Memorandum

Date: December 11, 2019
To: PFC 6 Documentation Set
From: David Potyondy
Re: Material-Modeling Support for PFC [fistPkg6.6] (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 fistPkg6.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. 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). 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*

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common group:</td>
<td></td>
</tr>
<tr>
<td>$N_m$</td>
<td>SS_ParallelBonded</td>
</tr>
<tr>
<td>$T_m$, $\alpha$, $C_r$, $\rho_r$ [kg/m$^3$]</td>
<td>2, 0.7, 1, 1960</td>
</tr>
<tr>
<td>$S_g$, $T_g$, ${D_{\ell,i} [mm], \phi}$, $D_{\text{mult}}$</td>
<td>0, 0, ${4.0,6.0,1.0}$, 1.0</td>
</tr>
<tr>
<td>Packing group:</td>
<td></td>
</tr>
<tr>
<td>$S_{\gamma i}$, $P_i$ [MPa], $\varepsilon_p$, $\varepsilon_{\text{lim}}$, $n_{\text{lim}}$</td>
<td>10000, 30, $1\times10^{-2}$, $8\times10^{-3}$, $2\times10^6$, 1, 0.30</td>
</tr>
<tr>
<td>$C_p$, $n_l$</td>
<td></td>
</tr>
<tr>
<td>Parallel-bonded material group:</td>
<td></td>
</tr>
<tr>
<td>Linear group:</td>
<td></td>
</tr>
<tr>
<td>$E^<em>$ [GPa], $\kappa^</em>$, $\mu$</td>
<td>1.5, 1.5, 0.4</td>
</tr>
<tr>
<td>Parallel-bond group:</td>
<td></td>
</tr>
<tr>
<td>$g$, $\bar{g}$, $\bar{E}^<em>$ [GPa], $\bar{\kappa}^</em>$, $\bar{\beta}$</td>
<td>0, 1.0, 1.5, 1.5, 1.0</td>
</tr>
<tr>
<td>${\bar{\sigma}<em>i}</em>{\text{(out)}}$ [MPa], ${\bar{\tau}}_{\text{(out)}}$ [MPa], $\bar{\phi}$ [degrees]</td>
<td>${1.0,0}$, ${20.0,0}$, 0</td>
</tr>
<tr>
<td>Linear material group:</td>
<td></td>
</tr>
<tr>
<td>$E_n$ [GPa], $\kappa_n^*$, $\mu_n$</td>
<td>1.5, 1.5, 0.4</td>
</tr>
</tbody>
</table>

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

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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.

- $E_v^* = 3.0$ GPa
- cube, $s = 50$ mm
- $P_m = 30$ MPa
- $g_i = 0$

**SS_ParallelBonded**
- 1276 grains, $c_b = 6.6$
- $\bar{D} = 4.9$ mm, $D_{50} = 5.2$ mm

Parallel-bond cement (gold, 50% size)
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>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_m)</td>
<td>SS_ParallelBonded2D</td>
</tr>
<tr>
<td>(T_m, \alpha, C_p, \rho, \left[\text{kg/m}^3\right])</td>
<td>2, 0.7, 1, 1960</td>
</tr>
<tr>
<td>(S_{\phi}, T_{2D}, \left{D_{(i,m)} [\text{mm}], \phi_i\right}, D_{min})</td>
<td>0, 0, {4.0, 6.0, 1.0}, 1.0</td>
</tr>
<tr>
<td>(S_{\phi m}, P_{\phi m} [\text{MPa}], \varepsilon_{\phi m}, e_{\phi m, n_{lim}})</td>
<td>10000, 30, (1 \times 10^{-2}), (8 \times 10^{-3}), (2 \times 10^6), 1, 0.08</td>
</tr>
<tr>
<td>(C_{\phi m}, n_{c})</td>
<td>(1.0,0), {20.0,0}, 0</td>
</tr>
<tr>
<td>(g, [\text{mm}], \bar{\tau}, \bar{E} [\text{GPa}], \bar{\kappa}, \bar{\beta})</td>
<td>0, 1.0, 1.5, 1.5, 1.0</td>
</tr>
<tr>
<td>((\bar{e})<em>{(m,u)} [\text{MPa}], (\bar{e})</em>{(m,u)} [\text{MPa}], \bar{\phi} [\text{degrees}])</td>
<td>{1.0,0}, {20.0,0}, 0</td>
</tr>
<tr>
<td>(E_u [\text{GPa}], \kappa_u, \mu_u)</td>
<td>1.5, 1.5, 0.4</td>
</tr>
</tbody>
</table>

