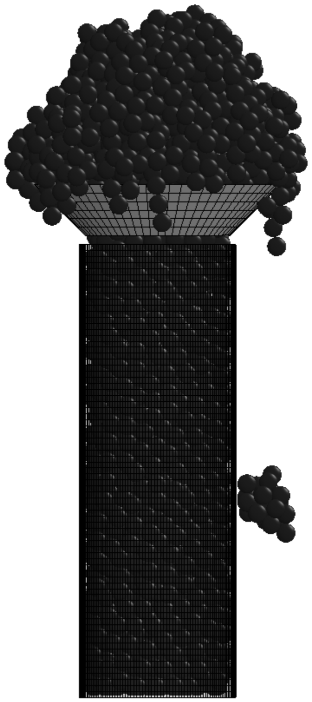
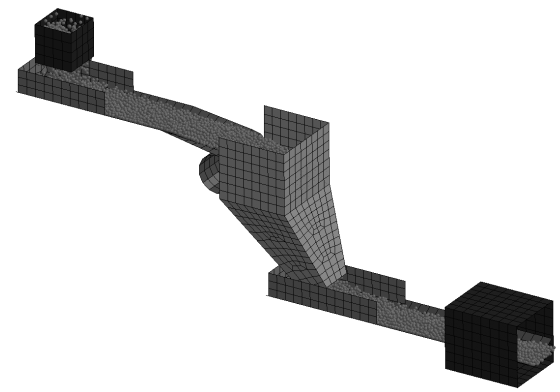


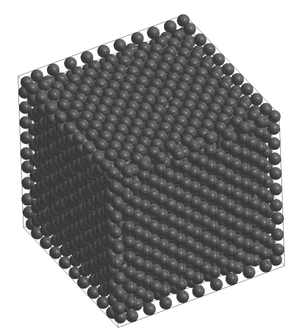
Discrete Element Method in LS-DYNA® (DEM)



Jason Wang, Ph.D.
Hailong Teng, Ph.D.
Zhidong Han, Ph.D.
Morten Rikard Jensen, Ph.D.*

Livermore Software Technology Corporation

Livermore, November, 2012



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Draft

Acknowledgements

The authors are thankful for the input from Kirk A. Fraser, Roche, Canada and Dr. George Laird, Predictive Engineering on the development of this new feature. Also the mesh generation by Mike Burger, LSTC for several of the demo examples is appreciated.

Disclaimer

Preface

These notes are a basic unofficial introduction to the new Discrete Element Method (DEM) recently implemented in LS-DYNA®. At current time, November 2012, the shown features are new and still under development so changes and fixes can occur in later versions of LS-DYNA®. In these notes, figures marked with 🎞 are embedded avi's in the pdf file.

It is the hope of the authors that the reader will be able to:

- Understand the idea behind the DEM method.
- Know the keywords in order to use this new feature.
- Use LS-PrePost® to build the DEM model.
- Start LS-DYNA® with the correct syntax to obtain additional output files.
- Know the files related to the DEM method.
- Post-process a DEM model applying LS-PrePost®.

Contents

Chapter 1

Introduction

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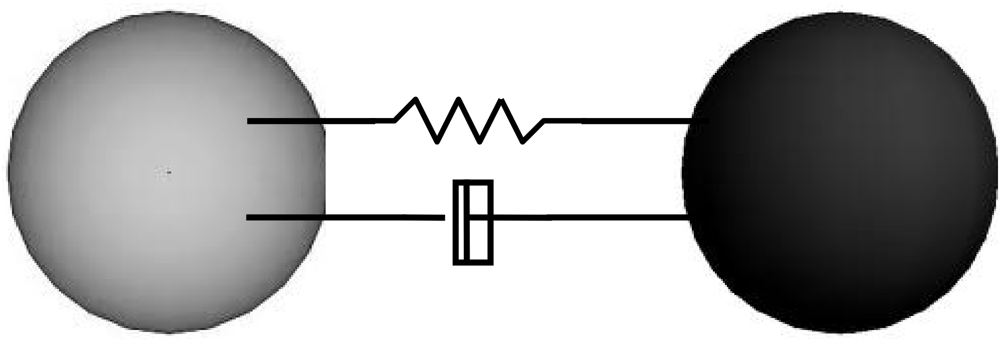
Introduction

- The Discrete Element Method (DEM) is implemented in LS-DYNA® from version ls971 R5.1.1.

- The method models parts with rigid spheres and handle interaction between these as well as interaction between particles and other structural parts. The interaction between the spheres are done in contact points using springs and dampers.



- First is searched for contact using bucket sorting as for regular contacts. Then forces are applied accordingly. A radius is given on the element card that is taken into account for sphere to sphere contact and also for sphere contacting other structural parts.

Draft

Introduction

- The default settings leads to a connection that only consider compression, the spheres will separate for tension. Further, the spheres has only 3 DOF by default so they don’t rotate. Both settings can be overwritten in the keyword cards as shown in Chapter 2. Furthermore, both damping and friction can be applied.

- There are several new keyword cards related to this method as seen in Chapter 2 and later chapters. The part will use *PART and typically *MAT_020. Other materials can be given but all that is used from the material card is the bulk modulus and the density, the latter only if the _VOLUME option is used at *ELEMENT_DISCRETE_SPHERE. The bulk modulus used is the one that LS-DYNA® will calculate internally for all materials.

- The method has been used for modeling granular materials, e.g. sand and rocks. But there are many other applications for this approach as well, e.g. powder compaction.

Draft

Introduction

- Several stages has been carried out in implementing this new method. First was implemented reaction between spheres and also contact to structural parts. Then Capillary forces was implemented in order to model wet sand. DEM was then extended to been coupled with a modified version of the *AIRBAG_PARTICLE feature for modeling Mine Blast. Recently, a packing algorithm was implemented in LS-PrePost® to pack the spheres and a new bound model is implemented in LS-DYNA® for modeling continuums.

  - The base for the general implementation of the DEM method is [P. A. Cundall et al, 1979]. This is the interaction between the particles.

  - To model wet sand, e.g. for mine blast Capillary forces needs to be taken into account. This is done based on the paper by [Y. I. Rabinovich et al, 2005].

Introduction

- LSTC's Bound Model was developed to handle "bonding" of the discrete spheres. This allows a continuum to be modeled and also make it possible for the spheres to obtain tension. The feature is described in more details in Chapter 7.

- Blast load is done by *PARTICLE_BLAST based on experience with *AIRBAG_PARTICLE and makes it possible to model the explosive with discrete spheres. Further, these can be coupled to discrete spheres that can model sand, which can be both dry or wet. This approach is especially for modeling burred land mines. Details is shown in Chapter 9 where keyword and examples are illustrated.

- In order to create parts using discrete spheres a new packing algorithm has been implemented in LS-PrePost [Z. Han et. al, 2012]. The algorithm fills closed volumes with spheres and is shown in Chapter 3.

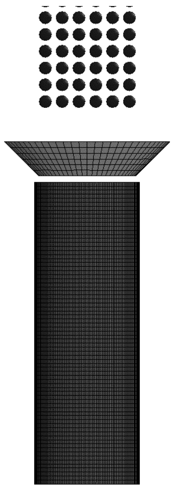
Applications

Falling Ball Impacting a Solid Plate

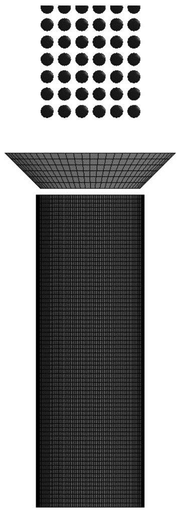
Applications

Dry and Wet Sand in Funnel

Dry Sand



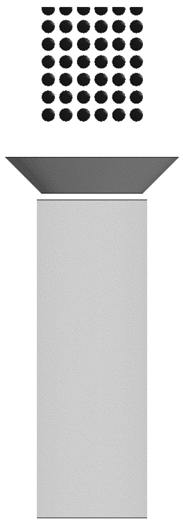
Wet Sand



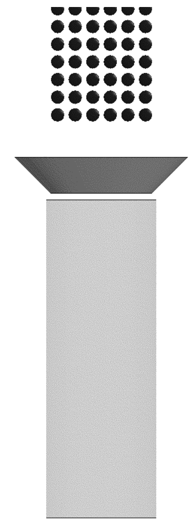
Applications

Dry and Wet Sand in Funnel

Dry Sand



Wet Sand

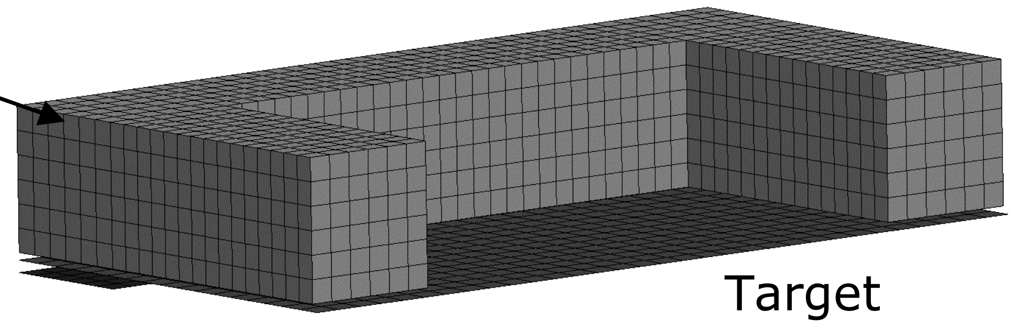


- Here the funnel is made transparent. Notice the nice packing of the particles.

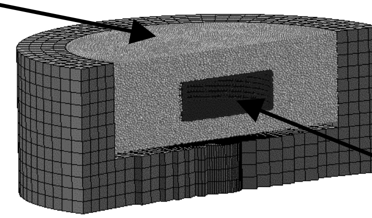
- The main difference between these models are the setting for sand, which is done at *CONTROL_DISCRETE_ELEMENT. The related parameters are CAP, GAMMA, VOL and ANG.

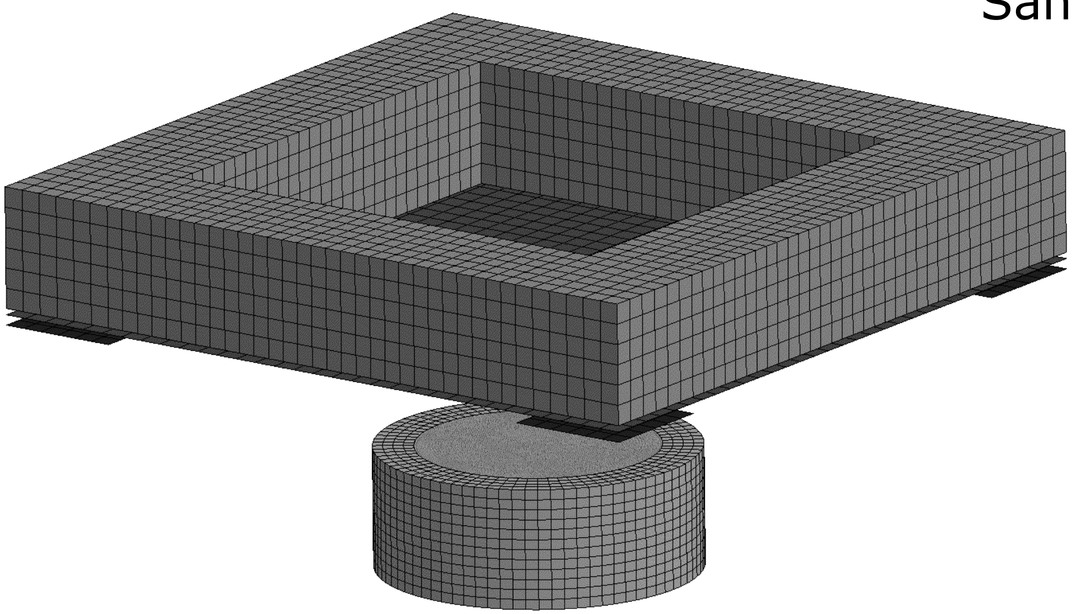
Applications

Buried Land Mine



- An explosive is buried into sand. The explosive is modeled with *PARTICLE_BLAST and the sand is using DEM.



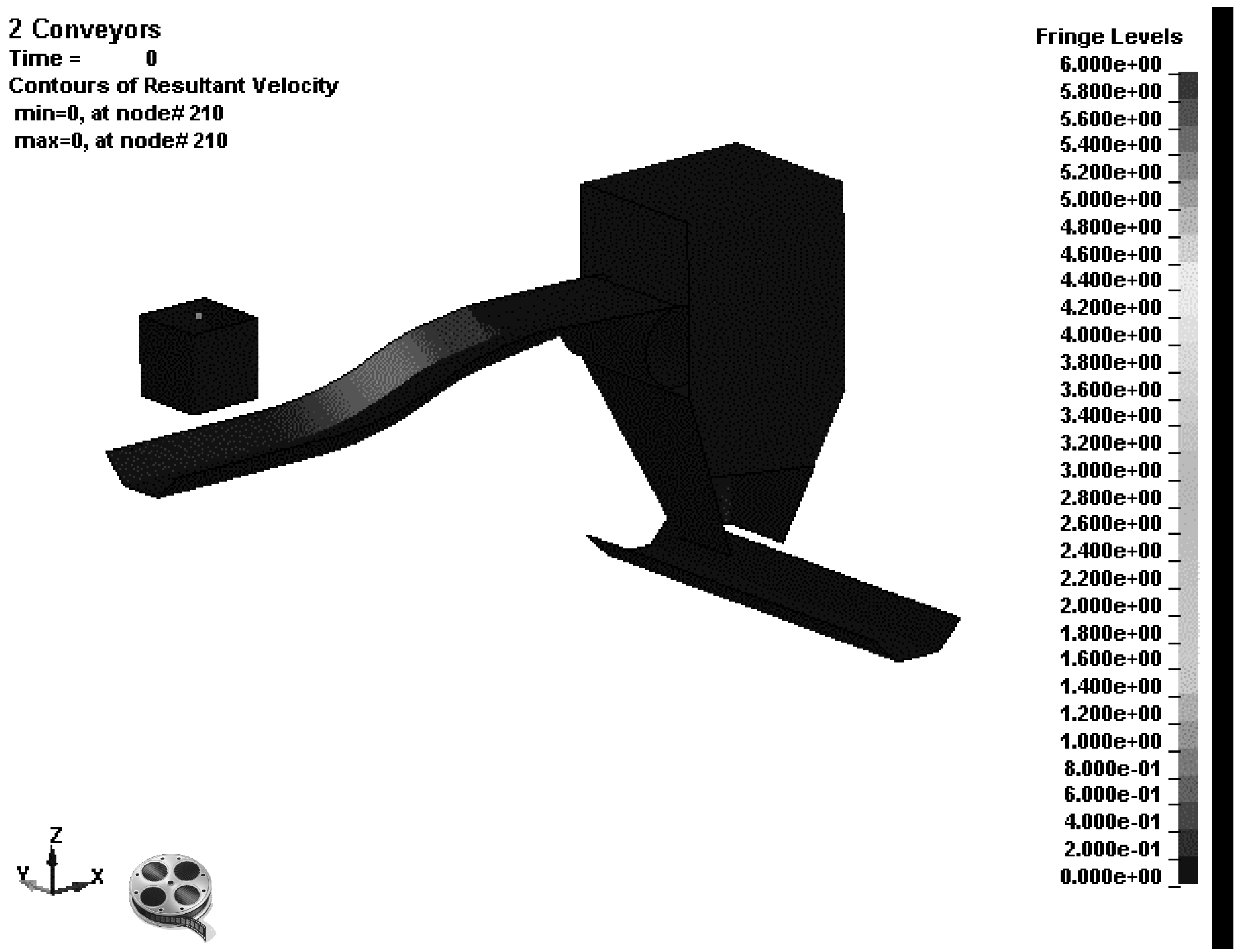


- Notice how the sand and explosive mix together during the impact.

Applications

Courtesy of Kirk A. Fraser
Roche, Canada

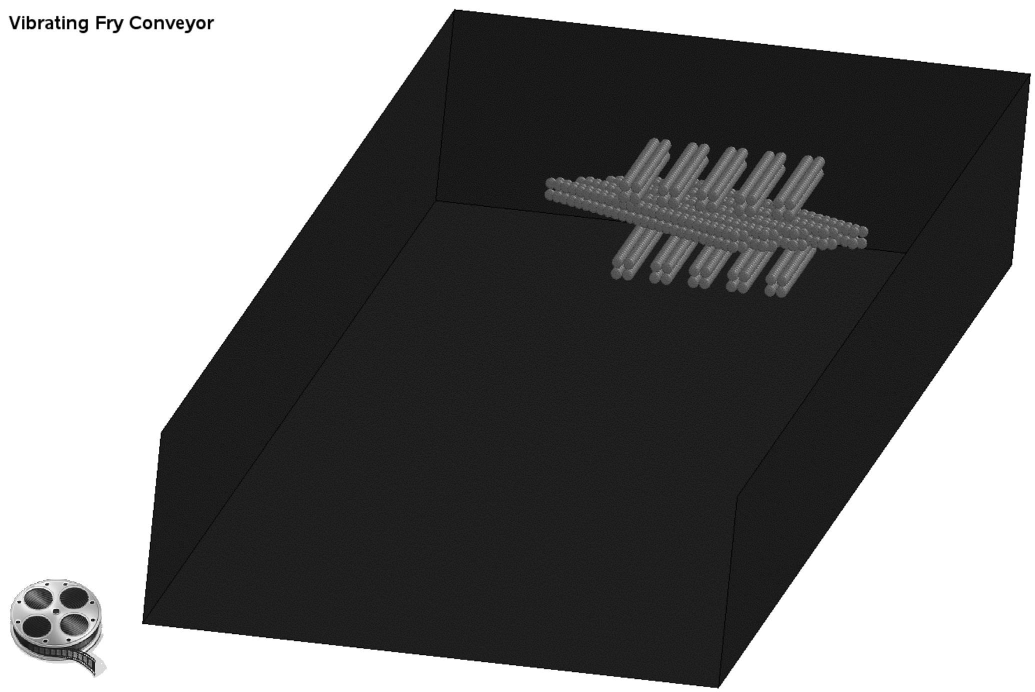
Conveyor Model



Draft

Applications

Fry Conveyor Model with Bonded DEM



- Here the *DEFINE_DE_BOND is used to bond the DEM particles together. It is seen that the fries have elastic behaviour, as the bonding is elastic.

Courtesy of Kirk A. Fraser
Roche, Canada

Chapter 2

Main Keywords

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Introduction

- There are several relevant keyword cards for the DEM method:

  - ***NODE:** Gives the location of the particle.

  - ***ELEMENT_DISCRETE_SPHERE_*option*:** Element ID, mass, inertia and radius of the particle.

  - ***CONTROL_DISCRETE_ELEMENT:** Setting damping coefficients, stiffness scaling and options for wet sand.

  - ***DEFINE_DE_TO_SURFACE_COUPLING:** Define contact between DEM spheres and structural parts. In the moment only implemented for contact with shells. For solids one can use a _NODE_TO_SURFACE contact.

  - ***DEFINE_DE_ACTIVE_REGION:** Gives a region of interest. If particles are outside this domain, they are deactivated in the particle to particle search and in the contact routines to structural parts.

Introduction

- Keyword cards for the DEM method con’t:

  - ***DEFINE_DE_BOND:** Define a bond model between the discrete spheres. Two method currently available, spring method or linear elastic for fracture analysis. The keyword is discussed in Chapter 7.

  - ***DEFINE_DE_INJECTION:** The option makes it possible to generate a flow of discrete spheres without specifying them initially in the input deck. This saves CPU time as well as memory. The injection geometry is currently limited to a rectangular plane.

  - ***DATABASE_BINARY_DEMFOR:** Setting the output interval for the binary DEM coupling file. It shows the forces in the interface defined by *DEFINE_DE_TO_SURFACE_COUPLING. This is described in Chapter 5.

- In the following these cards are described in more details.

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General Specification

- The DEM part is given by *PART and call's a *SECTION_SOLID or a SECTION_SHELL. The element formulation is ignored, since these are DEM elements and the radius for the particles is given at *ELEMENT_DISCRETE_SPHERE. The material often used is *MAT_RIGID. But others can be used, as mentioned earlier.
- This specification makes the input compatible with other parts specified in LS-DYNA®.

```
*PART
$# title
Glass Beads
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         1         1         1         0         0         0         0         0
*SECTION_SOLID
$#   secid    elform       aet
         1         0         0
*MAT_RIGID_TITLE
Glass Beads
$#     mid        ro         e        pr         n    couple         m     alias
         1    2400.0 6.000E+09  0.240000     0.000     0.000     0.000
$#     cmo      con1      con2
  0.000000         0         0
$# lco or a1        a2        a3        v1        v2        v3
     0.000     0.000     0.000     0.000     0.000     0.000
```

Draft

General Specification

- The density from the material card is only used is the _VOLUME option is applied at *ELEMENT_DISCRETE_SPHERE.

- Young's modulus and Poisson's ratio is used for contact between spheres and for contact with structural parts. In fact what is used is the Bulk modulus, internally calculated based on the material input. Notice that few material models in LS-DYNA® directly has the Bulk modulus as input.

- The stiffness of the material is used to calculate the time step for the spheres, see Chapter 6.

- The constraints on the material card (CMO, CON1, CON2) are ignored as are the rest of the flags. How to apply constraints is mentioned in Chapter 6.

Draft

Defining the Particle

- The location of the particle is done by specifying a node in that location using *NODE. This gives node number, X,Y and Z initial locations. The node number is then used in *ELEMENT_DISCRETE_SPHERE.

- The mass, inertia and the radius of the spheres is set using the *ELEMENT_DISCRETE_SPHERE_*option* card.

*ELEMENT_DISCRETE_SPHERE_{*OPTION*}

Card 1	1	2	3	4	5	6	7	8
Variable	NID	PID	MASS	INERTIA	RADIUS			
Type	I	I	F	F	F			
Default	none	none	none	none	none			

Defining the Particle

NID:
Node ID.

PID:
Part ID for the part that the sphere belongs to.

MASS:
Mass of the particle. If the _VOLUME option is flagged, then the mass of the particle is MASS x RHO_{mat}, where the latter is the density given at the material card (*MAT_XXX). This means that MASS in this case is the volume.

INERTIA:
Gives the inertia of the sphere. If the _VOLUME option is flagged, then the inertia of the particle is calculated as:

$$I = INERTIA \cdot RHO_{mat}$$

Defining the Particle

INERTIA Con’t:
Where MASS is the value of the given parameter MASS, R is the radius of the particle and RHO_{mat} is the density given at the material card (*MAT_XXX).

RADIUS:
The radius of the particle. This will not influence the mass of the part but is used for contact between particles and to structure.

Draft

Global Control for Particles

- Defining global control options for the DEM elements is done at the *CONTROL_DISCRETE_ELEMENT card. This is for particle to particle contact.

*CONTROL_DISCRETE_ELEMENT

Card 1	1	2	3	4	5	6	7	8
Variable	NDAMP	TDAMP	Fric	FricR	NormK	ShearK	CAP	MXNSC
Type	F	F	F	F	F	F	I	I
Default	0	0	0	0	0.01	2/7	0	0

NDAMP:

Normal damping coefficient. This coefficient is multiplied to the relative velocity between two particles as NDAMP * V_{rel}. NDAMP is unitless.

Draft

Global Control for Particles

TDAMP:

Tangential damping coefficient. This coefficient is multiplied to the relative velocity between two particles as NDAMP * V_{rel}. TDAMP is unitless.

Fric:

0: 3 DOF

NE.0: 6 DOF

This is the translational friction between the particles. If not given, the particles will only have 3 DOF, the translational ones. However, if a translational friction is given, there will be created rotation due to that and the DOF will be set to both translational and rotational DOF. If Fric is set to 0 and and the particles only have translational DOF, the correct behaviour in many applications is not captured.

FricR:

Rolling friction coefficient. This is only valid for non-zero values of Fric. In fact, if FricR is specified, Fric is set so 6 DOF is activated.

Global Control for Particles

NormK:

Scale factor of normal spring coefficient. The spring stiffness is calculated as:

$$K_{Spring} = K_{Bulk} \cdot RADIUS \cdot NormK$$

where K_{Bulk} is the bulk modulus and RADIUS is the particle radius. If no value is given for NormK, it is default set to 0.01. If a negative value is given for NormK, then the absolute value is the spring stiffness, K_{Spring}.

