DEM ANALYSIS OF INTACT ROCK STRENGTH UNDER CONFINED EXTENSION

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QUESTIONS WE ASK…

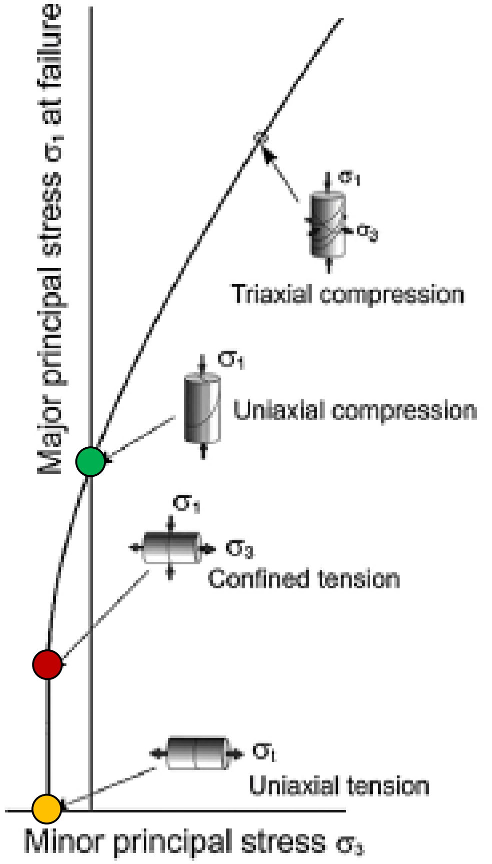
- Can DEM with bonded spherical particles only yield realistic UCS/UTS?

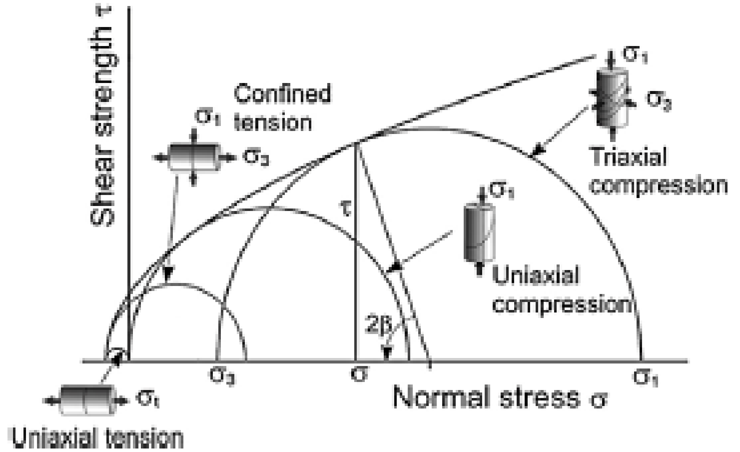
- How do rock behaviors transition between uniaxial tension and uniaxial compression?

Failure envelope shape		Failure plane orientation
Smooth e.g. Hoek-Brown	*implies* →	Smooth transition
Tension cutoff	→	Sharp transition

- If tension cutoff is legitimate, where should it end?

Hoek and Martin (2014)

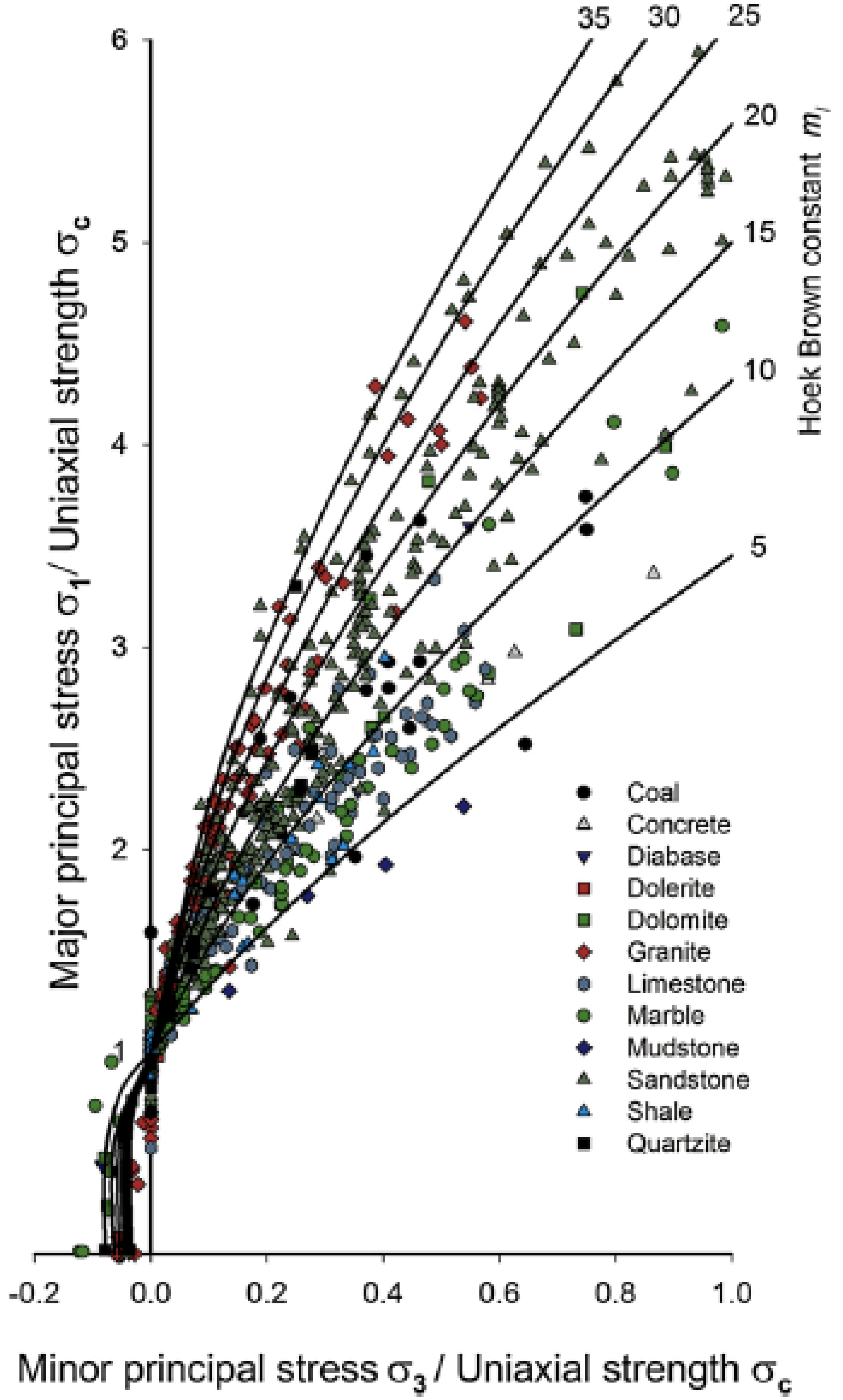




STRENGTH RATIOS OF REAL ROCKS

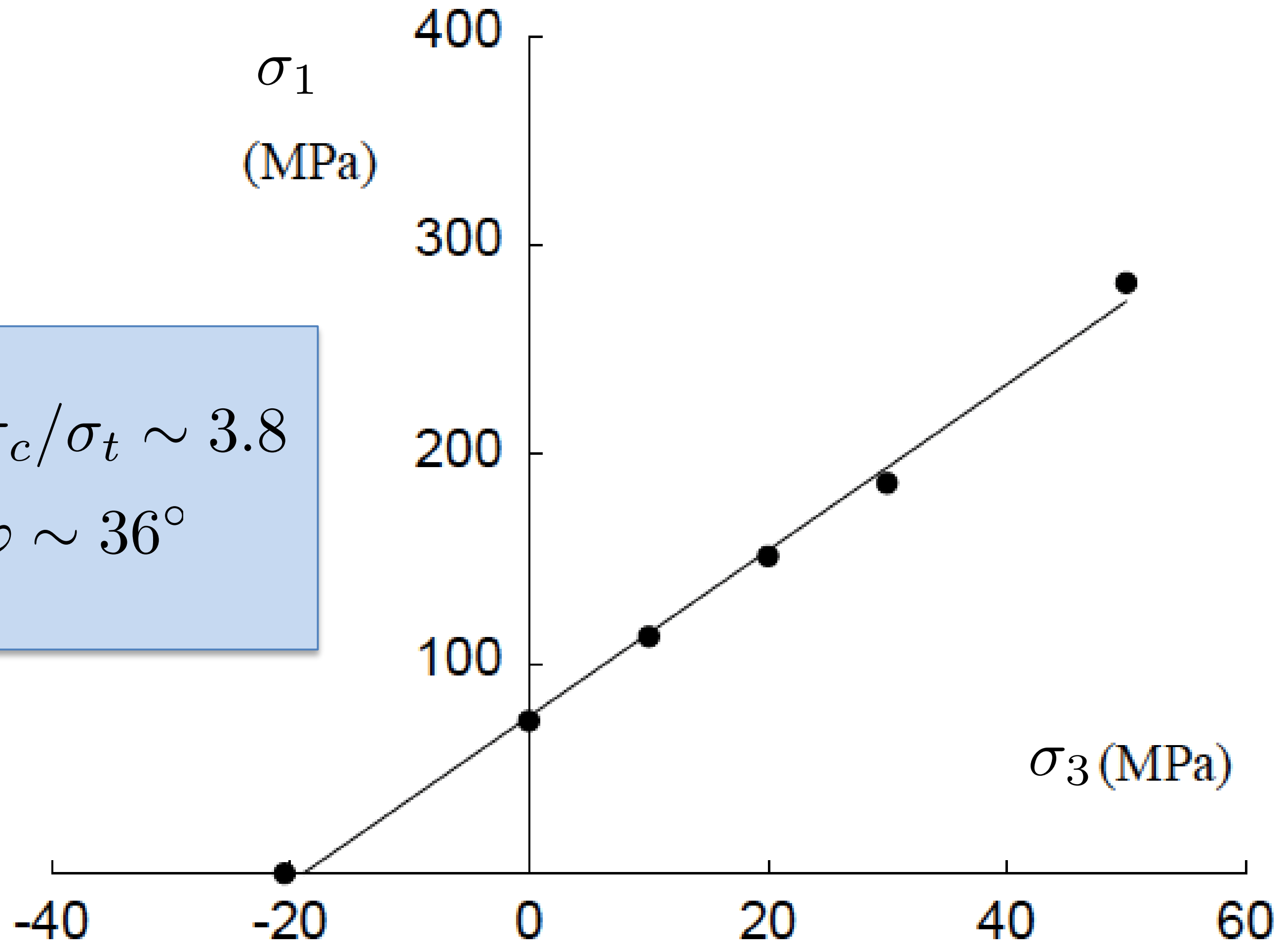
Analysis of data containing reliable tensile values. Hoek and Martin (2014)

