

*Principles and Development of Bio-Inspired Materials,
Vienna, 14 April 2010*

Topological Interlocking as a Materials Design Concept

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Collaboration with:

School of Civil and Resource Engineering, UWA:

- Arcady Dyskin
- Elena Pasternak
- Chuan Khor

Clausthal University of Technology:

- Stephan Schaare (former PhD student)
- Andrey Molotnikov (now at Monash)

Bremen International University:

- Alexei Kanel-Belov

Bremen University:

- Thomas Krause

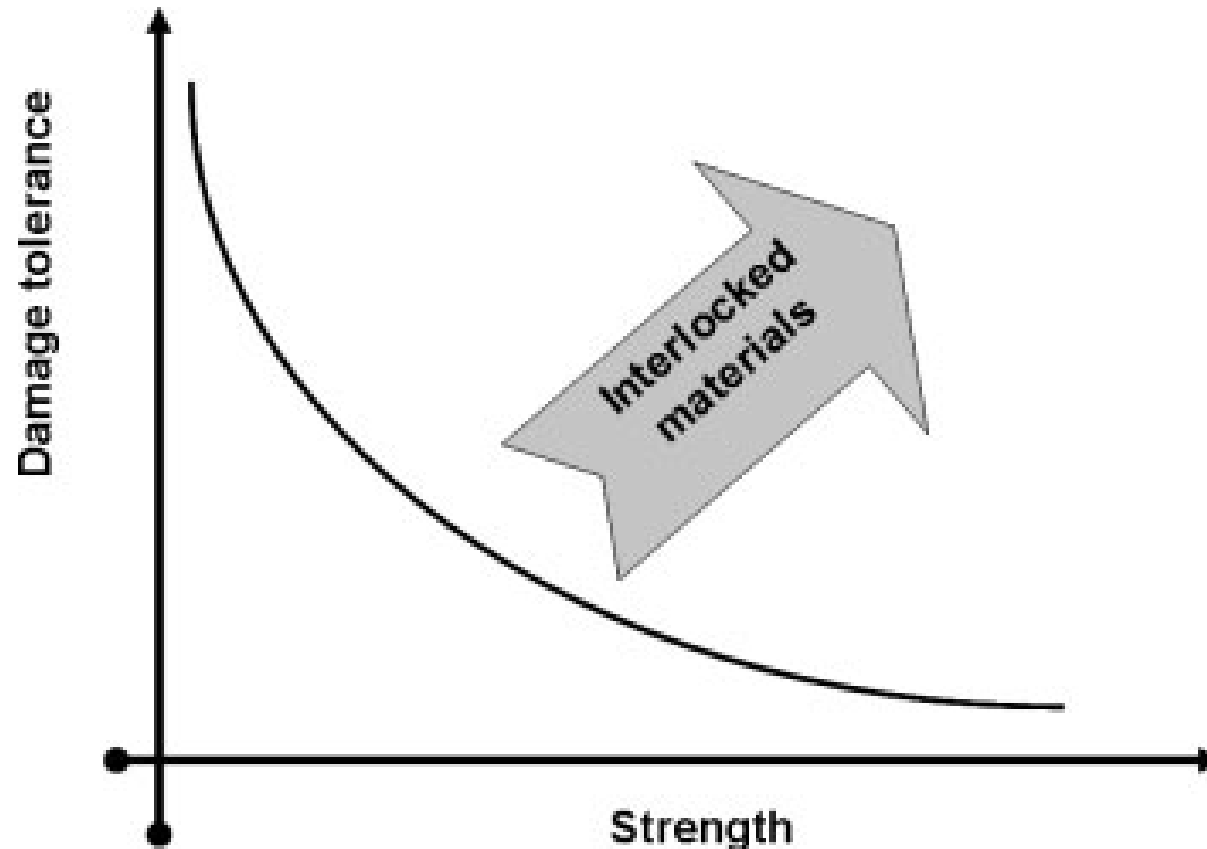
Grenoble University:

- Yves Brechet
- Marc Fivel

Geometry inspired materials people



Pushing the performance limits

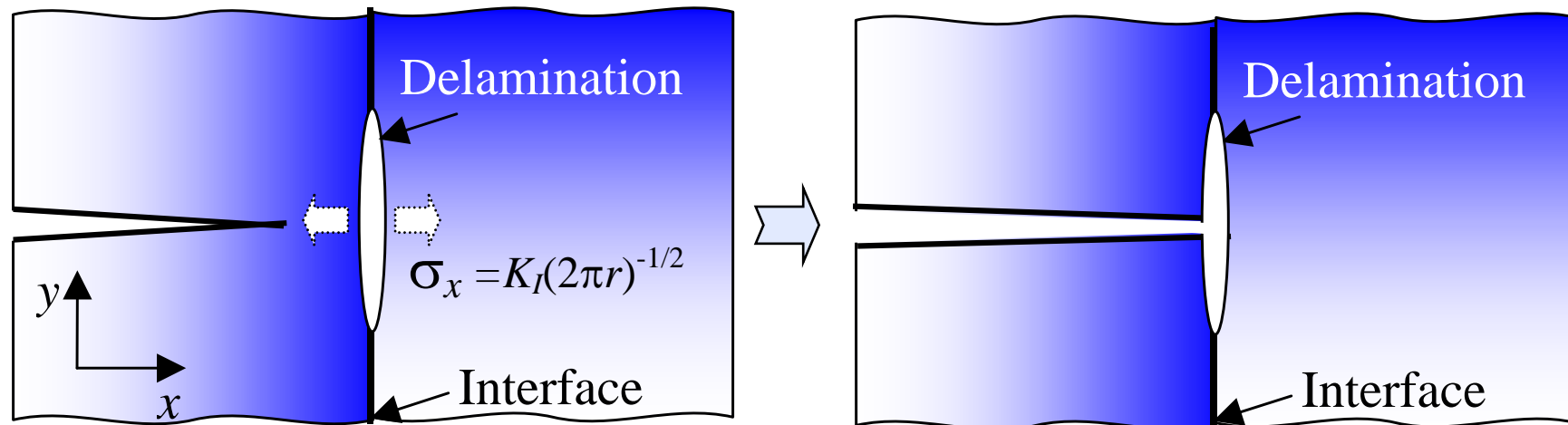


Benefits of fragmentation



Olivier Bouaziz, Arcelor-Mittal, France

Prevention of crack propagation

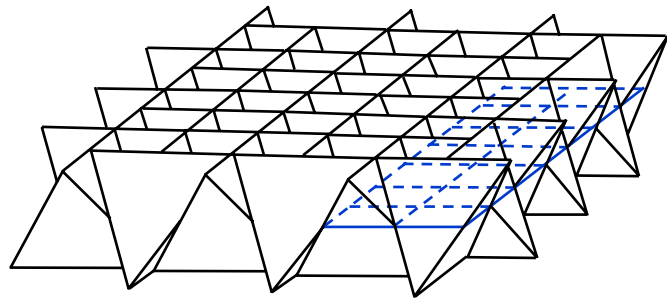


‘Delamination’ due to stress concentration.

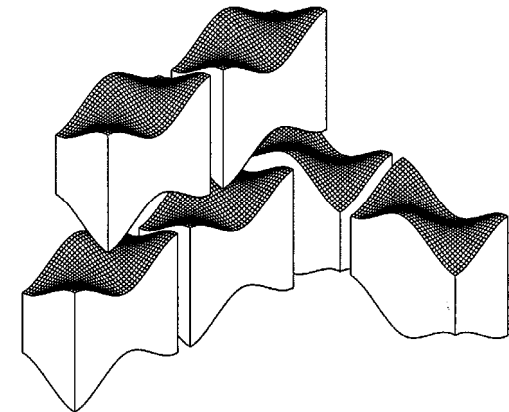
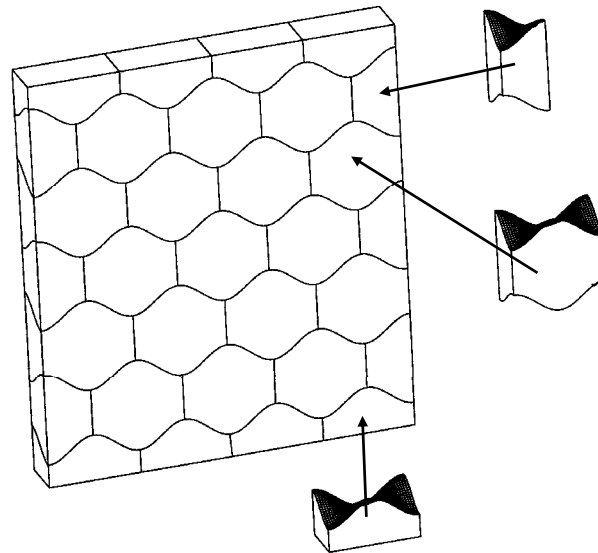
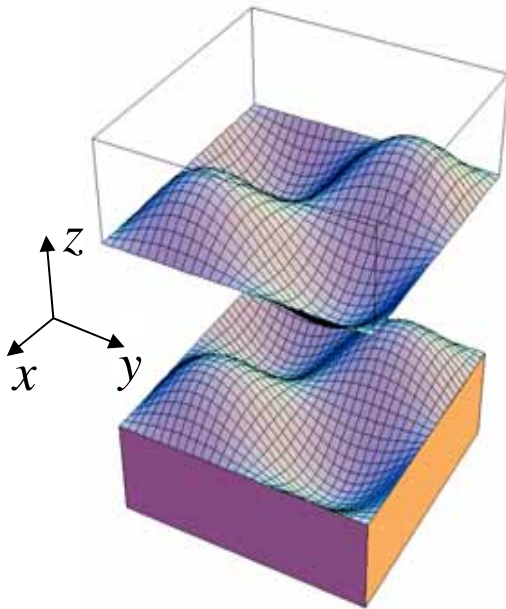
‘Delamination’ leads to arrest of crack.

Missing adhesion isolates the failed element and prevents crack propagation across interfaces.

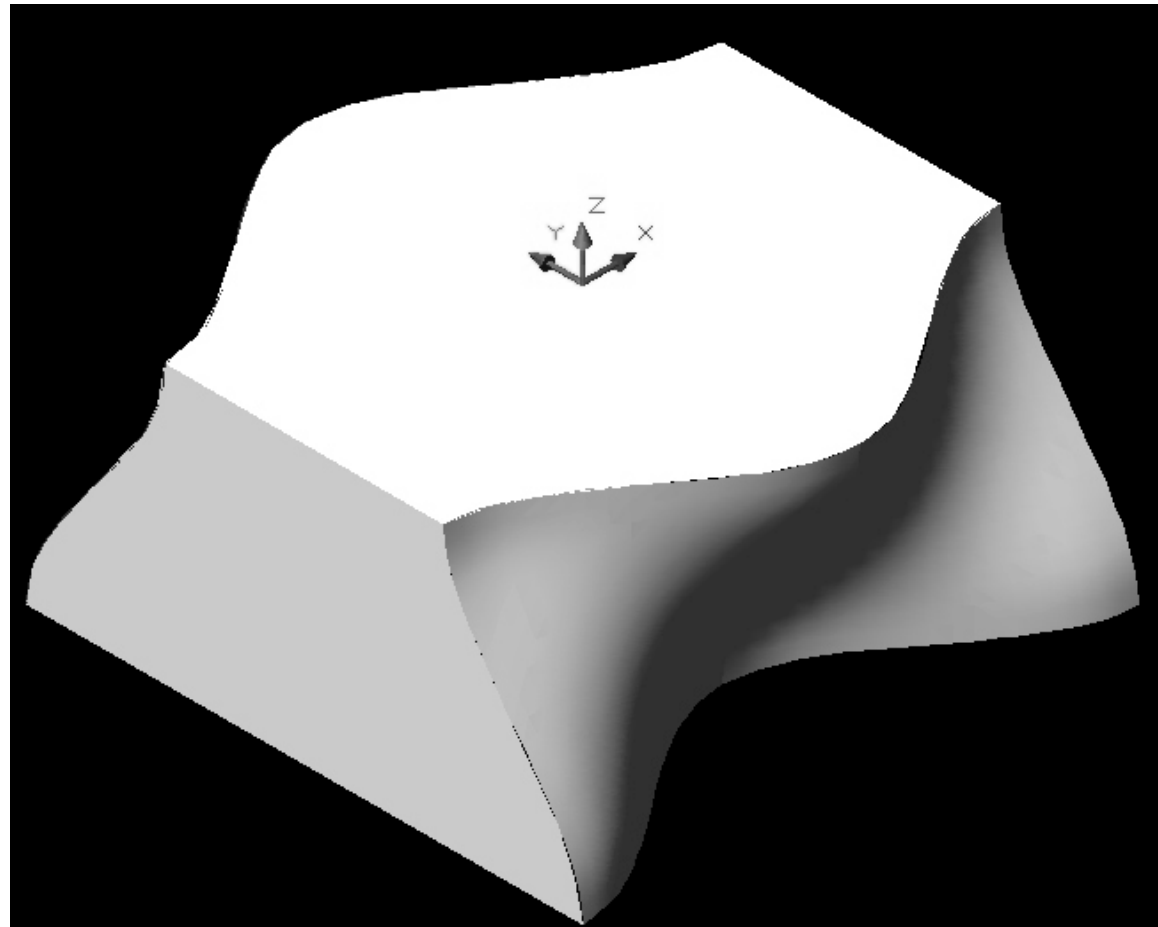
Two classes of interlocking shapes

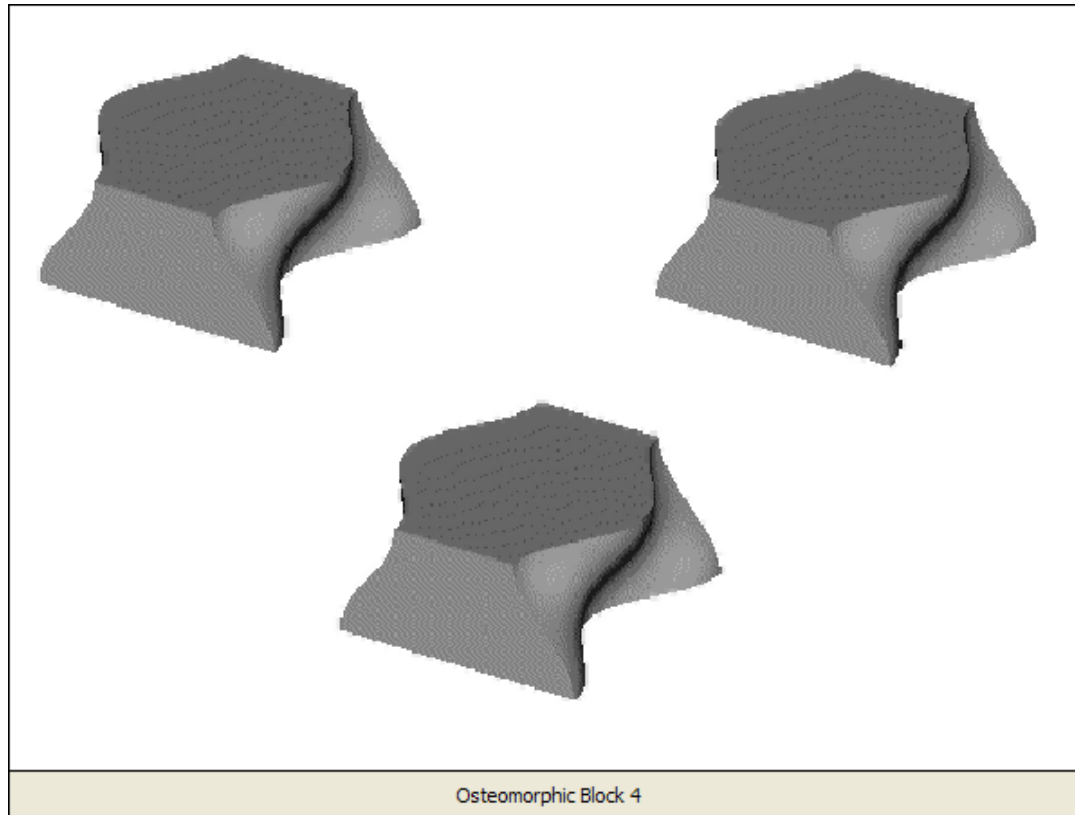


- Interlocking of identical convex elements
- Interlocking by non-planar surfaces (Osteomorphic blocks)



