The Need of Advanced Techniques for Manufacturing

Piezocomposite and Piezoelectric Actuator Design

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Materials Opportunities in Layered Manufacturing Techniques
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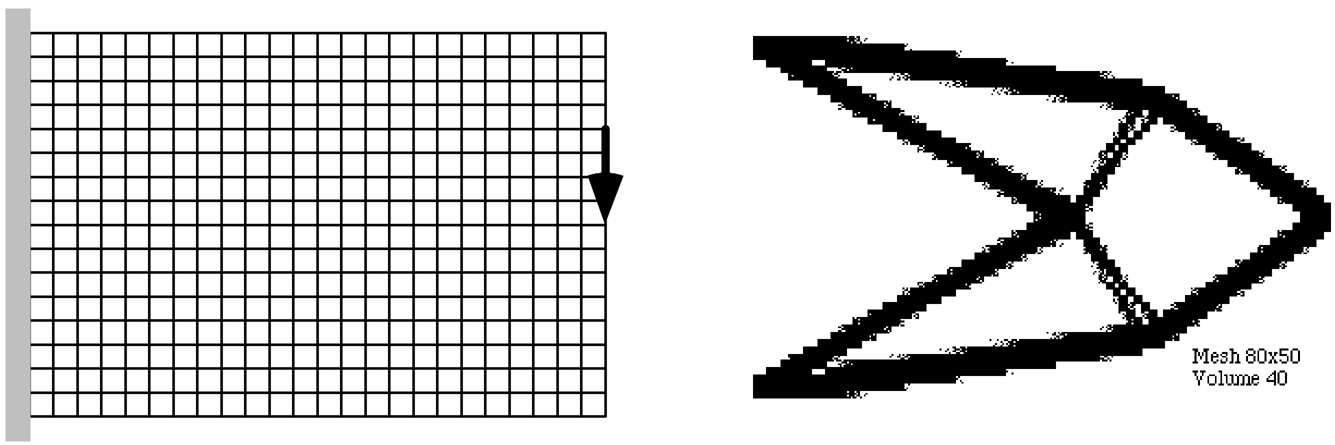
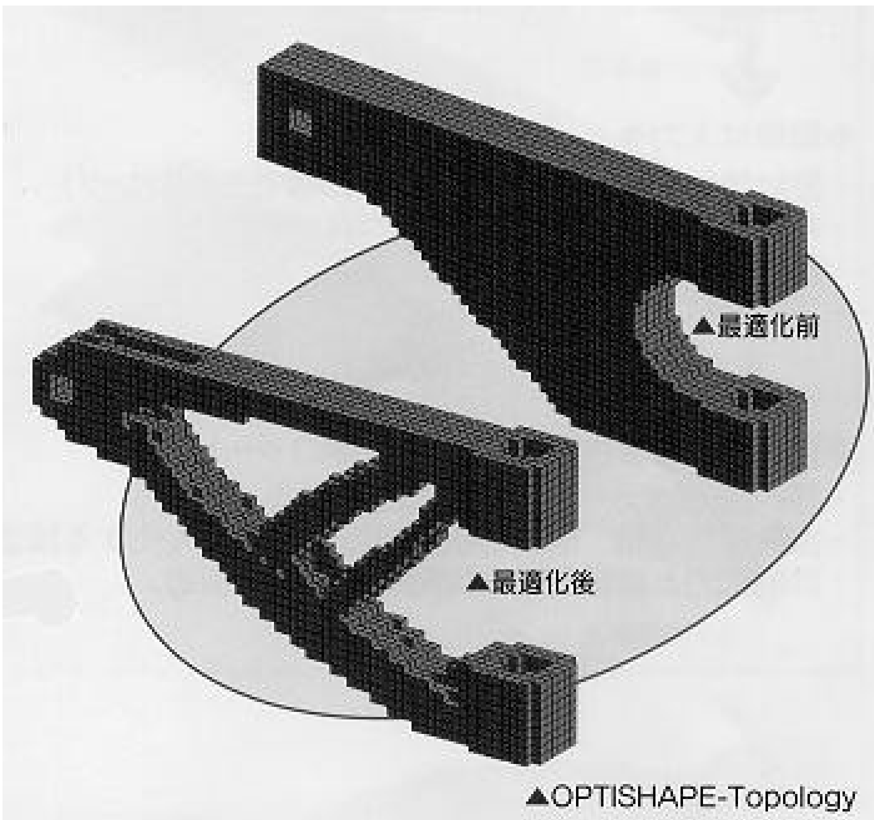
Homogenization Design Method

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



HDM : 3D Shaping



Truly Three-dimensional shaping of a structure for optimum

Requirement of emerging manufacturing methods

Extension of HDM

- 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 HDM

Piezocomposite

and

Piezoelectric Actuator Design

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

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

T_{ij} - stress

S_{kl} - strain

E_k - electric field

D_i - electric displacement

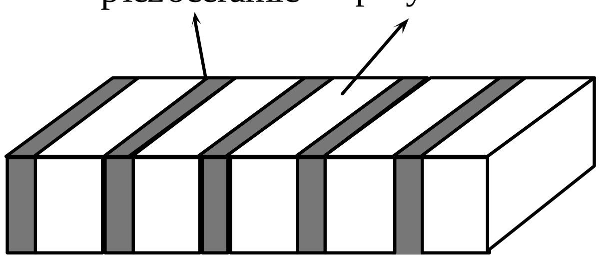
c^{E}_{ijkl} - stiffness property

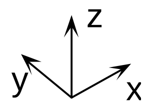
e_{ikl} - piezoelectric strain property

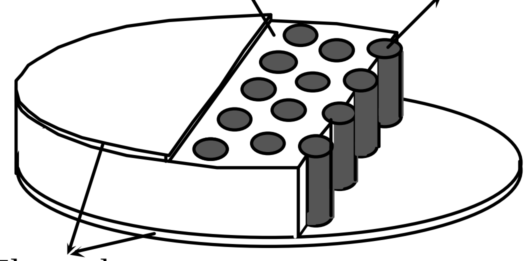
ε^{S}_{ik} - dielectric property

Introduction - Piezocomposites

Combination of a piezoelectric material with other non-piezoelectric materials (ex.: holes)





