Memorandum

ITASCA
Consulting Group, Inc.

Date: March 5, 2021

To: PFC 7 Documentation Set

From: David Potyondy

Re: Material-Modeling Support for PFC [fistPkg7.1] (Example Materials 2)

Ref: ICG7766-L

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1.0 EXAMPLE MATERIALS

The PFC 6.0 FISHTank produces linear, contact-bonded, parallel-bonded, soft-bonded, flat-jointed and user-defined materials. Examples for each material are provided in the Example Materials memos. Each example serves as a base case and provides a material at the lowest resolution sufficient to demonstrate system behavior. There is a material-genesis project for each material, and these projects are in the **`fistPkg7.N/ExampleProjects/MatGen-M`** directory, where **`N`** is the version number of the PFC FISHTank, and **`M`** is the material type. There are separate 2D and 3D projects for each material, and both projects are contained within the same example-project directory. Examples for the parallel-bonded and flat-jointed materials and the interface are provided in the following subsections.[1]

[1] The microstructural arrangement and stress-strain curves obtained with the current FISHTank may vary slightly from those shown here, which may have been generated by an earlier version of the FISHTank.

1.1 Parallel-Bonded Material Example

The parallel-bonded material example is in the **`MatGen-ParallelBonded`** example-project directory. A parallel-bonded material is created to represent a typical sandstone, which we take to be Castlegate sandstone.[2] We denote our sandstone material as the SS_ParallelBonded material with microproperties listed in Table 1. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus).[3] The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then parallel bonds are added between all grains that are in contact with one another (see Figure 1). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as for the contact-bonded material example in the Example Materials 1 memo.

Table 1 Microproperties of SS_ParallelBonded Material*

Property	Value
Common group:	
N_m	SS_ParallelBonded
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	2, 0.7, 1, 1960
$S_g,\ T_{SD},\ \{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\},\ D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\mathrm{lim}},\ n_{\mathrm{lim}}$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6}
$C_p,\ n_c$	1, 0.30
Parallel-bonded material group:	
Linear group:	
$E^*\ [\mathrm{GPa}],\ \kappa^*,\ \mu$	1.5, 1.5, 0.4
Parallel-bond group:	
$g_i\ [\mathrm{mm}],\ \bar{\lambda},\ \bar{E}^*\ [\mathrm{GPa}],\ \bar{\kappa}^*,\ \bar{\beta}$	0, 1.0, 1.5, 1.5, 1.0
$(\bar{\sigma}_c)_{\{\mathrm{m,sd}\}}\ [\mathrm{MPa}],\ (\bar{c})_{\{\mathrm{m,sd}\}}\ [\mathrm{MPa}],\ \bar{\phi}\ [\mathrm{degrees}]$	{1.0,0}, {20.0,0}, 0
Linear material group:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	1.5, 1.5, 0.4

* Parallel-bonded material parameters are defined in Table 4 of the base memo.

[2] Typical properties of Castlegate sandstone are listed in footnote 4 of the Example Materials 1 memo.
[3] A parallel-bonded clumped material can be created in the same way as for the contact-bonded material example.

