Particles as Discrete Elements in LS-DYNA: Interaction with themselves as well as Deformable or Rigid Structures

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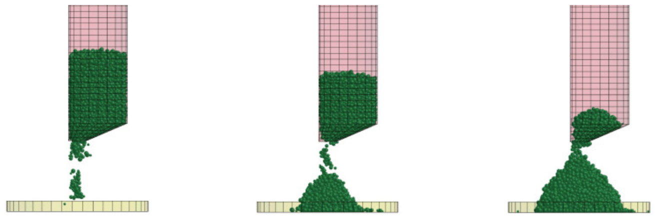

11th LS-DYNA Forum 2012

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Outline

- Introduction and Motivation
- Discrete-Element Method in LS-DYNA
- Examination of the Parameters
- Sample Applications
- Extension to Bonded Particles
- Conclusion

Introduction and Motivation

- Granular Media

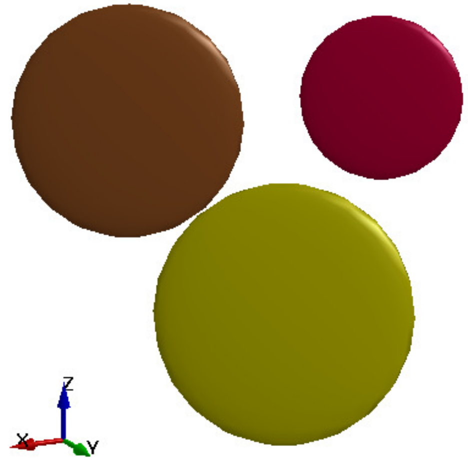
[*Wiese Förderelemente GmbH*]

- Numerical Simulations Help to Design
  - Storage
    - Silos
    - Piles
  - Transportation
    - Conveyor belts/ screws
    - Pumps
  - Processing
    - Sorting
    - Mixing/ Segregation
  - Filling
    - Hopper/ funnel flow
- Numerical Methods
  - Discrete-Element Method (DEM)
  - Finite-Element Method (FEM)

The Discrete-Element Method in LS-DYNA

- Definition of the Discrete Elements
  - Particles are approximated with spheres via
    - ***PART, *SECTION_SOLID**
    - Coordinate using ***NODE** and with a `NID`
    - Radius, Mass, Moment of Inertia

$$M = V\rho = \frac{4}{3}\pi r^3 \rho \qquad I = \frac{2}{5} M r^2 = \frac{8}{15}\pi r^5 \rho$$



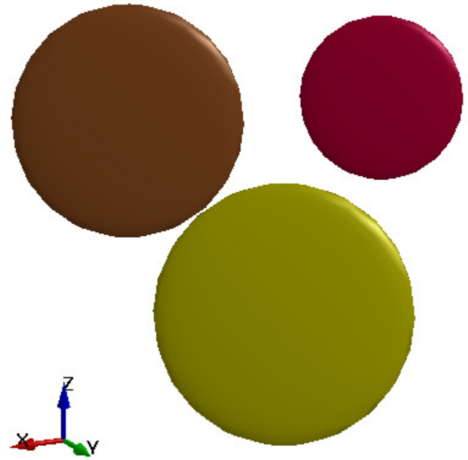

```
*ELEMENT_DISCRETE_SPHERE_{OPTION}
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#      NID        PID       MASS    INERTIA      RADII
      30001          4   570.2710   6036.748       5.14
      30002          5   399.0092   3328.938       4.57
      30003          6   139.1240    575.004       3.21
*NODE
$--+---1-------+-------2-------+-------3-------+-------4---+---5---+---6
$#    NID               X               Y               Z      TC      RC
    30001          -29.00           -26.8             8.7       0       0
    30002          -21.00           -24.8            18.2       0       0
    30003          -27.00           -14.7            21.2       0       0
```

The Discrete-Element Method in LS-DYNA

- Definition of the Discrete Elements
  - Particles are approximated with spheres via
    - **`*PART, *SECTION_SOLID`**
    - Coordinate using **`*NODE`** and with a `NID`
    - Radius, Mass, Moment of Inertia

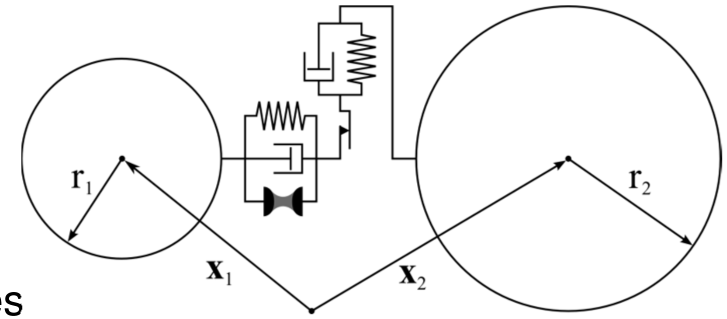
$$M = V\rho = \frac{4}{3}\pi r^3 \rho \qquad I = \frac{2}{5} M r^2 = \frac{8}{15}\pi r^5 \rho$$

  - Density is taken from **`*MAT_ELASTIC`**




```
*ELEMENT_DISCRETE_SPHERE_VOLUME
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#      NID        PID        MASS    INERTIA      RADII
      30001          4   570.2710   6036.748       5.14
      30002          5   399.0092   3328.938       4.57
      30003          6   139.1240    575.004       3.21
*NODE
$--+---1-------+-------2-------+-------3-------+-------4---+---5---+---6
$#    NID              X                Y                Z       TC       RC
    30001         -29.00            -26.8              8.7        0        0
    30002         -21.00            -24.8             18.2        0        0
    30003         -27.00            -14.7             21.2        0        0
```

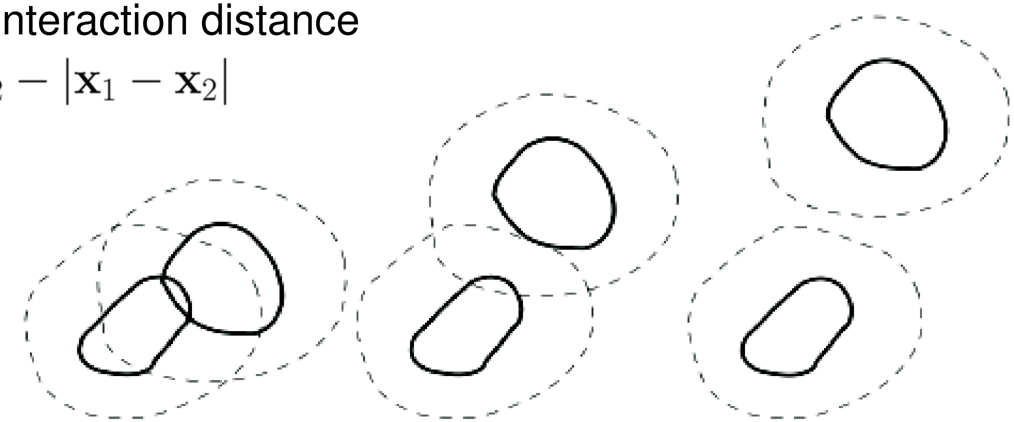
- Definition of the Contact between Particles
  - Mechanical contact
    - Discrete-element formulation according to [*Cundall & Strack* 1979]
  - Extension to model cohesion using capillary forces




```
*CONTROL_DISCRETE_ELEMENT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#    NDAMP     TDAMP      Fric     FricR     NormK    ShearK       CAP     MXNSC
      0.700     0.400      0.41     0.001      0.01    0.0029         0         0
$#    Gamma    CAPVOL    CAPANG
       26.4      0.66      10.0
```