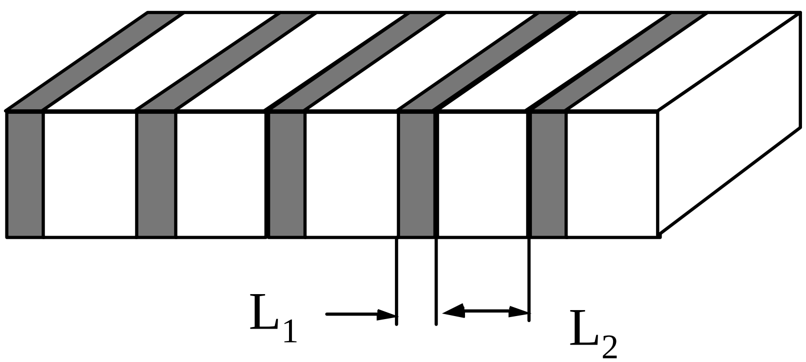


2-2 piezocomposite

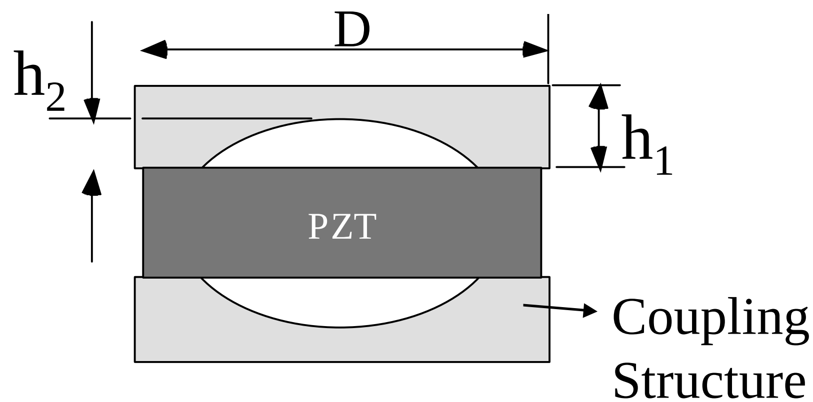
1-3 piezocomposite

Advantages: high energy conversion, low acoustic impedance, etc...

Design Practice : Parametric



Piezocomposite



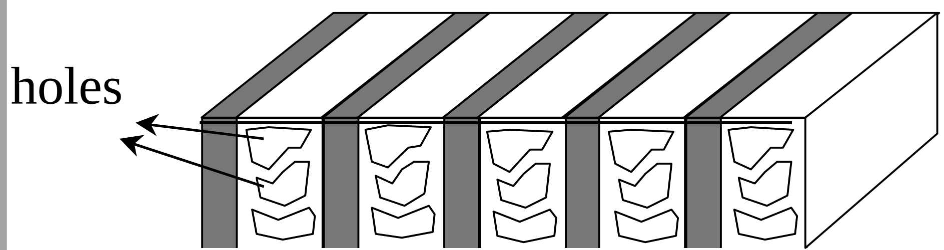
Moonie transducer

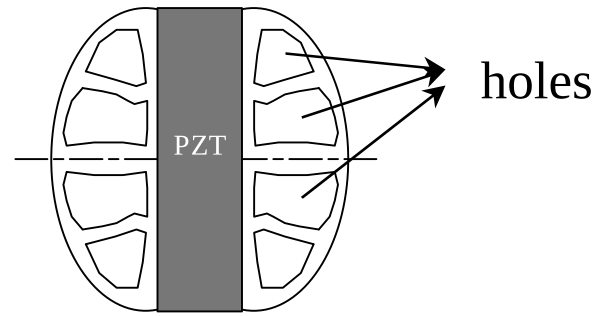
Mathematician Changes Design Practice

Using Parametric Analysis:

- Influence of volume fraction, Poisson’s ratio, etc…: Smith (1993), Avellaneda and Swart (1994)
- Use of negative Poisson’s ratio material: Smith (1991), Avellaneda and Swart (1994)
- Porosity in the matrix polymer: Avellaneda and Swart (1994)

