Calibration of the Flat-Jointed Material

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April 13, 2018

This slide set has been created to supplement the materials provided and discussed at the PFC Training Course in Minneapolis on April 9-12, 2018. It assumes that you are familiar with this material. If you did not attend this course, then you may wish to review the Material-Modeling Support webinar, which can be obtained from the Itasca website at the link below.

- Material-Modeling Support package is described in Potyondy (2017), and is the focus of this webinar.

Potyondy, D. (2017) "Material-Modeling Support in PFC [fistPkg25]," Itasca Consulting Group, Inc., Technical Memorandum ICG7766-L (March 16, 2017), Minneapolis, Minnesota.

*Operates within *PFC*, see Material Modeling Support link: www.itascacg.com/material-modelling-support.

Calibration Procedure (generic FJ material)

Start with the FJ material for sandstone that is described in the fistPkg memo (see the next two slides). Modify its properties as you proceed.

Decide on specimen size. You can use a height over diameter ratio of one, because we have frictionless platens. Choose grain size to obtain at least 10 grains across the specimen diameter.

Fix the microstructure (grain shape, grain size, grain-size distribution, material pressure; installation gap, bonded-gapped-slit fractions, FJ radii).

For a fixed microstructure, the following calibration procedure will allow you to match Young's modulus (E), direct-tension strength (sig_t), unconfined-compressive strength (UCS), and initial slope of the strength envelope (m_i of Hoek-Brown peak-strength criterion)*.

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* The HB criterion is summarized in Fig. 9 in Potyondy (2018).

Potyondy, D.O. (2018) "A Flat-Jointed Bonded-Particle Model for Rock," paper ARMA 18-1208 submitted to Proceedings of 52nd U.S. Rock Mechanics/Geomechanics Symposium, Seattle, USA, 17–20 June 2018.

There are ~25 grains across specimen diameter for this 2D material. For a 3D material, we choose ~10 grains across diameter to obtain representative response, and reasonable computation time. After the calibration is complete, you may increase the number of grains. The current calibration properties should be relatively independent of grain size.