Fairhurst ($\sigma_t \leq 2$ MPa)			Hoek–Brown (shear data)			Data set and reference
σ_c (MPa)	σ_t (MPa)	$\sigma_c/\|\sigma_t\|$	σ_c (MPa)	σ_t (MPa)	m_i	
128.5	–7.74	16.6	129	–15.6	8.25	Carrara marble (Ramsey and Chester, 2004)
516.5	–33.72	13.9	557	–65.9	8.45	Blair dolomite (Brace, 1964)
95.5	–6.41	14.9	102	–10.6	9.65	Berea sandstone (Bobich, 2005)
125.5	–8.72	14.4	131	–12.4	10.60	Webtuck dolomite (Brace, 1964)
614.0	–25.5	24.1	592	–28.7	20.65	Granite aplite (Hoek, 1965)
220	–7.06	31.1	227	–6.01	32.4	Lac du Bonnet granite (Lau and Gorski, 1992)

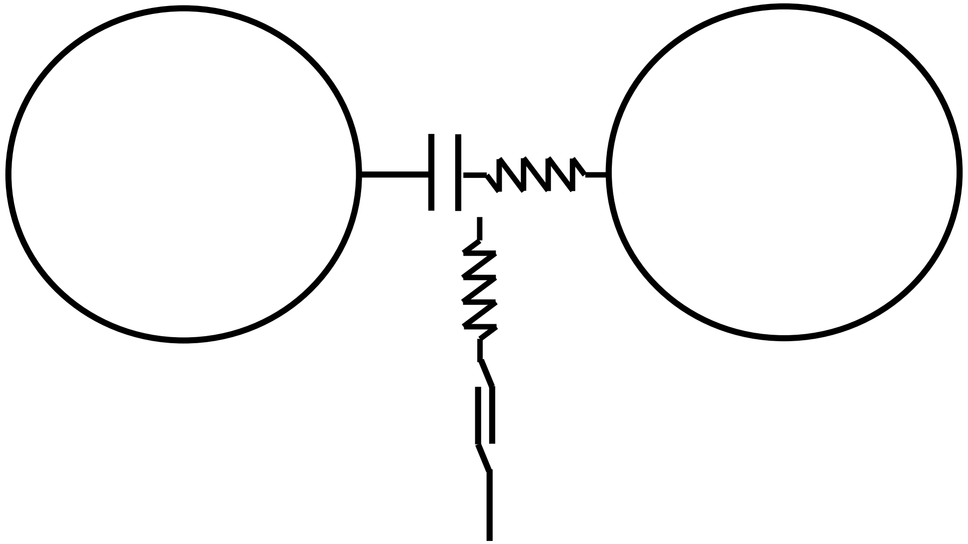


FAILURE ENVELOPE - LINEAR CONTACT BOND MODEL

$$\sigma_c/\sigma_t \sim 3.8$$
$$\varphi \sim 36^\circ$$



Huang (1999)



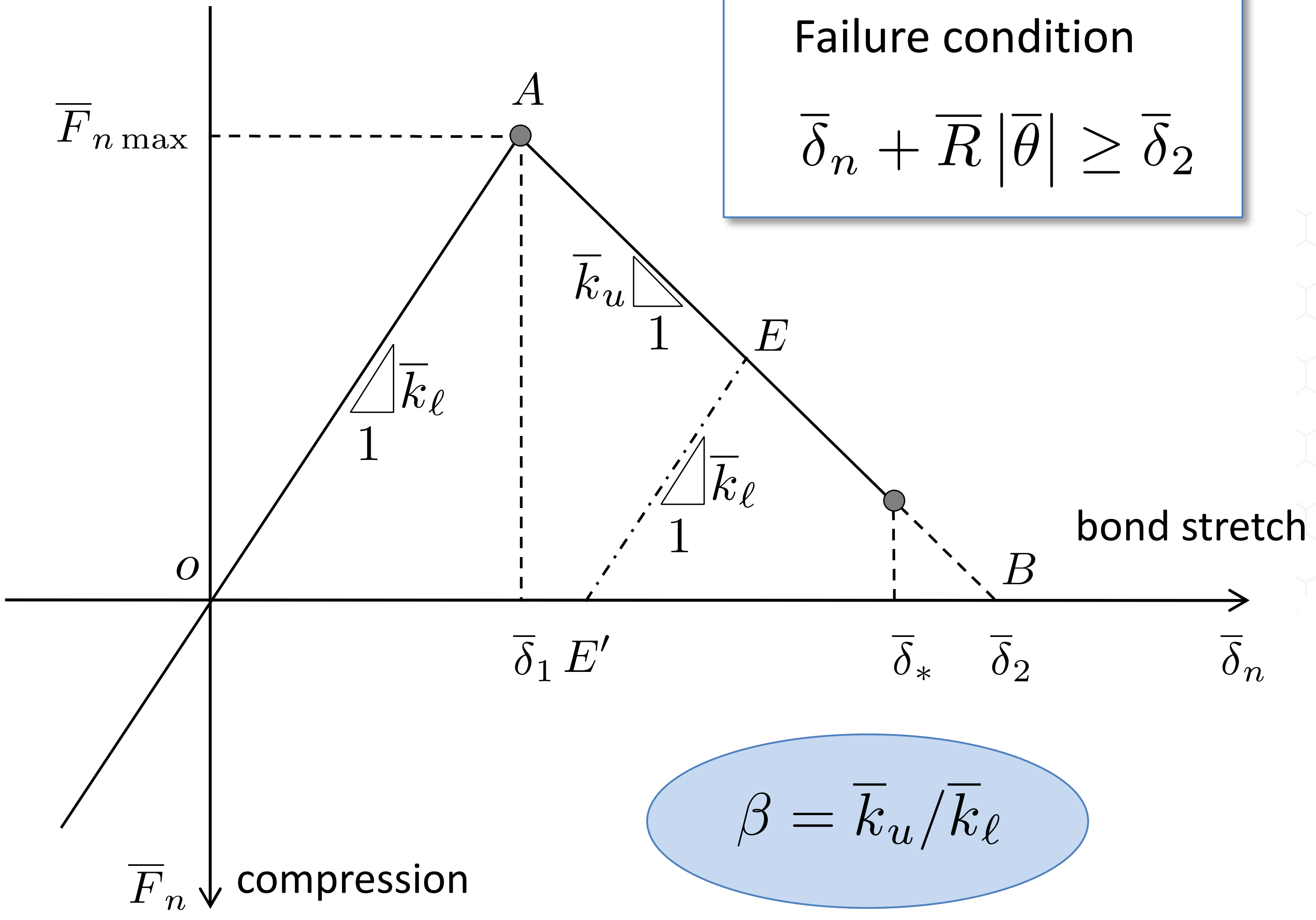
Soft contact
Spherical particles
Dense packing
Short-range interaction
Elasto-perfectly brittle contact

PREVIOUS EFFECTS TO INCREASE UCS/UTS…

- Clumped particles (Cho et al., 2007)
- Grain based model (Potyondy, 2010)
- Flat joint model (Potyondy, 2012)
- Increasing interaction range (Scholtes and Donze, 2013)
- Introducing initial damage (Schöpfer et al, 2009)

DISPLACEMENT-SOFTENING CONTACT MODEL

Ma and Huang (2018)



Failure condition

$$\overline{\delta}_n + \overline{R}\,|\overline{\theta}| \geq \overline{\delta}_2$$

$$\beta = \overline{k}_u / \overline{k}_\ell$$

softening coefficient

- Modified from the parallel bond model in PFC 5.0 ($\beta \to \infty$)
- Point contact between particles – elastic, frictional
- Area contact – elastic and bonded; softening law implemented in the normal direction;

First version of the model

$$\overline{\tau}_c \gg \overline{\sigma}_c$$

thus… only one additional parameter

SIMULATION PARAMETERS

$$W \times H = 60 \times 120\,\text{mm}$$ (2D)

$$D \times H = 40 \times 80\text{ mm}$$ (3D)