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 : HDM

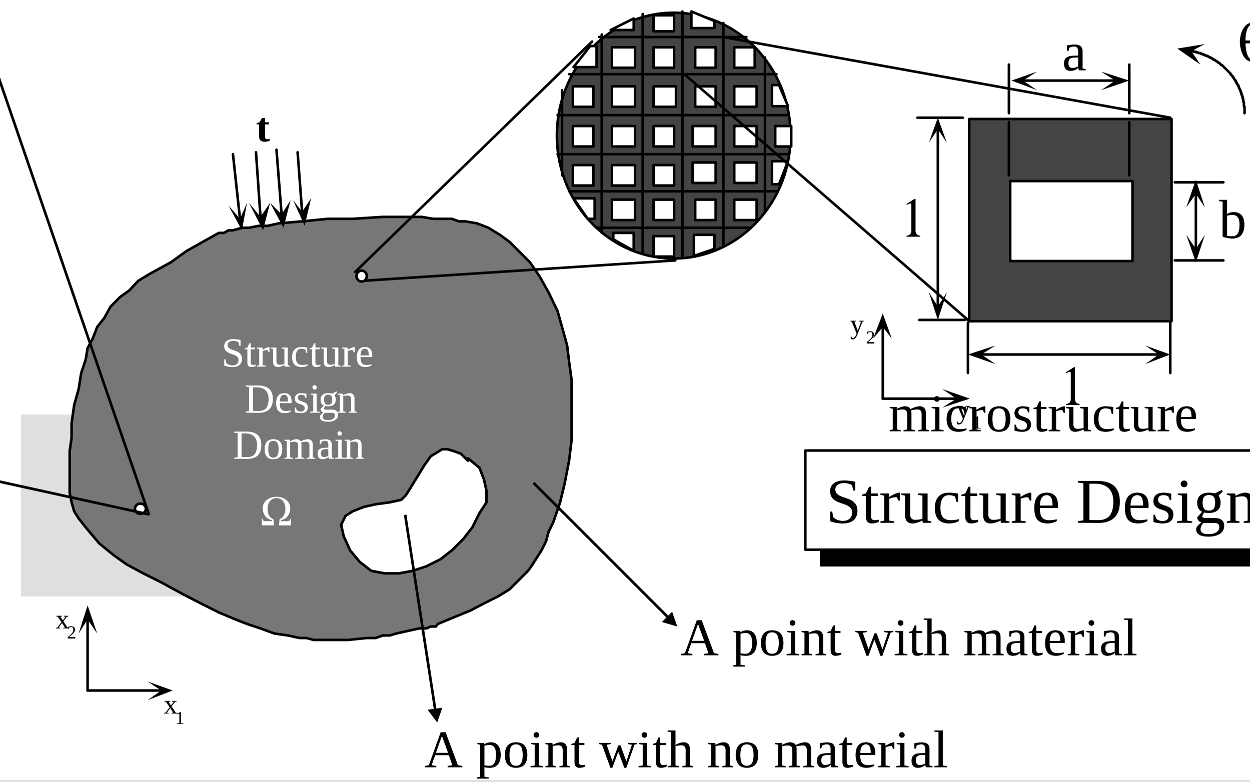
Simple:
Density Method

property

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

fraction of material in each point

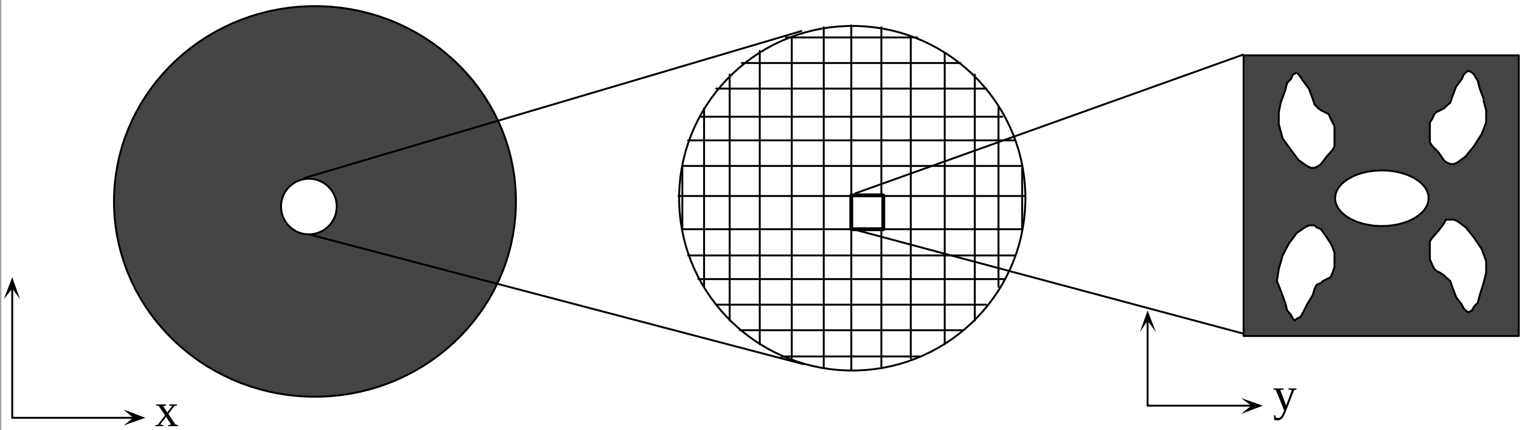
General:
Homogenization Method



Material Design

Structure Design

Homogenization in Piezoelectricity



Component **Enlarged Periodic Microstructure** **Enlarged Unit Cell (Microscale)**

- Telega (1990), Galka et al. (1992), and Turbé and Maugin (1991)
- Asymptotic analysis
- Periodic microstructures, scale of microstructure very small compared to the size of the part
- Acoustic wavelength larger than unit cell dimensions

Optimization Problem

Maximize: $\underset{\mathbf{x}}{F(\mathbf{x})}$, where $\mathbf{x}=[x_1,x_2,\ldots,x_n,\ldots,x_{NDV}]$

