Interaction Possibilities of Bonded and Loose Particles in LS-DYNA

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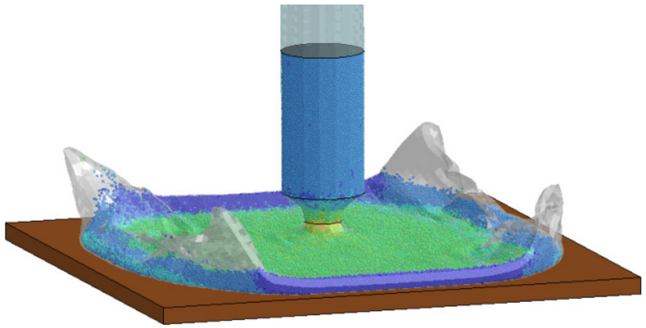


Information day: Multiphysics with LS-DYNA

4 March 2013, Stuttgart

Outline

- Introduction and Motivation
- Discrete-Element Method in LS-DYNA
- Sphere Packing with LS-PrePost
- Sample Applications
- Extension to Bonded Particles
- Conclusion

Introduction and Motivation

- Granular Media

[*Wiese Förderelemente GmbH*]

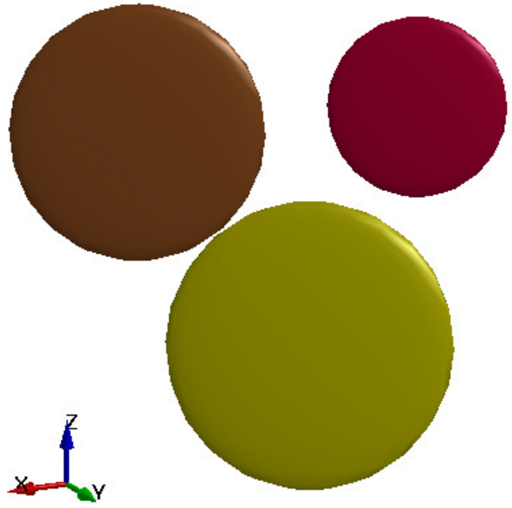
- Numerical Simulations Help to Design
  - Storage
    - Silos, Piles
  - Transportation
    - Conveyor belts, screws, Pumps
  - Processing
    - Sorting, Mixing, Segregation
  - Filling
    - Hopper/ funnel flow
- Characteristics of Granular Media
  - Solid behavior when compacted
  - Fluid-like behavior when in motion
- 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

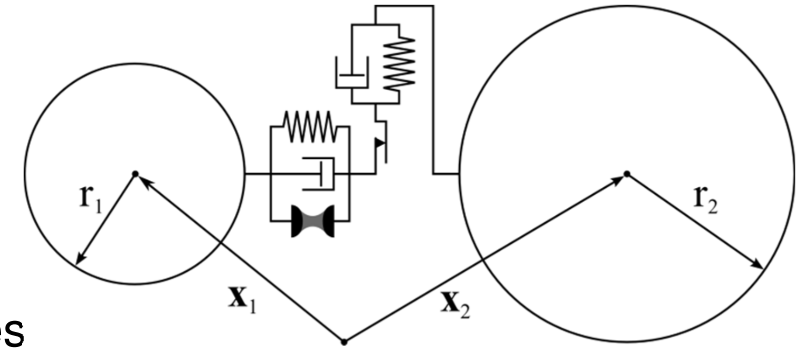
$$M = V\rho = \frac{4}{3}\pi r^3 \rho \qquad I = \frac{2}{5} M r^2 = \frac{8}{15}\pi r^5 \rho$$

  - 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
```

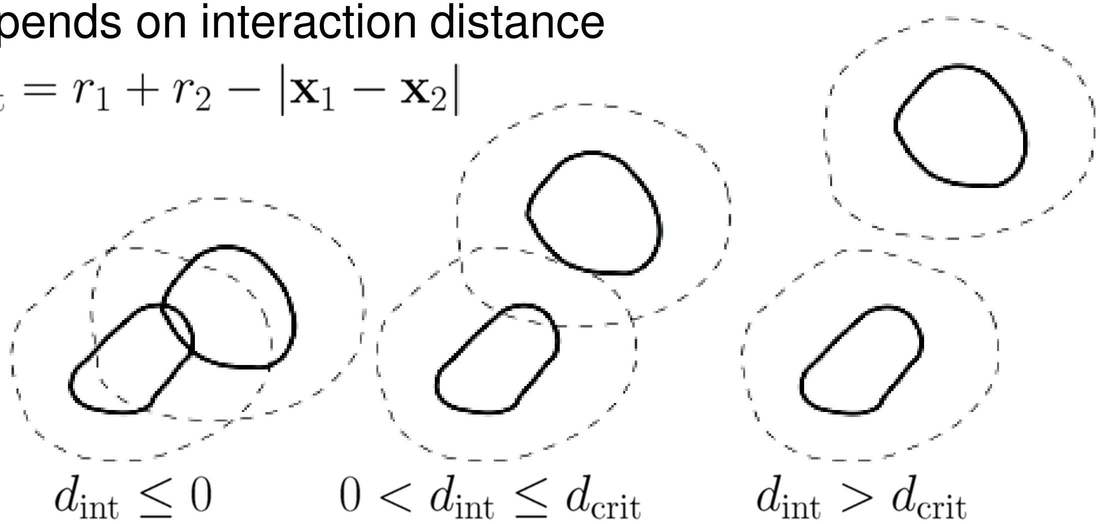
- **Definition of the Contact between Particles**
  - Mechanical contact
    - Discrete-element formulation according to [*Cundall & Strack* 1979]
  - Extension to model cohesion using capillary forces

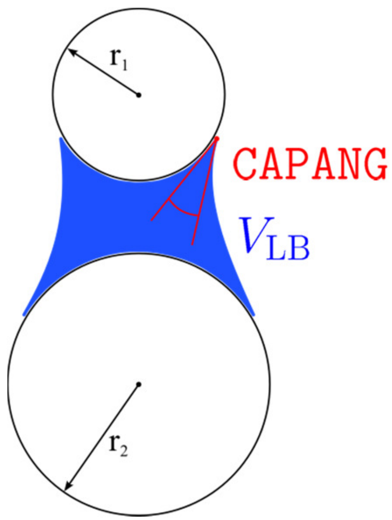



```
*CONTROL_DISCRETE_ELEMENT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#    NDAMP     TDAMP      Fric    FricR    NormK    ShearK       CAP     MXNSC
      0.700     0.400      0.41    0.001     0.01    0.0029         0         0
$#    Gamma    CAPVOL    CAPANG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

- Possible collision states
  - Depends on interaction distance

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





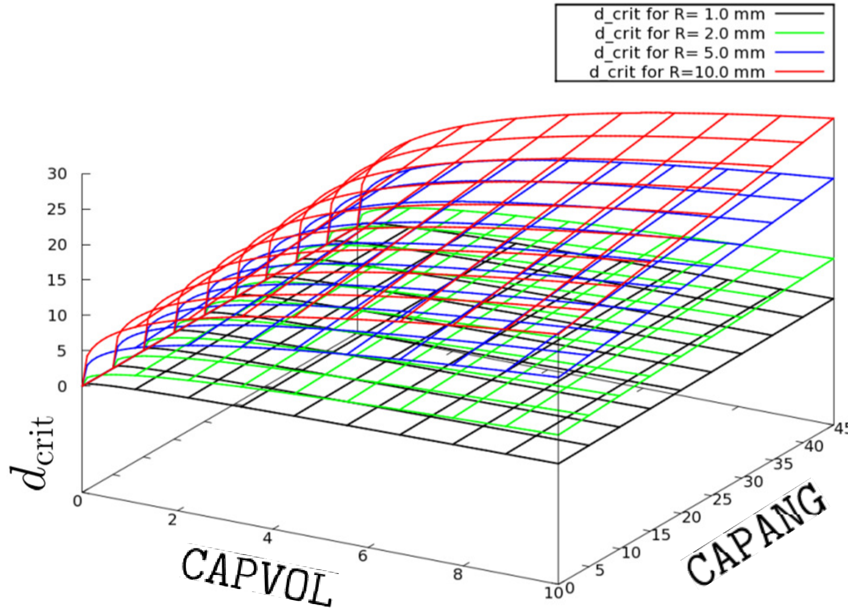
Capillary Force Contribution – The Formulas

- Characterization of the liquid bridge
  - Volume

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

  - Rupture distance

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

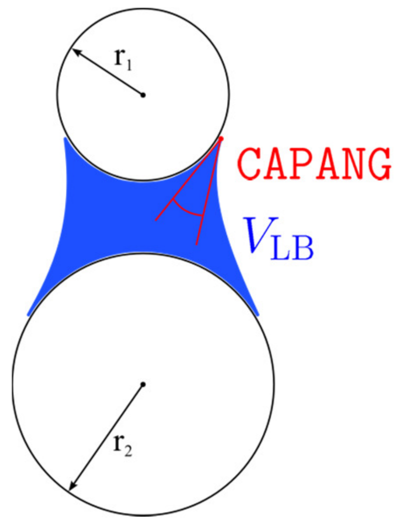


  - Capillary force

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

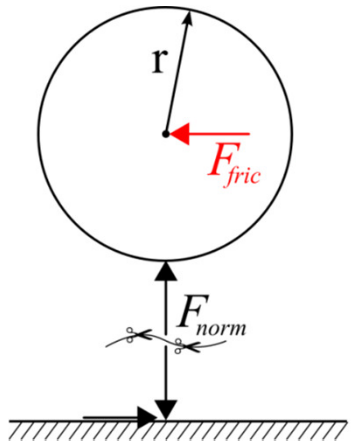
with

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



Definition of the Particle-Structure Interaction

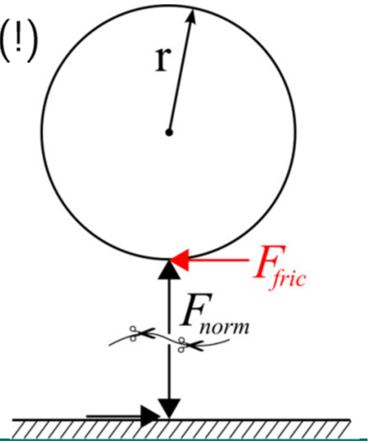
- Classical contact, e.g.: ***CONTACT_AUTOMATIC_NODES_TO_SURFACE**
  - Benefits of classical contact definitions
    - static and dynamic friction coefficients
    - constraint contacts are admissible
  - Drawbacks of the classical contact definitions
    - friction force is applied to particle center
    - not possible to apply rolling friction



