Interlocking versus Friction and Adhesion

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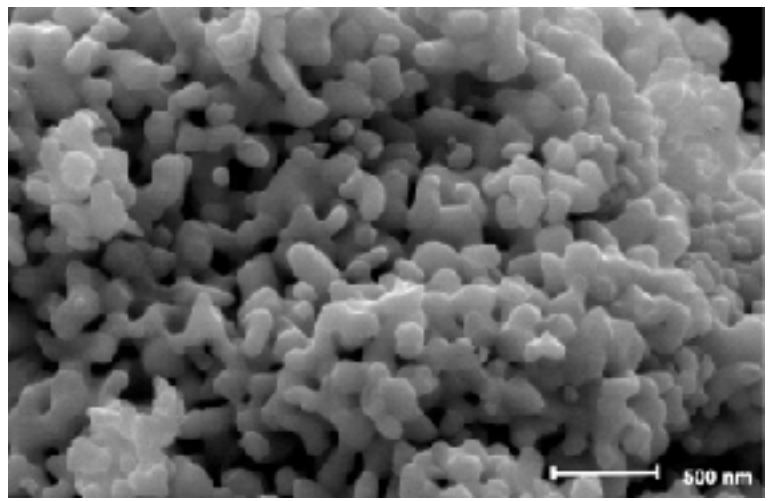
Introduction

The scale-up of particle interactions depends on particle shape.

nonconvex shape $\rightarrow$ interlocking $\rightarrow$ enhanced strength

Keller and Jaeger
Granular Matter 18, 2016.



SEM image of UO2 particles

Open questions

How to quantify interlocking?

What are typical microstructures?

Which interactions are affected (friction or adhesion)?

This work

Packings of hexapods of increasing aspect ratio

Trieu-Duy Tran (LMGC), Saeid Nezamabadi (LMGC), Jean-Philippe Bayle (CEA), Lhassan Amarsid (CEA)