subject to: $c^E_{ijkl} \geq c_{low}$, i, j, k, l are specified values

$$0<x_{low} \leq x_n \leq 1$$

$$W = \sum_{n=1}^{NDV} x_n^p V_n > W_{low}$$

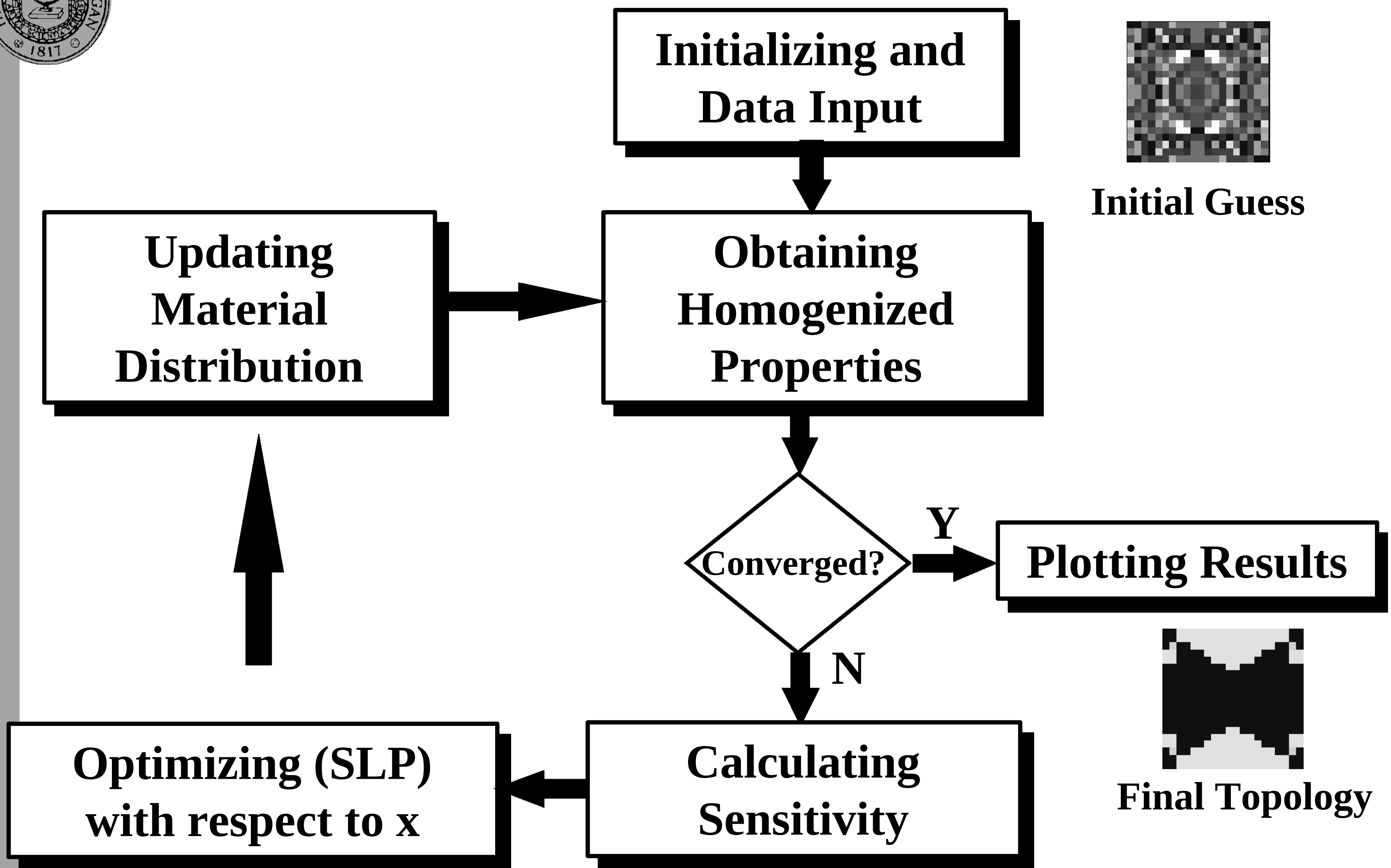
symmetry conditions

$F(\mathbf{x})$ - function of d_h, $d_h g_h$, k_h, or k_t

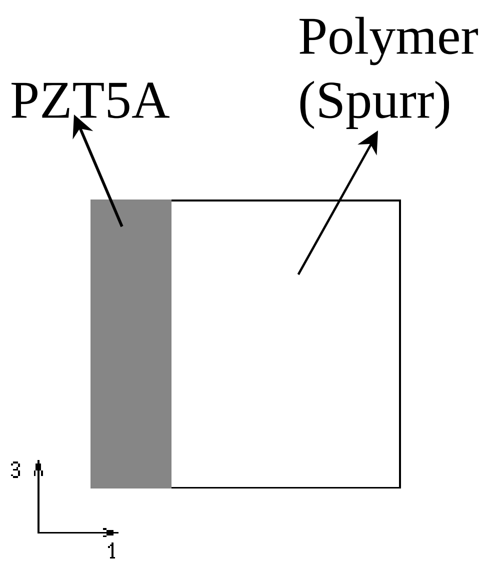
$\mathbf{x}$ - design variables

W - constraint to reduce intermediate densities

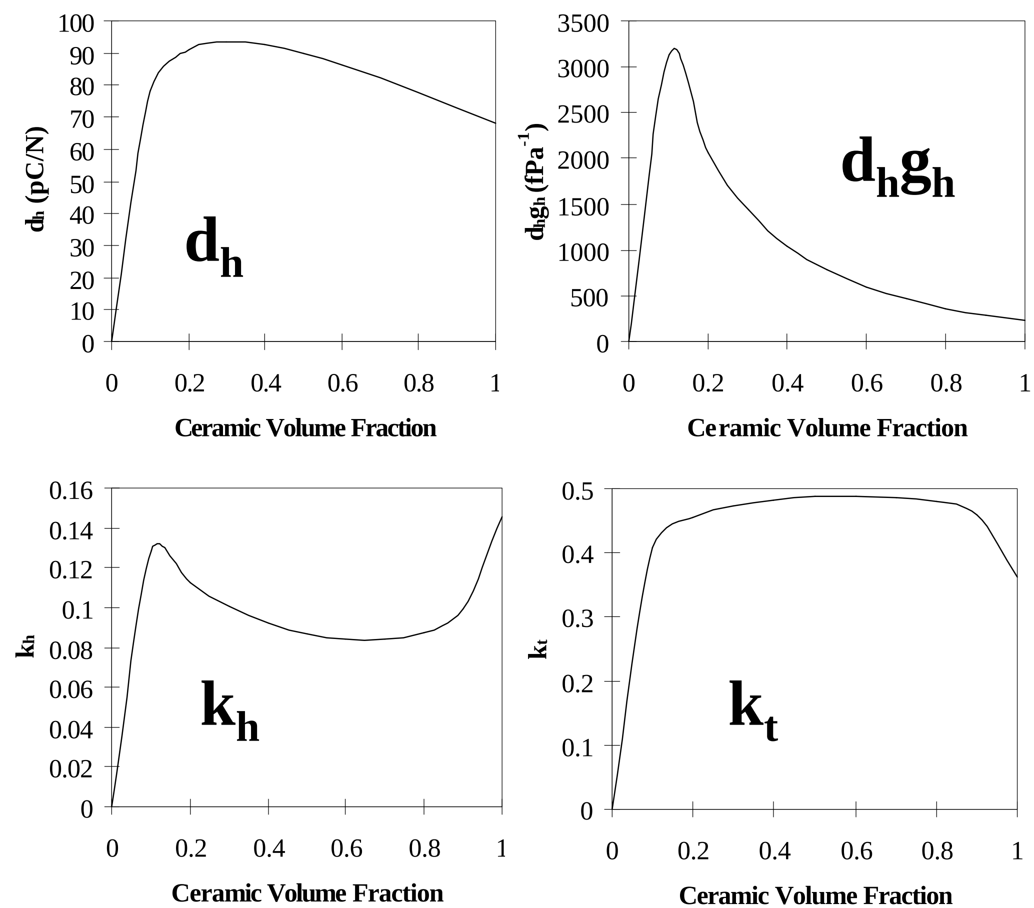
(V_n - volume of each element)


Initializing and Data Input
Initial Guess
Updating Material Distribution
Obtaining Homogenized Properties
Converged?
Y
Plotting Results
N
Optimizing (SLP) with respect to x
Calculating Sensitivity
Final Topology