$$\overline{R} = 0.8 - 1.66\,\text{mm}$$

$$E_c = \overline{E}_c = 50\,\text{GPa}$$

$$\kappa = k_n / k_s = 4.0$$

$$\overline{\kappa} = \overline{k}_n / \overline{k}_s = 4.0$$

$$\mu = 0.5$$

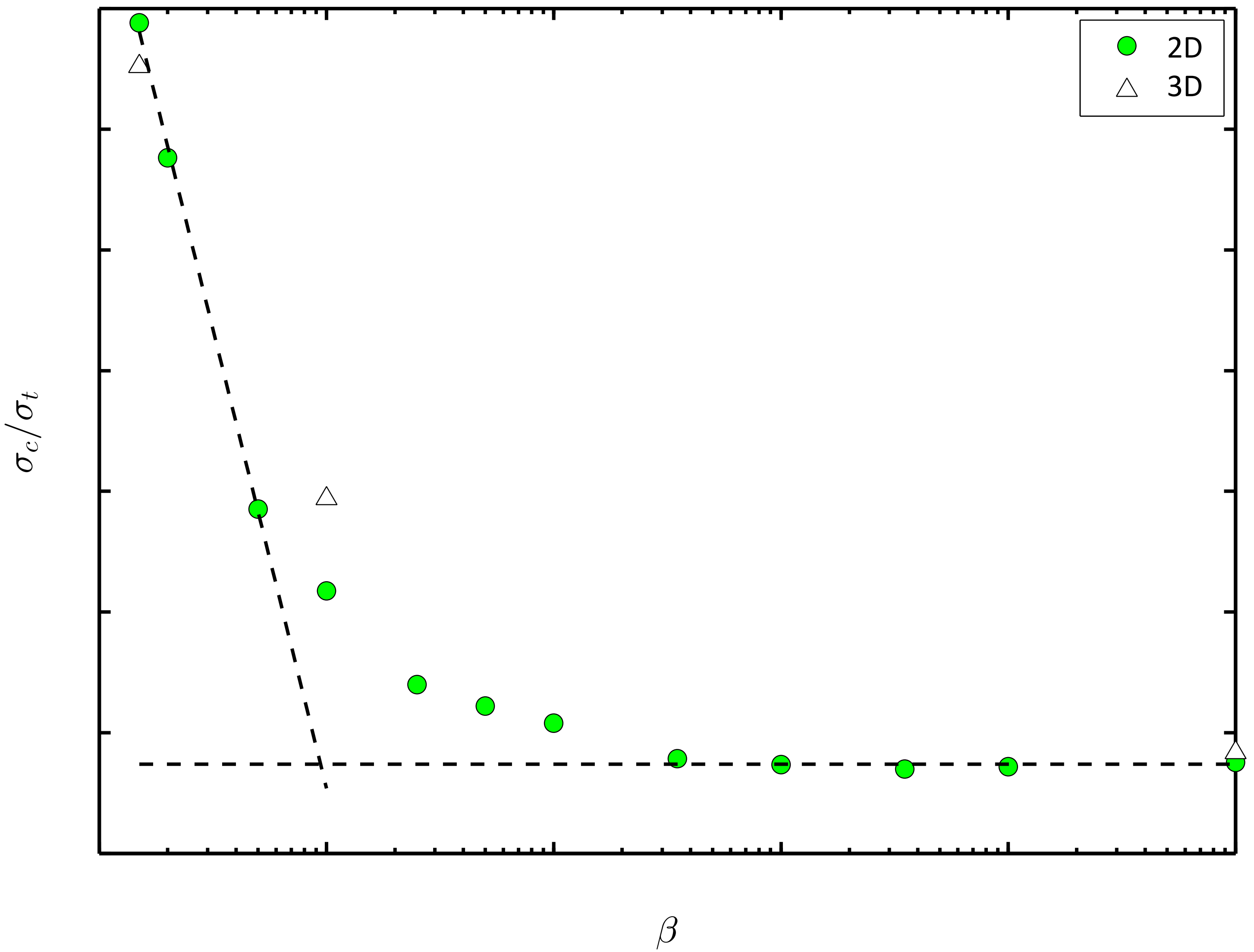
$$\overline{\sigma}_c|_{\beta \to \infty} = 50\text{ MPa}$$

$$\overline{\sigma}_c|_{\beta} = \sqrt{\frac{\beta}{1+\beta}}\,\overline{\sigma}_c|_{\beta \to \infty} \qquad \Delta\overline{\sigma}_c = \pm 10\%\overline{\sigma}_c$$

Nominal energy loss for one bond breakage is kept constant

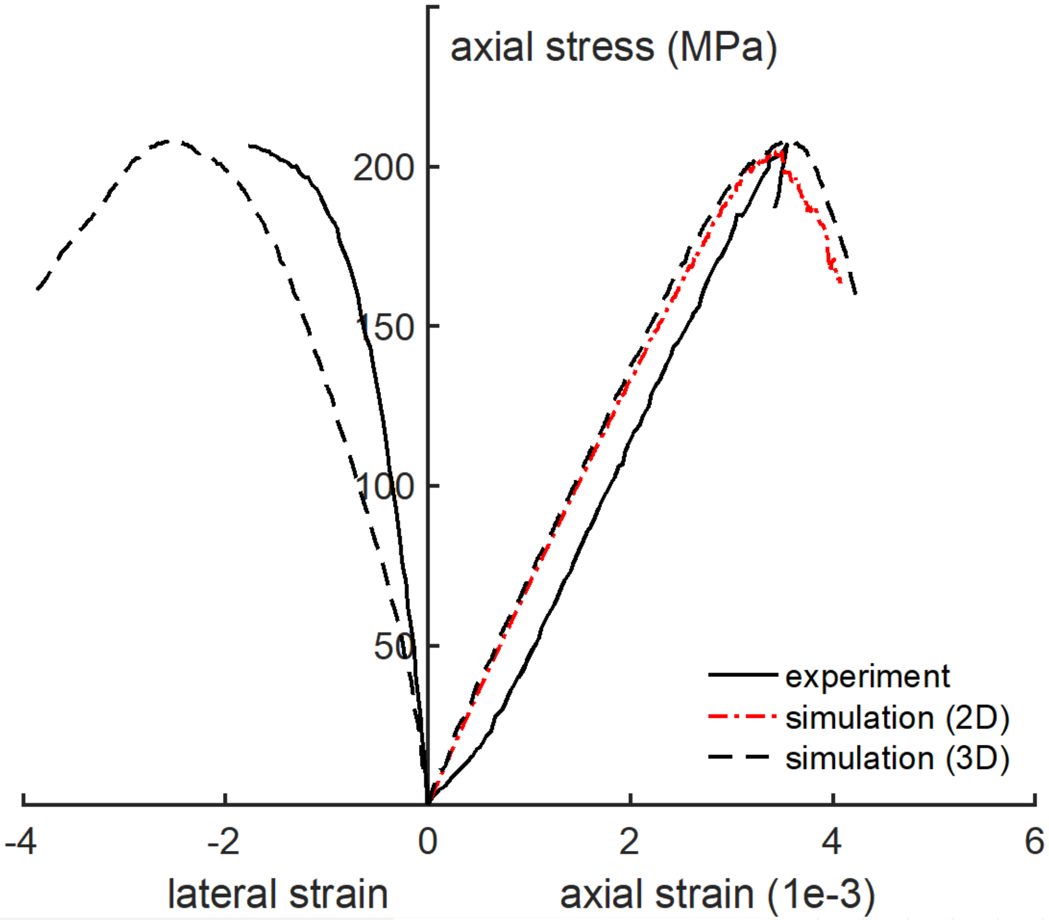
$$\overline{U}_b = \frac{\overline{\sigma}_c \overline{\delta}_2}{2\overline{R}} = \frac{\overline{\sigma}_c^2}{2\overline{R}\overline{k}_n}\left(\frac{1+\beta}{\beta}\right) = \frac{\overline{\sigma}_c^2}{\overline{E}_c}\left(\frac{1+\beta}{\beta}\right)$$