- New contact for discrete elements:

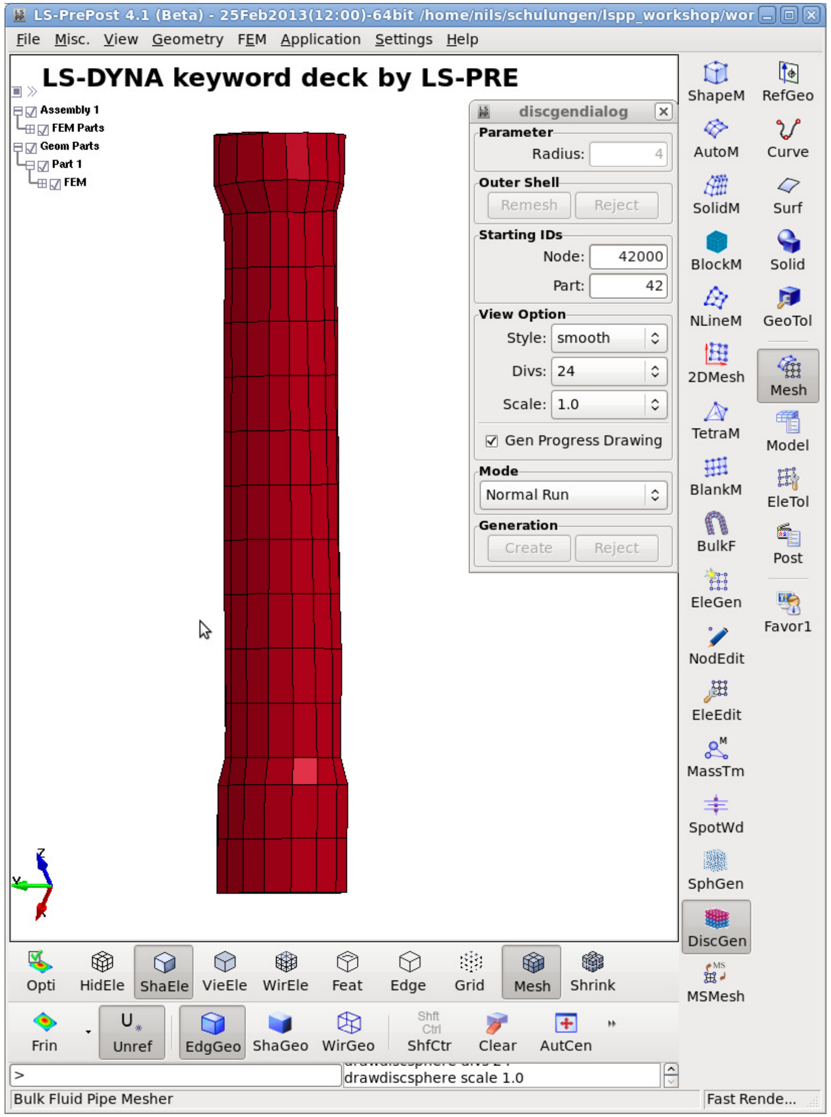
```
*DEFINE_DE_TO_SURFACE_COUPLING
$#    SLAVE     MASTER      STYPE      MTYPE
        300          1          0          1
$#    FricS      FricD       DAMP      BSORT       LCVx       LCVy       LCVz
        0.5       0.01        0.2        100          0          0          0
```

  - Damping determines if the collision is elastic or “plastic” $0 \leq \mathrm{DAMP} \leq 1.0$ (!)
  - Benefits of the new contact definition
    - friction force is applied at the perimeter
    - static and rolling friction coefficients
    - possibility to define transportation belt velocity via `LCVxyz`
  - Drawbacks of the new contact definition
    - no possibility to tweak via penalty scale factors



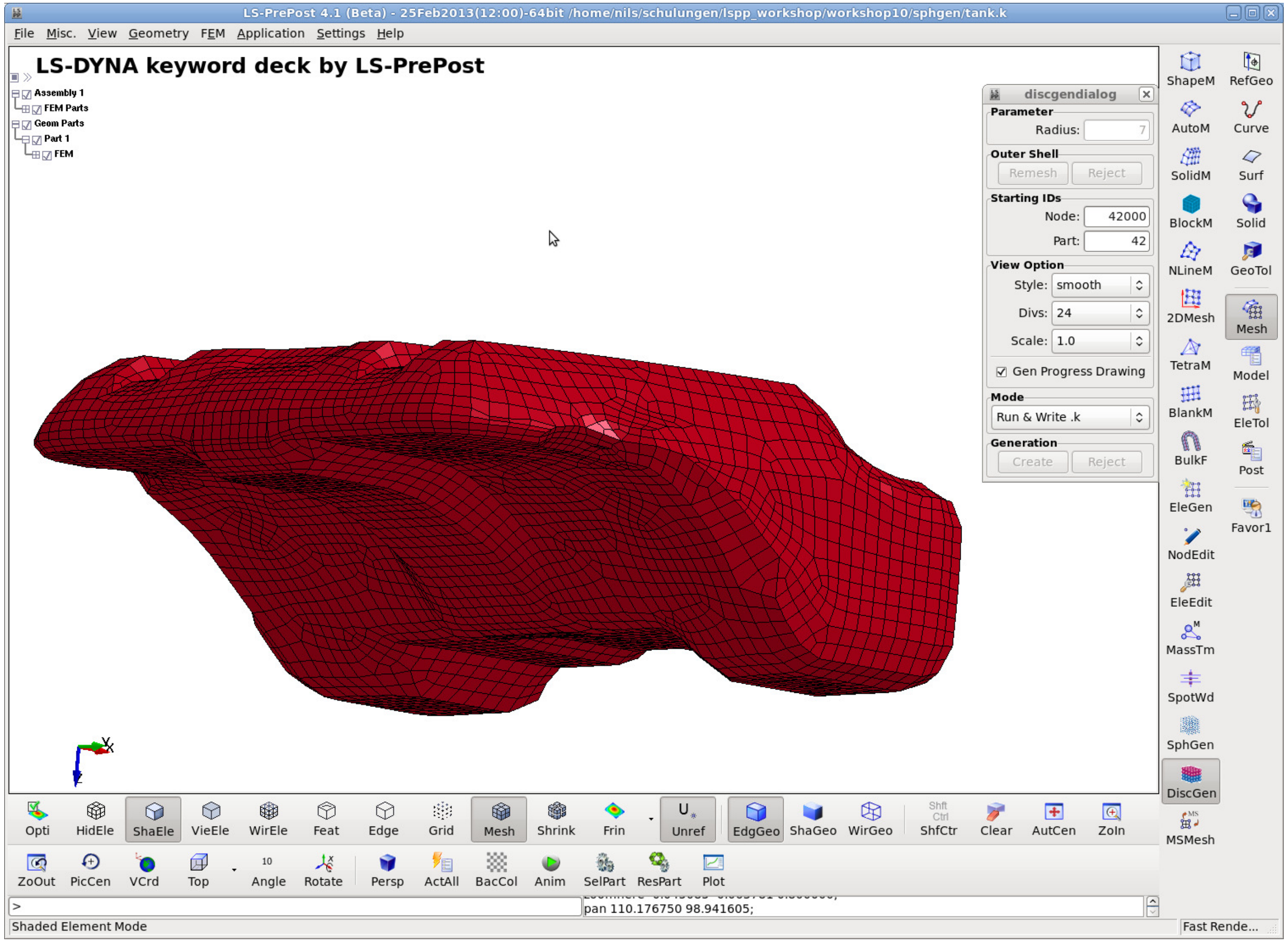
Sphere Packing with LS-PrePost

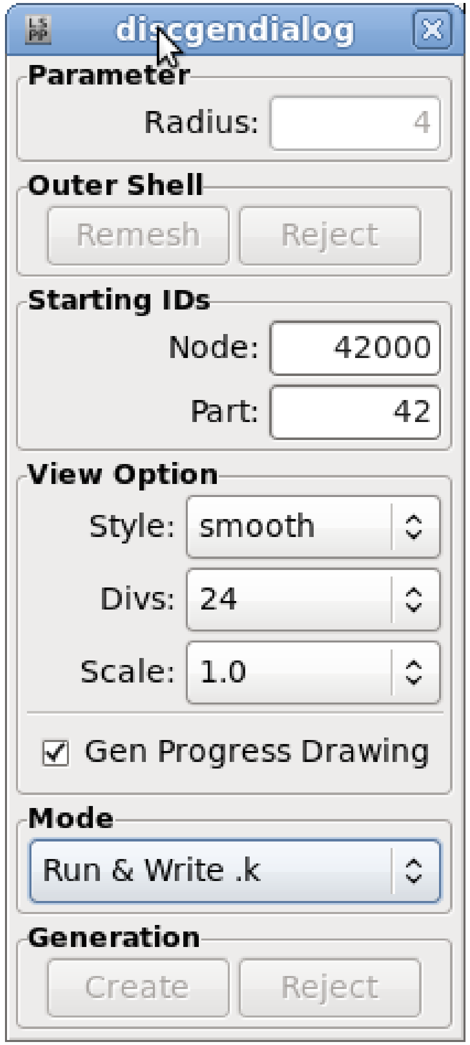
- General Information
  - Automatic packing algorithm for meshed objects
    - Bounded volume is required
    - Boundary with 3- or 4-noded shell elements
    - Support of double-connected volumes
      - mesh for inner and outer surface needed
      - surface normals need to be consistent
  - Specifications of the sphere packing engine
    - Currently limitation to equal radii
    - Single-thread implementation
    - Generation speed: ~600-1000 spheres/s on i7-3930 @ 3.2 GHz
    - Only available in developer version! LS-PrePost 4.1 (beta) of 25 February 2013 or later