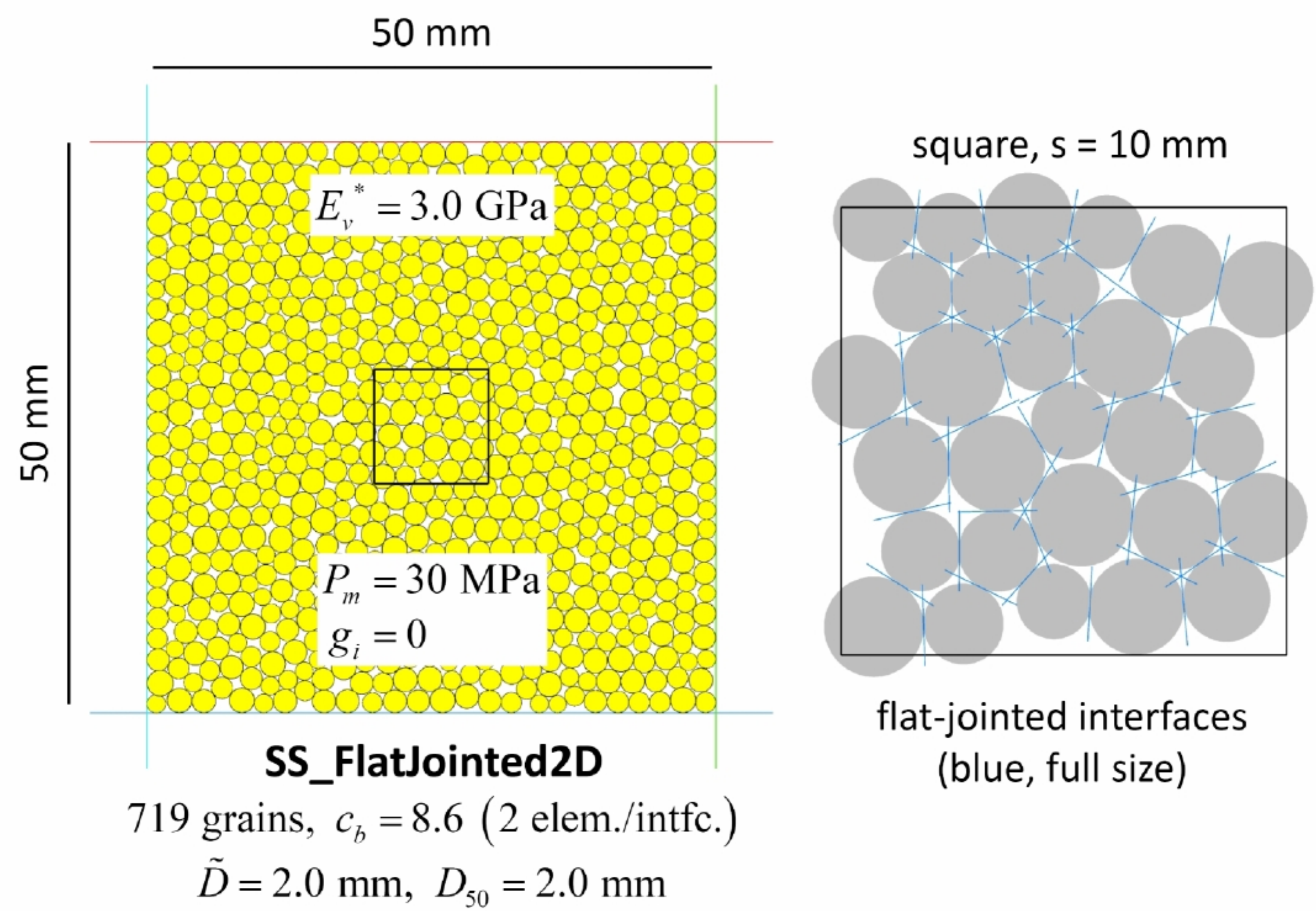

Figure 4 ***SS_FlatJointed2D material at the end of material genesis with grains and flat-jointed interfaces in the microstructural box.***

*Table 4 Microproperties of CG_FlatJointed2D Material**

Property	Value
Common group:	
N_m	SS_FlatJointed2D
T_m, α, C_ρ, $\rho_v\,[\mathrm{kg/m^3}]$	3, 0.7, 1, 1960
S_g, T_{SD}, $\{D_{\{l,u\}}\,[\mathrm{mm}],\ \phi\}$, D_{mult}	0, 0, $\{1.6, 2.4, 1.0\}$, 1.0
Packing group:	
S_{RN}, $P_m\,[\mathrm{MPa}]$, ε_P, $\varepsilon_{\lim}$, $n_{\lim}$ C_p, n_c	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6} 1, 0.08
Flat-jointed material group:	
C_{MS}, $g_i\,[\mathrm{mm}]$, ϕ_B, ϕ_G, $(g_o)_{\{\mathrm{m,sd}\}}\,[\mathrm{mm}]$, N_r	false, 0, 1, 0, $\{0, 0\}$, 2
$\{C_\lambda,\ \lambda_v\}$, $E^*\,[\mathrm{GPa}]$, κ^*, μ	$\{0, 1.0\}$, 3.0, 1.5, 0.4
$(\sigma_c)_{\{\mathrm{m,\ sd}\}}\,[\mathrm{MPa}]$, $(c)_{\{\mathrm{m,\ sd}\}}\,[\mathrm{MPa}]$, $\phi\,[\mathrm{degrees}]$	$\{1.0, 0\}$, $\{20.0, 0\}$, 0
Linear material group:	
$E_n^*\,[\mathrm{GPa}]$, κ_n^*, μ_n	1.5, 1.5, 0.4

* Flat-jointed material parameters are defined in Table 5 of the base memo.

Should be "CG_FlatJointed2D"

These are the parameters we will vary to calibrate our model.

E^*, **fjm_emod**	FLT	$[0.0, \infty)$	0.0	effective modulus
κ^*, **fjm_krat**	FLT	$[0.0, \infty)$	0.0	stiffness ratio
μ, **fjm_fric**	FLT	$[0.0, \infty)$	0.0	friction coefficient
$(\sigma_c)_{\{m,sd\}}$ **fjm_ten_{m,sd}**	FLT	$[0.0, \infty)$	$\{0.0, 0.0\}$	tensile-strength dist. [stress] (mean and std. deviation)
$(c)_{\{m,sd\}}$ **fjm_coh_{m,sd}**	FLT	$[0.0, \infty)$	$\{0.0, 0.0\}$	cohesion dist. [stress] (mean and std. deviation)
ϕ, **fjm_fa**	FLT	$[0.0, 90.0)$	0.0	friction angle [degrees]

(A) Keep stiffness ratio equal to 1.5. This parameter will effect the Poisson’s ratio, increasing it will increase the Poisson’s ratio; but do not increase it beyond ~4.

(B) Keep friction coefficient at 0.4. This parameter affects many things. It is the friction along element interfaces at which the bond has broken. The friction coefficient between granite surfaces is ~0.6. I would not go much higher than this.