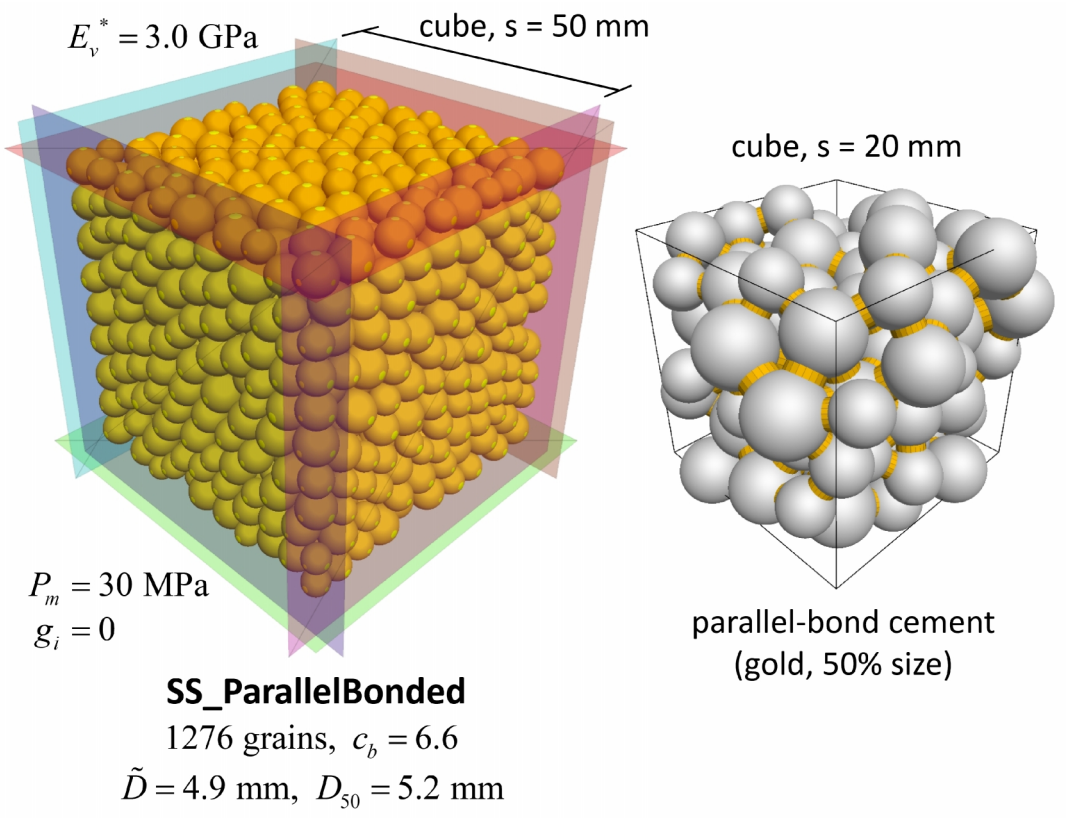

Figure 1 ***SS_ParallelBonded material at the end of material genesis with grains and intact parallel bonds in the microstructural box.***

1.2 Parallel-Bonded Material Example (2D model)

The parallel-bonded material example for the 2D model is in the **`MatGen-ParallelBonded`** example-project directory. The files for the 2D model contain the **`p2*`** extension (e.g., **`MatGen.p2prj`** and **`mpParams.p2dat`**). A 2D parallel-bonded material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.[4] We denote our sandstone material as the SS_ParallelBonded2D material with microproperties listed in Table 2. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus).[5] The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then parallel bonds are added between all grains that are in contact with one another (see Figure 2). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as for the contact-bonded material example in the Example Materials 1 memo.

Table 2 Microproperties of SS_ParallelBonded2D Material*

Property	Value
Common group:	
N_m	SS_ParallelBonded2D
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	2, 0.7, 1, 1960
$S_g,\ T_{SD},\ \{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\},\ D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\mathrm{lim}},\ n_{\mathrm{lim}}$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6}
$C_p,\ n_c$	1, 0.08
Parallel-bonded material group:	
Linear group:	
$E^*\ [\mathrm{GPa}],\ \kappa^*,\ \mu$	1.5, 1.5, 0.4
Parallel-bond group:	
$g_i\ [\mathrm{mm}],\ \bar{\lambda},\ \bar{E}^*\ [\mathrm{GPa}],\ \bar{\kappa}^*,\ \bar{\beta}$	0, 1.0, 1.5, 1.5, 1.0
$(\bar{\sigma}_c)_{\{\mathrm{m,\,sd}\}}\ [\mathrm{MPa}],\ (\bar{c})_{\{\mathrm{m,\,sd}\}}\ [\mathrm{MPa}],\ \bar{\phi}\ [\mathrm{degrees}]$	{1.0,0}, {20.0,0}, 0
Linear material group:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	1.5, 1.5, 0.4

* Parallel-bonded material parameters are defined in Table 4 of the base memo.