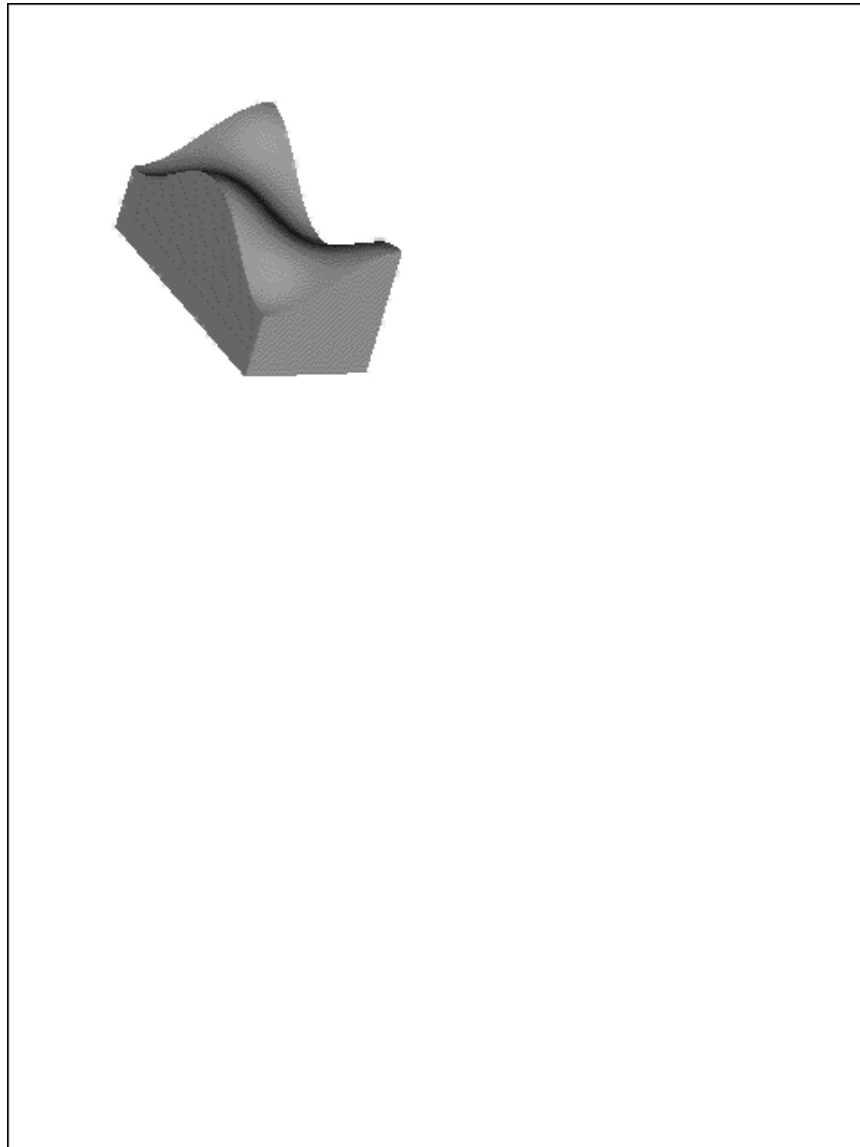
Osteomorphic block



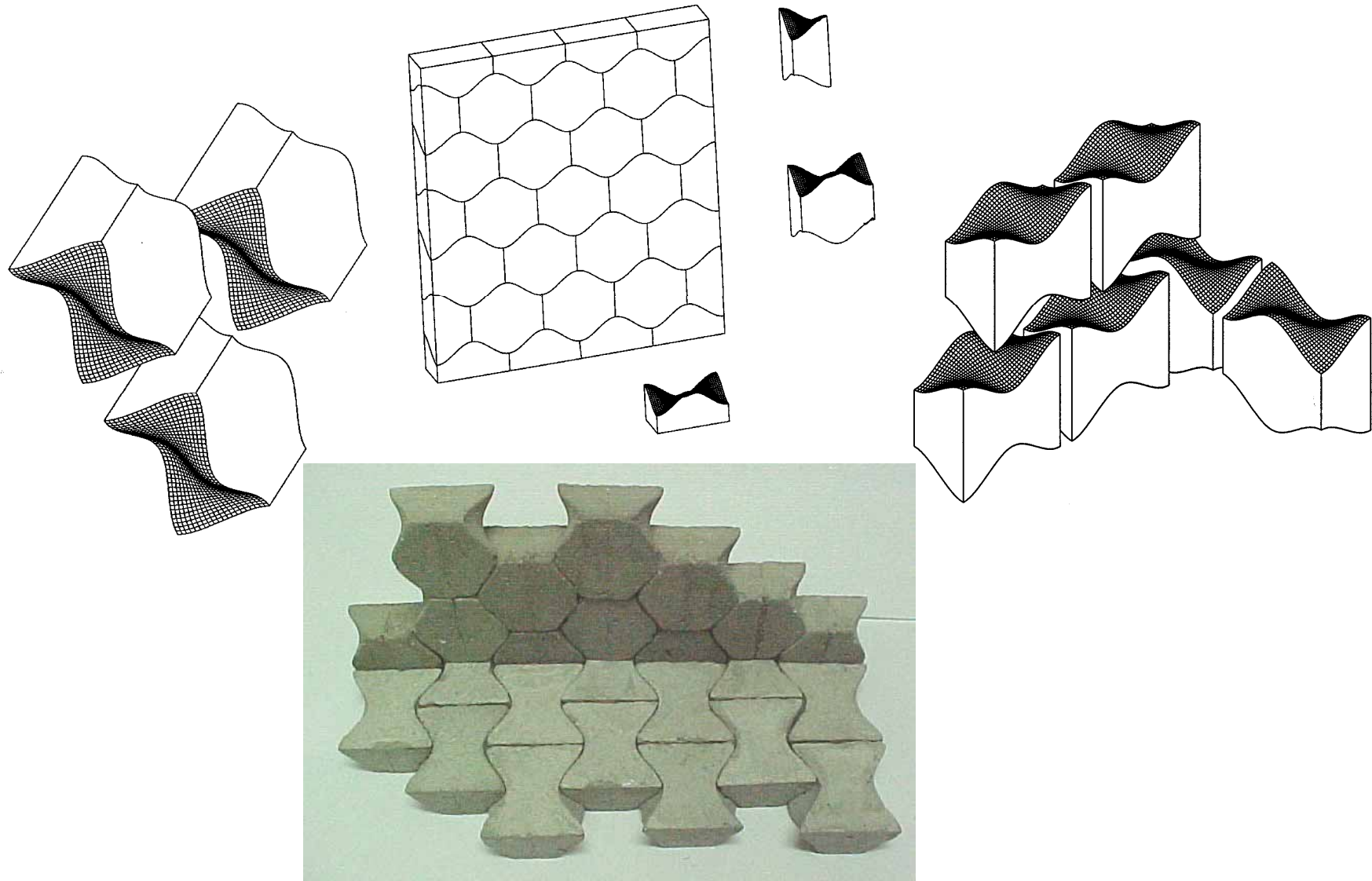


Osteomorphic Block 4

Wall assembly



Assemblies of osteomorphic blocks



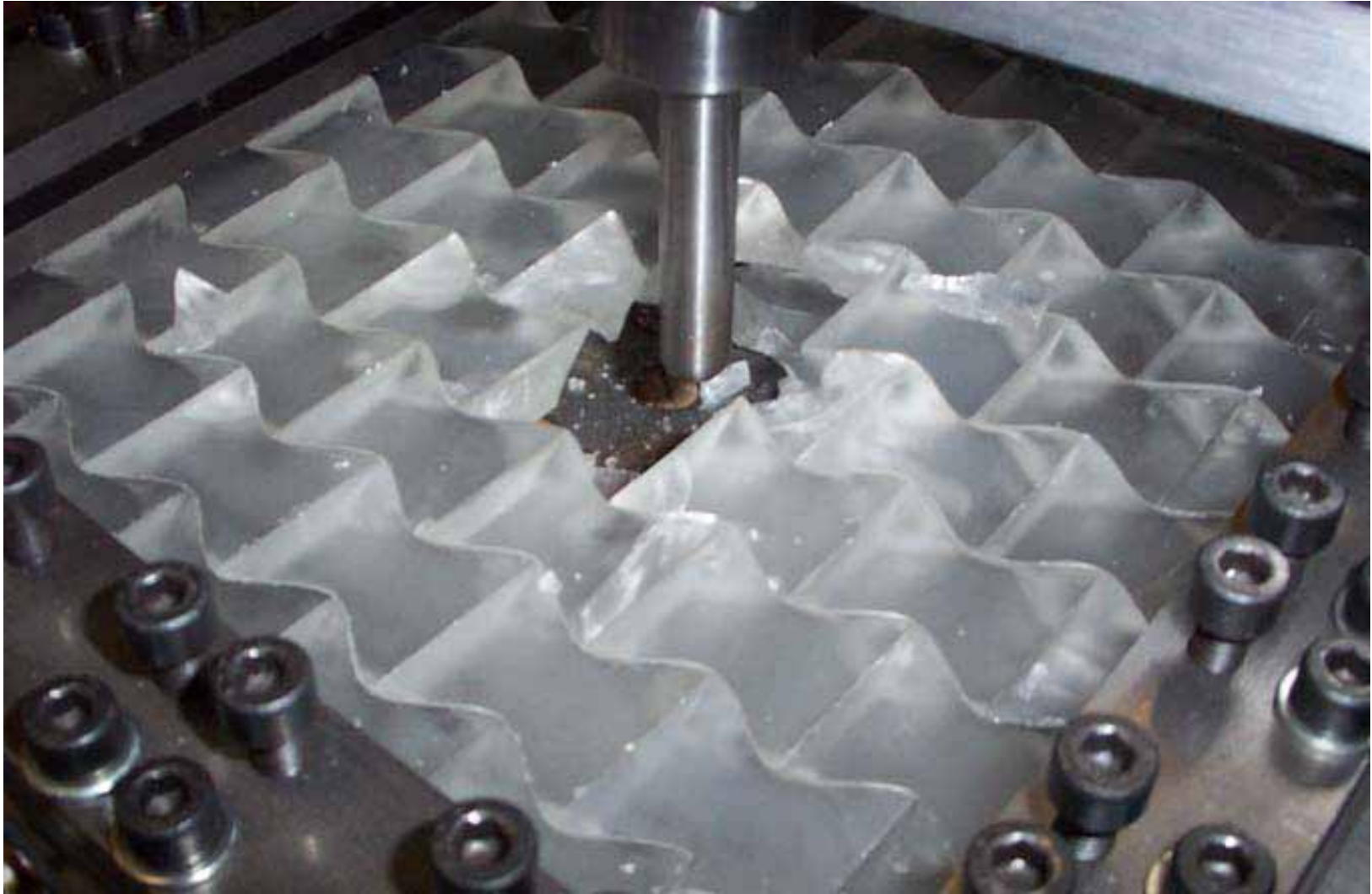
Column structure



Point loading of fragmented plate



Fracture resistance of the assembly



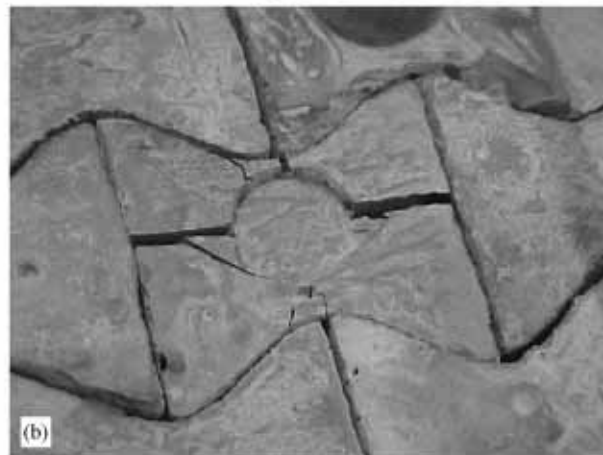
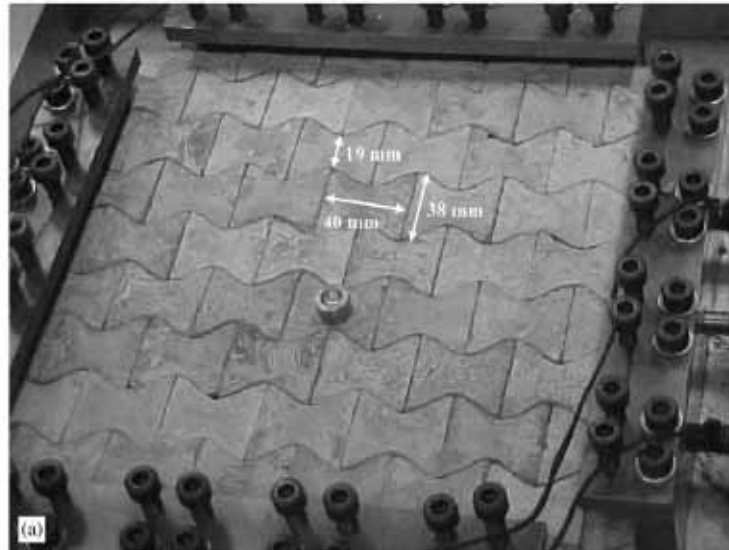
Massive plate



Failure of a massive plate



Example with concrete

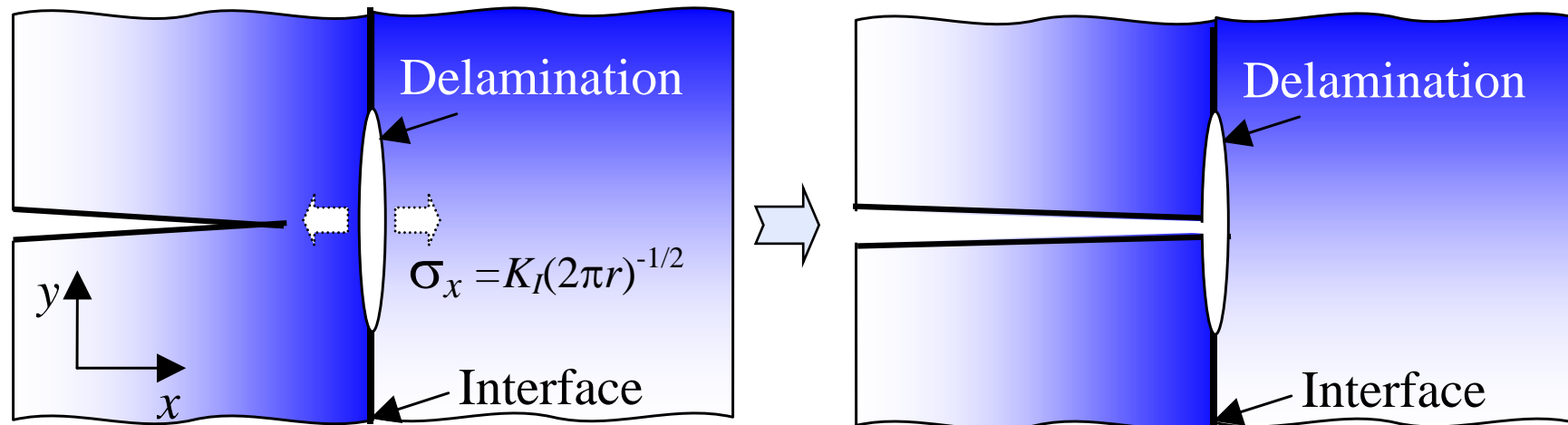


fragmented plate



massive plate

Prevention of crack propagation

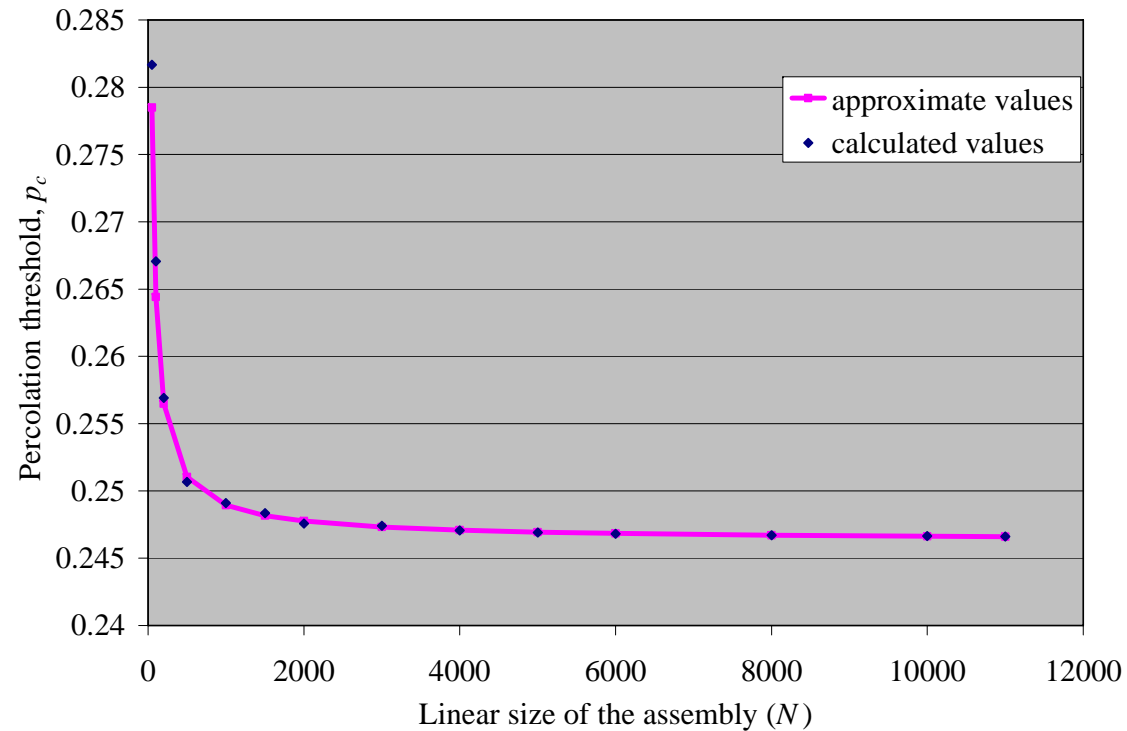


‘Delamination’ due to stress concentration.

