Memorandum

ITASCA
Consulting Group, Inc.

Date: March 16, 2017

To: PFC 5 Documentation Set

From: David Potyondy

Re: Material-Modeling Support in PFC [fistPkg25] (Example Materials 1)

Ref: ICG7766-L

TABLE OF CONTENTS

1.0 EXAMPLE MATERIALS

The PFC 5.0 FISHTank produces linear, contact-bonded, parallel-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 **`fistPkgN/ExampleProjects/MatGen-M`** directory, where **`N`** is the version number of the PFC 5.0 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 linear and contact-bonded materials 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 Linear Material Example

The linear material example is in the **`MatGen-Linear`** example-project directory. A linear material is created to represent a typical aggregate base layer of an asphalt-surface roadway (Potyondy et al., 2016). We denote our aggregate material as the AG_Linear material with microproperties listed in Table 1. The material is created in a cylindrical material vessel (of initial 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure via the boundary-contraction packing procedure as shown in Figure 1. The material is then subjected to triaxial testing. During the triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient modulus (see Figure 2).[2] The hysteretic response is the expected behavior, and the resilient modulus (181 MPa) is similar to the effective modulus of the linear material (500 MPa).

Table 1 Microproperties of AG_Linear Material

Property	Value
Common group:	
N_m	AG_Linear
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ \left[\mathrm{kg/m^3}\right]$	0, 0.7, 0, 2650
$S_g,\ T_{SD},\ \left\{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\right\},\ D_{mult}$	0, 0, $\{14, 20, 1.0\}$, 1.0
Packing group:	
$S_{RN},\ P_m\ [\mathrm{kPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$ $C_p,\ n_c,\ \mu_{CA},\ v_{\lim}\ [\mathrm{m/s}]$	10000, 150, 1×10^{-2}, 8×10^{-3}, 2×10^{6} 0, 0.58, 0, 1.0
Linear material group:	
$E^*\ [\mathrm{MPa}],\ \kappa^*,\ \mu$	500, 1.5, 0.4

* Linear material parameters are defined in Table 2 of the base memo.

[2] The confinement is similar to that defined in resilient modulus laboratory protocols, and axial strains correspond with vertical strains in the aggregate base layer for typical traffic loads.

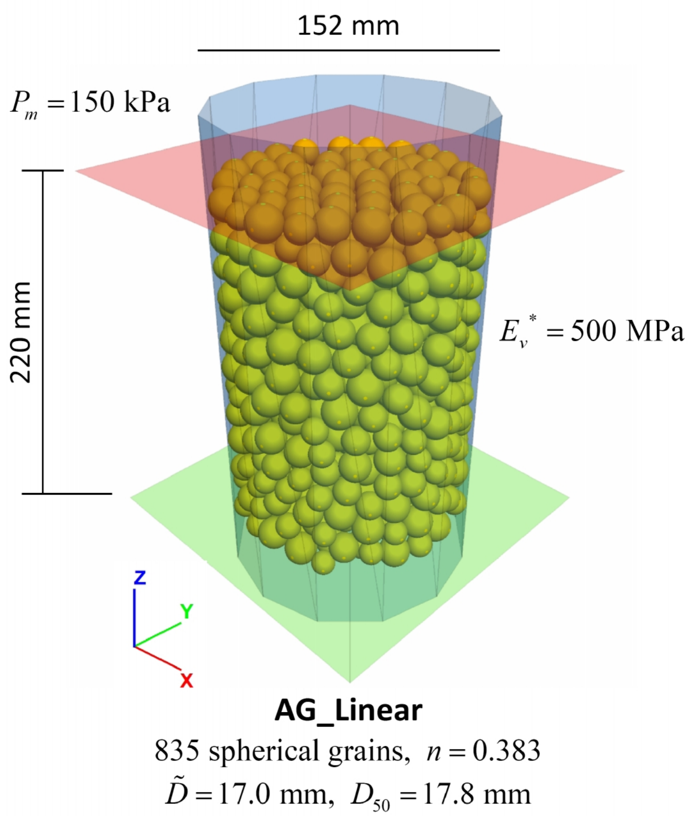

Figure 1 ***AG_Linear material packed at 150 kPa material pressure at the end of material genesis.***

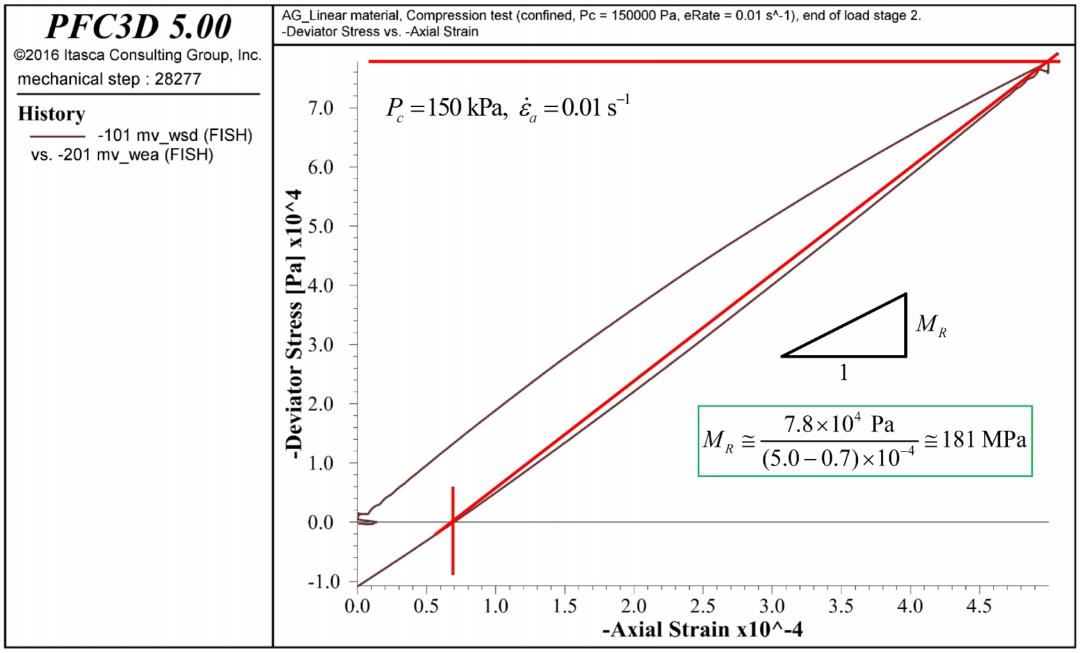

Figure 2 Deviator stress versus axial strain for AG_Linear material tested at 150 kPa confinement, and measurement of resilient modulus.

The linear material example is modified to replace the spherical grains with clumped grains by replacing the call to **`mpParams.p3dat`** in **`MatGen.p3dvr`** with a call to **`mpParams-Clumped.p3dat`**. The new material is denoted as a linear clumped material with microproperties listed in Table 2. The clumped material has two grain shapes. The first shape is a dyad consisting of two spherical pebbles, and the second shape is a peanut consisting of three spherical pebbles. The clumped grains are drawn from a uniform size distribution with diameters ranging from 14 to 20 mm, and with 75% of the grains being dyads and 25% of the grains being peanuts. The diameter of each clumped grain is the diameter of a sphere with the same volume as the grain. The material-creation and testing procedures for the clumped material are the same as those for the AG_Linear material.

The clumped material is created in a cylindrical material vessel (of initial 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure via the boundary-contraction packing procedure as shown in Figure 3. The porosity of the clumped material (0.328) is less than that of the spherical material (0.383) — the dyads and peanuts have packed to a denser state than the spheres. The clumped material is then subjected to triaxial testing. During the triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient modulus (see Figure 4). The hysteretic response is the expected behavior, and the resilient modulus is similar to the effective modulus of the linear material. The clumped material is stiffer (308 MPa) than the spherical material (181 MPa), with increased stiffness attributed to reduced porosity.

Table 2 Microproperties of AG_Linear Clumped Material*

Property	Value
Common group:	
N_m	AG_Linear [clumped]
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ [\mathrm{kg/m^3}]$	0, 0.7, 0, 2650
$S_g,\ n_{SD},\ T_{SD},\ \{N_{ct},\ D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\},\ D_{mult}$	$1,\ 2,\ 0,\ \begin{Bmatrix}\text{dyad}, & 14, 20, 0.75 \\ \text{peanut}, & 14, 20, 0.25\end{Bmatrix},\ 1.0$
Packing group:	
$S_{RN},\ P_m\ [\mathrm{kPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$ $C_p,\ n_c,\ \mu_{CA},\ v_{\lim}\ [\mathrm{m/s}]$	$10000,\ 150,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$ 0, 0.43, 0, 1.0
Linear material group:	
$E^*\ [\mathrm{MPa}],\ \kappa^*,\ \mu$	500, 1.5, 0.4

* Linear material parameters are defined in Table 2 of the base memo.

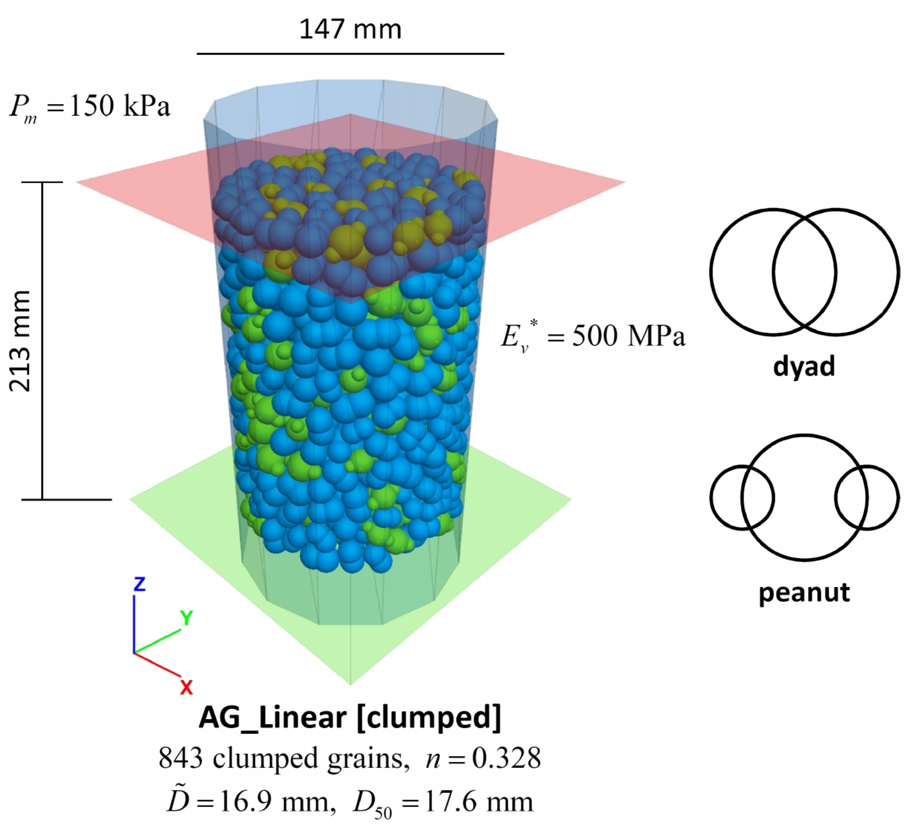

Figure 3 AG_Linear clumped material packed at 150 kPa material pressure at the end of material genesis.