Tran, Nezamabadi, Bayle, Amarsid, Radjai, Soft Matter 20, 2024

Tran, Nezamabadi, Bayle, Amarsid, Radjai, Advanced Powder Technology 36, 2025

Simulations

hexapod

$\alpha = 1$ $\alpha = 1.25$ $\alpha = 1.5$ $\alpha = 1.75$ $\alpha = 2$

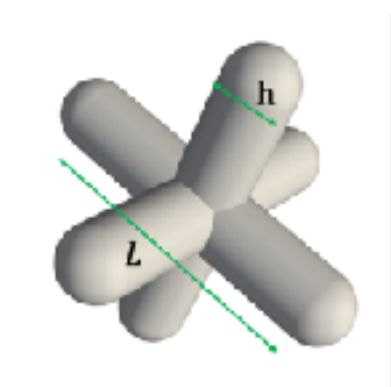
thick

$\alpha = 2.5$ $\alpha = 3$ $\alpha = 5$ $\alpha = 7$ $\alpha = 9$

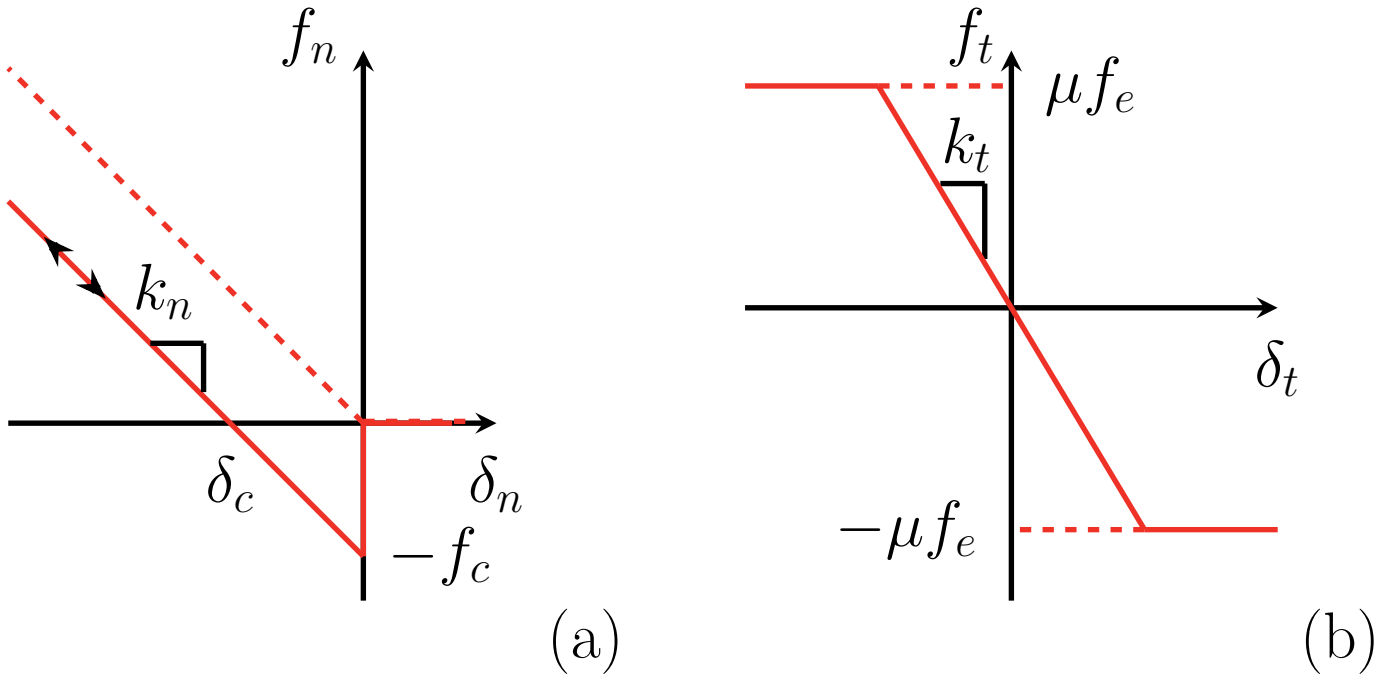
thin

$$\alpha = \frac{L + h}{h}$$

$$\eta = \frac{L}{L + h} = 1 - \frac{1}{\alpha}$$