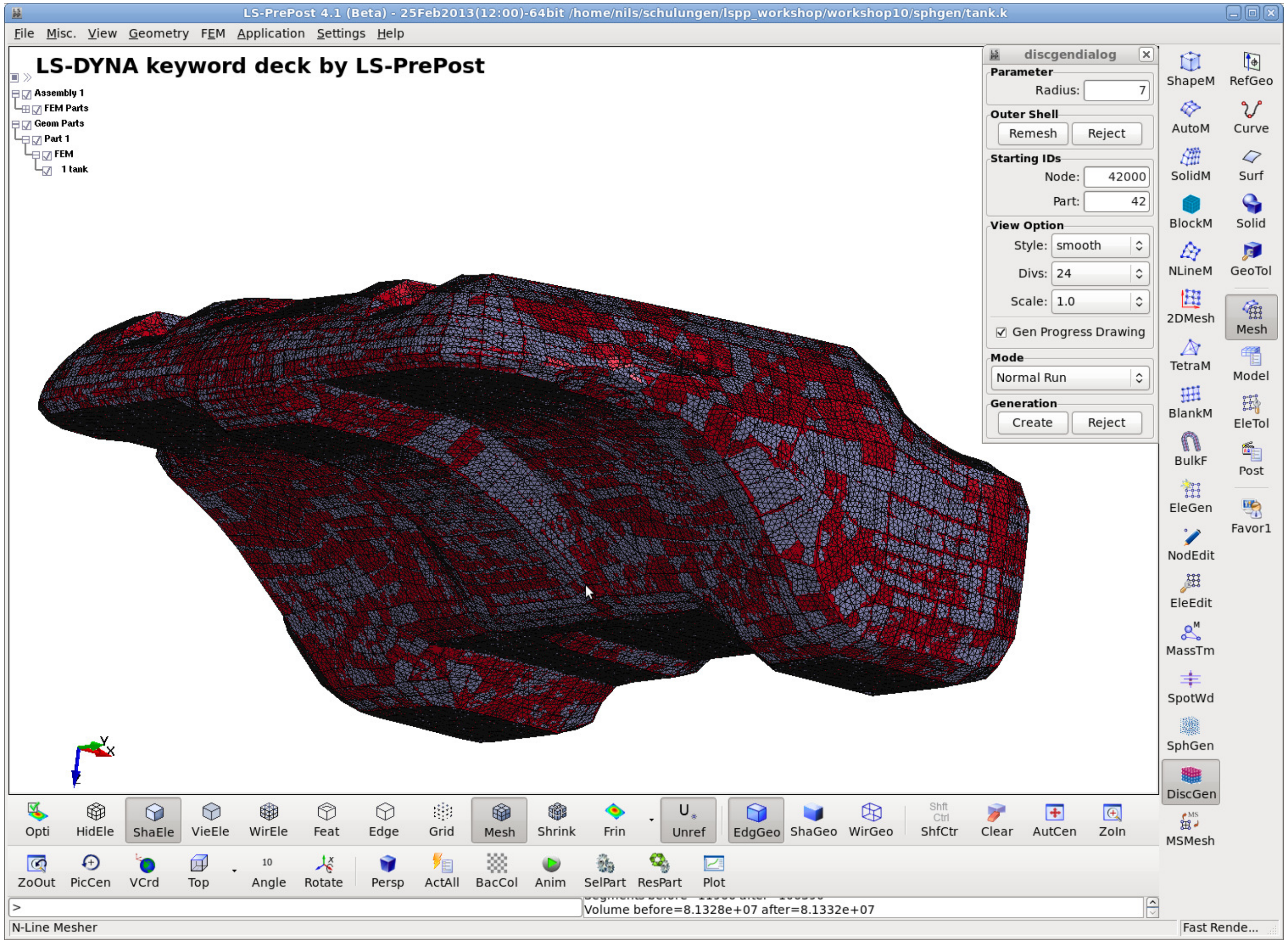
Sphere Packing Example

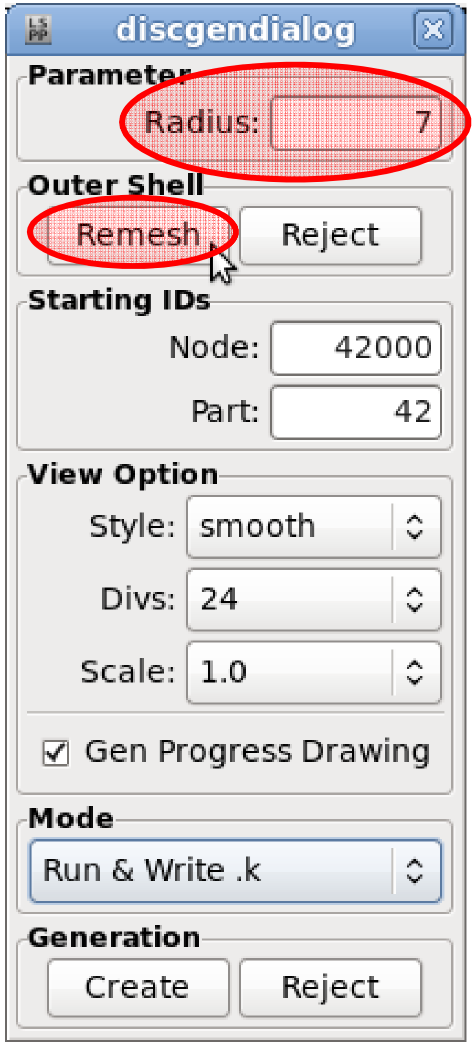
- Open surface mesh or geometry and generate surface mesh
- Enter the *discgendialog* under *Mesh/DiscGen*





- Select the bounding surface mesh to be packed
- Enter desired sphere radius
- Re-mesh the surface (important!)