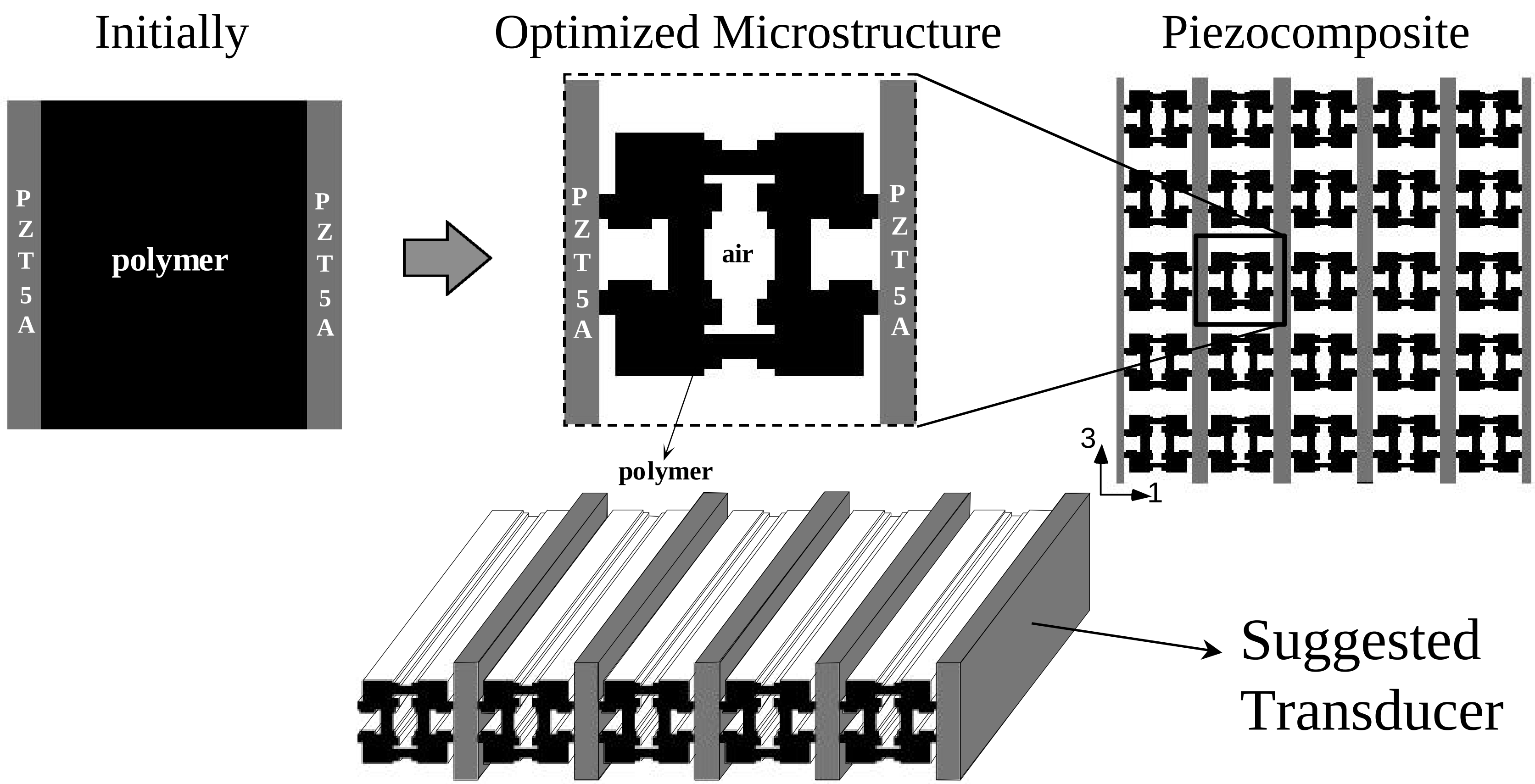
Reference unit cell for comparison: 2-2 piezocomposite



(Poled in the
3 direction)



2D Piezocomposite Unit Cell
hydrophone



Improvement

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

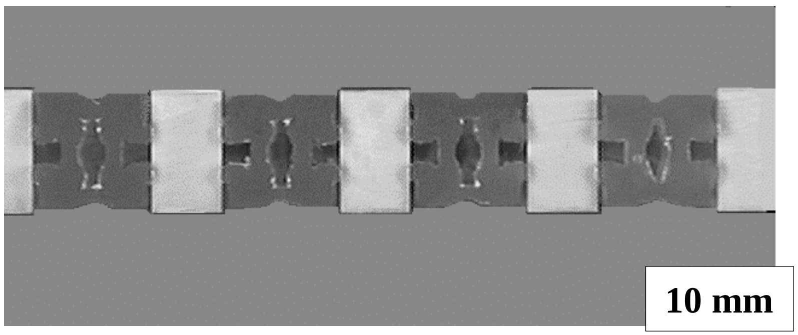
$|d_h|$: 2.8 times $\rho \Downarrow \Rightarrow Z \Downarrow$ v_t ($\cong$ same)

$d_h g_h$: 7.1 times

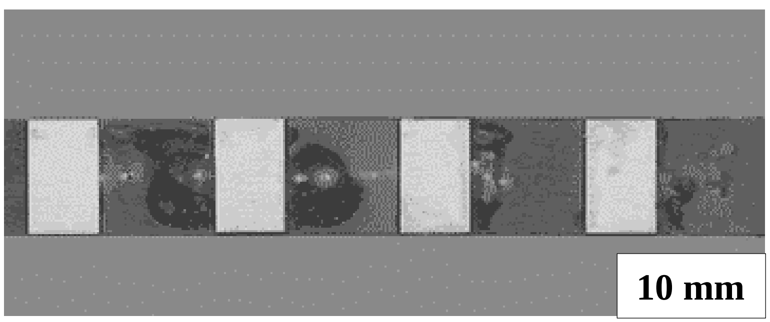
k_t: 1.13 times   stiffness constraint: $c^E_{11} > 8.10^8 N/m^2$