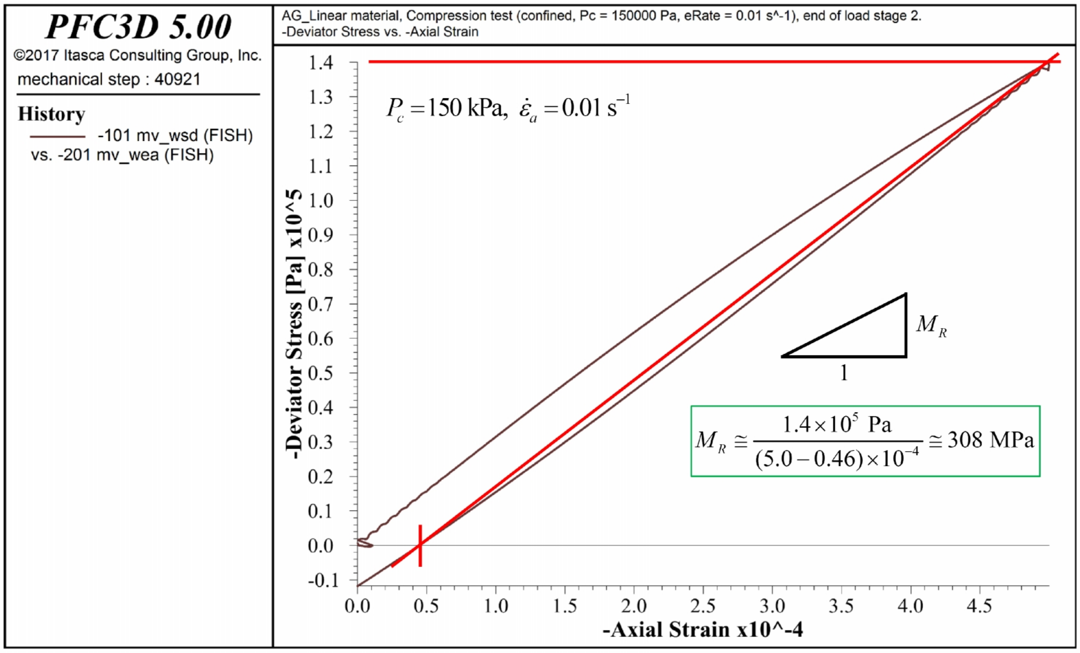

Figure 4 ***Deviator stress versus axial strain for AG_Linear clumped material tested at 150 kPa confinement, and measurement of resilient modulus.***

1.2 Linear Material Example (2D model)

The linear material example for the 2D model is in the **`MatGen-Linear`** example-project directory. The files for the 2D model contain the **`p2*`** extension (e.g., **`MatGen.p2prj`** and **`mpParams.p2dat`**). A 2D linear material (consisting of rigid unit-thickness disks) is created to represent a typical aggregate base layer of an asphalt-surface roadway (Potyondy et al., 2016). We denote our aggregate material as the AG_Linear2D material with microproperties listed in Table 3. The 2D material is created in a rectangular-cuboid material vessel (of 240-mm height, 170-mm width and unit depth, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 5. The material is then subjected to compression testing. During the compression test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient modulus and Poisson's ratio (see Figures 6 and 7, and note that the modulus computation requires the value of Poisson's ratio as discussed in Section 5.2 of the base memo).[3] The hysteretic response is the expected behavior, and the resilient modulus (228 MPa) is similar to the effective modulus of the linear material (500 MPa).

Table 3 Microproperties of AG_Linear2D Material*

Property	Value
Common group:	
N_m	AG_Linear2D
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ \left[\mathrm{kg/m^3}\right]$	$0,\ 0.7,\ 0,\ 2650$
$S_g,\ T_{SD},\ \left\{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\right\},\ D_{mult}$	$0,\ 0,\ \{7,10,1.0\},\ 1.0$
Packing group:	
$S_{RN},\ P_m\ [\mathrm{kPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$	$10000,\ 150,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$
$C_p,\ n_c,\ \mu_{CA},\ v_{\lim}\ [\mathrm{m/s}]$	$0,\ 0.25,\ 0,\ 1.0$
Linear material group:	
$E^*\ [\mathrm{MPa}],\ \kappa^*,\ \mu$	$500,\ 1.5,\ 0.4$

* Linear material parameters are defined in Table 2 of the base memo.

[3] The confinement is similar to that defined in resilient modulus laboratory protocols, and axial strains correspond with vertical strains in the aggregate base layer for typical traffic loads.

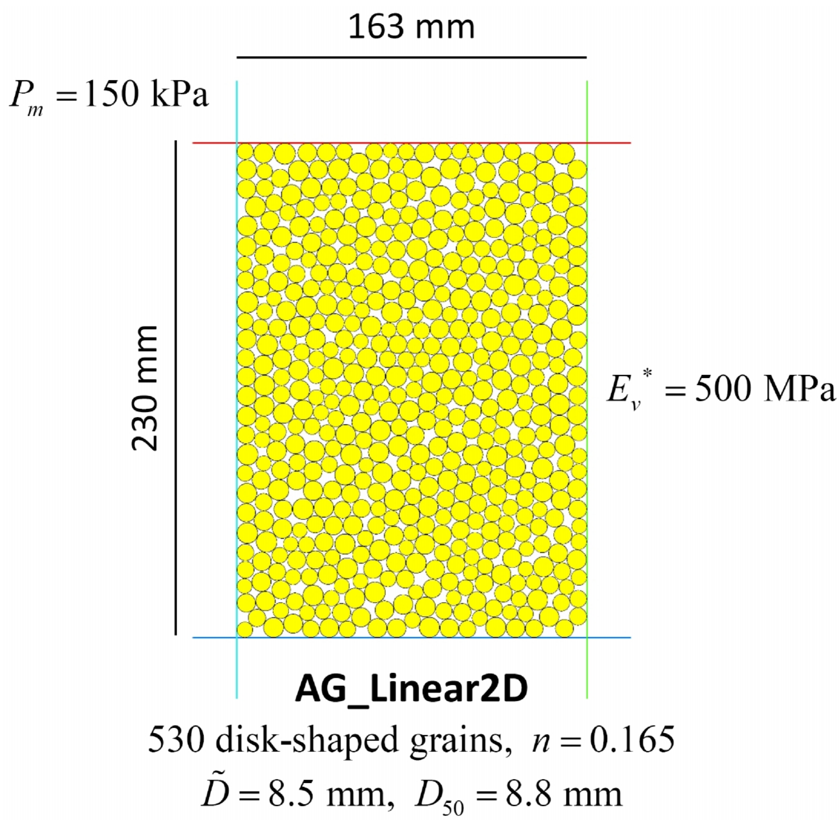

Figure 5 AG_Linear2D material packed at 150 kPa material pressure at the end of material genesis.

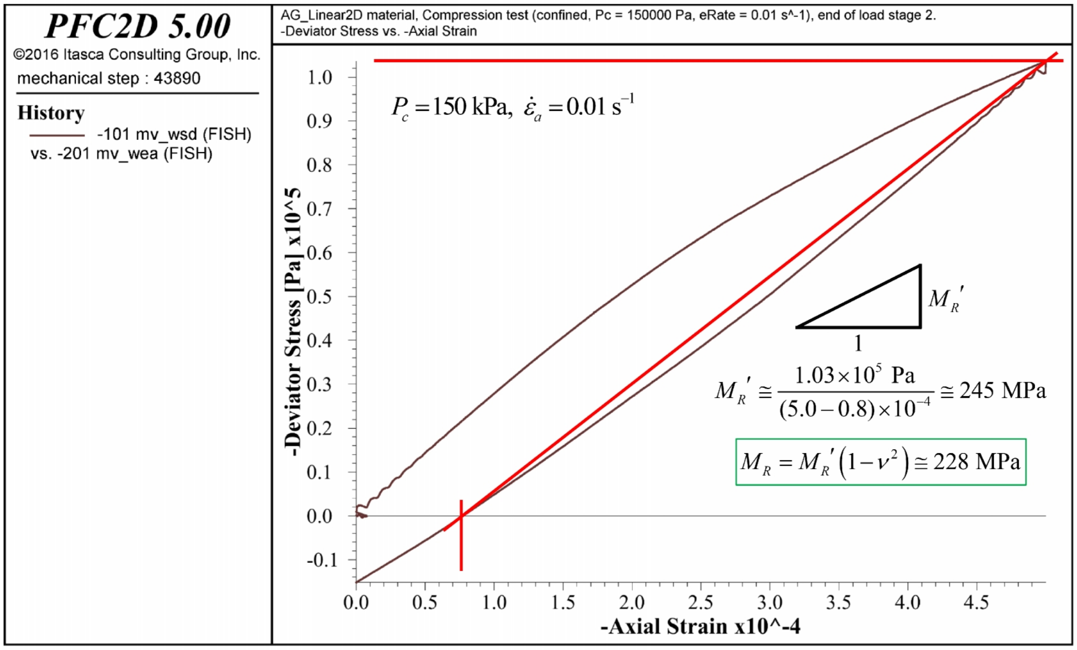

Figure 6 ***Deviator stress versus axial strain for AG_Linear2D material tested at 150 kPa confinement, and measurement of resilient modulus.***

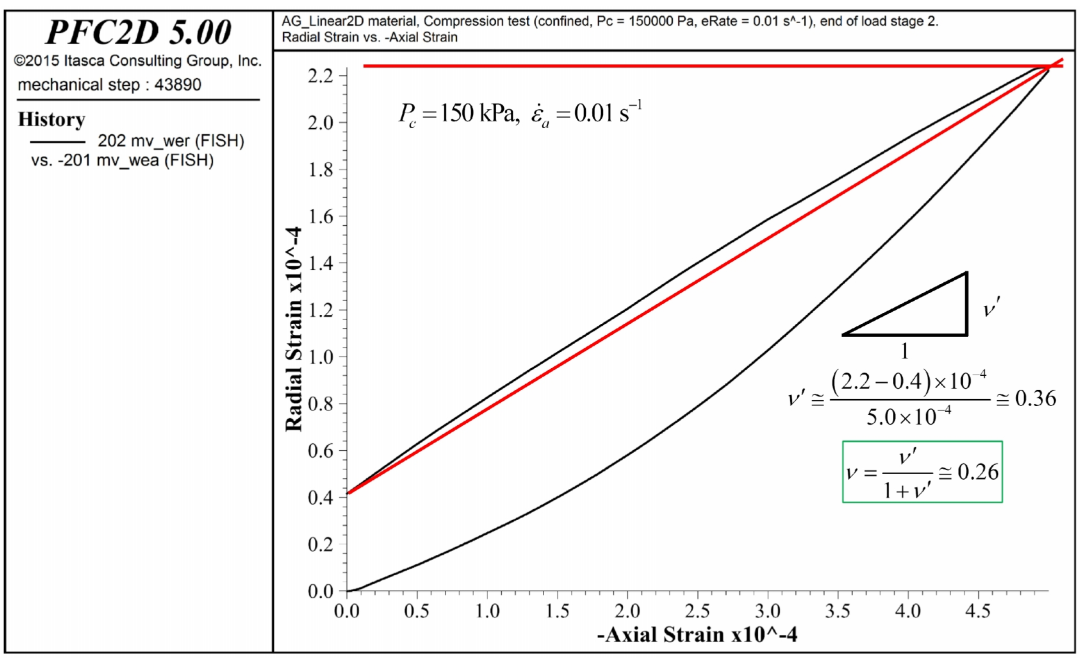

Figure 7 ***Radial strain versus axial strain for AG_Linear2D material tested at 150 kPa confinement, and measurement of Poisson's ratio.***

The linear material example for the 2D model is modified to replace the disk-shaped grains with clumped grains by replacing the call to **`mpParams.p2dat`** in **`MatGen.p2dvr`** with a call to **`mpParams-Clumped.p2dat`**. The new material is denoted as a linear clumped material with microproperties listed in Table 4. The clumped material has two grain shapes. The first shape is a dyad consisting of two disk-shaped pebbles, and the second shape is a peanut consisting of three disk-shaped pebbles. The clumped grains are drawn from a uniform size distribution with diameters ranging from 7 to 10 mm, and with 75% of the grains being dyads and 25% of the grains being peanuts. The diameter of each clumped grain is the diameter of a unit-thickness disk with the same volume as the grain. The material-creation and testing procedures for the clumped material are the same as those for the AG_Linear2D material.

The 2D clumped material is created in a rectangular-cuboid material vessel (of 240-mm height, 170-mm width and unit depth, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 8. The porosity of the clumped material (0.131) is less than that of the disk-only material (0.165) — the dyads and peanuts have packed to a denser state than the disks. The material is then subjected to compression testing. During the compression test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient modulus and Poisson's ratio (see Figures 9 and 10, and note that the modulus computation requires the value of Poisson's ratio as discussed in Section 5.2 of the base memo). The hysteretic response is the expected behavior, and the resilient modulus is similar to the effective modulus of the linear material. The clumped material is stiffer (463 MPa) than the disk-only material (228 MPa), with increased stiffness attributed to reduced porosity.

Table 4 Microproperties of AG_Linear2D Clumped Material*

Property	Value
Common group:	
N_m	AG_Linear2D [clumped]
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ \left[\mathrm{kg/m^3}\right]$	$0,\ 0.7,\ 0,\ 2650$
$S_g,\ n_{SD},\ T_{SD},\ \left\{N_{ct},\ D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\right\},\ D_{mult}$	$1,\ 2,\ 0,\ \begin{Bmatrix}\text{dyad}, & 7,10,0.75\\ \text{peanut}, & 7,10,0.25\end{Bmatrix},\ 1.0$
Packing group:	
$S_{RN},\ P_m\ [\mathrm{kPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$ $C_p,\ n_c,\ \mu_{CA},\ v_{\lim}\ [\mathrm{m/s}]$	$10000,\ 150,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$ $0,\ 0.25,\ 0,\ 1.0$
Linear material group:	
$E^*\ [\mathrm{MPa}],\ \kappa^*,\ \mu$	$500,\ 1.5,\ 0.4$

* Linear material parameters are defined in Table 2 of the base memo.