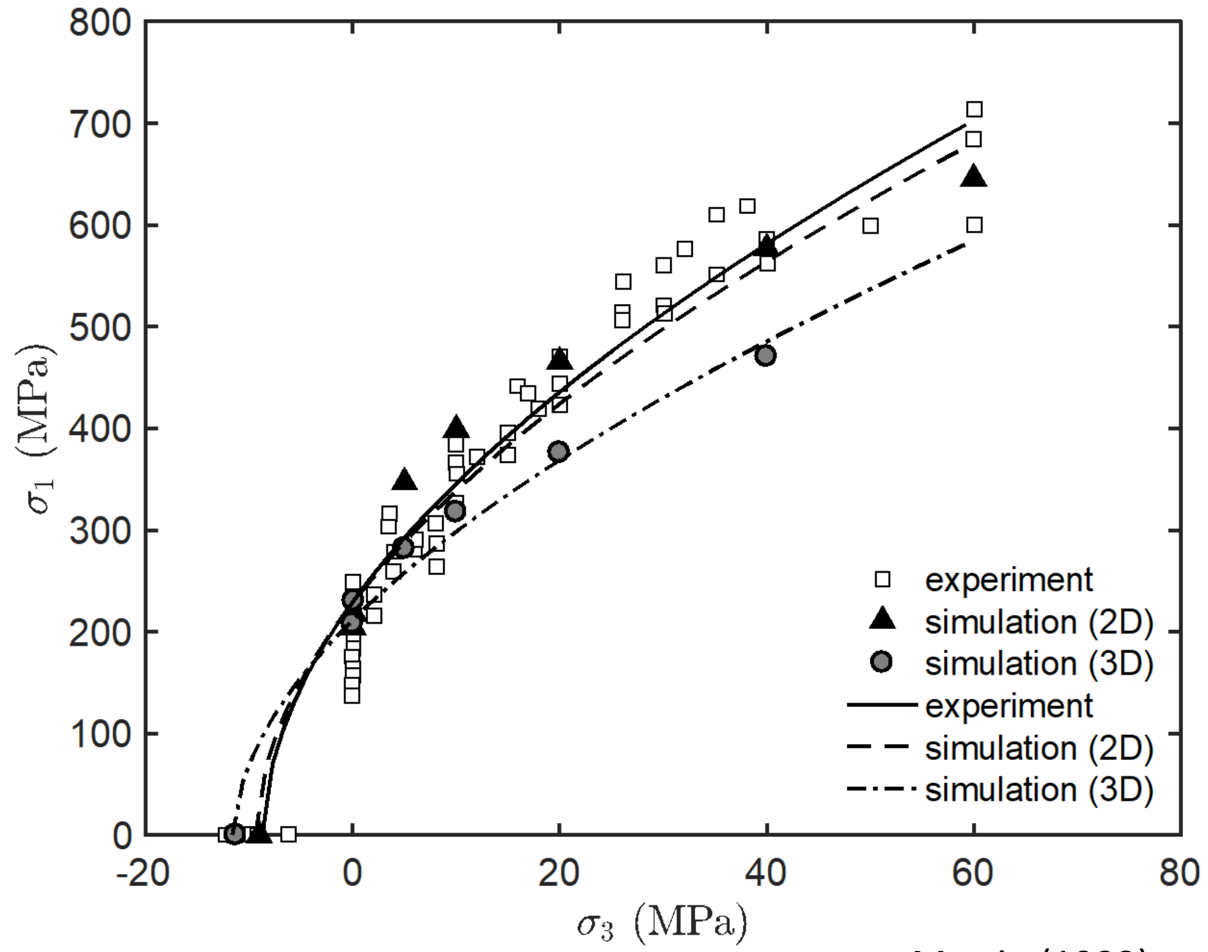
UCS/UTS



UCS and UTS can be calibrated separately by adjusting

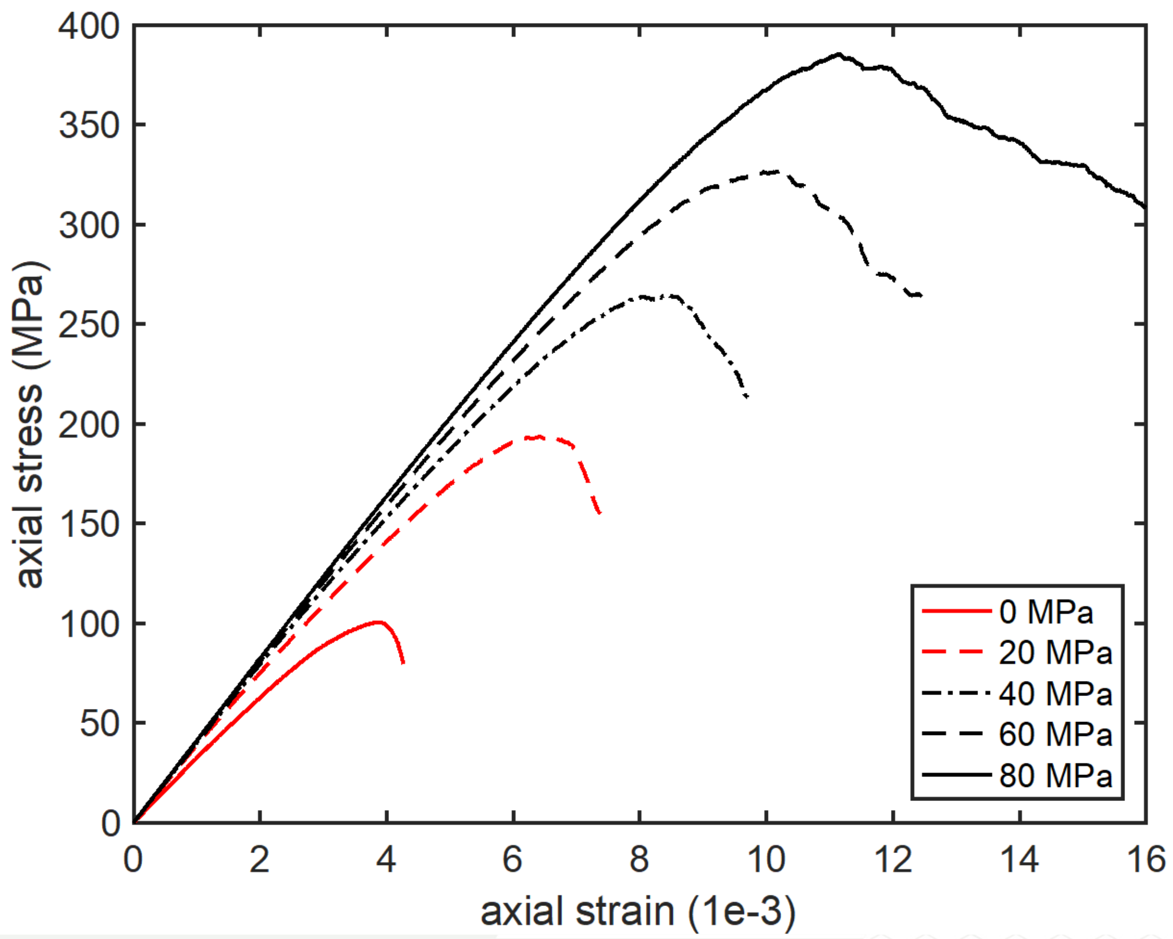
$\overline{\sigma}_c$ and β

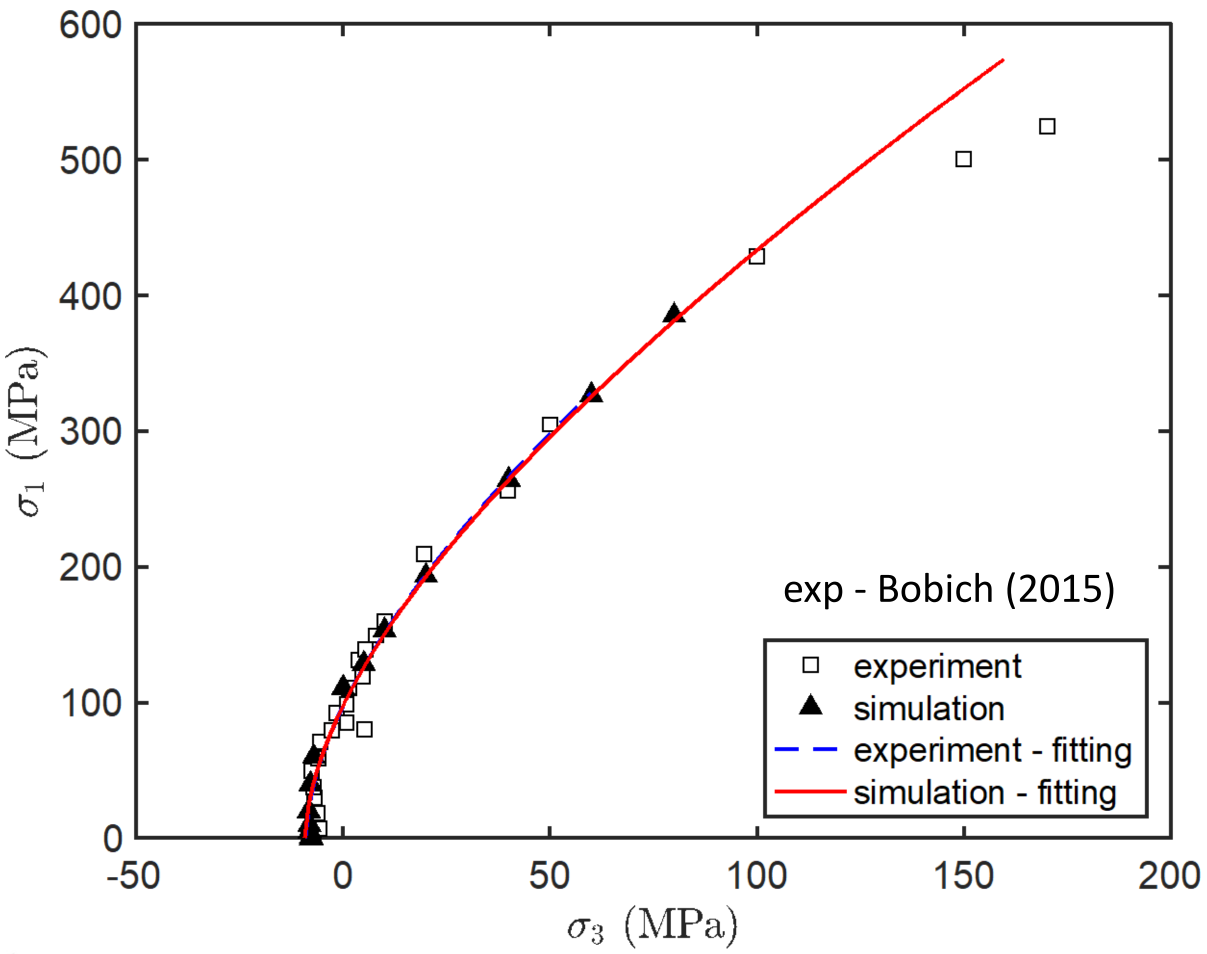




exp - Martin (1993)

BEREA SANDSTONE



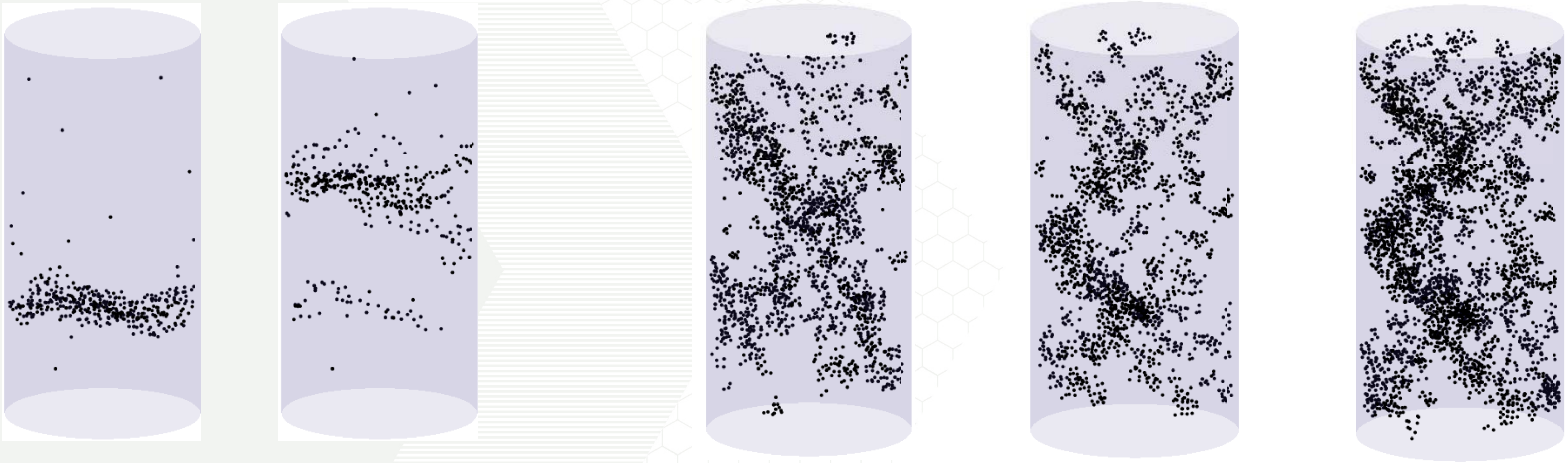


COMPARISON WITH GRANITE AND SANDSTONE

Calibrated micro-scale parameters and the corresponding mechanical properties for modeling Lac du Bonnet (LdB) granite and Berea sandstone.