\(^*\) 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. 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). 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*

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common group:</td>
<td>SS_SoftBonded</td>
</tr>
<tr>
<td>( N_w )</td>
<td>3, 0.7, 1, 1960</td>
</tr>
<tr>
<td>( T_n, \alpha, C_p, \rho_c [\text{kg/m}^3] )</td>
<td>0, 0, {4.0,6.0,1.0}, 1.0</td>
</tr>
<tr>
<td>( S_g, T_{gb}, {D_{i,u} [\text{mm}], \phi}, D_{mult} )</td>
<td>10000, 30, 1\times10^{-2}, 8\times10^{-3}, 2\times10^6</td>
</tr>
<tr>
<td>Packing group:</td>
<td>1, 0.30</td>
</tr>
<tr>
<td>( S_{gb}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim} )</td>
<td>{1.0,0}, {20.0,0}, 0.0</td>
</tr>
<tr>
<td>( C_p, n_g )</td>
<td>0.0, 0.0, 4.0, 0.0, 0.0</td>
</tr>
<tr>
<td>Soft-bonded material group:</td>
<td></td>
</tr>
<tr>
<td>( g_s [\text{mm}], \lambda, E^+ [\text{GPa}], \kappa^+, \beta )</td>
<td>0, 1.0, 1.5, 1.5, 1.0</td>
</tr>
<tr>
<td>( (\sigma_c)<em>{(m,u)} [\text{MPa}], (c)</em>{(m,u)} [\text{MPa}], \phi[\text{degrees}] )</td>
<td>{1.0,0}, {20.0,0}, 0.0</td>
</tr>
<tr>
<td>( \zeta, \gamma, \mu, \lambda, \lambda_i )</td>
<td>0.0, 0.0, 4.0, 0.0, 0.0</td>
</tr>
<tr>
<td>Linear material group:</td>
<td></td>
</tr>
<tr>
<td>( E_c [\text{GPa}], \kappa_c^+, \mu_c )</td>
<td>1.5, 1.5, 0.4</td>
</tr>
</tbody>
</table>

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

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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  \textit{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. 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). 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*

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common group:</td>
<td></td>
</tr>
<tr>
<td>$N_m$</td>
<td>SS_SoftBonded2D</td>
</tr>
<tr>
<td>$T_m$, $\alpha$, $C_p$, $\rho$, $\left[kg/m^3\right]$</td>
<td>3, 0.7, 1, 1960</td>
</tr>
<tr>
<td>$S_k$, $T_{3D}$, $\left{D_{(\ell,t)}[mm], \phi_j \right}$, $D_{multi}$</td>
<td>0, 0, ${4.0,6.0,1.0}$, 1.0</td>
</tr>
<tr>
<td>Packing group:</td>
<td></td>
</tr>
<tr>
<td>$S_{kn}$, $P_{kn}$ [MPa], $\varepsilon_p$, $\varepsilon_{lim}$, $n_{lim}$</td>
<td>10000, 30, $1 \times 10^{-2}$, $8 \times 10^{-3}$, $2 \times 10^6$</td>
</tr>
<tr>
<td>$C_p$, $n_t$</td>
<td>1, 0.08</td>
</tr>
<tr>
<td>Soft-bonded material group:</td>
<td></td>
</tr>
<tr>
<td>$g_i$, [mm], $\lambda$, $E^<em>$ [GPa], $\kappa^</em>$, $\beta$</td>
<td>0, 1.0, 1.5, 1.5, 1.0</td>
</tr>
<tr>
<td>$\left(\sigma_r\right)<em>{(m,s)}, \left(c\right)</em>{(m,s)}$ [MPa], $\phi$ [degrees]</td>
<td>${1.0, 0}$, ${20.0, 0}$, 0.0</td>
</tr>
<tr>
<td>$\xi$, $\gamma$, $\mu$, $\lambda_b$, $\lambda_t$</td>
<td>0.0, 0.0, 0.4, 0.0, 0.0</td>
</tr>
<tr>
<td>Linear material group:</td>
<td></td>
</tr>
<tr>
<td>$E_u^<em>$ [GPa], $\kappa_u^</em>$, $\mu_u$</td>
<td>1.5, 1.5, 0.4</td>
</tr>
</tbody>
</table>