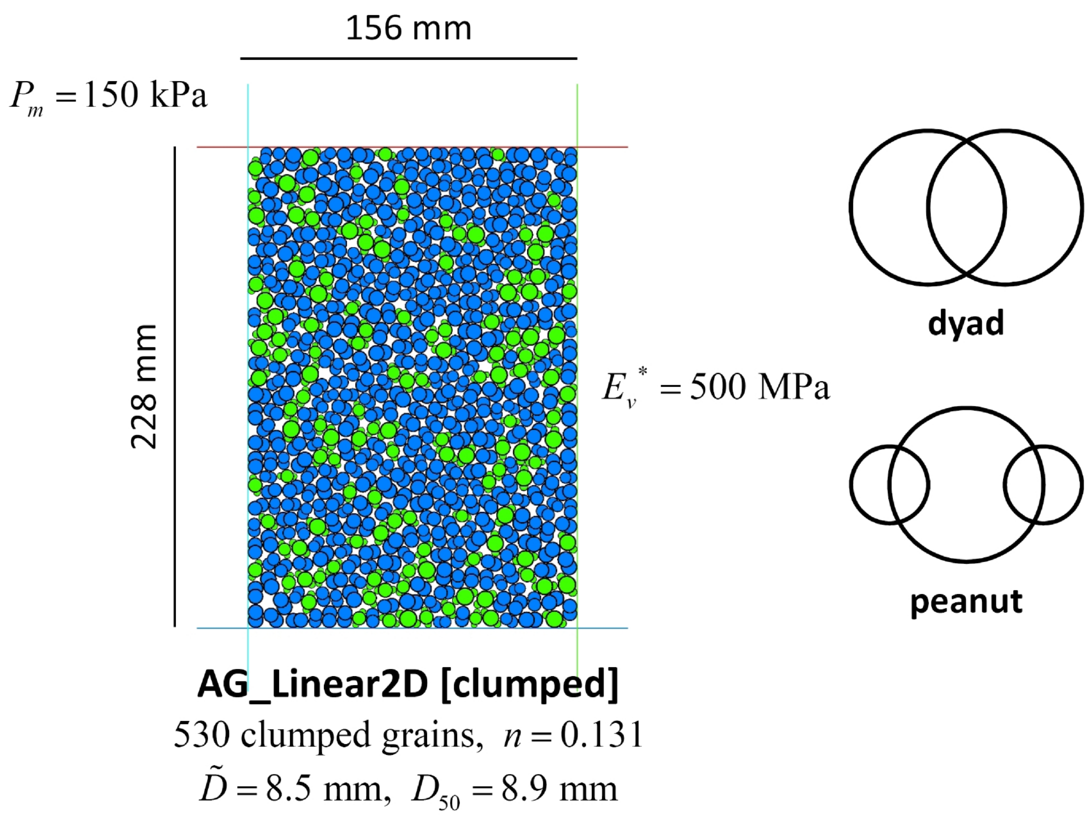

Figure 8 AG_Linear2D clumped material packed at 150 kPa material pressure at the end of material genesis.

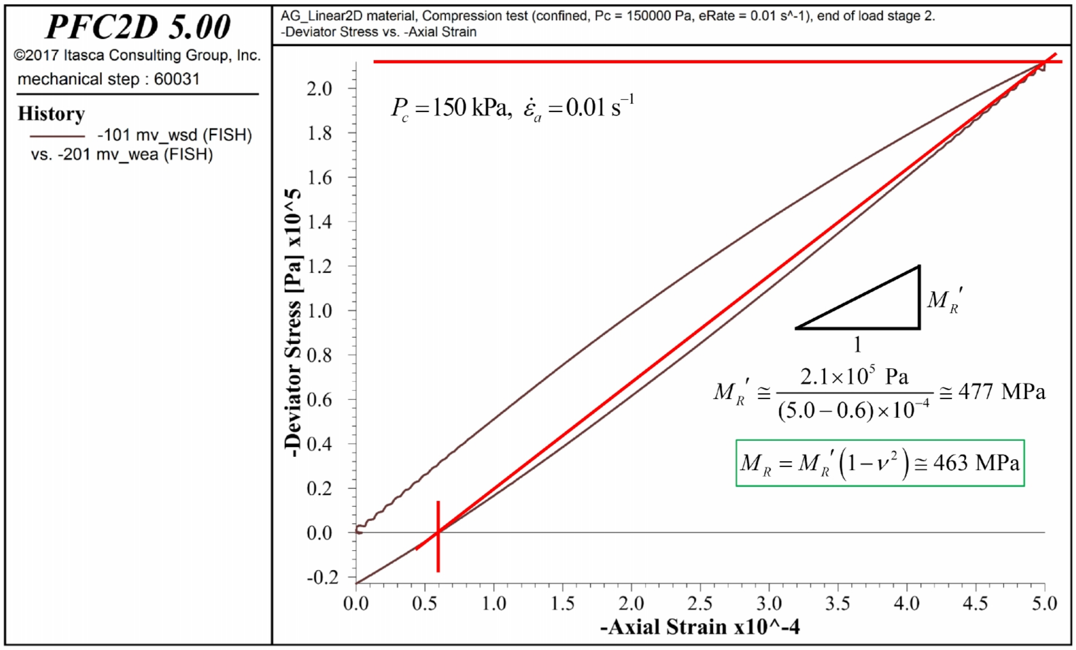

Figure 9 ***Deviator stress versus axial strain for AG_Linear2D clumped material tested at 150 kPa confinement, and measurement of resilient modulus.***

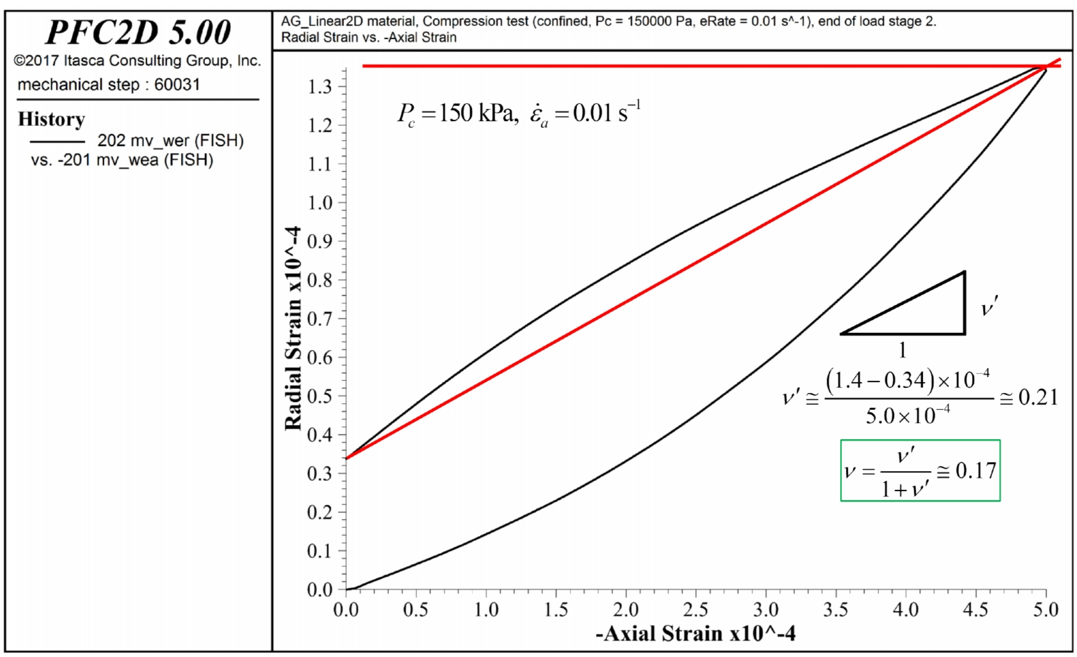

Figure 10 ***Radial strain versus axial strain for AG_Linear2D clumped material tested at 150 kPa confinement, and measurement of Poisson's ratio.***

1.3 Contact-Bonded Material Example

The contact-bonded material example is in the **`MatGen-ContactBonded`** example-project directory. A contact-bonded material is created to represent a typical sandstone, which we take to be Castlegate sandstone.[4] We denote our sandstone material as the SS_ContactBonded 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). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then contact bonds are added between all grains that are in contact with one another (see Figure 11). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results are shown in Figures 12–18.

Table 5 Microproperties of SS_ContactBonded Material*

Property	Value
Common group:	
N_m	SS_ContactBonded
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ \left[\mathrm{kg/m^3}\right]$	$1,\ 0.7,\ 1,\ 1960$
$S_g,\ T_{SD},\ \left\{D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\right\},\ D_{mult}$	$0,\ 0,\ \{4.0, 6.0, 1.0\},\ 1.0$
Packing group:	
$S_{RN},\ P_m\ [\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$	$10000,\ 30,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$
$C_p,\ n_c$	$1,\ 0.30$
Contact-bonded material group:	
Linear group:	
$E^*\ [\mathrm{GPa}],\ \kappa^*,\ \mu$	$3.0,\ 1.5,\ 0.4$
Contact-bond group:	
$g_i\ [\mathrm{mm}]$	0
$(T_\sigma)_{\{\mathrm{m,sd}\}}\ [\mathrm{MPa}],\ (S_\sigma)_{\{\mathrm{m,sd}\}}\ [\mathrm{MPa}]$	$\{1.0, 0\},\ \{20.0, 0\}$
Linear material group:	
$E_n^*\ [\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	$3.0,\ 1.5,\ 0.4$

* Contact-bonded material parameters are defined in Table 3 of the base memo.

---

[4] The following properties are typical of Castlegate sandstone: density of $1960\ \mathrm{kg/m^3}$; median grain size of 0.19 mm; direct-tension strength of 1.0 MPa; unconfined-compressive strength of 20.0 MPa; and Young's modulus and Poisson's ratio measured during unconfined-compression test of 2.9 GPa and 0.33, respectively.

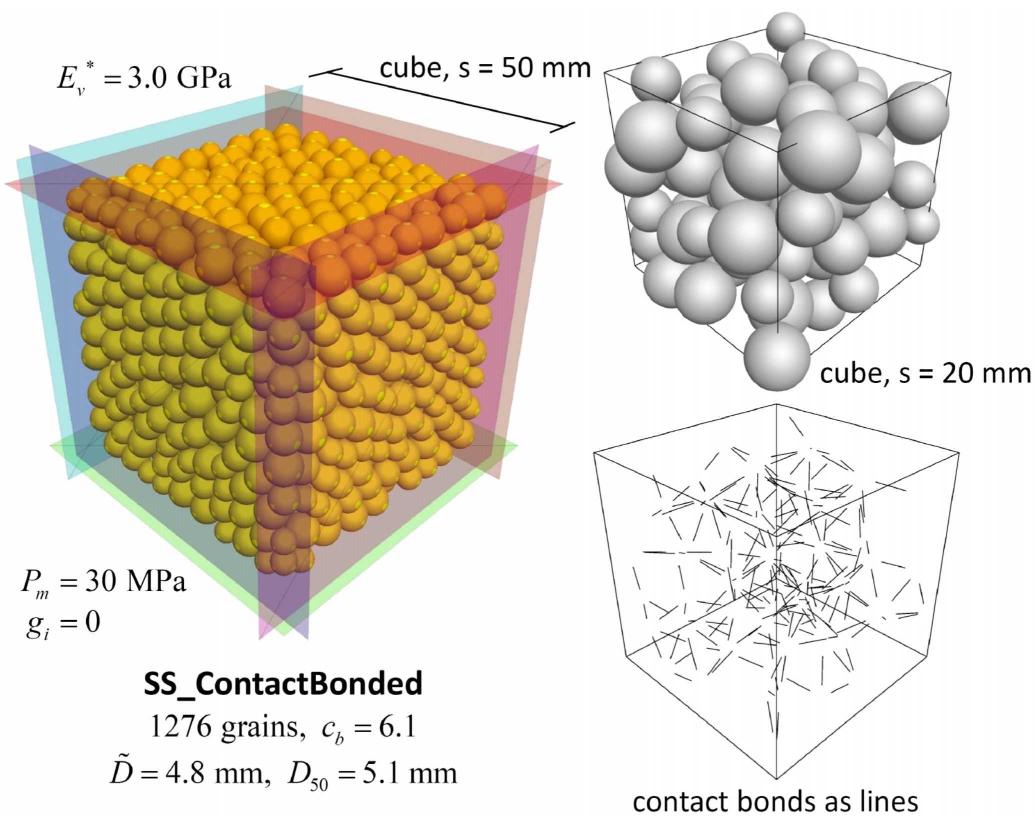

Figure 11 SS_ContactBonded material at the end of material genesis with grains and contact bonds in the microstructural box.