‘Delamination’ leads to arrest of crack.

Missing adhesion isolates the failed element and prevents crack propagation across interfaces.

High tolerance to local failures; large percolation limit



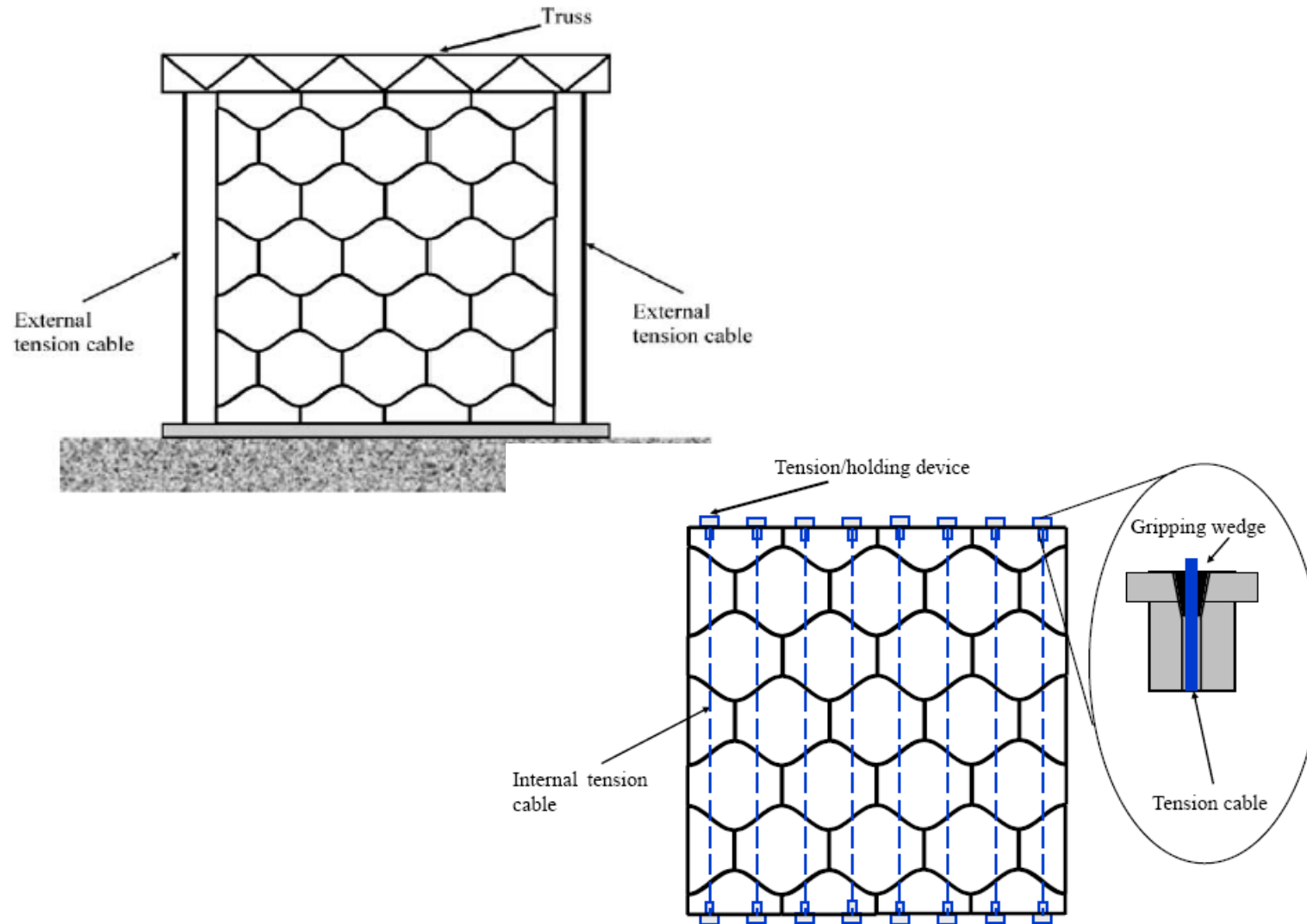
Percolation limit:

$$p_c(N) = p_c^\infty + 0.8186 N^{-0.827}$$

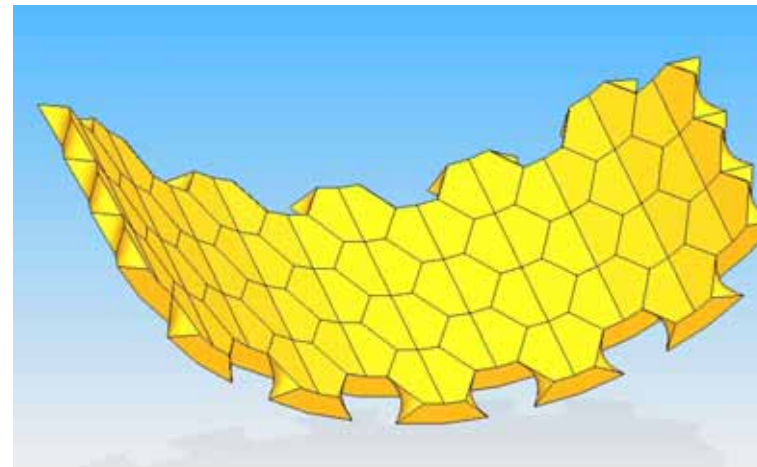
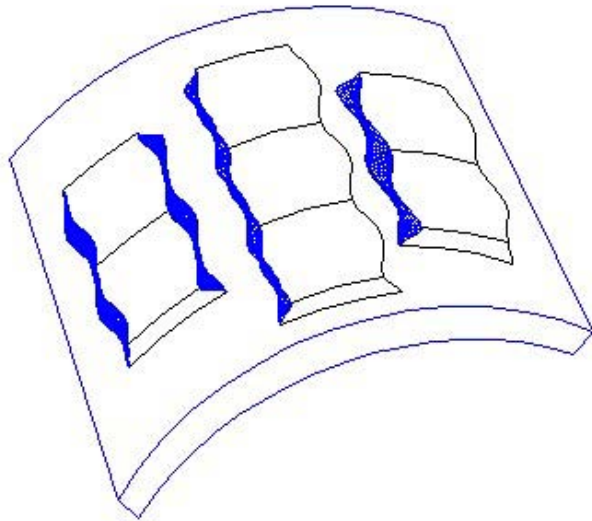
$$p_c^\infty = 0.2462$$

A. Molotnikov

Tensioning options



Protective cladding based on osteomorphic tiles

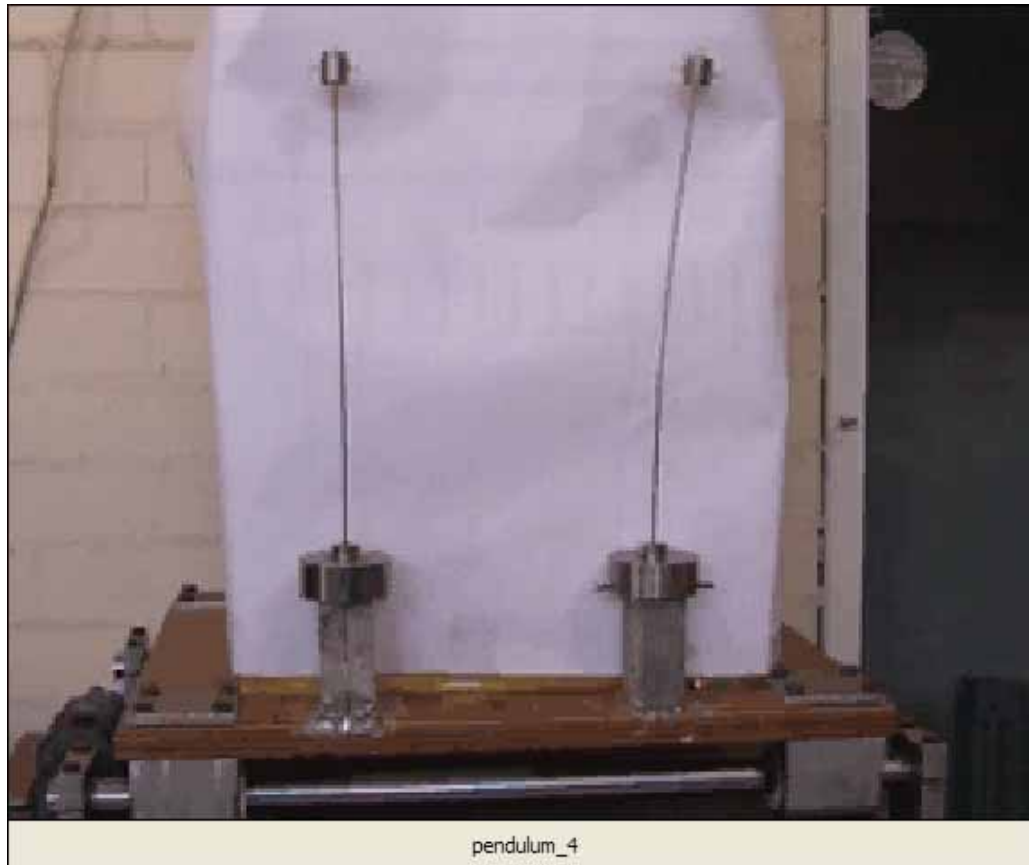


Osteomorphic tiles for cladding of curved surfaces
Space shuttle?

Endeavour tiles



Improved damping



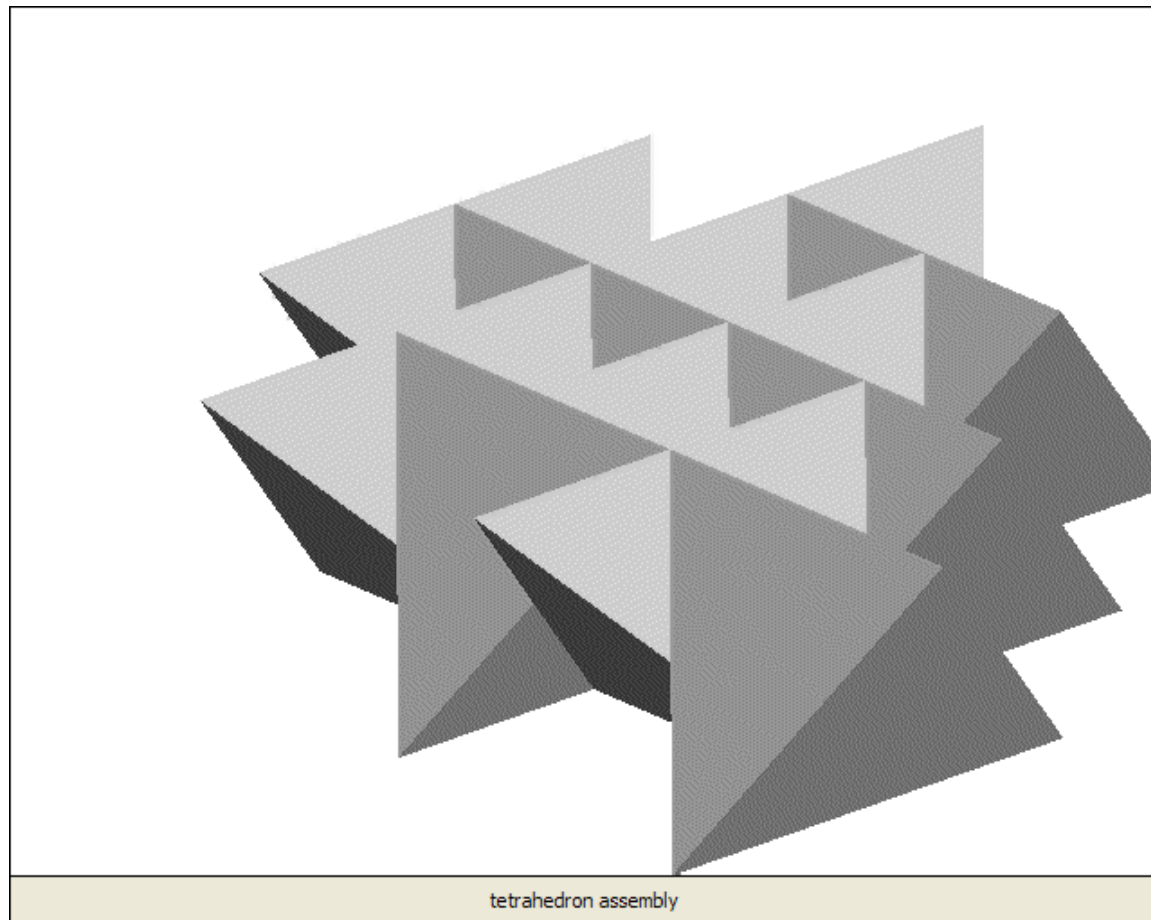
Manufacture of blocks (student project)



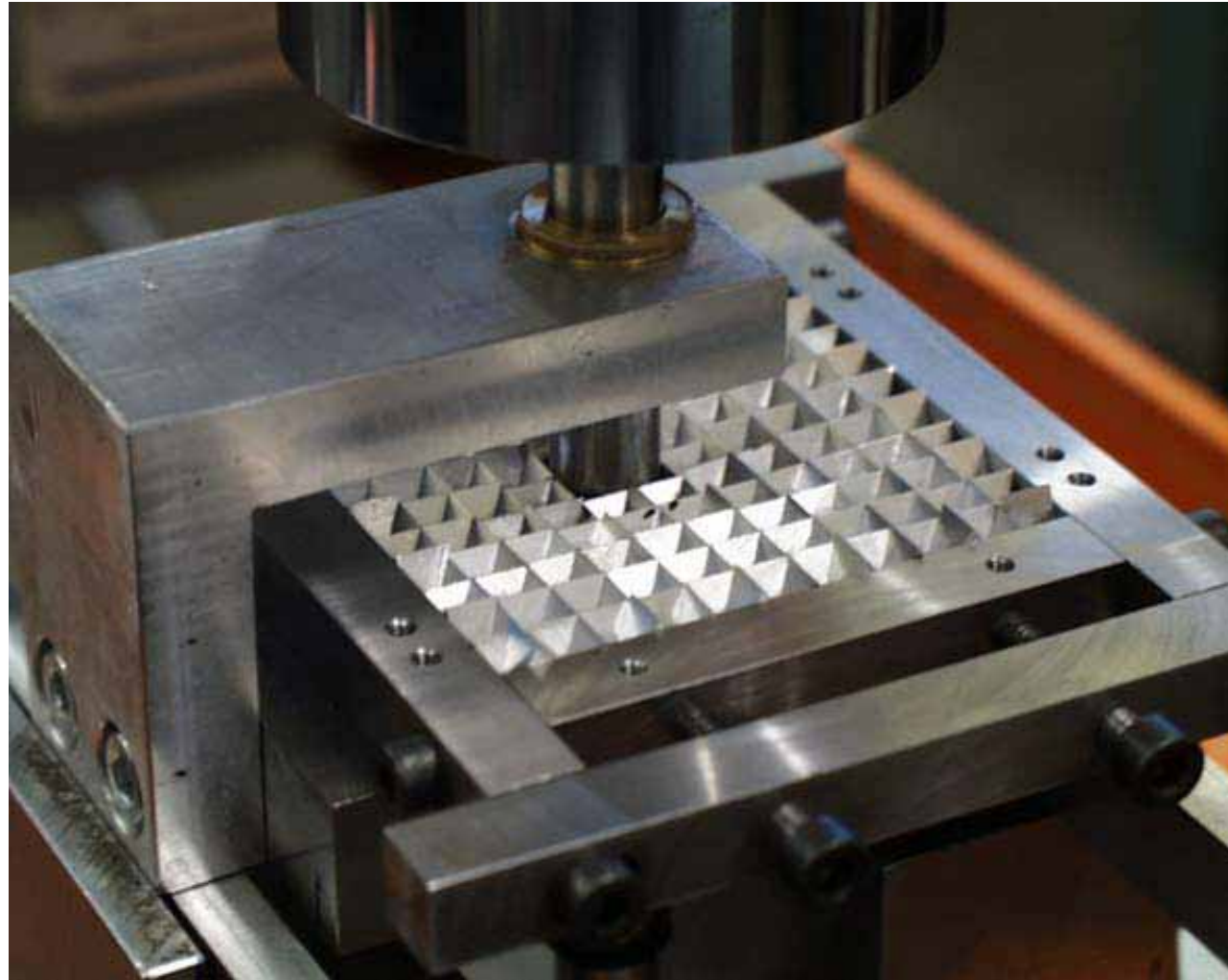
Properties of assemblies of osteomorphic blocks