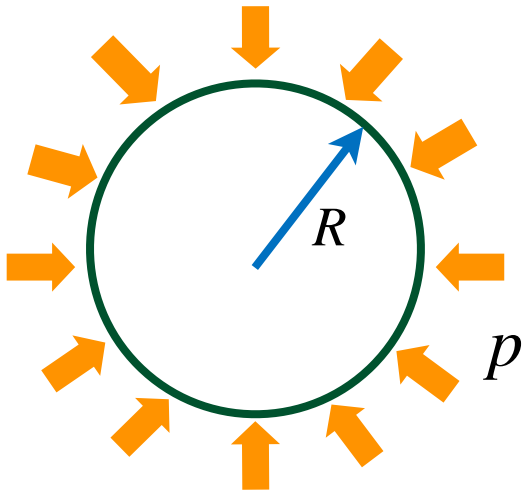
force laws



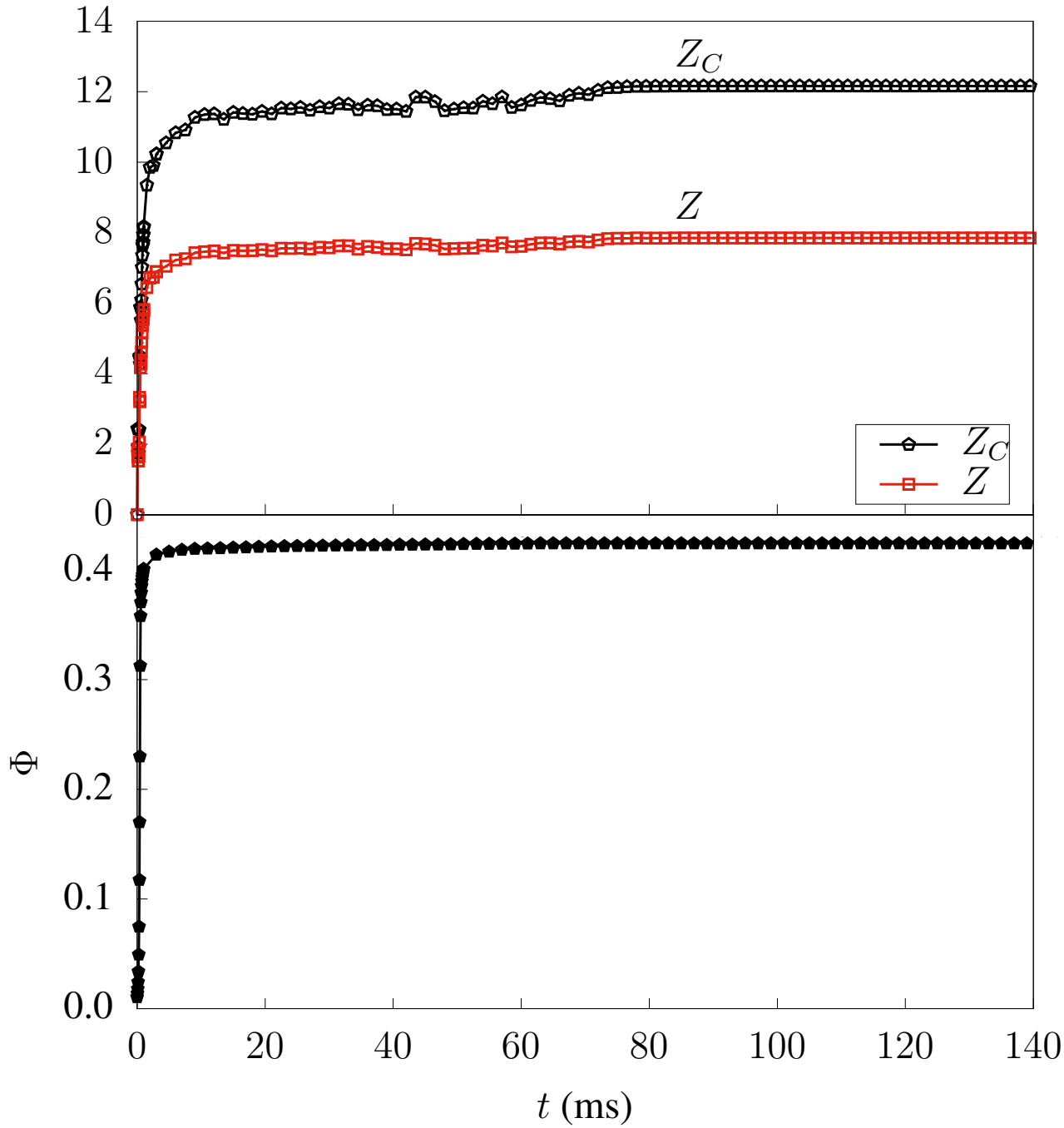
f_c adhesion force, irreversible

μ friction coefficient

isotropic compaction



$$\alpha = 4$$



constraint number

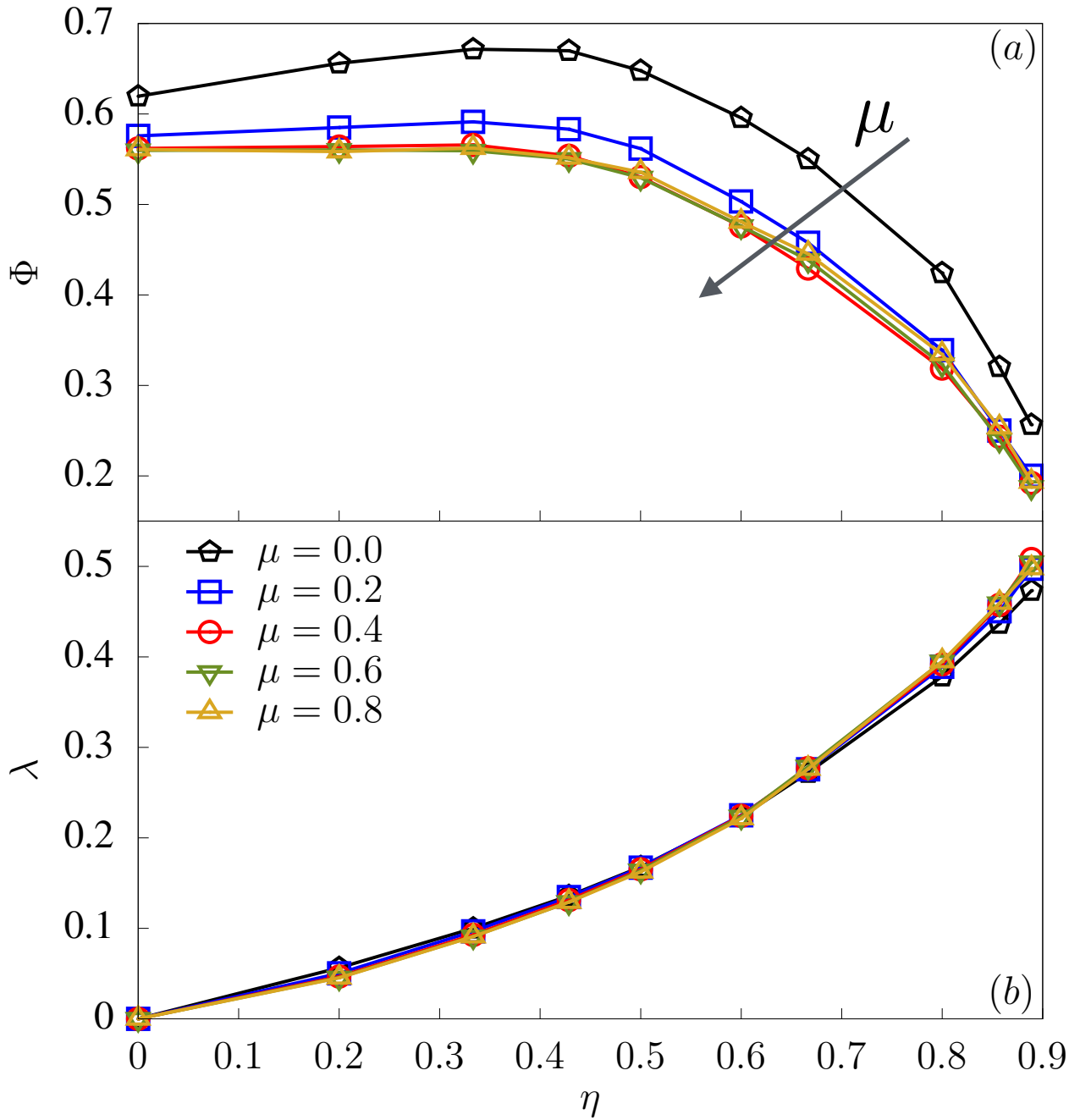
coordination number

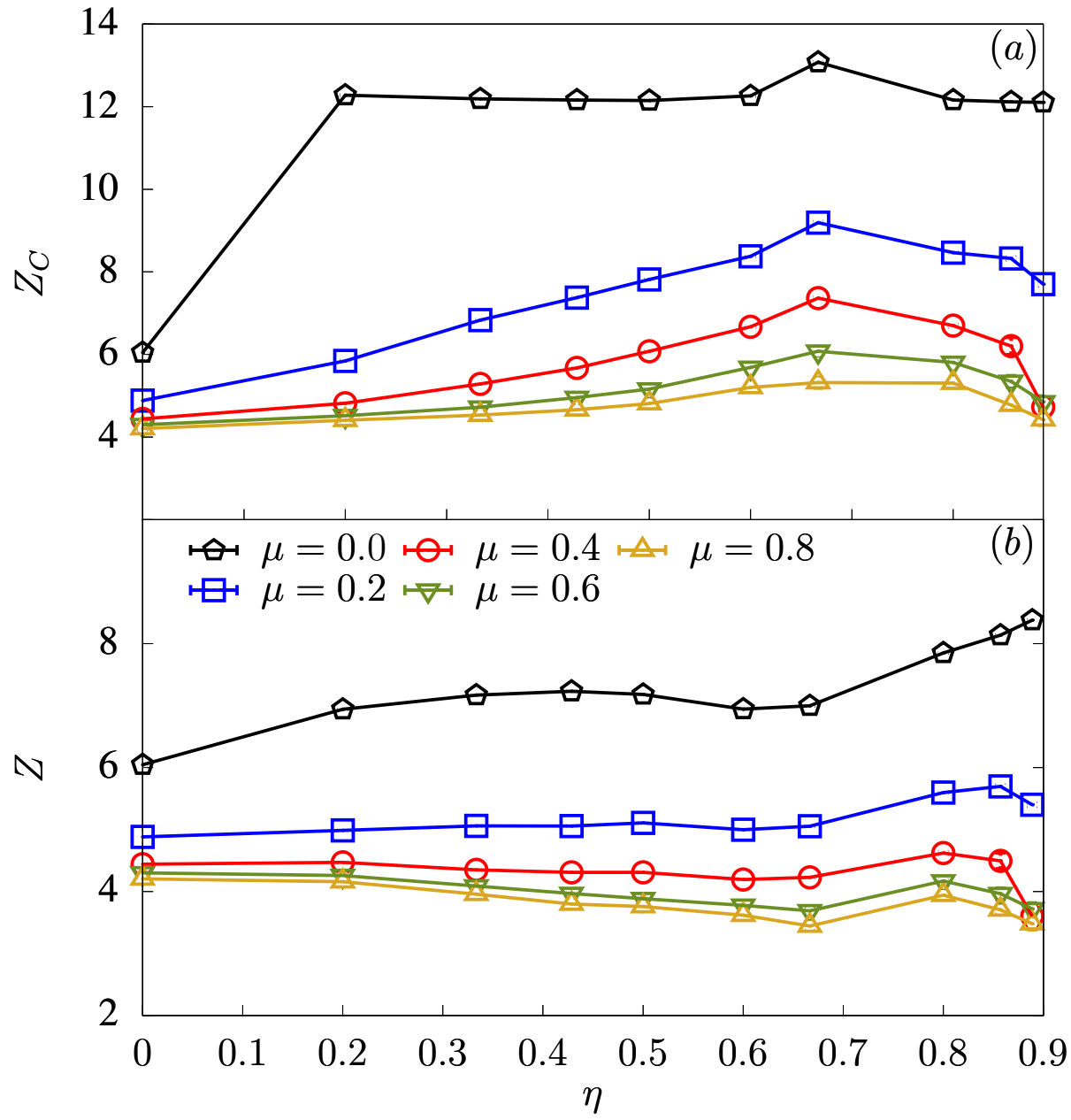
solid fraction

Microstructure

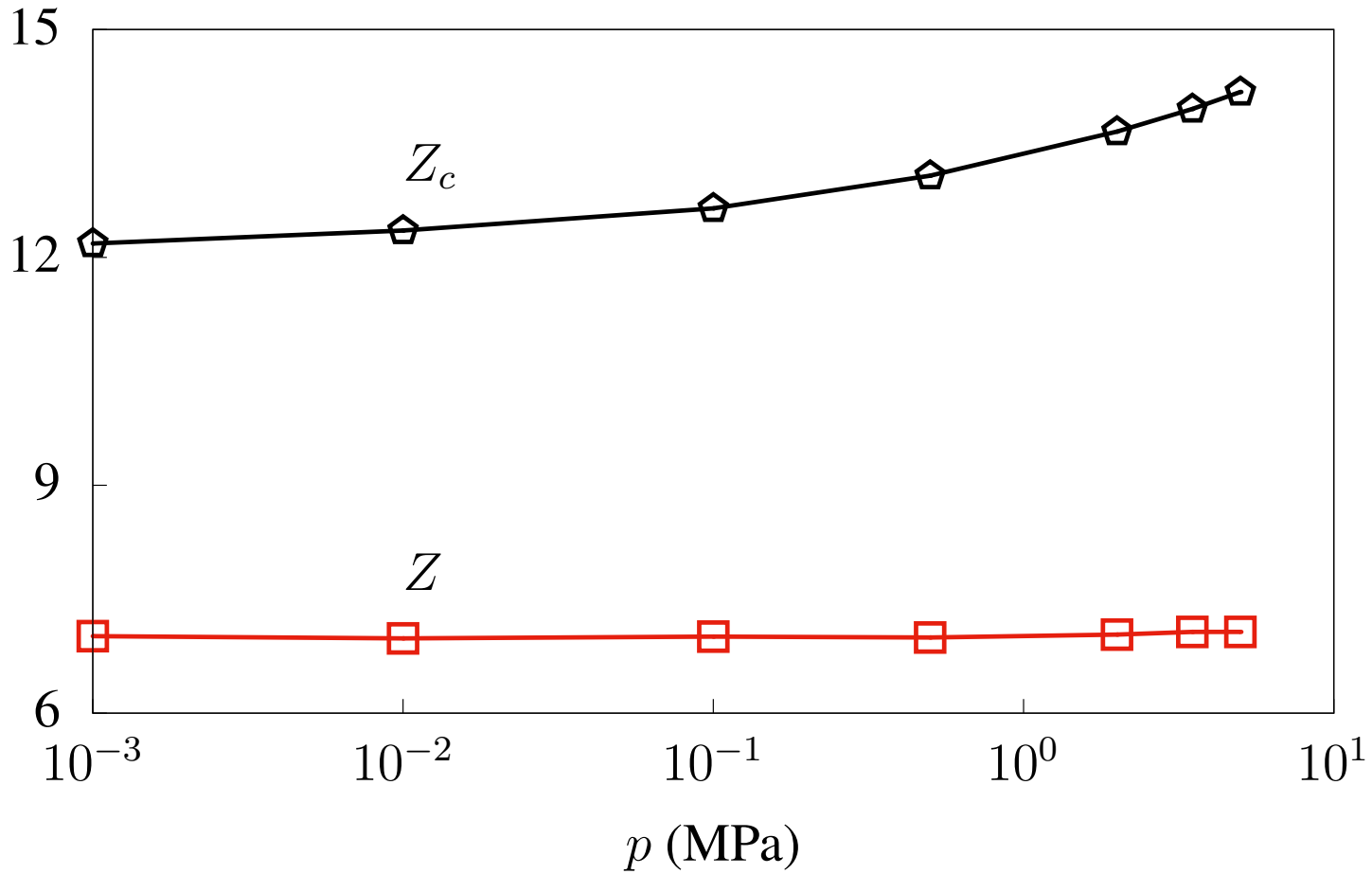
$$\lambda = 1 - \frac{\langle \ell \rangle}{d}$$

