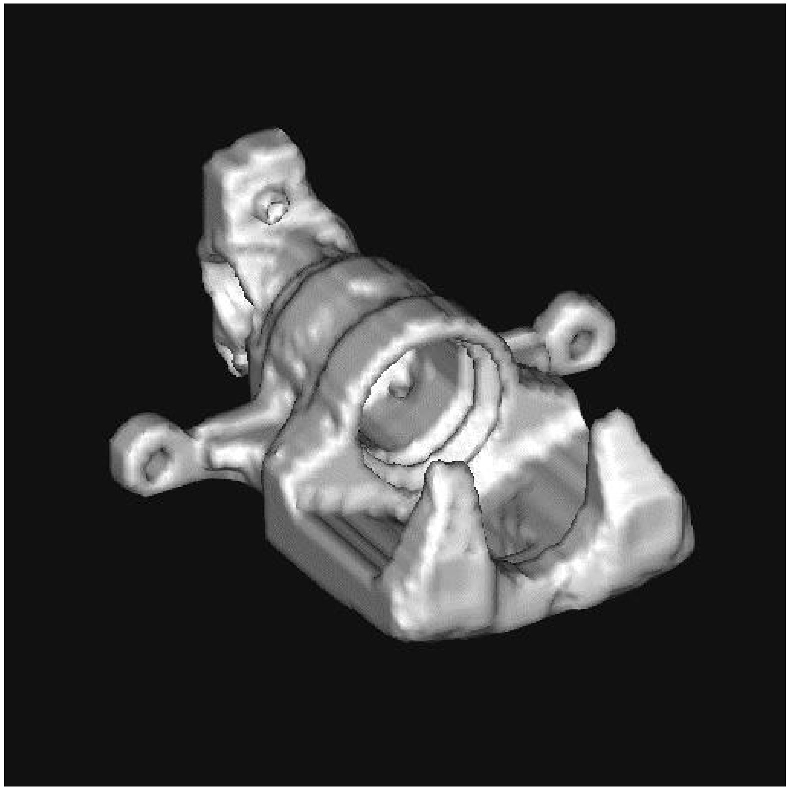
$$c_{\Omega}^{h}(x,y,z)=\sum_{k=1}^{k_{\max}} \underline{c_{\Omega,k}^{h}(x,y)}\,\Phi_k(z)$$

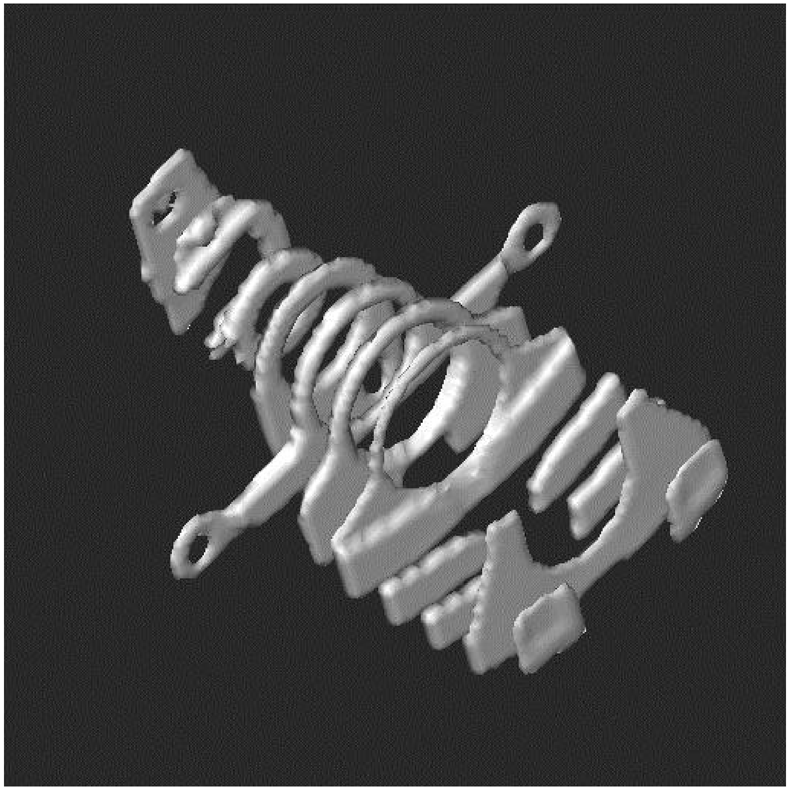
2D image Basis Functions

$c_{\Omega,k}^{h}$: Characteristic function of each image
Greyscale values (0-255)