[4] Typical properties of Castlegate sandstone are listed in footnote 4 of the Example Materials 1 memo.
[5] A 2D parallel-bonded clumped material can be created in the same way as for the 2D contact-bonded material example.

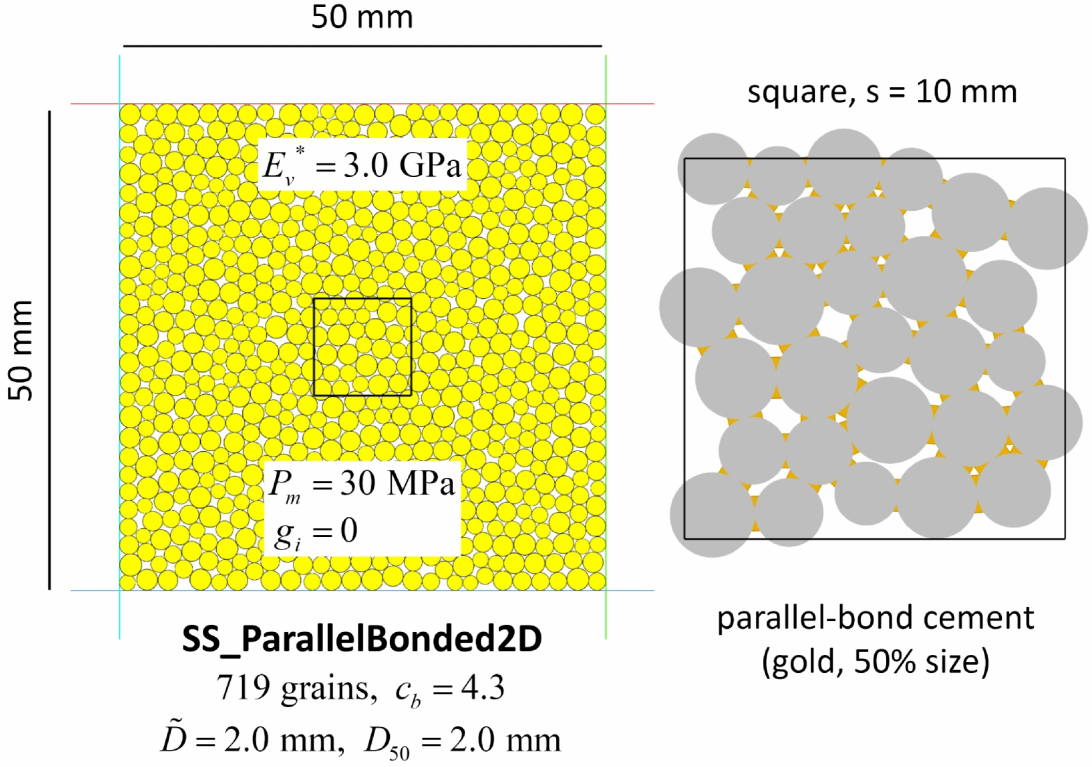

Figure 2 ***SS_ParallelBonded2D material at the end of material genesis with grains and intact parallel bonds in the microstructural box.***

1.3 Soft-Bonded Material Example

The soft-bonded material example is in the **`MatGen-SoftBonded`** example-project directory. A soft-bonded material is created to represent a typical sandstone, which we take to be Castlegate sandstone.[6] We denote our sandstone material as the SS_SoftBonded material with microproperties listed in Figure 3. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus).[7] The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then soft bonds are added between all grains that are in contact with one another (see Figure 1). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as for the contact-bonded material example in the Example Materials 1 memo.