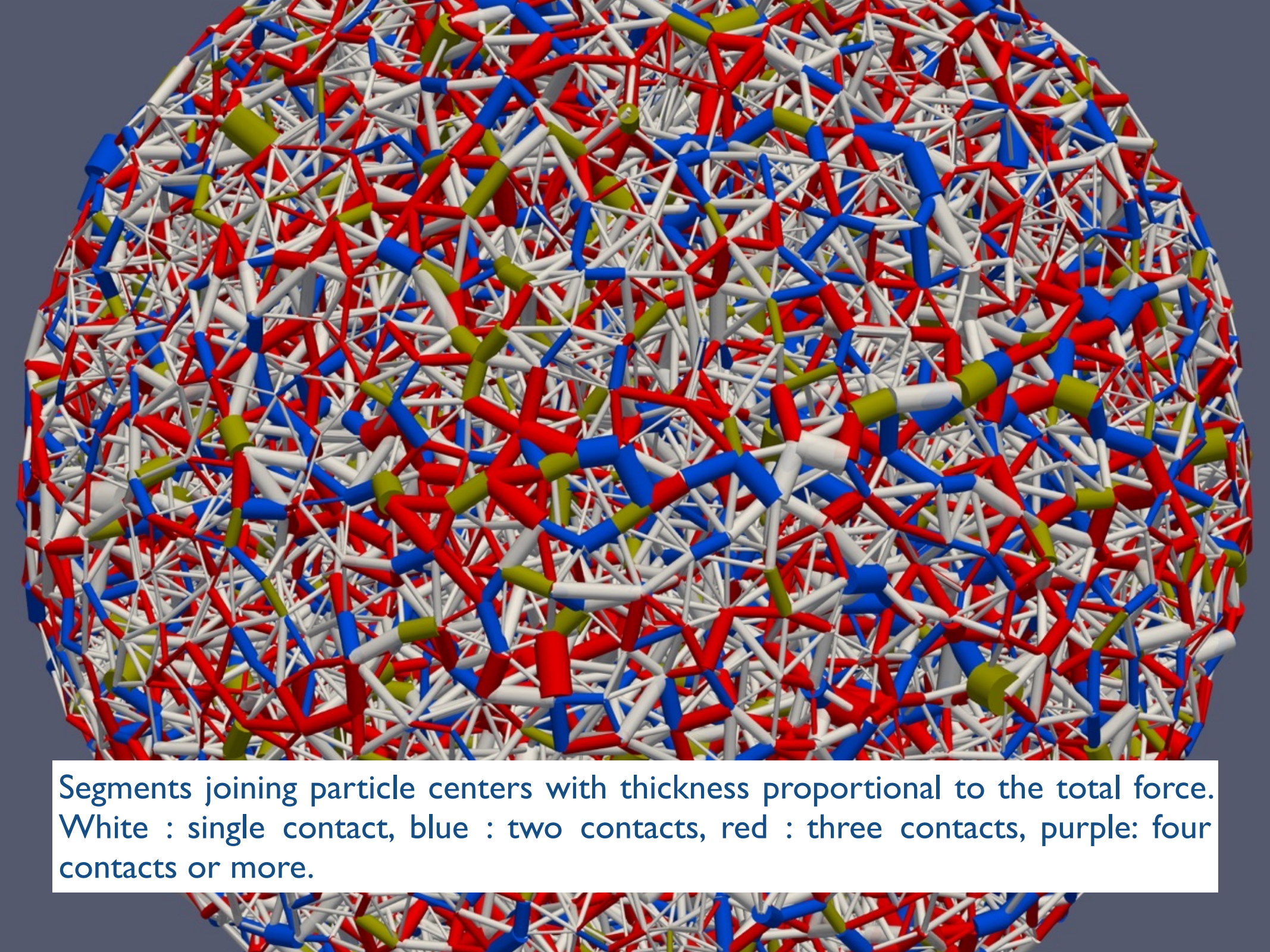
$$d = L + h$$



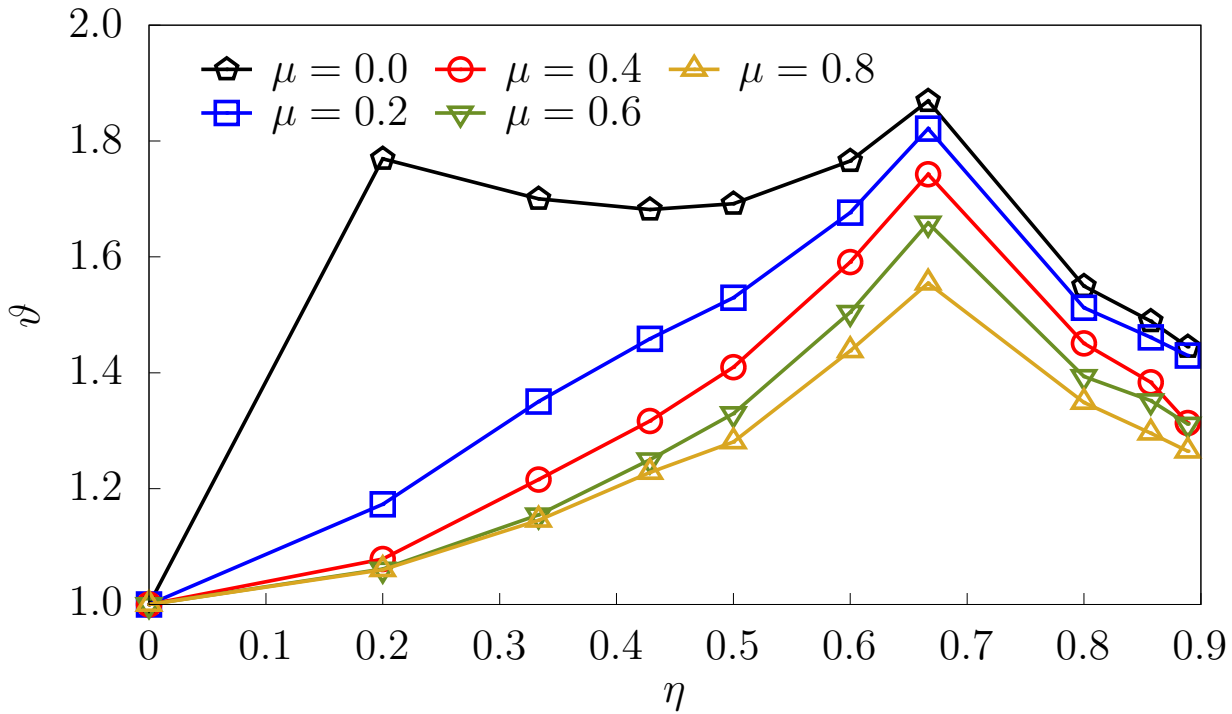

(a)
(b)
Z_C
Z
η
$\mu = 0.0$
$\mu = 0.2$
$\mu = 0.4$
$\mu = 0.6$
$\mu = 0.8$
14
12
10
8
6
4
8
6
4
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