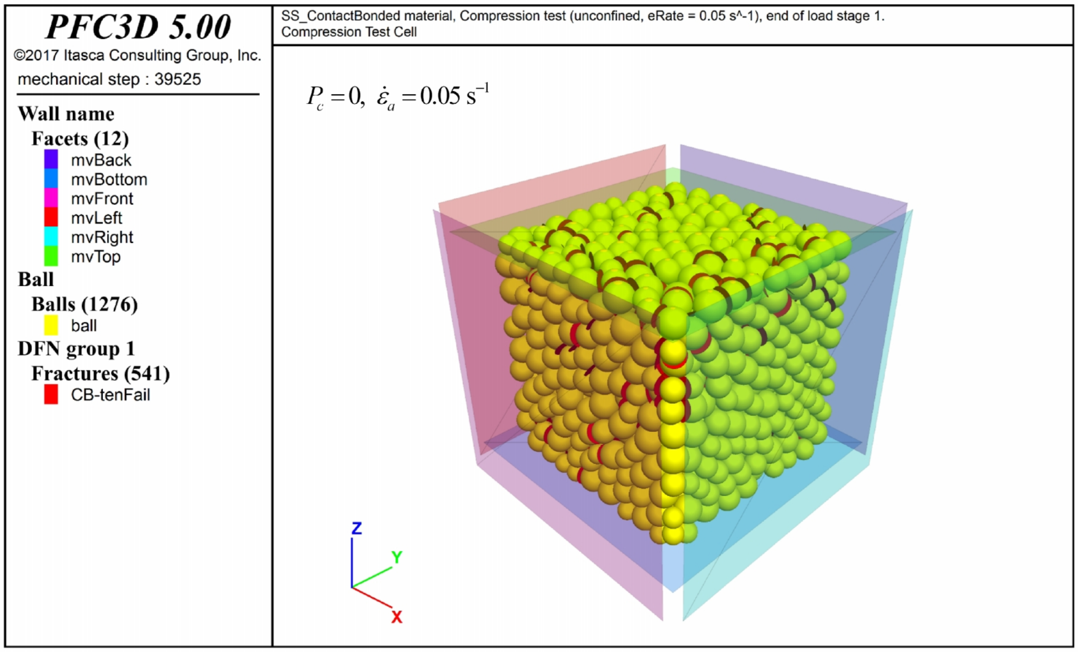

Figure 12 ***SS_ContactBonded material at the end of the fully unconfined test with grains and cracks.***

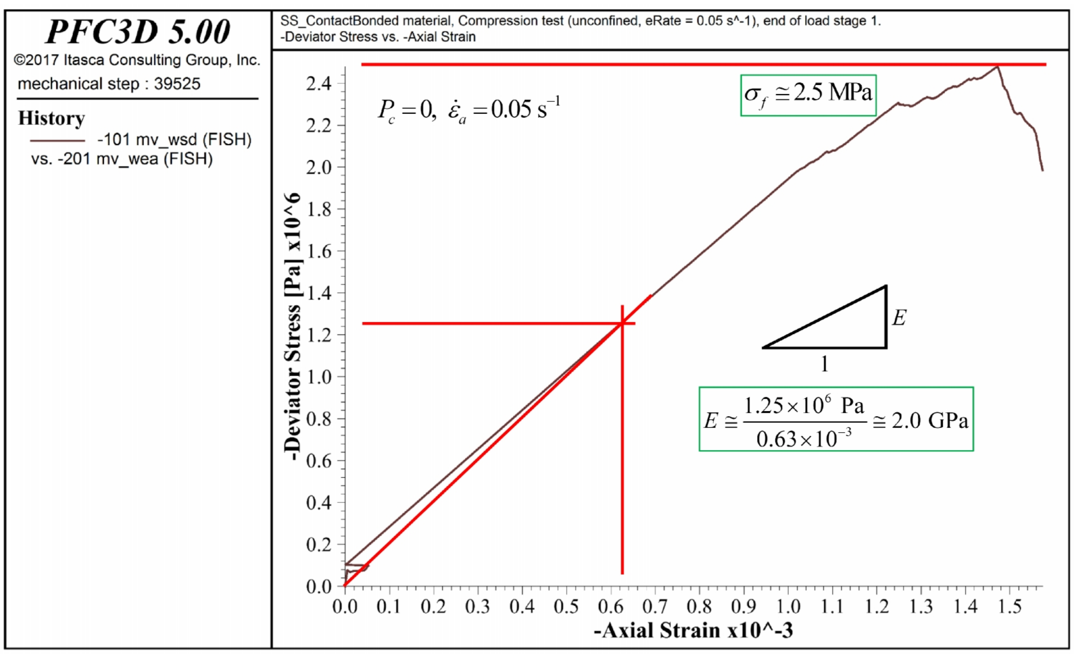

Figure 13 ***Deviator stress versus axial strain for SS_ContactBonded material tested fully unconfined, and measurement of peak strength and Young's modulus.***

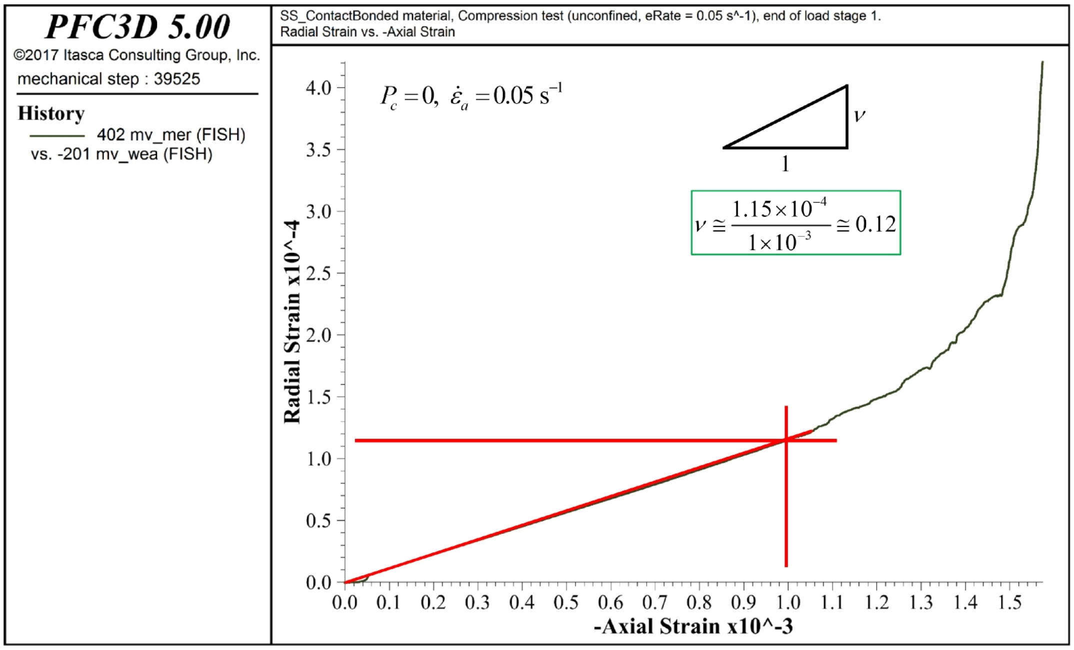

Figure 14 Radial strain versus axial strain for SS_ContactBonded material tested fully unconfined, and measurement of Poisson's ratio.

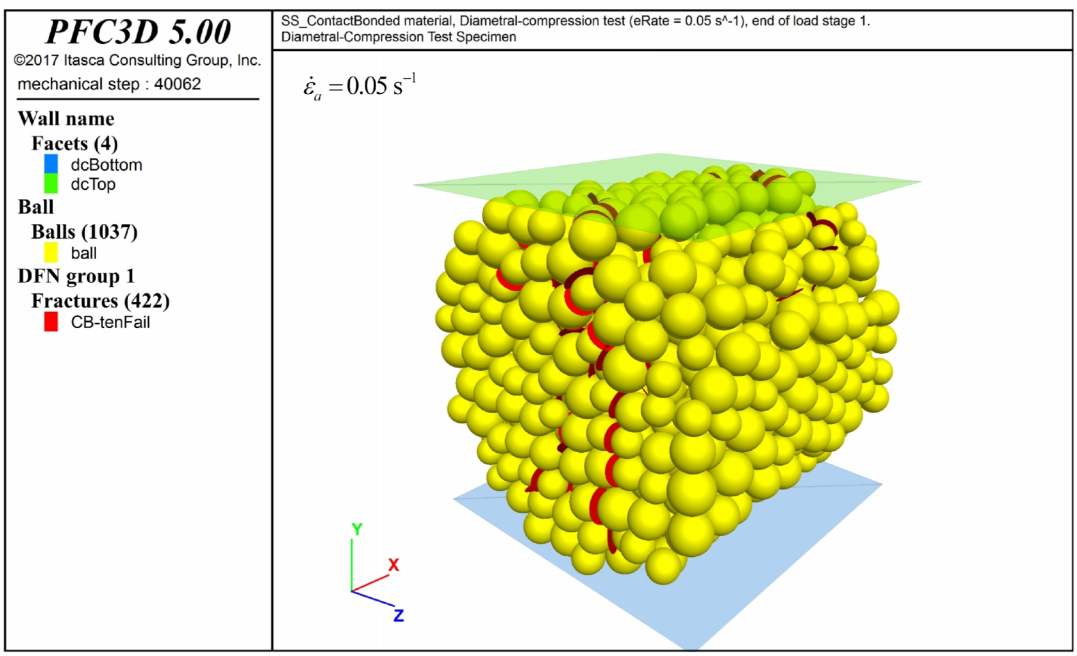

Figure 15 SS_ContactBonded material at the end of diametral-compression test with grains and cracks.

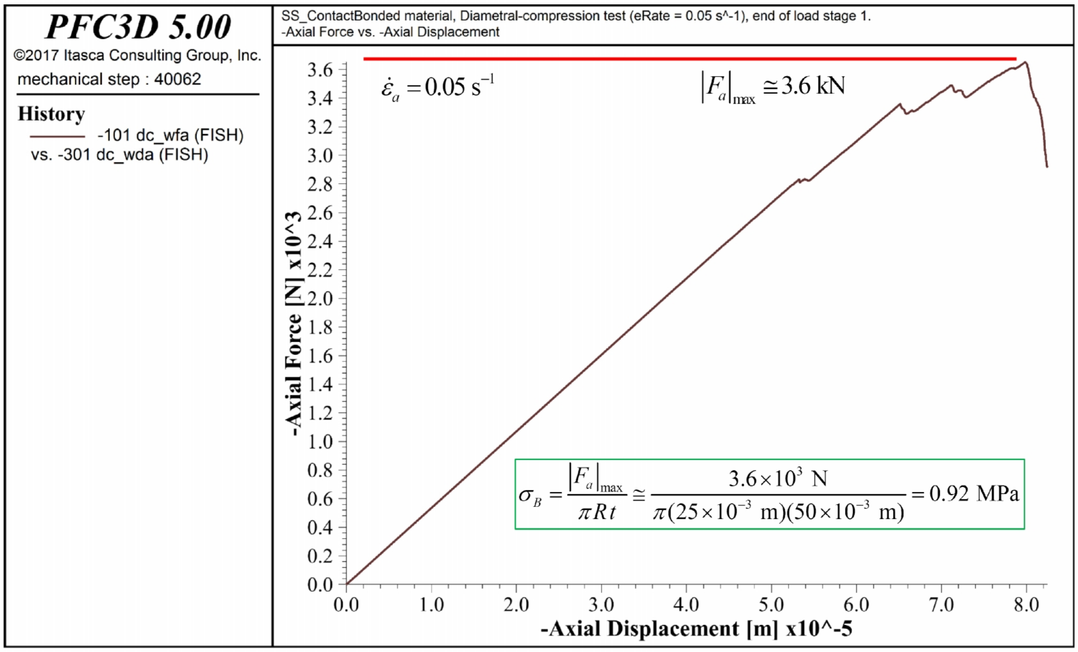

Figure 16 ***Axial force versus axial displacement for SS_ContactBonded material during the diametral-compression test, and measurement of Brazilian tensile strength.***