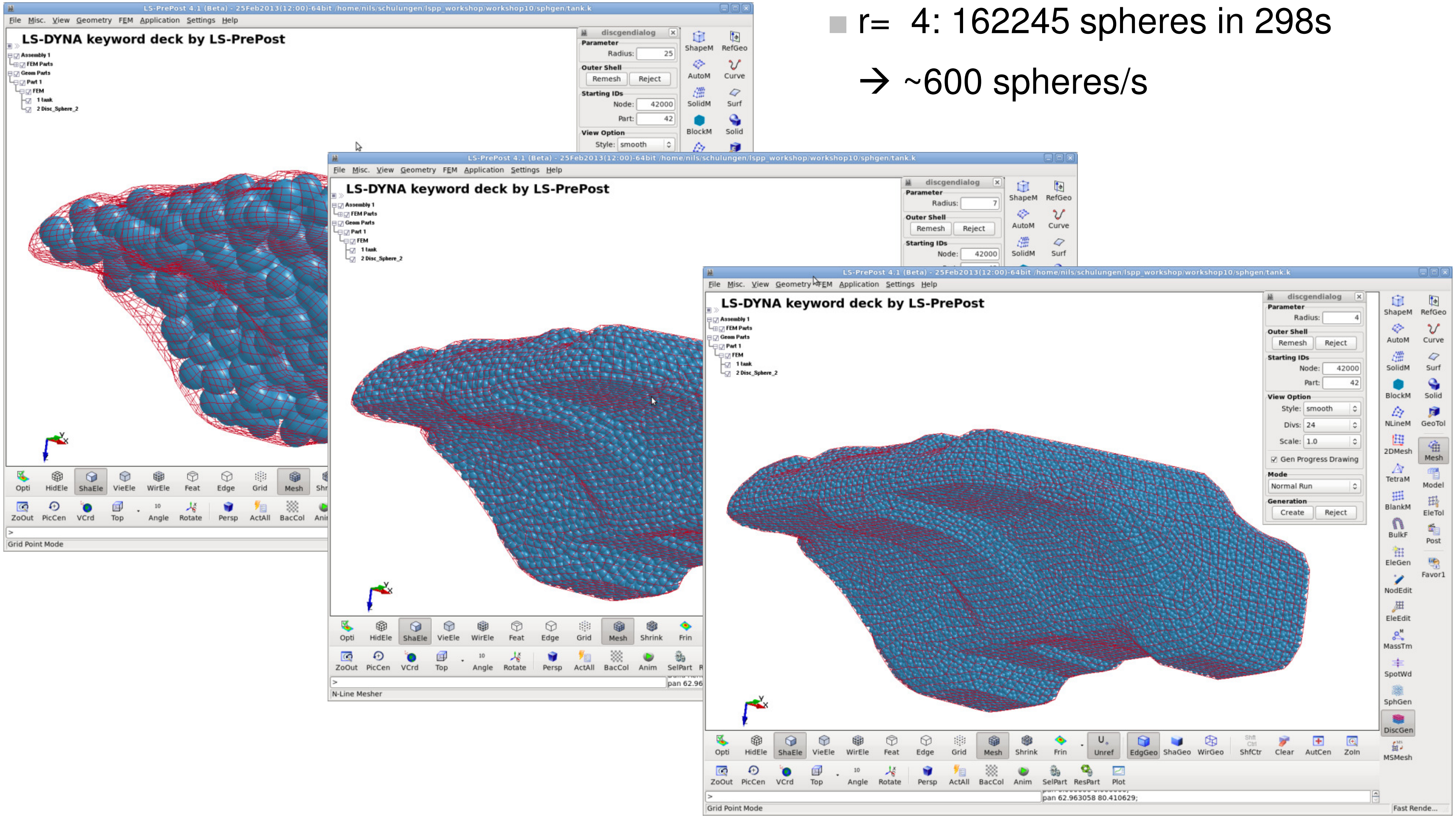




- Benchmark with 3 different sphere sizes

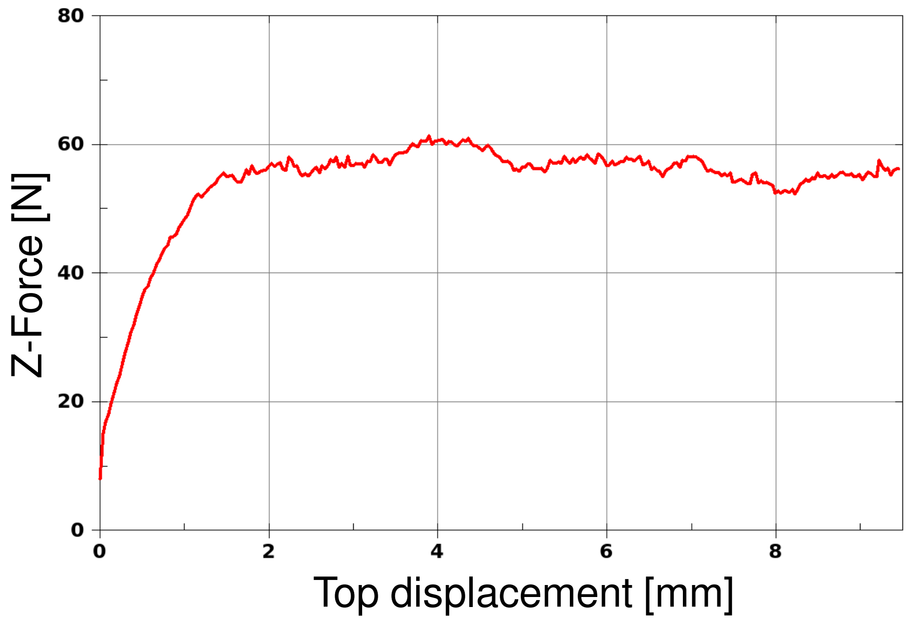
- Performance
  - r=25: 628 spheres in 1s
  - r= 7: 29509 spheres in 47s
  - r= 4: 162245 spheres in 298s

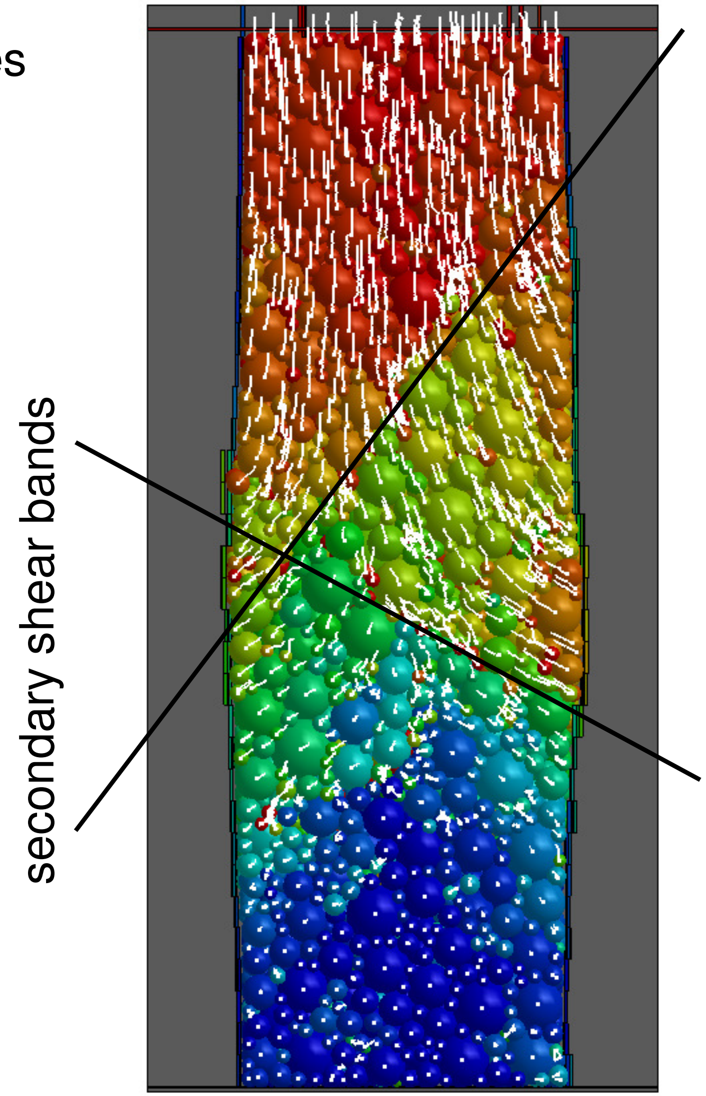
  → ~600 spheres/s



Sample Applications

- Biaxial Compression Test
  - Standard test to determine parameters of loose particles
    - 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-displacement diagram



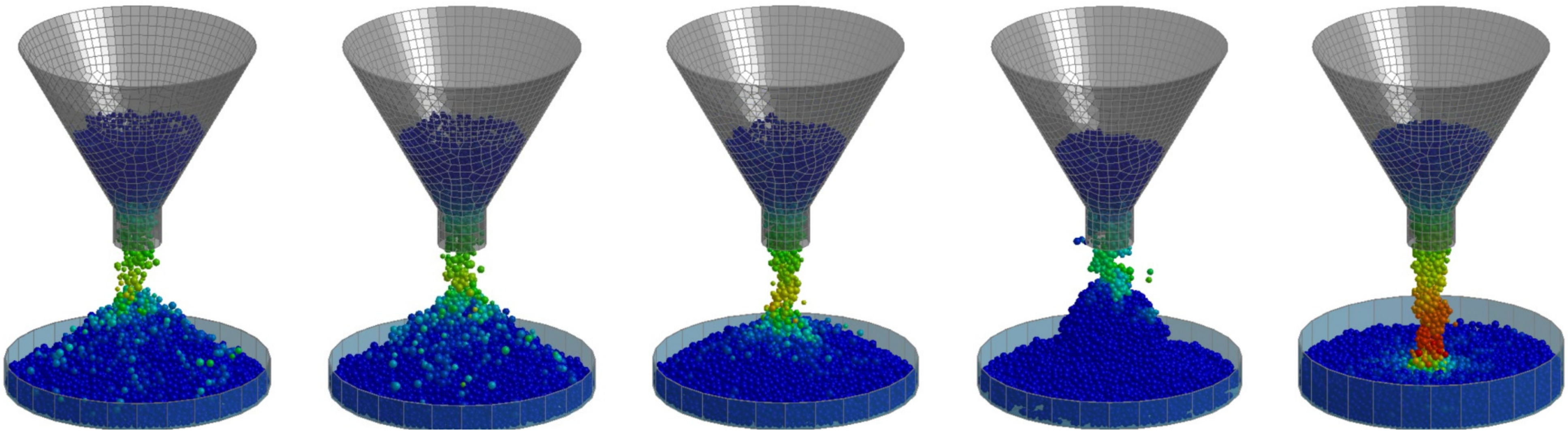


Granular Flow Through a Funnel

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

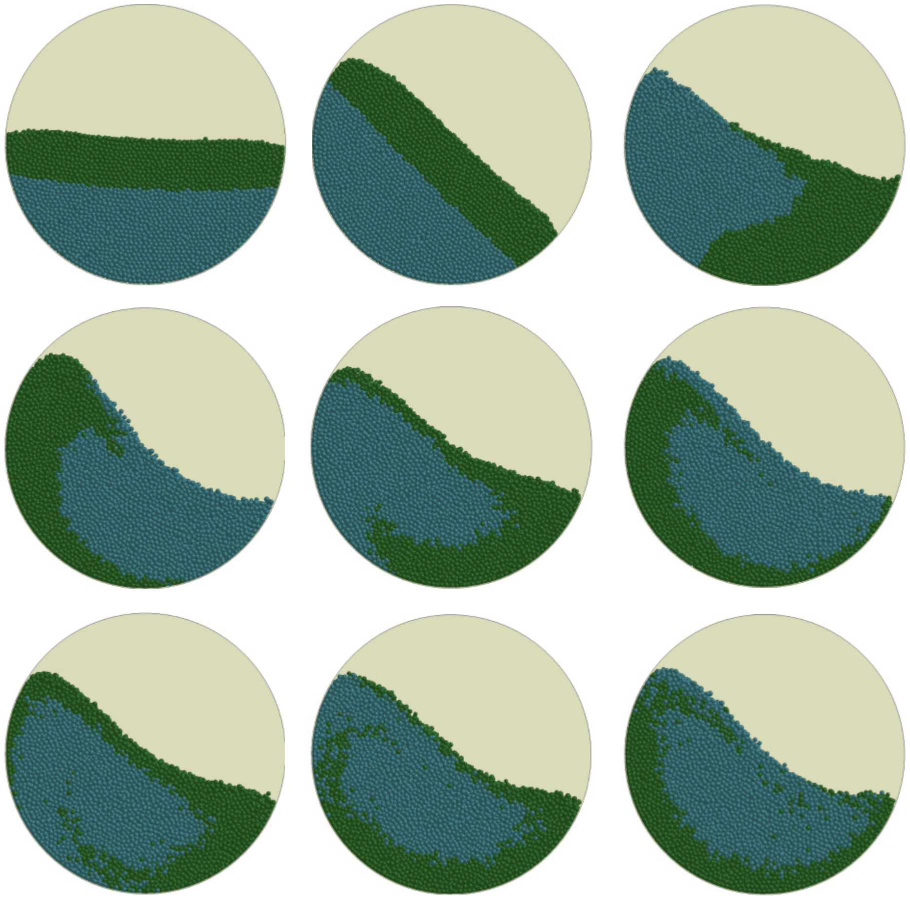
```
$-------+-------1--------+--------2---------+--------3---------+--------4---------+--------5
RHO        0.80E-6           2.63E-6           2.63E-6           2.63E-6            1.0E-6
P-P Fric      0.57              0.57              0.57              0.10              0.00
P-P FricR     0.10              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
```