	LdB granite		Berea sandstone
	2D	3D	3D
Softening coefficient β	0.03	0.045	0.15
Normal bond strength $\overline{\sigma}_c$ (MPa)	13 ± 1.3	15 ± 1.5	15 ± 1.5
Shear bond strength $\overline{\tau}_c$ (MPa)	320 ± 32	320 ± 32	320 ± 32
Point contact modulus E_c (GPa)	67.59	78.79	20.0
Parallel bond modulus $\overline{E}_c$ (GPa)	67.59	78.79	20.0
Elastic modulus E (GPa)	67.52	69.08	17.98
Uniaxial compressive strength σ_c (MPa)	204.73	207.94	108.35
Uniaxial tensile strength σ_t (MPa)	9.05	11.3	6.80
Strength ratio σ_c/σ_t	22.62	18.40	15.88

BEREA SANDSTONE



$\sigma_1 = 5\ \mathrm{MPa}$ $\sigma_1 = 10\ \mathrm{MPa}$ $\sigma_3 = 5\ \mathrm{MPa}$ $\sigma_3 = 10\ \mathrm{MPa}$ $\sigma_3 = 40\ \mathrm{MPa}$

confined extension

triaxial compression

BRAZILIAN TEST (2D)

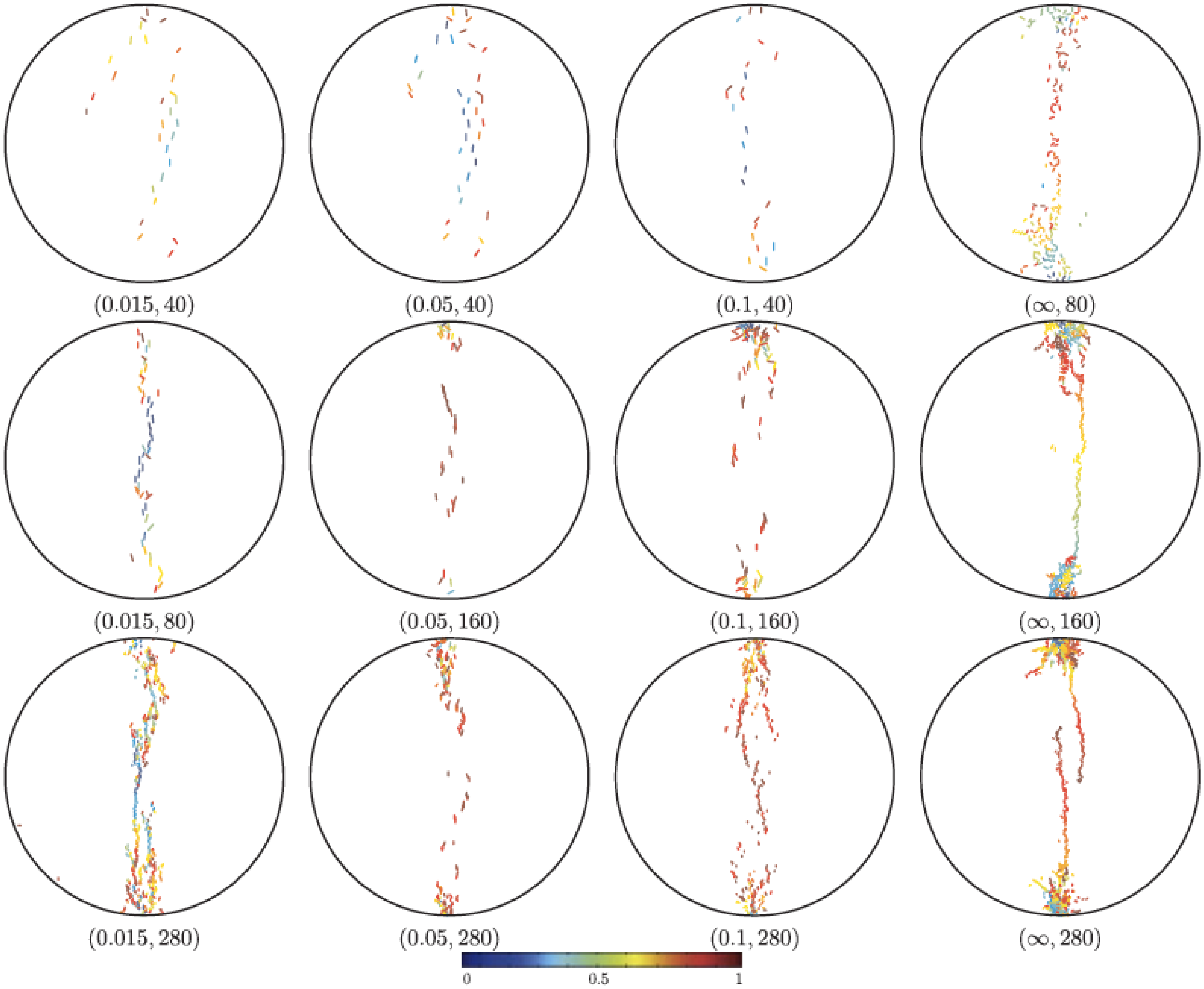
Two primary failure scenarios

- Indentation-type
- Center crack type

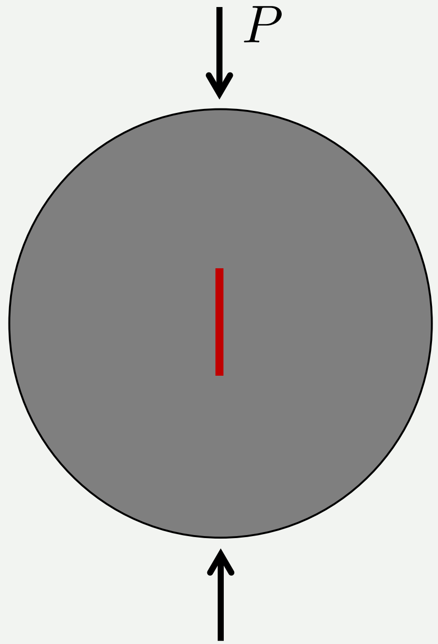
Both β (i.e., UCS/UTS) and sample size affect the failure scenarios.

(β, D)

D (mm)



BRAZILIAN TEST (3D)

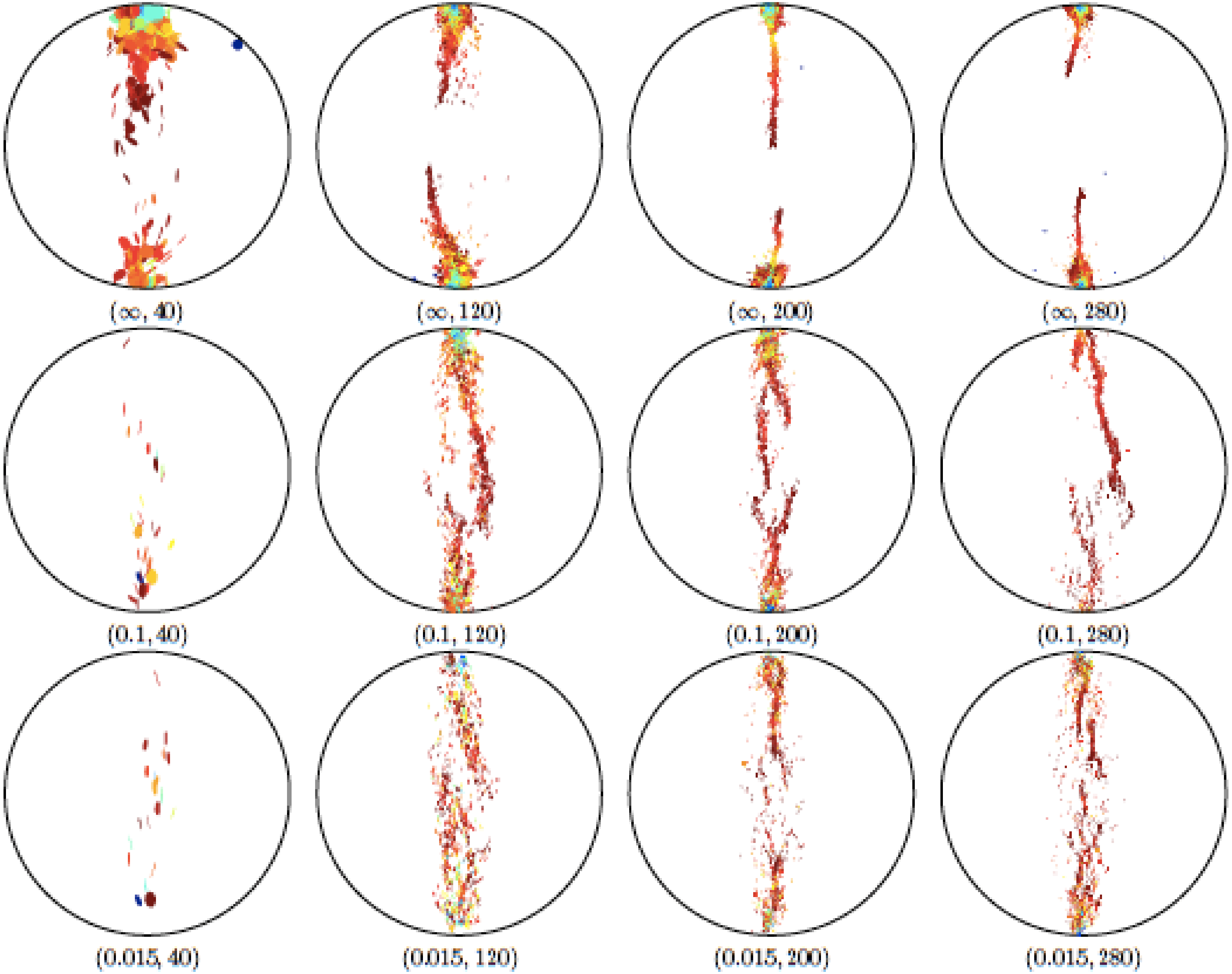


$$\sigma_B = \frac{2P}{\pi D t}$$

Hondros (1959)