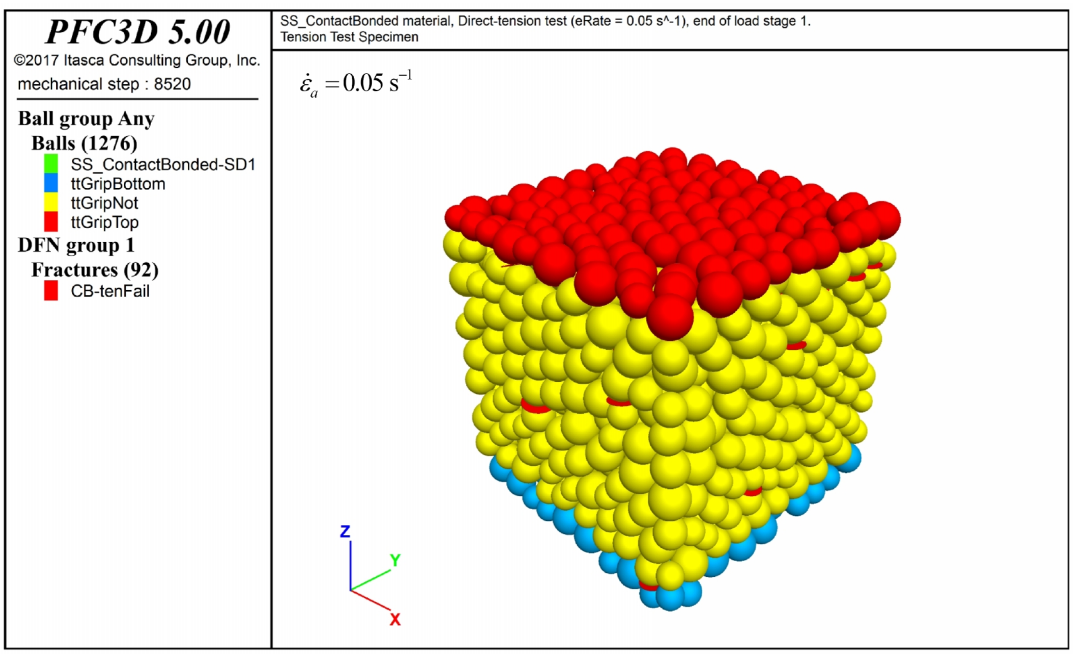

Figure 17 ***SS_ContactBonded material at the end of the direct-tension test with grains and cracks.***

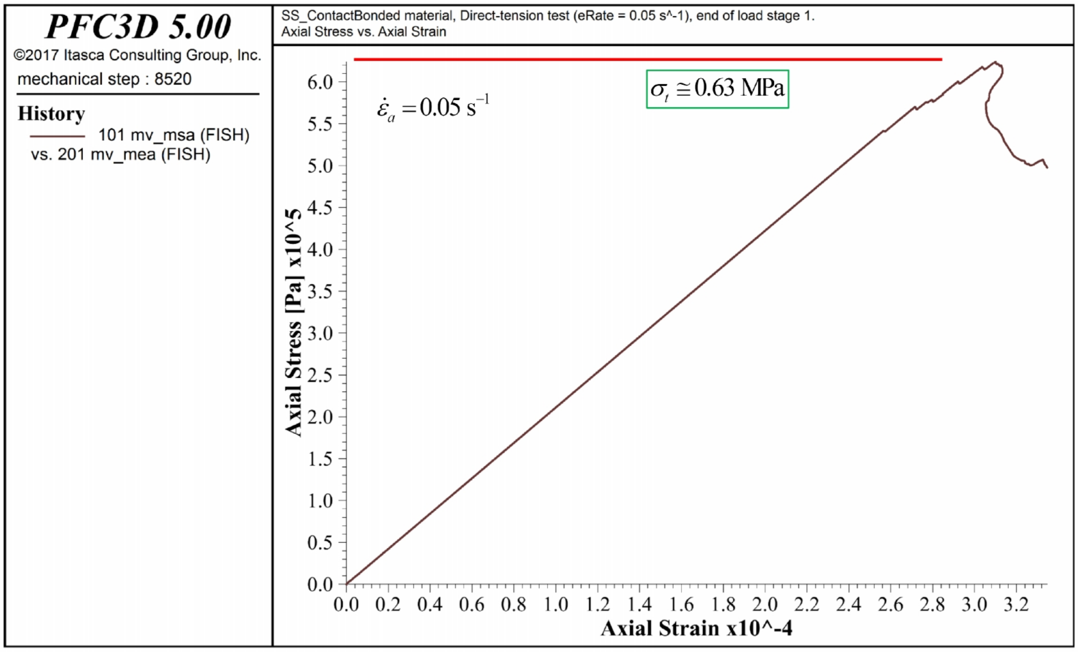

Figure 18 Axial stress versus axial strain for SS_ContactBonded material during the direct-tension test, and measurement of tensile strength.

The contact-bonded material example is modified to replace the spherical grains with clumped grains by replacing the call to **`mpParams.p3dat`** in **`MatGen.p3dvr`** with a call to **`mpParams-Clumped.p3dat`**. The new material is denoted as a contact-bonded clumped material with microproperties listed in Table 6. The clumped material has two grain shapes. The first shape is a dyad consisting of two spherical pebbles, and the second shape is a peanut consisting of three spherical pebbles (see Figure 3). The clumped grains are drawn from a uniform size distribution with diameters ranging from 4 to 6 mm, and with 75% of the grains being dyads and 25% of the grains being peanuts. The diameter of each clumped grain is the diameter of a sphere with the same volume as the grain. The material-creation and testing procedures for the clumped material are the same as those for the SS_ContactBonded material.

The clumped 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 contact bonds are added between all grains that are in contact with one another (see Figure 19). The bond coordination number of the clumped material (10.3) is larger than that of the spherical material (6.1), and the porosity of the clumped material (0.299) is less than that of the spherical material (0.330) — the dyads and peanuts have packed to a denser state than the spheres. The clumped material is then subjected to compression, diametral-compression and direct-tension tests. The compression-test results are shown in Figures 20 and 21. The clumped material is stronger (5.8 MPa versus 2.5 MPa) and stiffer (2.8 GPa versus 2.0 GPa) than the spherical material, with increased strength and stiffness attributed to increased bond coordination number and reduced porosity.

Table 6 Microproperties of SS_ContactBonded Clumped Material

Property	Value
Common group:	
N_m	SS_ContactBonded [clumped]
$T_m,\ \alpha,\ C_\rho,\ \rho_v\left[\mathrm{kg/m^3}\right]$	$1,\ 0.7,\ 1,\ 1960$
$S_g,\ n_{SD},\ T_{SD},\ \left\{N_{ct},\ D_{\{l,u\}}\ [\mathrm{mm}],\ \phi\right\},\ D_{mult}$	$1,\ 2,\ 0,\ \begin{Bmatrix}\text{dyad}, & 4.0, 6.0, 0.75\\ \text{peanut}, & 4.0, 6.0, 0.25\end{Bmatrix},\ 1.0$
Packing group:	
$S_{RN},\ P_m\,[\mathrm{MPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$ $C_p,\ n_c$	$10000,\ 30,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$ $1,\ 0.30$
Contact-bonded material group:	
Linear group:	
$E^*\,[\mathrm{GPa}],\ \kappa^*,\ \mu$	$3.0,\ 1.5,\ 0.4$
Contact-bond group:	
$g_i\,[\mathrm{mm}]$	0
$(T_\sigma)_{\{\mathrm{m,sd}\}}\,[\mathrm{MPa}],\ (S_\sigma)_{\{\mathrm{m,sd}\}}\,[\mathrm{MPa}]$	$\{1.0, 0\},\ \{20.0, 0\}$
Linear material group:	
$E_n^*\,[\mathrm{GPa}],\ \kappa_n^*,\ \mu_n$	$3.0,\ 1.5,\ 0.4$

* Contact-bonded material parameters are defined in Table 3 of the base memo.

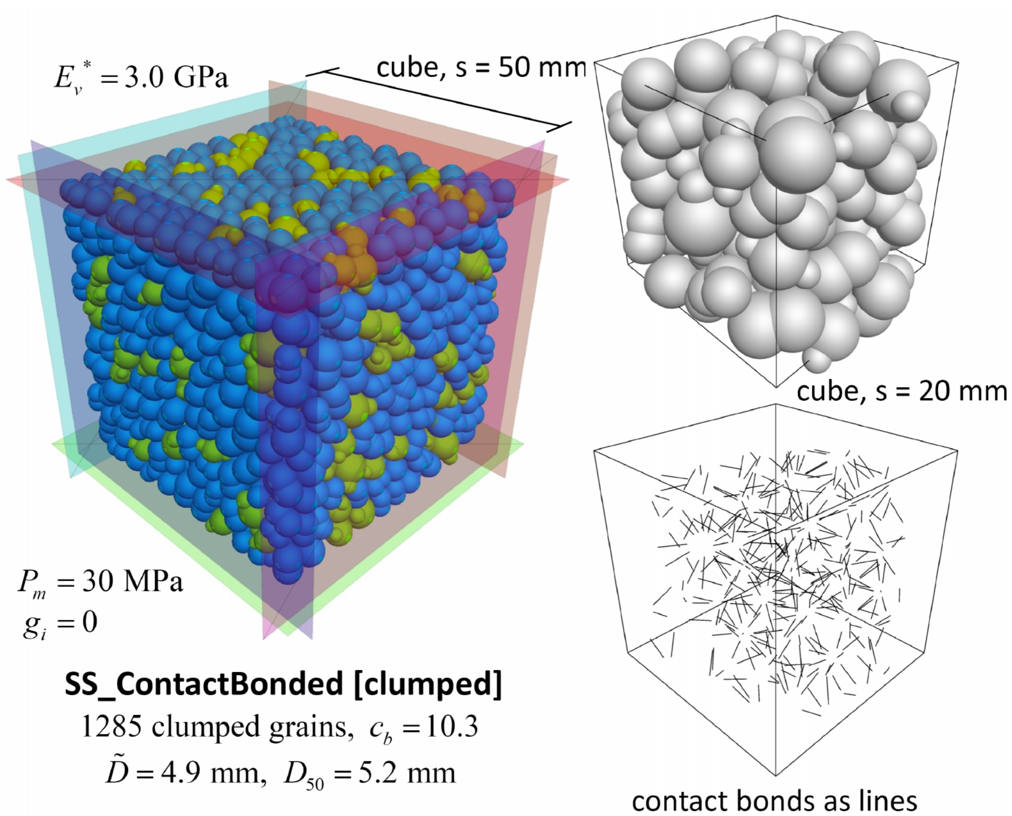

Figure 19 SS_ContactBonded clumped material at the end of material genesis with grains and contact bonds in the microstructural box.

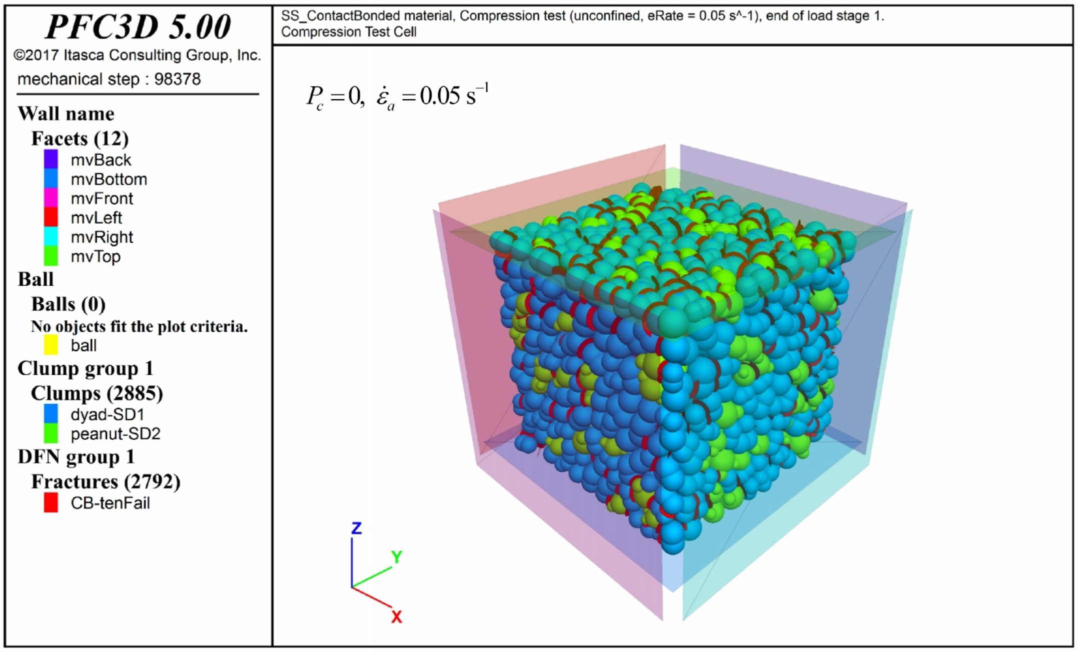

Figure 20 ***SS_ContactBonded clumped material at the end of the fully unconfined test with grains and cracks.***