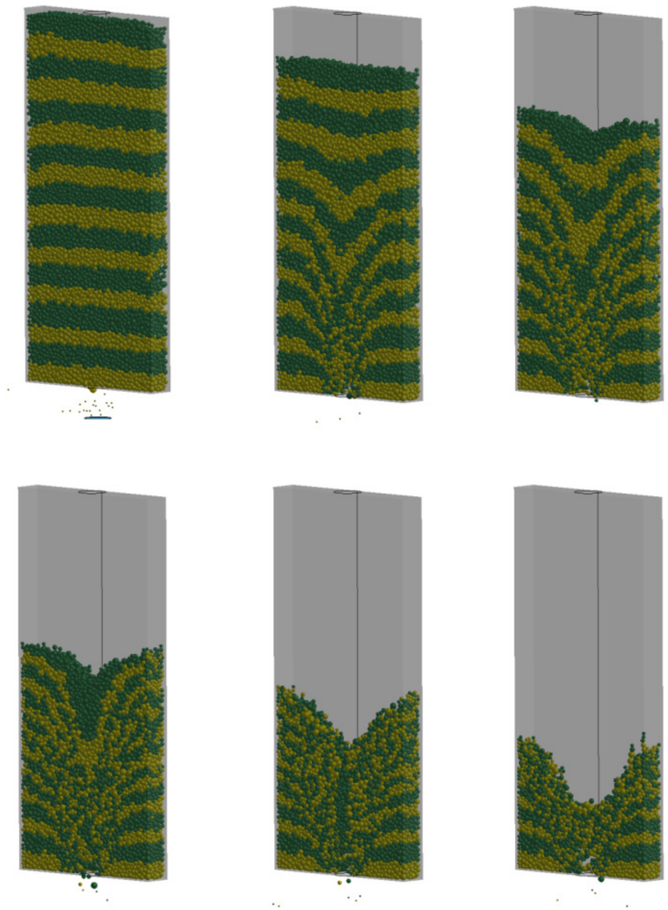
foamed clay | dry sand | wet sand | fresh concrete | "water"



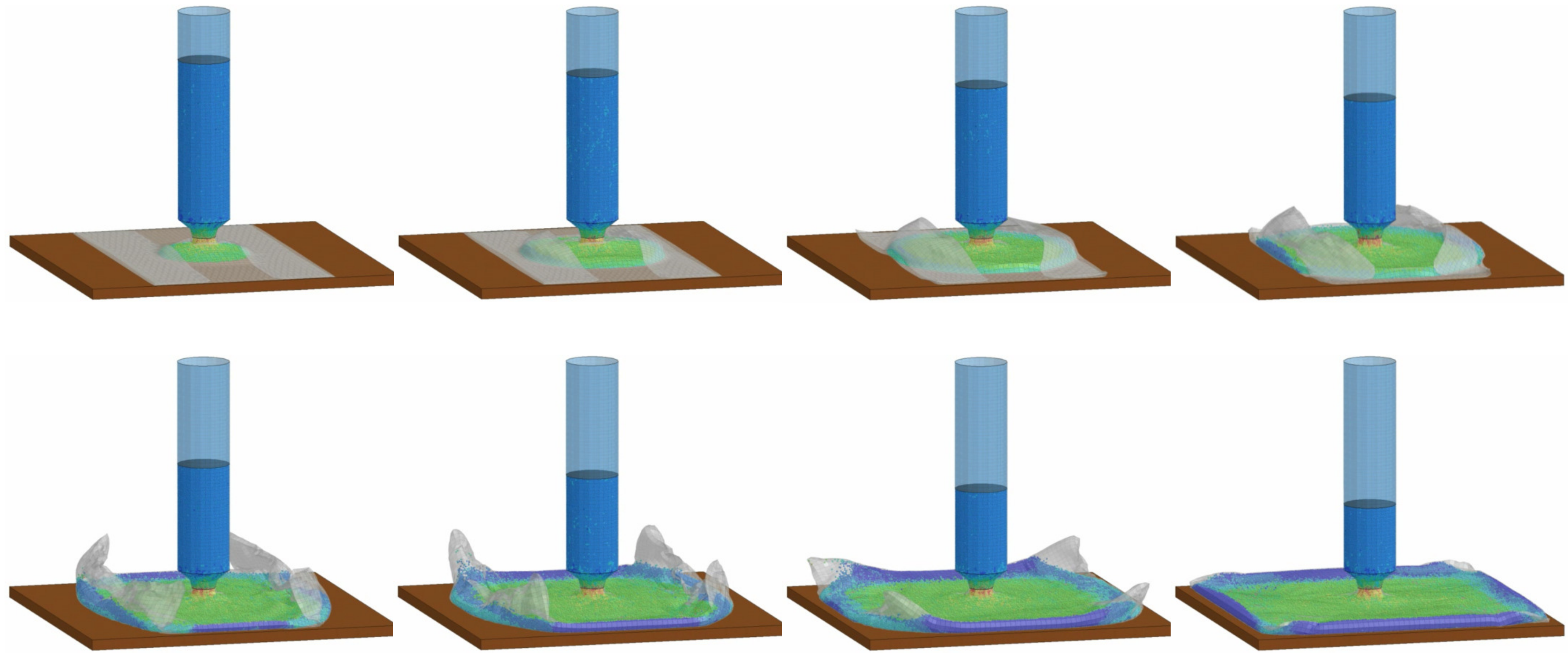
- Drum Mixer
  - 12371 particles with two densities
    - Green: foamed clay
    - Blue: sand

- Hopper Flow
  - 17000 particles of the same kind
    - Radii from 1.5 – 3 mm
    - Static & rolling friction of 0.5





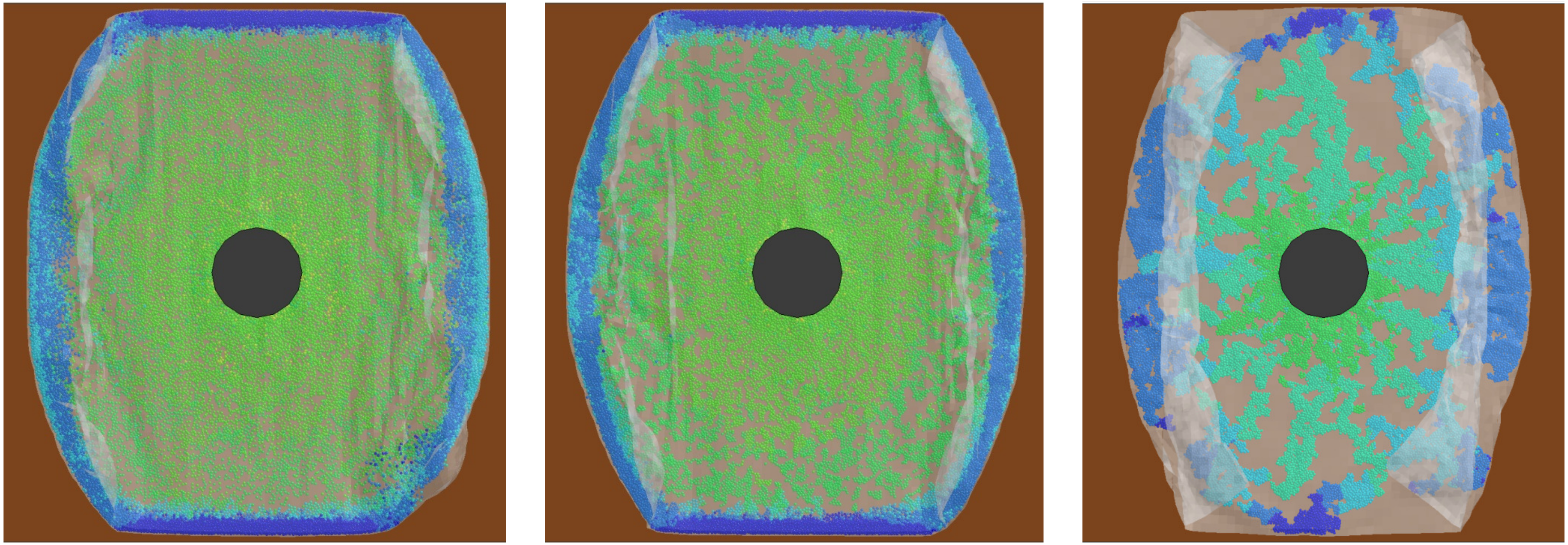
- Filling Process
  - Dry particles are injected into a bag
    - Inside: 89331 particles (dry sand: `fric = 0.57, fricr = 0.001`)
    - Outside: 0.35 mm thick fabric membrane (air bag)