Table 3 Microproperties of SS_SoftBonded Material*

Property	Value
Common group:	
N_m	SS_SoftBonded
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	3, 0.7, 1, 1960
$S_g,\ T_{SD},\ \{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\},\ D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\mathrm{lim}},\ n_{\mathrm{lim}}$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6}
$C_p,\ n_c$	1, 0.30
Soft-bonded material group:	
$g_i\ [\mathrm{mm}],\ \lambda,\ E^*\ [\mathrm{GPa}],\ \kappa^*,\ \beta$	0, 1.0, 1.5, 1.5, 1.0
$(\sigma_c)_{\{\mathrm{m,\ sd}\}}\ [\mathrm{MPa}],\ (c)_{\{\mathrm{m,\ sd}\}}\ [\mathrm{MPa}],\ \phi\ [\mathrm{degrees}]$	{1.0,0}, {20.0,0}, 0.0
$\zeta,\ \gamma,\ \mu\ \lambda_b\ \lambda_t$	0.0, 0.0, 0.4, 0.0, 0.0
Linear material group:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	1.5, 1.5, 0.4

* Soft-bonded material parameters are defined in Table 5 of the base memo.

[6] Typical properties of Castlegate sandstone are listed in footnote 4 of the Example Materials 1 memo.
[7] A soft-bonded clumped material can be created in the same way as for the contact-bonded material example.

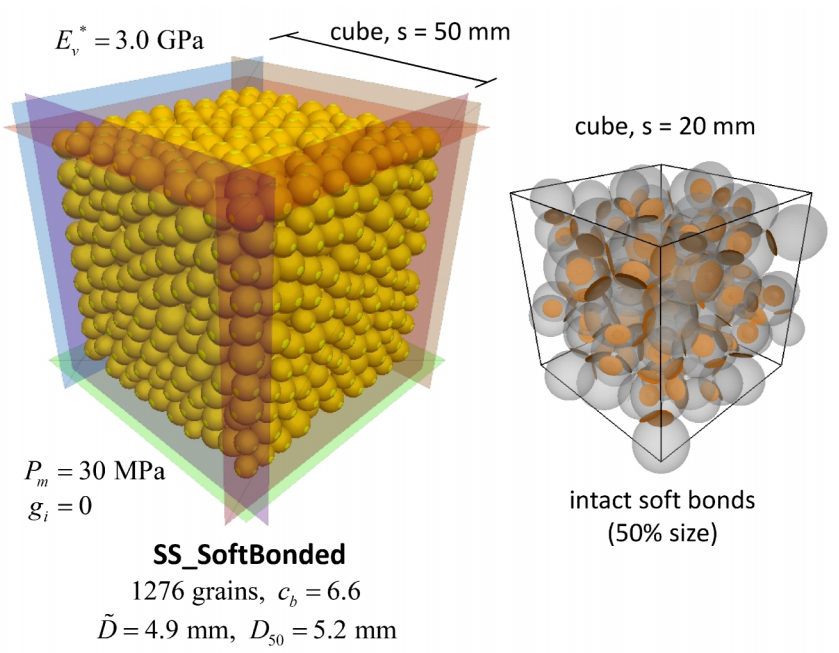

Figure 3 SS_SoftBonded material at the end of material genesis with grains and intact soft bonds in the microstructural box.

1.4 Soft-Bonded Material Example (2D model)

The soft-bonded material example for the 2D model is in the **`MatGen-SoftBonded`** example-project directory. The files for the 2D model contain the **`p2*`** extension (e.g., **`MatGen.p2prj`** and **`mpParams.p2dat`**). A 2D soft-bonded material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.[8] We denote our sandstone material as the SS_SoftBonded2D material with microproperties listed in Table 4. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus).[9] The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then soft bonds are added between all grains that are in contact with one another (see Figure 2). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as for the contact-bonded material example in the Example Materials 1 memo.

Table 4 Microproperties of SS_SoftBonded2D Material*

Property	Value
Common group:	
N_m	SS_SoftBonded2D
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	3, 0.7, 1, 1960
$S_g,\ T_{SD},\ \{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\},\ D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\mathrm{lim}},\ n_{\mathrm{lim}}$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6}
$C_p,\ n_c$	1, 0.08
Soft-bonded material group:	
$g_i\ [\mathrm{mm}],\ \lambda,\ E^*\ [\mathrm{GPa}],\ \kappa^*,\ \beta$	0, 1.0, 1.5, 1.5, 1.0
$(\sigma_c)_{\{\mathrm{m,\ sd}\}}\ [\mathrm{MPa}],\ (c)_{\{\mathrm{m,\ sd}\}}\ [\mathrm{MPa}],\ \phi\ [\mathrm{degrees}]$	{1.0,0}, {20.0,0}, 0.0
$\zeta,\ \gamma,\ \mu\ \lambda_b\ \lambda_t$	0.0, 0.0, 0.4, 0.0, 0.0
Linear material group:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	1.5, 1.5, 0.4

* Soft-bonded material parameters are defined in Table 5 of the base memo.