- Possible collision states
  - Depends on interaction distance

$$d_{\text{int}} = r_1 + r_2 - |\mathbf{x}_1 - \mathbf{x}_2|$$

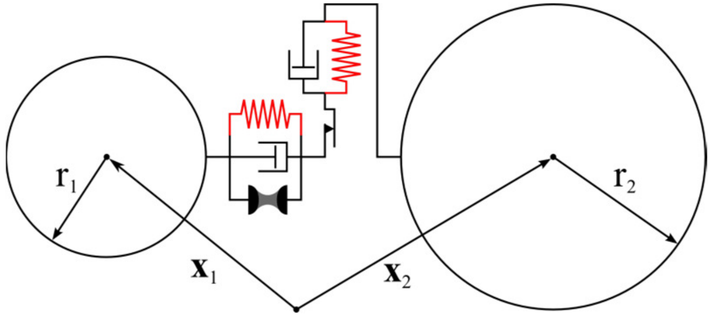


$d_{\text{int}} \leq 0$ $\quad 0 < d_{\text{int}} \leq d_{\text{crit}}$ $\quad d_{\text{int}} > d_{\text{crit}}$

Elastic Contribution

- Normal contact forces

$$F_n = K_n \, d_{\text{int}}$$



*CONTROL_DISCRETE_ELEMENT								
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8								
$#	NDAMP	TDAMP	Fric	FricR	NormK	ShearK	CAP	MXNSC
	0.700	0.400	0.41	0.001	0.01	0.0029	0	0

- Normal spring constant

$$K_n = \begin{cases} \dfrac{\kappa_1 \, r_1 \; \kappa_2 \, r_2}{\kappa_1 \, r_1 + \kappa_2 \, r_2} \, \texttt{NormK} & : \text{ if } \texttt{NormK} > 0 \\ \texttt{NormK} & : \text{ if } \texttt{NormK} < 0 \end{cases}$$

κ_i : compression moduli taken from ***MAT_ELASTIC**

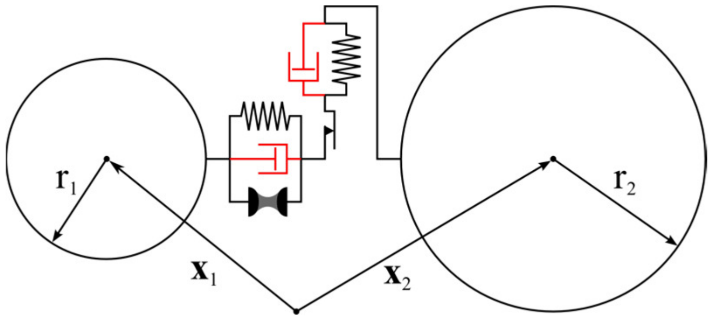
- Tangential spring constant relative to normal spring constant

$$K_t = K_n \, \texttt{ShearK}$$

- Default values: `NormK = 0.01, ShearK = (2/7)*NormK`

Damping Contribution

- Normal damping force



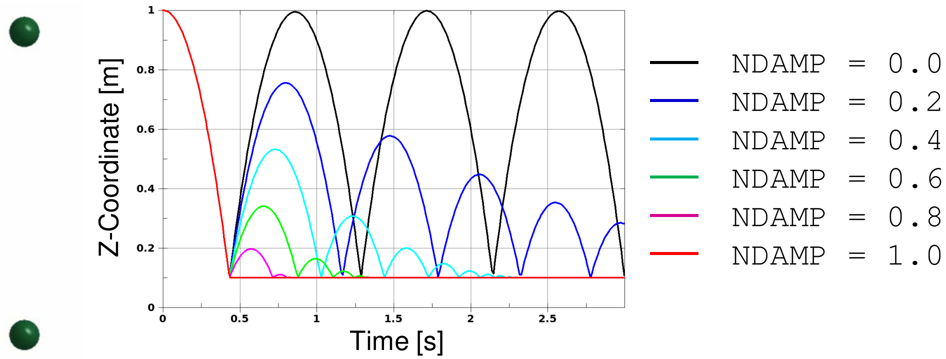
$$F_n = D_n \, \dot{d}_{\text{int}}$$

```
*CONTROL_DISCRETE_ELEMENT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#   NDAMP     TDAMP      Fric     FricR     NormK    ShearK       CAP     MXNSC
     0.700     0.400      0.41     0.001      0.01    0.0029         0         0
```

- Damping constants as a ratio of the critical damping

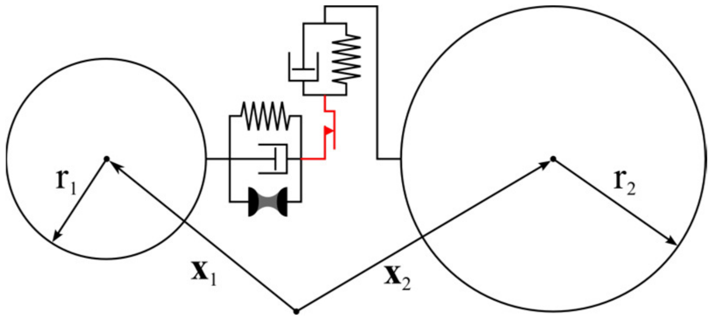
$$D_n = \texttt{DAMP}\,\eta_{\text{crit}} = \texttt{DAMP}\;2\sqrt{\frac{m_1\,m_2}{m_1+m_2}K_{n/t}} \qquad \text{with} \qquad 0 \leq \texttt{DAMP} \leq 1.0 \;\; (!)$$

- Influence of the normal damping during particle contact
  - particle is dropped from 1m height
  - values for `NDAMP` are altered



- Frictional Contribution
  - Friction force based on *Coulomb*'s law of friction

$$F_{fr} \leq \mu_{fr} \ F_n$$

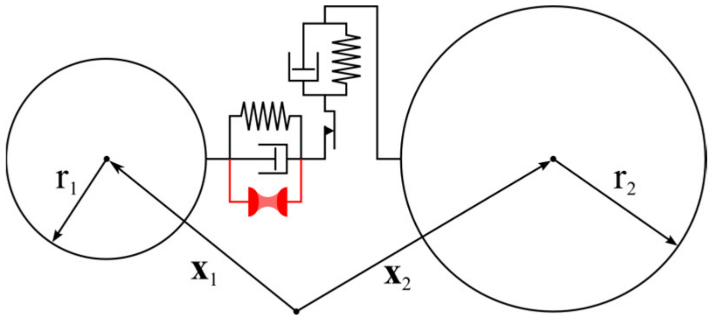



```
*CONTROL_DISCRETE_ELEMENT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#    NDAMP     TDAMP      Fric     FricR     NormK    ShearK       CAP     MXNSC
      0.700     0.400      0.41     0.001      0.01    0.0029         0         0
```