- High resistance to fracture propagation
- High tolerance to missing blocks
- Low bending rigidity
- Property of self-adjustment
- Versatile applications

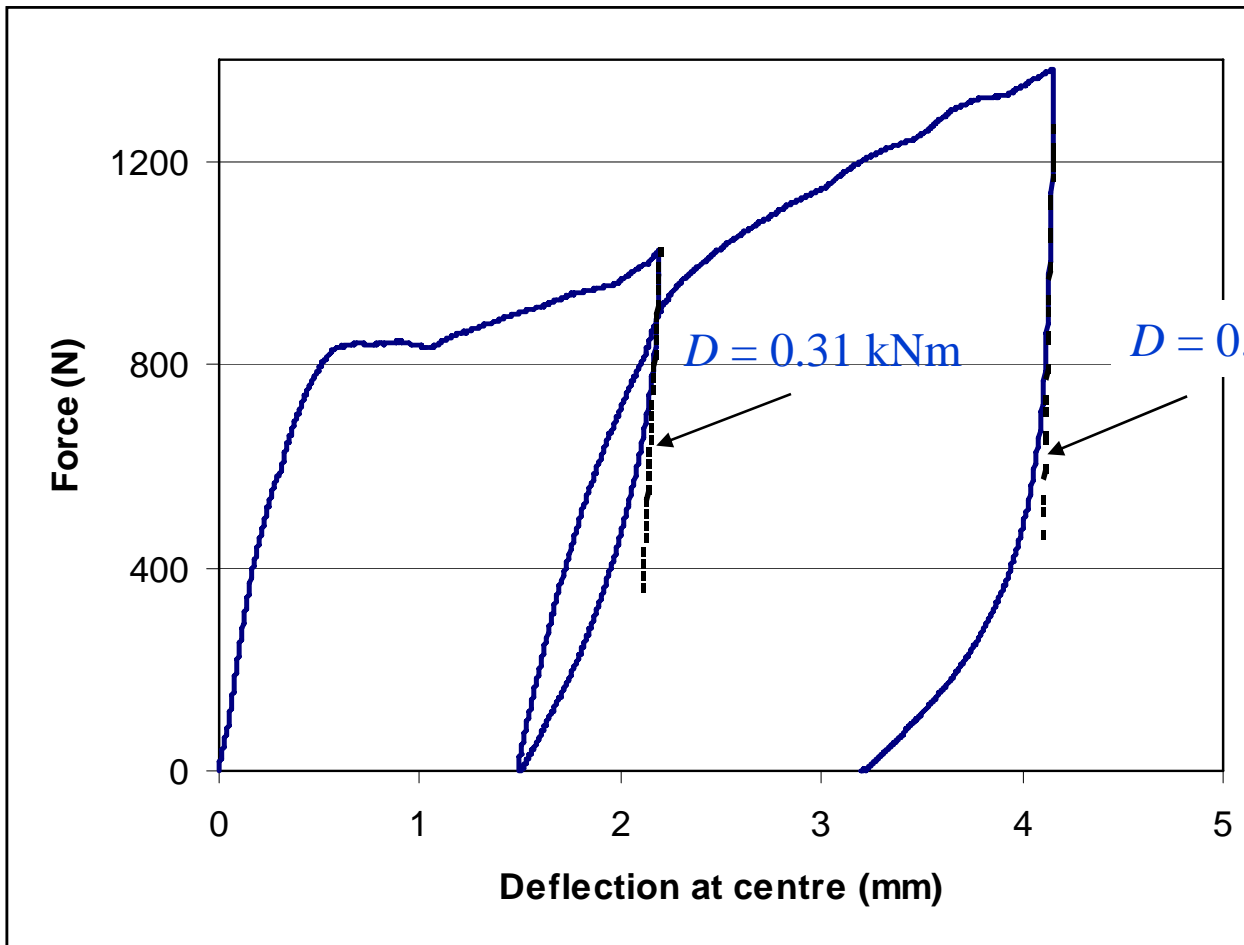
Assembly of tetrahedra



Concentrated load testing



Test results



D : cylindrical bending stiffness

$D = 0.31$ kNm

$D = 0.34$ kNm

For reference
solid plate of the
same thickness as
the assembled
layer: $a/\sqrt{2} \cong 0.71$ cm

$D = 2.33$ kNm

Residual deflection

Blocks themselves show no plastic deformation



- **The assembly is still holding**
- **The elements rotate and 'lock' the indenter**

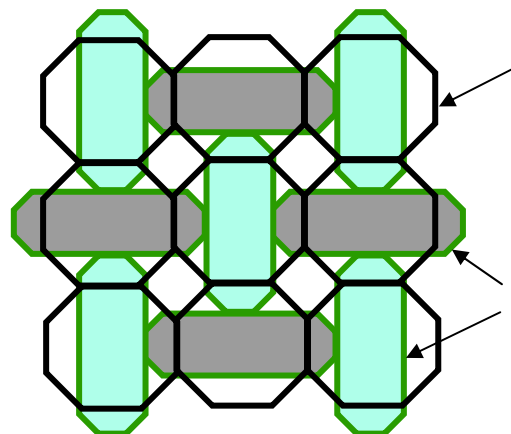
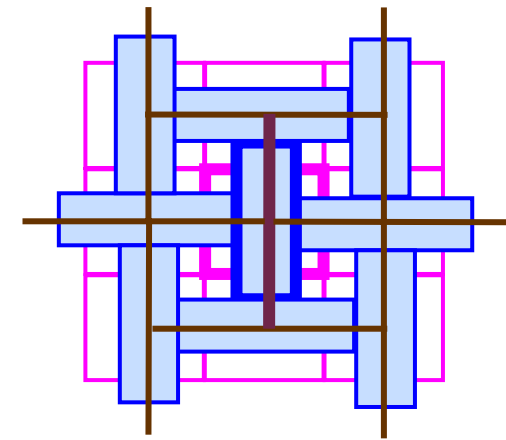
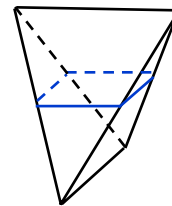
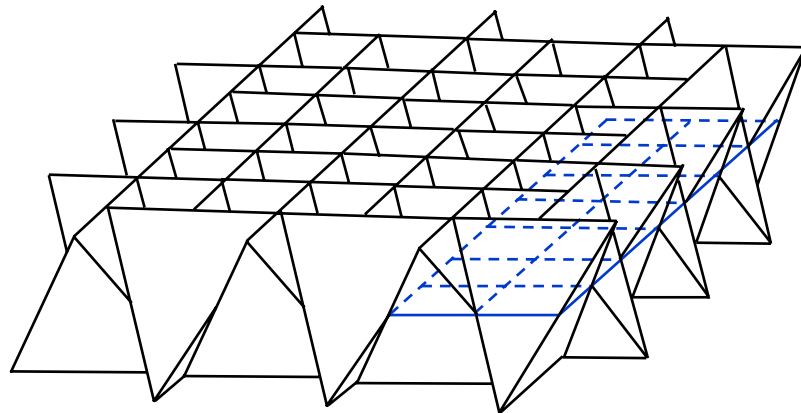
Tolerance to missing blocks

Assemblies with missing blocks retain their integrity.



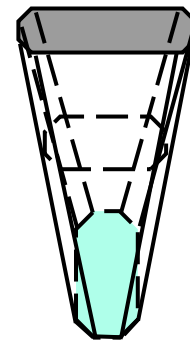
Assemblies of tetrahedra and related structures