(β, D)

D (mm)



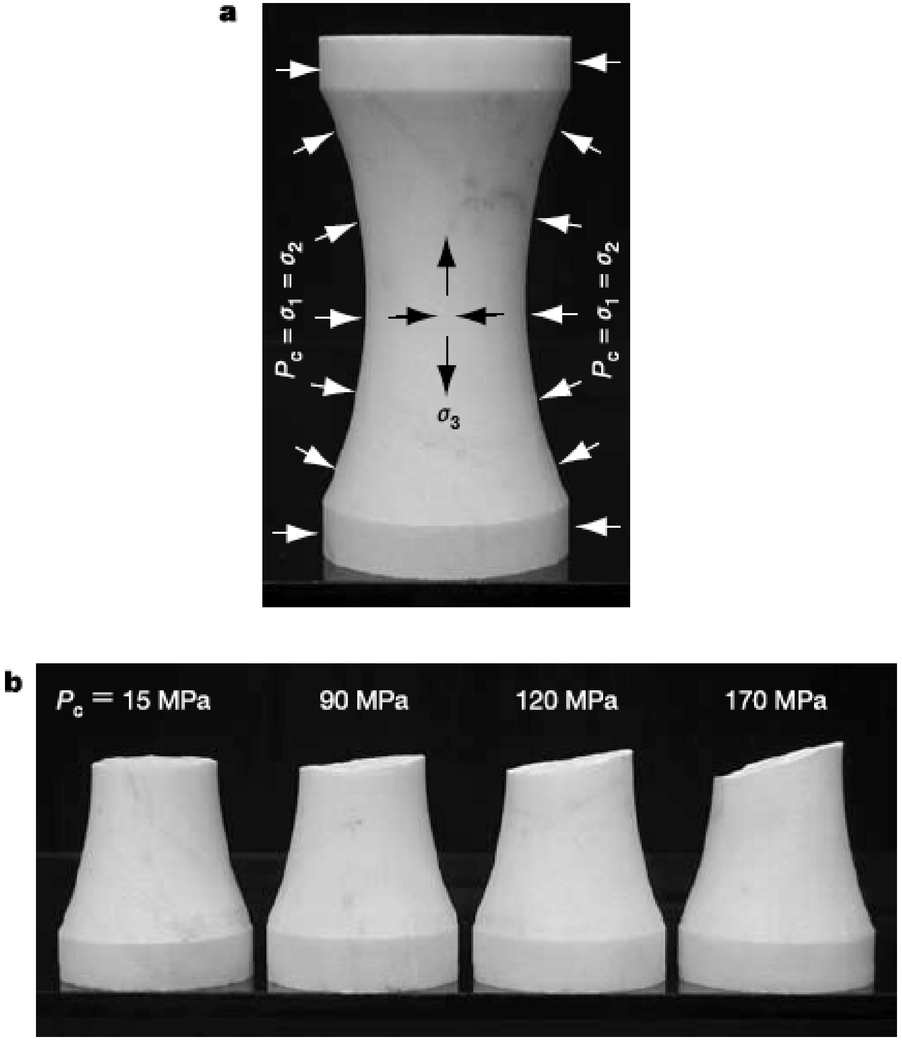
CONFINED EXTENSION EXPERIMENTS – BRACE (1960)

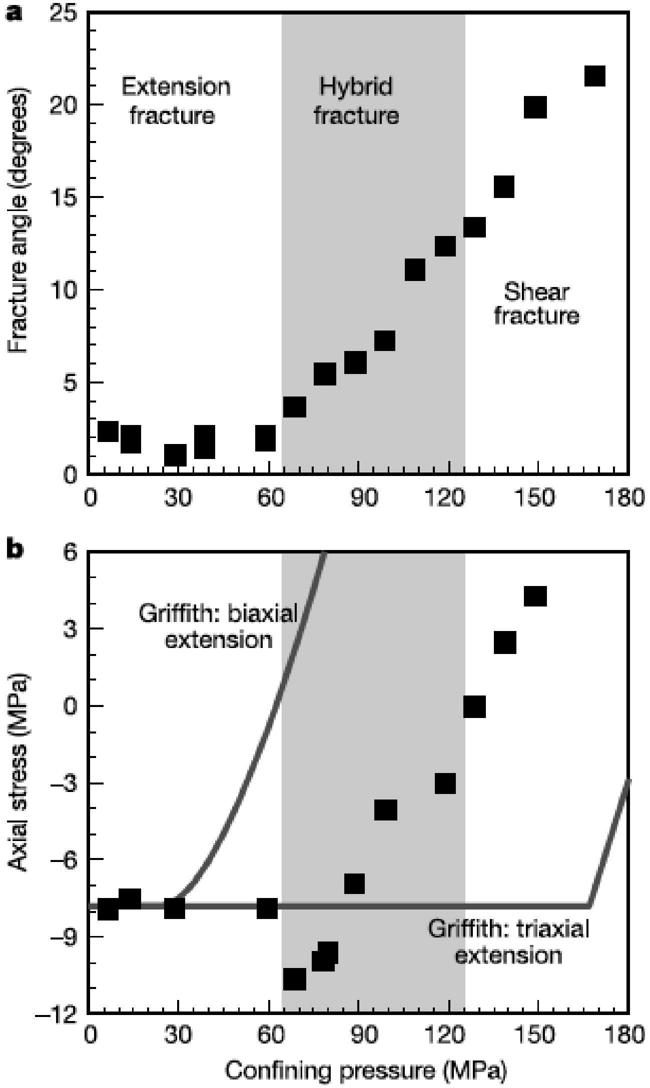
- 20 triaxial extension tests
- dog-bone shaped specimens
- five rock types: granite, quartzite, diabase and two dolomites
- 7 samples fail at axial stresses close to their uniaxial tensile strengths with the failure plane more or less normal to the axial direction

Primary experimental source to support the tension cutoff…

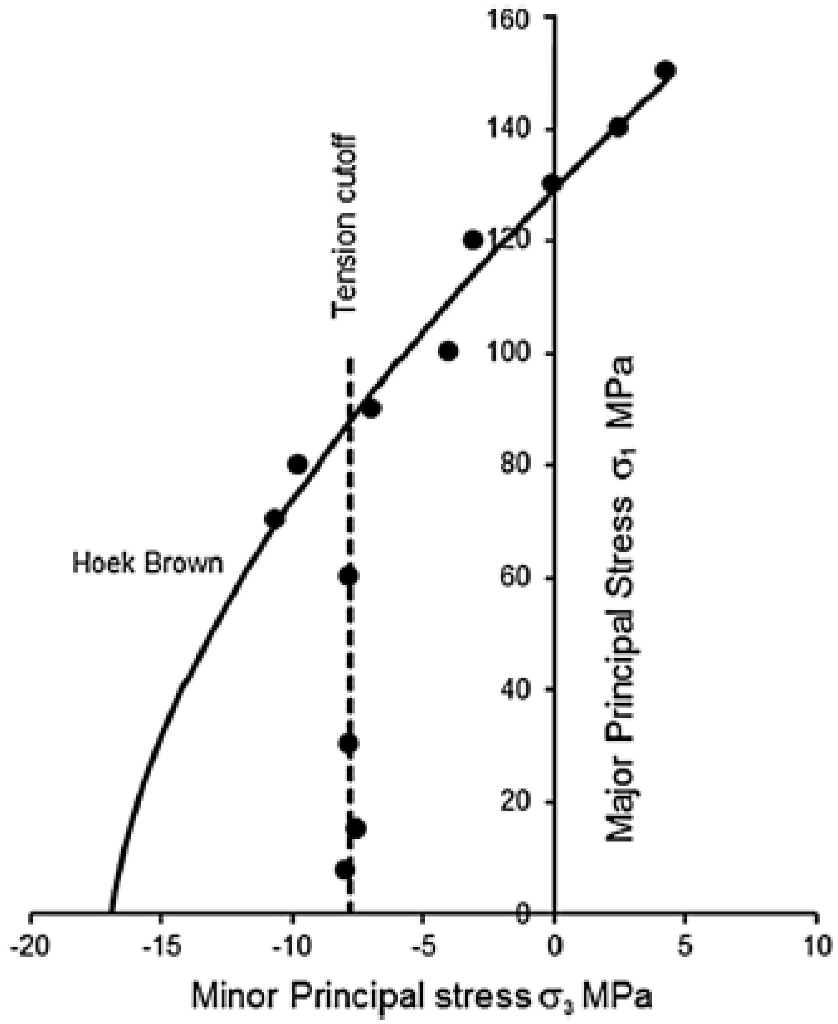
RAMSEY AND CHESTER (2004)