Experimental Verification

- Rapid Prototyping: Stereolithography Technique

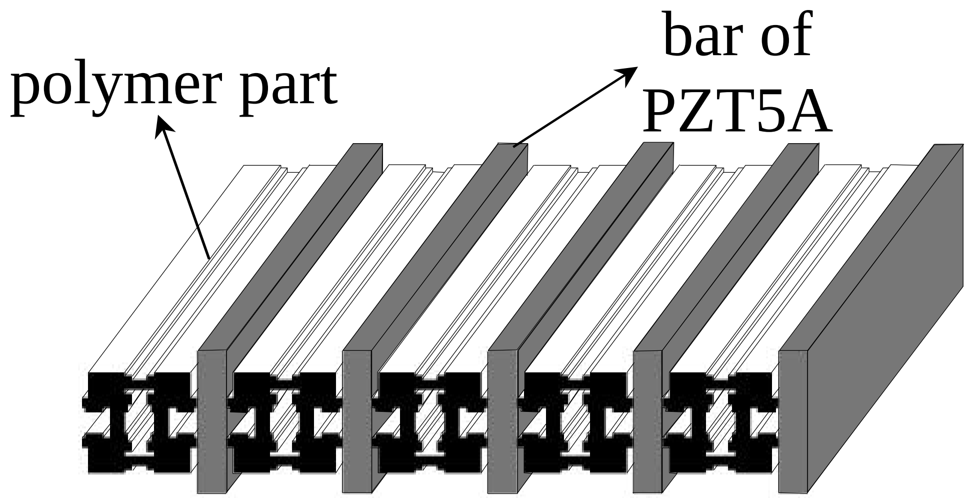


Optimized Transducer



Reference Transducer

Experimental Result

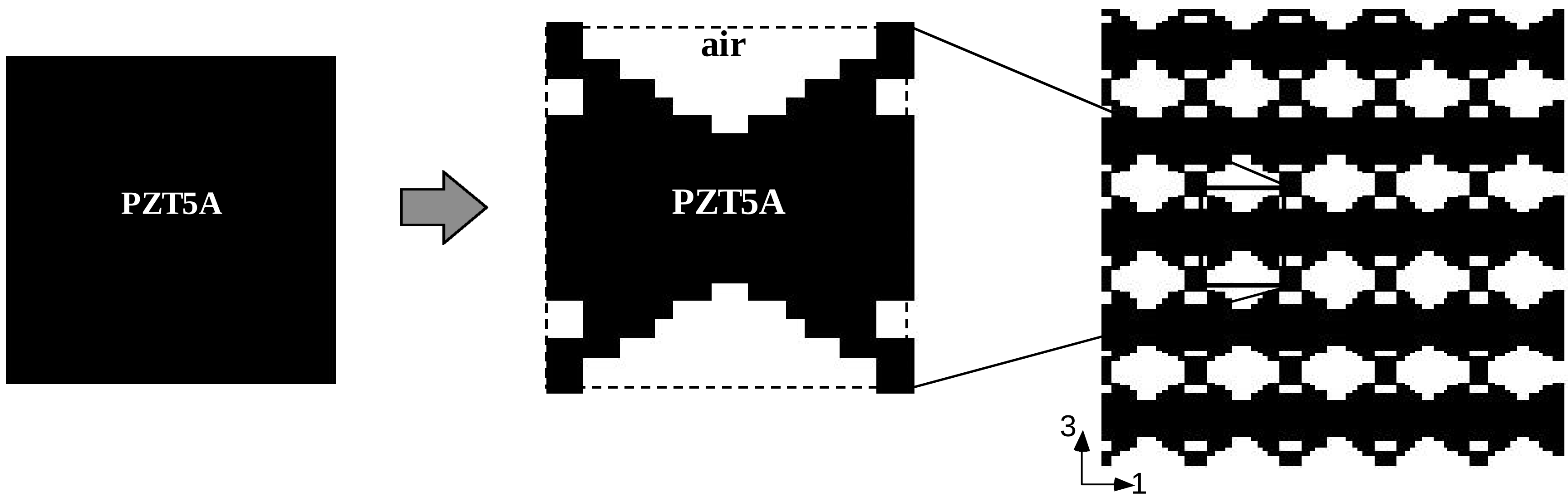


Measured Performances

	$d_h(pC/N)$	$d_h g_h\ (fPa^{-1})$	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”