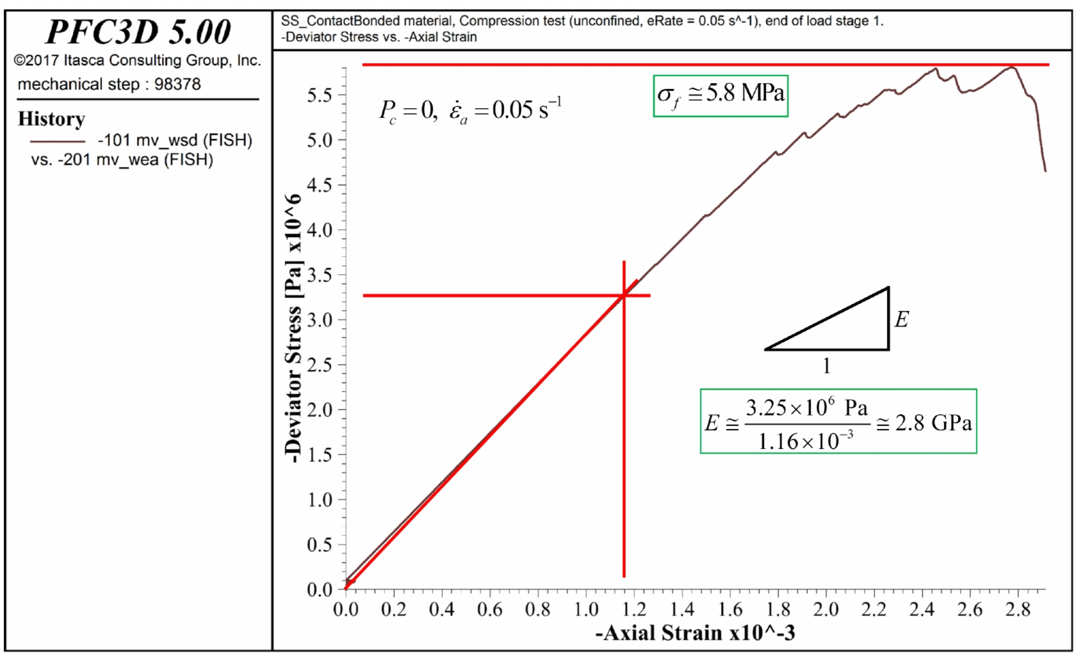

Figure 21 ***Deviator stress versus axial strain for SS_ContactBonded clumped material tested fully unconfined, and measurement of peak strength and Young's modulus.***

1.4 Contact-Bonded Material Example (2D model)

The contact-bonded material example for the 2D model is in the **`MatGen-ContactBonded`** example-project directory. The files for the 2D model contain the **`p2*`** extension (e.g., **`MatGen.p2prj`** and **`mpParams.p2dat`**). A 2D contact-bonded material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.[5] We denote our sandstone material as the SS_ContactBonded2D material with microproperties listed in Table 7. 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 contact bonds are added between all grains that are in contact with one another (see Figure 22). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results are shown in Figures 23–29.

Table 7 Microproperties of SS_ContactBonded2D Material*

Property	Value
Common group:	
N_m	SS_ContactBonded2D
$T_m,\ \alpha,\ C_\rho,\ \rho_v\ \left[\text{kg/m}^3\right]$	1, 0.7, 1, 1960
$S_g,\ T_{SD},\ \left\{D_{\{l,u\}}\ [\text{mm}],\ \phi\right\},\ D_{mult}$	0, 0, $\{1.6, 2.4, 1.0\}$, 1.0
Packing group:	
$S_{RN},\ P_m\ [\text{MPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$ $C_p,\ n_c$	10000, 30, 1×10^{-2}, 8×10^{-3}, 2×10^{6} 1, 0.08
Contact-bonded material group:	
Linear group:	
$E^*\ [\text{GPa}],\ \kappa^*,\ \mu$	3.0, 1.5, 0.4
Contact-bond group:	
$g_i\ [\text{mm}]$	0
$(T_\sigma)_{\{\text{m,sd}\}}\ [\text{MPa}],\ (S_\sigma)_{\{\text{m,sd}\}}\ [\text{MPa}]$	$\{1.0, 0\}$, $\{20.0, 0\}$
Linear material group:	
$E_n^*\ [\text{GPa}],\ \kappa_n^*,\ \mu_n$	3.0, 1.5, 0.4

* Contact-bonded material parameters are defined in Table 3 of the base memo.

[5] Typical properties of Castlegate sandstone are listed in footnote 4.

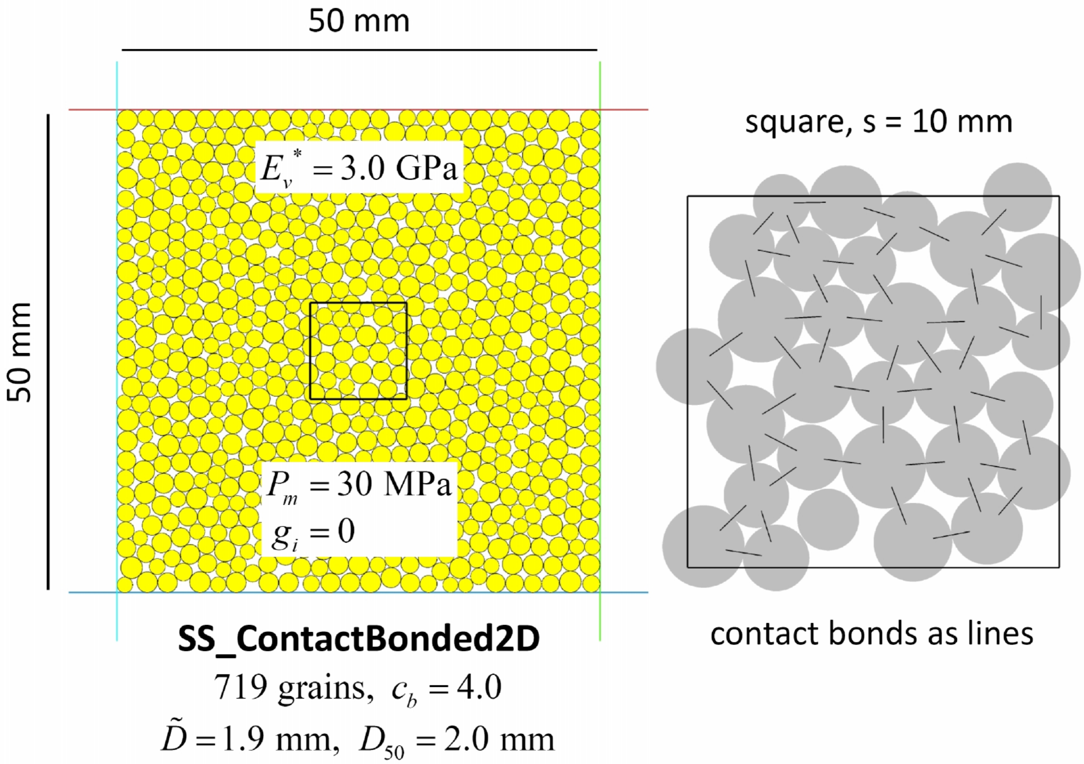

Figure 22 SS_ContactBonded2D material at the end of material genesis with grains and contact bonds in the microstructural box.

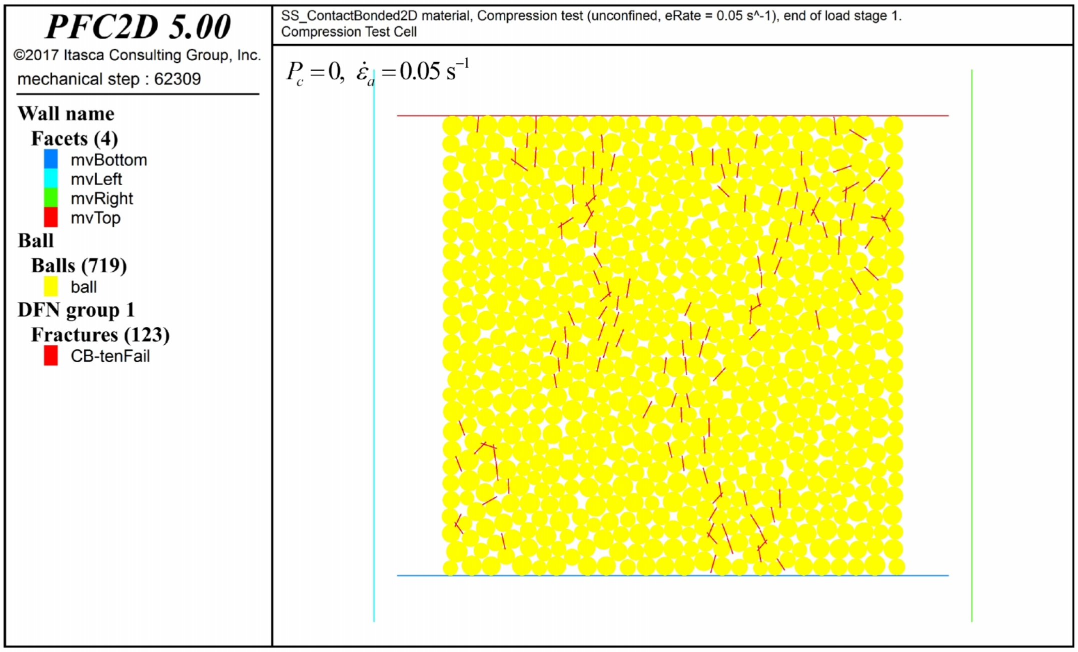

Figure 23 ***SS_ContactBonded2D material at the end of the fully unconfined test with grains and cracks.***

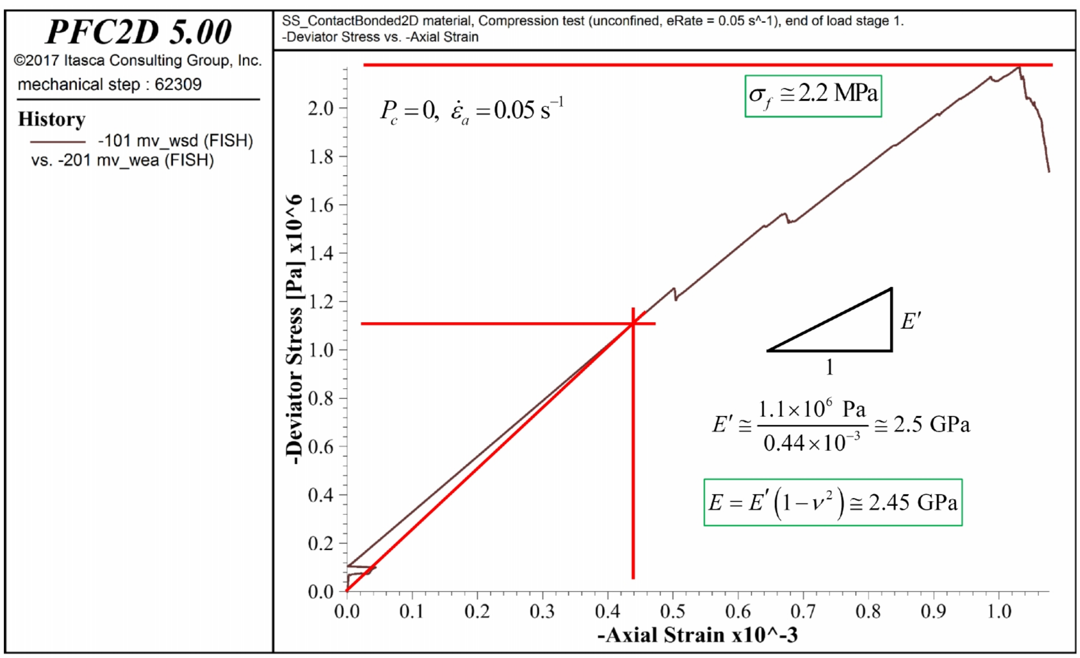

Figure 24 ***Deviator stress versus axial strain for SS_ContactBonded2D material tested fully unconfined, and measurement of peak strength and Young's modulus.***