(1) Set friction angle to zero. Set tensile strength and cohesion to 1e20. Keep standard deviation of these strengths equal to zero to simplify the microstructure --- no distribution of strengths, just one value for each.

(2) Perform UCS test, but only apply a small strain. Measure the Young’s modulus. Adjust effective modulus (E*) to obtain target modulus. Modulus will be proportional to E*.

(3) Set tensile strength and cohesion equal to target tensile strength (sig_t). Perform direct-tension test. Confirm that damage consists of one primary extension fracture oriented perpendicular to loading direction, and consisting of nearly all tensile bond breaks. Adjust tensile strength (sig_c) to obtain target tensile strength. Tensile strength will be proportional to sig_c.

(4) Perform UCS test, and measure modulus and peak strength. The modulus should equal the target modulus. Confirm that damage consists of initial distribution of tensile cracks aligned sub-parallel to compression direction, and then a small number of shear cracks form near peak. Adjust cohesion to obtain target UCS. UCS will be proportional to cohesion.

(5a) Perform a series of triaxial tests with increasing confinements to obtain the strength envelope. The strength should increase and the response should become less brittle with increasing confinement as shown in Fig. 17 of Potyondy (2018).

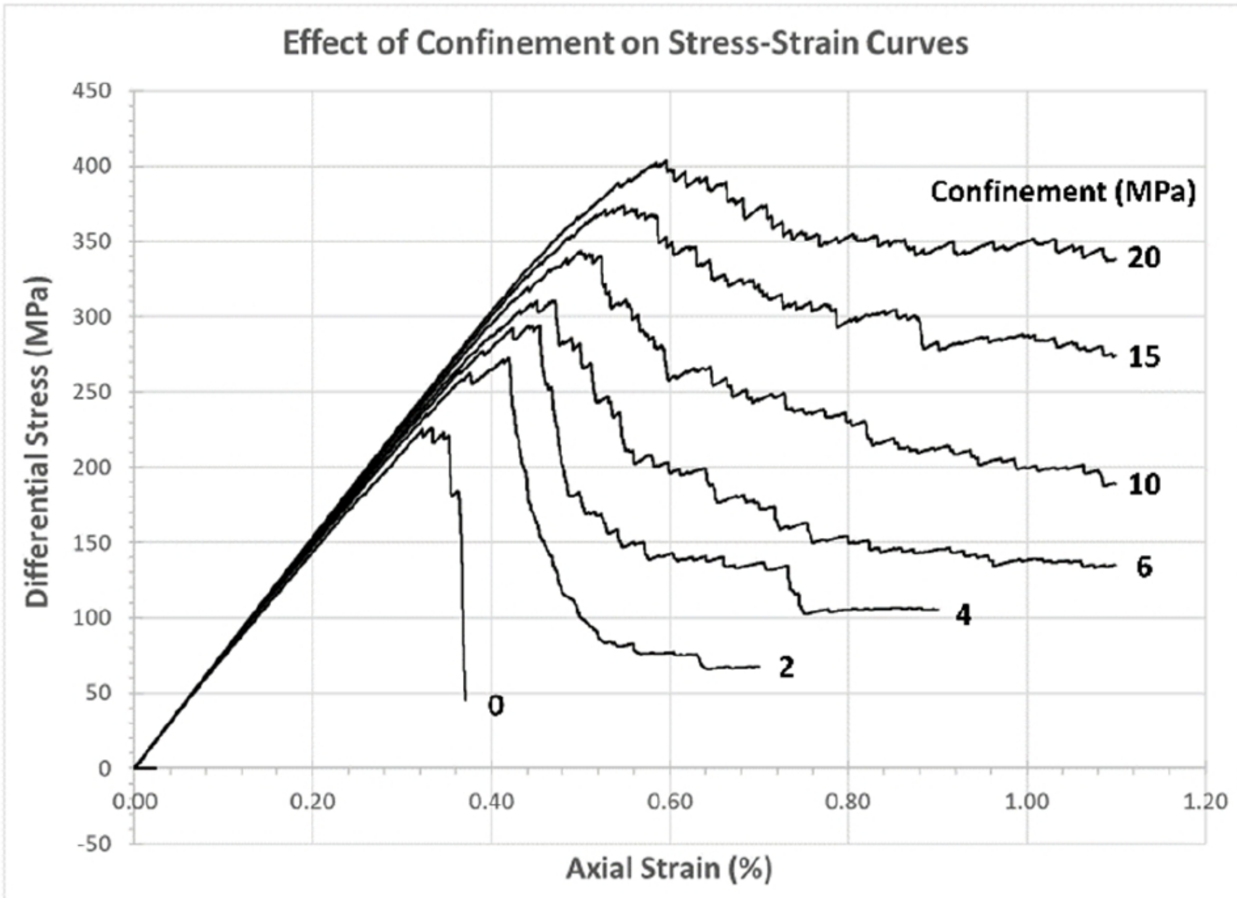

Fig. 17. Differential stress versus axial strain during confined-compression tests on the flat-jointed material.