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Improvement

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

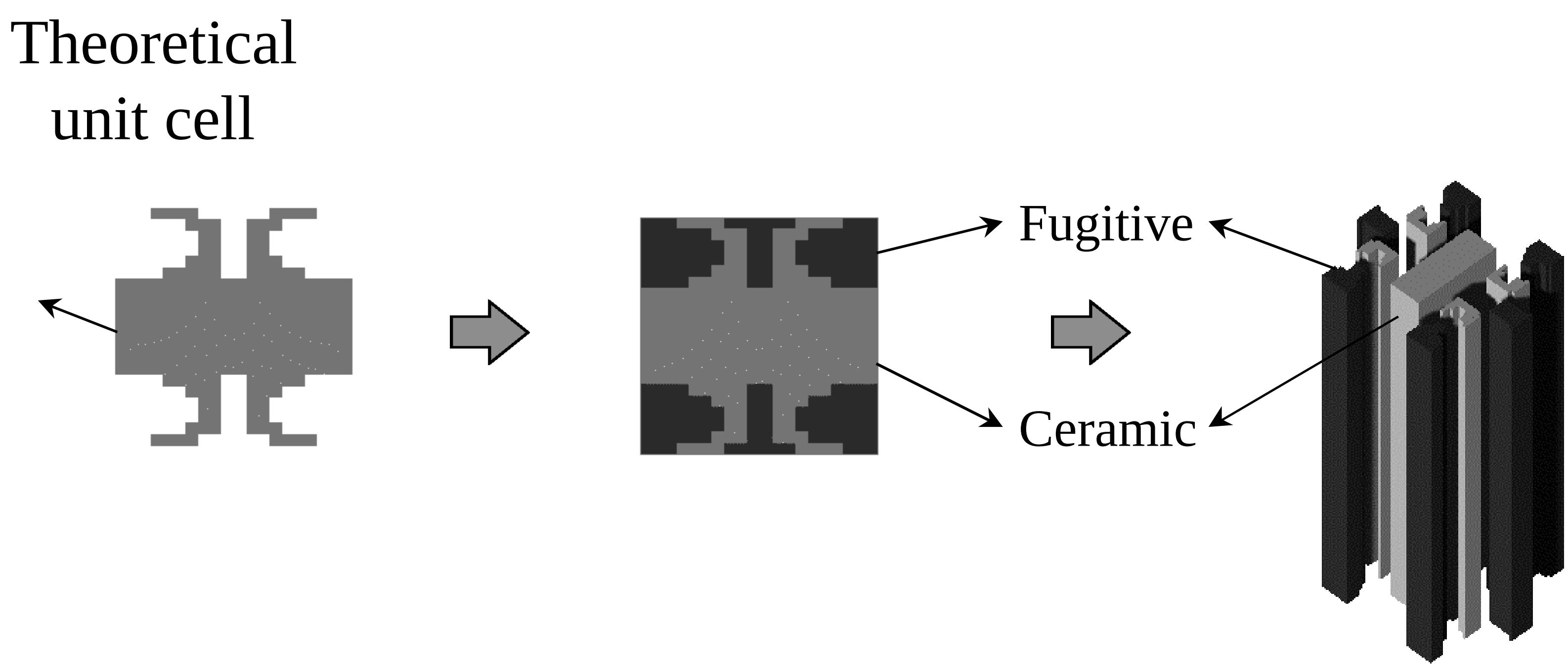
$|d_h|$: 3. times

$d_h g_h$: 9.22 times

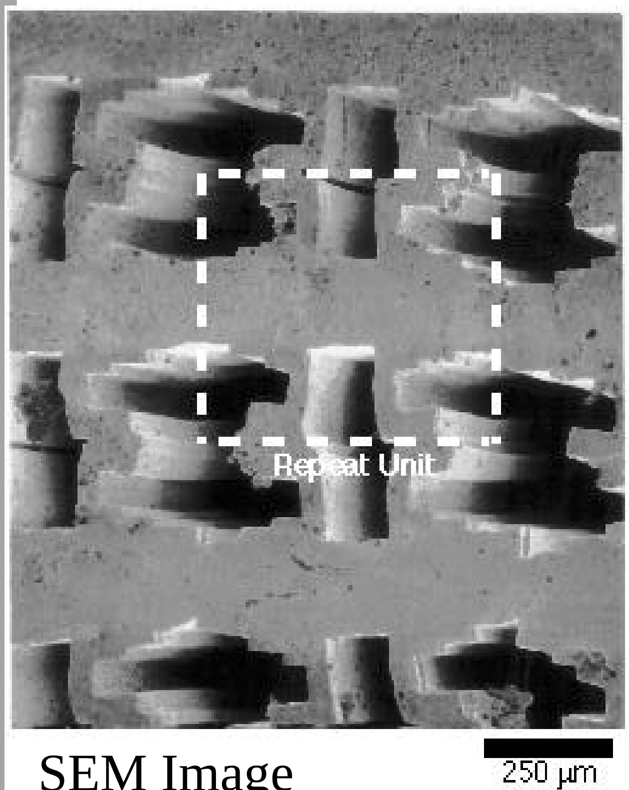
k_h: 3.6 times stiffness constraint: $c^E_{33} > 1.10^{10} N/m^2$

Piezocomposite Manufacturing

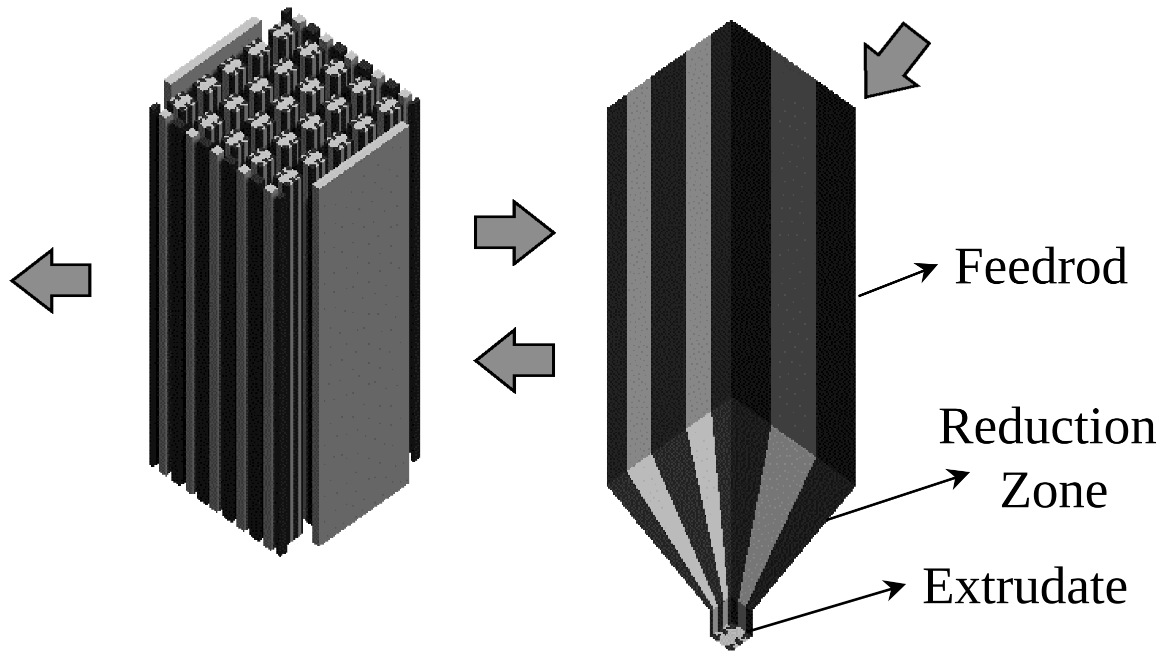
Microfabrication by coextrusion technique



Ceramic



SEM Image

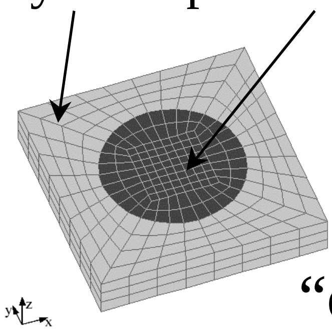


Crumm and Halloran (1997)