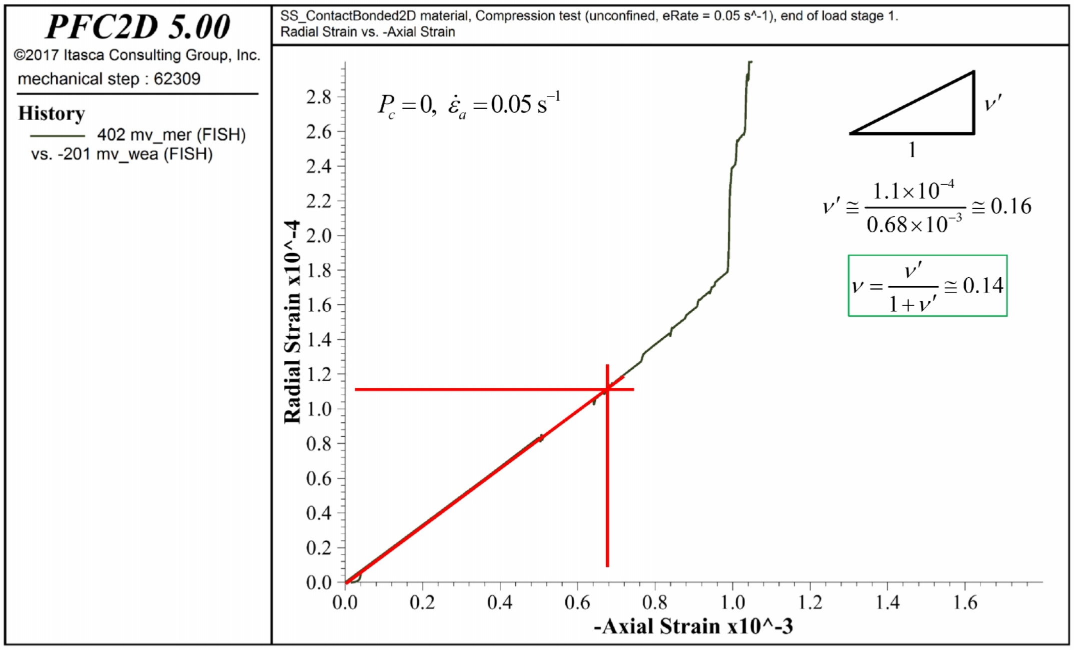

Figure 25 Radial strain versus axial strain for SS_ContactBonded2D material tested fully unconfined, and measurement of Poisson's ratio.

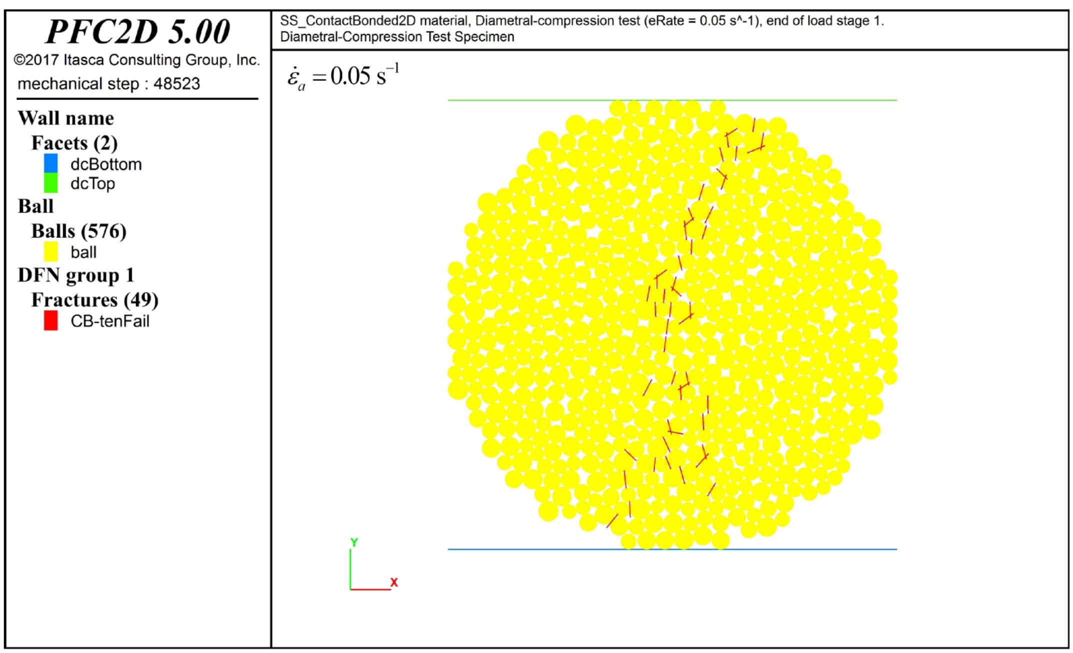

Figure 26 SS_ContactBonded2D material at the end of diametral-compression test with grains and cracks.

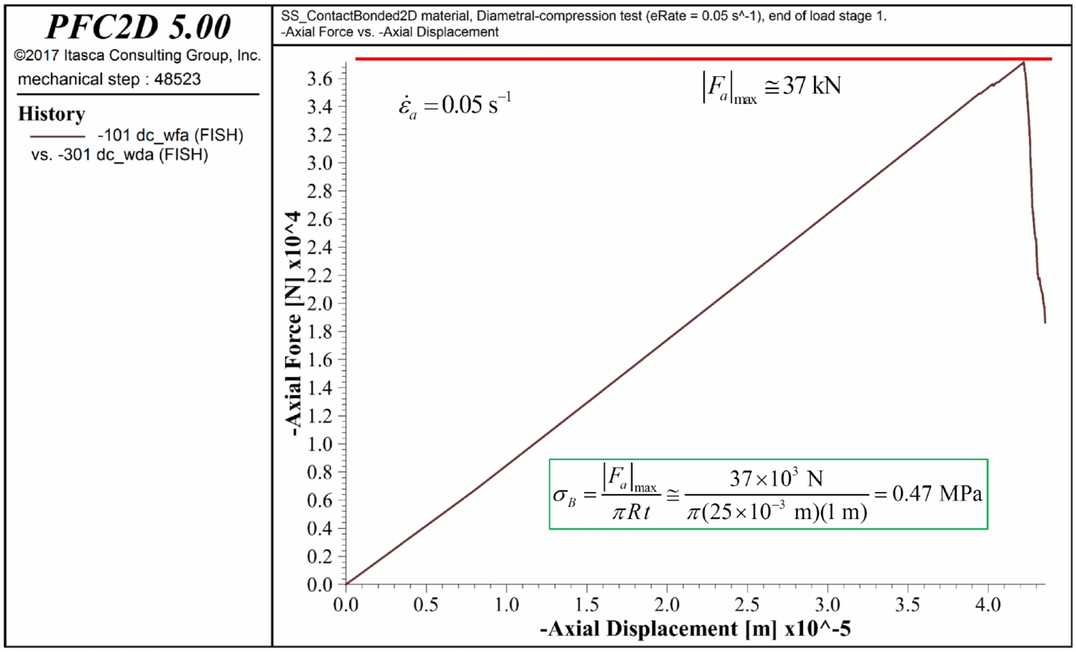

Figure 27 Axial force versus axial displacement for SS_ContactBonded2D material during the diametral-compression test, and measurement of Brazilian tensile strength.

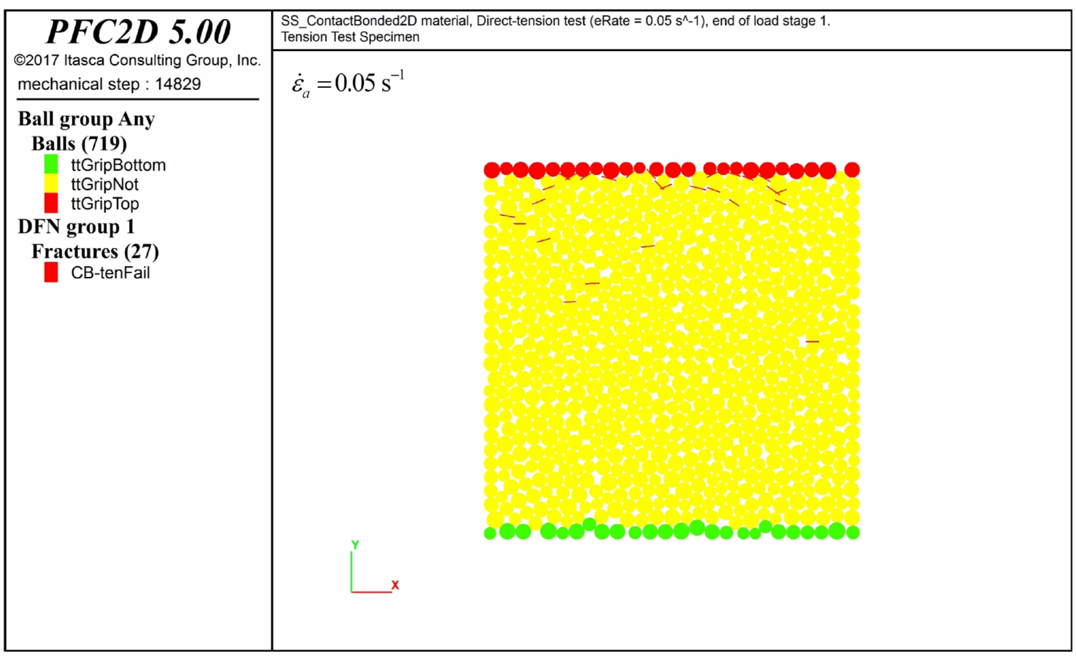

Figure 28 SS_ContactBonded2D material at the end of the direct-tension test with grains and cracks.

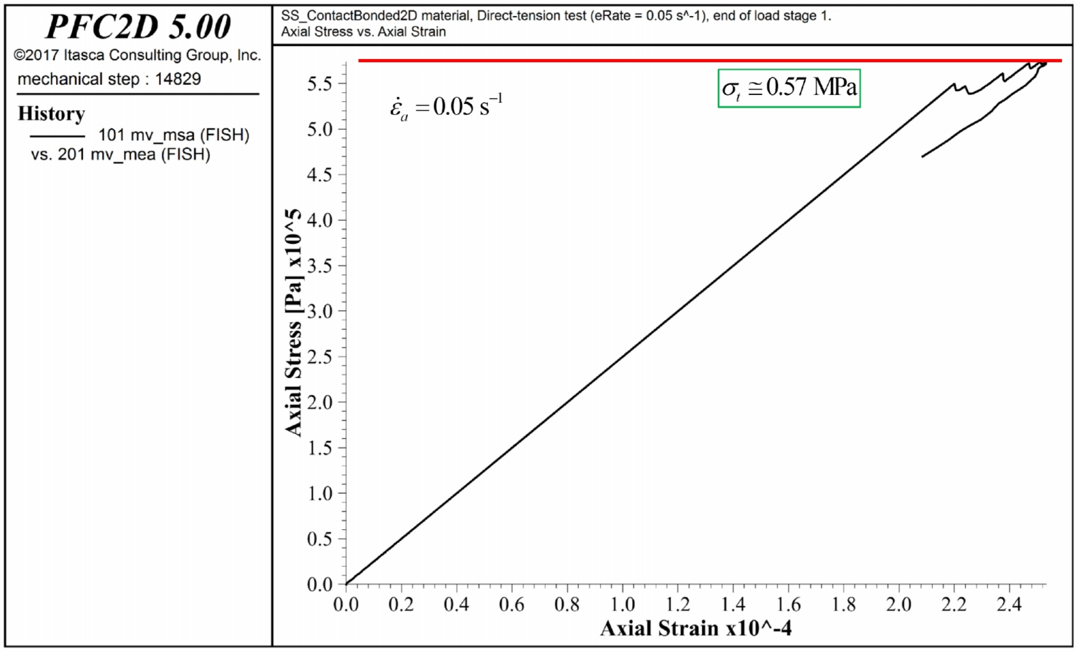

Figure 29 Axial stress versus axial strain for SS_ContactBonded2D material during the direct-tension test, and measurement of tensile strength.

The 2D contact-bonded material example is modified to replace the disk-shaped grains with clumped grains by replacing the call to **`mpParams.p2dat`** in **`MatGen.p2dvr`** with a call to **`mpParams-Clumped.p2dat`**. The new material is denoted as a 2D contact-bonded clumped material with microproperties listed in Table 8. The clumped material has two grain shapes. The first shape is a dyad consisting of two disk-shaped pebbles, and the second shape is a peanut consisting of three disk-shaped pebbles (see Figure 8). The clumped grains are drawn from a uniform size distribution with diameters ranging from 1.6 to 2.4 mm, and with 75% of the grains being dyads and 25% of the grains being peanuts. The diameter of each clumped grain is the diameter of a unit-thickness disk with the same volume as the grain. The material-creation and testing procedures for the clumped material are the same as those for the AG_ContactBonded2D material.