(5b) Plot the strength envelope, and compare its slope with that of your target material, as shown in Fig. 19 of Potyondy (2018). Adjust friction angle to obtain target slope. Modifying the friction angle may affect the UCS, and so you may need to iterate on steps 4 and 5 to match all of your target values.

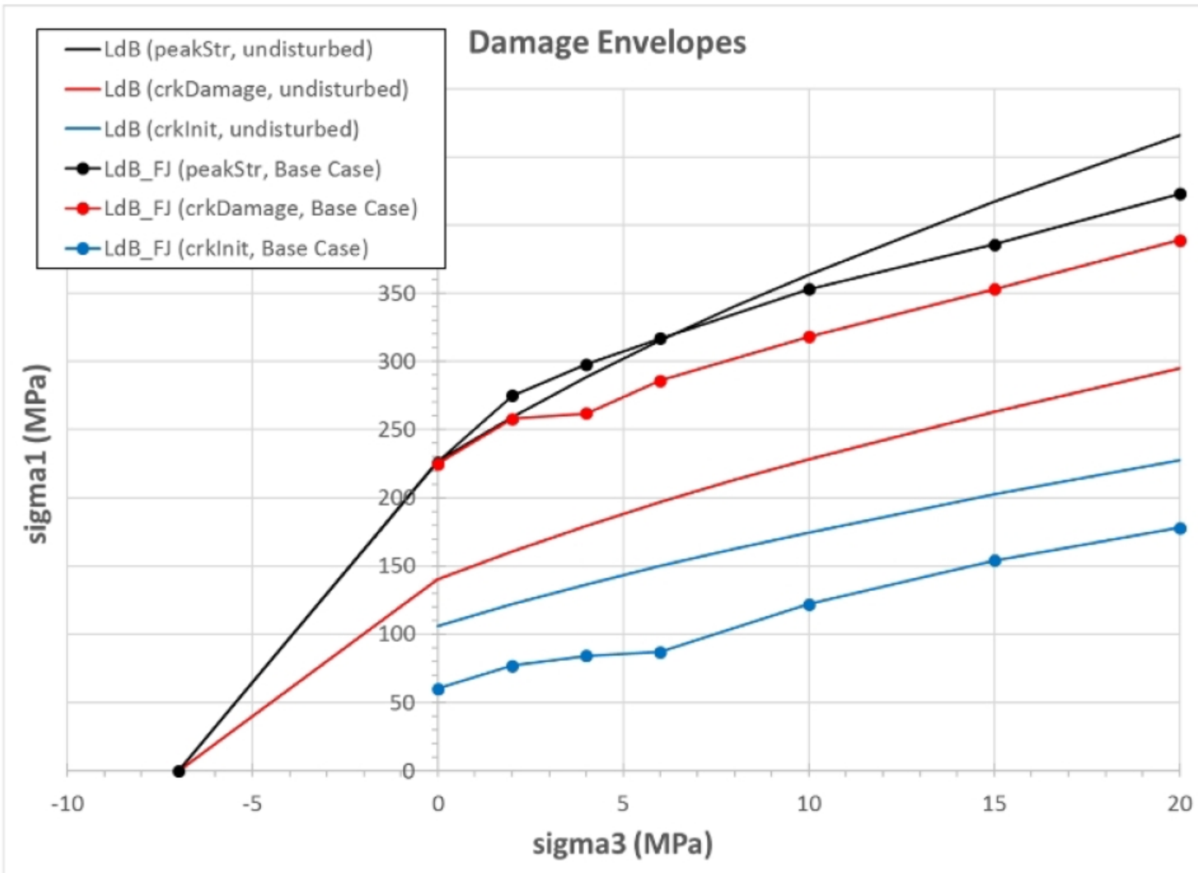

Fig. 19. Damage envelopes for the flat-jointed material and undisturbed Lac du Bonnet granite.

If you have been successful in completing the previous steps, you will have a synthetic brittle material that is similar to your target material --- similar in the sense that it matches the targeted calibration properties (E, sig_t, UCS, m_i).

The synthetic material can be subjected to your particular boundary-value problem (e.g., rock cutting, predicting excavation damage, thermally-induced rock breakage, notched-disk bending, etc.). Your model can also be used to observe the effect of microstructural changes on material response --- e.g., varying the installation gap will modify the strength envelope as shown in Fig. 20 of Potyondy (2018) [next slide].