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

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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  \textit{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.\(^\text{10}\) 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).\(^\text{11}\) 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 |
| \(T_m, \alpha, C_p, \rho_v \text{[kg/m}^3]\) | 4, 0.7, 1, 1960 |
| \(S_g, T_{3D}, \{D_{\{i,a\}} \text{[mm]}, \phi\}, D_{\text{multi}}\) | 0, 0, \{4.0,6.0,1.0\}, 1.0 |
| Packing group: |  |
| \(S_{\text{pv}}, P_m \text{[MPa]}, \varepsilon_p, \varepsilon_{\text{lim}}, n_{\text{lim}}\) | 10000, 30, 1\times10^{-2}, 8\times10^{-3}, 2\times10^{6} |
| \(C_p, n_i\) | 1, 0.30 |
| Flat-jointed material group: |  |
| \(C_{\text{all}}, g_i \text{[mm]}, \phi_b, \phi_i, \{g_{\phi_i}\}_{\text{[mm]}}, \{N_r, N_a\}\) | false, 0, 1, 0, \{0,0\}, \{1,3\} |
| \(|C_2, \lambda\}, E^* \text{[GPa]}, \kappa^*, \mu\) | \{0, 1.0\}, 3.0, 1.5, 0.4 |
| \(|\sigma_{i}\}_{\text{[MPa]}}, (c)_{\text{[MPa]}}, \phi[\text{degrees}]\) | \{1.0,0\}, \{20.0,0\}, 0 |
| Linear material group: |  |
| \(E^* \text{[GPa]}, \kappa^*, \mu\) | 1.5, 1.5, 0.4 |

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

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\(^{10}\) 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.
Material Modeling Support for PFC [fistPkg6.6] (Example Materials 2)

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. 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). 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>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common group:</td>
<td></td>
</tr>
<tr>
<td>$N_w$, $T_u$, $C_v$, $\rho$, [$\text{kg/m}^3$]</td>
<td>SS_FlatJointed2D</td>
</tr>
<tr>
<td>$S_y$, $T_{3D}$, ${D_{(0)} \text{[mm]}, \phi}$, $D_{muit}$</td>
<td>0, 0, ${1.6, 2.4, 1.0}$, 1.0</td>
</tr>
<tr>
<td>Packing group:</td>
<td></td>
</tr>
<tr>
<td>$S_{2D}$, $P_m$ [MPa], $\varepsilon_p$, $\varepsilon_{nm}$, $n_{lm}$</td>
<td>10000, 30, $1\times10^{-2}$, $8\times10^{-3}$, $2\times10^4$</td>
</tr>
<tr>
<td>$C_p$, $n_p$</td>
<td>1, 0.08</td>
</tr>
<tr>
<td>Flat-jointed material group:</td>
<td></td>
</tr>
<tr>
<td>$C_{3D}$, $g$, [mm], $\phi_b$, $\phi_i$, $(g_c)_{(\text{adj})}$ [mm], $N_r$</td>
<td>false, 0, 1, 0, ${0,0}$, 2</td>
</tr>
<tr>
<td>${C_j, \lambda_j}$, $E'\text{[GPa]}$, $\kappa'$, $\mu$</td>
<td>${0,1.0}$, 3.0, 1.5, 0.4</td>
</tr>
<tr>
<td>$(\sigma_c)<em>{(\text{adj})}$ [MPa], $(c)</em>{(\text{adj})}$ [MPa], $\phi$ [degrees]</td>
<td>${1.0,0}$, ${20.0,0}$, 0</td>
</tr>
<tr>
<td>Linear material group:</td>
<td></td>
</tr>
<tr>
<td>$E'_n$ [GPa], $\kappa'\phi$, $\mu$</td>
<td>1.5, 1.5, 0.4</td>
</tr>
</tbody>
</table>

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

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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…}