- Friction coefficient
  - `Fric = 0.0`
    - yields a central force system for each particle
    - reduction to 3 translations as DOF
  - `Fric > 0.0`
    - yields a general force system for each particle
    - full 6 DOF are enabled (3 translations and 3 rotations)

- Extension to model rolling resistance
  - `FricR > 0.0`
    - typical values for sand grains around 0.01
    - larger values may account for rough particles or other particle shapes

- Capillary Force Contribution
  - Idea of a liquid bridge with fixed volume [Rabinovich et al. 2005]
  - Only activated for $0 < d_{\text{int}} \leq d_{\text{crit}}$

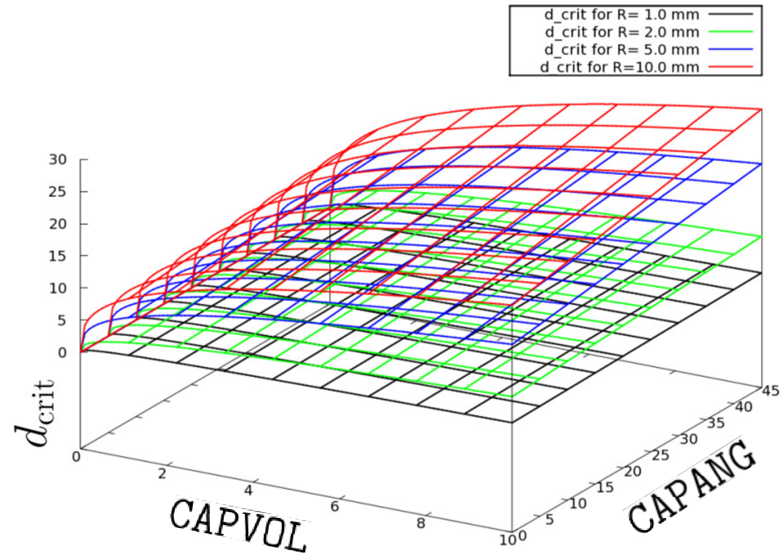



```
*CONTROL_DISCRETE_ELEMENT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#    NDAMP     TDAMP      Fric     FricR     NormK    ShearK       CAP     MXNSC
      0.700     0.400      0.41     0.001      0.01    0.0029         1         0
$#    Gamma    CAPVOL    CAPANG
       26.4      0.66      10.0
```

- Involved parameters
  - `CAP = 0`
    - dry particles
  - `CAP = 1`
    - "wet" particles
    - additional input card is required
  - `Gamma > 0.0` : Liquid surface tension
  - `CAPVOL > 0.0` : Volume fraction of the liquid bridge with respect to 1/10 of the contacting sphere volumes
  - `CAPANG > 0.0` : Contact angle between liquid bridge and sphere

Capillary Force Contribution – The Formulas

Characterization of the liquid bridge



- Volume

$$V_{\mathrm{LB}} = \frac{4}{3}\,\pi\,(r_1^3 + r_2^3)\,\frac{1}{10}\,\mathtt{CAPVOL}$$

- Rupture distance

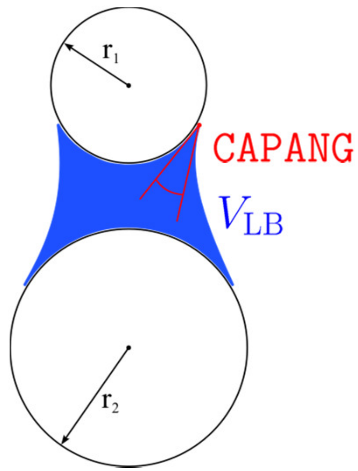
$$d_{\mathrm{crit}} = \left(1 + \frac{\mathtt{CAPANG}}{2}\right)\sqrt[3]{V_{\mathrm{LB}}}$$

- Capillary force

$$F_n = \overbrace{\underbrace{-\frac{2\,\pi\,\mathtt{Gamma}\,\overline{r}\,\cos(\mathtt{CAPANG})}{1 + \dfrac{d_{\mathrm{int}}}{d_{\mathrm{sp/sp}}}}}_{\text{Case II: } 0 < d_{\mathrm{int}} \le d_{\mathrm{crit}}} - 2\,\pi\,\mathtt{Gamma}\,\overline{r}\,\cos(\mathtt{CAPANG})}^{\text{Case I: } d_{\mathrm{int}} \le 0}$$

with

$$\overline{r} = \frac{2\,r_1\,r_2}{r_1 + r_2} \qquad d_{\mathrm{sp/sp}} = d_{\mathrm{int}} + \sqrt{d_{\mathrm{int}}^2 + 2\,\frac{V_{\mathrm{LB}}}{\pi\,\overline{r}}}$$

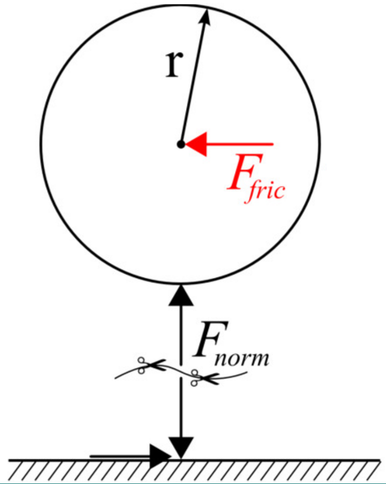


Definition of the Particle-Object Contact I

- Classical nodes-to-surface contact definition
  - Well-proven and tested contact definition

```
*CONTACT_AUTOMATIC_NODES_TO_SURFACE_ID
$#      CID
          2
$#     SSID       MSID      SSTYP      MSTYP     SBOXID     MBOXID        SPR        MPR
        300          1          4          3          0          0          0          0
$#       FS         FD         DC         VC        VDC     PENCHK         BT         DT
        0.6        0.4        0.0        0.0       20.0          0        0.0    1.0E+20
$#      SFS        SFM        SST        MST       SFST       SFMT        FSF        VSF
        1.0       60.0        0.0        0.0        1.0        1.0        1.0        1.0
```

- Contact between
  - `SSTYPE= 4` : slave node set
  - `MSTYPE=()` : segment set `(0)`, shell element set `(1)`, part set `(2)`, part `(4)`
- Benefits of the contact definition
  - static and dynamic friction coefficients
  - penalty scale factors
  - works great with MPP
- Drawbacks of the contact definition
  - not possible to apply rolling friction
  - friction force is applied to particle center

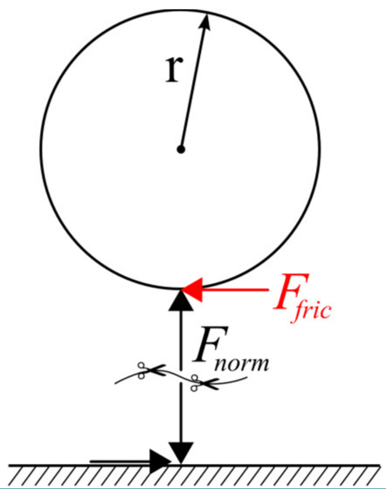


Definition of the Particle-Object Contact II

- New contact definition for discrete elements

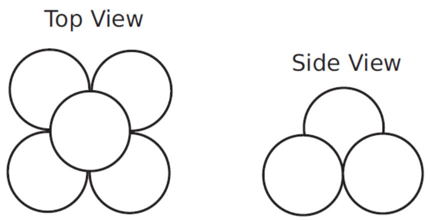
```
*DEFINE_DE_TO_SURFACE_COUPLING
$#    SLAVE     MASTER     STYPE     MTYPE
        300          1         0         1
$#    FricS      FricD      DAMP     BSORT      LCVx      LCVy      LCVz
        0.5       0.01       0.2       100         0         0         0
```