Square-based interlocking

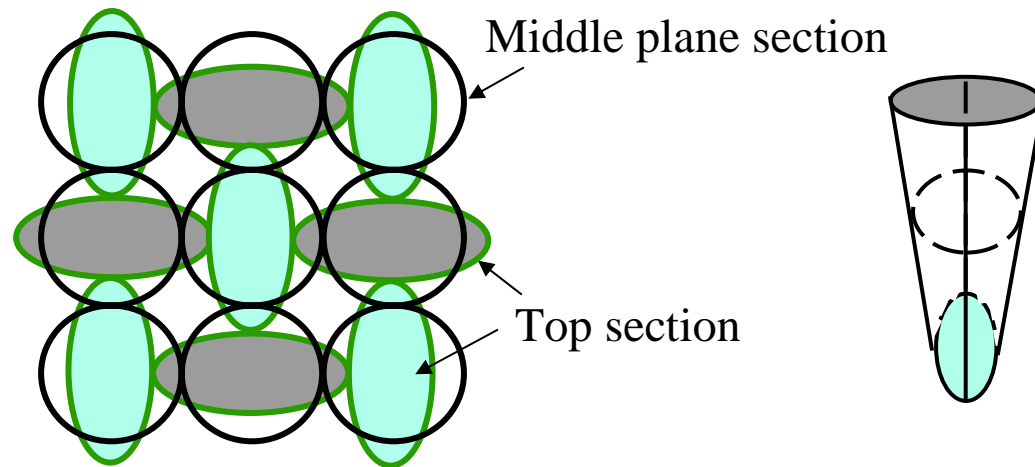


Middle plane section

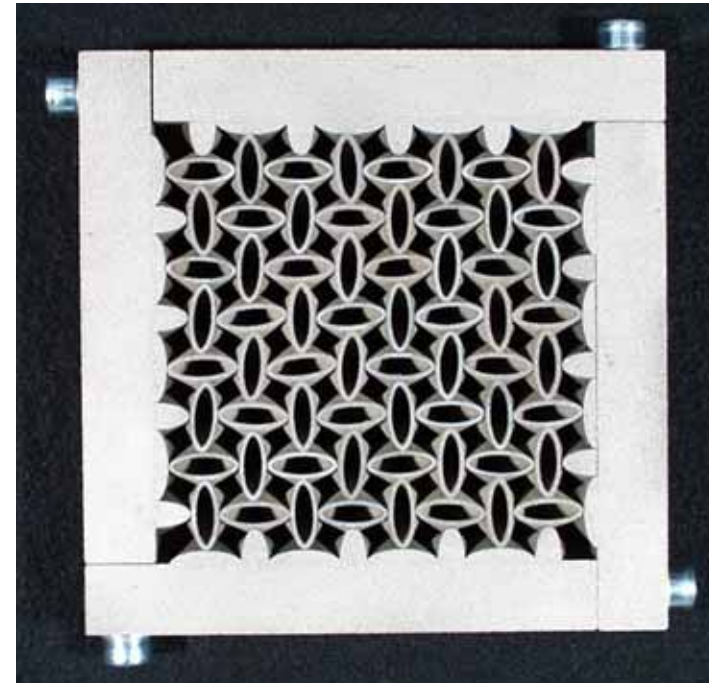
Top section



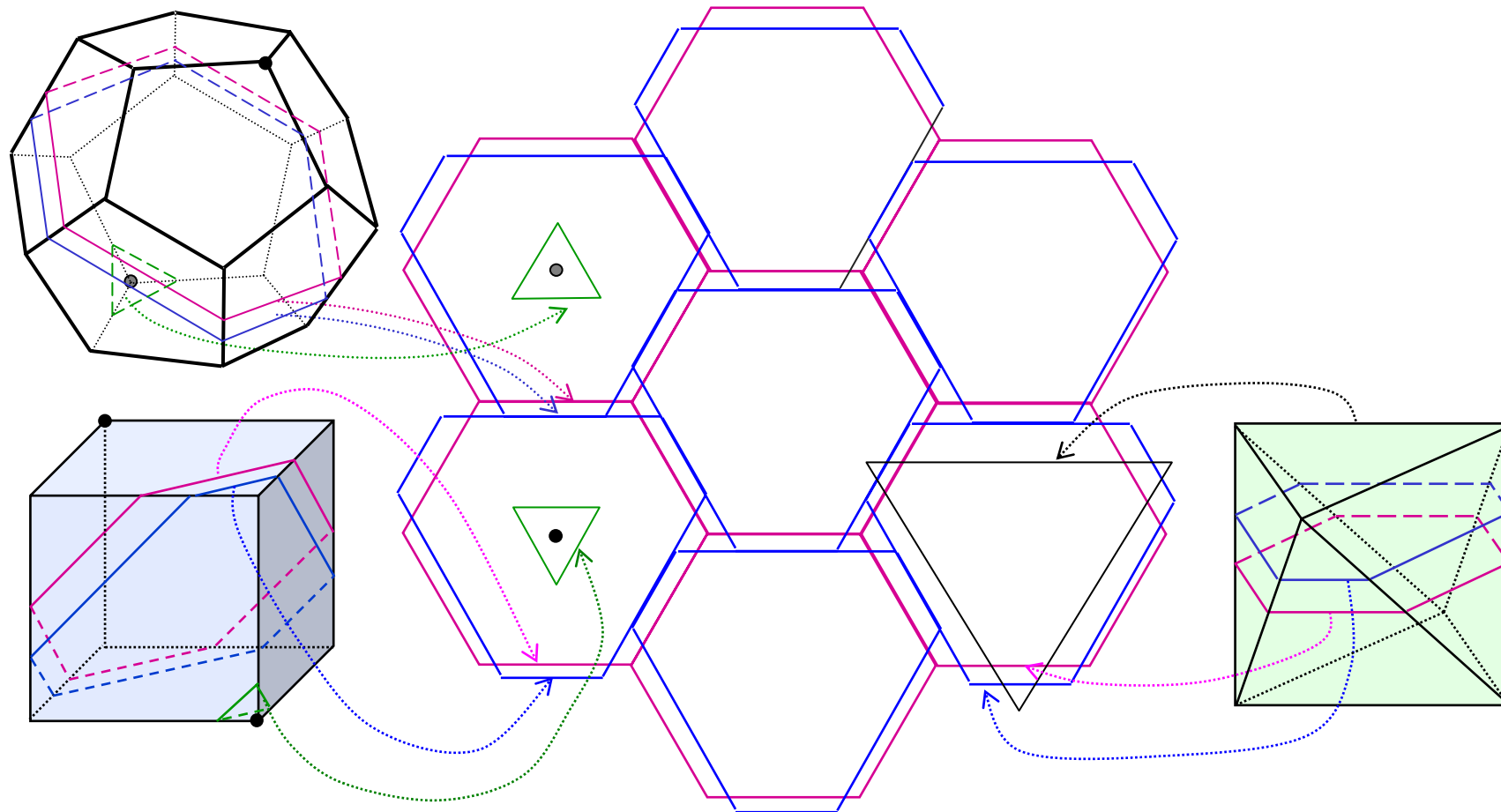
Assembly of tubular elements



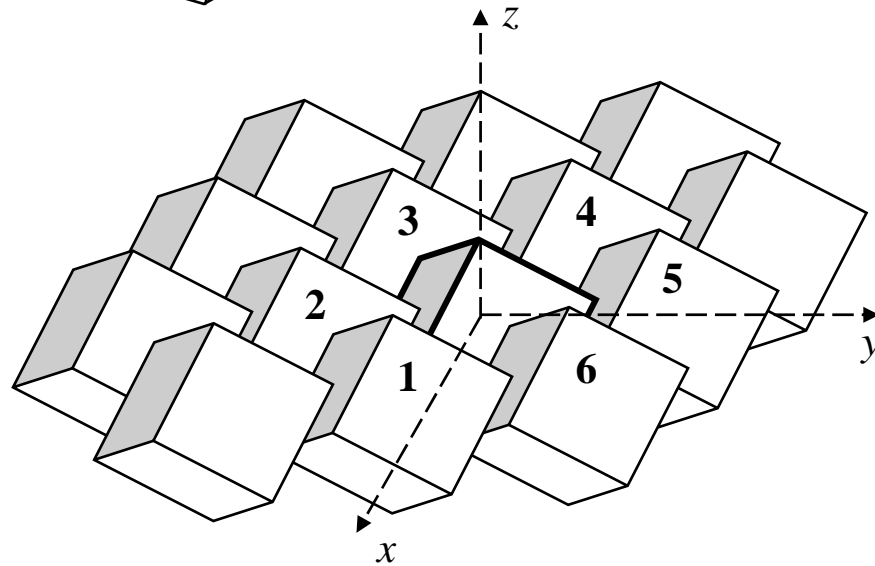
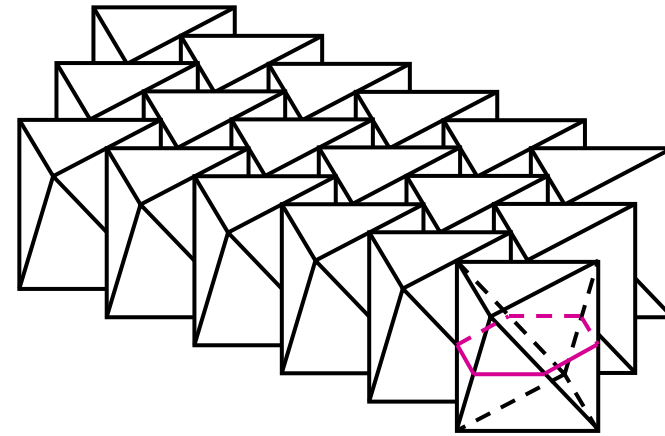
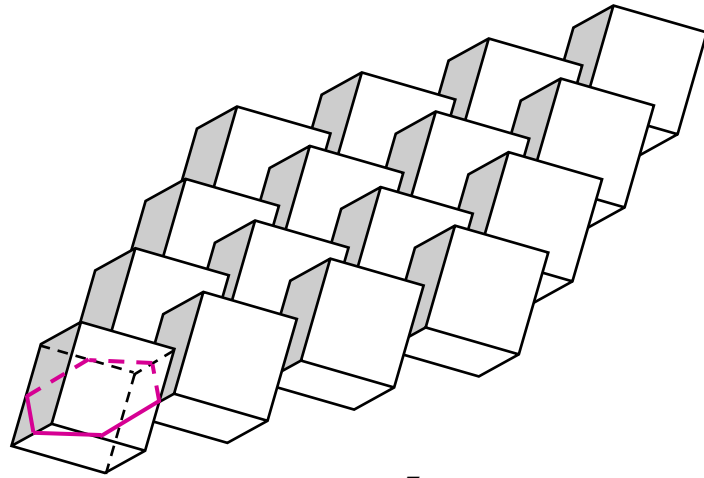
“Smooth” surface of the elements, very high porosity and permeability of the assembly



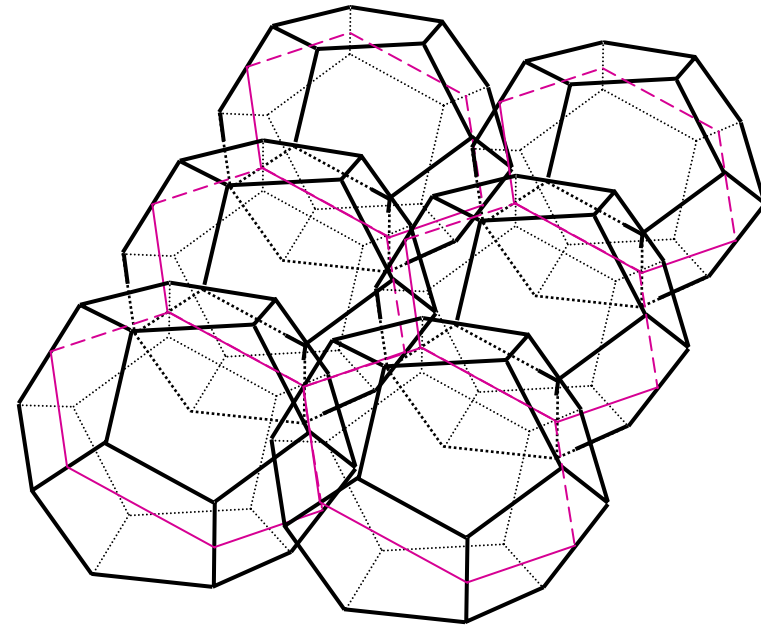
Hexagon-based interlocking



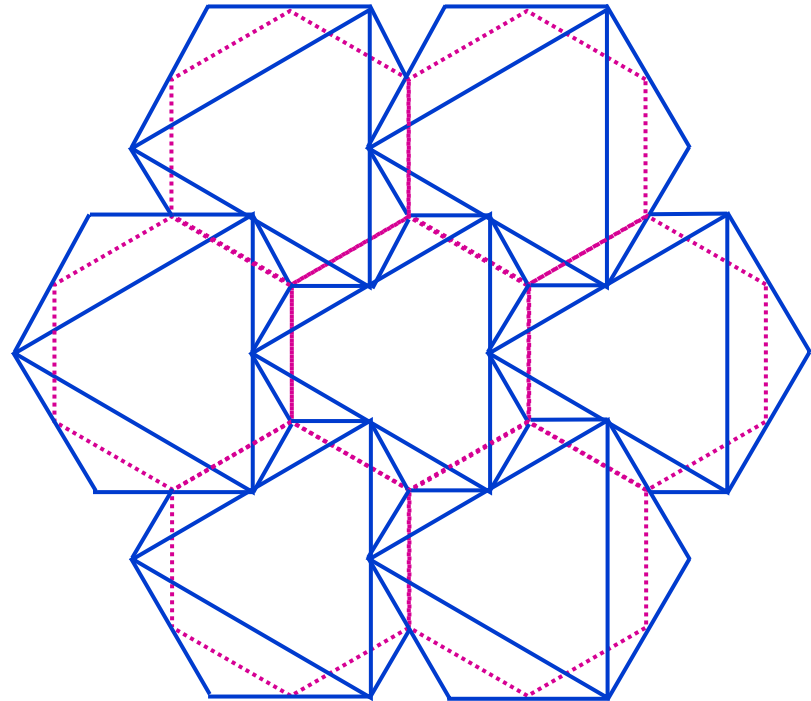
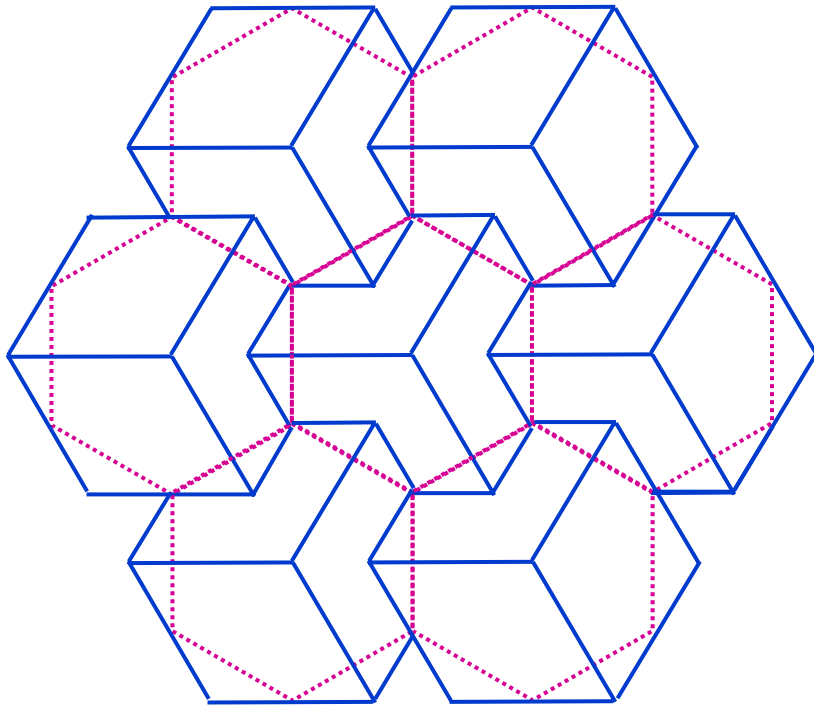
Interlocking of Platonic Bodies



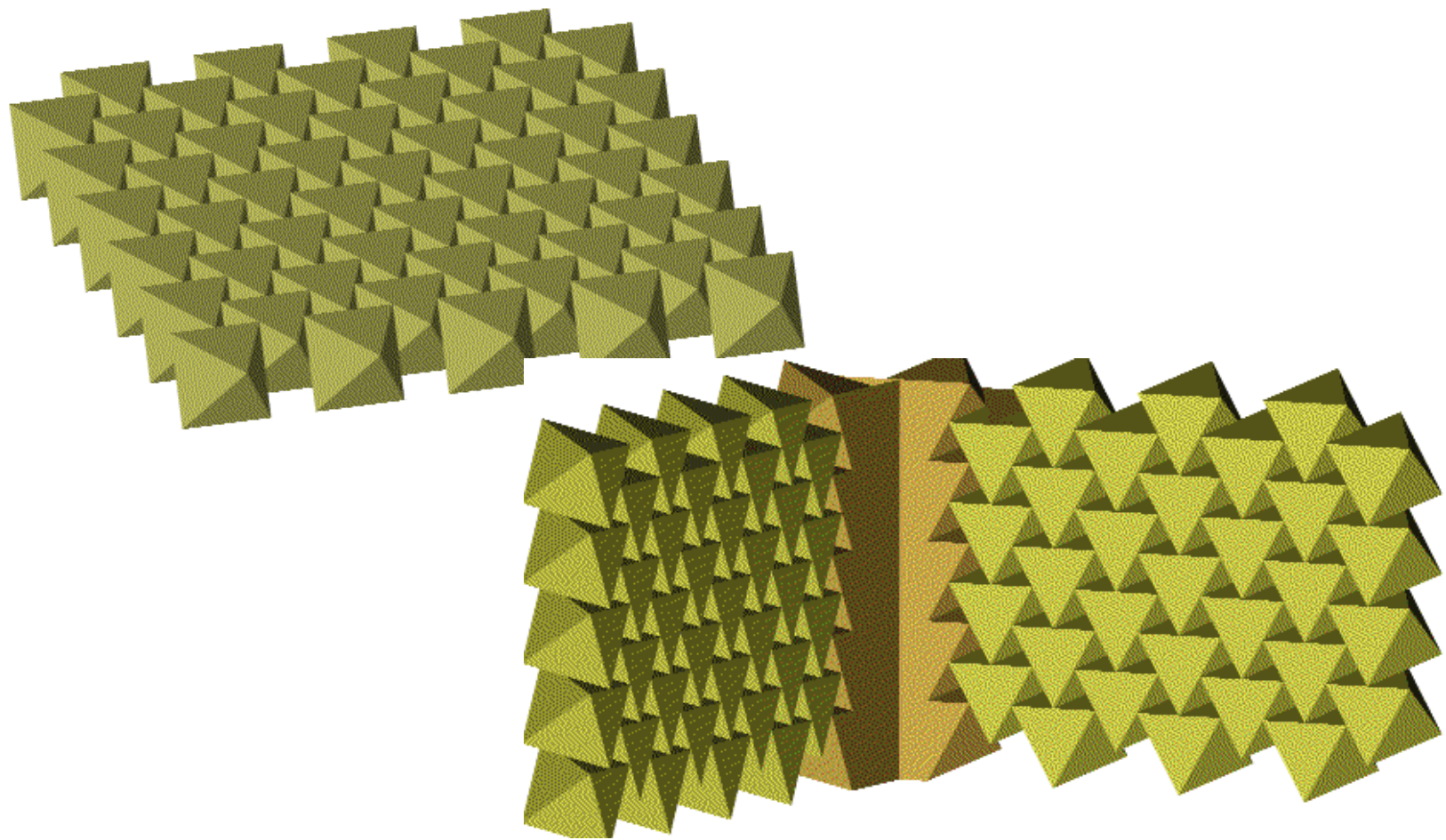
Cubes 1,3,5 and 2,4,6 hinder downward and upward displacements, respectively.