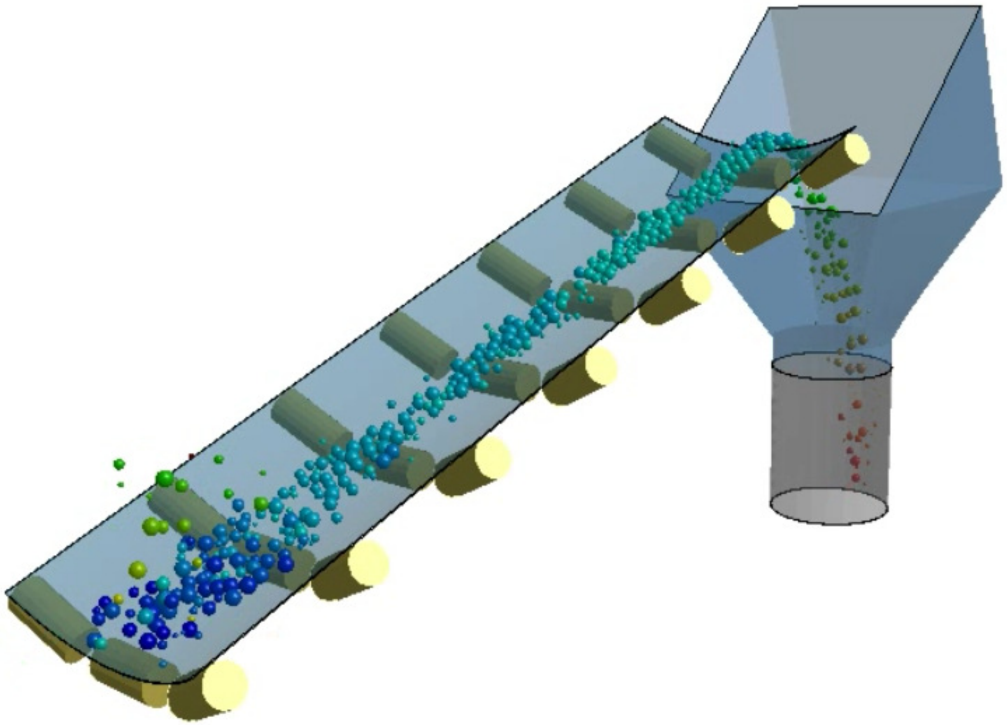
Filling Process

- Influence of capillary forces
- Snapshots taken at the same time

dry sand | wet sand | fresh concrete



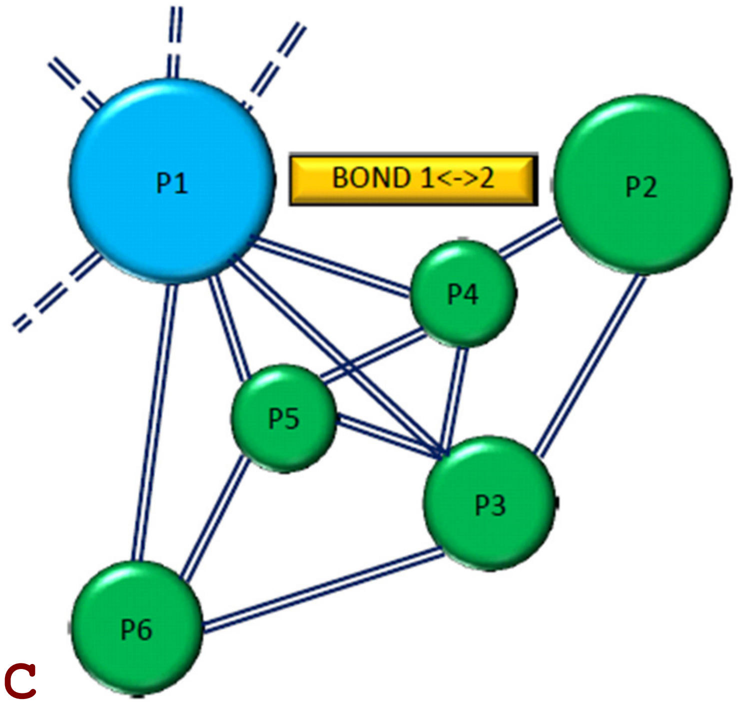
- Bulk Flow Analysis
  - Introduction of a particle source and “sink”
    - *DEFINE_DE_INJECTION
      - possibility to prescribe
        - location and rectangular size of the source
        - mass flow rate, initial velocity
        - min. and max. radius
    - *DEFINE_DE_ACTIVE_REGION
      - definition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



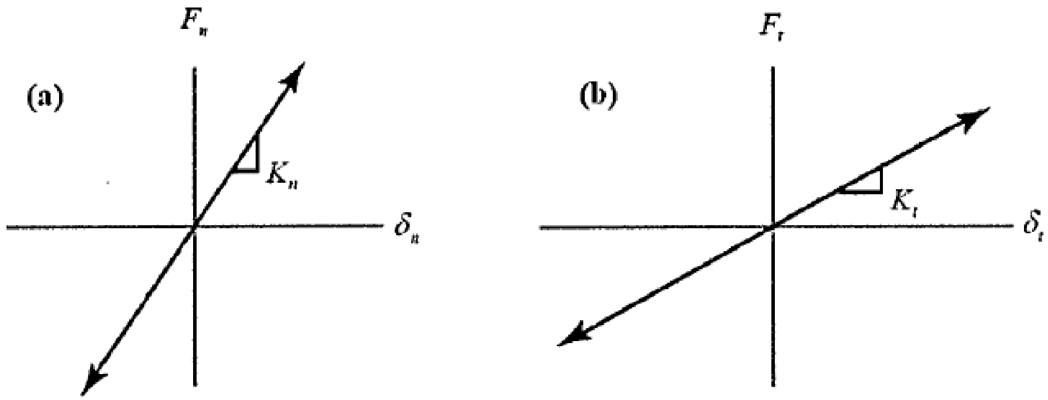
- Problem Description
  - Belt conveyor
    - Deformable belt
    - Transport velocity
    - Contact with rigid supports
  - Generated particles
    - Plastic grains

Extension to Bonded Particles

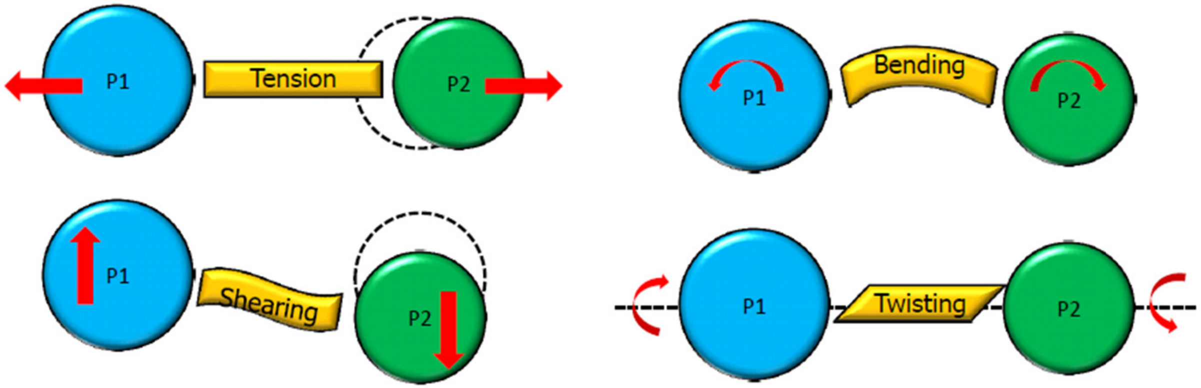
- Introduction of ***DEFINE_DE_BOND**
  - All particles are linked to their neighboring particles through bonds
  - Bonds represent the complete mechanical behavior of solid mechanics
  - Bonds are independent of the DEM



- Bond Properties can be Computed Automatically using Bulk and Shear Modulus of ***MAT_ELASTIC**



- Every Bond is Subjected to
  - Stretching
  - Bending
  - Shearing
  - Twisting



- Failure Mechanism and Bond Breakage
  - Results in micro-damage
  - Controlled by a critical fracture energy release rate
  - Suitable to describe
    - Material separation
    - Progressive failure phenomena
  - Possible applications include
    - Rock crushing
    - Rock blasting
    - Concrete failure

[*Wikipedia*]

[*Wikipedia*]

- Manual Definition of the Bonds: `bondform=1`

```
*DEFINE_DE_BOND
$#       sid      stype     bdform       dim
          42          0          1         3
$#       pbn        pbs      pbn_s     pbs_s       sfa     alpha
         1.0        1.0      0.285     0.013       1.0       0.2
```

  - Parallel bond normal/ shear stiffness: `pbn, pbs`
  - Maximum normal/ shear stress: `pbn_s, pbs_s` $(0 = \infty)$
  - Bond radius multiplier, damping: `sfa, alpha`

- Automatic Definition of the Bonds: `bondform=2`
  - linear-elastic bond formulation for brittle materials fracture analysis

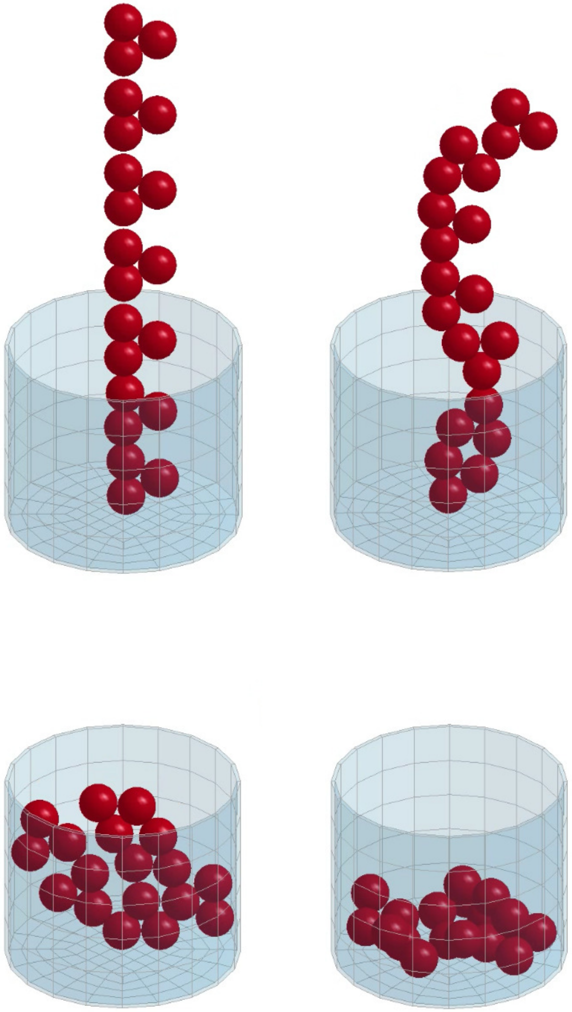
```
*DEFINE_DE_BOND
$#       sid      stype     bdform      idim
          42          0          2         3
$#    pbk_sf     pbs_sf     fenrgk    fenrgs     bondr     alpha
         1.0        1.0      0.285     0.013      3.75       0.0
$#    precrk     cktype
          12          1
```