ShearK:

Used to scale the shear spring stiffness. It is not given as a direct coefficient but as the ratio between scaling in shear and NormK. So the given value is $ShearK_{given}$ = ShearK/NormK. The default value is 2/7.

MXNSC:

In the manual is stated maximum number of subcycling cycles, however it has nothing to do with traditional subcycling. The flag is reserved for an option to compute the DEM on GPU's. It is not yet implemented.

Draft

Global Control for Particles

CAP:

0: Dry particles

NE.0: Wet particles. Requires an additional keyword card.

When CAP is given a value different than 0, capillary forces are considered. The implementation follows [Y. I. Rabinovich et. al, 2005]. This makes it possible to model e.g. both dry and wet sand using the DEM method. The forces are calculated as:

$$F = 4 \cdot \pi \cdot RADIUS^2 \cdot \alpha \cdot GAMMA \cdot COS(ANG \cdot \frac{d\alpha}{dH})$$

Where

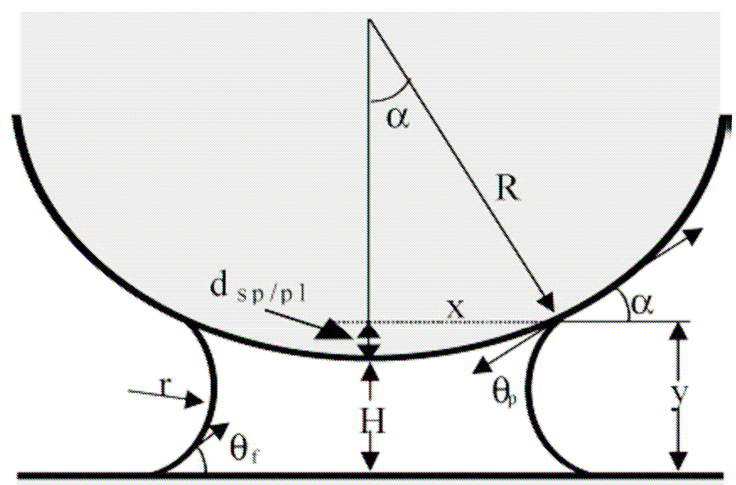
RADIUS: Particle radius.

α : The "embracing angle".

GAMMA : Liquid surface tension.

ANG : Contact angle.

H : Separation distance.



[Y. I. Rabinovich et. al, 2005]

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Global Control for Particles

CAP not equal 0.

Optional	1	2	3	4	5	6	7	8
Variable	Gamma	Vol	Ang					
Type	F	F	F					
Default	0	0	0					

GAMMA and ANG are described on the previous page.

VOL:

Volume fraction. This is used for calculating the liquid bridge volume. In LS-DYNA® is assumed that the liquid is equally distributed on each particle. When two wet spheres are in contact, part of the liquid forms a bridge and generates capillary forces.

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Global Control for Particles

VOL, continued:

The liquid bridge volume is calculated as:

$$V = FAC \cdot VOL \cdot (\text{Volume of two spheres}) = \frac{FAC \cdot VOL \cdot 4}{3.0 \cdot \pi \cdot (R0^3 + R1^3)}$$

VOL is a user input and is given at the card. It is percentage volume that the water field is between the particles and is used in the above equation. The value is given in as values between 0 and 1. A value of 0.35 or less is often used. The FAC is to take into account that a sphere may be in contact with multiple spheres so for each bridge only FAC of its liquid contribute to the formation of a bridge. The FAC parameter is hardwired in LS-DYNA® to 0.1.

Draft

Defining Area of Interest

- In order to save CPU time, one can specify a region of interest. Particles inside this region are active but if the particle is outside, it is taken out of the calculation. In fact, the particle is deactivated for both particle interaction and contact between particle and structure. This is done with the *DEFINE_DE_ACTIVE_REGION option.

*DEFINE_DE_ACTIVE_REGION

Card 1	1	2	3	4	5	6	7	8
Variable	ID	TYPE	Xm	Ym	Zm			
Type	I	I	F	F	F			
Default	None	0	0.	0.	0.			

The region can either be defined as a box or a set of parts. The parts gives the flexibility of regions of any shape. The region can be extended using scale factors for the margins, see next page.

Defining Area of Interest

ID:

Part set ID or ID of *DEFINE_BOX_*option*, depending of the setting of TYPE.

TYPE:

0: The ID given above is for a *SET_PART
1: ID above represents a box ID, specified with *DEFINE_BOX_*option*.

Xm, Ym, Zm:

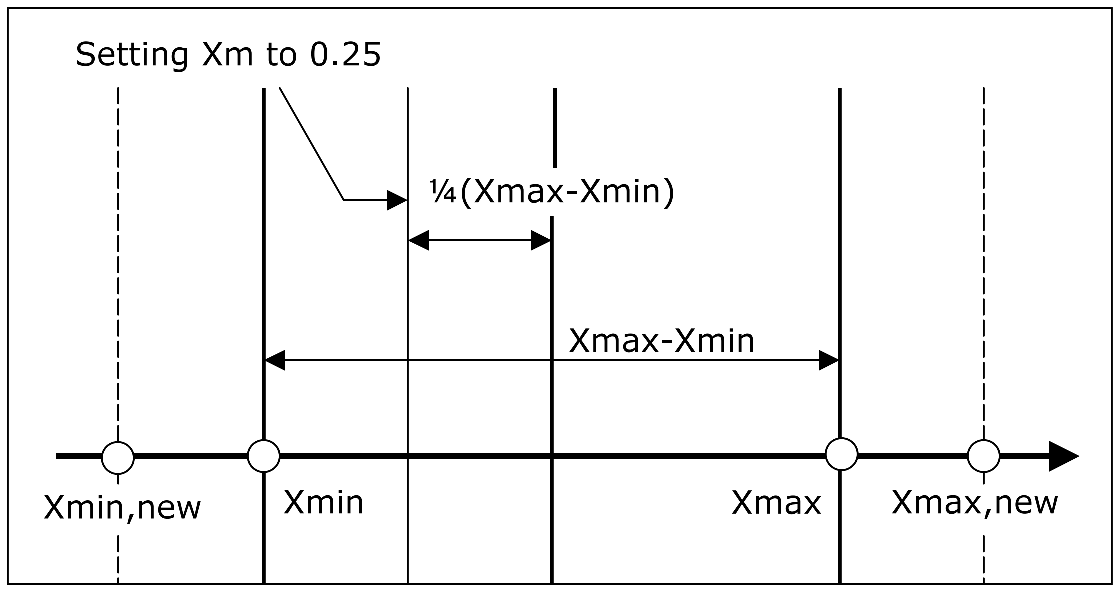
Factors to scale the regions margin. This means that the limits given by the specified region can be extended, creating a buffer zone. The equations used are here illustrated for the X-direction:

$$Xmargin = (Xmax - Xmin) \cdot Xm$$

$$Xmax, new = Xmax + X\_margin$$

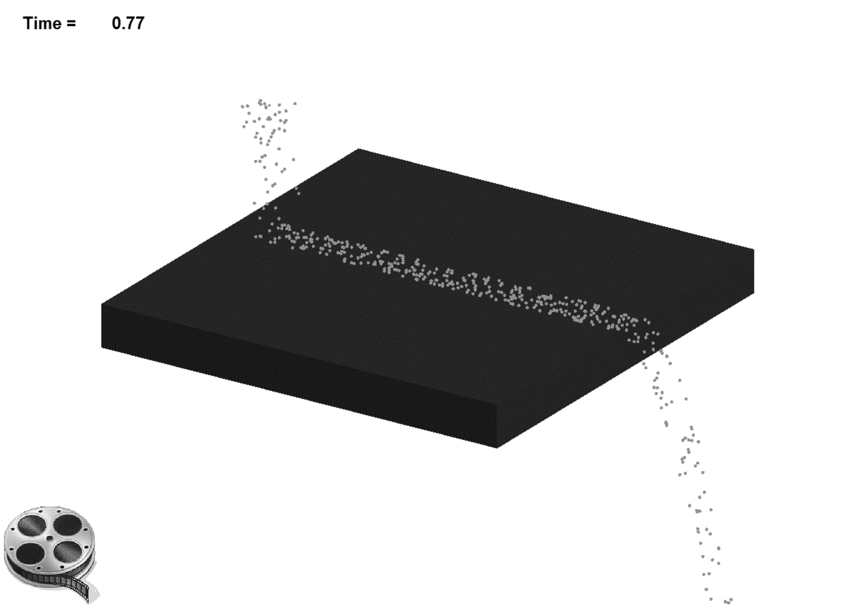
$$Xmin, new = Xmin - X\_margin$$

In this example Xm is set to 0.25, which leads to an added buffer zone of Xmargin=1/4(Xmax-Xmin).



Automatic Particle Generation

- If there is a flow of new particles that gets into the model, like e.g. sand flowing through a funnel, it can be beneficial to add the particles as they are needed. This can save CPU time and make the model less complex. The keyword *DEFINE_DE_INJECTION can do this.
- The current implementation limits the source geometry to be a finite rectangular plane. The maximum and minimum sizes of the particles are given together with a mass rate inflow.
- The new generated particles can be given a velocity, which can be specified using a vector.



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Automatic Particle Generation

*DEFINE_DE_INJECTION

Card 1	1	2	3	4	5	6	7	8
Variable	PID	SID	XC	YC	ZC	XL	YL	CID
Type	I	I	F	F	F	F	F	I
Default	None	None	0.0	0.0	0.0	0.0	0.0	0

Card 2

Card	1	2	3	4	5	6	7	8
Variable	RMASS	RMIN	RMAX	VX	VY	VZ	TBEG	TEND
Type	F	F	F	F	F	F	F	F
Default	None	None	RMIN	0.0	0.0	0.0	0.0	1.0E20

Draft

Automatic Particle Generation

*DEFINE_DE_INJECTION

PID:

Part ID for new generated particles.

SID:

Node set ID for new generated particles. This option is optional but can be needed if the new generated particles are to be in contact with an other part using *DEFINE_DE_TO_SURFACE_COUPLING, since the slave side of that (DEM) can only be given as a node or node set.

XC, YC, ZC:

The coordinates for the center of the finite rectangular injection plane.

XL, YL:

The edge lengths of the rectangular injection plane. The lengths are along the global X and Y axis, unless a local coordinate system, CID, is specified.

CID:

Local coordinate system for defining the injection plane or for the velocity vector given for the new generated particles. See next page.

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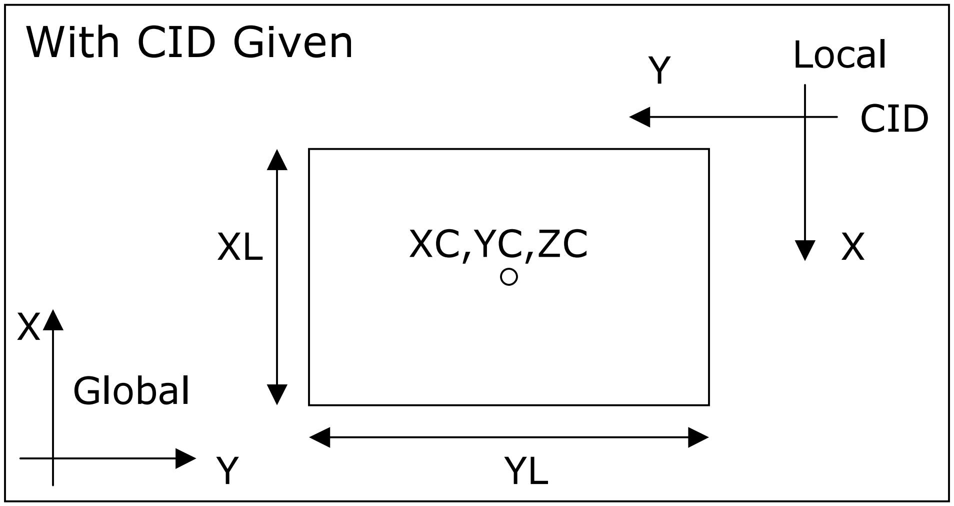
Automatic Particle Generation

*DEFINE_DE_INJECTION



RMASS:

The mass flow rate for the new generated particles. Mass pr Unit time.

RMIN:

Minimum particles radius – used for the automatic generation routine.

RMAX:

Maximum particles radius – used for the automatic generation routine.

The RMASS will specify how much mass pr time unit and this then has to be distributed to the new generated particles. To find how many is needed, the RMIN and RMAX radiuses are used in a packing routine.

Automatic Particle Generation

*DEFINE_DE_INJECTION

VX, VY, VZ:

Vector components for the initial velocity of the new generated particles. If the local coordinate system is define, i.e. if CID has a value, the components are in this local coordinate system.

TBEG:

Birth time for the generation of new particles.

TEND:

Death time for the generation of new particles.

NOTE!

If the CID is given it influences both the orientation of the plane AND the initial velocity vector. Both options will then be related to the same local coordinate system.

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Chapter 3

Generating DEM Particles in LS-PrePost®

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Overview of Packing Routine

- DEM particles can be generated and packed using LS-PrePost®. The packing routine is implemented from version 4.0 [Z. Han et al., 2012].
- The DEM packing is done by a pure geometrical approach. Geometrical approach described in [Y. T. Feng et. al, 2003].
- Packing density is limited to a max value of 74%.
- A bounded volume is required. This volume must be made with shells. Both triangular and quads can be used.
- Reliability for arbitrary volumes.
- Efficiency for a large number of spheres (~100 million).

Overview of Packing Routine

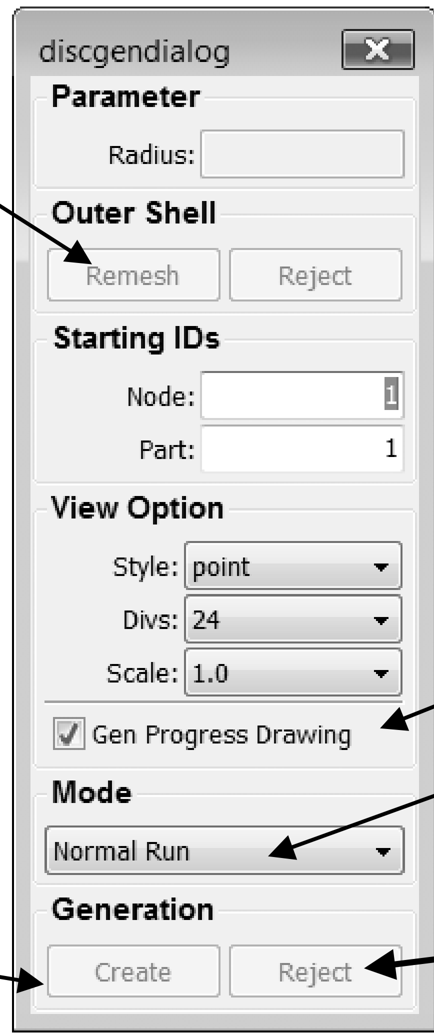
- Based on the advance-front approach, [Y. T. Feng et. al, 2003].
- Power diagram (3D weighted Delaunay triangulation) is used for contact searching, sphere inserting, and updating neighboring connection, [J. Jerier et al.,2010].
- Linear packing speed: ~10K spheres per second per CPU (single thread).
- One must verify the normal directions of the elements, especially for inner boundaries. This is required in order to find what side of the shell is the enclosed volume. This volume is used for the filling.
- The interface is fairly simple: Select the part and run the packing engine.

Packing Routine in LS-PrePost®

This will remesh the shell geometry. But it is not really a remeshing but is used to show the user how the mesh would be based on Mass, if the specified radius is applied.

Options for viewing only. The style option makes it possible to see spheres instead of points. Divs is used to discretize each sphere. The higher the more accurate the shape. The Scale option will scale the radius of the spheres but this is only visual.

Create particles.



Setting Radius of the particles.

Suggested ID's for new generated *NODE ID's and ID for new generated part. Based on existing geometry.

This is used to have particles drawn on screen if packing routine is running outside LS-PrePost® but it is not fully implemented yet.

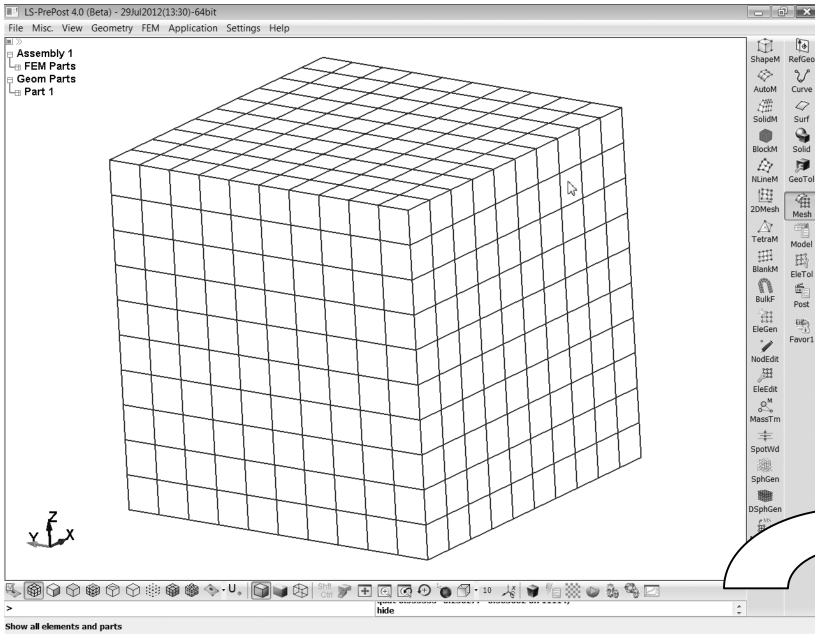
Select mode – e.g. Run, import etc. See later slides for details.

Reject the generated particles.

Draft

Packing Routine in LS-PrePost®

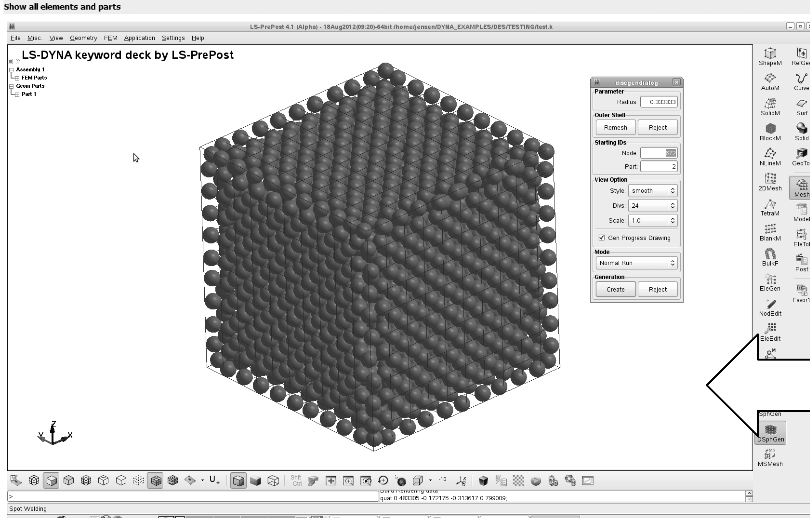
Procedure for Packing

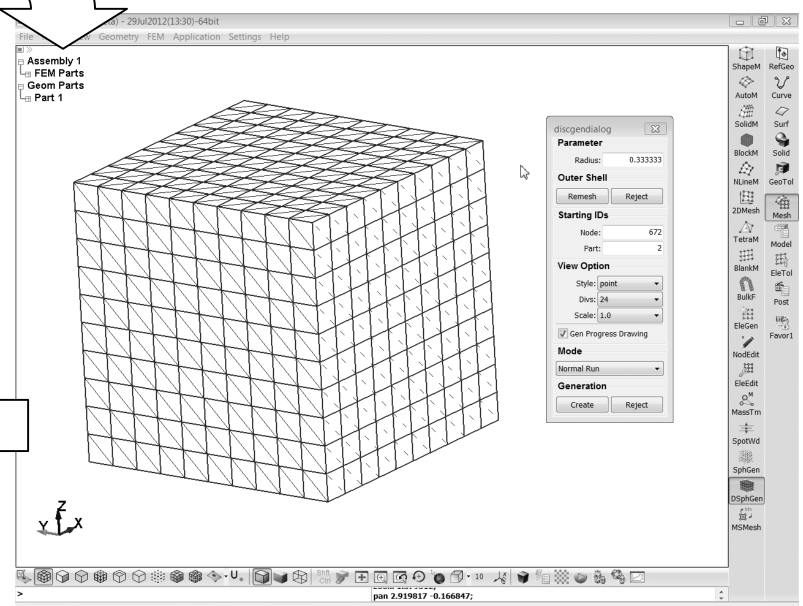


- Steps to generate particles.
  - Make a shell bounded volume.
  - Select the Mesh Menu. 

  - Select the DEM generation menu. 

  - Set the values or use default.
  - Pick the volume with the mouse.
  - Create.
  - Exit from the menu (notice that there is no Accept button).

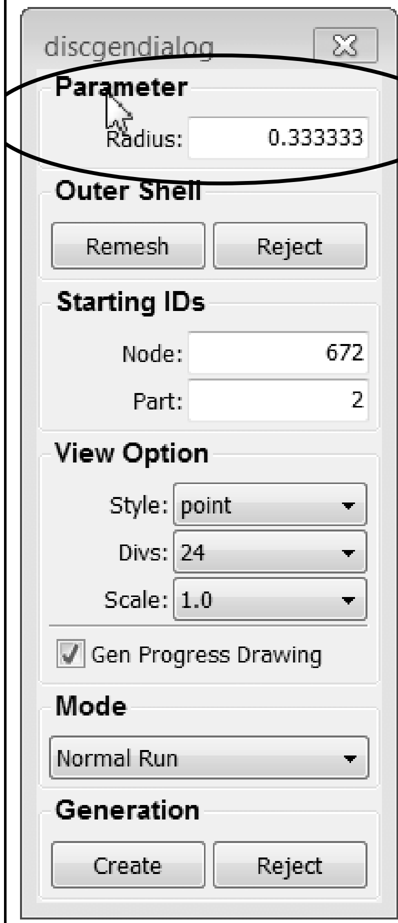




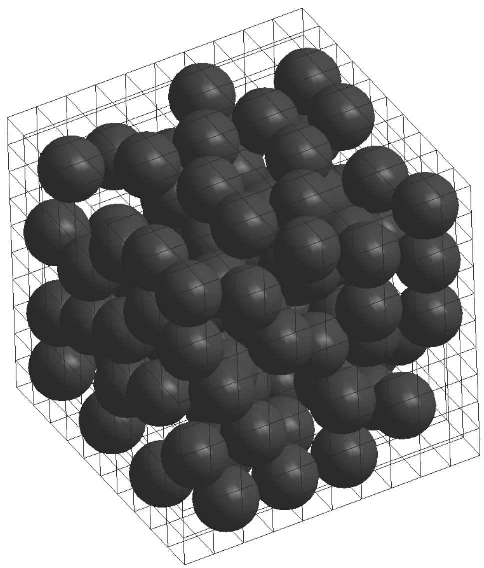
Packing Routine in LS-PrePost®

Dialog Box

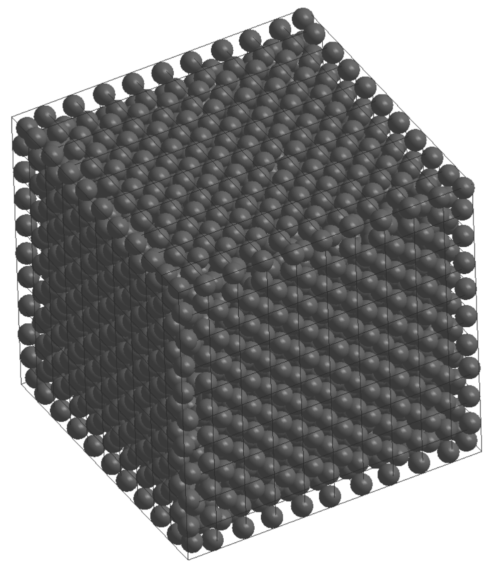
- Default values are suggested for the particle generation. The suggested radius is based on element size but the user should use own value!