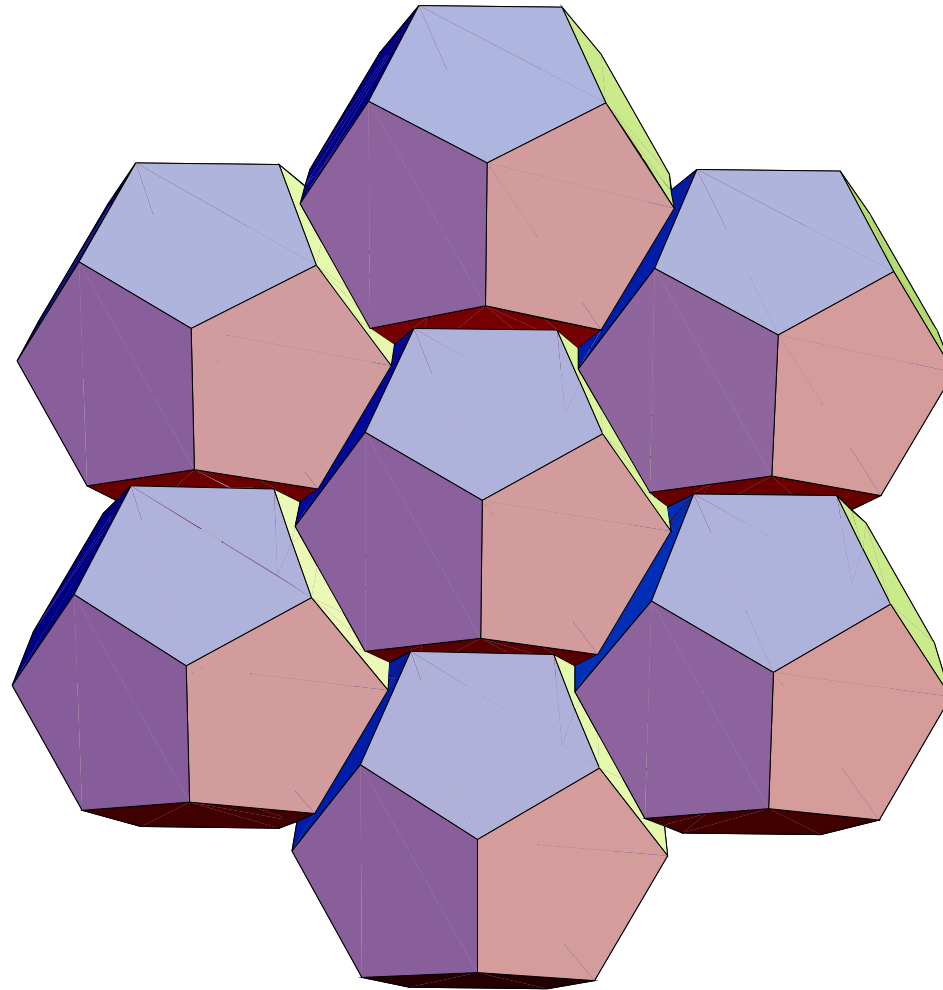
Cubes and Octahedra



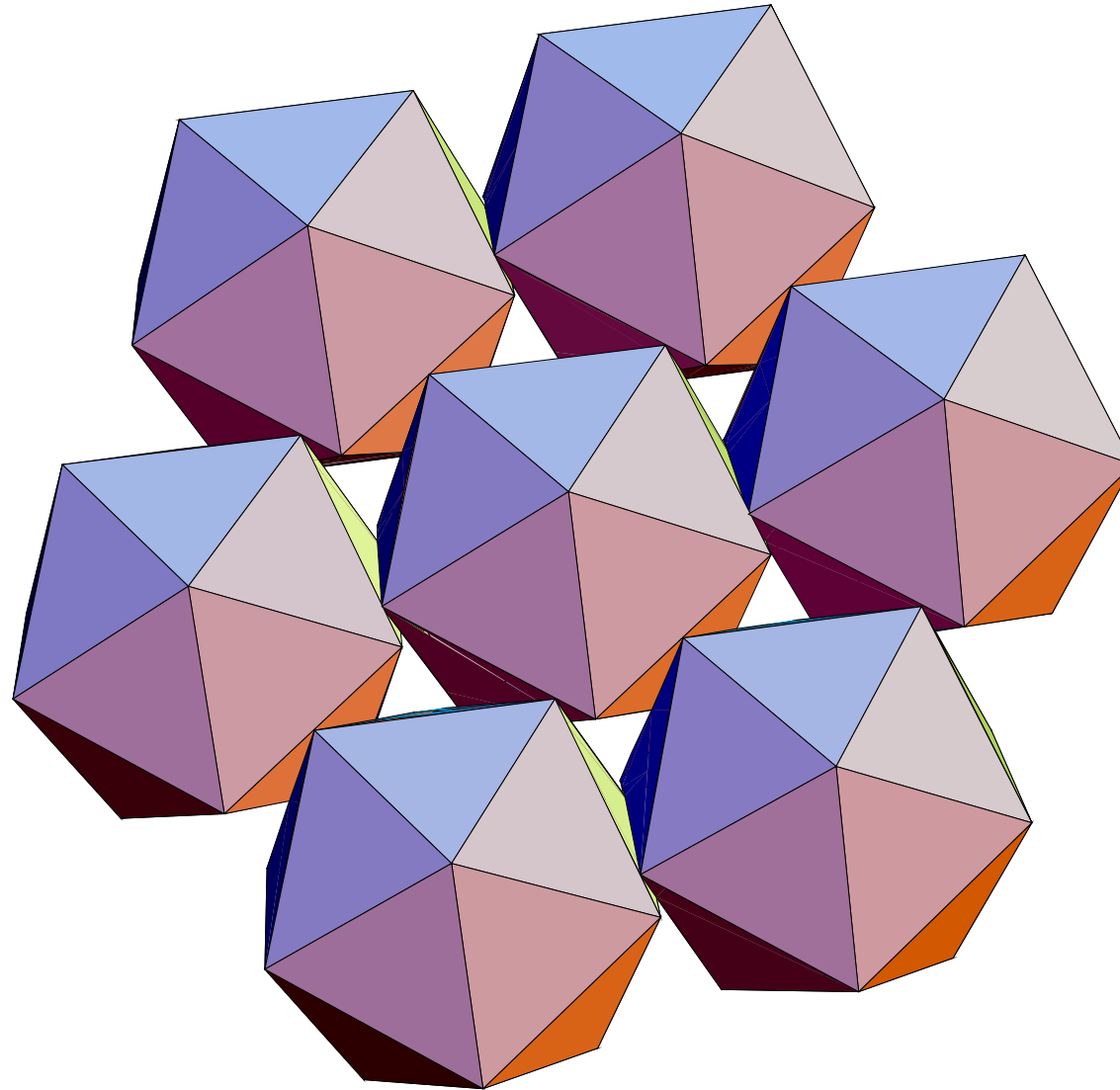
Assemblies of octahedra



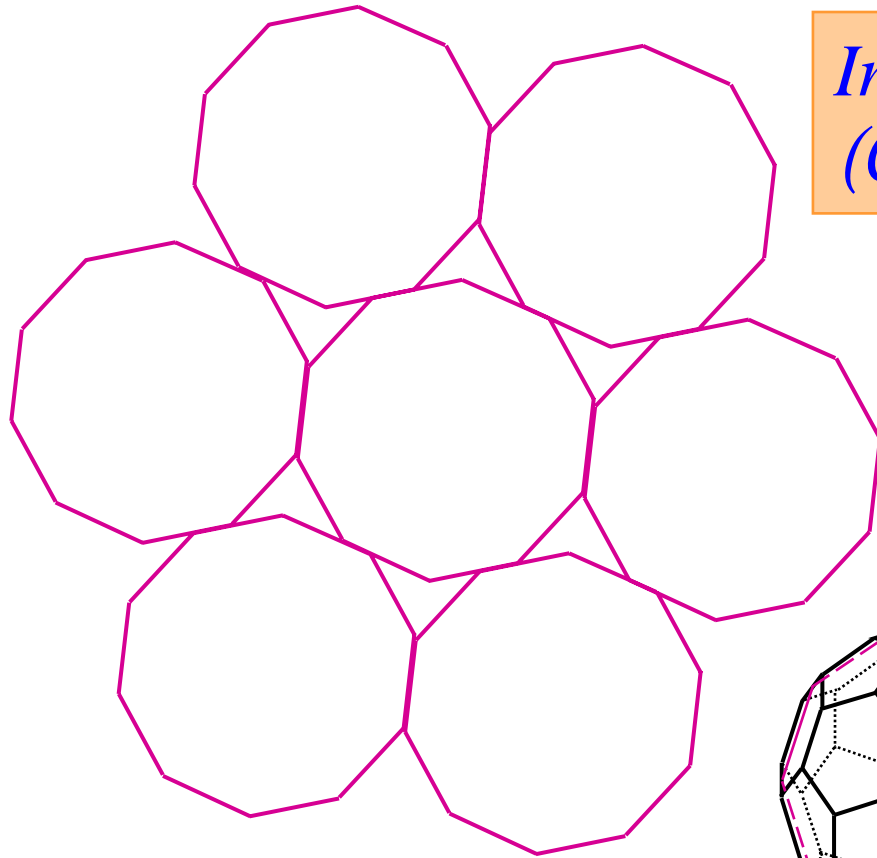
Assembly of dodecahedra



Assembly of icosahedra

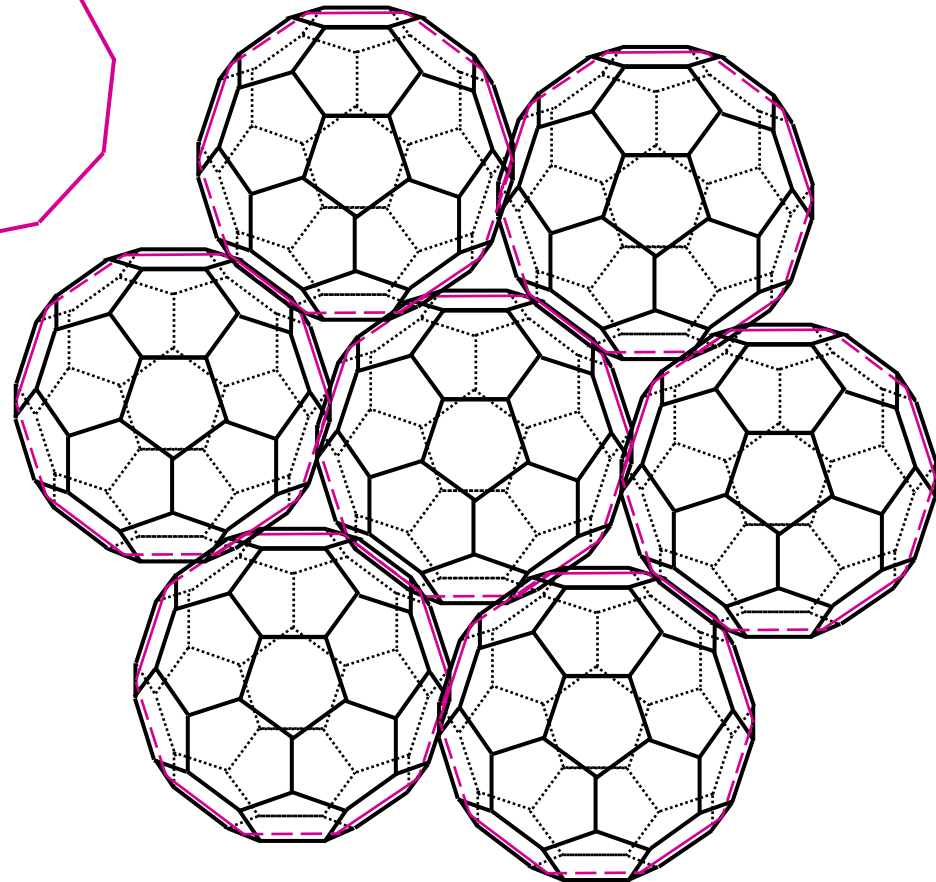


*Interlocking of Buckyballs
(C_{60} molecules)*

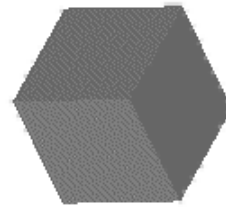


*Decagons
in the middle section*

*A. Dyskin et al., Phys.
Lett., 2003*

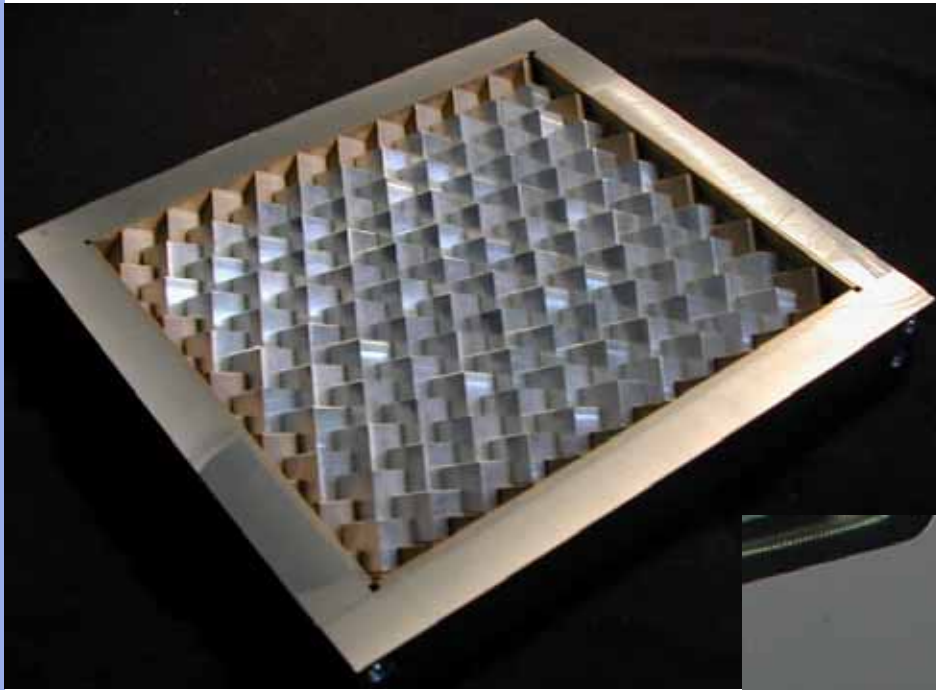


Assembly of cubes

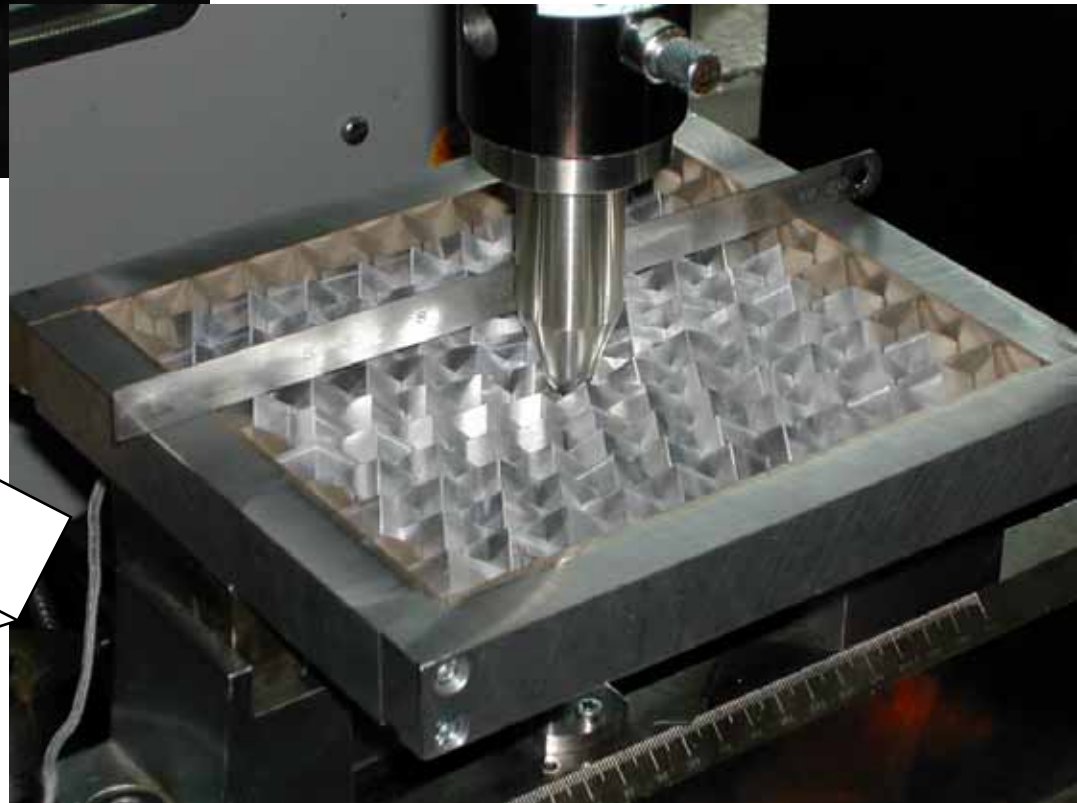
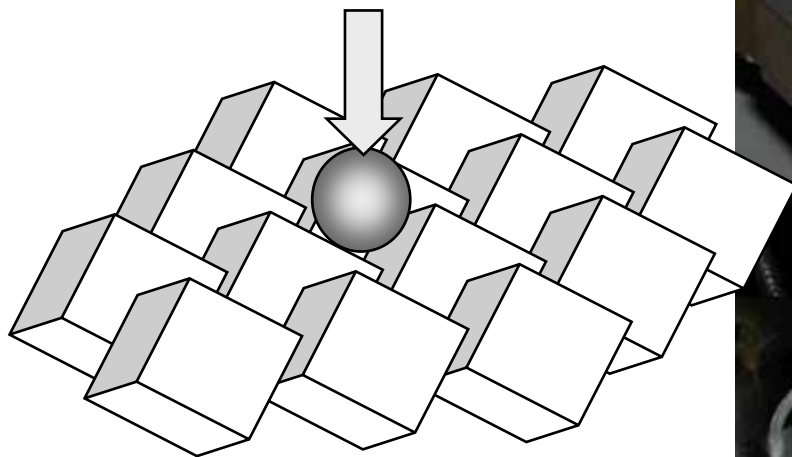