The 2D clumped 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 contact bonds are added between all grains that are in contact with one another (see Figure 30). The bond coordination number of the clumped material (6.4) is larger than that of the disk-only material (4.0), and the porosity of the clumped material (0.106) is less than that of the disk-only material (0.139) — the dyads and peanuts have packed to a denser state than the disks. The clumped material is then subjected to compression, diametral-compression and direct-tension tests. The compression-test results are shown in Figures 31–33. The clumped material is stronger (5.1 MPa versus 2.2 MPa) and stiffer (3.6 GPa versus 2.5 GPa) than the spherical material, with increased strength and stiffness attributed to increased bond coordination number and reduced porosity.

Table 8 Microproperties of SS_ContactBonded2D Clumped Material

Property	Value
Common group:	
N_m	SS_ContactBonded2D
$T_m,\ \alpha,\ C_\rho,\ \rho_v\left[\mathrm{kg/m^3}\right]$	$1,\ 0.7,\ 1,\ 1960$
$S_g,\ n_{SD},\ T_{SD},\ \left\{N_{ct},\ D_{\{l,u\}}\left[\mathrm{mm}\right],\ \phi\right\},\ D_{mult}$	$1,\ 2,\ 0,\ \begin{Bmatrix}\text{dyad}, & 1.6, 2.4, 0.75\\ \text{peanut}, & 1.6, 2.4, 0.25\end{Bmatrix},\ 1.0$
Packing group:	
$S_{RN},\ P_m\left[\mathrm{MPa}\right],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$ $C_p,\ n_c$	$10000,\ 30,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$ $1,\ 0.08$
Contact-bonded material group:	
Linear group:	
$E^*\left[\mathrm{GPa}\right],\ \kappa^*,\ \mu$	$3.0,\ 1.5,\ 0.4$
Contact-bond group:	
$g_i\left[\mathrm{mm}\right]$	0
$\left(T_\sigma\right)_{\{\mathrm{m,\ sd}\}}\left[\mathrm{MPa}\right],\ \left(S_\sigma\right)_{\{\mathrm{m,\ sd}\}}\left[\mathrm{MPa}\right]$	$\{1.0, 0\},\ \{20.0, 0\}$
Linear material group:	
$E_n^*\left[\mathrm{GPa}\right],\ \kappa_n^*,\ \mu_n$	$3.0,\ 1.5,\ 0.4$

* Contact-bonded material parameters are defined in Table 3 of the base memo.

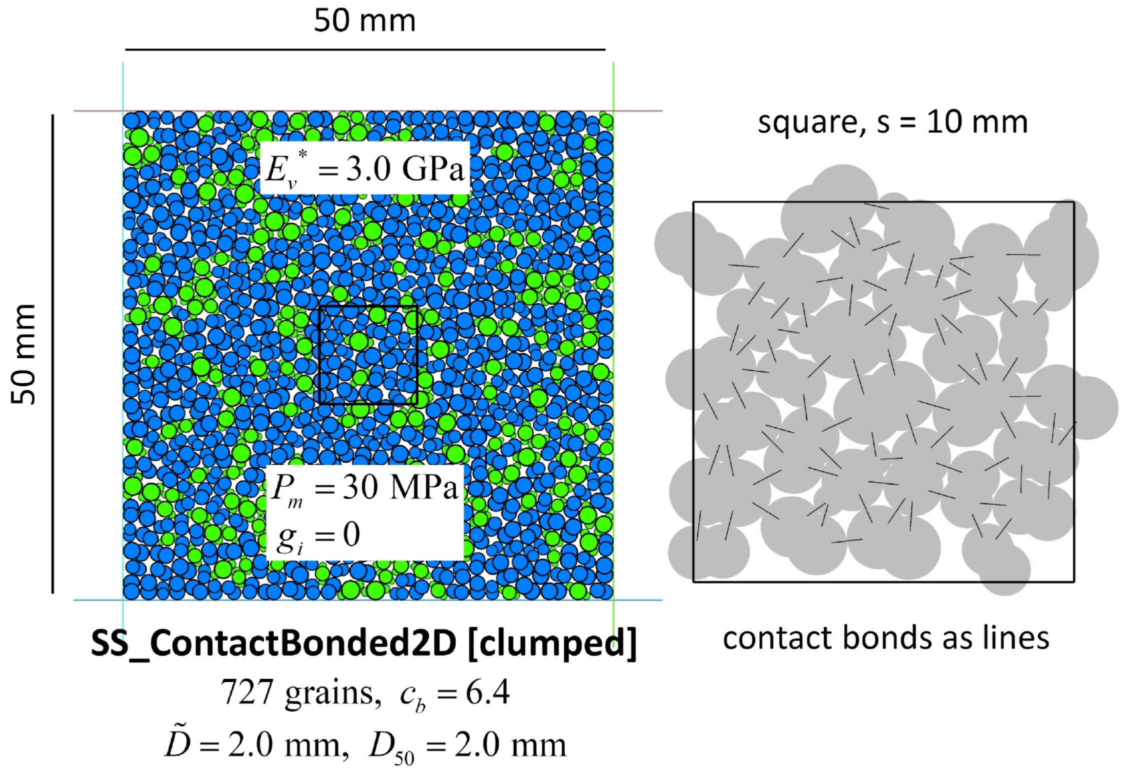

Figure 30 ***SS_ContactBonded2D clumped material at the end of material genesis with grains and contact bonds in the microstructural box.***

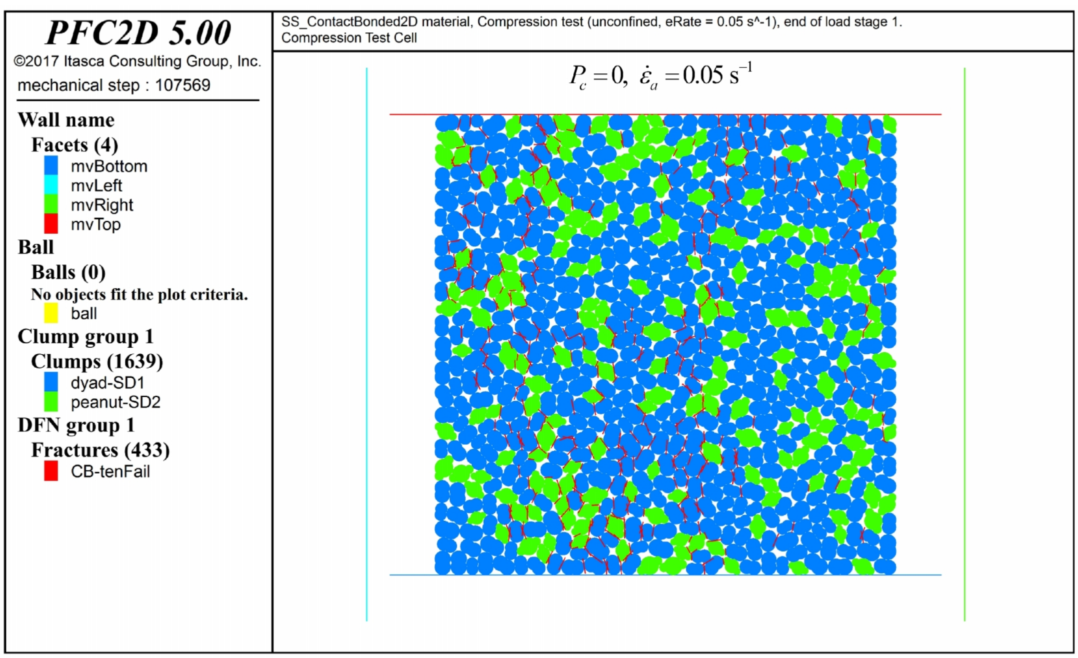

Figure 31 ***SS_ContactBonded2D clumped material at the end of the fully unconfined test with grains and cracks.***

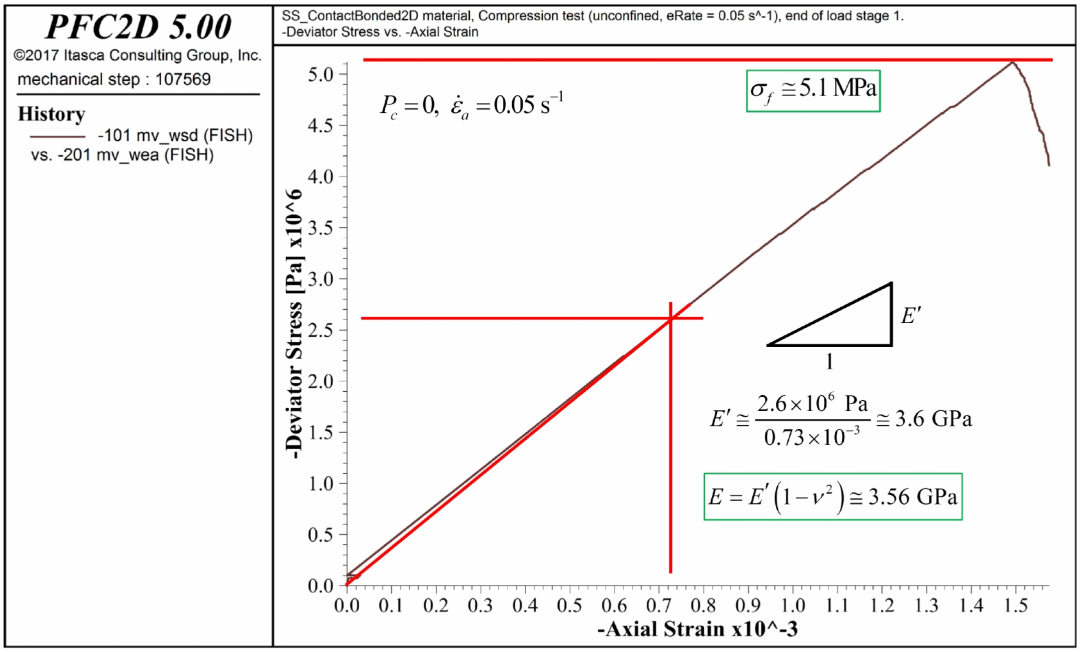

Figure 32 Deviator stress versus axial strain for SS_ContactBonded2D clumped material tested fully unconfined, and measurement of peak strength and Young's modulus.

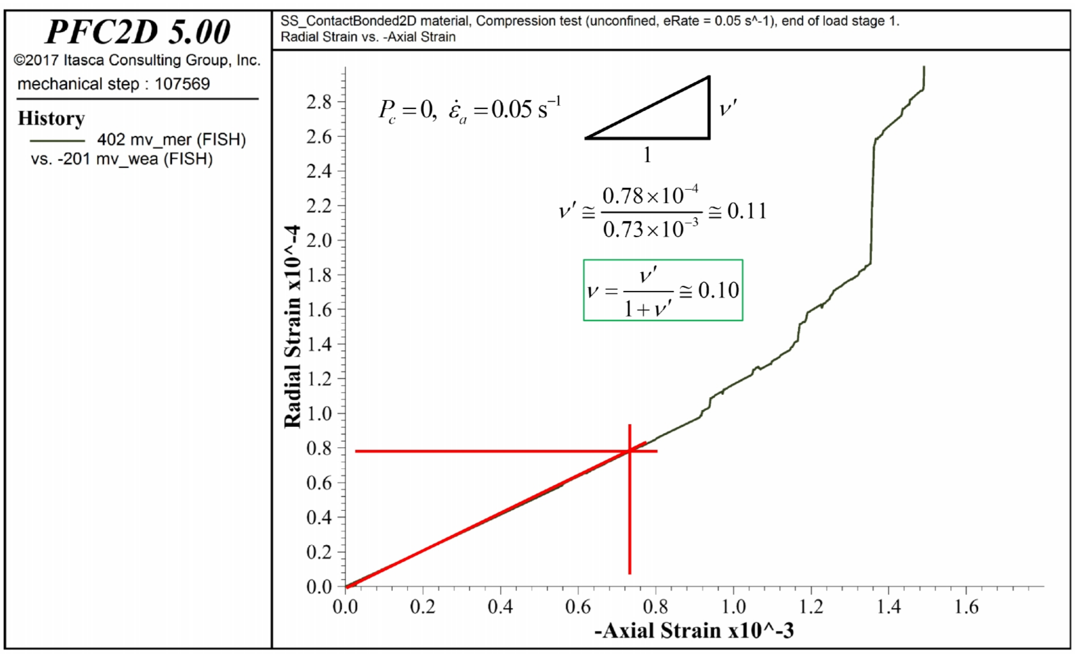

Figure 33 Radial strain versus axial strain for SS_ContactBonded2D clumped material tested fully unconfined, and measurement of Poisson's ratio.