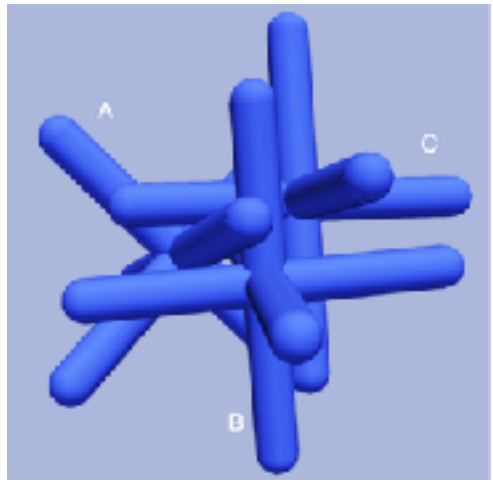
effect of confining pressure





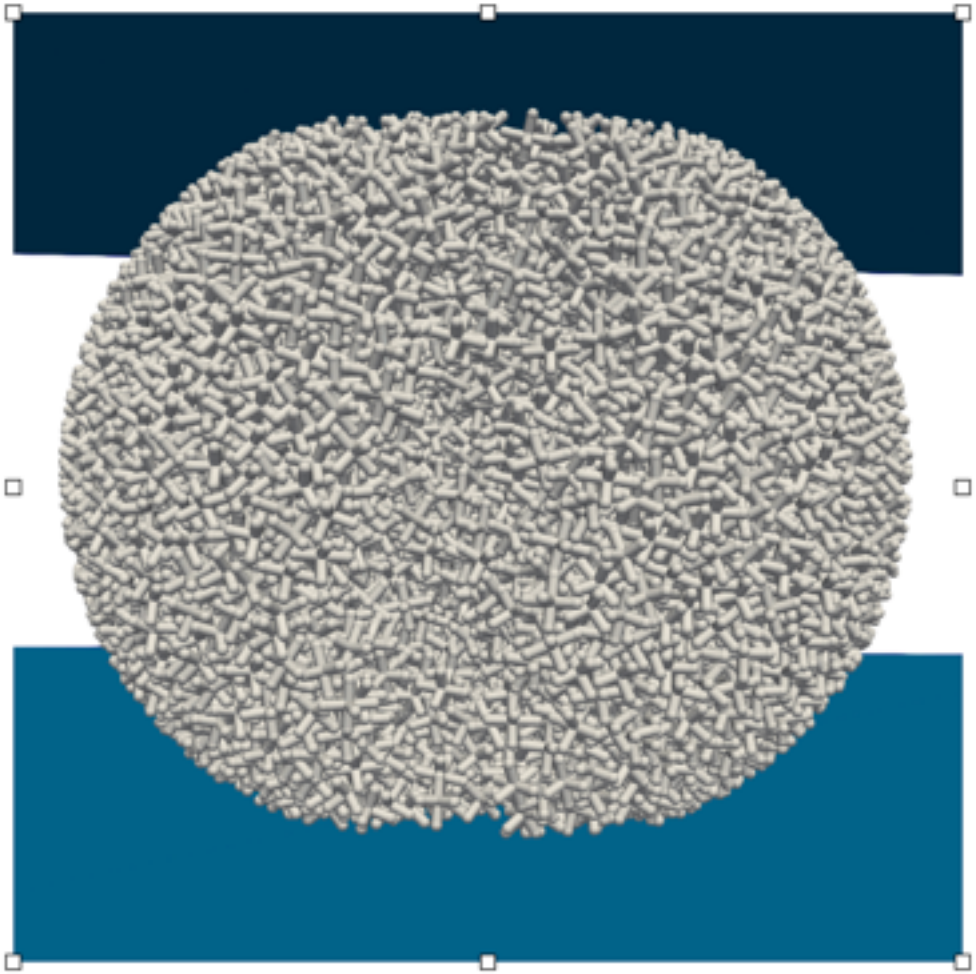
Segments joining particle centers with thickness proportional to the total force. White : single contact, blue : two contacts, red : three contacts, purple: four contacts or more.