- Contact between
  - STYPE=0: slave node set STYPE=1: slave node
  - MTYPE=0: part set MTYPE=1: part
- Damping determines if the collision is elastic or "plastic" $0 \leq \mathtt{DAMP} \leq 1.0$ (!)
- Benefits of the contact definition
  - static and rolling friction coefficients
  - friction force is applied at the perimeter
  - possibility to define transportation belt velocity via LCVxyz
  - easy to set up!
- Drawbacks of the contact definition
  - no possibility to tweak via penalty scale factors
  - sometimes problems with MPP



Examination of the Parameters

- Static Friction Benchmark
  - PEBBLE Test of Idaho National Laboratory
    - J. J. Cogliati & A. M. Ougouag: In *PHYSOR 2010 - Advances in Reactor Physics to Power the Nuclear Renaissance,* Pittsburgh, Pennsylvania (2010)



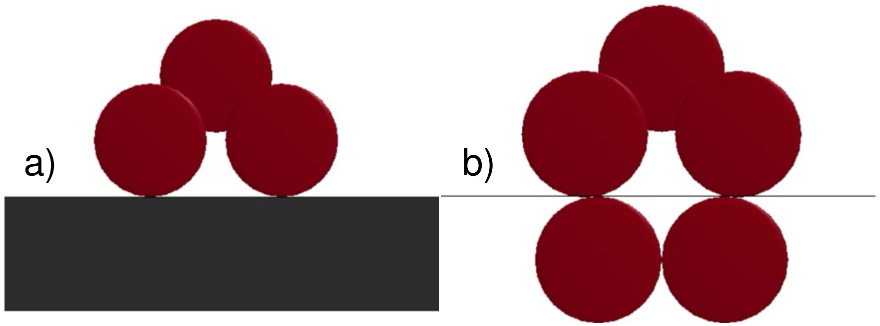
Critical coefficients of friction

$$\mu_{\mathrm{sph/sph}} = \sqrt{2} - 1 \approx 0.41421$$

$$\mu_{\mathrm{sph/surf}} = \frac{1}{5\,(1+\sqrt{2})} \approx 0.08284$$

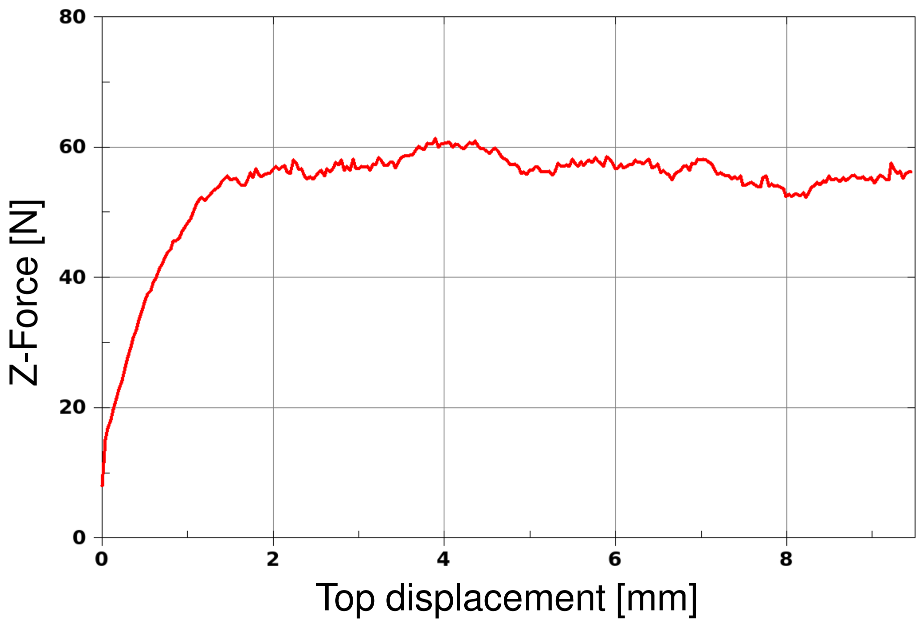
- Case to pass the test
  - stable pyramid for $\mu_{\mathrm{sph/sph}} + \epsilon$ and $\mu_{\mathrm{sph/surf}} + \epsilon \quad \forall\ \epsilon \leq 0.001$

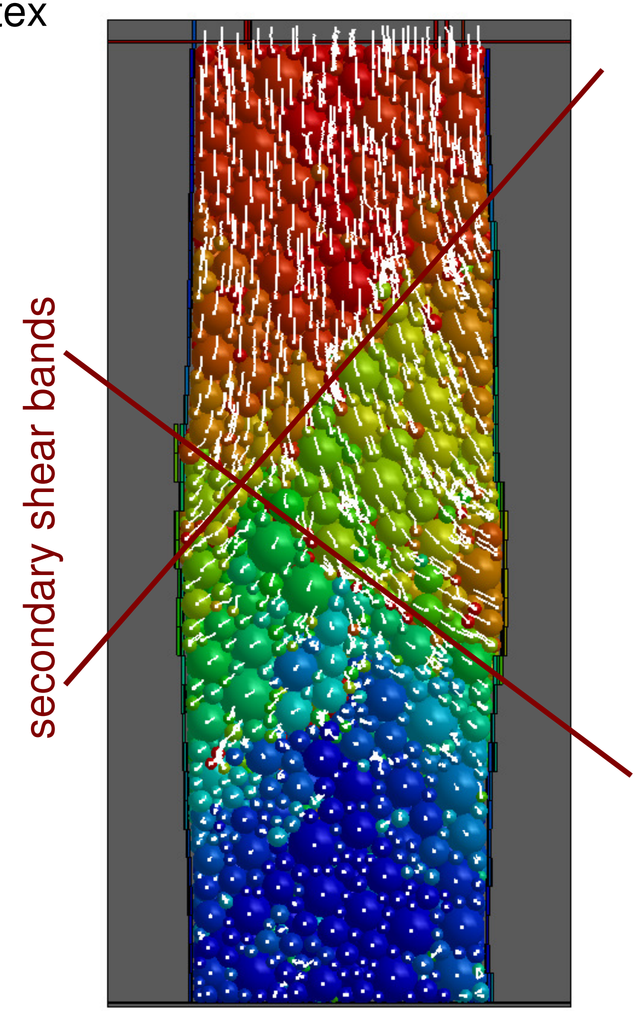
- LS-DYNA simulation
  - Pyramid becomes unstable for
    - a) $\epsilon_{\mathrm{sph/surf}} = 0.000007$
    - b) $\epsilon_{\mathrm{sph/sph}} = 0.00017$
  - Test is well passed!