Cube Assembly

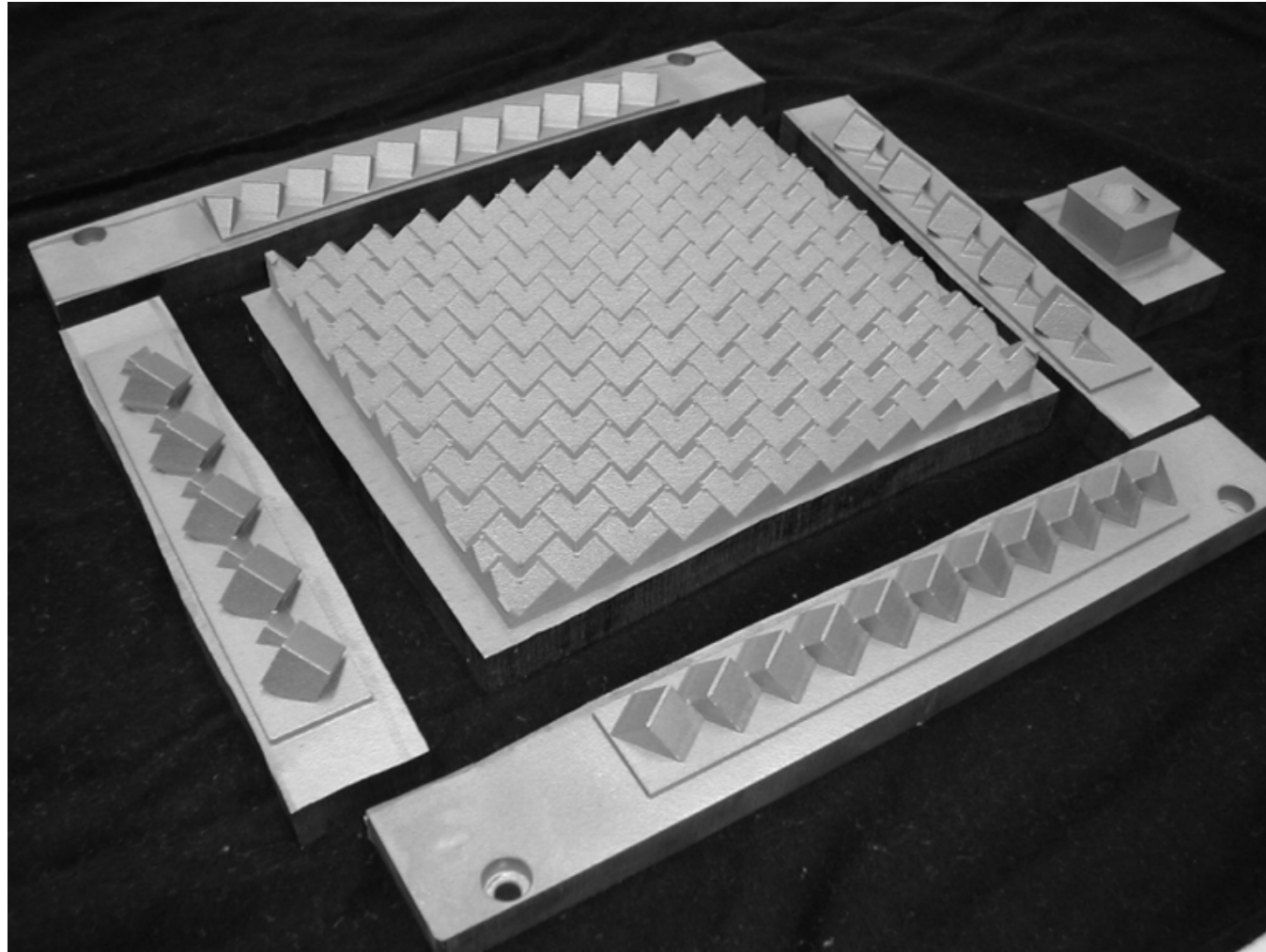
Deformation of assembly of cubes



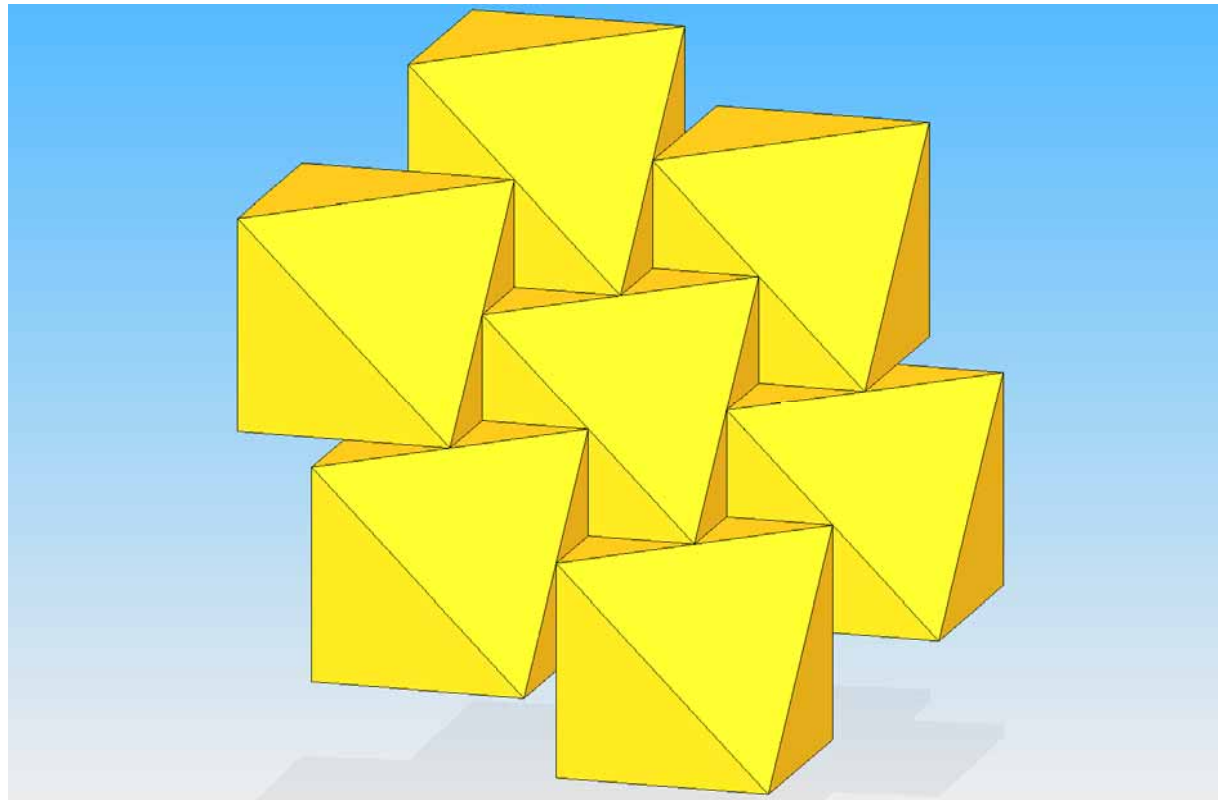
Concentrated load



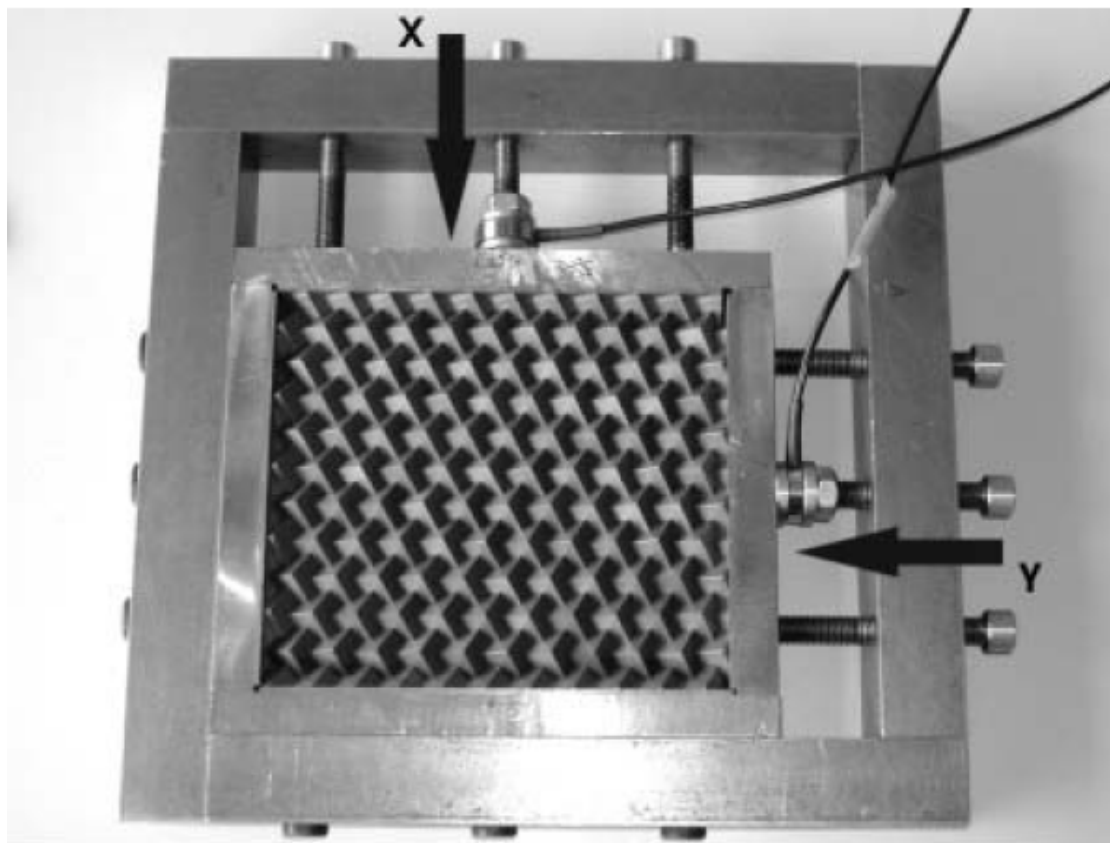
Template for assembly of cubes



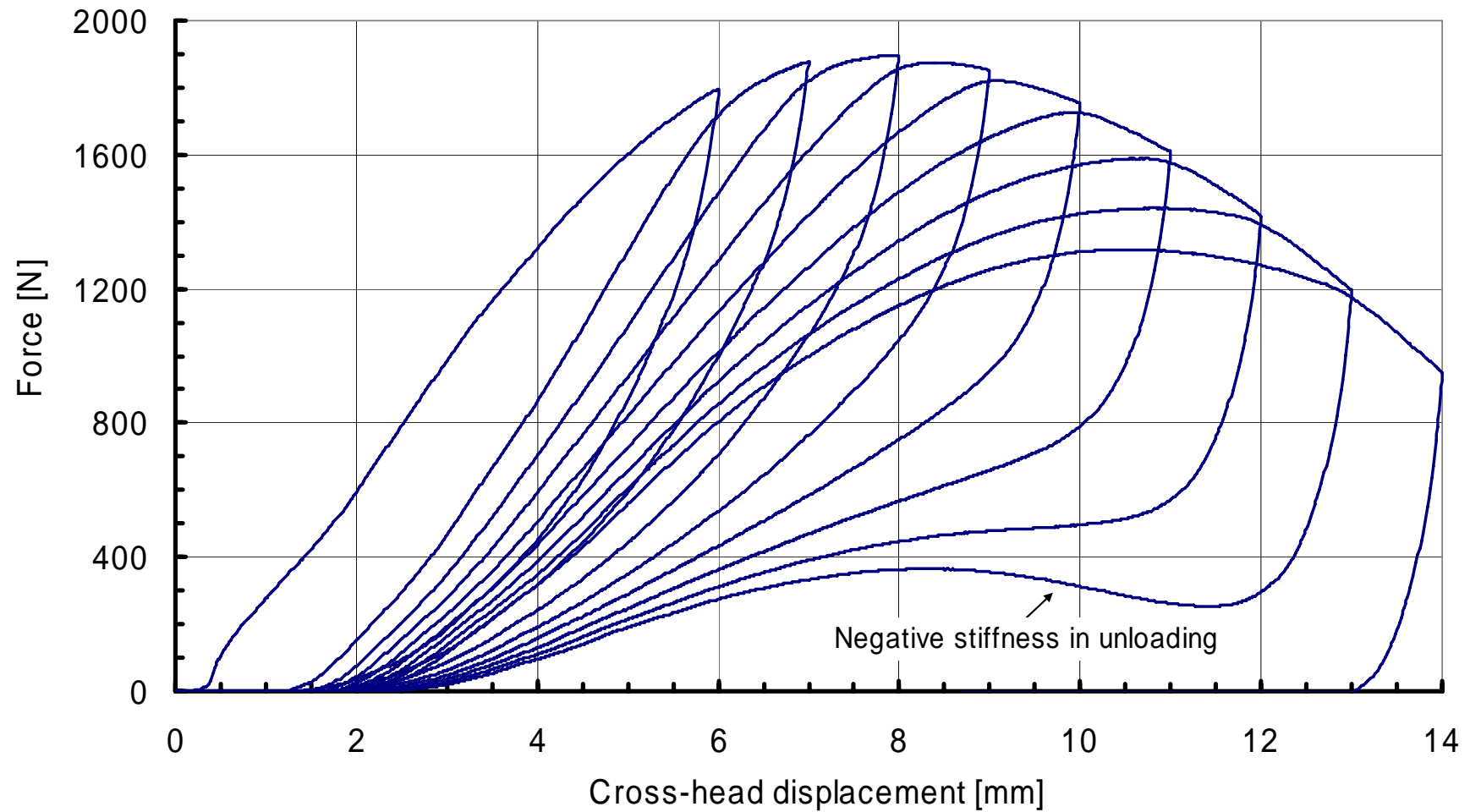
Truncated cubes



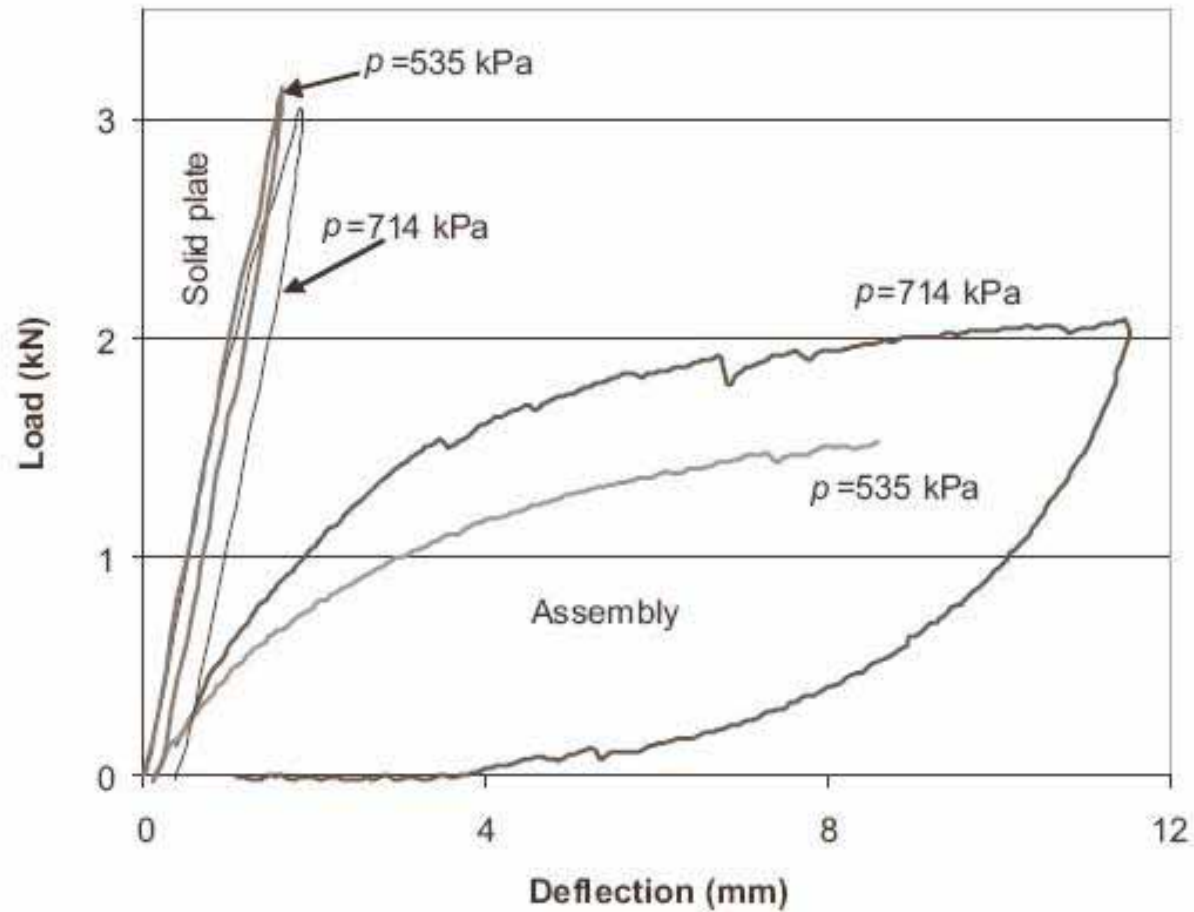
Deformation of assembly of cubes



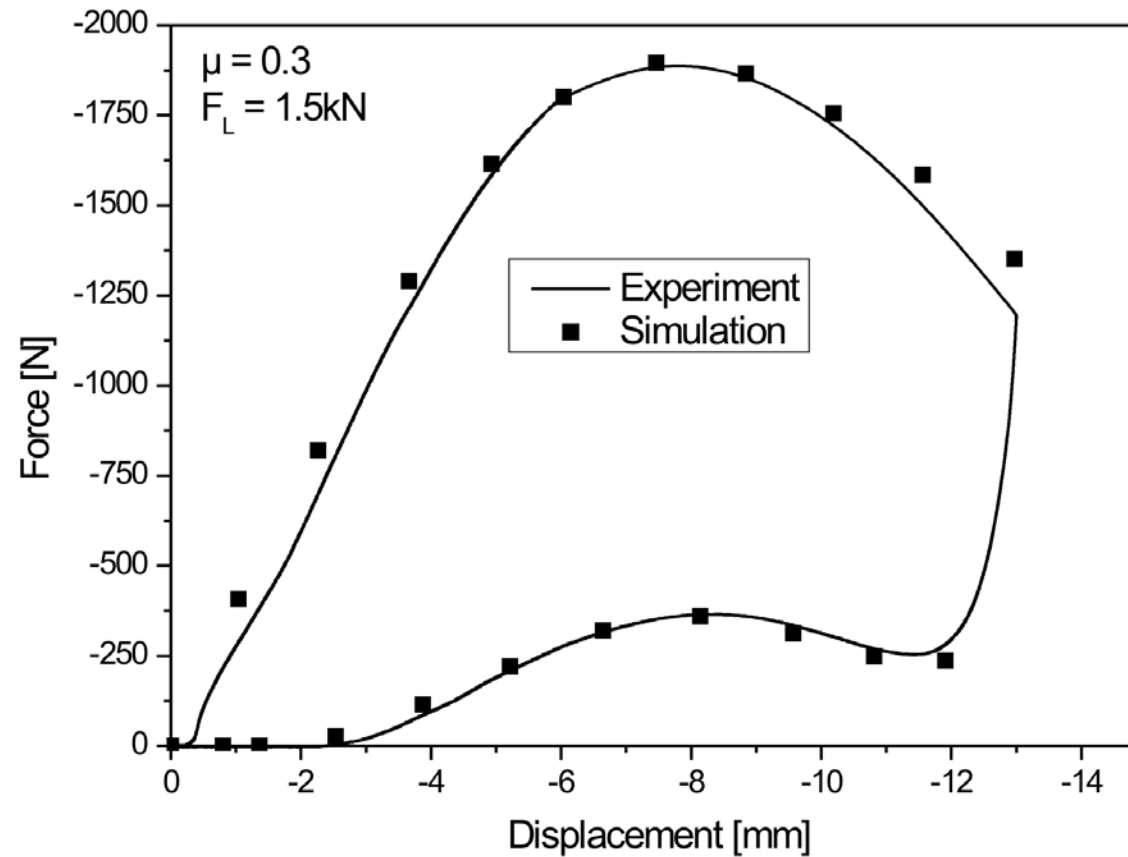
Negative stiffness in unloading of assembly of cubes