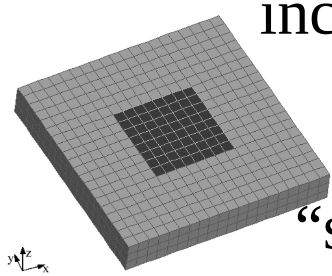
3D Piezocomposite

Reference unit cells: 1-3 piezocomposite

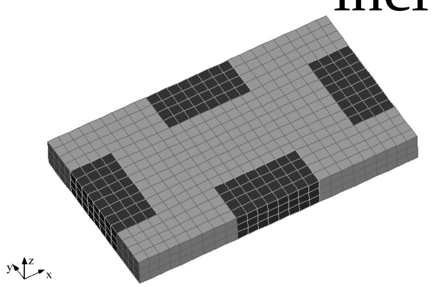
polymer piezoceramic



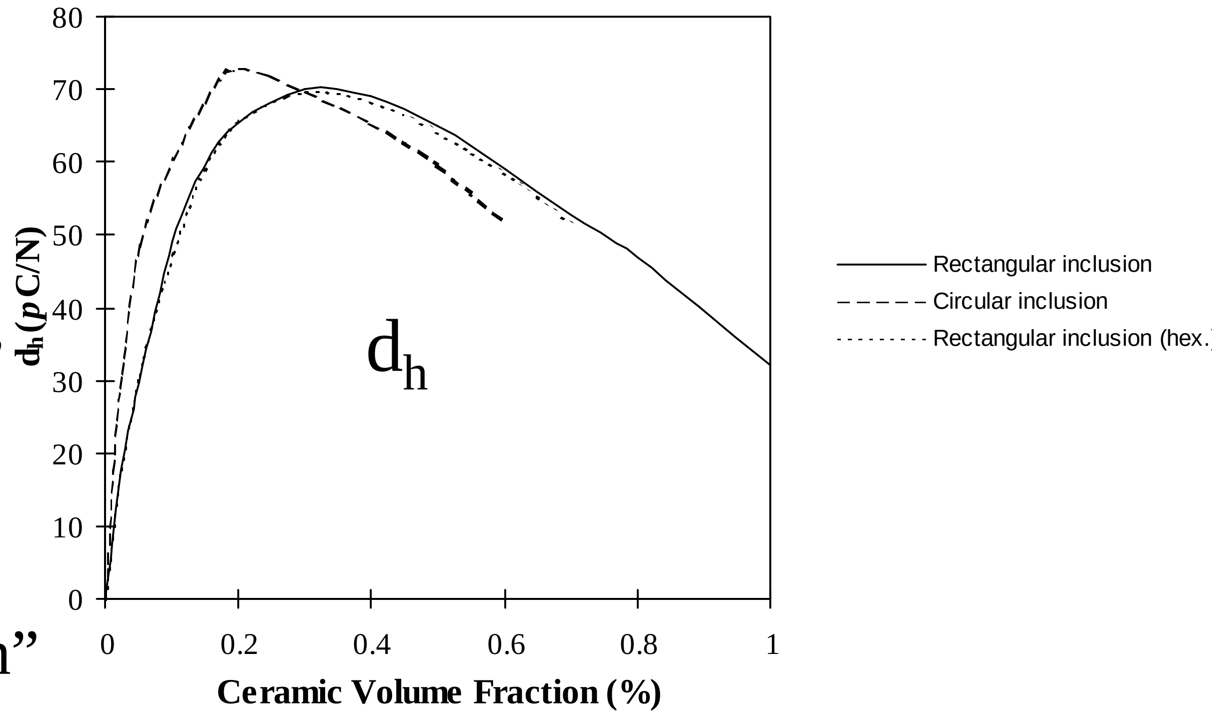
“circular inclusion”



“square inclusion”



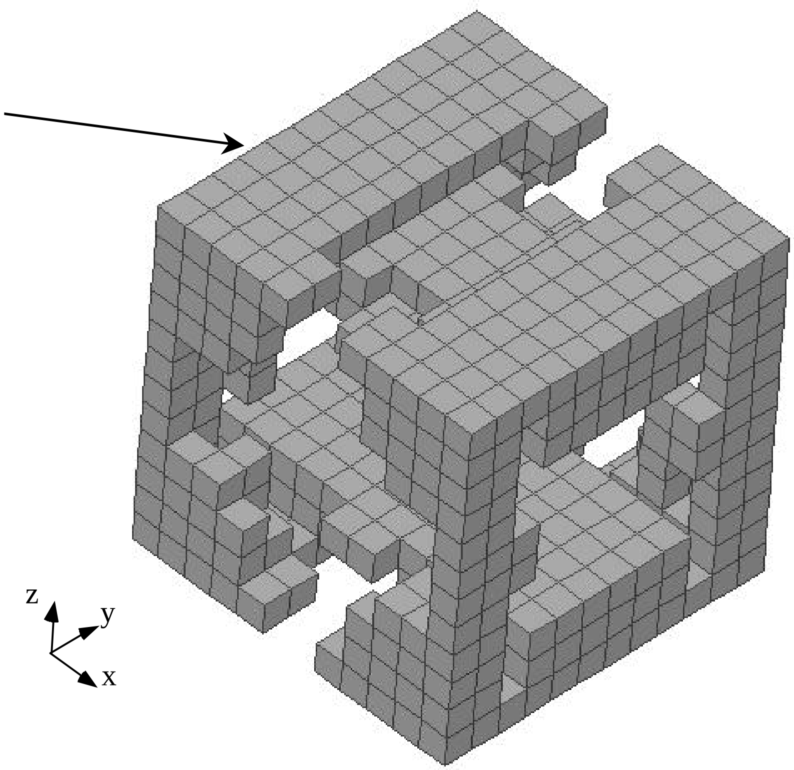
“staggered formation”



Similar Behavior for $d_h g_h$, k_h, and k_t

3D Piezocomposite Unit Cell
hydrophone

piezoceramic



Poled in
the *z* direction

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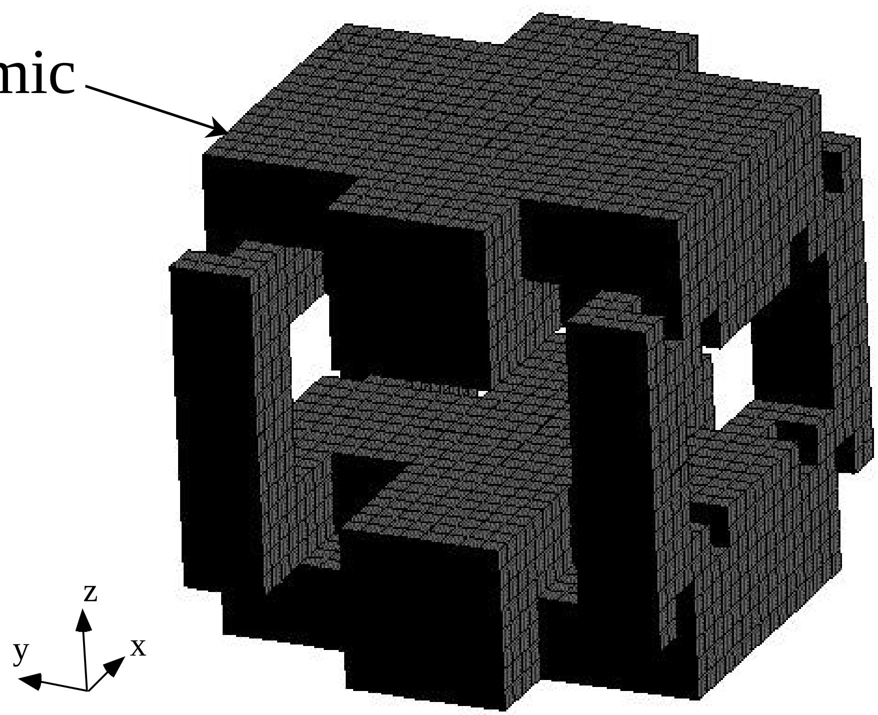
3D Piezocomposite Unit Cell
hydrophone

piezoceramic



Polarized in
the *z* direction

Summary

We have shown that
Layered Manufacturing Method
open up possibility of
topology design of piezoceramic composites
and piezoelectric actuators
for large scale performance improvement
by the homogenization design method