  - Scale factor for normal/ shear stiffness: `pbk_sf, pbs_sf`
  - Fracture energy release rate for volumetric/ shear deformation: `fenrgk, fenrgs`
  - Influence radius and damping: `bondr, alpha`
  - ID of 3D shell set for the pre-crack: `precrck, cktype=0,1` for part set or part

Application with Manual Bond Definition

- Possibility to define clustered particle sets
  - Useful, to approximate non-spherical particles
  - Estimation with rolling friction might not be sufficient
  - High normal stiffness, low shear stiffness
  - Here: Definition of infinite maximum bond stress (unbreakable bonds)

```
*DEFINE_DE_BOND
$#       sid      stype     bdform        dim
          42          0          1          3
$#       pbn        pbs      pbn_s      pbs_s
        10.0        0.1        0.0        0.0
```

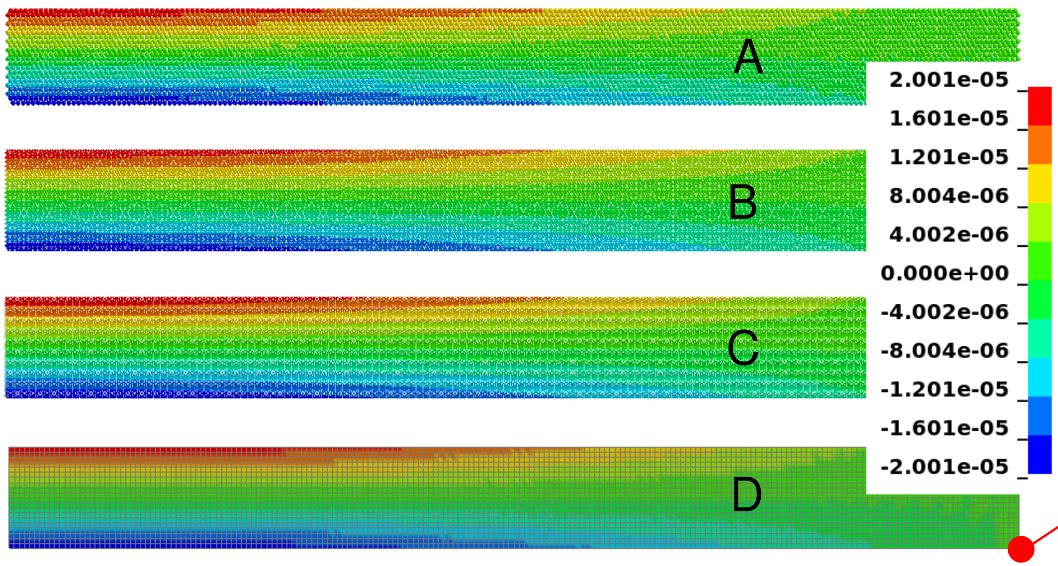


- Drawback: No pre-processing available yet!

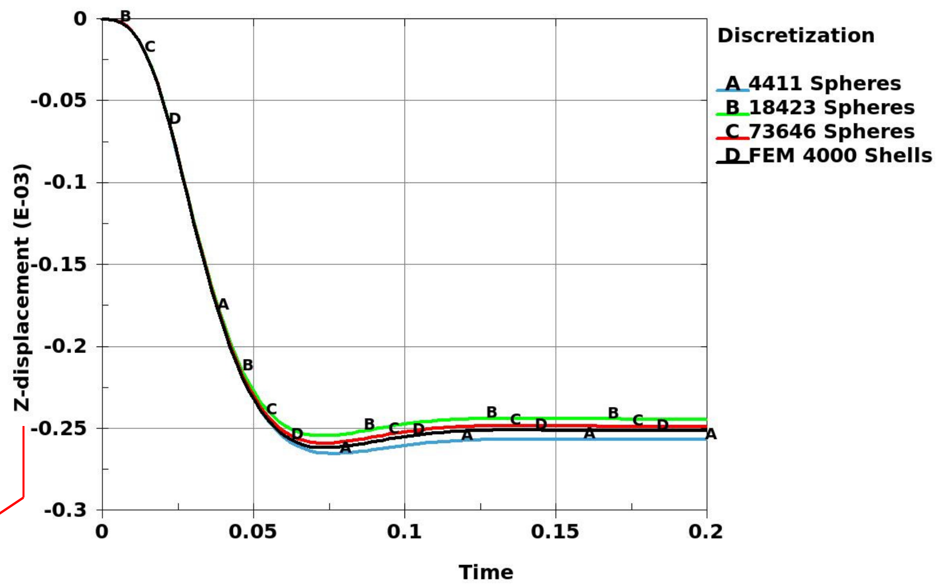
Application with Automatic Bond Definition

- Benchmark test: Beam under gravity loading
  - Goal: Reproduce linear-elastic material behavior
  - Comparison of finite-element and discrete-element discretization
    - A: 4411 bonded spheres
    - B: 18423 bonded spheres
    - C: 73646 bonded spheres
    - D: 4000 linear shells

Normal displacement [mm]



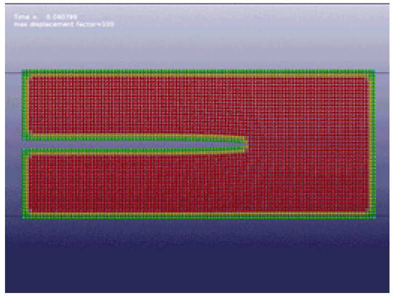
Z-displacement [mm]



Benchmark for Crack Propagation

- 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:



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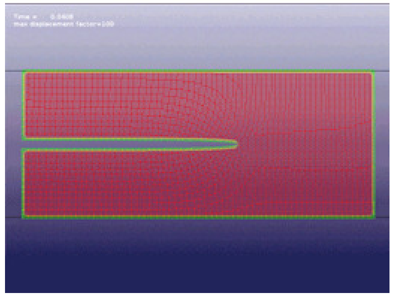
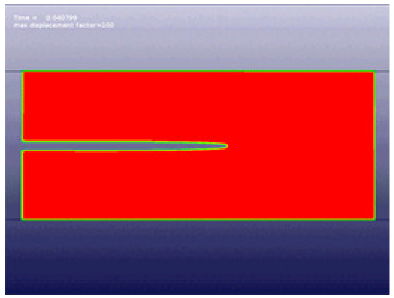
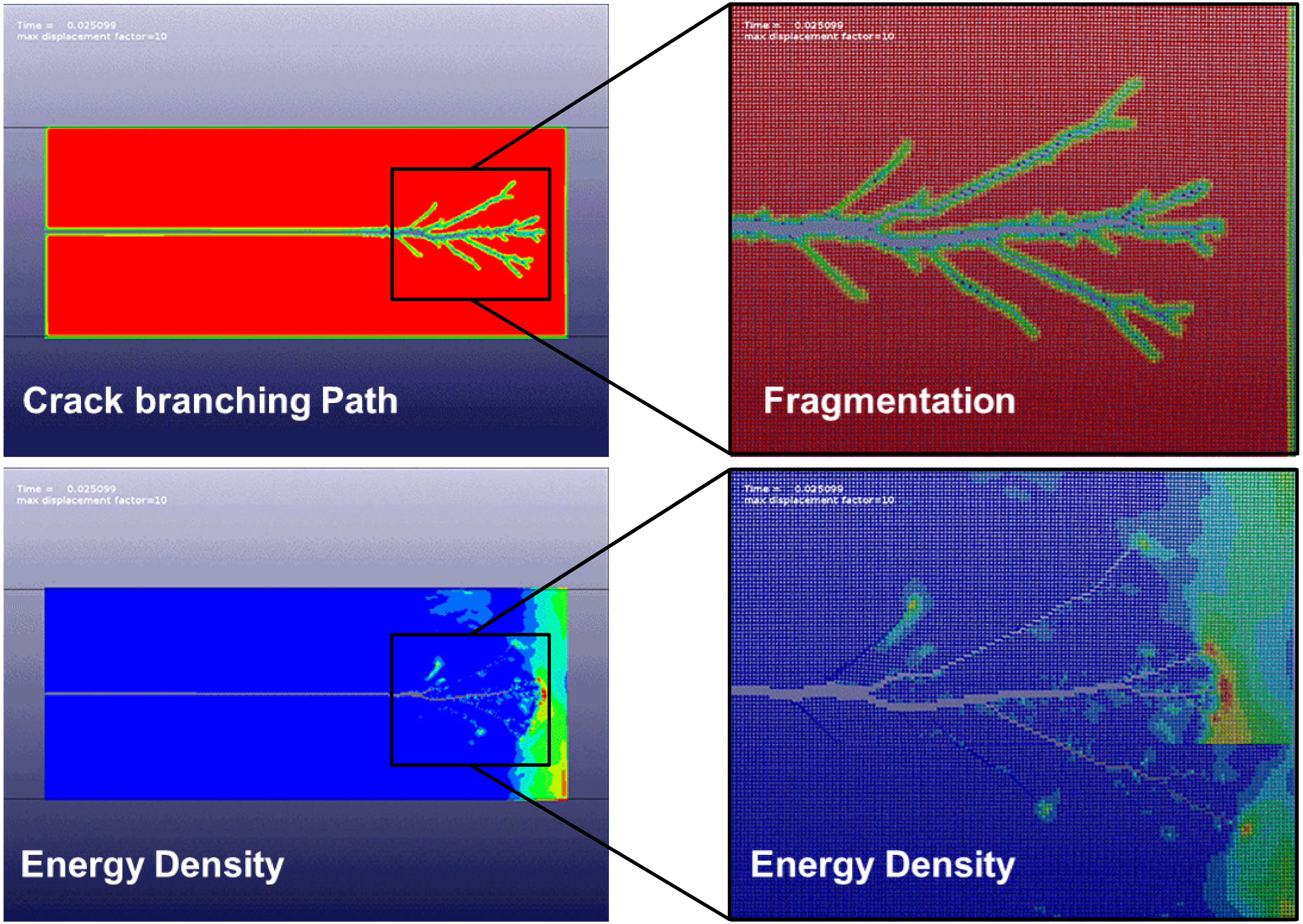