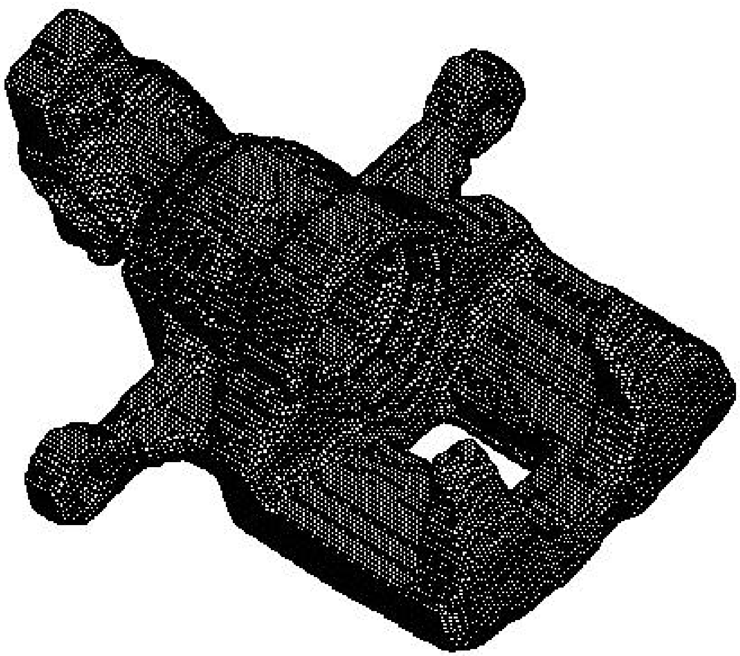
$\Phi_k(z)$: Approximation functions

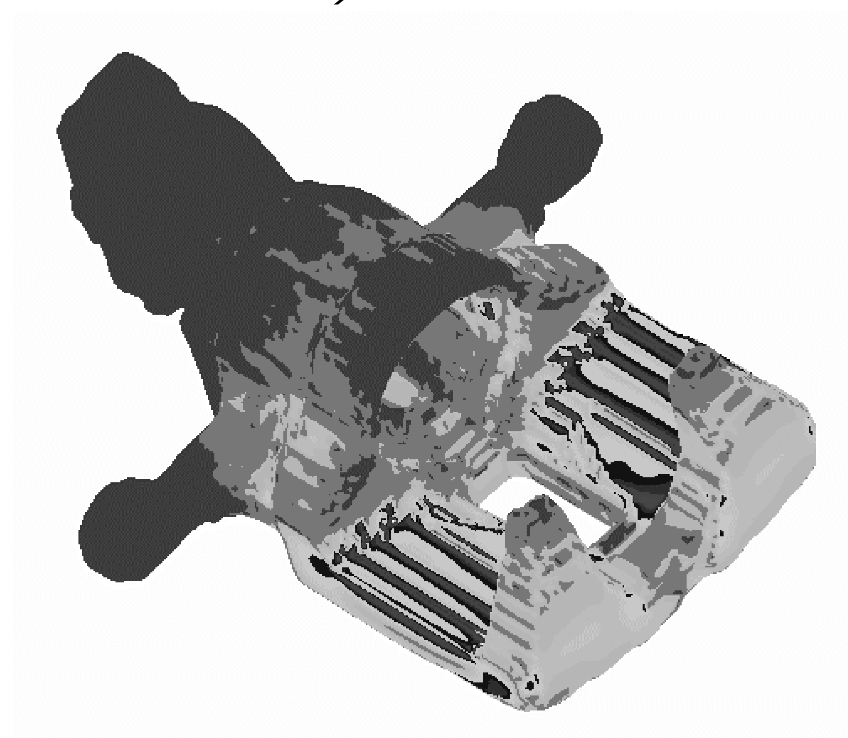
Brake Caliper





Analysis Result





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