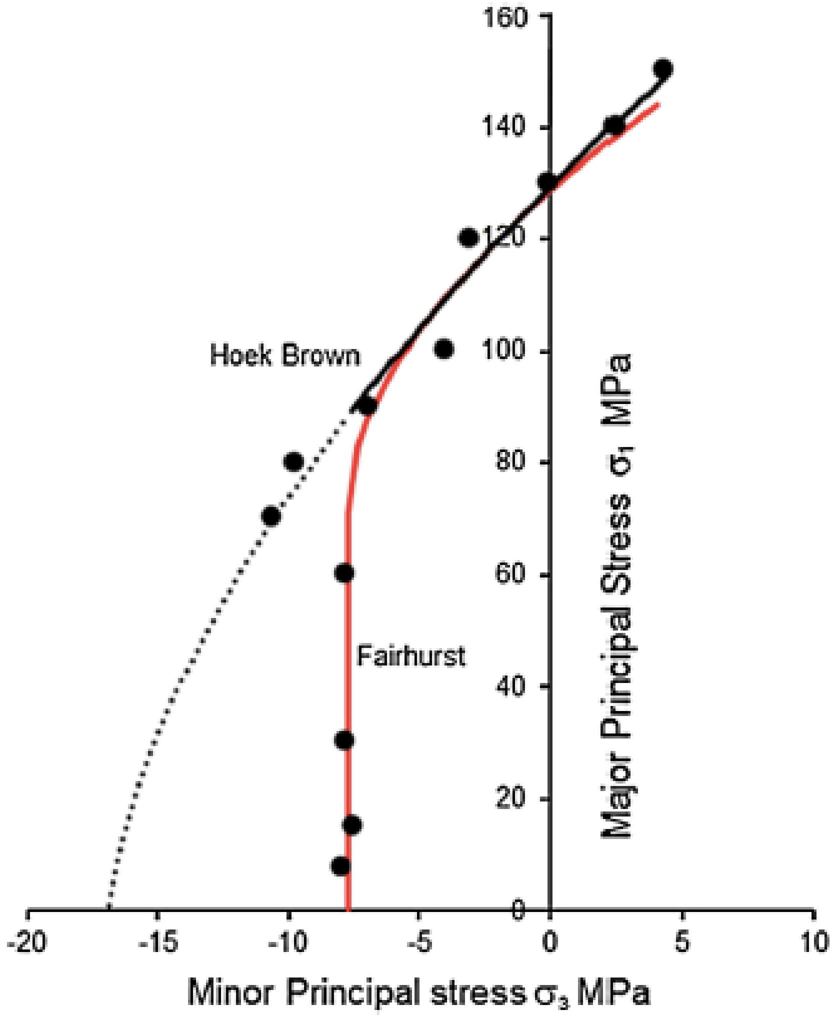
Carrara marble





DATA REANALYZED BY HOEK AND MARTIN (2014)





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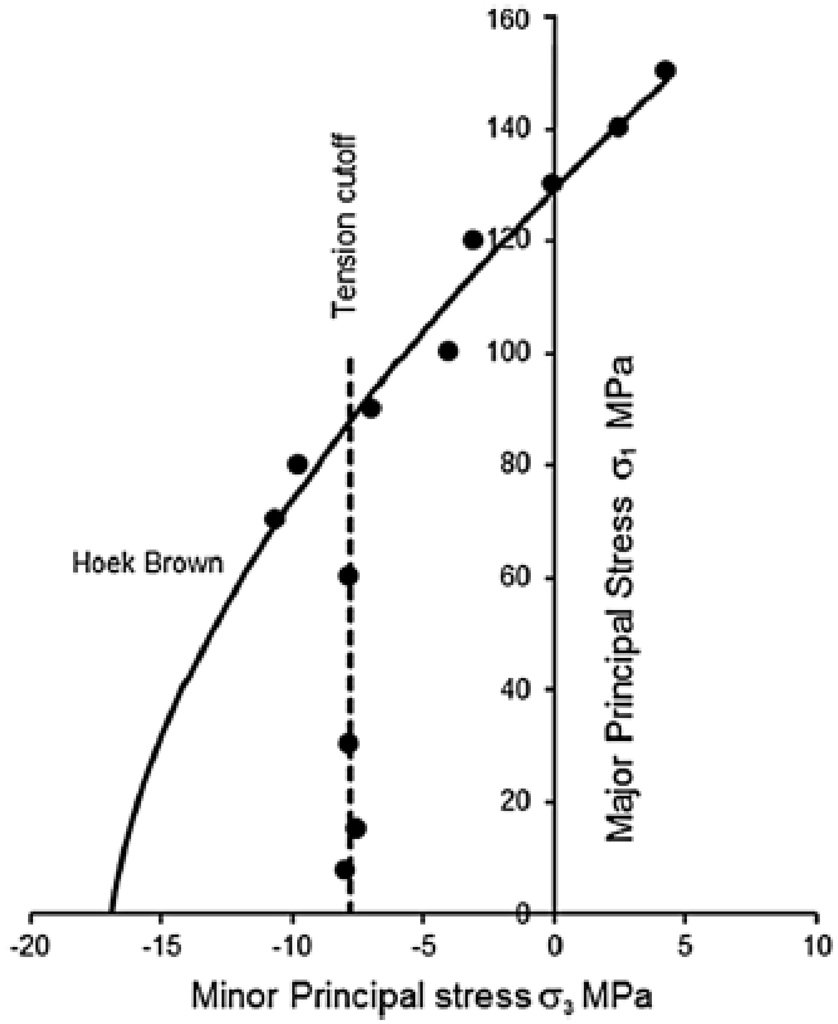
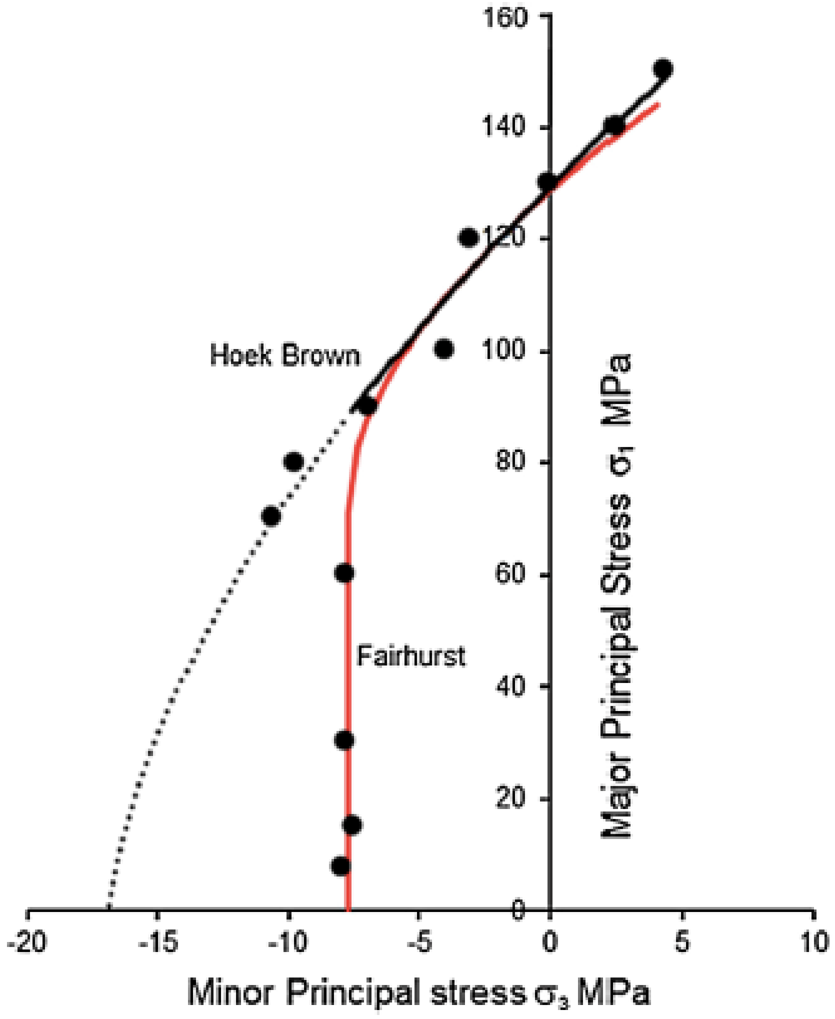
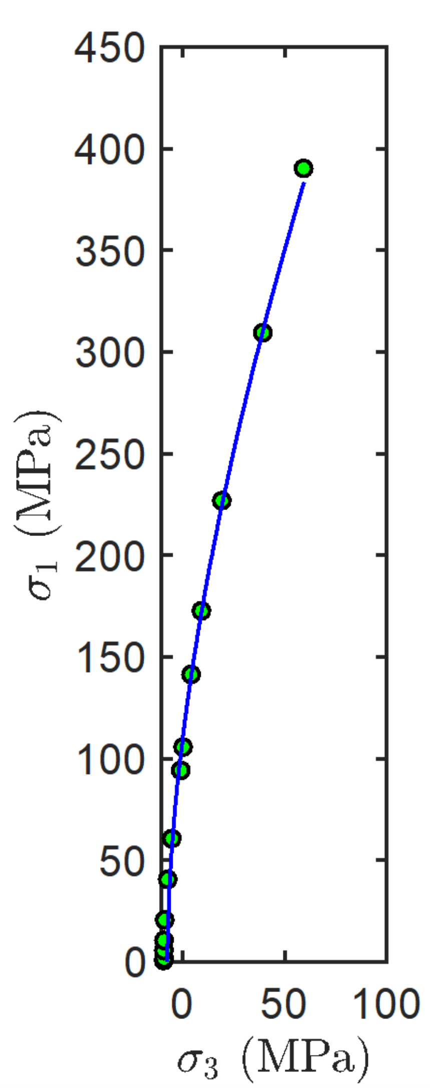
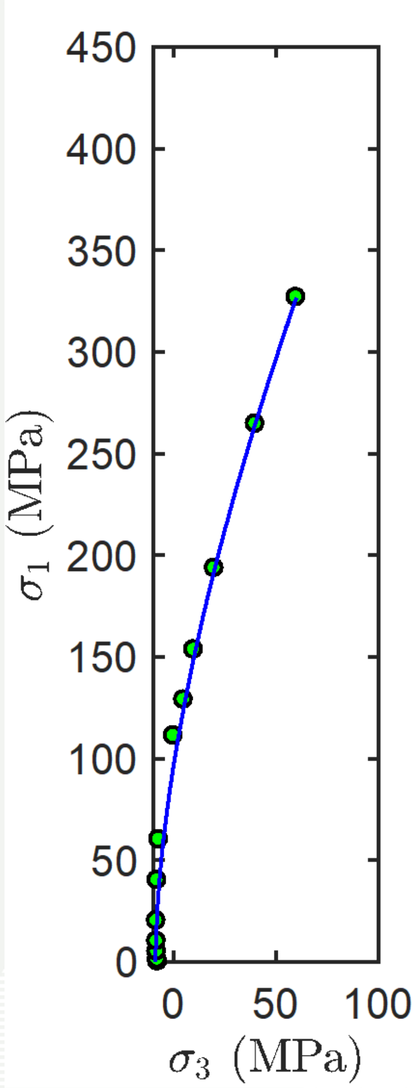
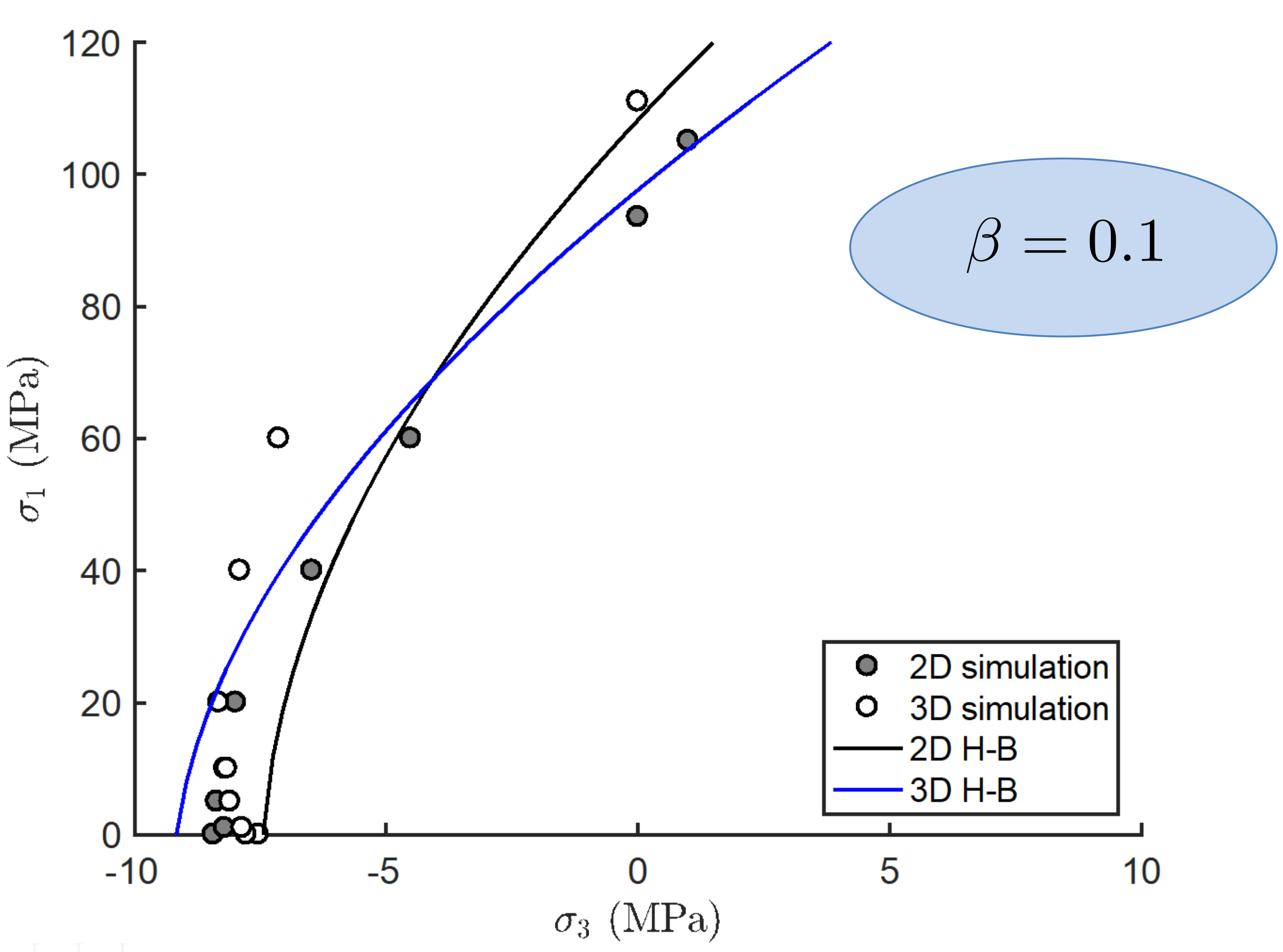