Biaxial Compression Test

- Standard geomechanics test to determine material parameters
  - Granular specimen (3300 particles) wrapped in latex
  - Pressure is applied to the side surfaces
  - Bottom, back and front surfaces are fixed
  - Top surface is displacement driven
- LS-DYNA simulation
  - Force versus displacement diagram

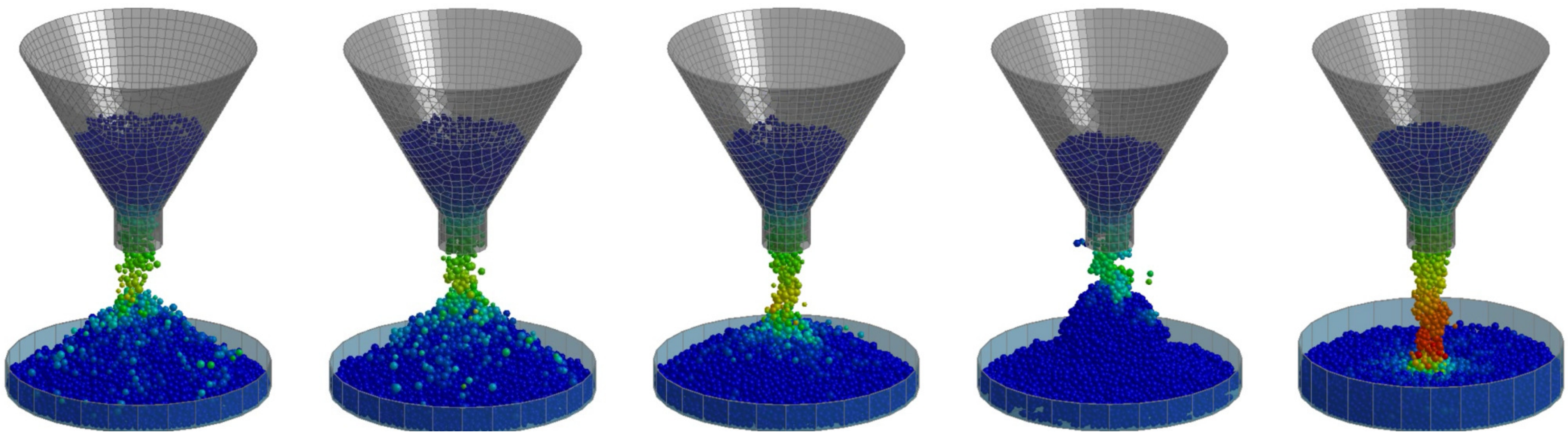




- Funnel Flow
  - Variation of the parameters in
    - ***CONTROL_DISCRETE_ELEMENT**
    - ***DEFINE_DE_TO_SURFACE_COUPLING**

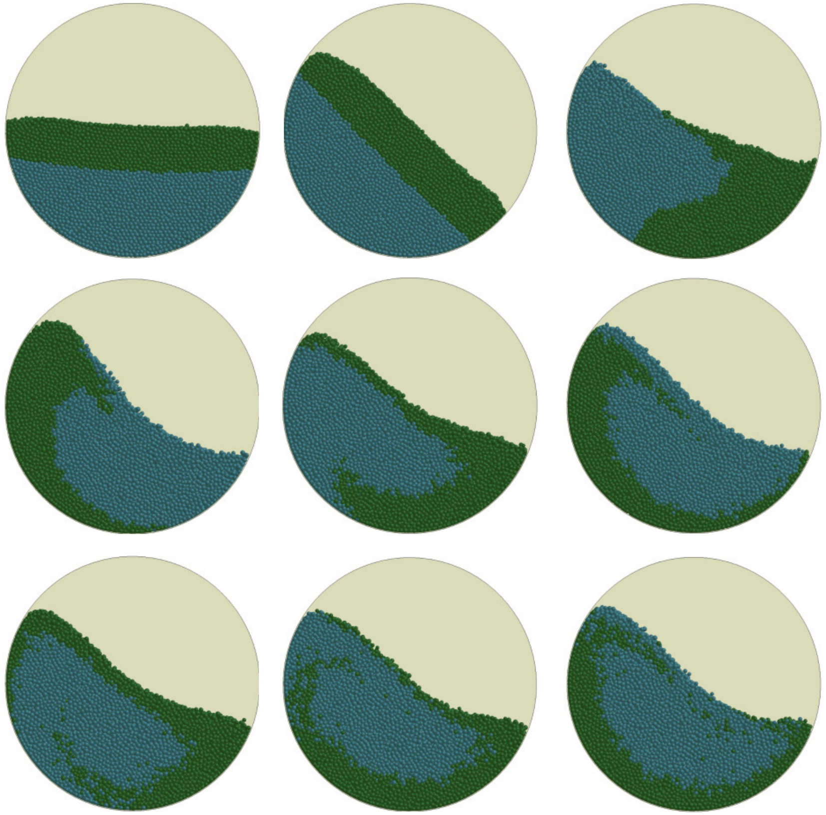
```
$-------+-------1--------+--------2---------+--------3---------+--------4---------+--------5
RHO         0.80E-6            2.63E-6            2.63E-6            2.63E-6             1.0E-6
P-P Fric       0.57               0.57               0.57               0.10               0.00
P-P FricR      0.10               0.10               0.01               0.01               0.00
P-W FricS      0.27               0.30               0.30               0.10               0.01
P-W FricD      0.01               0.01               0.01               0.01               0.00
CAP               0                  0                  1                  1                  1
Gamma          0.00               0.00            7.20E-8            2.00E-6             7.2E-8
$-------+-------1--------+--------2---------+--------3---------+--------4---------+--------5
```

foamed clay | dry sand | wet sand | fresh concrete | “water”

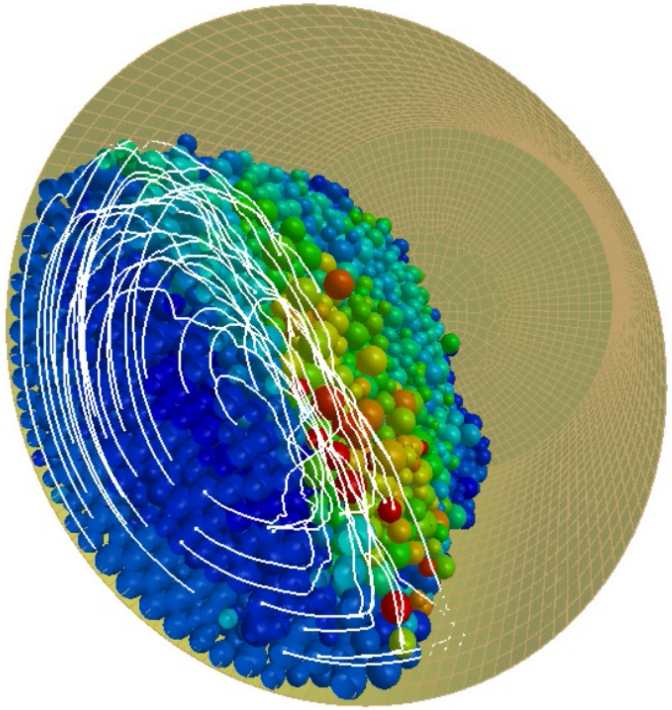


Sample Applications

- Drum Mixer I
  - 12371 particles with two densities
    - Green: foamed clay
    - Blue: sand