[8] Typical properties of Castlegate sandstone are listed in footnote 4 of the Example Materials 1 memo.
[9] A 2D soft-bonded clumped material can be created in the same way as for the 2D contact-bonded material example.

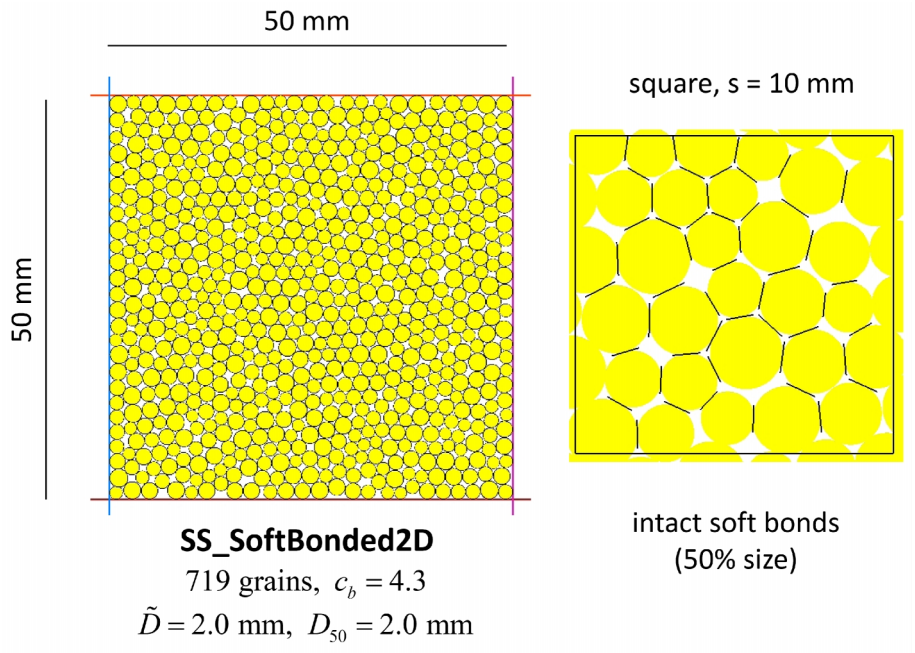

Figure 4 ***SS_SoftBonded2D material at the end of material genesis with grains and intact soft bonds in the microstructural box.***

1.5 Flat-Jointed Material Example

The flat-jointed material example is in the **`MatGen-FlatJointed`** example-project directory. A flat-jointed material is created to represent a typical sandstone, which we take to be Castlegate sandstone.[10] We denote our sandstone material as the SS_FlatJointed material with microproperties listed in Table 5. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus).[11] The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then the flat-joint contact model is installed between all grains that are in contact with one another and the flat-jointed material properties are assigned to those flat-jointed contacts (see Figure 5). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as for the contact-bonded material example in the Example Materials 1 memo.

Table 5 Microproperties of SS_FlatJointed Material*

Property	Value
Common group:	
N_m	SS_FlatJointed
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	4, 0.7, 1, 1960
$S_g,\ T_{SD},\ \{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\},\ D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\mathrm{lim}},\ n_{\mathrm{lim}}$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6}
$C_p,\ n_c$	1, 0.30
Flat-jointed material group:	
$C_{MS},\ g_i\ [\mathrm{mm}],\ \phi_B,\ \phi_G,\ (g_o)_{\{\mathrm{m,sd}\}}\ [\mathrm{mm}],\ \{N_r, N_\alpha\}$	false, 0, 1, 0, {0,0}, {1,3}
$\{C_\lambda,\ \lambda_v\},\ E^*\ [\mathrm{GPa}],\ \kappa^*,\ \mu$	{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:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	1.5, 1.5, 0.4

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

[10] Typical properties of Castlegate sandstone are listed in footnote 4 of the Example Materials 1 memo.
[11] A flat-jointed clumped material can be created in the same way as for the contact-bonded material example.