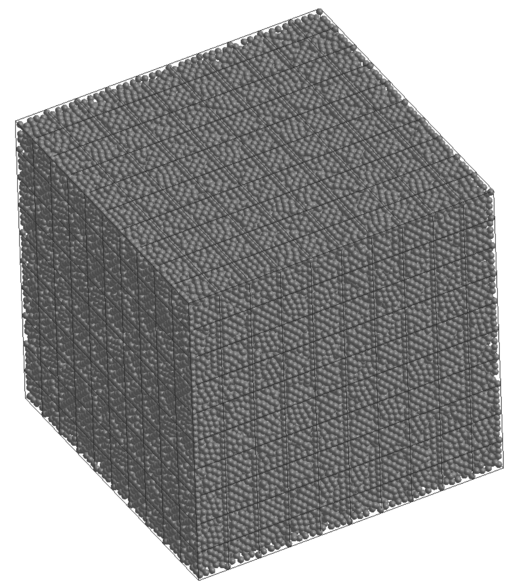
Radius=1.0



Radius=0.33



Radius=0.1

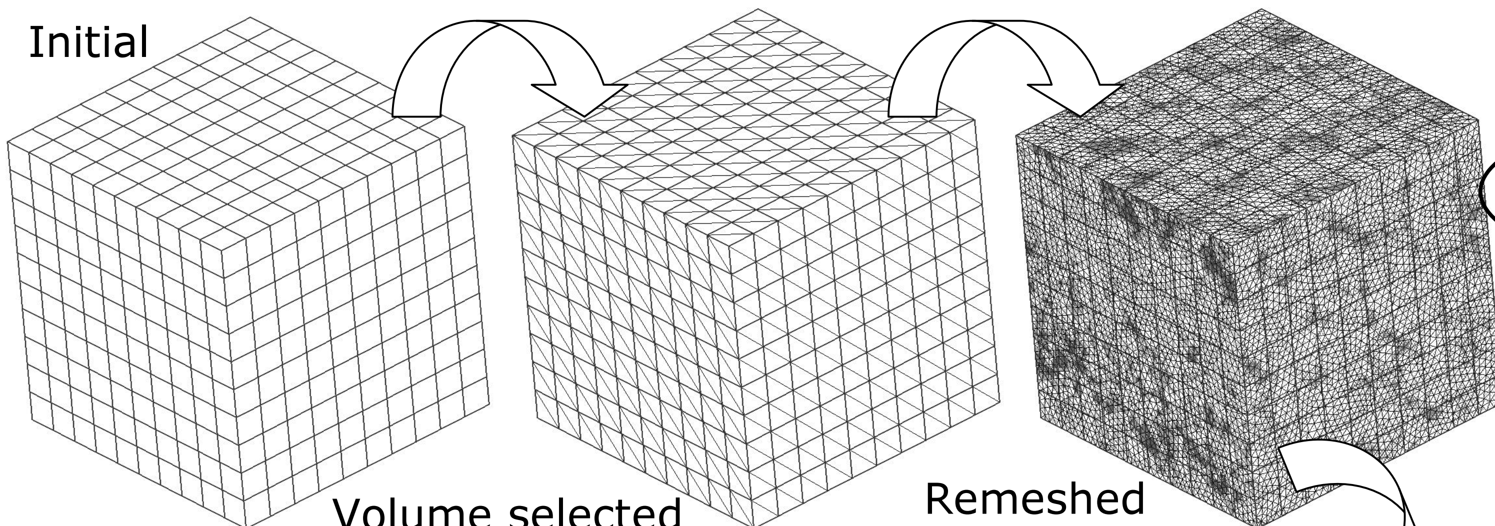


- The radius is the most important parameter for generating the DEM particles.

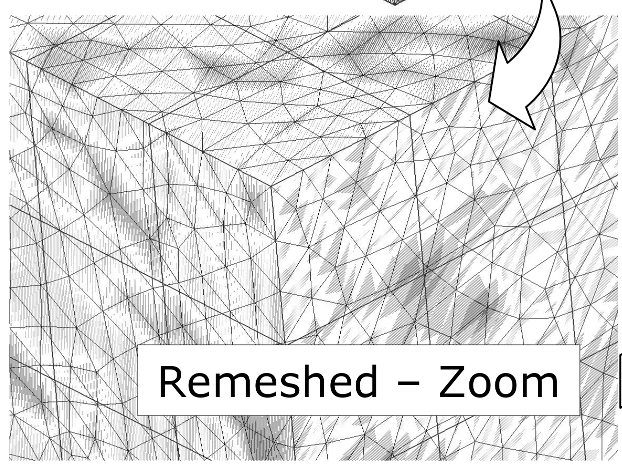
Packing Routine in LS-PrePost®

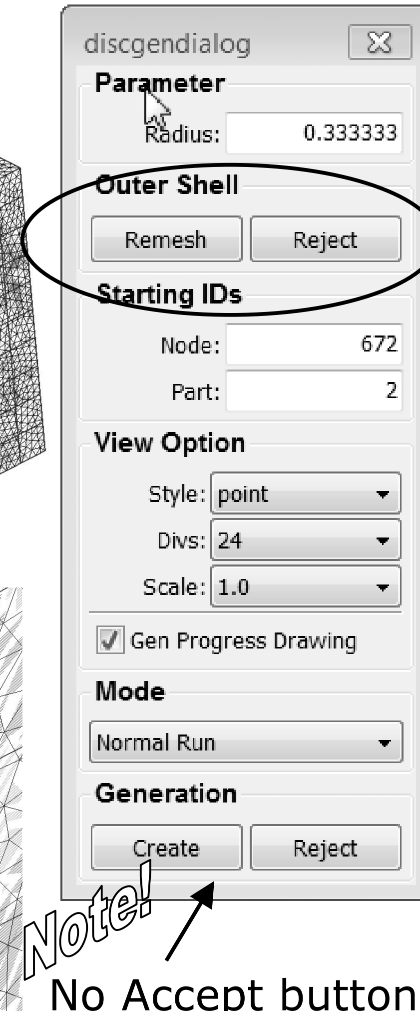
Remesh Option

- The remeshing option is only to show how a mesh would have been if the particle radius was used, meaning it shows the corresponding FE mesh.



- There is no setting for the remeshing feature. The option does <u>not</u> influence the generation of the particles.

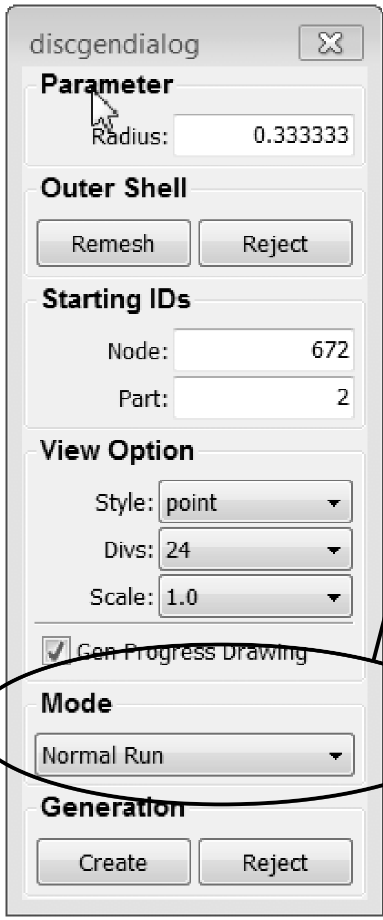


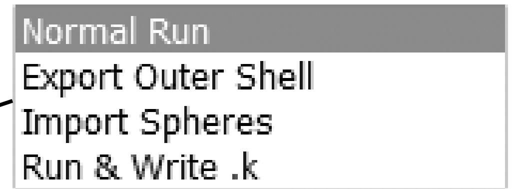


Packing Routine in LS-PrePost®

Dialog Box

- There are different options for the DEM generation.

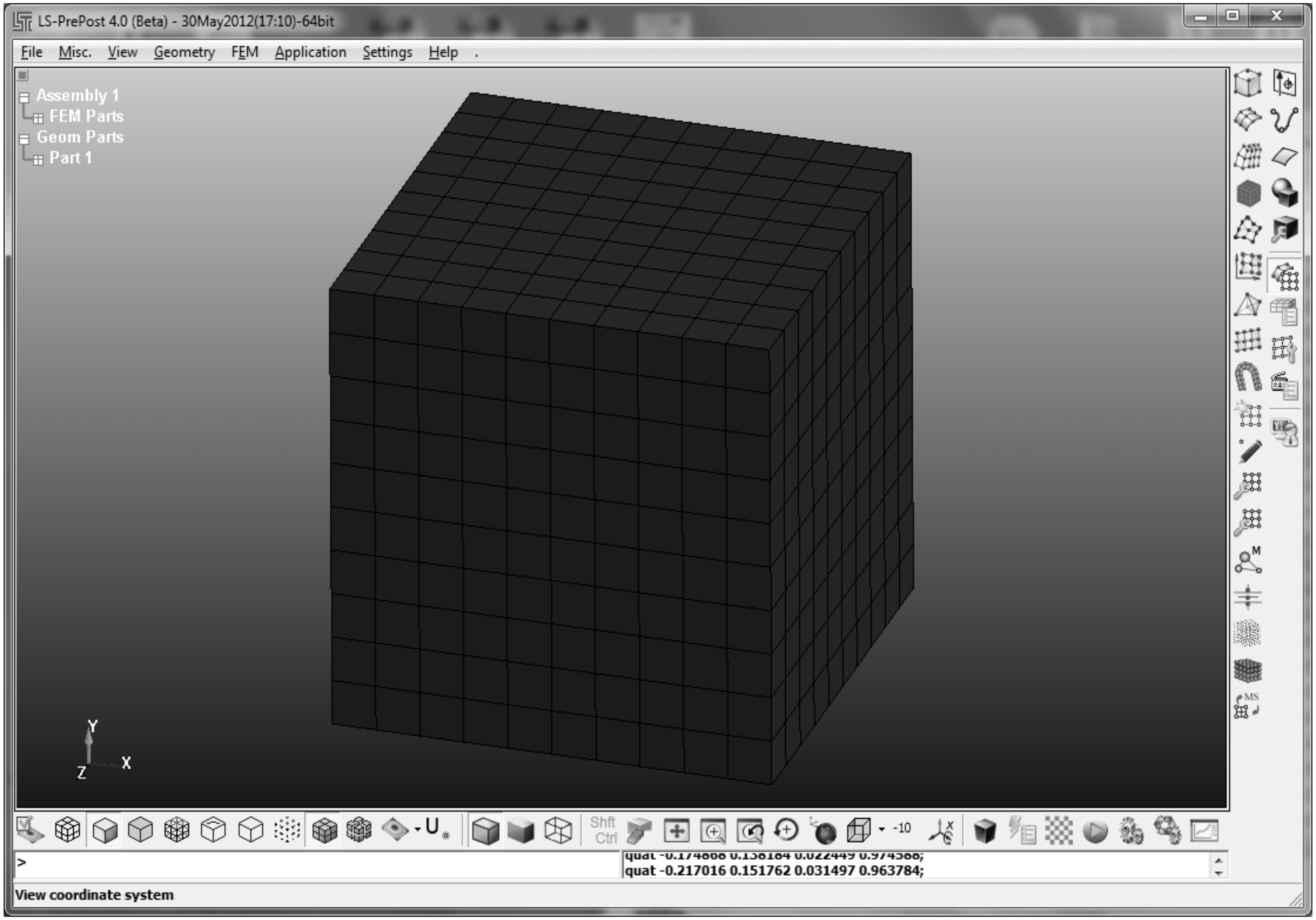




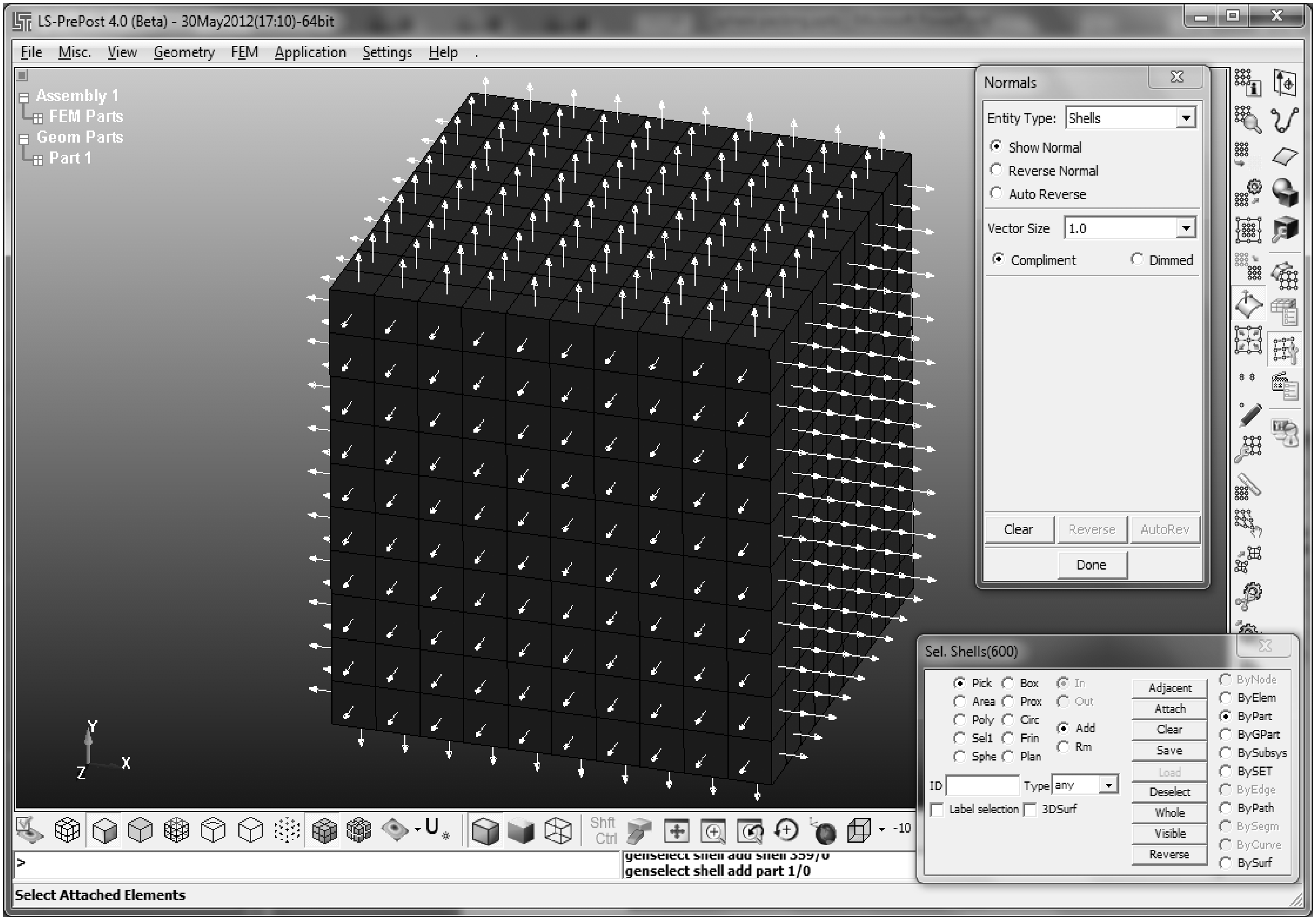
- *__Normal Run__*: Start the packing on the local CPU. Fully implemented.
- *__Export Outer Shell:__* Export the boundary shells to a file for a remote packing engine. A file named *lspp.points* is created.
- *__Import Spheres__*: Import the packing results generated by a remote packing engine. Not implemented yet.
- *__Run & Write .k__*: The packing results will be exported as an LS-DYNA® Keyword file. Will generate particles as "*Normal Run*" mode. Further is generated the files *lspp.mesh* and *lspp.k*. The function is currently not fully implemented.

Draft

Example 1: A Cube
A Single-connected Domain

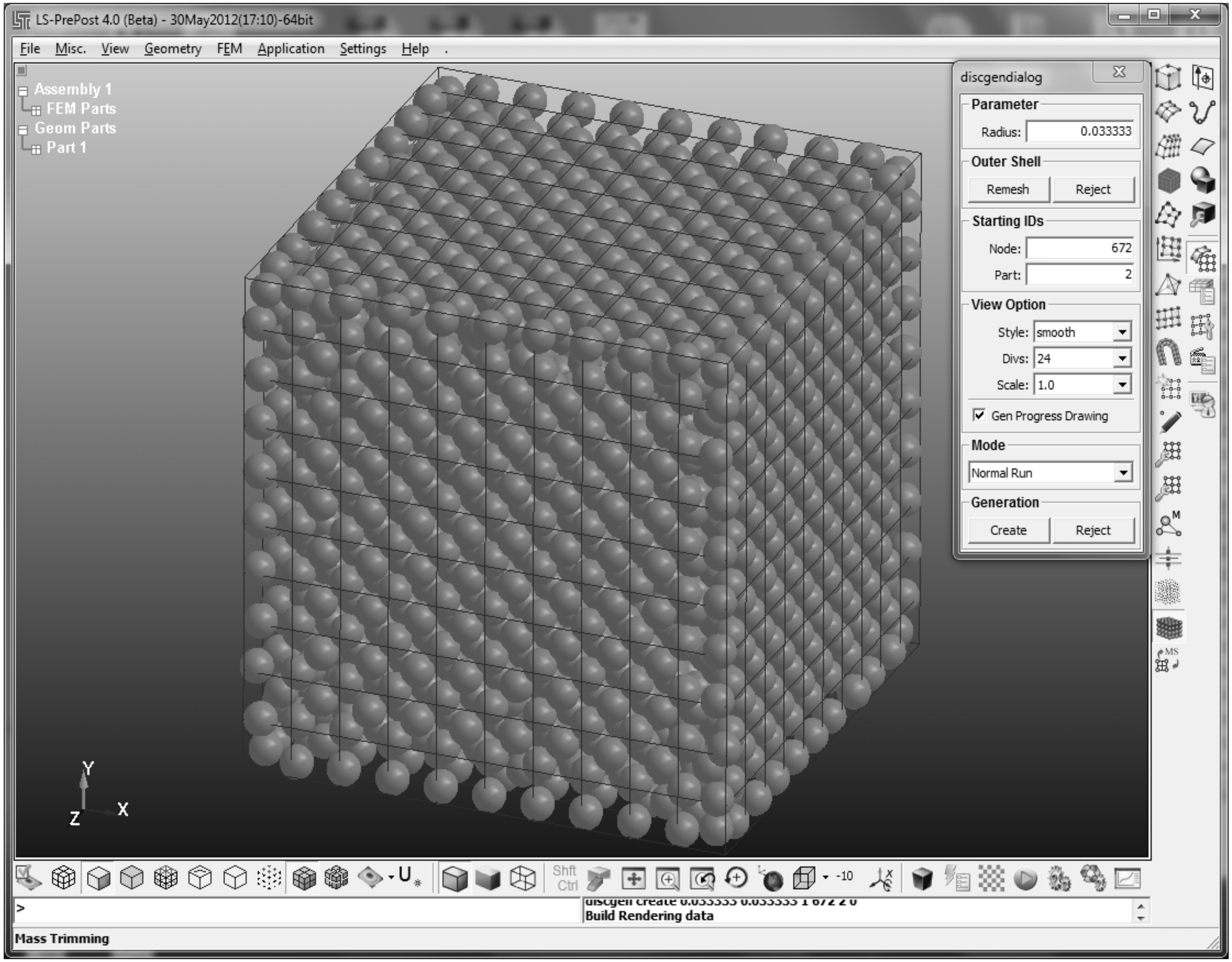


Verify the Normals



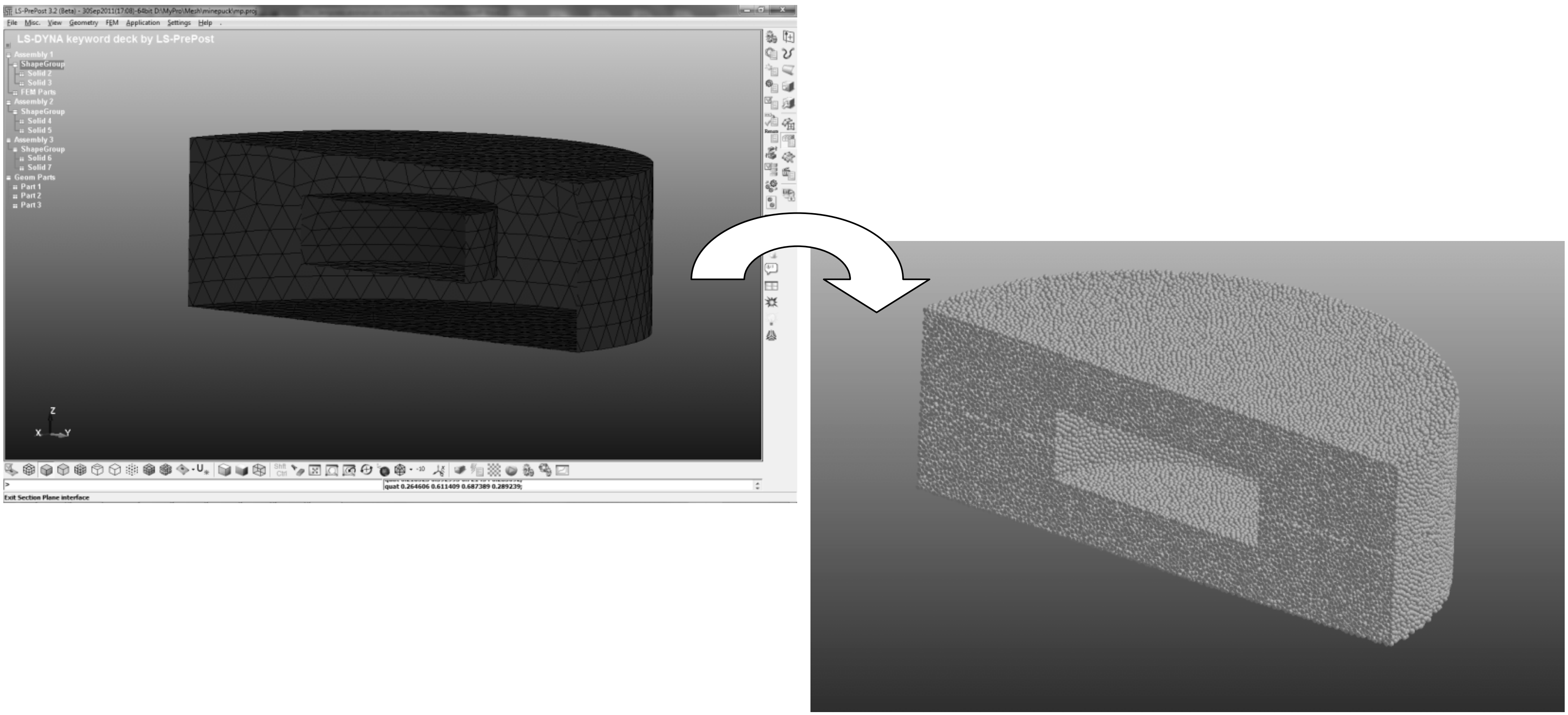
Draft

Start the Packing Routine



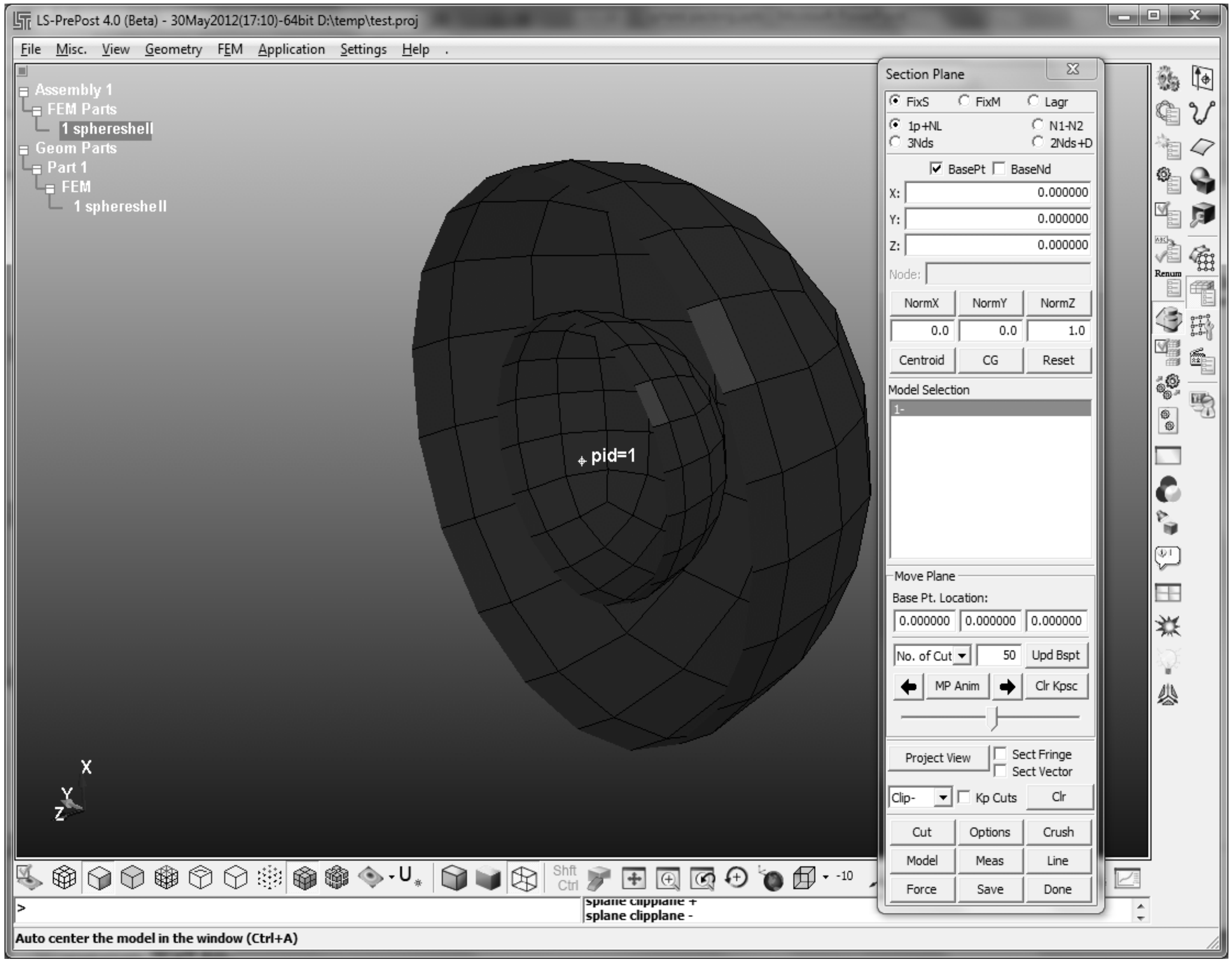
Discrete Element Models

- So far only a simple single part geometry has been shown, however, LS-PrePost® can handle much more complex and sophisticated geometries.