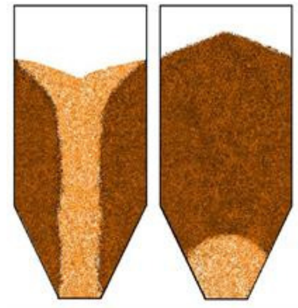


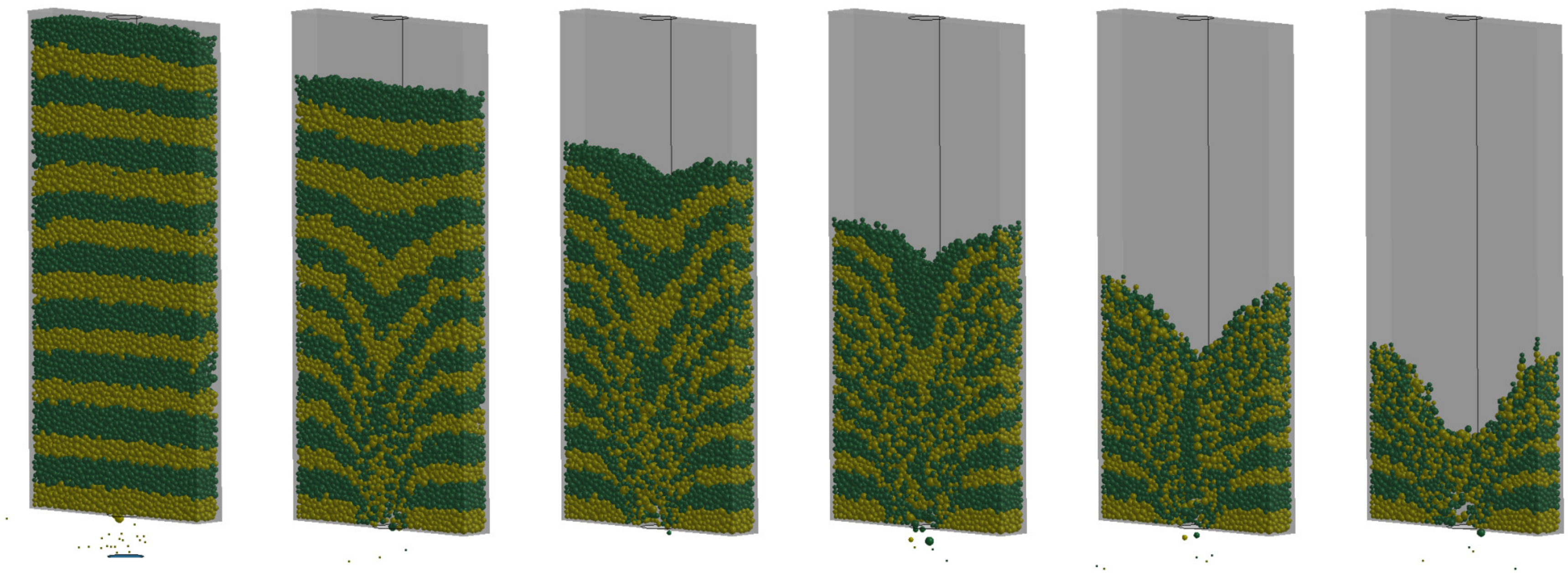
- Drum Mixer II
  - 6640 particles of the same kind
    - Fringe color: particle velocity
    - White lines: particle path



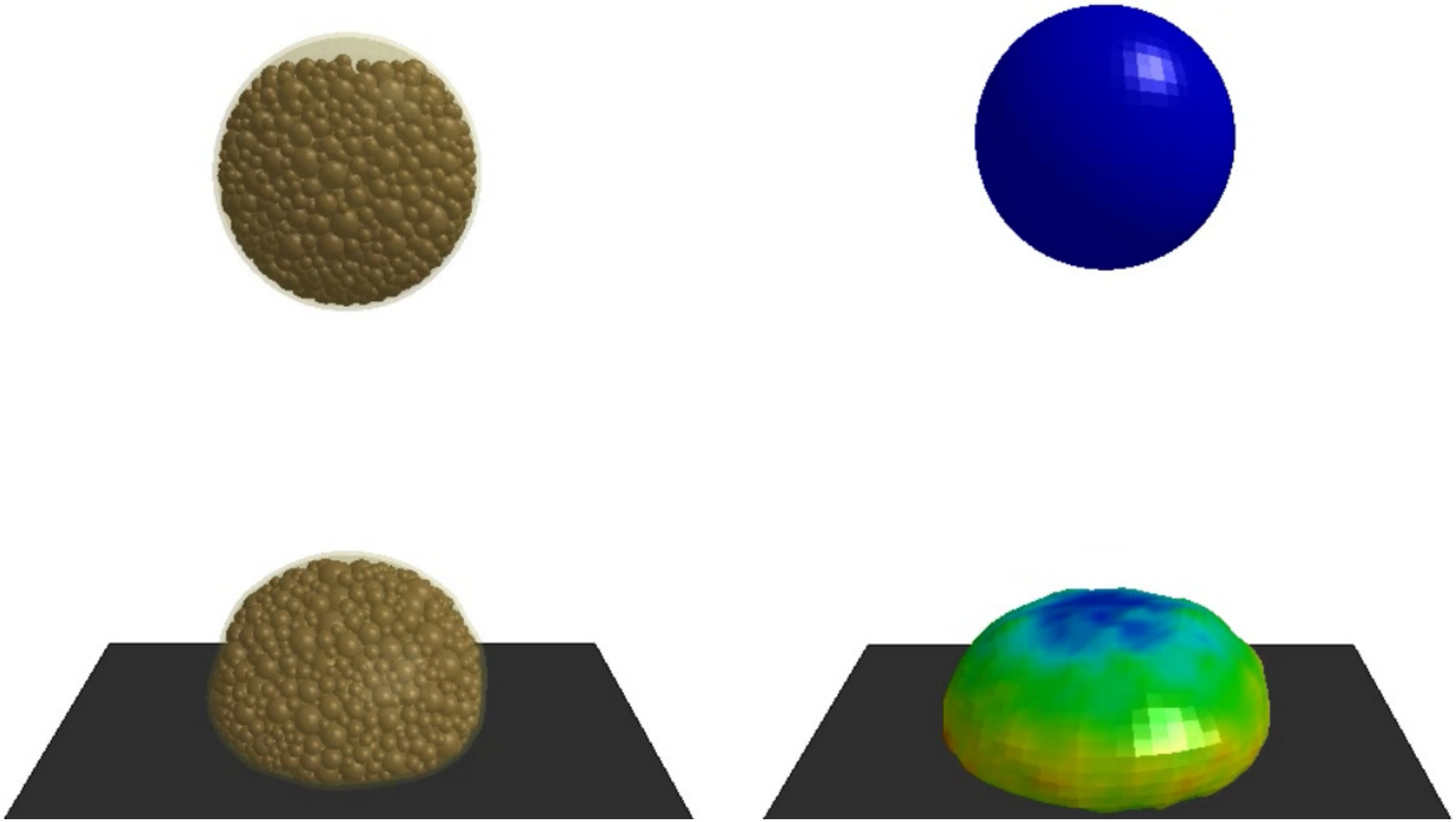
Hopper Flow

- Problem description
  - Rigid silo walls
    - 350 x 150 x 25 mm
    - shell elements 2mm thick
  - 17000 rough particles
    - radius from 1.5 – 3 mm
    - static & rolling friction of 0.5
  - Gravity-driven outflow
- Problems to avoid
  - Ratholing
  - Arching