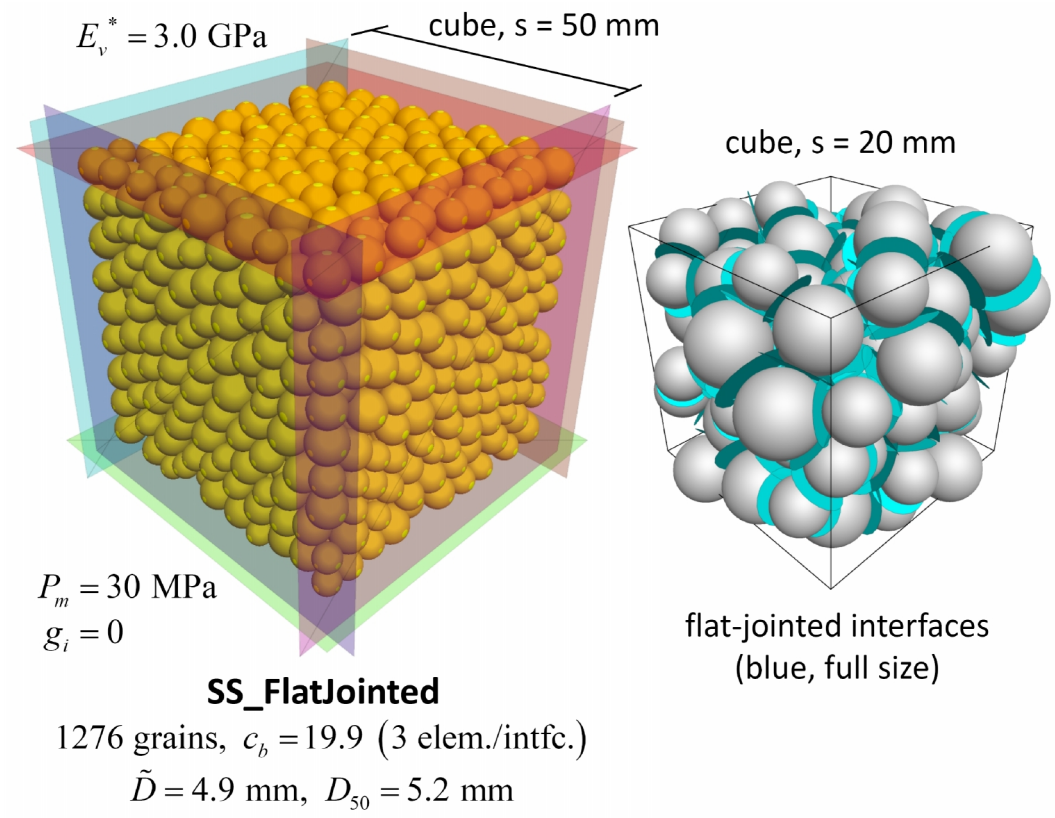

Figure 5 ***SS_FlatJointed material at the end of material genesis with grains and flat-jointed interfaces in the microstructural box.***

1.6 Flat-Jointed Material Example (2D model)

The flat-jointed material example for the 2D model is in the **`MatGen-FlatJointed`** example-project directory. The files for the 2D model contain the **`p2*`** extension (e.g., **`MatGen.p2prj`** and **`mpParams.p2dat`**). A 2D flat-jointed material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.[12] We denote our sandstone material as the SS_FlatJointed2D material with microproperties listed in Table 6. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus).[13] The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then the flat-joint contact model is installed between all grains that are in contact with one another and the flat-jointed material properties are assigned to those flat-jointed contacts (see Figure 6). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as for the contact-bonded material example in the Example Materials 1 memo.