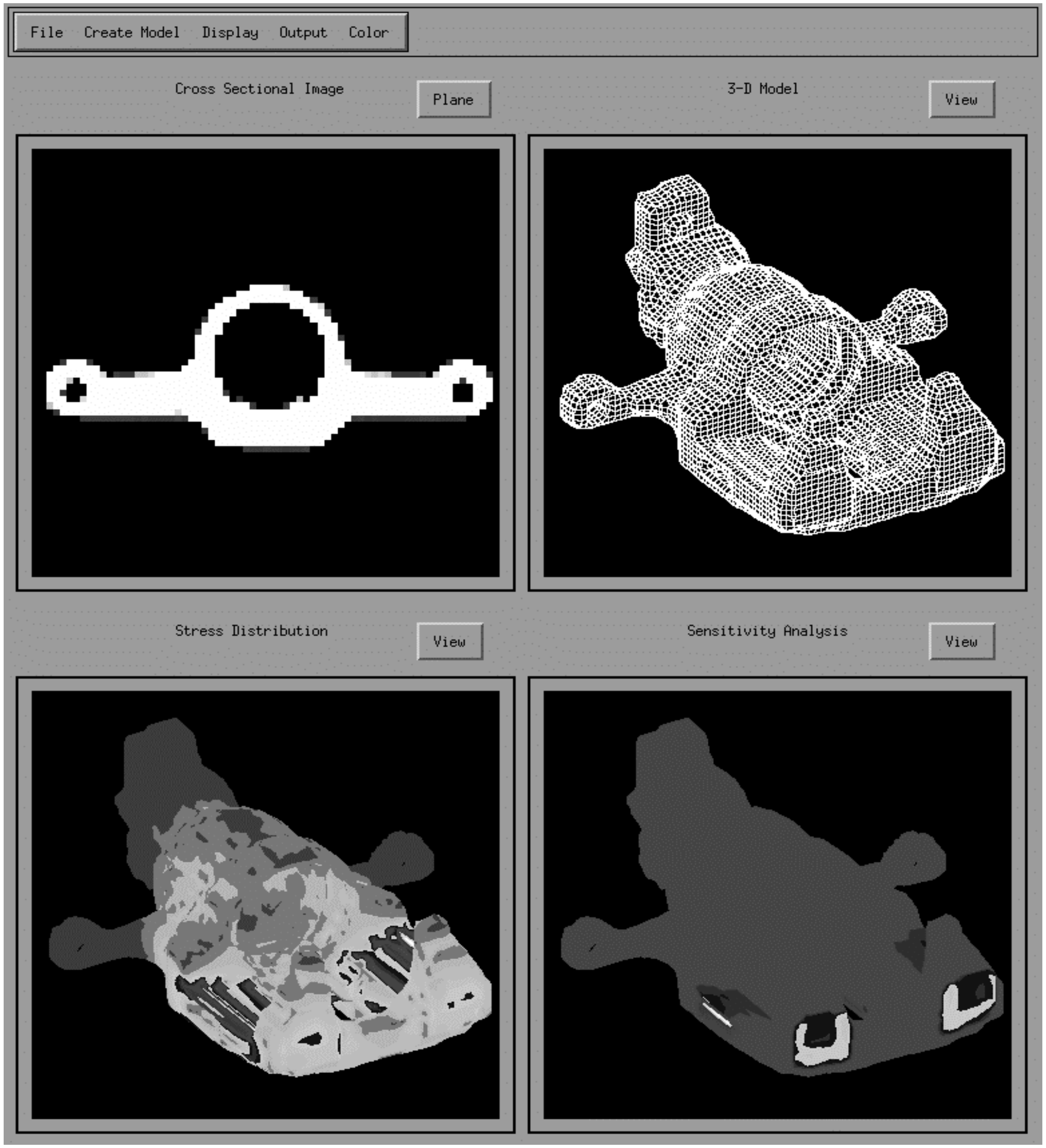
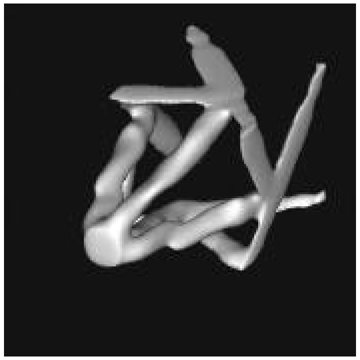
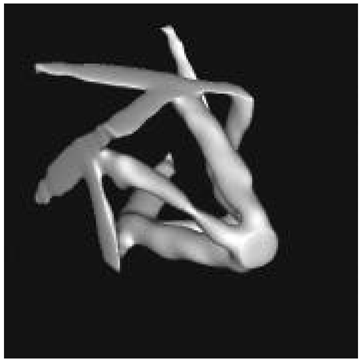
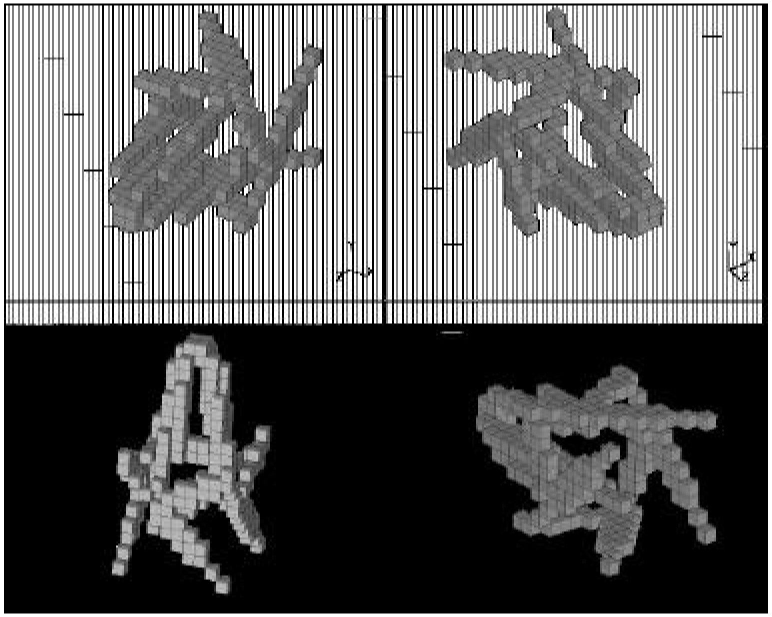