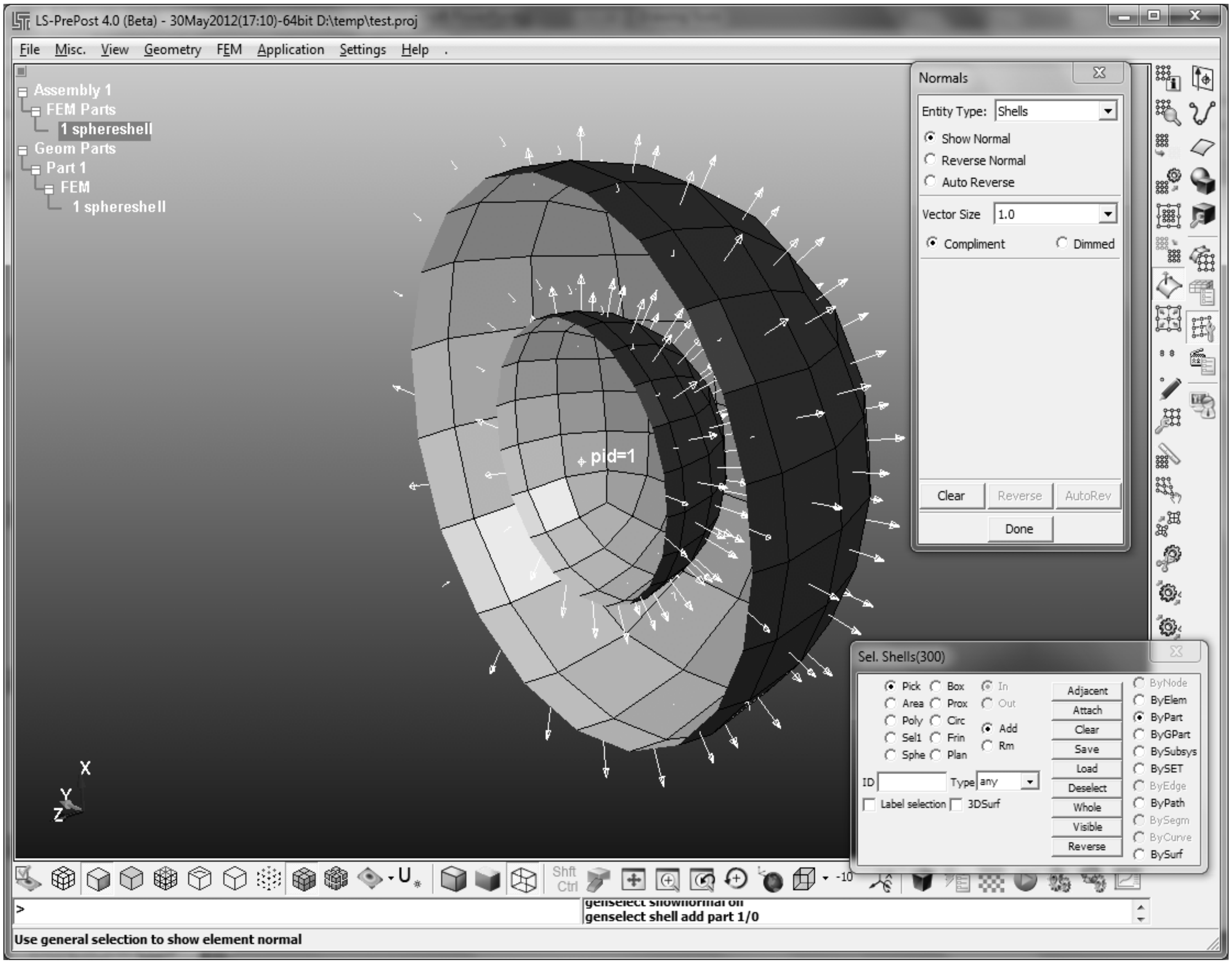
Draft

Example 2: A Hollow Sphere
A Doubly-connected Domain

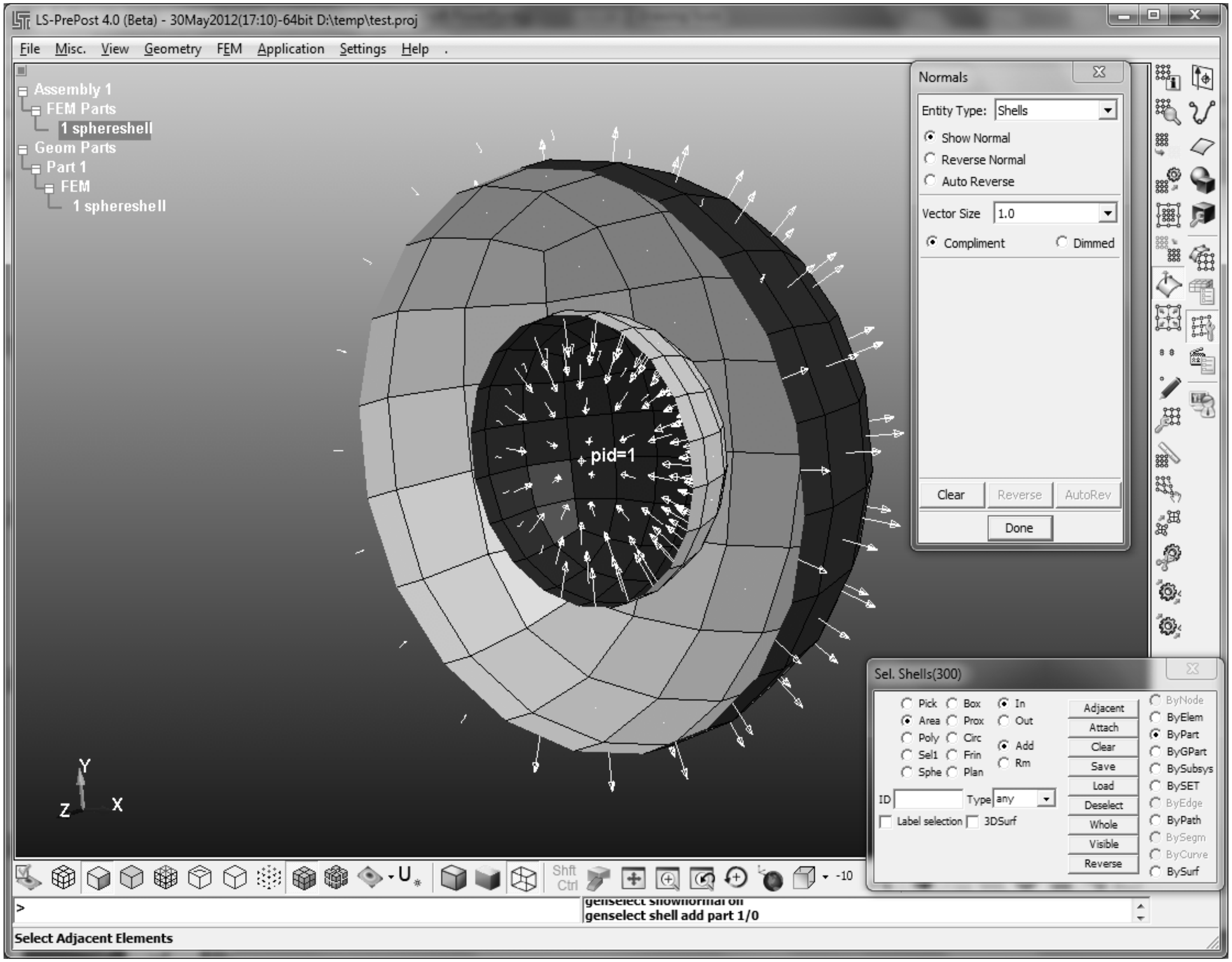


Draft

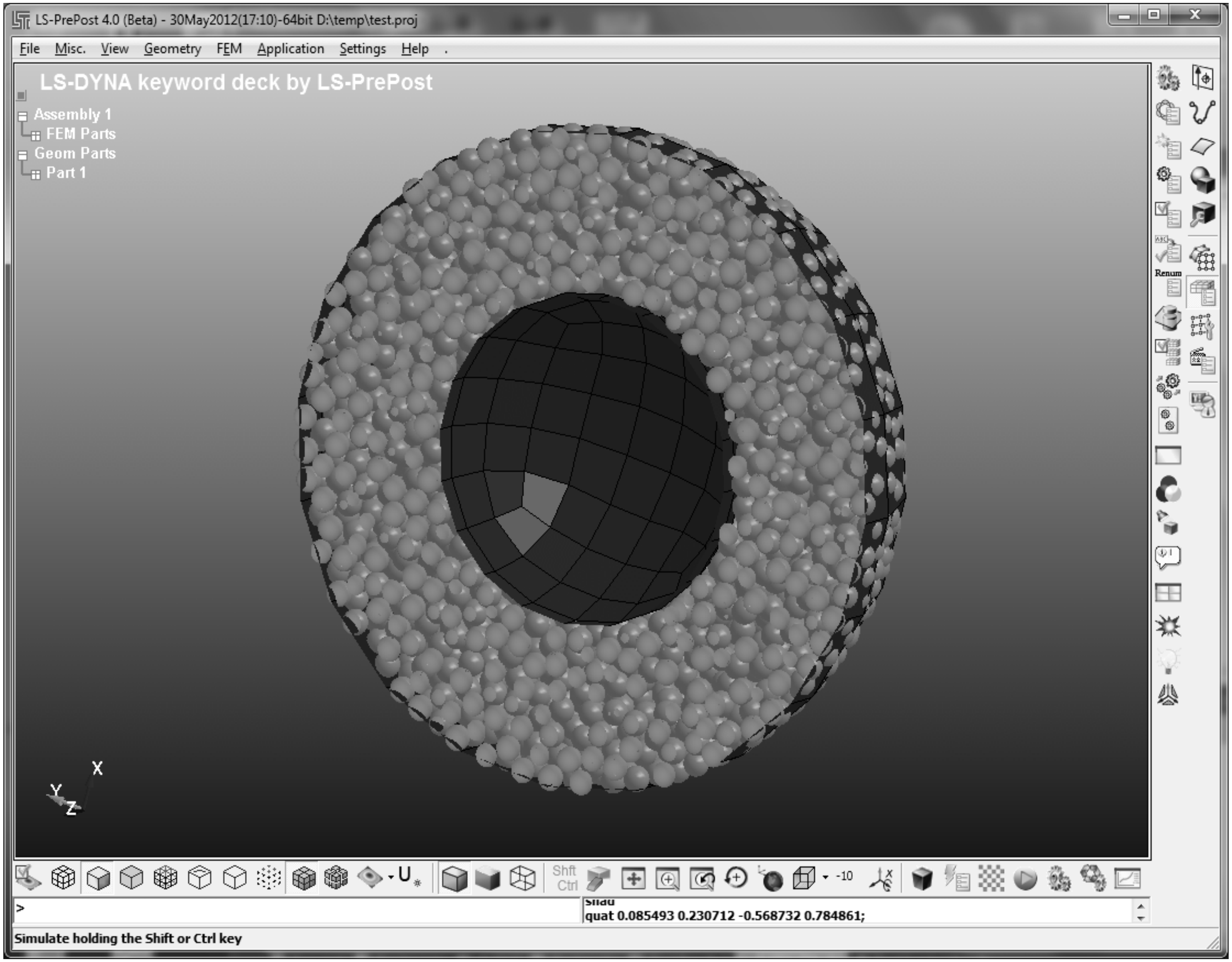
Verify the Normals



Reverse the Normals



Start the Packing Routine

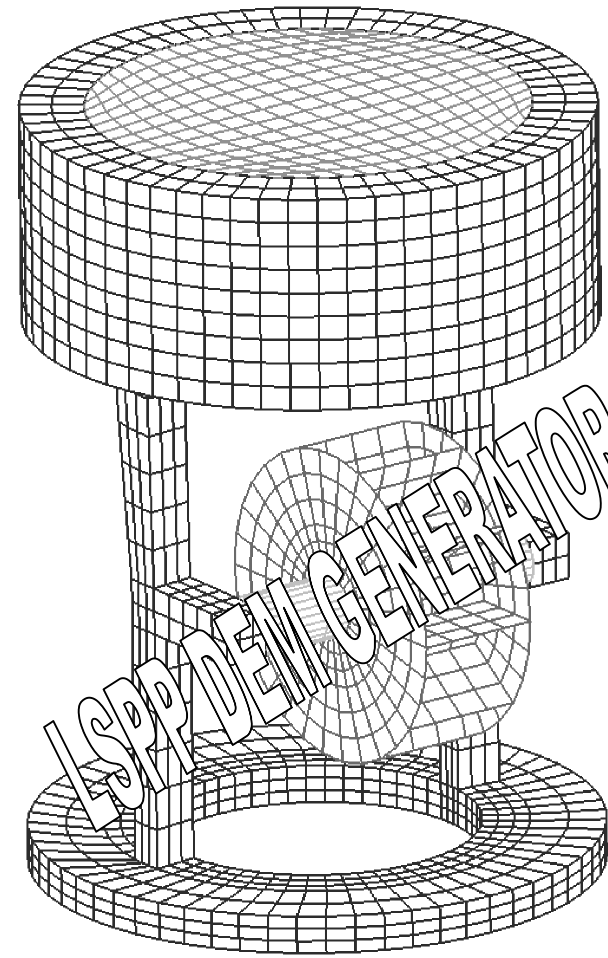


Chapter 4

Examples

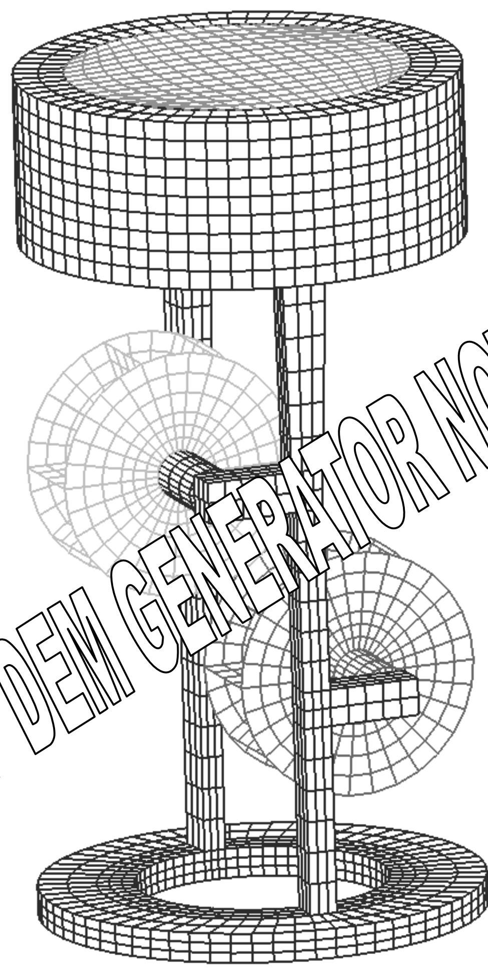
Examples

Sand Wheel



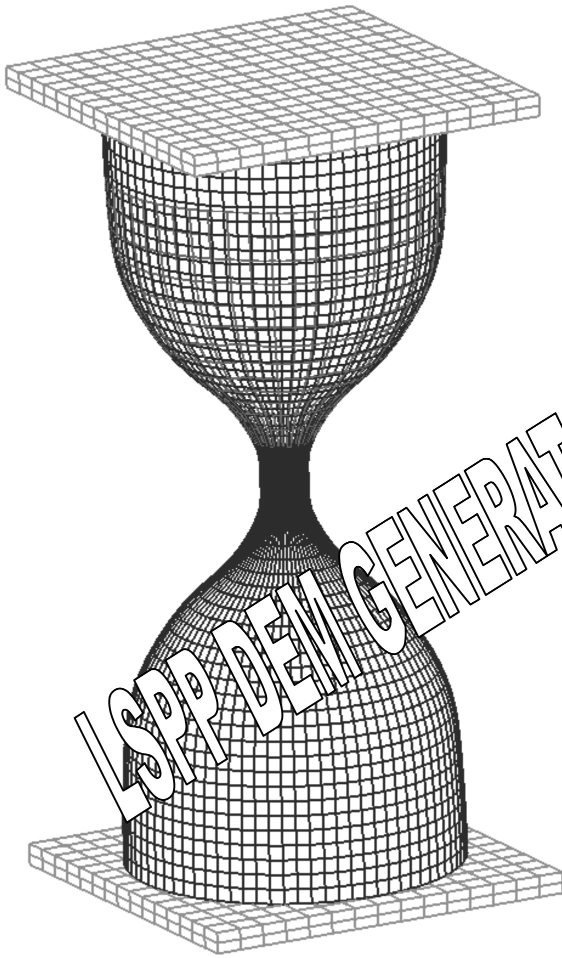
Examples

Double Sand Wheel



Examples

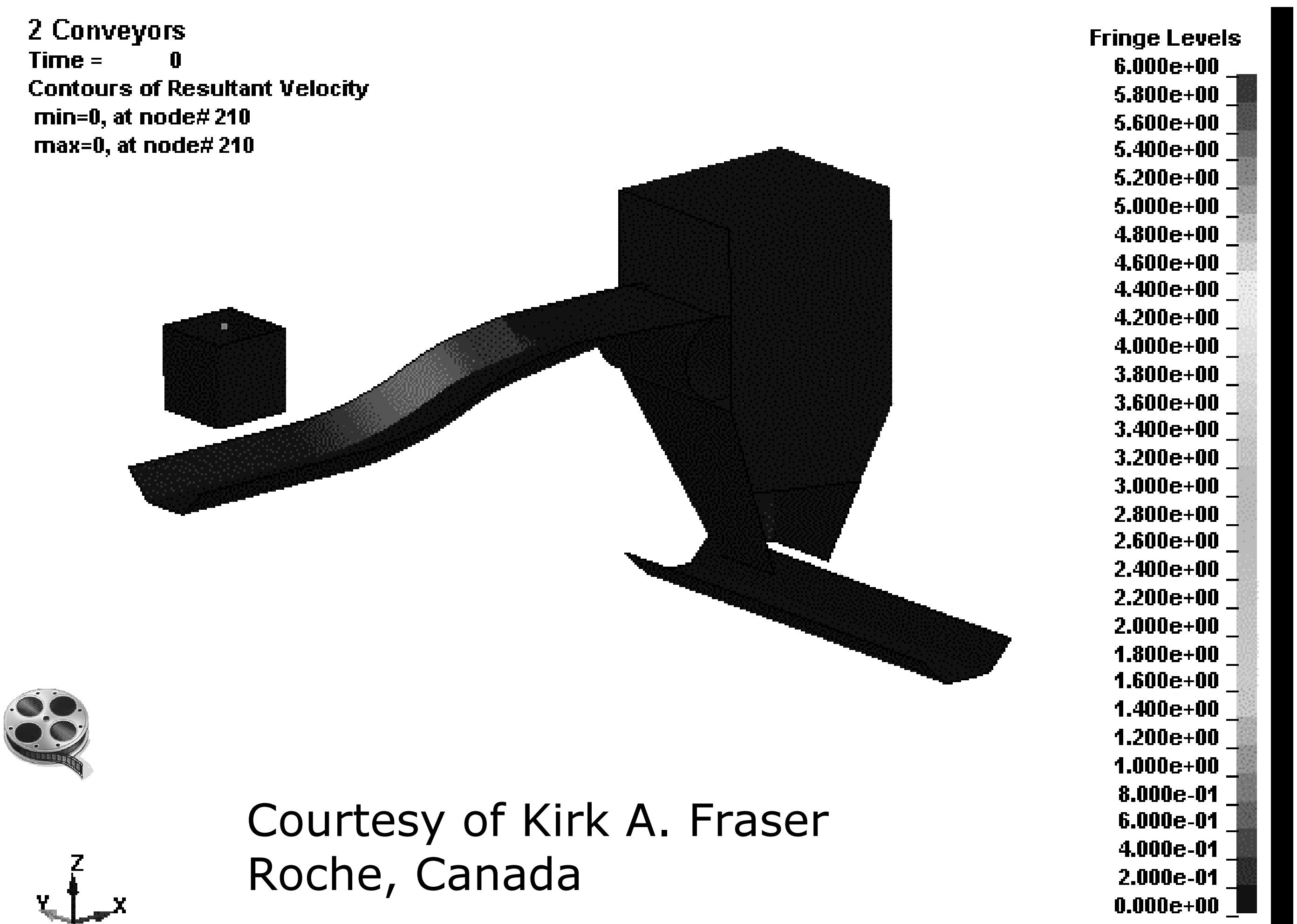
Hourglass Timer



LSPP DEM GENERATOR NOT WORKING FOR THIS YET

Examples

Conveyor Model



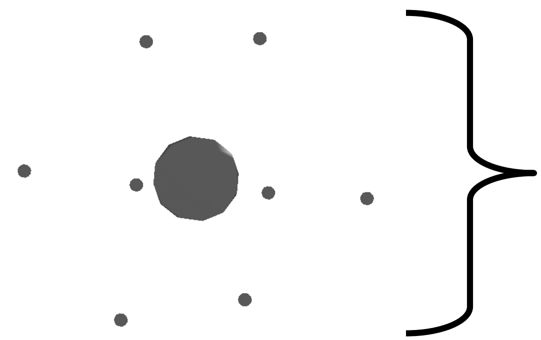
Courtesy of Kirk A. Fraser
Roche, Canada

Examples

Benchmark Test – SMP and MPP

- A benchmark test provide by Dr. George Laird, Predictive Engineering and Kirk A. Fraser, Roche, Canada was used to test the performance in SMP and MPP.