Table 6 Microproperties of SS_FlatJointed2D Material*

Property	Value
Common group:	
N_m	SS_FlatJointed2D
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	4, 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:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\mathrm{lim}},\ n_{\mathrm{lim}}$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6}
$C_p,\ n_c$	1, 0.08
Flat-jointed material group:	
$C_{MS},\ g_i\ [\mathrm{mm}],\ \phi_B,\ \phi_G,\ (g_o)_{\{\mathrm{m,sd}\}}\ [\mathrm{mm}],\ N_r$	false, 0, 1, 0, {0,0}, 2
$\{C_\lambda,\ \lambda_v\},\ E^*\ [\mathrm{GPa}],\ \kappa^*,\ \mu$	{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:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	1.5, 1.5, 0.4

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

[12] Typical properties of Castlegate sandstone are listed in footnote 4 of the Example Materials 1 memo.
[13] A 2D flat-jointed clumped material can be created in the same way as for the 2D contact-bonded material example.

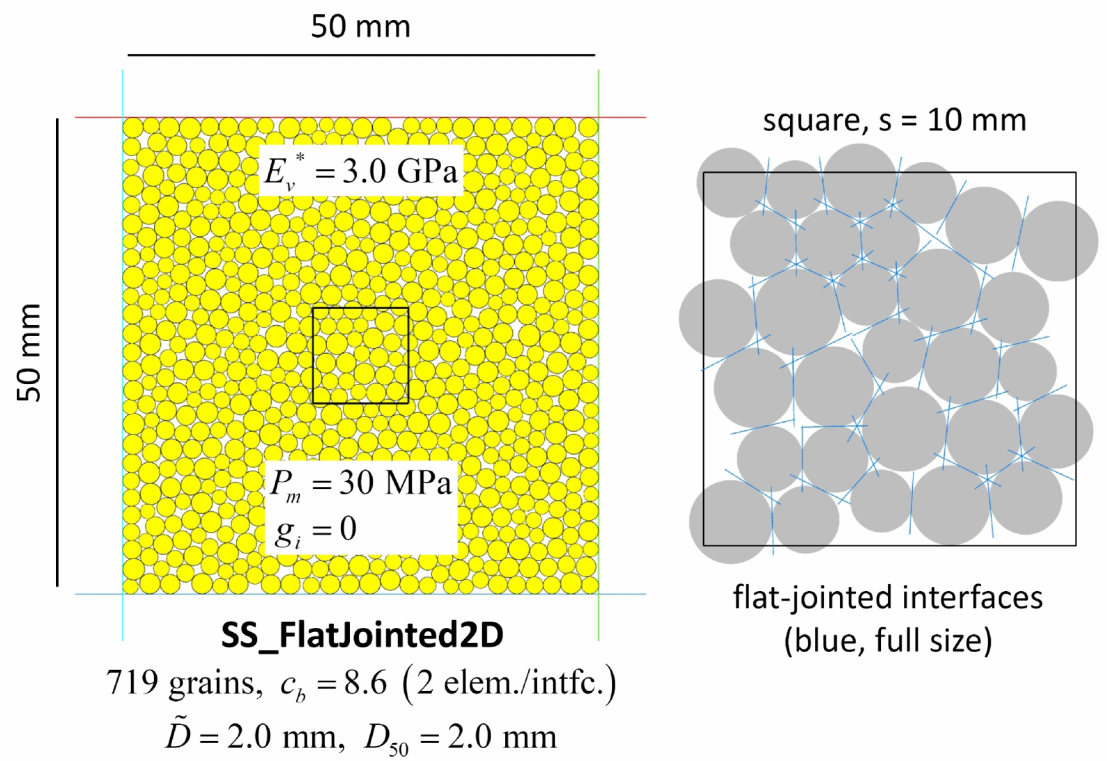

Figure 6 ***SS_FlatJointed2D material at the end of material genesis with grains and flat-jointed interfaces in the microstructural box.***

1.7 Smooth-Jointed Interface Example

The smooth-jointed interface example is in the **`MatGen-Interface`** example-project directory…
{DP: To be developed and described here…}