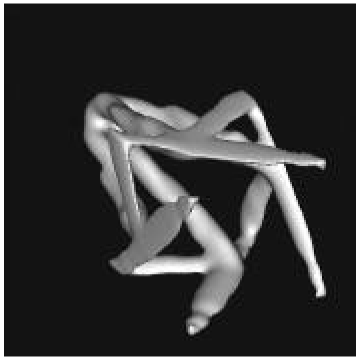
Possible image-based design software

Optimization









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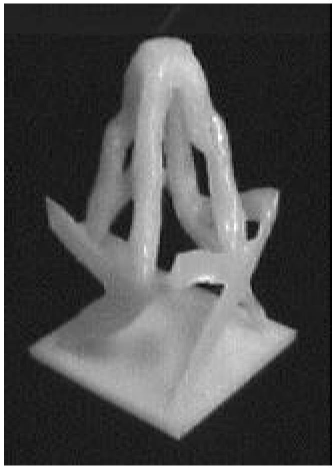
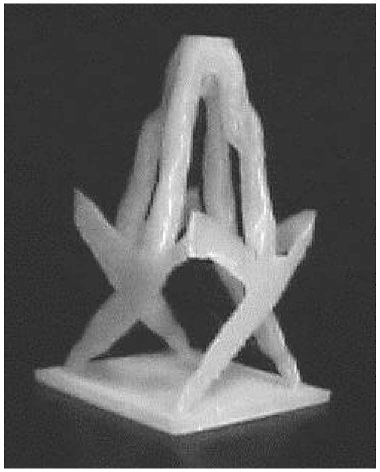
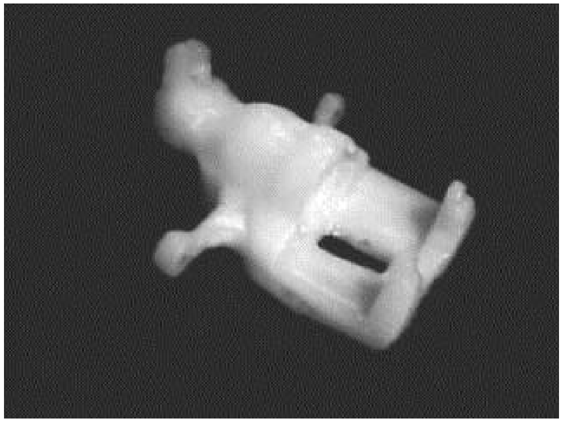
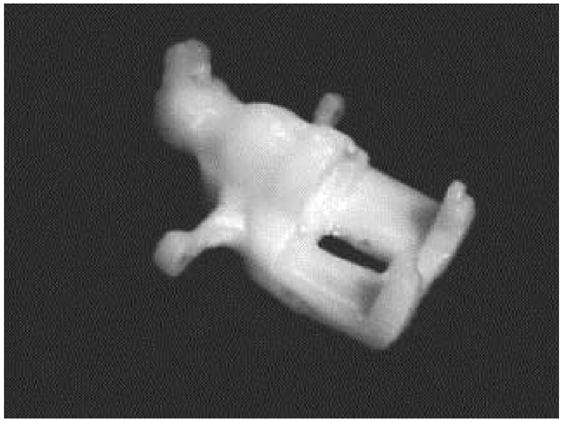
Prototypes









Summary

Concept of OPTISHAPE : Topology Optimization is continuously extended not only to structures but also materials, mechanisms, electro-magnetic fields, and others

VOXELCON for I-DEAS
OPTISHAPE for I-DEAS

NASTRAN-OPTISHAPE

Toward
Image Based CAE

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