- The model consists of 90k discrete particles that are bonded together 9 in a configuration using bond formulation 1 (see *DEFINE_DE_BOND in Chapter 7). This gives 10k individual "clusters" of particles.



There is 10k of these "clusters"

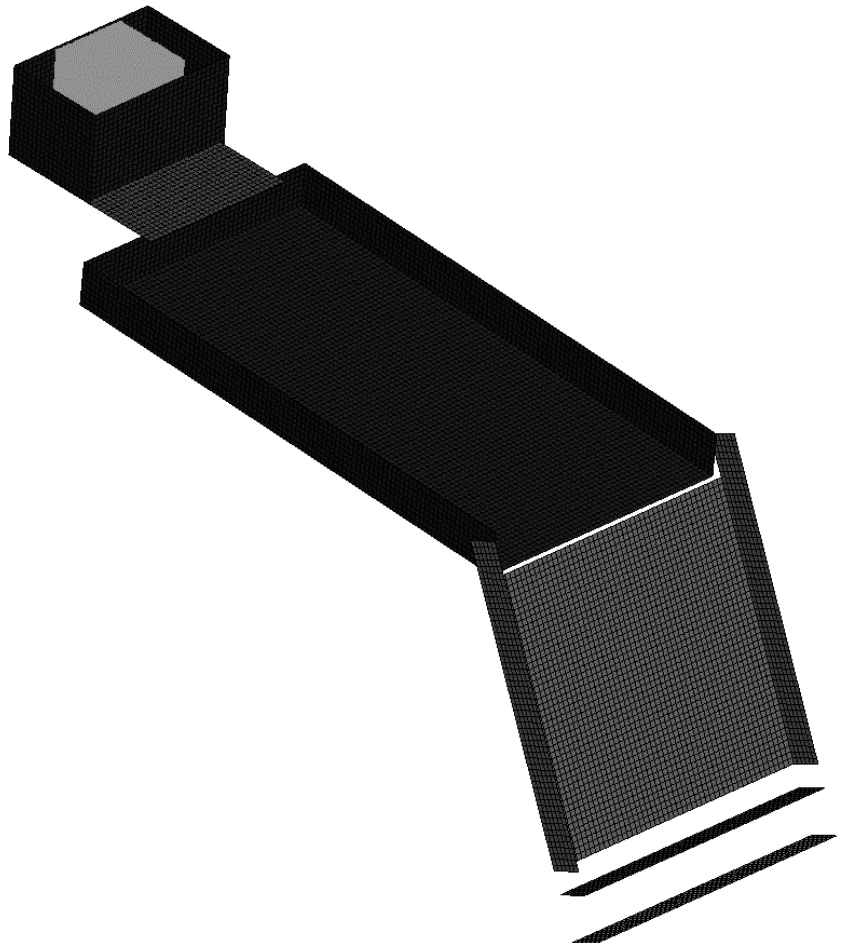
- The particles are impacting and being transported on a conveyor band that shakes.

- The set-up this way involves both interaction between the particles and several lagrangian parts.

Draft

Examples

Benchmark Test – SMP and MPP

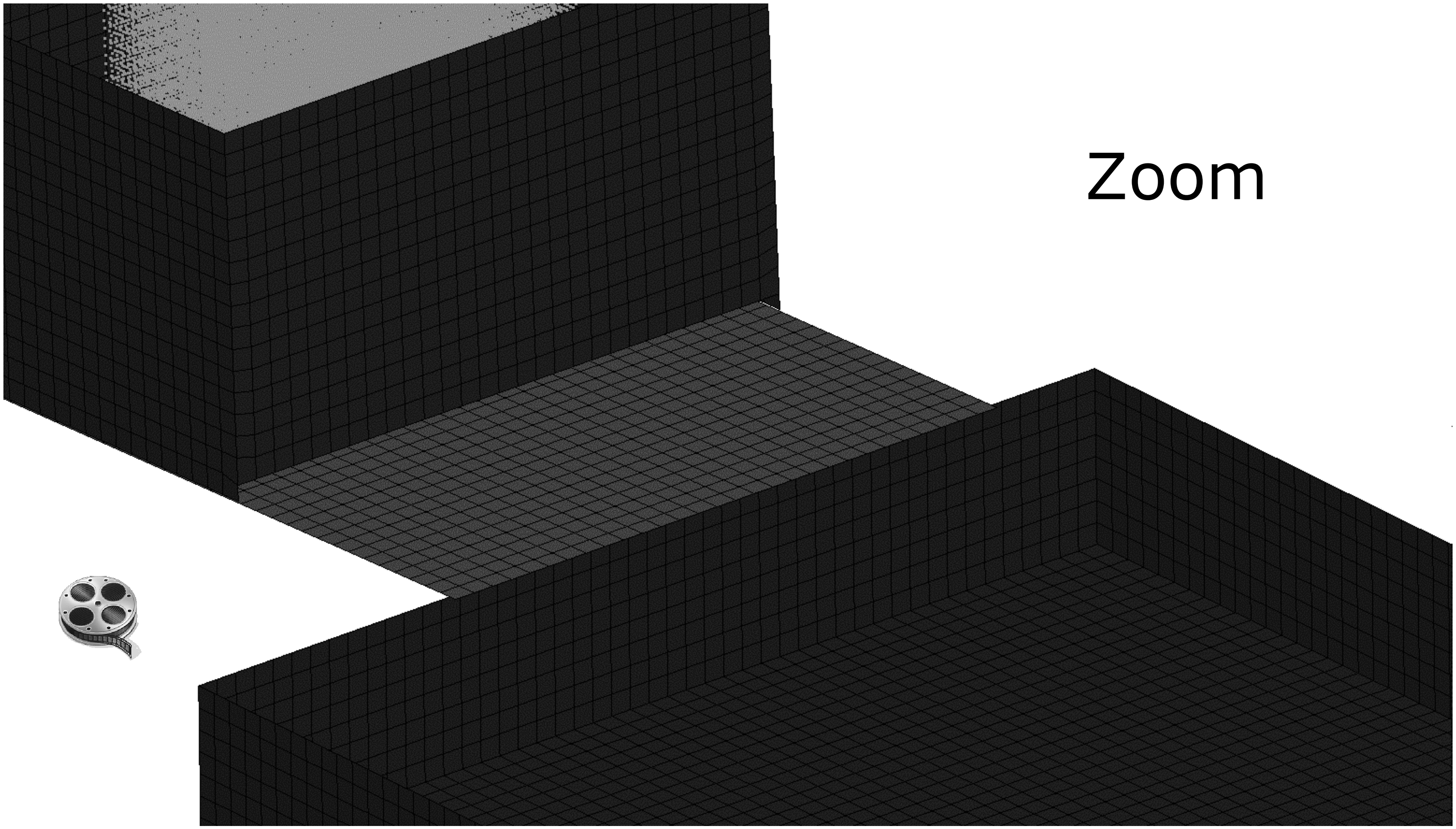


Courtesy of Kirk A. Fraser, Roche, Canada and Dr. George Laird, Predictive Engineering.

Examples

Benchmark Test – SMP and MPP

Zoom



Courtesy of Kirk A. Fraser, Roche, Canada and Dr. George Laird, Predictive Engineering.

Draft

Examples

Benchmark Test – SMP and MPP

- The benchmark model was running on a Xeon64 machine using single precision of the latest Dev version which was Dev. 77498 (11/01/2012). The benchmark for MPP and SMP were on two different platforms where the one for MPP is slightly newer and hence faster.

MPP

# CPU	Elapsed time [Sec]
1	
4	59161
12	47636
24	40827
48	27682

SMP

# CPU	Elapsed time [Sec]
1	
2	68546
3	52378
4	41869
5	43001
6	51742
7	
8	

Examples

Benchmark Test – SMP and MPP

- It is seen from this particular model that SMP shouldn't use more than 4 CPU's. This common to see this performance behaviour, see e.g. [M. R. Jensen, 2009].

- It can also be seen that work still has to be done to get better scaling in MPP but this is already in progress. It should be noticed that for MPP the hybrid version was not used which perhaps could improve the performance, also default decomposition was applied. The hybrid version is special version of the MPP executable and is described in [M. R. Jensen, 2009].

Chapter 5

Post-Processing DEM Models using LS-PrePost®

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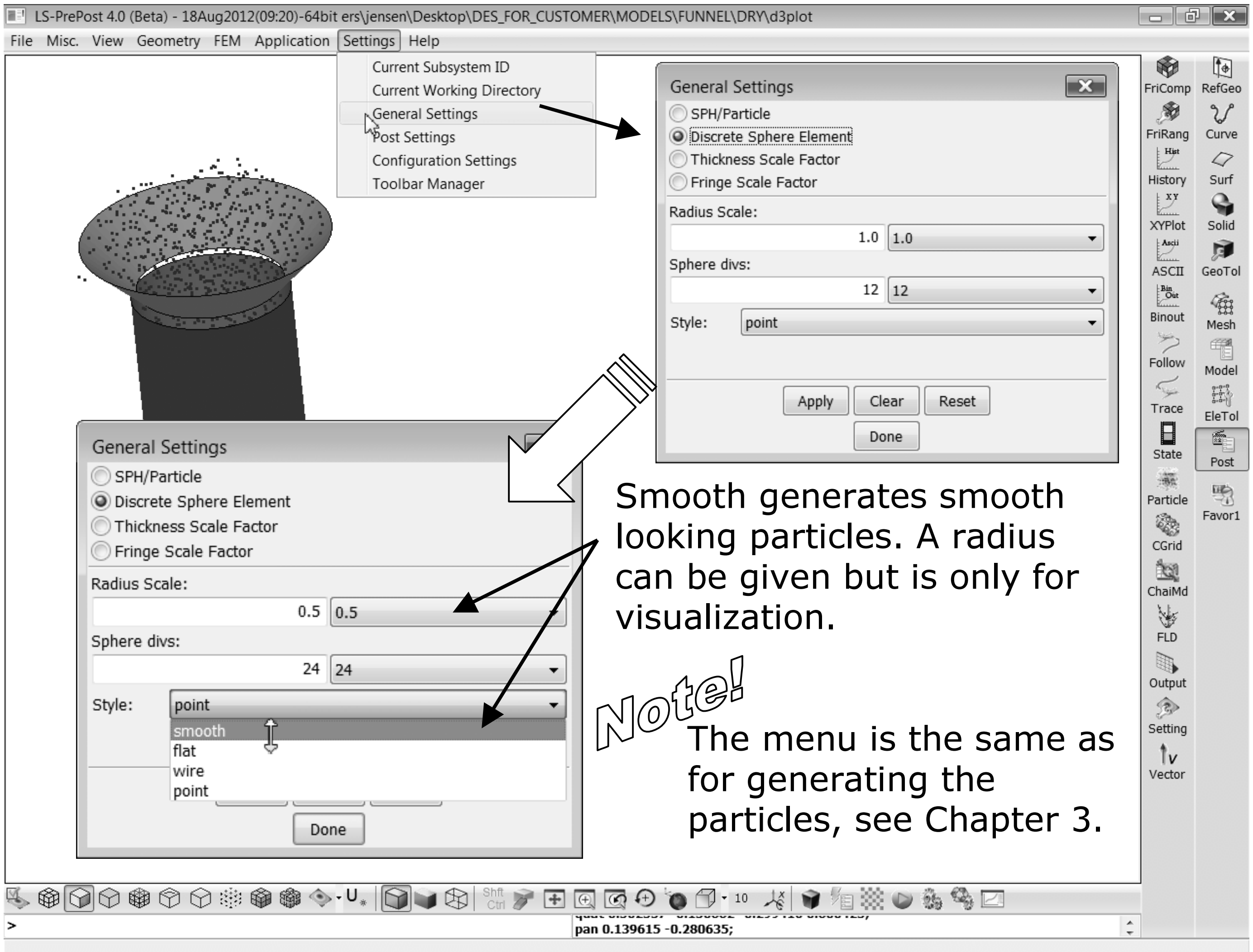
Viewing Particles

- The DEM particles are by default shown in LS-PrePost® as points. This can be changed using the viewing options under Settings → General Settings → Discrete Sphere Element.



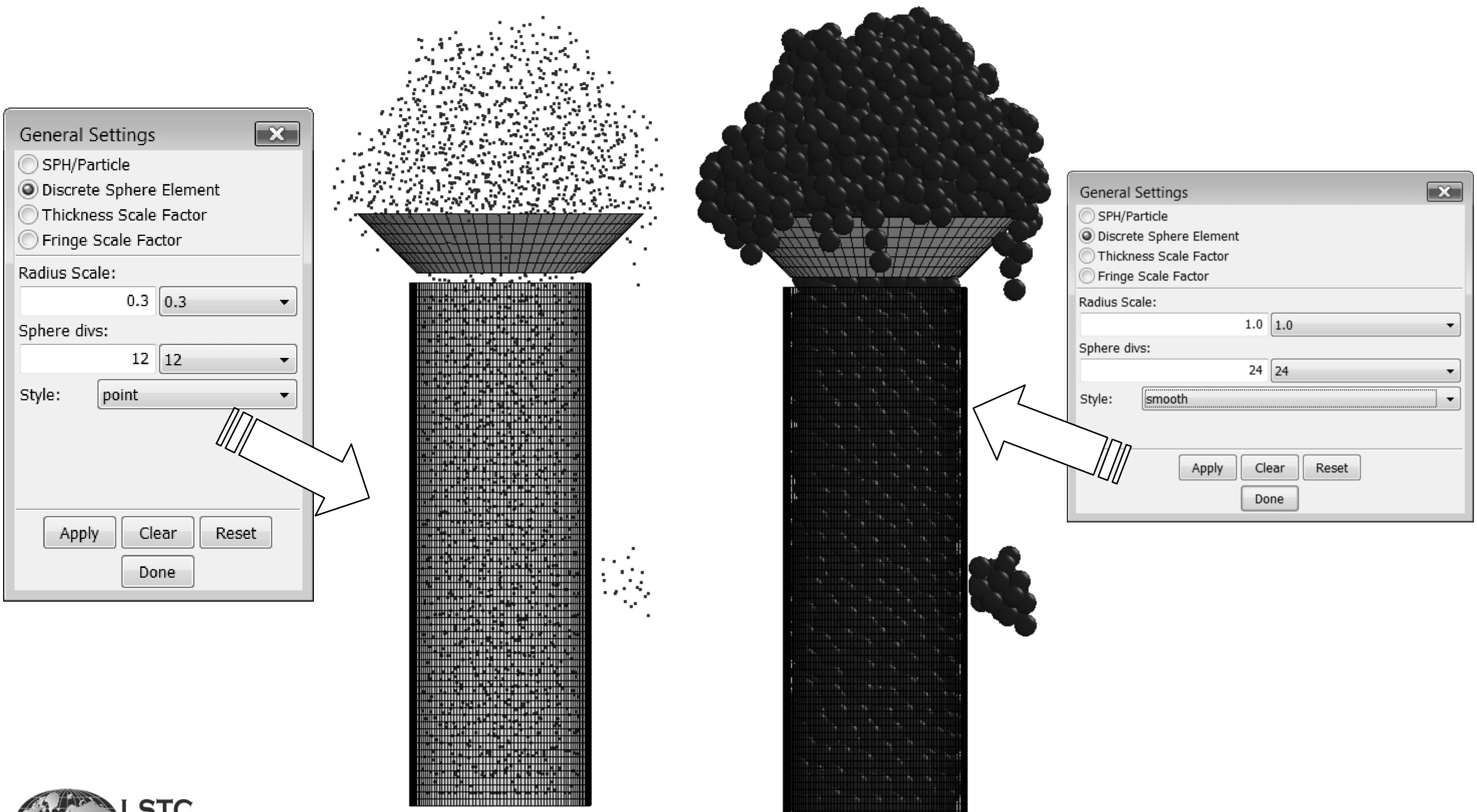
Smooth generates smooth looking particles. A radius can be given but is only for visualization.

Note!

The menu is the same as for generating the particles, see Chapter 3.

Viewing Particles

- The visualization of the particles can strongly be improved by using the smooth option in the setting menu.



Draft

DATABASES

- There are two special databases related to the DEM method. One is for binary output and one is for ASCII output. They both contains information about the force on structures impacted by the DEM particles. In the next slides these options are shown in more details.

  - *DATABASE_RCFORC. This will generate a file named *demrcf* that has the same format as the *rcforc file*. Thus this is an ASCII file and all that has to be given is the output frequency at the *DATABASE_RCFORC card.

  - *DATABASE_BINARY_DEMFOR. At this card the output frequency is given but no file will be written, unless the dem option is used at the command line:

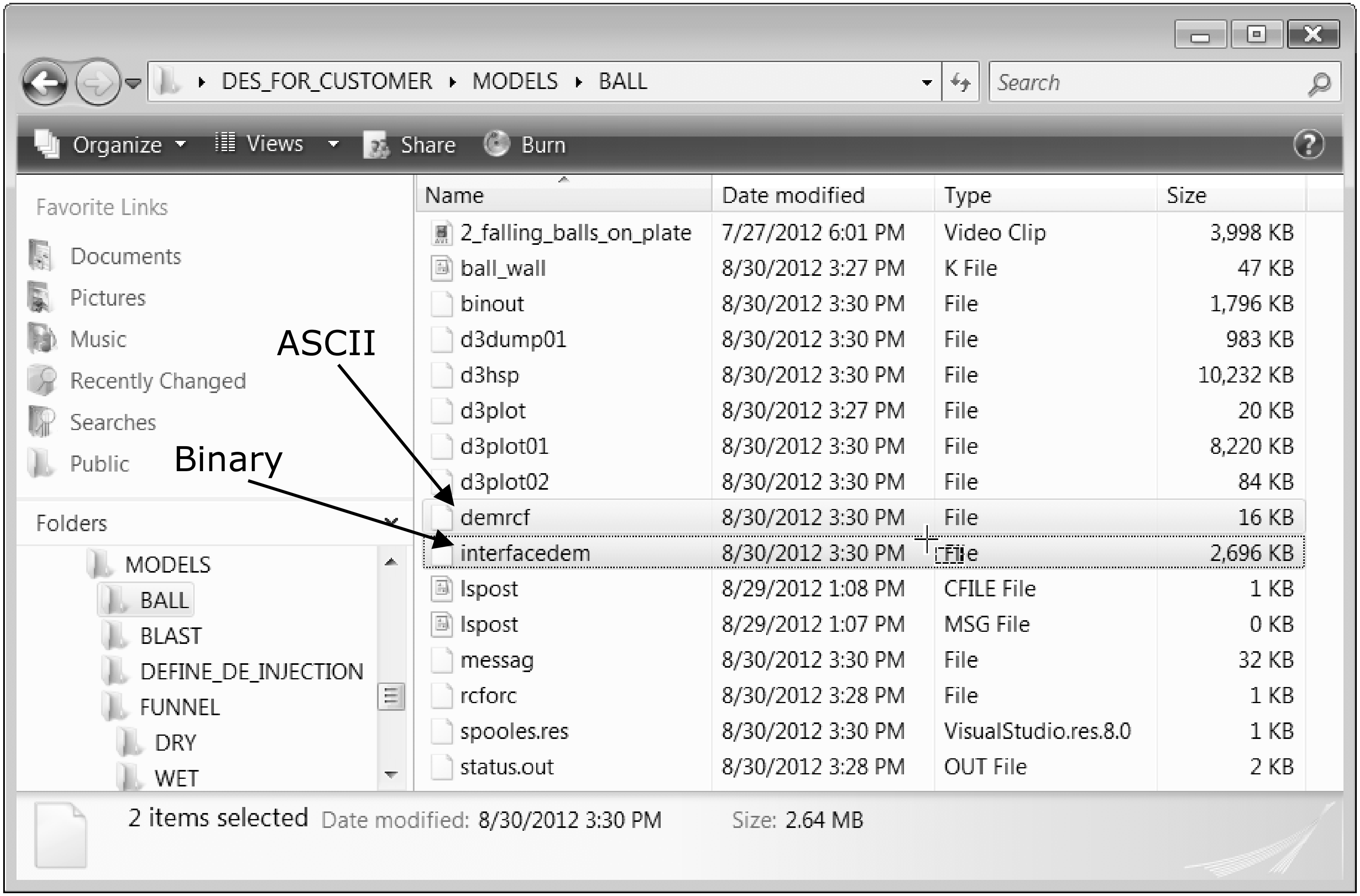
    ls971 I=inputfile.k dem=deminterface

    The deminterface is an arbitrary name.

- There will be no stresses for the particles, since these are rigid spheres but nodal quantities such as velocity etc. can be plotted in LS-PrePost® in a usual manner.

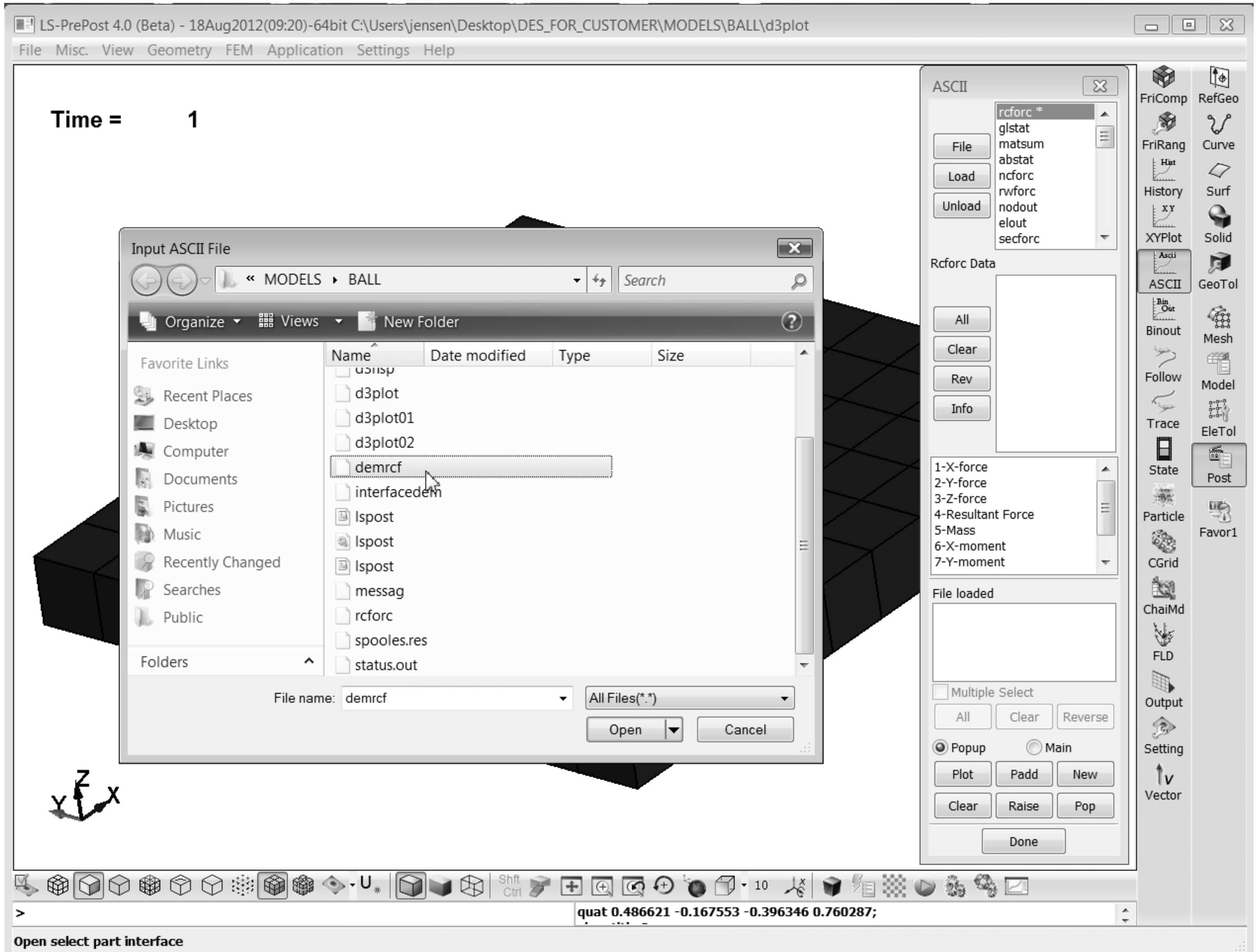
DATABASES

Generated Files



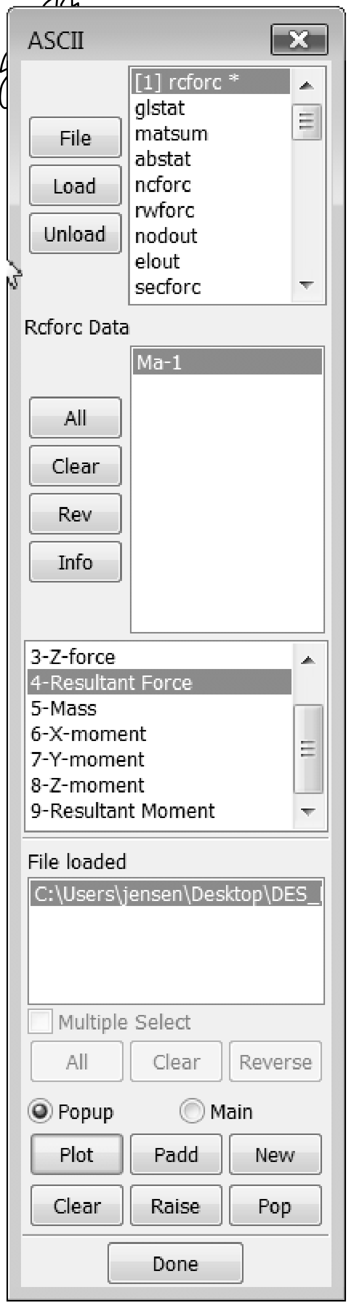
DATABASES
demrcf ASCII File

Open the file as *rcforc* file. Select File and All Files, then click on the *demrcf* file to open it.