A PARTICULAR CASE (BETA = 0.1)

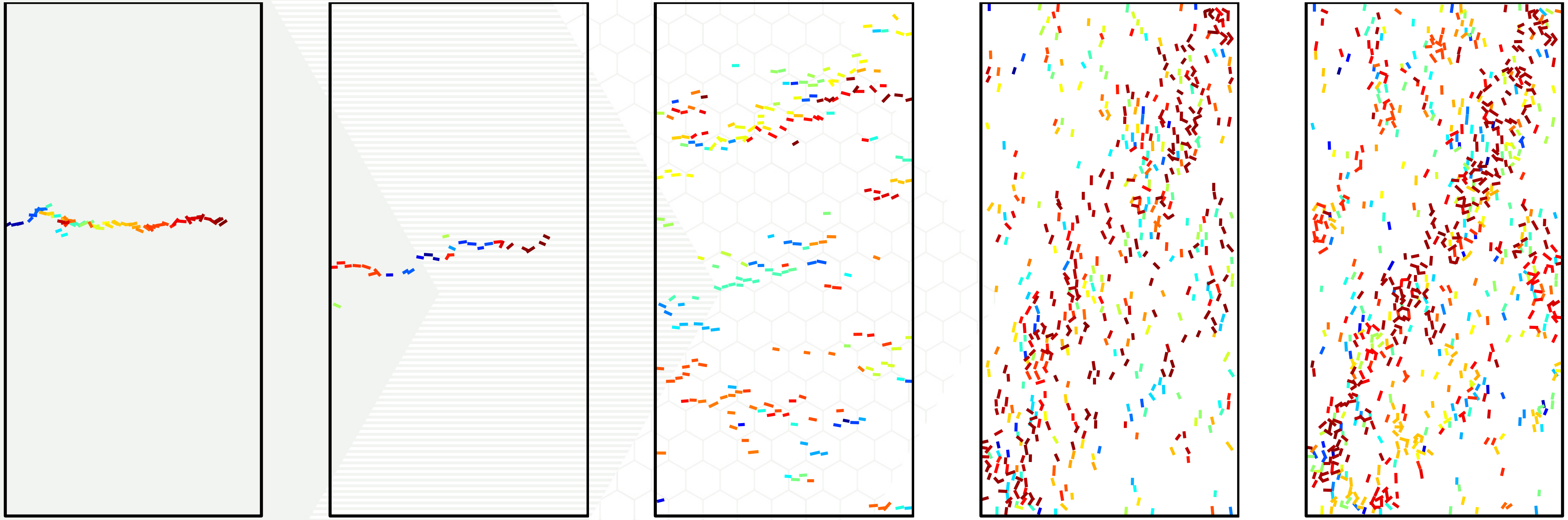






FAILURE MECHANISMS

$\beta = 0.1$



$\sigma_x = 0$ MPa, -8.37 MPa

$\sigma_x = 10$ MPa, $\sigma_y = -8.20$ MPa

$\sigma_x = 60$ MPa, $\sigma_y = -4.51$ MPa

$\sigma_x = 10$ MPa, 172.07 MPa

$\sigma_x = 60$ MPa, 389.66 MPa

WHERE DOES TENSION CUTOFF END?

$$\omega = \sigma_* / \sigma_t$$

Theoretical –

- Griffith 2D $\omega = 3$
- Murrell (1963) extension of Griffith

  $\omega = 5 \qquad \sigma_1 > \sigma_2 = \sigma_3 = -\sigma_t$

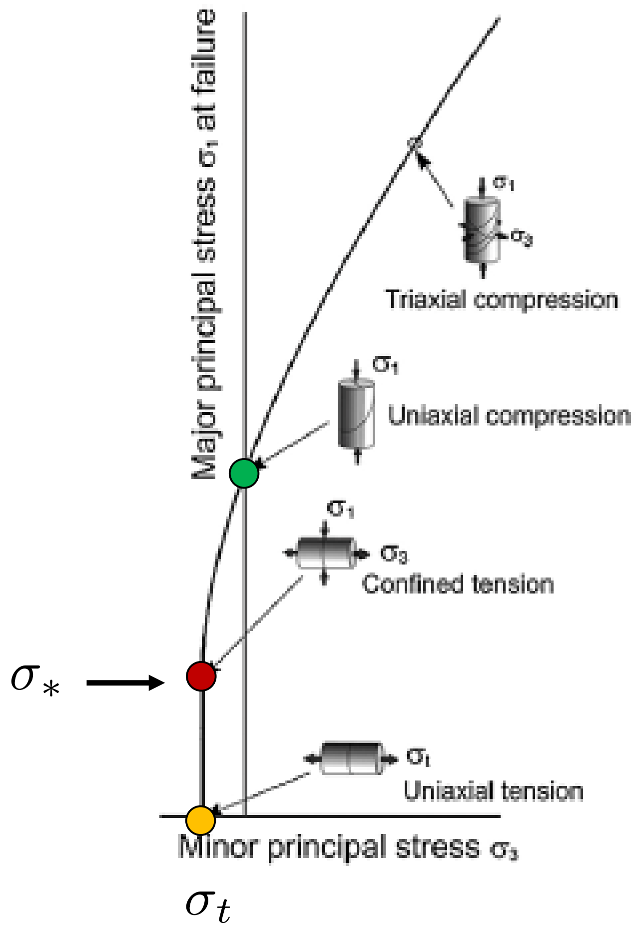
  $\omega = 21.39 \qquad \sigma_1 = \sigma_2 > \sigma_3 = -\sigma_t$
- Fairhurst (1964) $\omega = 7.8$

Experimental –

- Ramsey and Chester (2004) $\omega = 60/7.8 = 7.69$

DEM results - $\omega \approx 2.4$ 2D

$\omega \approx 7.6$ 3D



CONCLUSIONS

- Incorporating displacement-softening can overcome the issue of low UCS/UTS for DEM with only bonded spherical particles.
- Excellent match can be achieved for the full failure envelope of Berea sandstone.
- Both the indentation-type and the center crack type of failures can be reproduced for the Brazilian test.
- Confined extension simulations results support the use of a tension cutoff.
- The end of the tension cutoff from the simulations compares favorably with the prediction of Fairhurst and the experiments by Ramsey and Chester (2004).

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