Tunable stiffness



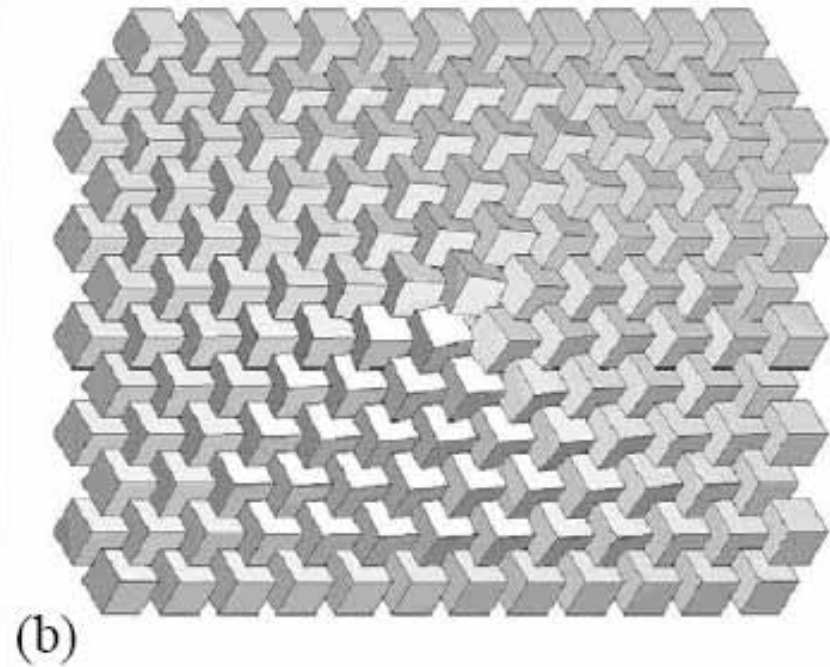
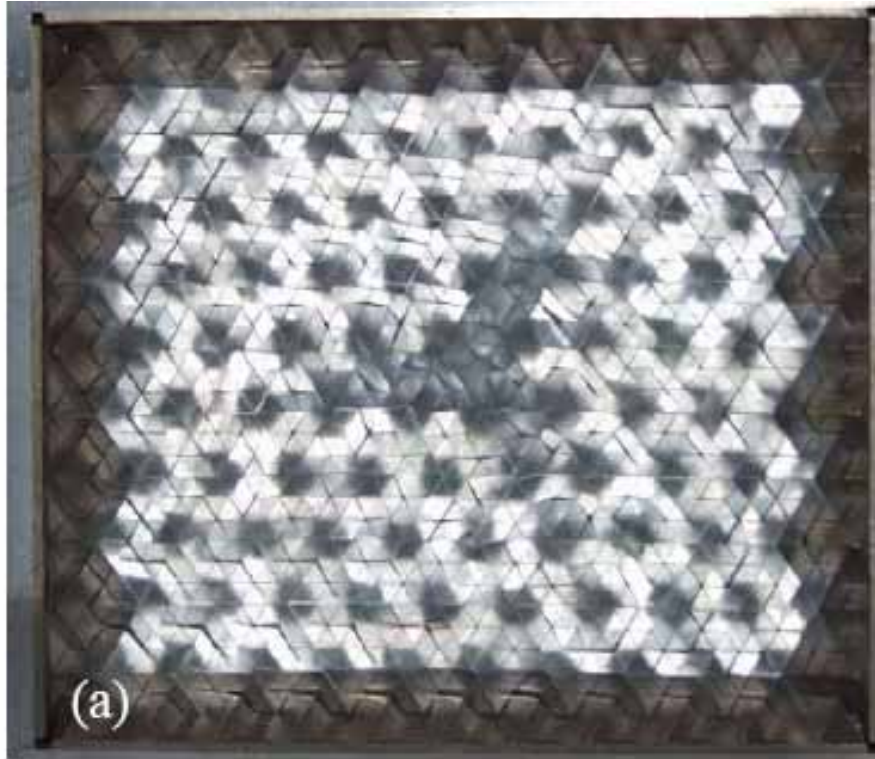
Experiment vs. simulation



High energy absorption/damping capacity

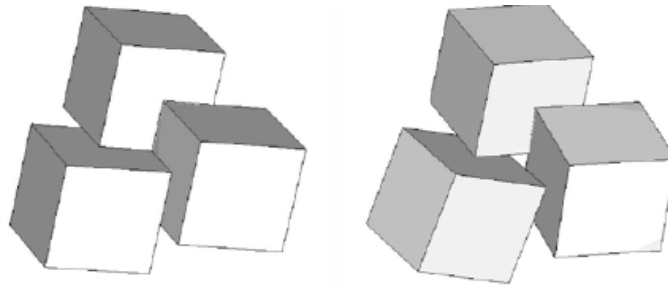
S. Schaare

Experiment vs. simulation

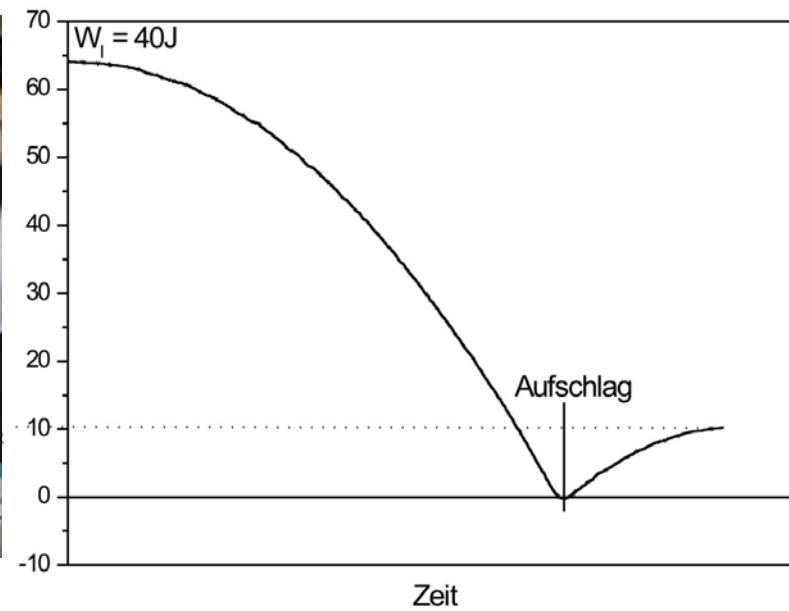


S. Arndt

Possible mechanism?



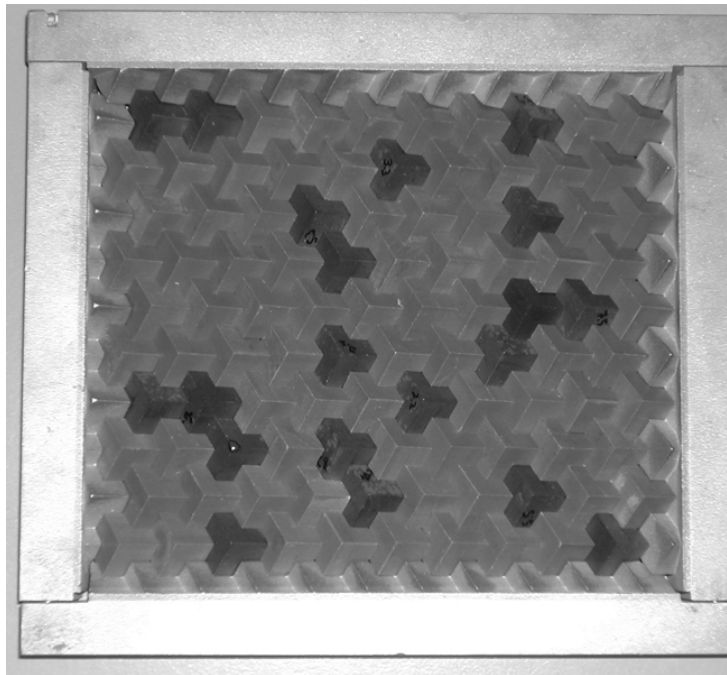
Energy absorption



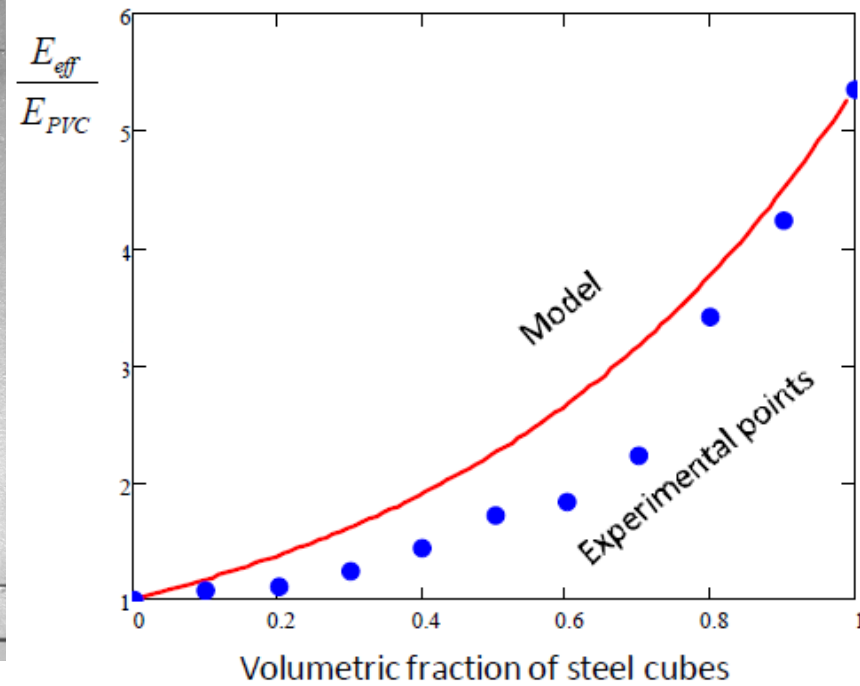
Multi-material mix: Example of PVC and steel cubes



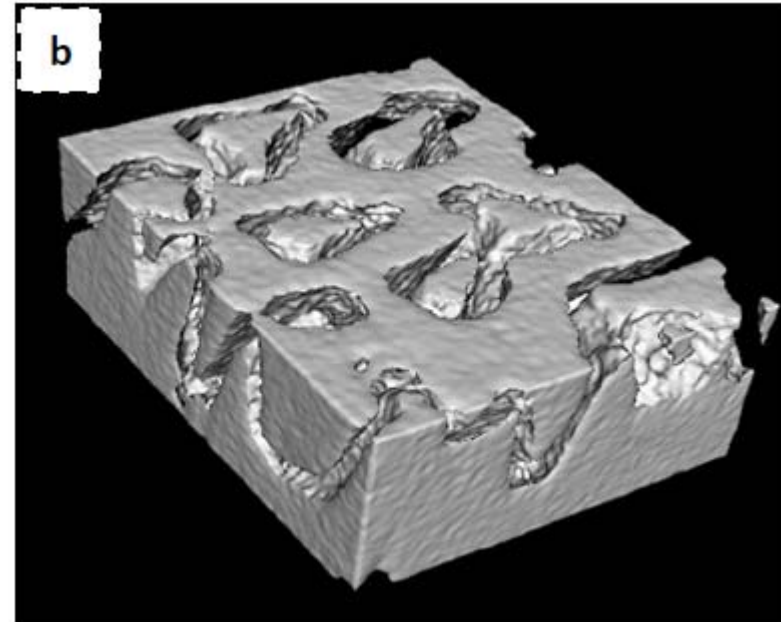
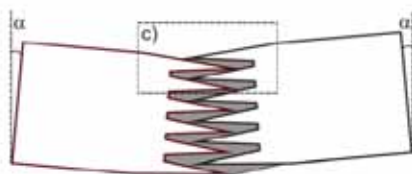
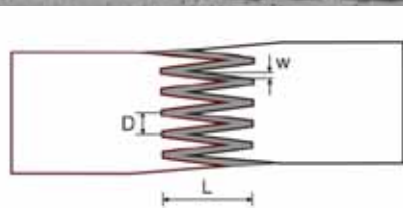
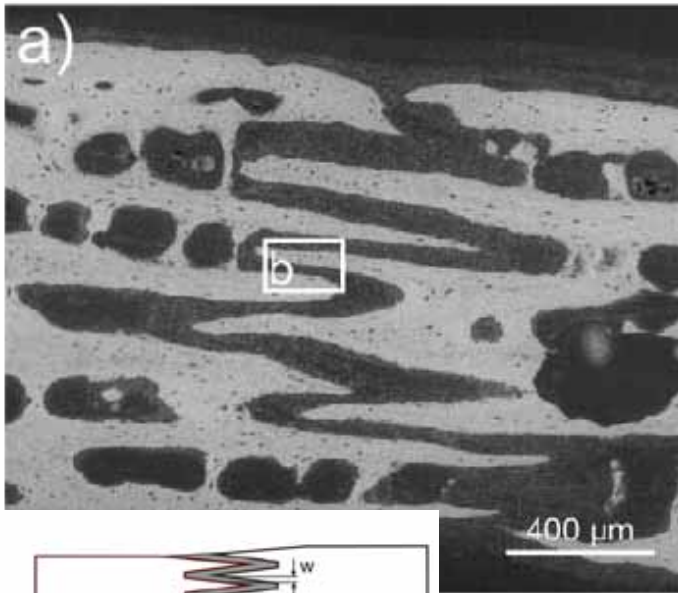
Random arrangement



20% steel blocks



Interlocking in turtle suture



S. Krauss, ... P. Fratzl, R. Shahar, Adv. Mater. 2009

Properties of assemblies of cube shaped blocks

- High resistance to fracture propagation
- Low bending rigidity
- Weight reduction
- Localisation of rotations
- Anomalous unloading response
- No tolerance to missing blocks
- Template required for assembling

Properties of assemblies of tetrahedral blocks

- High resistance to fracture propagation
- Tolerance to missing blocks
- Low bending rigidity
- Weight reduction
- Permeability of assemblies
- Assembling with template

Possible applications

- Architecture and Civil Engineering
- Automotive (crash protection)
- Armor
- Anti-terror barriers; road safety barriers
- Tooling (replacement of critical parts of a structure only)
- Self-adjusting assemblies of modules or containers
- Protective layers of various kinds
- Chemical Engineering
- Nanotechnology

Ref. A. Dyskin, Y. Estrin, et al., Acta Astronautica 57, 10-21 (2005)