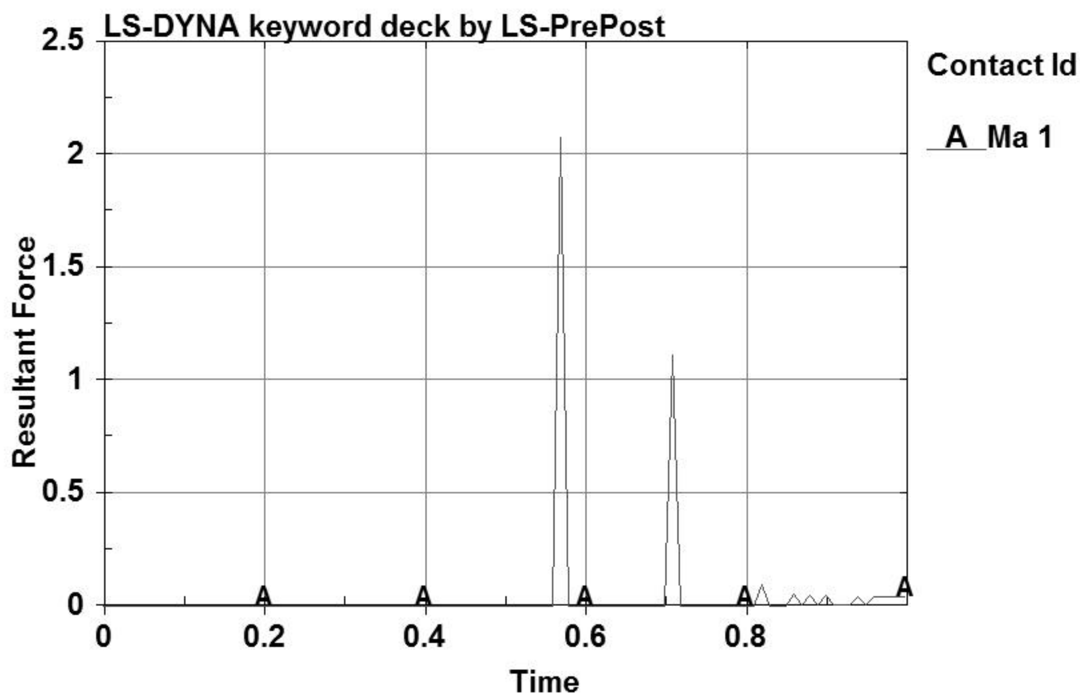


DATABASES

demrcf ASCII File



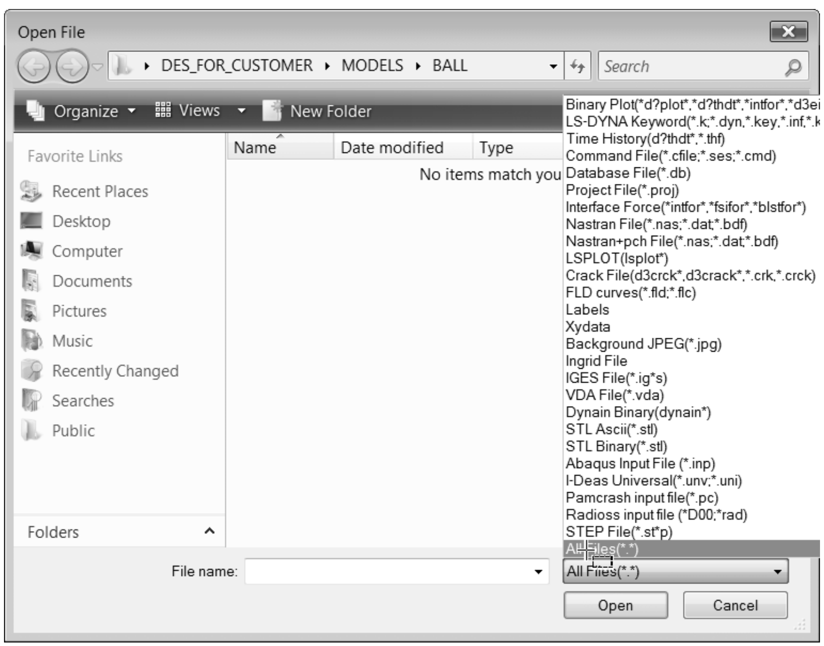
- The file has the force components for the interface between particles and structure defined by the *DEFINE_DE_TO_SURFACE_COUPLING. Notice that only the master surface is available.

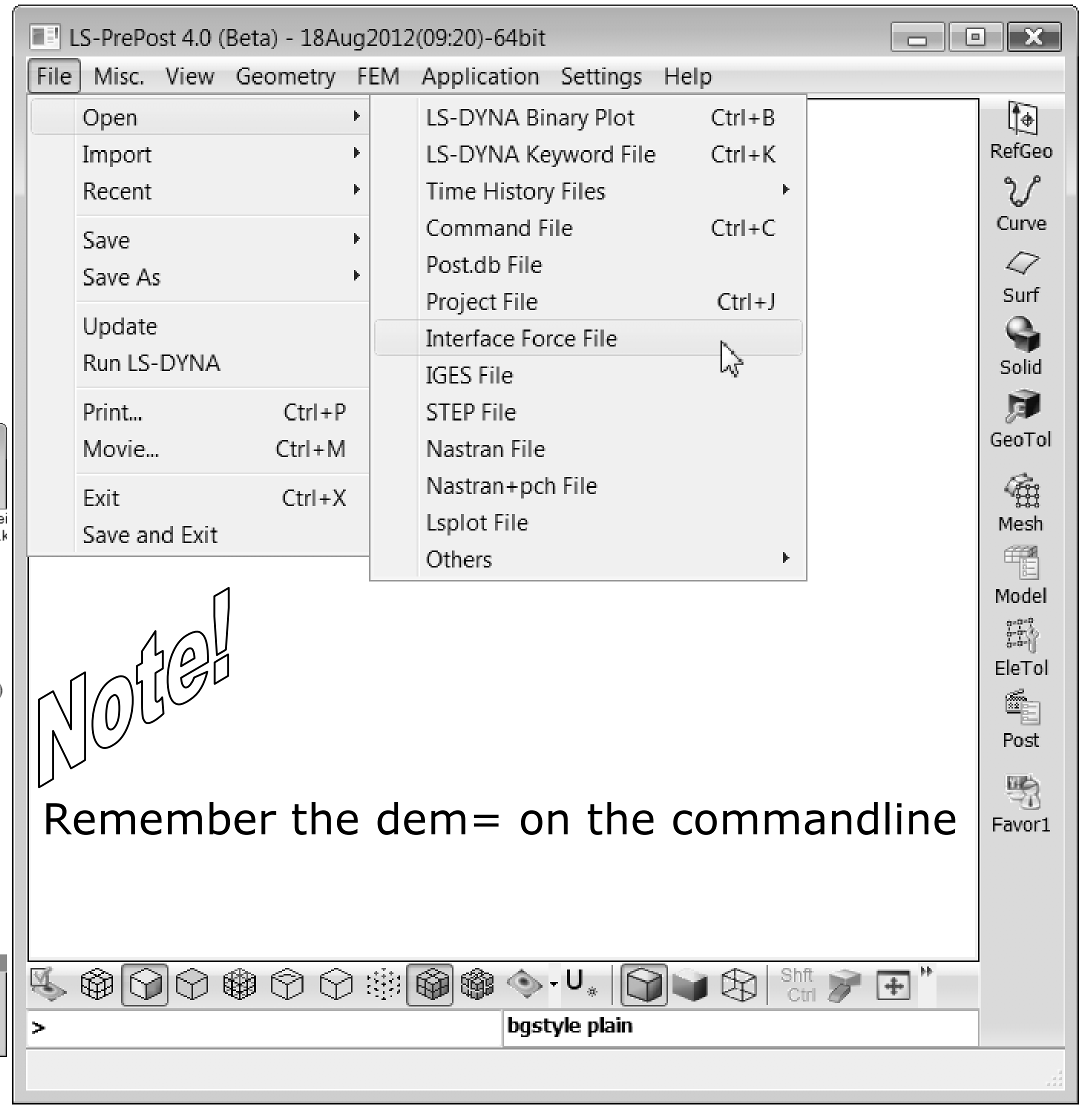


DATABASES

dem Binary File

- The binary *dem* file can be loaded to LS-PrePost using the option to open contact interface force files. There is currently no label for it so one select the All Files option. The file name is arbitrary.



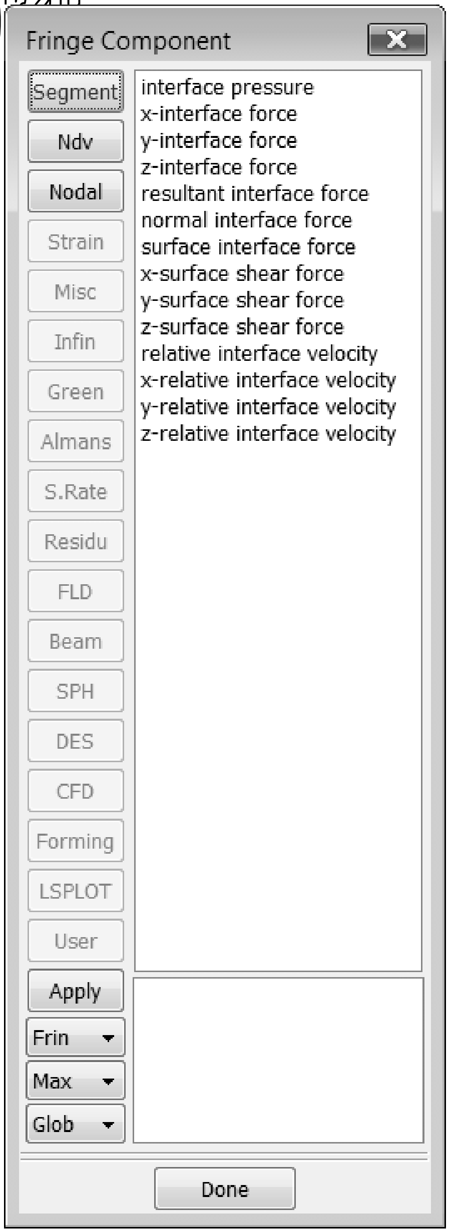


Note!

Remember the dem= on the commandline

DATABASES

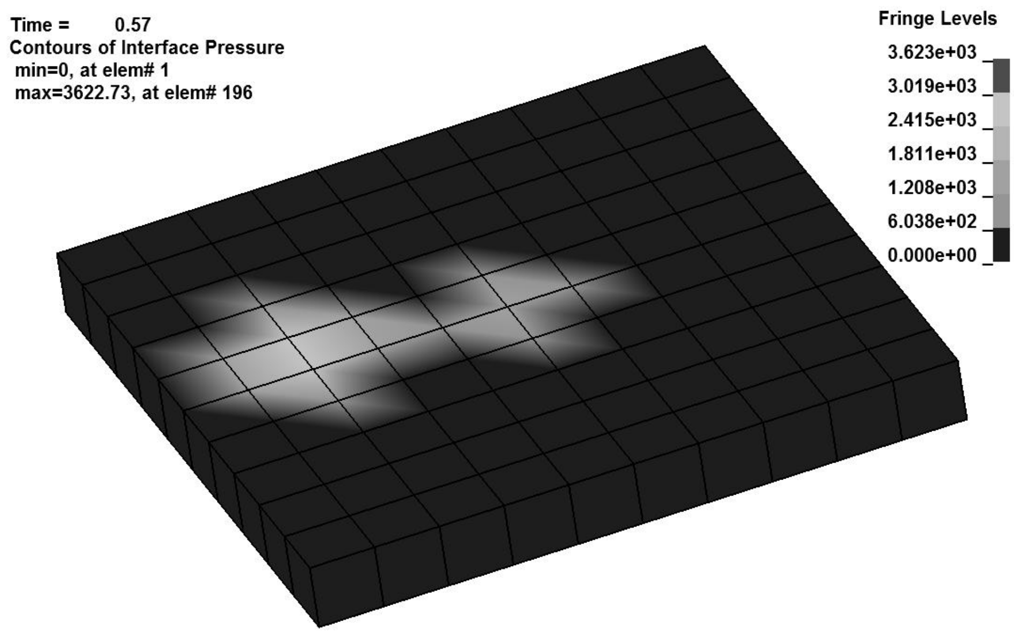
dem Binary File



- The content of the file is similar to what is in the interface force file that is used for contact. There are interface pressure and forces. Only the master side is written to the database. It can both be a Fringe plot or a history plot of a segment.

: History plot for selected segment.

: Fringe plot.



Chapter 6

General Comments

Draft

General Comments

Time Step:

- The used time step in the simulation is the smallest one calculated for all elements in the model. The time step for the DEM particles is calculated according to the springs following the work in [Cundall et al, 1979] but is slightly modified so the used equation in LS-DYNA® is:

$$\Delta t_{DES} = \mathrm{TSSFAC} \cdot 0.2 \cdot \pi \cdot \mathrm{DESTSSFAC} \cdot \sqrt{\frac{\mathrm{m}}{\mathrm{K_{Spring}}}}$$

Where:
m is the mass and K_{spring} is the spring stiffness. TSSFAC is the time step scale factor given at *CONTROL_TIMESTEP and DESTSSFAC is active for bond method 2 only (BDFORM=2 at *DEFINE_DE_BOND).

General Comments

- In Chapter 2 is shown the calculation of the spring stiffness which leads to the following equation for the calculated time step:

$$\Delta t_{DES} = \mathrm{TSSFAC} \cdot 0.2 \cdot \pi \cdot \mathrm{DESTSSFAC} \cdot \sqrt{\frac{m}{\mathrm{K_{Bulk}} \cdot \mathrm{RADIUS} \cdot \mathrm{NormK}}}$$

Where:

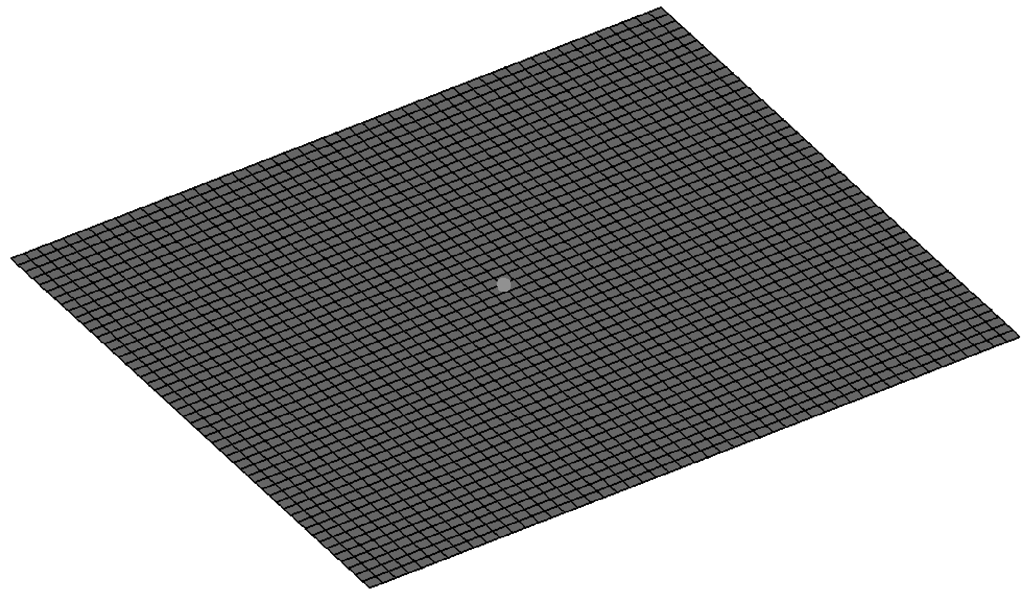
K_{Bulk} is the bulk modulus of the material, RADIUS the particle radius and NormK is a scale factor of the normal spring (default 0.01).

- Next, consider an example that illustrates how the time step is calculated in a simple set-up.

General Comments

Time Step - Example:

- As example of calculating the time step consider a DEM particle hitting a rigid plate.



- The properties for the particle is: ρ=7.8e-6, E=2e+5, ν=0.3. This gives the bulk modulus of the material to be:

$$K_{Bulk} = \frac{E}{3(1-2\upsilon)} \Rightarrow K_{Bulk} = \frac{2e+5}{3(1-2\cdot 0.3)} \approx \underline{166666.67}$$

Draft

General Comments

Time Step – Example Continued:

- The mass of the particle is 4.084e-6 and the radius is 0.5. The NormK and TSSFAC are not changed from default so these are 0.01 and 0.9, respectively. This gives the time step as:

$$\Delta t_{DES} = \mathrm{TSSFAC} \cdot 0.2 \cdot \pi \cdot \mathrm{DESTSSFAC} \cdot \sqrt{\frac{m}{\mathrm{K_{Bulk}} \cdot \mathrm{RADIUS} \cdot \mathrm{NormK}}}$$

$$\Downarrow$$

$$\Delta t_{DES} = 0.9 \cdot 0.2 \cdot \pi \cdot 1 \sqrt{\frac{4.084\mathrm{e}-6}{166666.67 \cdot 0.5 \cdot 0.01}} \approx 0.000039587$$

$$\Downarrow$$

$$\Delta t_{DES} = \underline{\underline{3.9587\mathrm{e}-5}}$$

Draft

General Comments

Time Step - Example Continued:

- In the *d3hsp* file the 100 smallest steps are not shown since this routine not yet has the information from the DEM routine. However, the used time step matches the calculated one.

```
No elements with calculated timesteps
       1 t 0.0000E+00 dt 3.96E-05 flush i/o buffers            11/08/12 17:28:54
```

- Information is also written in the *d3hsp* file about time and energies:

```
dt of cycle     100 is controlled by DE sphere          0
time..........................    3.91914E-03
time step.....................    3.95873E-05
kinetic energy................    3.41419E-03
internal energy...............    1.00000E-20
spring and damper energy......    1.00000E-20
system damping energy.........    0.00000E+00
sliding interface energy......   -4.80761E-04
external work.................    2.93327E-03
eroded kinetic energy.........    0.00000E+00
……………………………..
```

Very good agreement!

Draft

General Comments

Time Step:

- The experience so far is that this approach is working very well and there is no general recommendation to lower the time step further based on the use of the DEM particles in a model.

Boundary Conditions and Loading:

- If used, the constraint setting in *MAT_RIGID is ignored for the DEM particles. This is true both for the global and local option. Constraints will have to be set using *BOUNDARY_SPC_*option* or the TC and RC flags at *NODE.

- Forces can be applied by using *LOAD_NODE_*option* or *LOAD_BODY_*option* for e.g. gravity loading.

- All the *INITIAL_VELOCITY_*option* cards can be used to apply an initial velocity for the DEM particles.

- *BOUNDARY_PRESCRIBED_MOTION_*option* can be used as well.

Draft

General Comments

Contact:

- The DEM particles can be in contact with structural parts. This can be done either by using a general _NODES_ contact. Some of the most used contacts that works are the following contacts:

  *CONTACT_NODES_TO_SURFACE
  *CONTACT_AUTOMATIC_NODES_TO_SURFACE
  *CONTACT_ERODING_NODES_TO_SURFACE

- Note that for all contacts the radius of the sphere is taking into account and there is no method to avoid this. Further, the contact thickness scaling and setting on the contact cards are not valid for the DEM particles.

- Both the _MORTAR and the _SMOOTH option can be used where valid.

Draft

General Comments

Contact - continued:

- SOFT=1 can be used but not SOFT=2, since no segments can be generated based on the nodes only.

- Tied contact can be applied as well.

- The specific developed DEM contact is *DEFINE_DE_TO_SURFACE_COUPLING, which only is working for contact with structural parts modeled with shell elements.

- Currently it is recommended to use the standard LS-DYNA® contacts, e.g. *CONTACT_AUTOMATIC_NODES_TO_SURFACE.

Draft

General Comments

Damping:

- The general damping cards used in LS-DYNA® for mass and stiffness damping (*DAMPING_*option*) are ignored for the DEM particles.