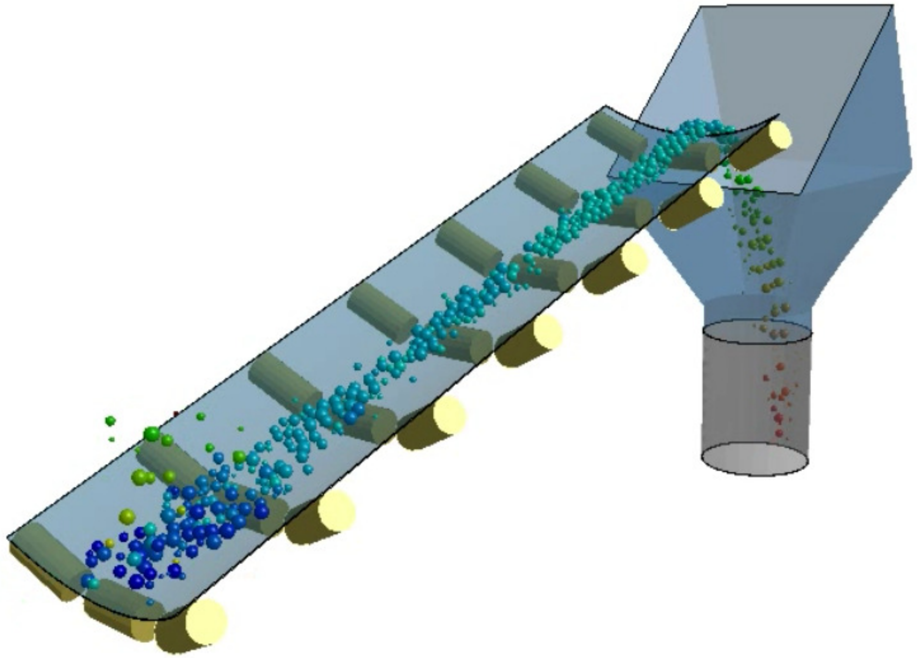


- Drop of a Particle-Filled Ball from 1m Above the Rigid Ground
  - Large deformations demand for a coupled solution
    - Inside: 1941 particles (dry sand)
    - Outside: 1.8 mm thick visco-elastic latex membrane



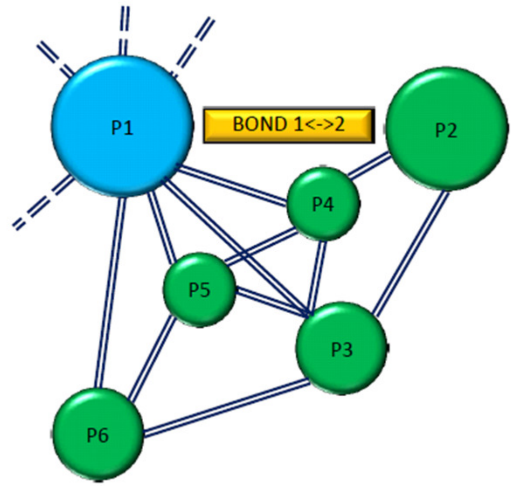
- Bulk Flow Analysis
  - Introduction of a particle source and "sink"
    - ***DEFINE_DE_INJECTION**
      - possibility to prescribe
        - location and rectangular size of the source
        - mass flow rate, initial velocity
        - min. and max. radius
    - ***DEFINE_DE_ACTIVE_REGION**
      - definition via bounding box

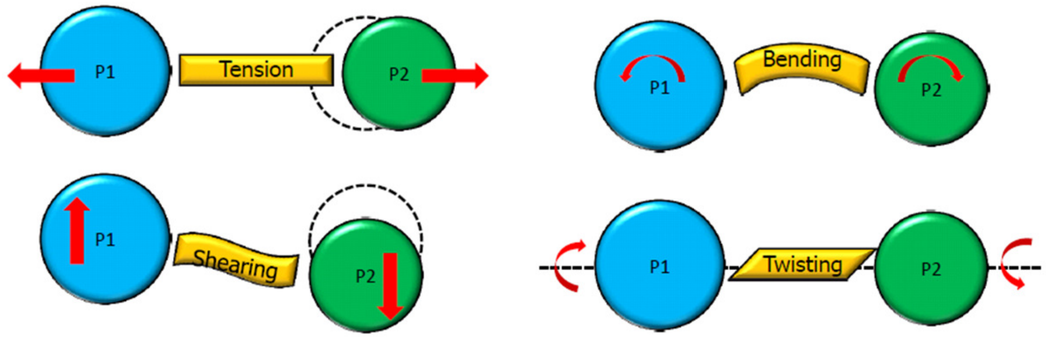
- Problem Description
  - Belt conveyor
    - Deformable belt
    - Transport velocity
    - Contact with rigid supports
  - Generated particles
    - Plastic grains



Extension to Bonded Particles

- Introduction of ***DEFINE_DE_BOND**
  - All particles are linked to their neighboring particles through Bonds
  - Bonds represent the complete mechanical behavior of Solid Mechanics
  - Bonds are calculated from the Bulk and Shear Modulus of materials
  - Bonds are independent of the DEM
  - Every bond is subjected to
    - Stretching, bending
    - Shearing, twisting



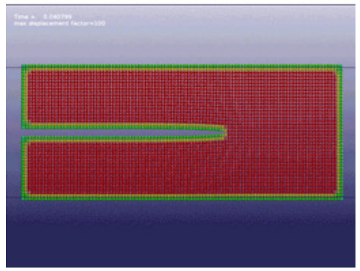


  - The breakage of a bond results in Micro-Damage
    which is controlled by a prescribed critical fracture energy release rate

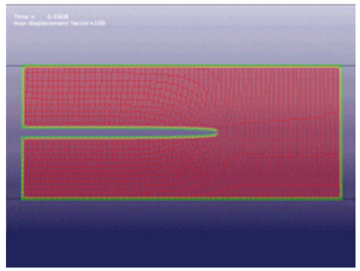
First Benchmark Test with Different Sphere Diameters

- Pre-notched plate under tension
  - Quasi-static loading
  - Material: Duran 50 glass
  - Density: 2235kg/m^3
  - Young's modulus: 65GPa
  - Poisson ratio: 0.2
  - Fracture energy release rate: 204 J/m^2
- Case I
  - 4000 spheres r = 0.5 mm
  - Crack growth speed: 2012 m/s
  - Fracture energy: 10.2 mJ
- Case II
  - 16000 spheres r = 0.25 mm
  - Crack growth speed: 2058 m/s
  - Fracture energy: 10.7 mJ
- Case III
  - 64000 spheres r = 0.125 mm
  - Crack growth speed: 2028 m/s
  - Fracture energy: 11.1 mJ

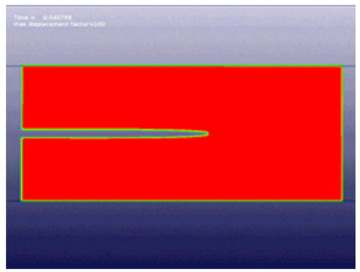
I:



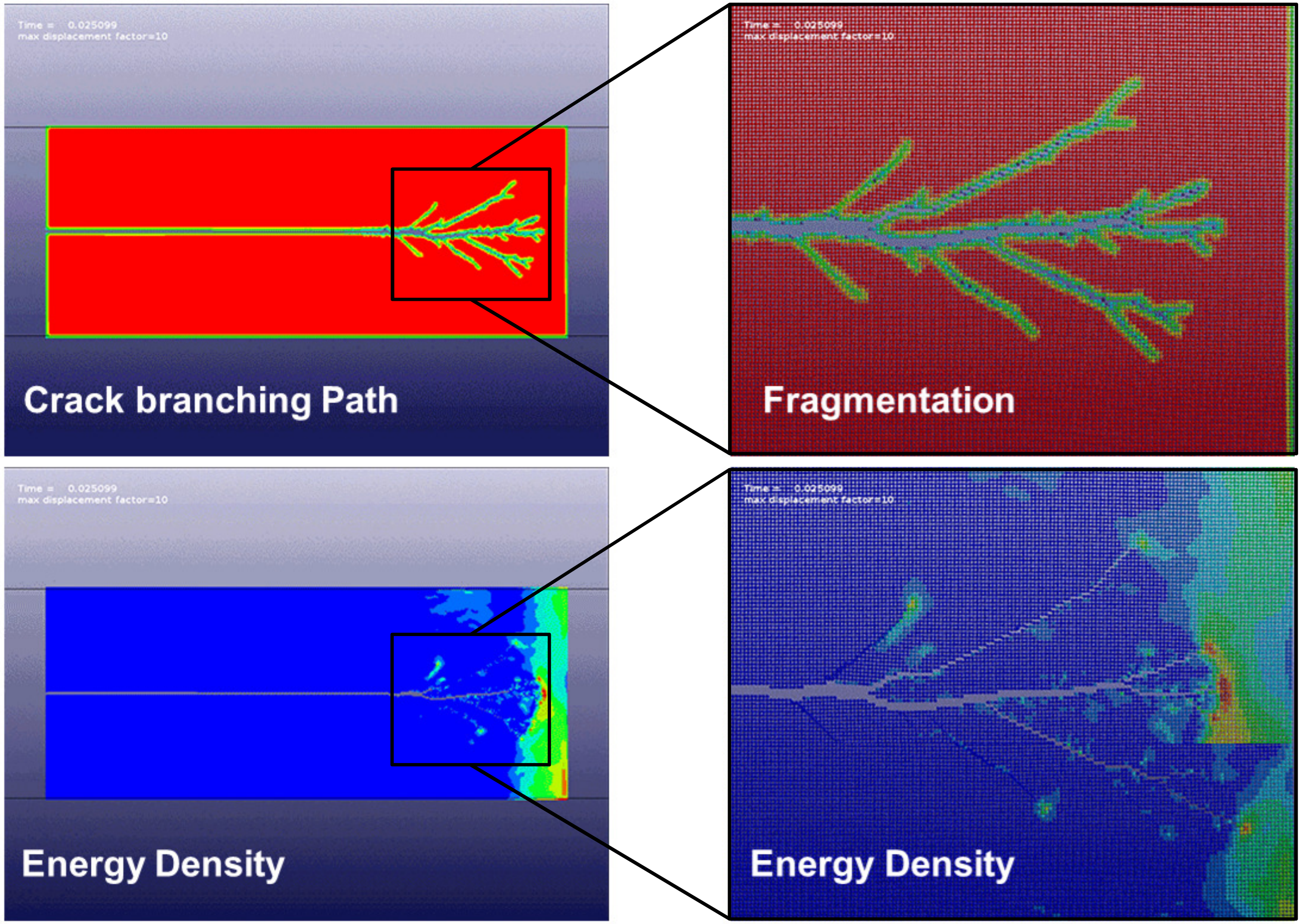
II:



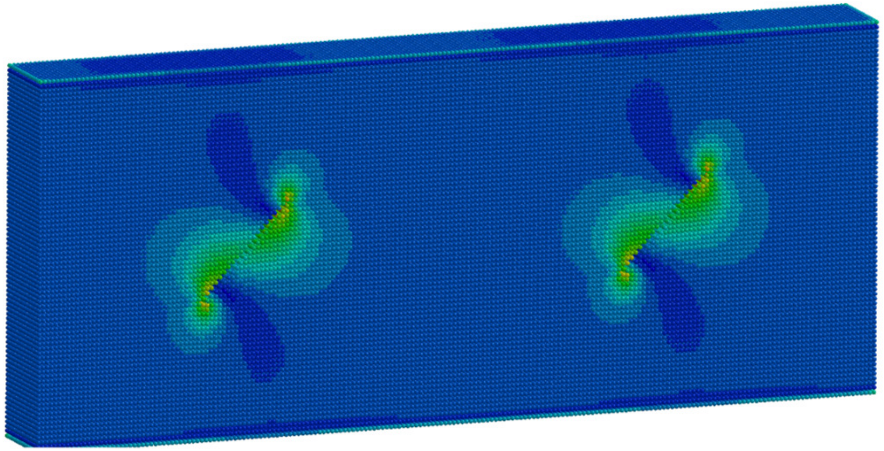
III:

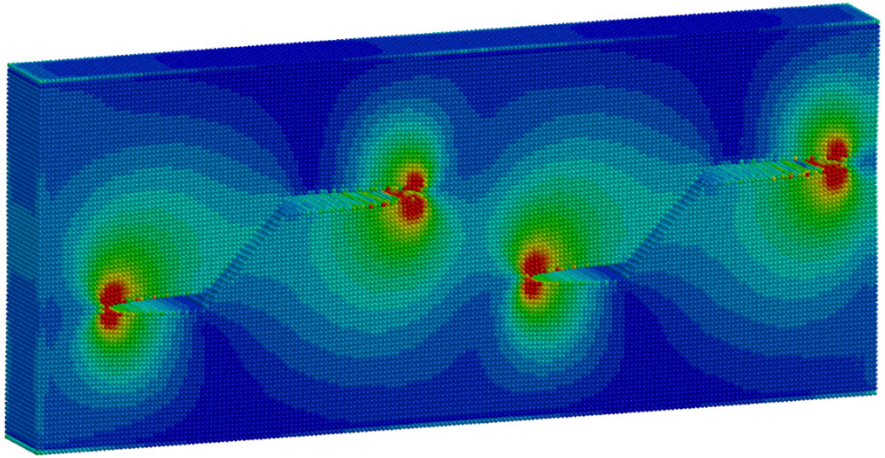


Fragmentation Analysis with Bonded Particles



- Pre-Cracked specimen
  - Loading plates via *CONTACT_CONSTRAINT_NODES_TO_SURFACE
  - Pre-cracks defined by shell sets





Conclusion

- Introduction of loose particles
  - Particle definition with volume option
  - Particle-particle interaction
    - contact stiffness, damping and friction
    - cohesion
  - Particle-structure interaction
    - deformable or rigid finite-element structures
    - contact stiffness, damping and friction
  - Particle source and “sink” for bulk flow analysis
- Extension to bonded particles
  - Linear-elastic solid behavior
  - Brittle fracture

Thank you for your attention!

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