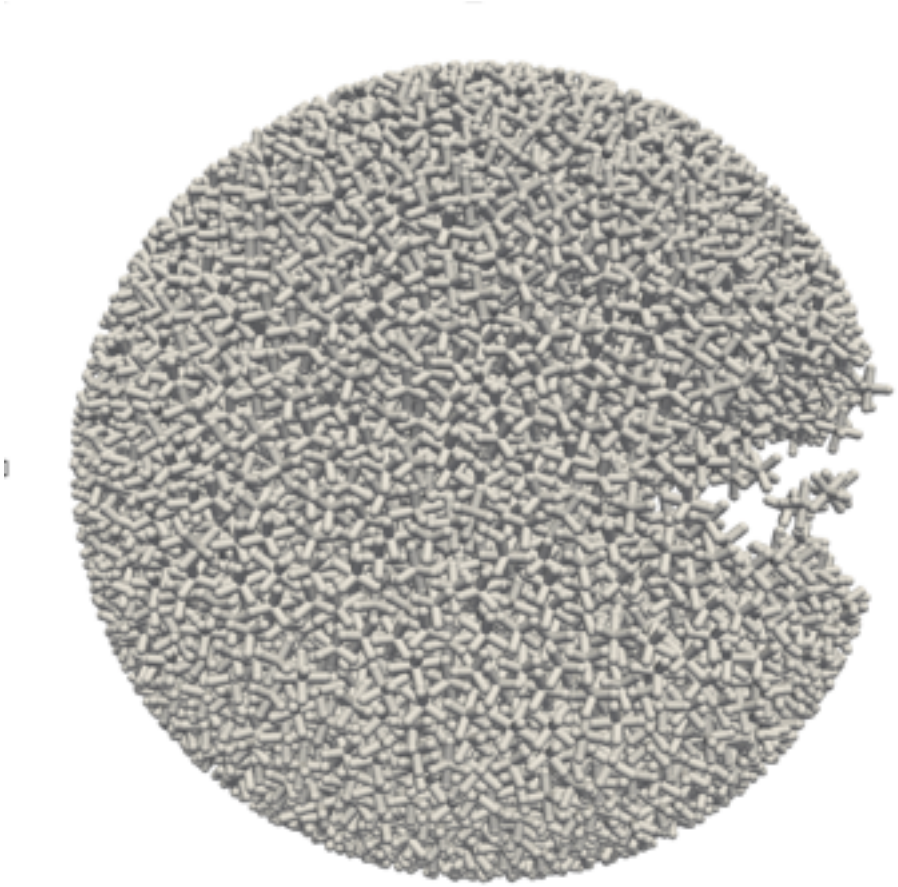


valence number

Compressive strength

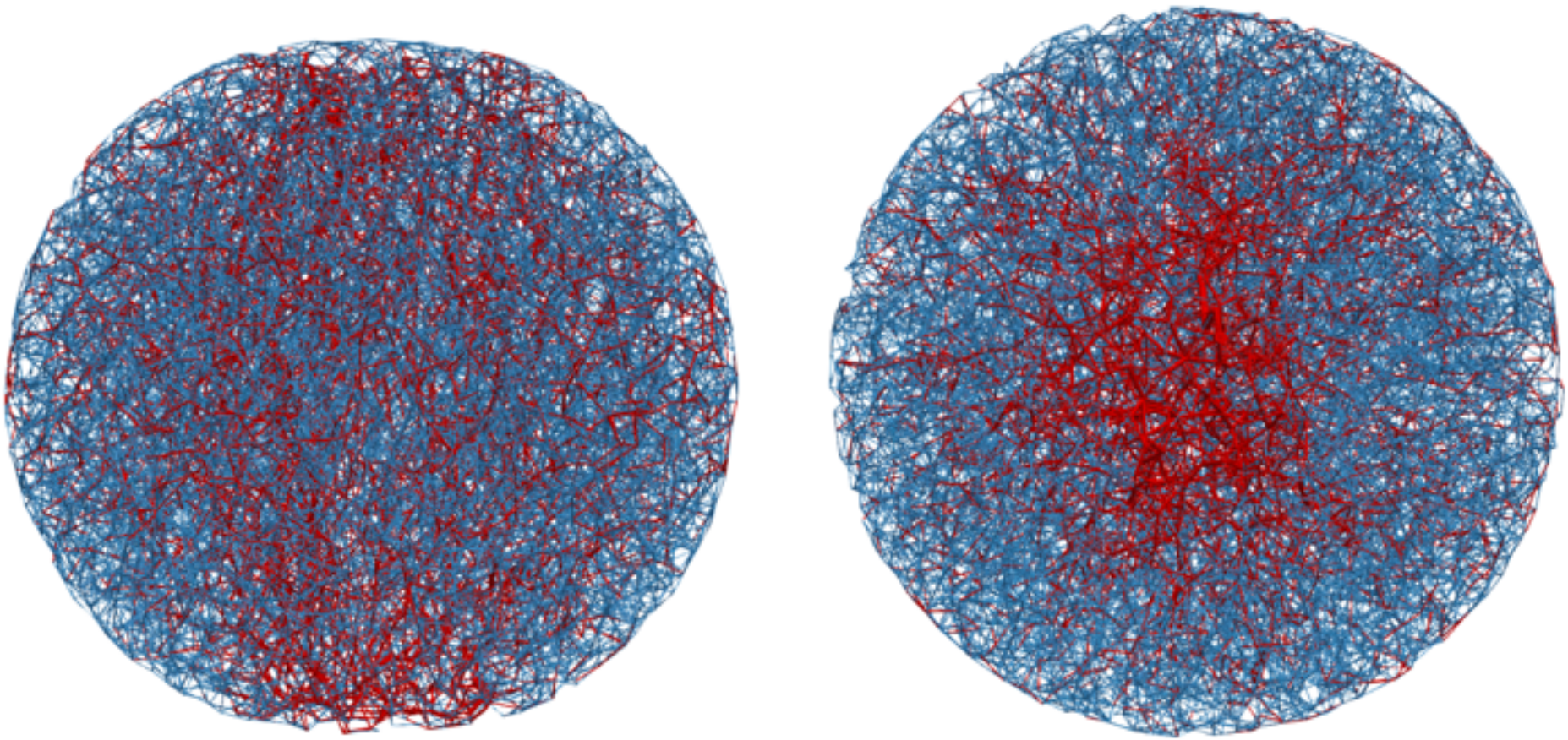


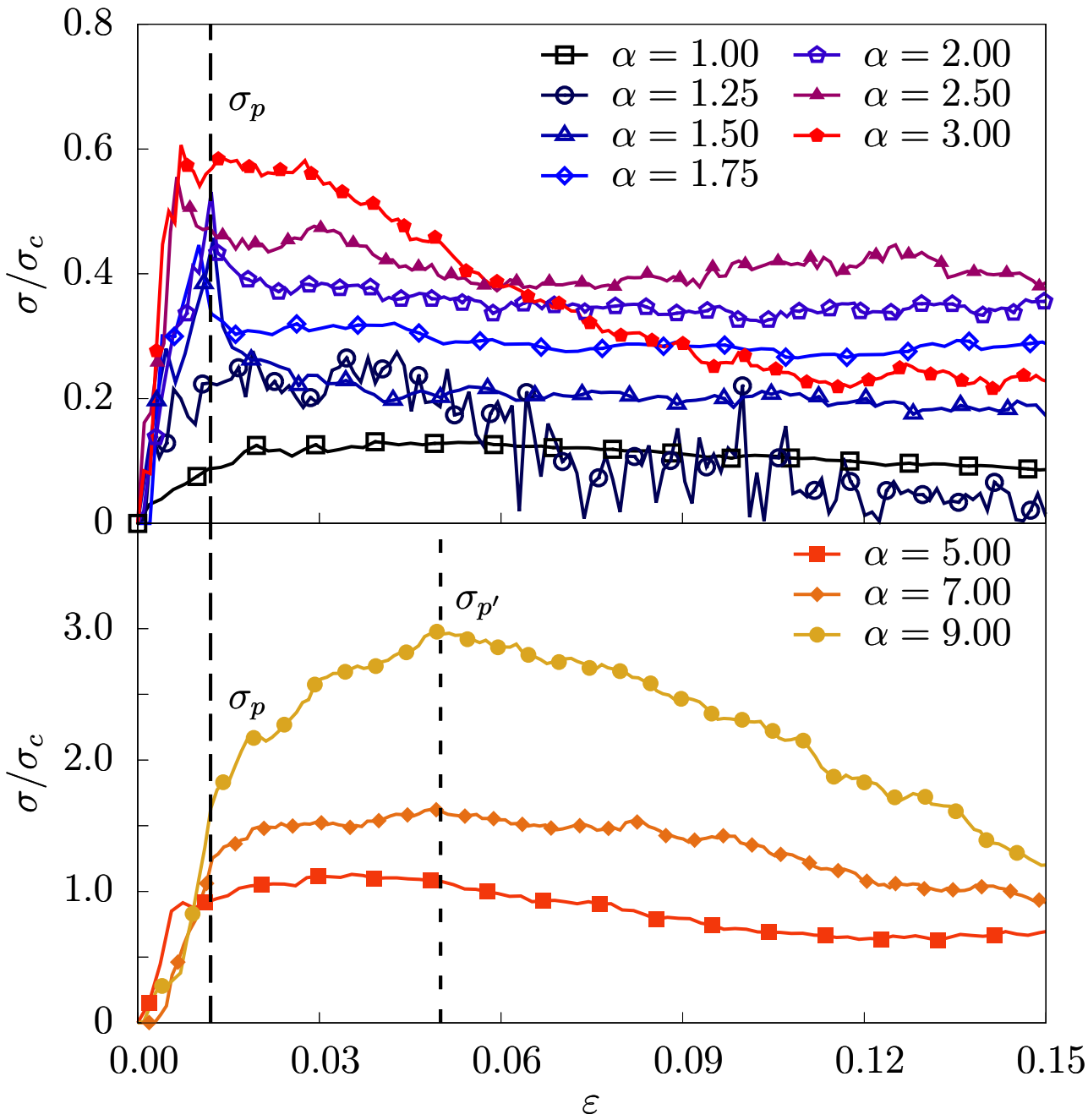
side view



top view

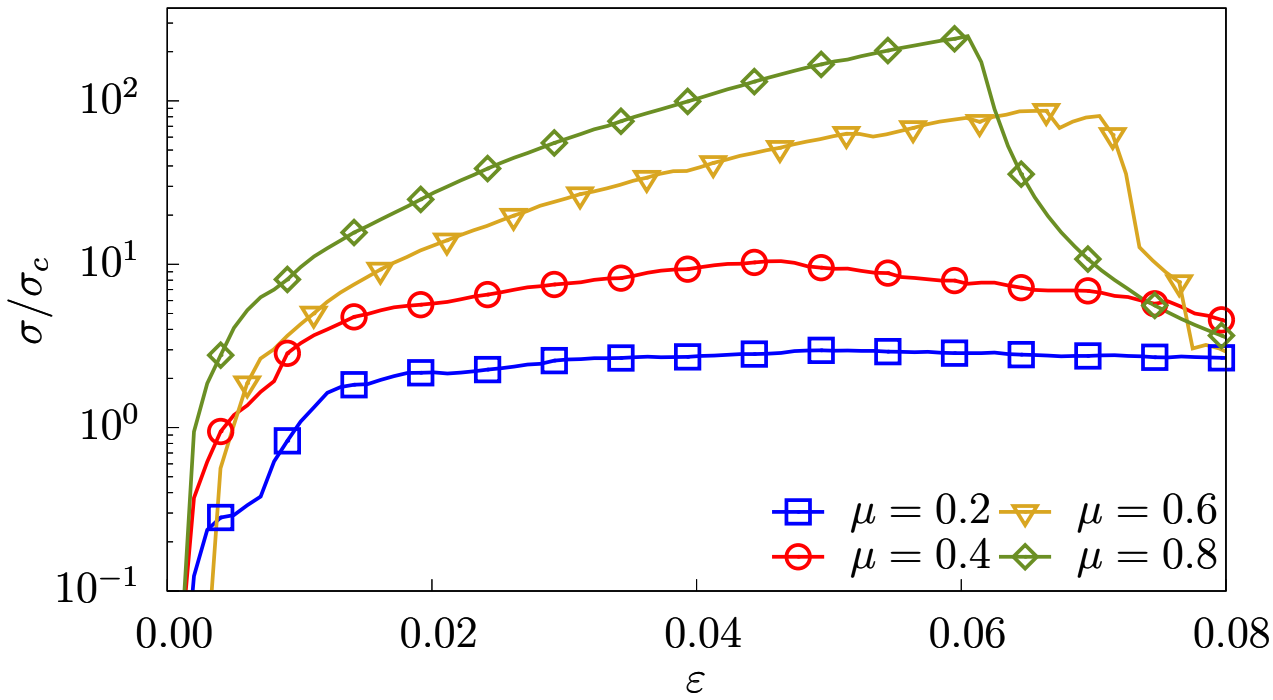
Force chains

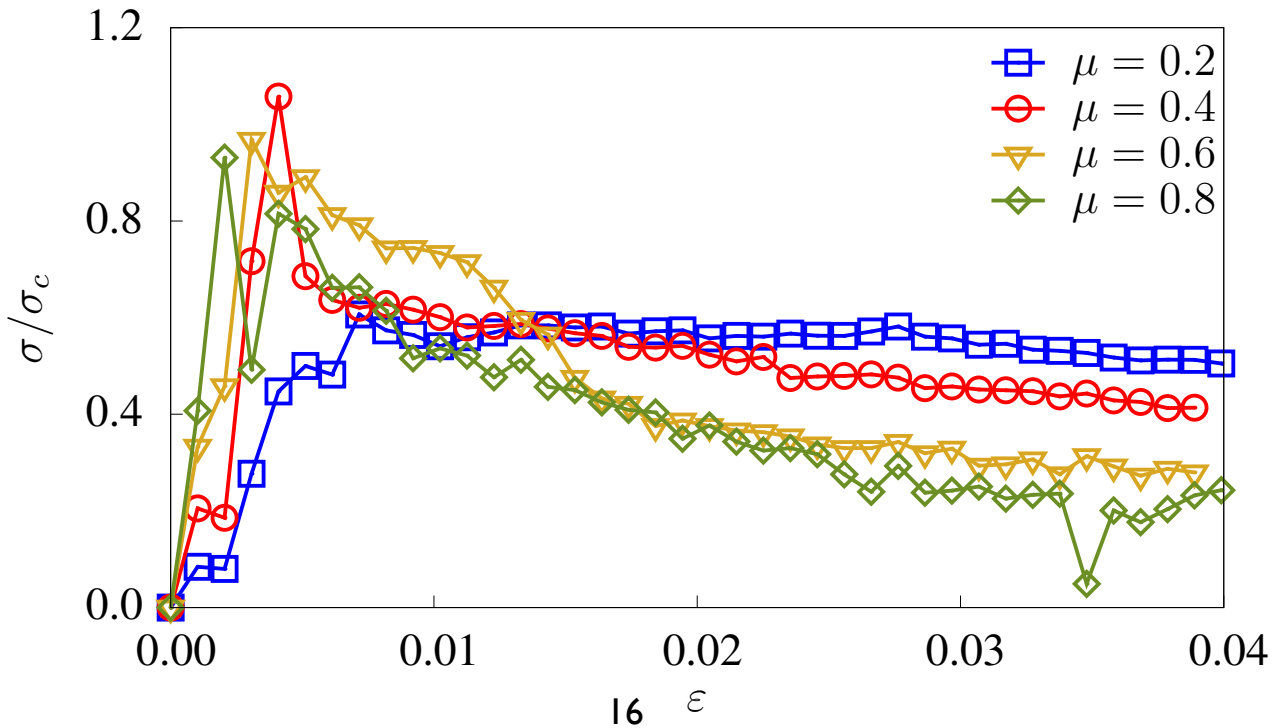


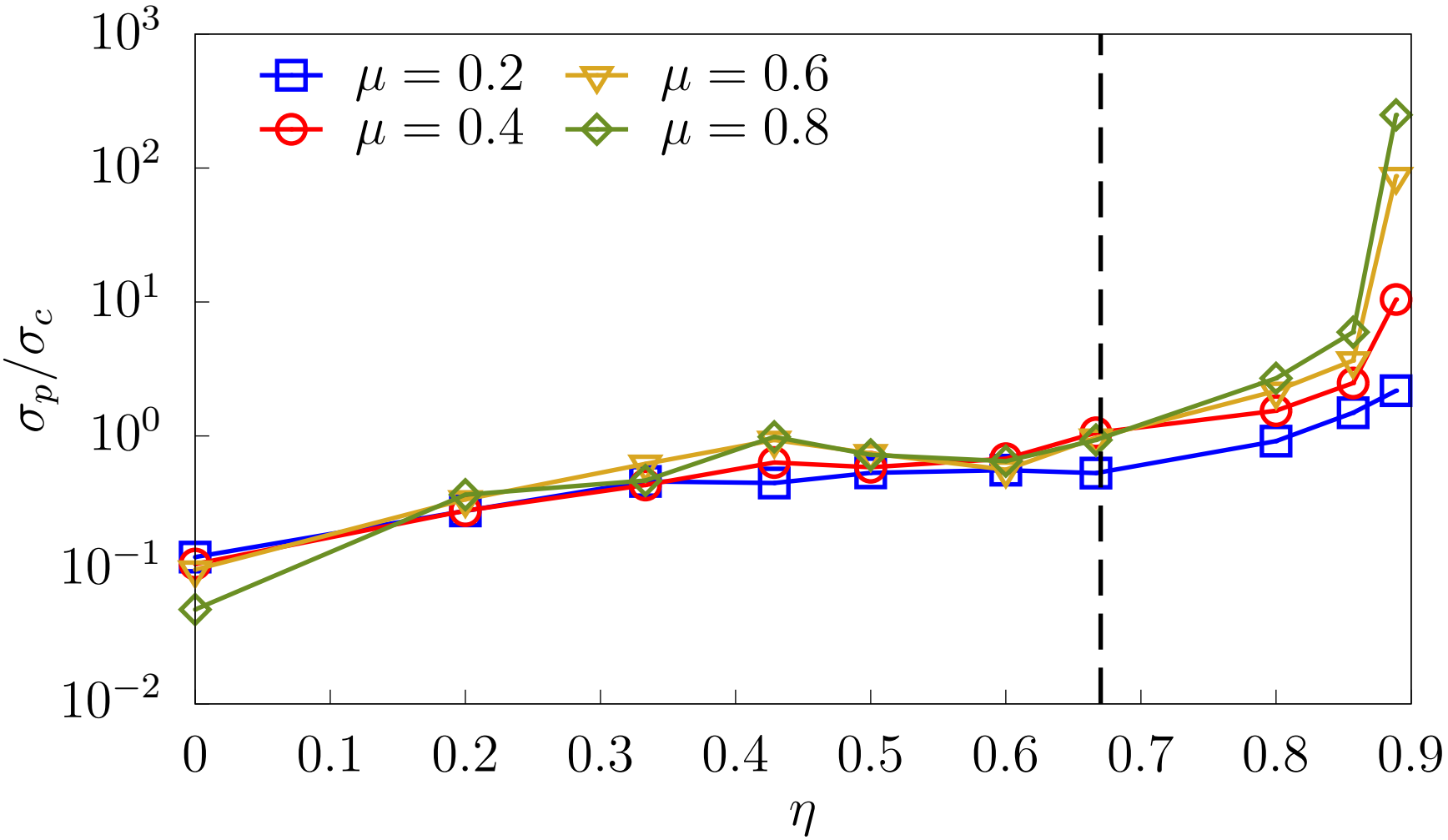


$$\sigma = \frac{4F}{\pi D_h^2}$$

$$\sigma_c = \frac{f_c}{d^2}$$


10^2
10^1
10^0
10^{-1}
σ/σ_c
0.00
0.02
0.04
0.06
0.08
ε
$\mu = 0.2$
$\mu = 0.4$
$\mu = 0.6$
$\mu = 0.8$


1.2
0.8
0.4
0.0
σ/σ_c
0.00
0.01
0.02
0.03
0.04
ε
$\mu = 0.2$
$\mu = 0.4$
$\mu = 0.6$
$\mu = 0.8$


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
σ_p/σ_c
$\mu = 0.2$
$\mu = 0.4$
$\mu = 0.6$