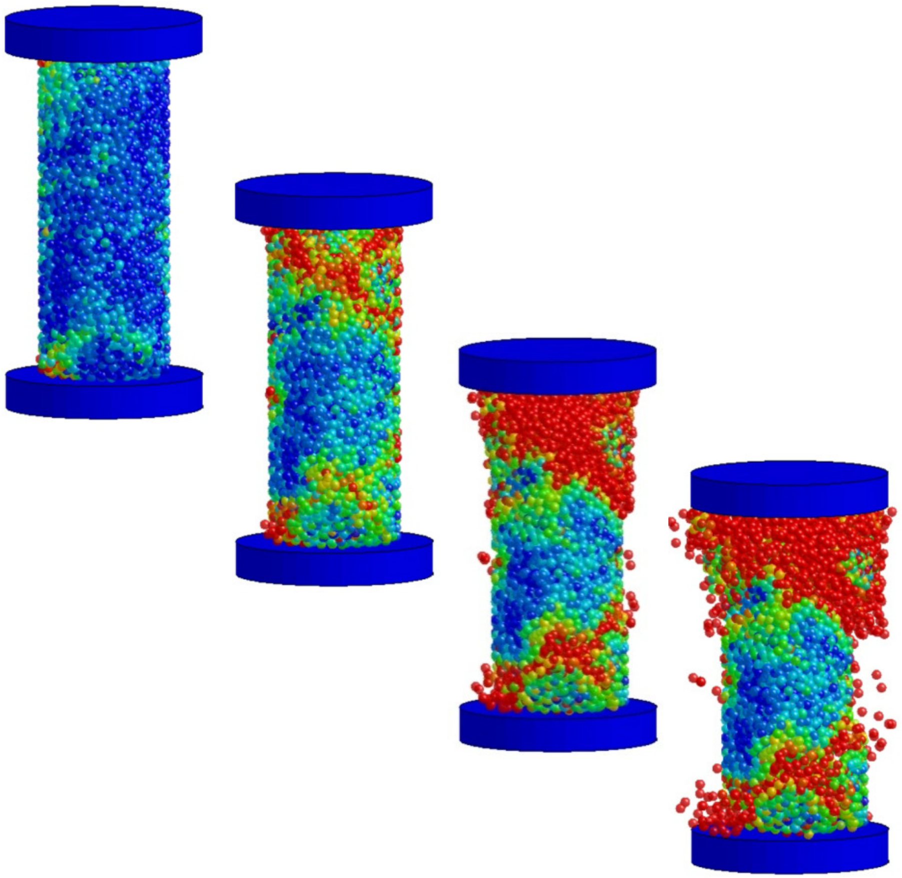
III:

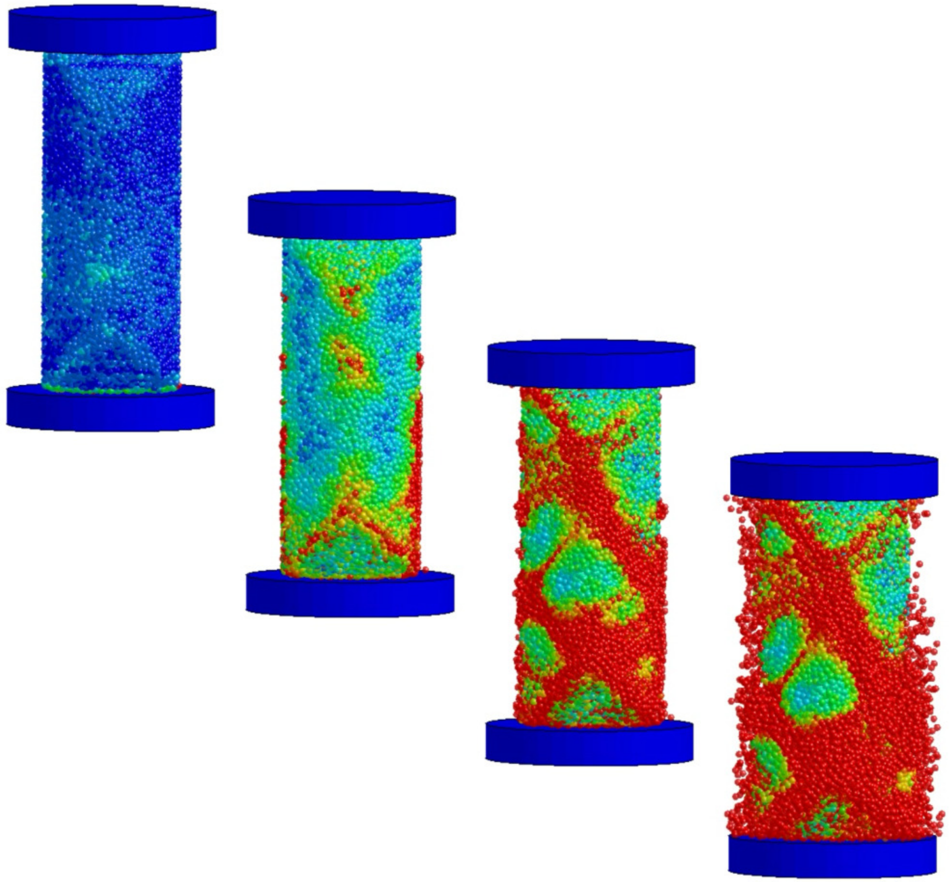


Fragmentation Analysis with Bonded Particles



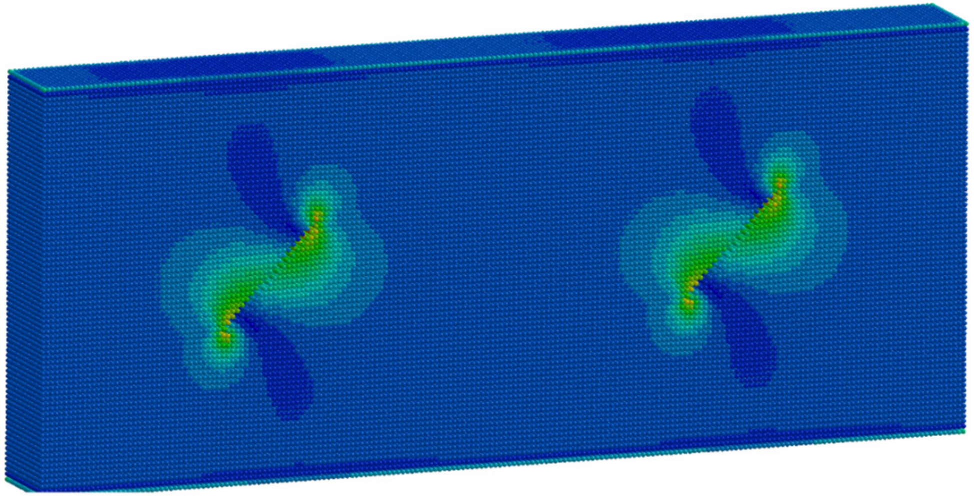
- Failure Analysis of a Concrete Specimen During Impact Loading
  - Column: h=100mm, r=20mm
  - Loading speed: 1 mm/ms
  - Colors indicate crack path
    - 4534 spheres, r=1.5 mm, rbond=5.25mm
    - 15725 spheres, r=1.0 mm, rbond=5.25mm

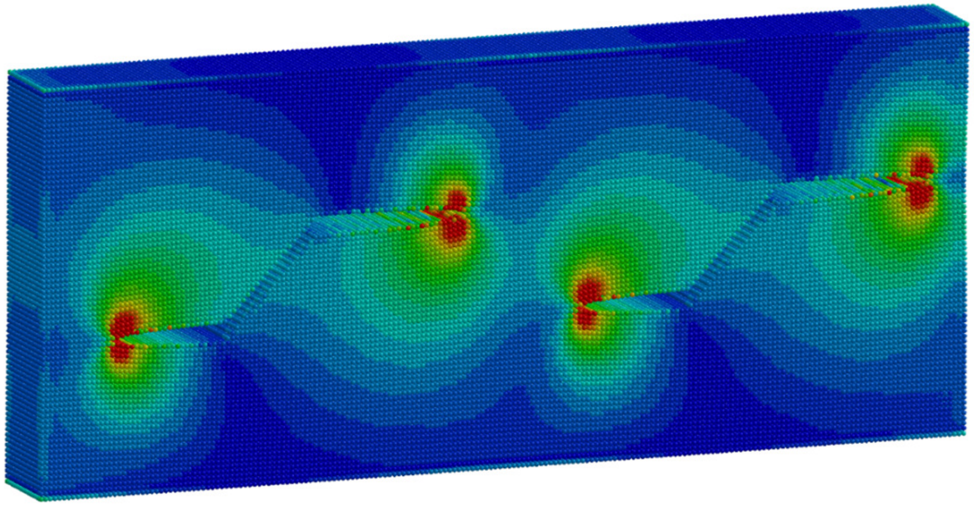




Failure of a Pre-Cracked Specimen

- 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
- Coupling to Fluid Flow
  - Current status with a constraint coupling
  - Penalty coupling is under way

Thank you for your attention!

DYNA MORE

Your LS-DYNA distributor and more