- Instead is used the NDAMP and TDAMP options at *CONTROL_DISCRETE_ELEMENT. These coefficients are not related to the critical damping coefficient but is given as a scale factor to the velocity of the DEM particle:

$$NDAMP * V_{Normal}$$

$$TDAMP * V_{Tangential}$$

Draft

General Comments

Misc.:

- There is no internal energy generated for the DEM parts. There will however be kinetic energy.
- For the bonded DEM method, *DEFINE_DE_BOND, there is not yet implemented databases to visualize the forces.
- There is Part section in the *d3hsp* file doesn't show that DEM particles are used.

```
part     id .....................         2
section  id .....................         2
material id .....................         2
section  title .................

material title .................

          material type ..............    20
          equation-of-state type .....     0
          hourglass type .............     2
          bulk viscosity type ........     1

    density ......................... = 7.80000E-06
    hourglass coefficient ........... = 1.00000E-01
    quadratic bulk viscosity ......... = 1.50000E+00
    linear bulk viscosity ............ = 6.00000E-02
    element type ..................... =     0
         eq.0: 4, 6, 8, 10-node solid element or SPH element
         eq.1: 2-node beam or truss or 2D shell element
         eq.2: 3, 4-node membrane/shell or 2D continuum element
         eq.3: 8-node thick shell element
```

General Comments

Draft

Misc.:

- However, the element information is shown for the DEM as it is for other elements:

```
d i s c e t e   s p h e r e   e l e m e n t s

   node        part         mass      inertia      radius
      9999          2  4.084E-06  4.084E-07  5.000E-01
     99999          2  4.084E-06  4.084E-07  5.000E-01
    109998          4  4.084E-06  4.084E-07  5.000E-01
    199998          4  4.084E-06  4.084E-07  5.000E-01
```

- The timing spend for the DEM particles self contact is show in the timing table at the bottom of the *d3hsp* file.

```
T i m i n g   i n f o r m a t i o n
                        CPU(seconds)   %CPU  Clock(seconds) %Clock
  ----------------------------------------------------------------
………………………………………………………
……………………………………………………..
  Rigid Bodies ......... 2.2915E-01    3.28     8.8416E-02    3.26
  DEM .................. 1.3710E-01    1.96     1.8933E-02    0.70
    DEM self contact ... 1.3672E-01    1.96     1.8700E-02    0.69
  Other ................ 1.3435E+00   19.25     5.0957E-01   18.80
  ----------------------------------------------------------------
  T o t a l s            6.9806E+00  100.00     2.7099E+00  100.00
```

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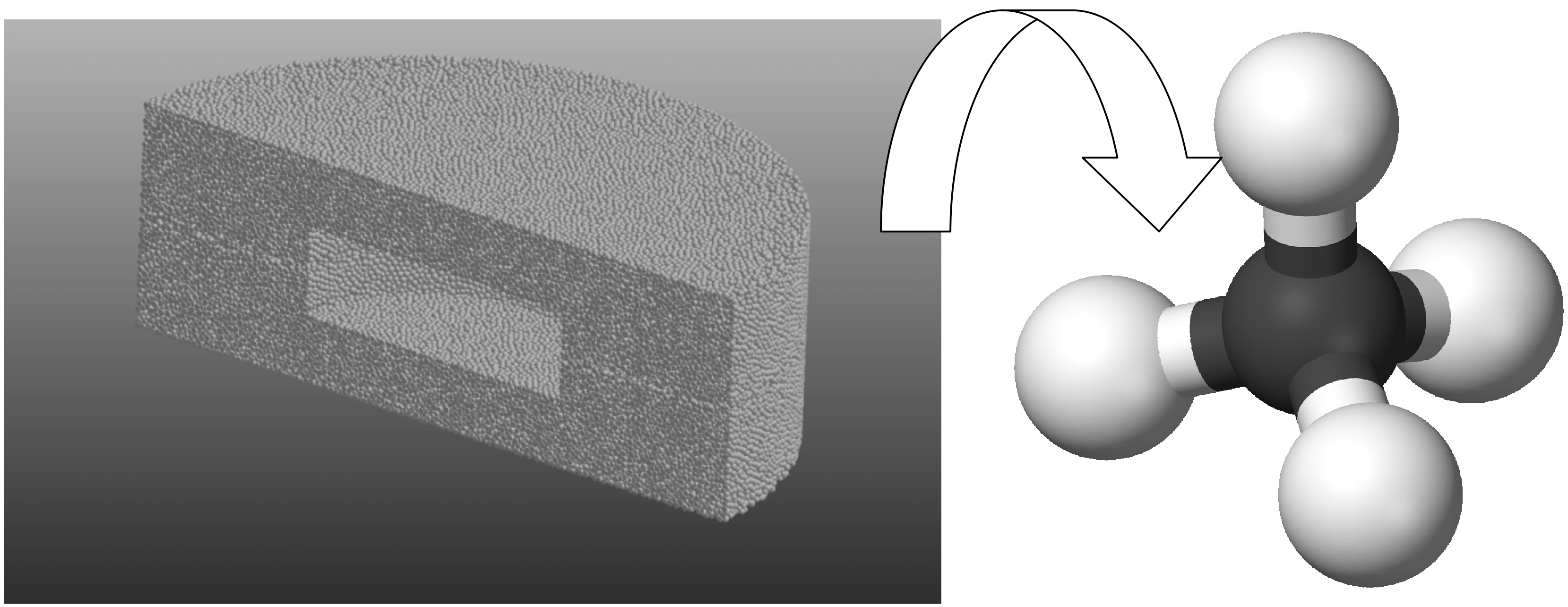
Chapter 7

Sphere Bond Models

Introduction

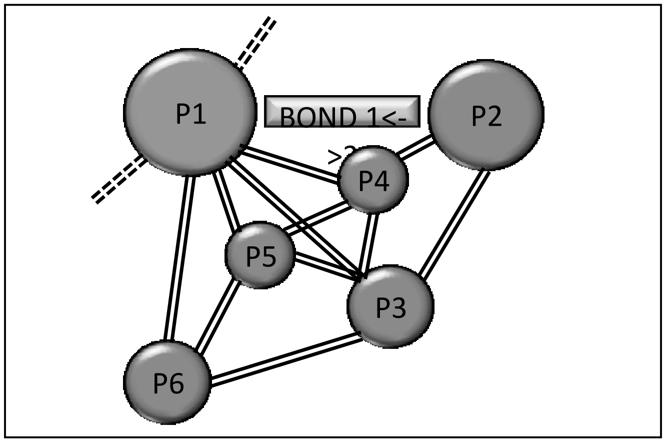
- So far DEM particles and their interaction has been considered. This has been done by a special interaction (contact) between the particles. They are all independent particles.

- Bond models to “bond” the particles have been developed. This makes modeling of a Continuum possible. It can also be seen as a system of particles.



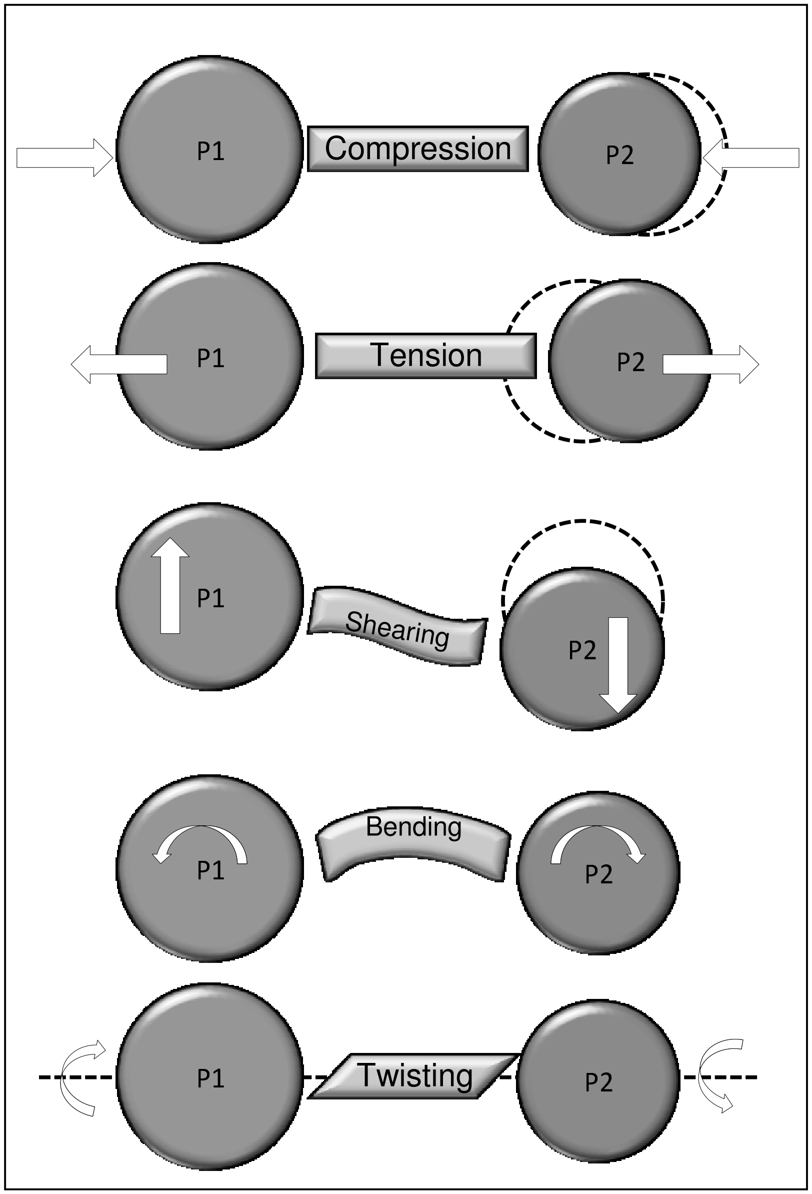
Introduction

- All particles are linked to their neighboring particles through bonds which are independent from the DEM model.
- There are currently two different bound methods implemented in LS-DYNA®.
  - A method where material parameters are given at the specific DEM card. Failure of the bonds can also be given as stress values.
  - A more complex method where a linear bond is generated and the strength is taken from the material cards of the particles. Further, fracture release rates and an initial fracture plane can be given to model initialization and growth of fracture.
- The keyword related to specifying the bonds is *DEFINE_DE_BOND that will be described in more details later.



Mechanical Behaviors of Bonds

- Every bond is subjected to:
  - Compression
  - Stretching
  - Shearing
  - Bending
  - Twisting
- The bonds can break depending on the settings and method given at the *DEFINE_DE_BOND card.



Draft

Bonded-Particle Model

*DEFINE_DE_BOND

Card 1	1	2	3	4	5	6	7	8
Variable	SID	STYPE	BDFORM	IDIM				
Type	I	I	I	I				
Default	None	0	1	3				

SID:

Node set or node for the discrete particles.

STYPE:

Type setting for SID.

EQ.0: Node set ID is given at SID.

EQ.1: A single node ID is given at SID.

Draft

Bonded-Particle Model

BDFORM:
Specification of the bond formulation between the particles. Currently, two options are available which both are under development and considered in the first beta phase.

EQ.1: Parallel-bond.

EQ.2: Linear elastic bond formulation.

The parallel-bond method is the simplest method and requires normal and shear stiffness to be given. A failure criteria given by a single parameter given for either shear or normal stress is implemented to fail the bond.
Linear elastic bond formulation is used to model fracture for brittle materials. This is done by applying a failure criteria that is based on fracture energy release rates.

IDIM:
Space dimension for the particles used for BDFORM=2.

EQ.2: 2D plane stress problems.

EQ.3: 3D problems.

Draft

Bonded-Particle Model

Card 2 if BDFORM=1

Card	1	2	3	4	5	6	7	8
Variable	PBN	PBS	PBN_S	PBS_S	SFA	ALPHA		
Type	F	F	F	F	F	F		
Default	None	None	None	None	1.0	0.0		

Draft

Bonded-Particle Model

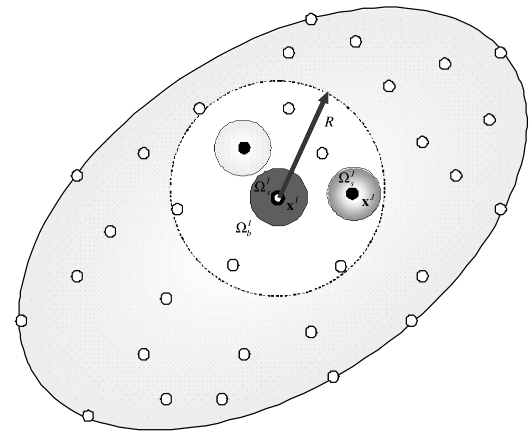
Card 2 if BDFORM=2

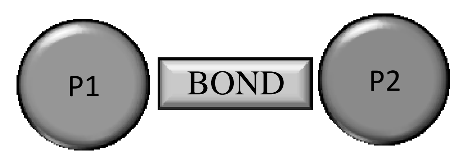
Card	1	2	3	4	5	6	7	8
Variable	PBK_SF	PBS_SF	FENRGK	FENRGS	BONDR			
Type	F	F	F	F	F			
Default	1.0	1.0	None	None	None			

BDFORM=2: Define Bond Properties

Based on Material Properties

- Bulk Modulus : **K**
- Shear Modulus: **G**
- Fracture Energy Release Rate: $\mathbf{G_c}$
- Influence Distance: *R*
  - Smaller R for less bonds and smaller time steps.
  - Larger R for more bonds and larger time steps.
  - Choices of R are dependent on the bar wave speed and the time step.
  - Macro-behaviors are NOT dependent on R.

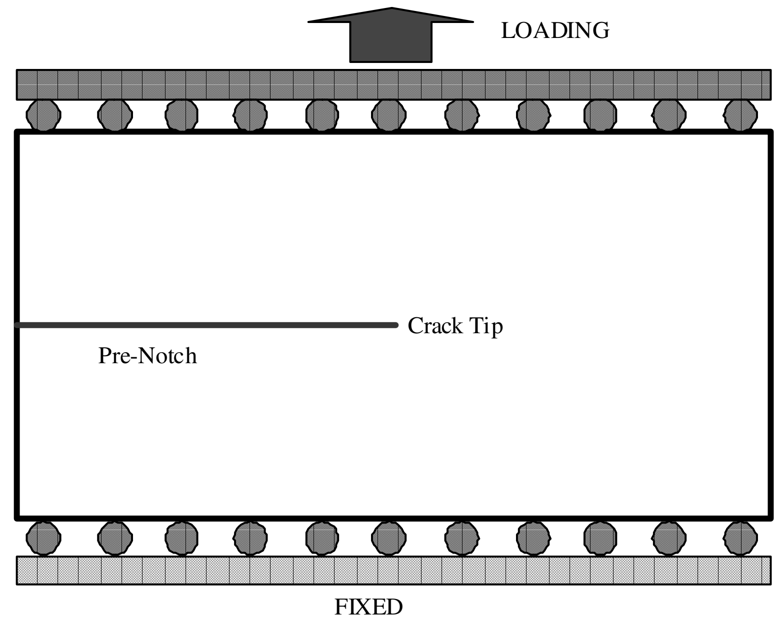




Draft

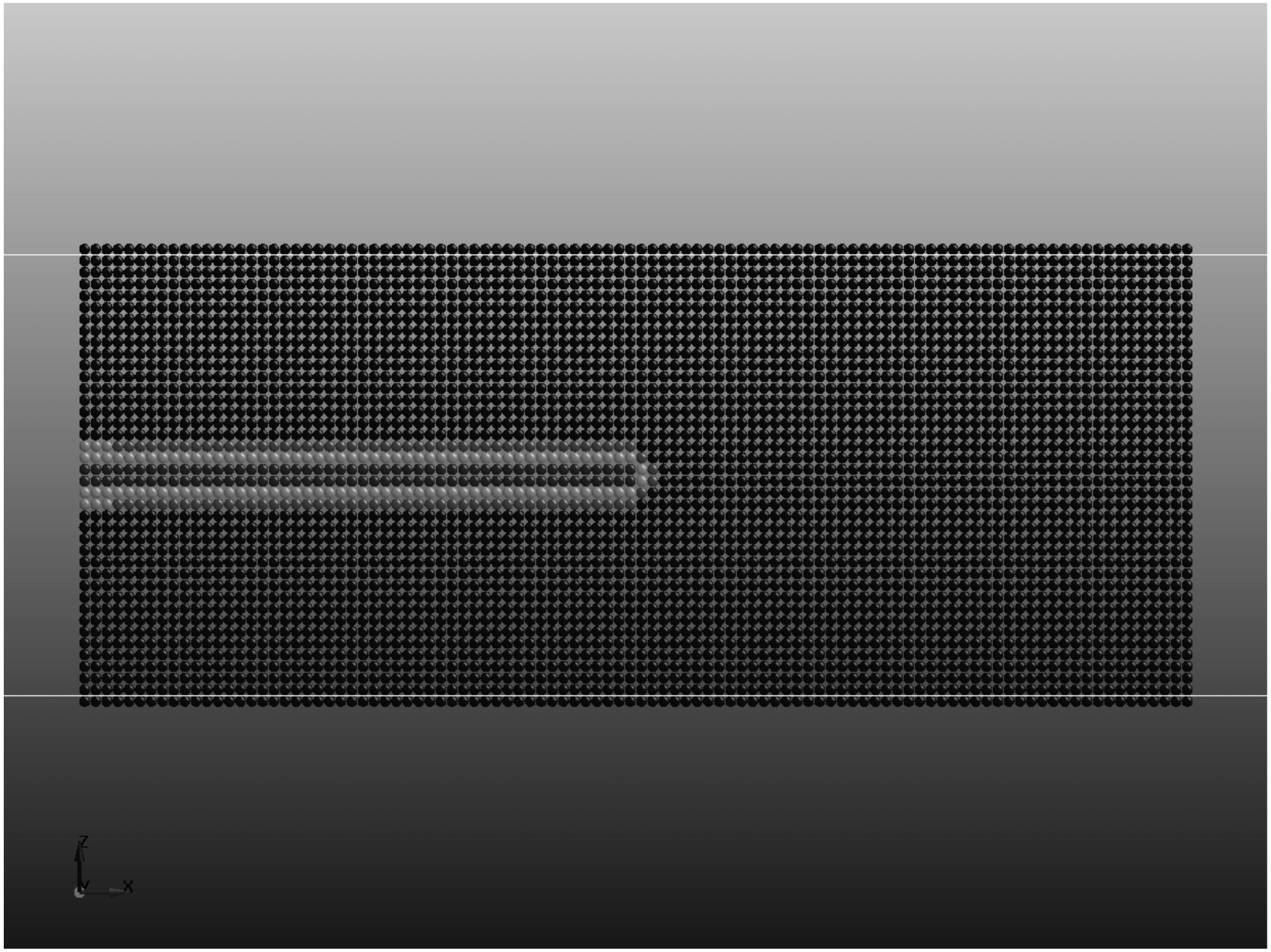
BDFORM=2
Benchmark Example

- A pre-notched rectangular plate
  - Size: 100mm x 40mm
  - pre-notch length: 50mm
- Material Properties
  - Density: 2,235 kg/m^3
  - Young's modulus: 65 Gpa
  - Poisson ratio: 0.2
  - Fracture energy release rate: 204 J/m^2



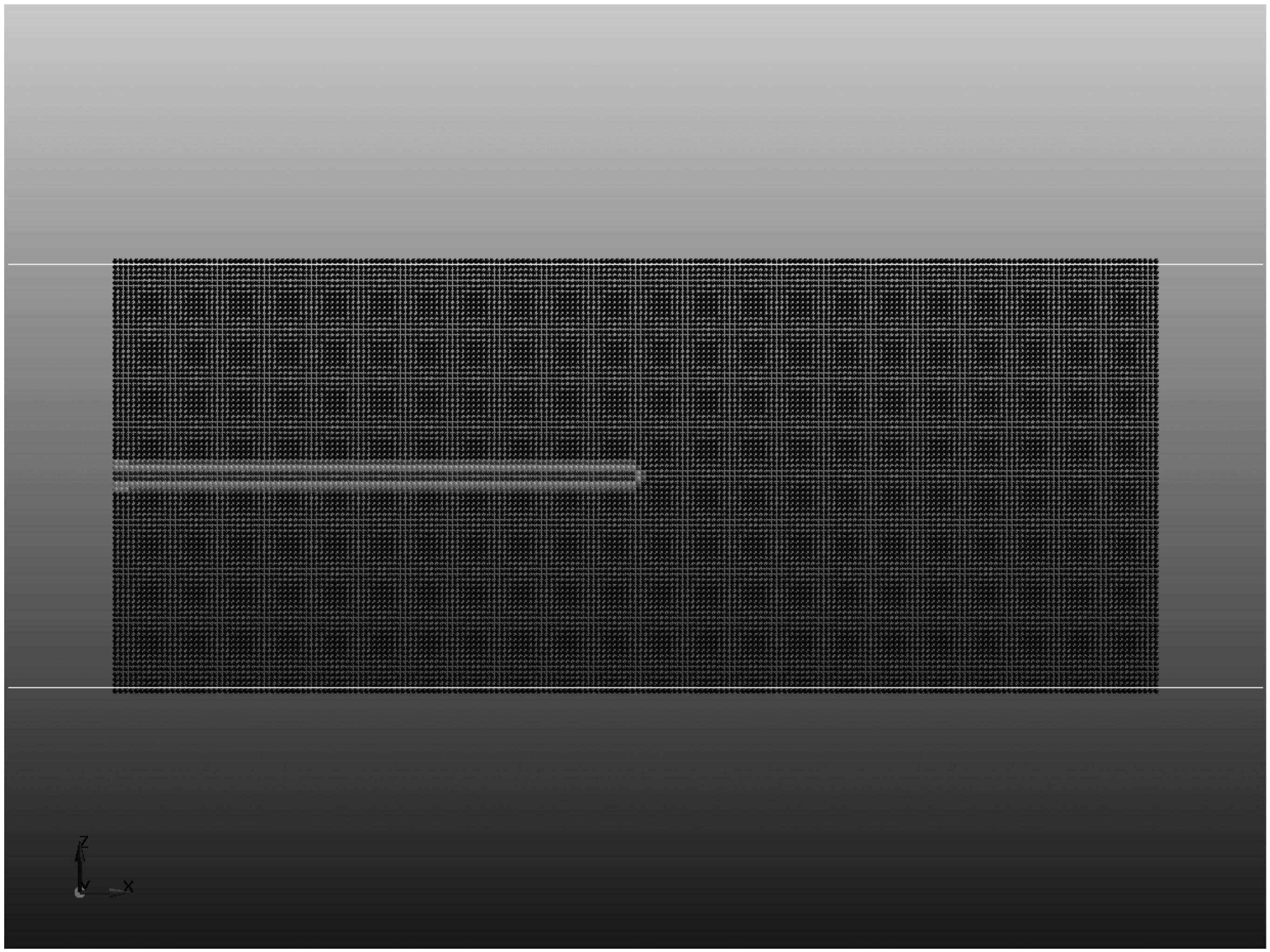
BDFORM=2

Sphere Size: R=0.5mm



BDFORM=2

Sphere Size: R=0.25mm



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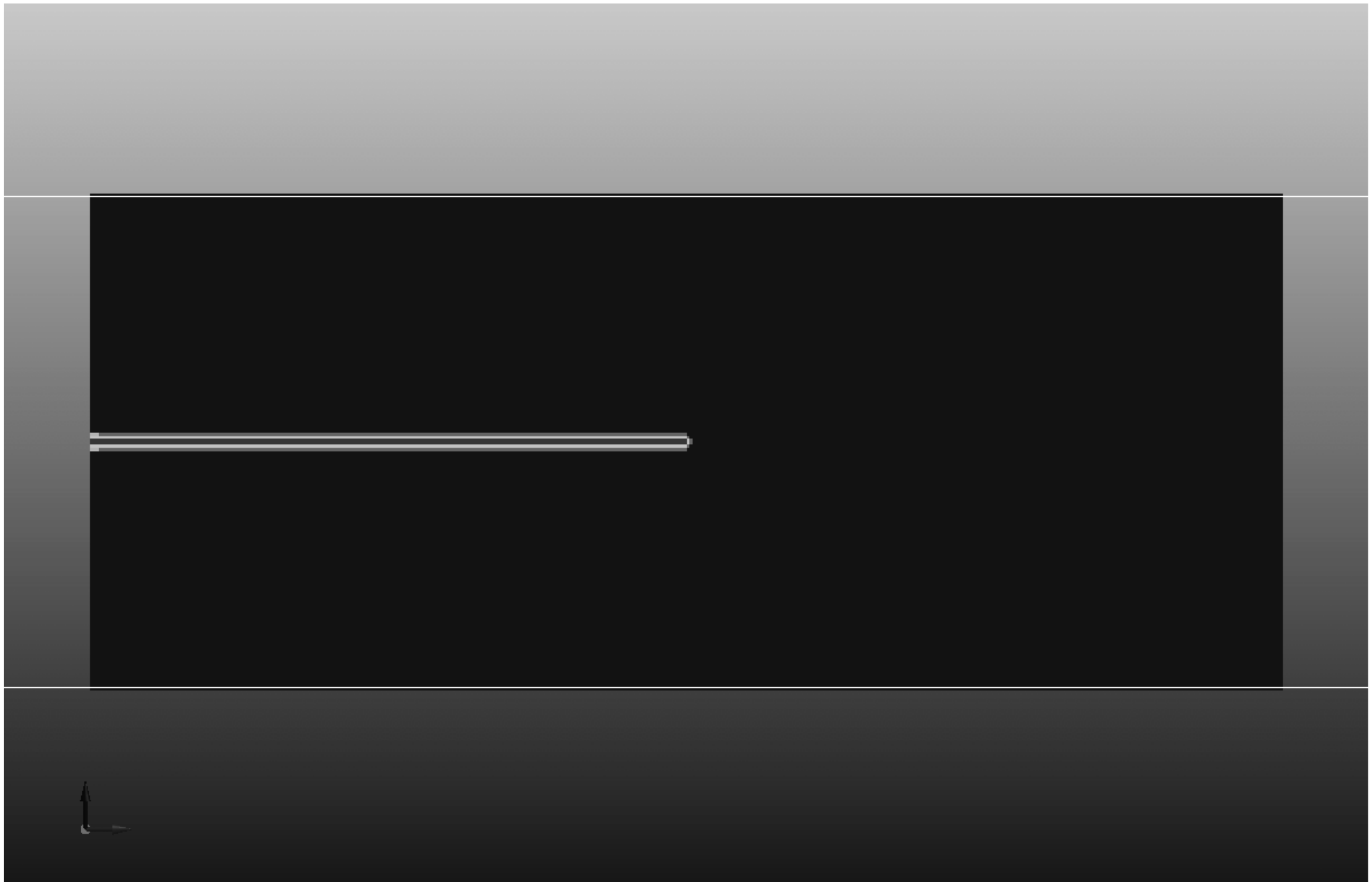
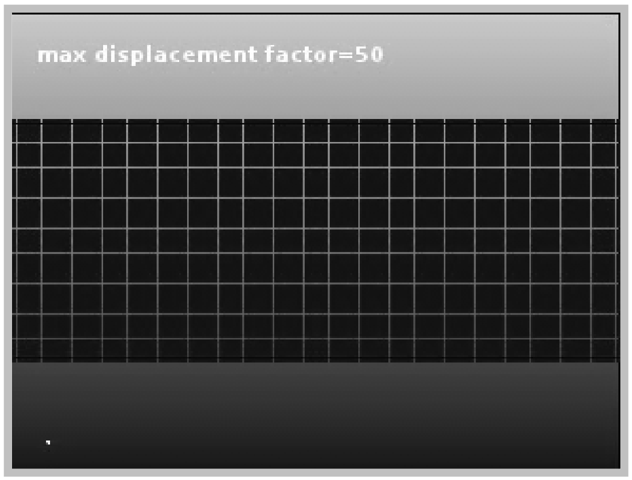
BDFORM=2