$\mu = 0.8$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
η

Adhesion or friction?

incipient failure: $\frac{\sigma_1}{\sigma_t} = \frac{2\sin\varphi}{1-\sin\varphi}$ ← bulk friction angle

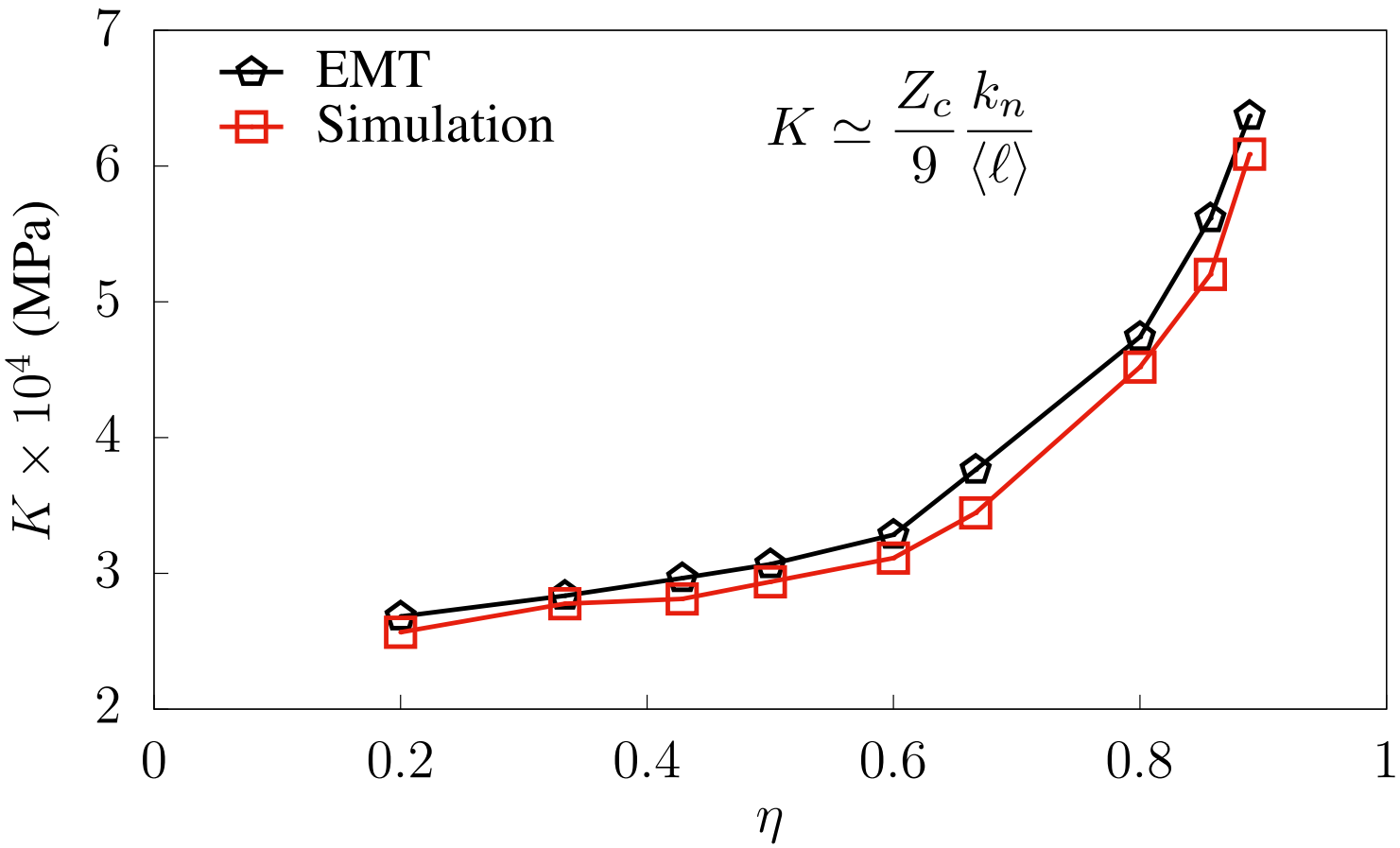
crack surface around the central axis: $\sigma_1 = \kappa\sigma_p \qquad \kappa \simeq 10$ ← geometric factor

tensile strength: $\sigma_t = \frac{n_c}{3}\langle\ell\rangle f_c$ with $n_c = \frac{3Z_c\Phi}{\pi\langle\ell\rangle^3}$

→ $\frac{\sigma_p}{\sigma_c} = \frac{1}{\kappa}\frac{Z_c\Phi}{\pi}\left(\frac{d}{\langle\ell\rangle}\right)^2\frac{2\sin\varphi}{1-\sin\varphi}$ upper bound

→ Given the parameters involved in this relation, a ratio as high as 200 can occur only if the bulk friction angle is close to 90 degrees. This occurs for high shape aspect ratio and high friction coefficient between particles.

bulk modulus



Conclusion

Two regimes were evidenced: 1) linear increase of strength at low nonconvexity, and 2) sharp increase at high nonconvexity, enhanced by friction coefficient between particles.

The linear increase of strengthin the first regime is governed by the increase of tensile strength as a result of the increase of contact density.

The fast diverging increase of strength in the second regime reflects the increase of bulk friction coefficient.

recent simulation with homogeneous boundary conditions confirm the absence of geometrical cohesion in assemblies of hexapods.