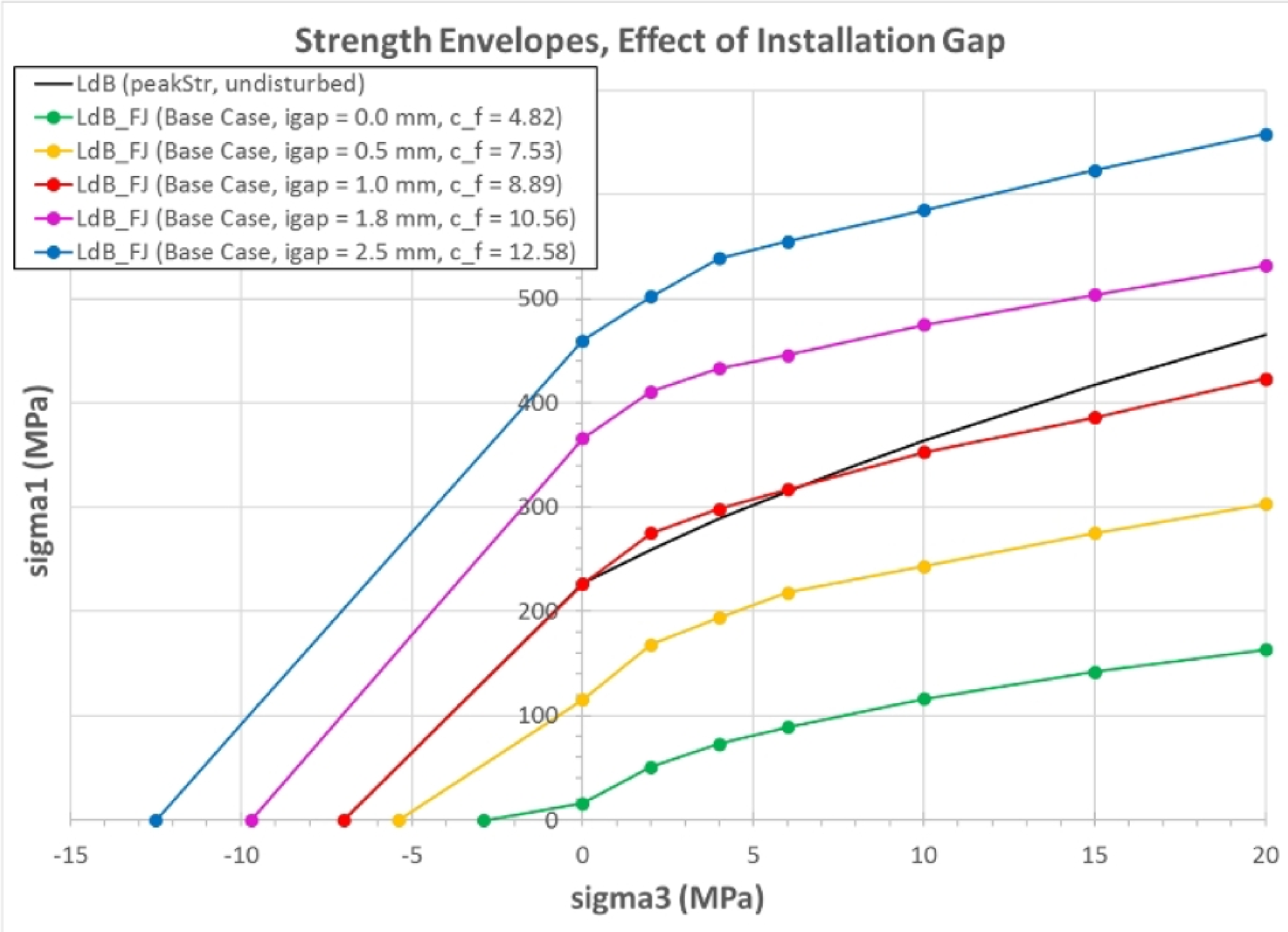

Fig. 20. Strength envelopes for the flat-jointed material as installation gap is varied.

If the microstructure is modified, then the material response will change. If you require a better match to your material response, then you must change the microstructure. The flat-jointed material provides a wide range of microstructures, and thus, it may be sufficient for your purposes. If not, then the microstructural features relevant to your desired response must be identified, and incorporated into the model. This may require a new contact-model formulation (perhaps with softening), different grain shapes or grain packings (perhaps with more interlock), or . . .

The possibilities are endless.

Good luck, and have fun.

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April 13, 2018