Sphere Size: R=0.125mm



BDFORM=2

Crack Propagation



R=0. 5mm

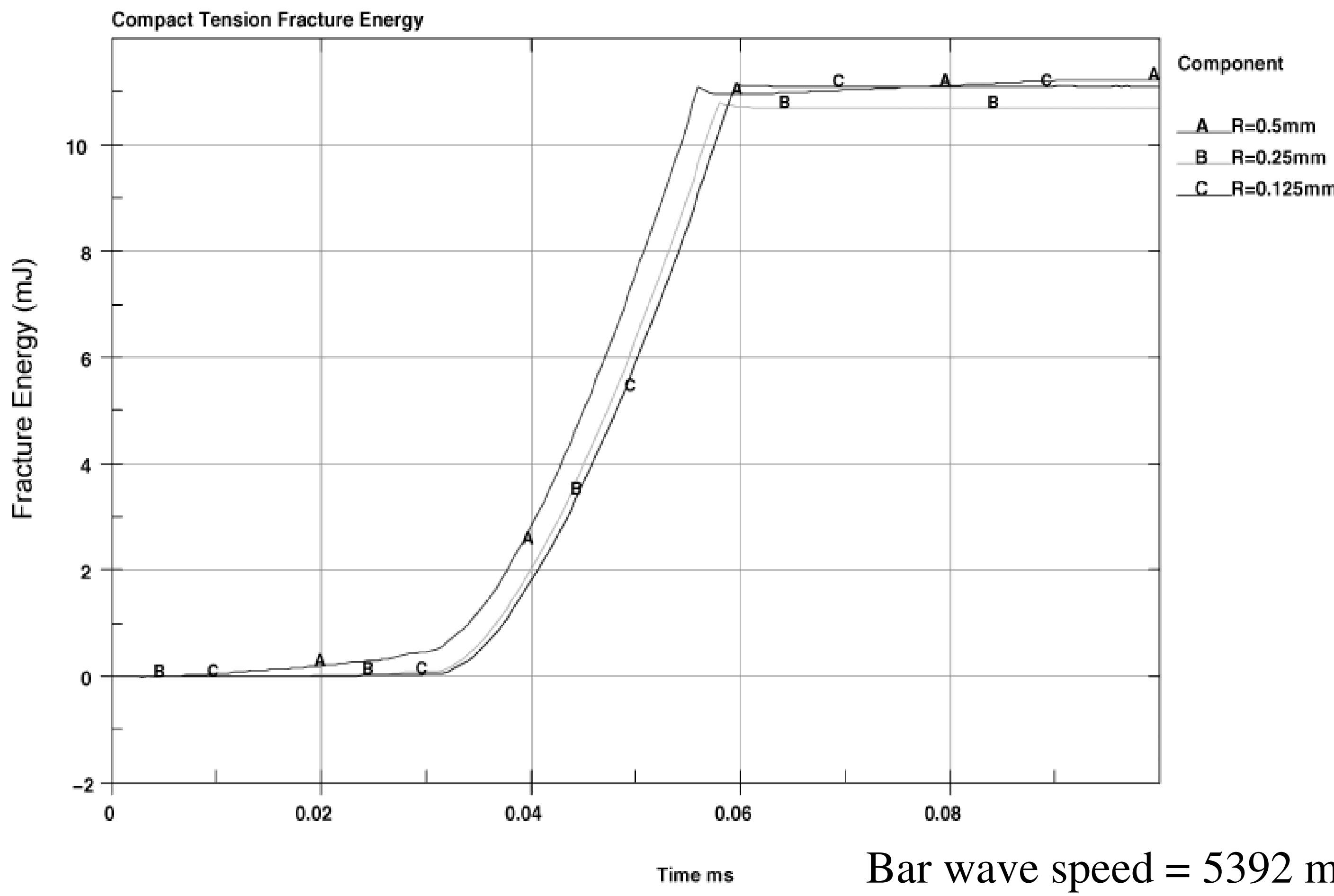
R=0.25mm

R=0.125mm

Draft

BDFORM=2

Released Fracture Energy



Bar wave speed = 5392 m/s

BDFORM=2

Fragmentation R=0.25mm

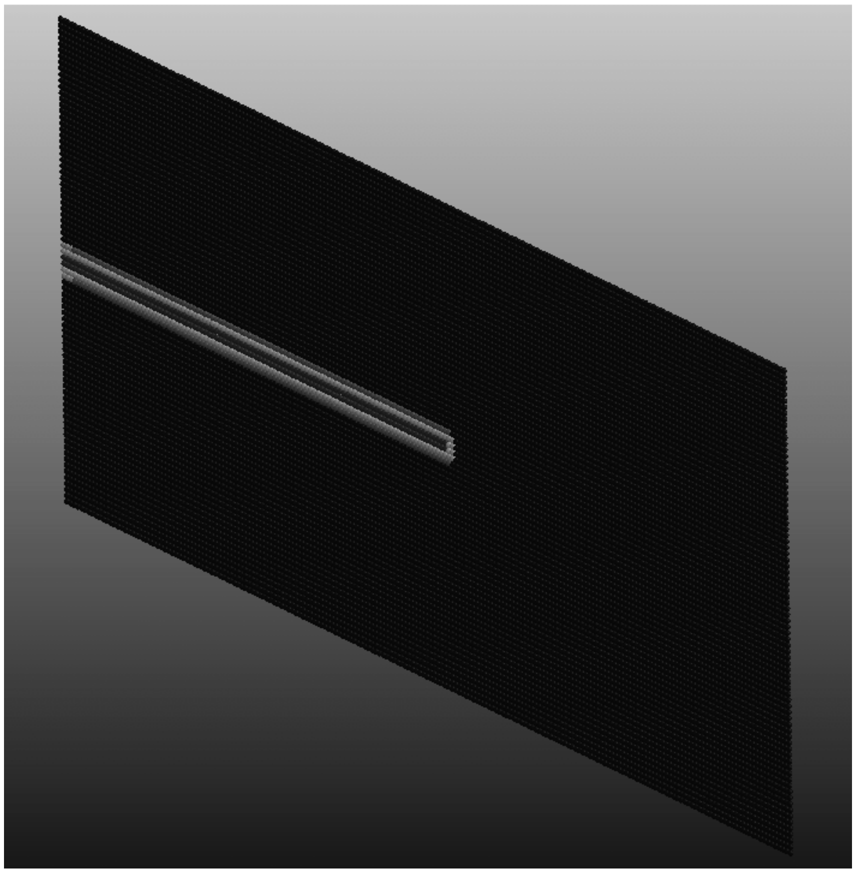
Crack Propagation Path

Energy Density

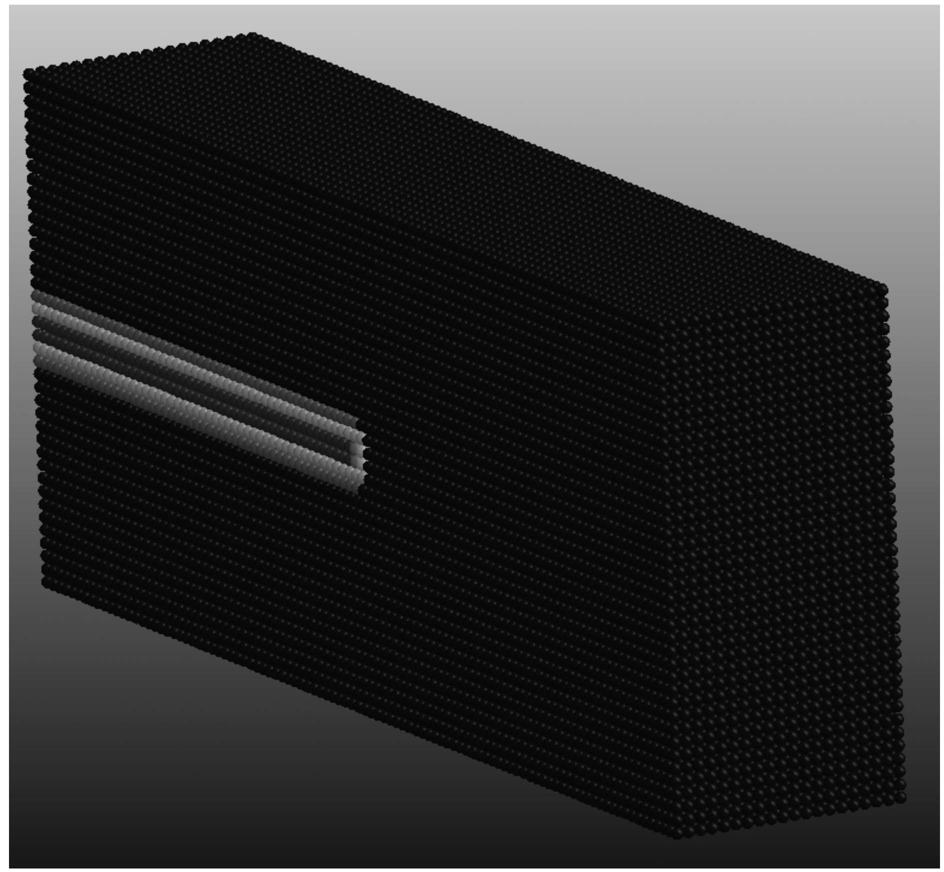
Draft

BDFORM=2

2D & 3D Models - with Same Material Properties



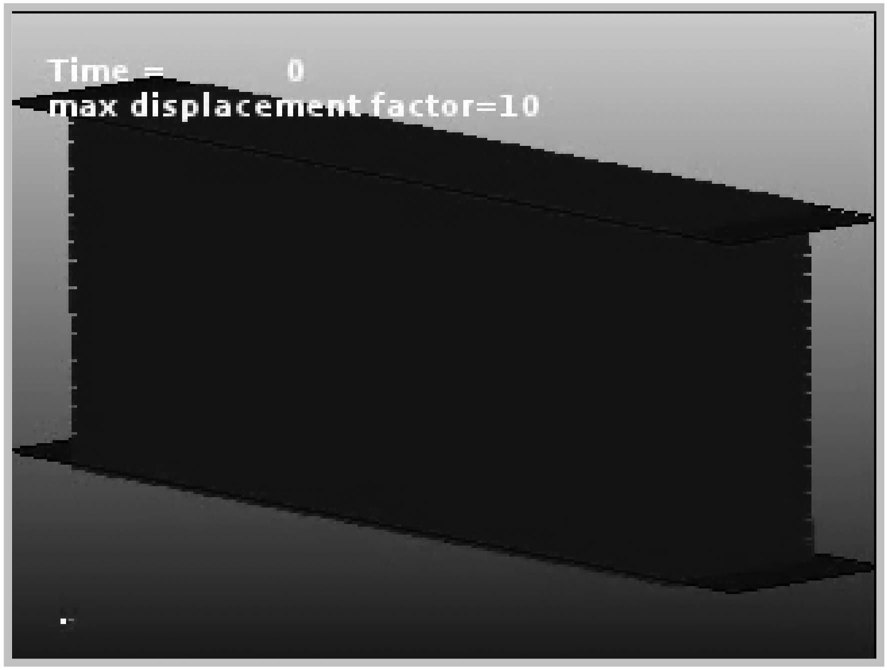
Single Layer of Spheres



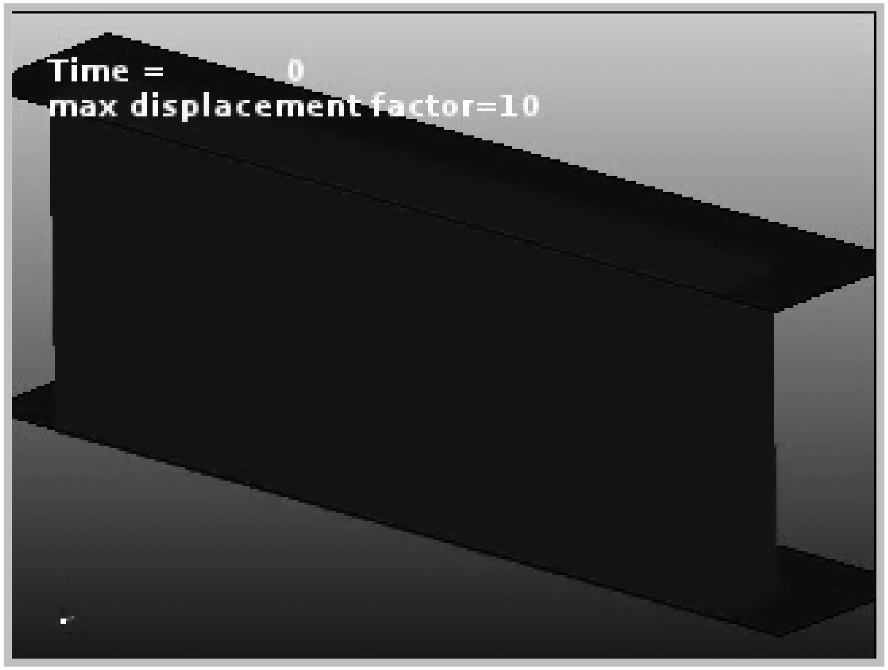
Multiple Layers of Spheres

Draft

BDFORM=2
Crack Propagation



R=0. 5mm



R=0.25mm

BDFORM=2

3D Fragmentation - R=0.25mm

Front View

Middle Plane (Section)

Features Under Development

- The Bond Models are still under development but both formulations have successfully been applied in customers models.
- For the BDFORM=2 formulation work is done on:
  - Supporting Equation of State (EOS).
  - Non-linear material model. This is already in beta testing.
- For both formulations MPP implementation is currently under development and being beta tested.

Chapter 8

Interaction Between DEM Particles and Structure

Draft

Introduction

- The DEM particles can get in contact with a structural part, e.g. particles on a conveyor belt.

- There are two ways to specify this interaction:
  - Using any of the “one way” contacts, which are the contacts with _NODES_ in their names. E.g. one can use the *CONTACT_AUTOMATIC_NODES_TO_SURFACE contact, where the slave side is the DEM particles. Notice that the SURFACE_TO_SURFACE contacts can not be used, since no segments can be generated based on the particles. Thus, SOFT=2 can’t be applied either. The use of a regular contact is similar to the approach often used for SPH particles in contact with a structure.

  - Applying the new DEM specific keyword: *DEFINE_DE_TO_SURFACE_COUPLING. Here damping and friction can be given, together with velocity curves for the particles in contact. The keyword was introduced to handle certain shortcomings of the regular contact and it is recommended to use this option over the use of e.g. the *CONTACT_AUTOMATIC_NODES_TO_SURFACE contact.

Draft

Using Standard Contact Specification

- If a standard contact is used, then the _NODES_TO_SURFACE option is to be used.

```
*CONTACT_AUTOMATIC_NODES_TO_SURFACE
$#    ssid      msid     sstyp     mstyp    sboxid    mboxid       spr       mpr
         2         1         4         3         0         0         0         0
$#      fs        fd        dc        vc       vdc    penchk        bt        dt
     0.000     0.000     0.000     0.000     0.000         0     0.000     0.000
$#     sfs       sfm       sst       mst      sfst      sfmt       fsf       vsf
     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
```

- In the shown contact, the slave side (SSID) is given by node set number 2 (SSTYP=4). This is a set of DEM particles. The master side (MSID) is given by part number 1 since MSTYP is set to 3. No friction nor other options are used.

- The friction could be set with FS and FD as can contact damping be applied using the VDC flag. Scaling of the contact stiffness can also be done (SFS, SFM). However, the radius of the particles can't be changes with SST nor SFST.

- The forces on the master side can be found using the *rcforc* file, specified by applying the *DATABASE_RCFORC keyword.

Draft

Using DEM Coupling Card

*DEFINE_DE_TO_SURFACE_COUPLING

Card 1	1	2	3	4	5	6	7	8
Variable	SLAVE	MASTER	STYPE	MTYPE				
Type	I	I	I	I				
Default	0	0	0	0				

Card 2	1	2	3	4	5	6	7	8
Variable	FricS	FricD	DAMP	BSORT	LCVx	LCVy	LCVz	
Type	F	F	F	I	I	I	I	
Default	0	0	0	100	0	0	0	

- The variables are described on the next slides.

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Using DEM Coupling Card

*DEFINE_DE_TO_SURFACE_COUPLING

SLAVE:

Node ID or node set ID depending on the setting of STYPE. This is for the slave side and must be the DEM particles.

MASTER:

Part ID or part set ID depending on the setting of MTYPE. This must be the structure and specifies the master side of the coupling.

STYPE:
EQ.0: Specify a *SET_NODE ID for SLAVE.
EQ.1: Give a NODE ID (NID) for SLAVE.

MTYPE:
EQ.0: Specify a *SET_PART ID for MASTER.
EQ.1: Give a part ID for MASTER.

FricS:
Translational friction coefficient.

Draft

Using DEM Coupling Card

*DEFINE_DE_TO_SURFACE_COUPLING

FricD:
Rolling friction coefficient.

DAMP:

Damping coefficient.

BSORT:

Number of cycles between bucket sorting. Default is 100 cycles. This is equivalent to the BSORT specified for contacts using *CONTACT_.

LCVx:
Loadcurve ID (LCID) gives the surface velocity in X-direction ($V_x(t)$).

LCVy :
Loadcurve ID (LCID) gives the surface velocity in Y-direction ($V_y(t)$).

LCVz :
Loadcurve ID (LCID) gives the surface velocity in Z-direction ($V_z(t)$).

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Using DEM Coupling Card

- The *DEFINE_DE_TO_SURFACE_COUPLING card has entity specification similar to the ones for regular contacts as seen on the previous slides.

```
*DEFINE_DE_TO_SURFACE_COUPLING
$#   slave    master     stype     mtype
         4         3         0         1
$#   fricS     FricD      damp     bsort      lcvx      lcvy      lcvz
```

- In the shown coupling cards, the slave side (SLAVE) is given by node set number 4 (STYPE=0). This is a set of DEM particles. The master side (MASTER) is given by part number 3 since MTYPE is set to 1. No friction nor other options are used.

- The friction could be set with FricS and FricD as can contact damping be applied using the DAMP flag.

- The coupling takes into account the radius of the particle and adds half the shell thickness on each side of the master segments as contact thickness. This is similar to the _AUTOMATIC_ standard contacts.

- The forces on the master side can be found using the *demrcf* file, specified by applying the *DATABASE_RCFORC keyword. This is described in more details in Chapter 5.

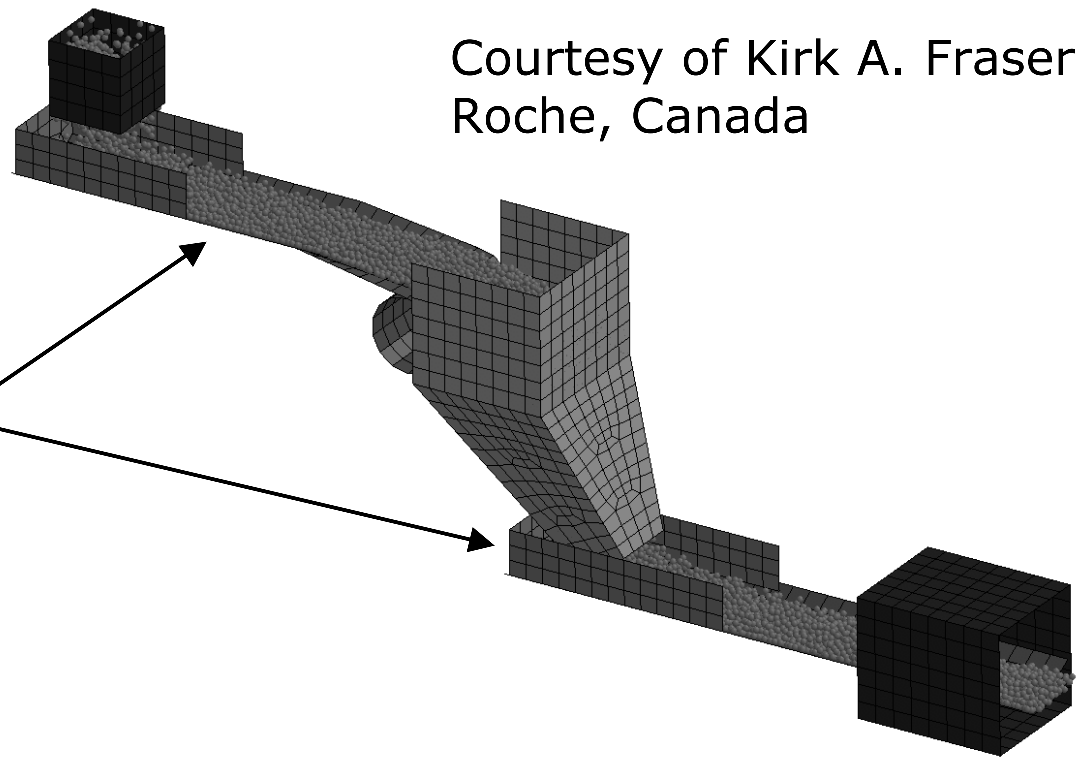
Using DEM Coupling Card

*DEFINE_DE_TO_SURFACE_COUPLING - LCVi

- The LCVx, LCVy and LCVz is used to apply a prescribed velocity to the DEM particles that would represent the velocity of the master side of the coupling. This means that in e.g. a conveyor simulation, the belt doesn't need to have a prescribed motion but the belt velocity can be given using one of the three load curves the coupling part. That is a significant simplification when building the model.

Courtesy of Kirk A. Fraser
Roche, Canada

These two conveyor belts needs to be given a velocity in order to transport the particles. To simplify the modeling, the LCVx is used. One for each of the belts, see next slides.



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Using DEM Coupling Card

*DEFINE_DE_TO_SURFACE_COUPLING - LCVi

- In the deck the belts are parts # 3 and # 5 that are coupled to the particles (node set # 38) using *DEFINE_DE_TO_SURFACE_COUPLING. The node set is generated at the *DEFINE_DE_INJECTION card.

Particles

Belts

Curves gives constant V_x

Generating particles, can be used as node set # 38

```
*DEFINE_DE_TO_SURFACE_COUPLING
$    SLAVE    MASTER     STYPE     MTYPE
        38         3         0         1
$    FRICS     FRICD      DAMP     BSORT      LCVx      LVCy      LCVz
       0.3       0.3       0.9                  26
*DEFINE_DE_TO_SURFACE_COUPLING
$    SLAVE    MASTER     STYPE     MTYPE
        38         5         0         1
$    FRICS     FRICD      DAMP     BSORT      LCVx      LVCy      LCVz
       0.3       0.3       0.9                  27
*DEFINE_CURVE
$ lcid, sidr, sfa, sfo, offa, offo, dattyp
26,
0.0, 4.0
100.0, 4.0
*DEFINE_CURVE
$ lcid, sidr, sfa, sfo, offa, offo, dattyp
27,
0.0, 4.0
100.0, 4.0
*DEFINE_DE_INJECTION
$      PID       SID        XC        YC        ZC        XL        YL       CID
        22        38      0.00      0.00      0.50       .48       .48         0
$    RMASS      RMIN      RMAX        VX        VY        VZ      TBEG      TEND
   277.800      0.02                                    -6.7
```

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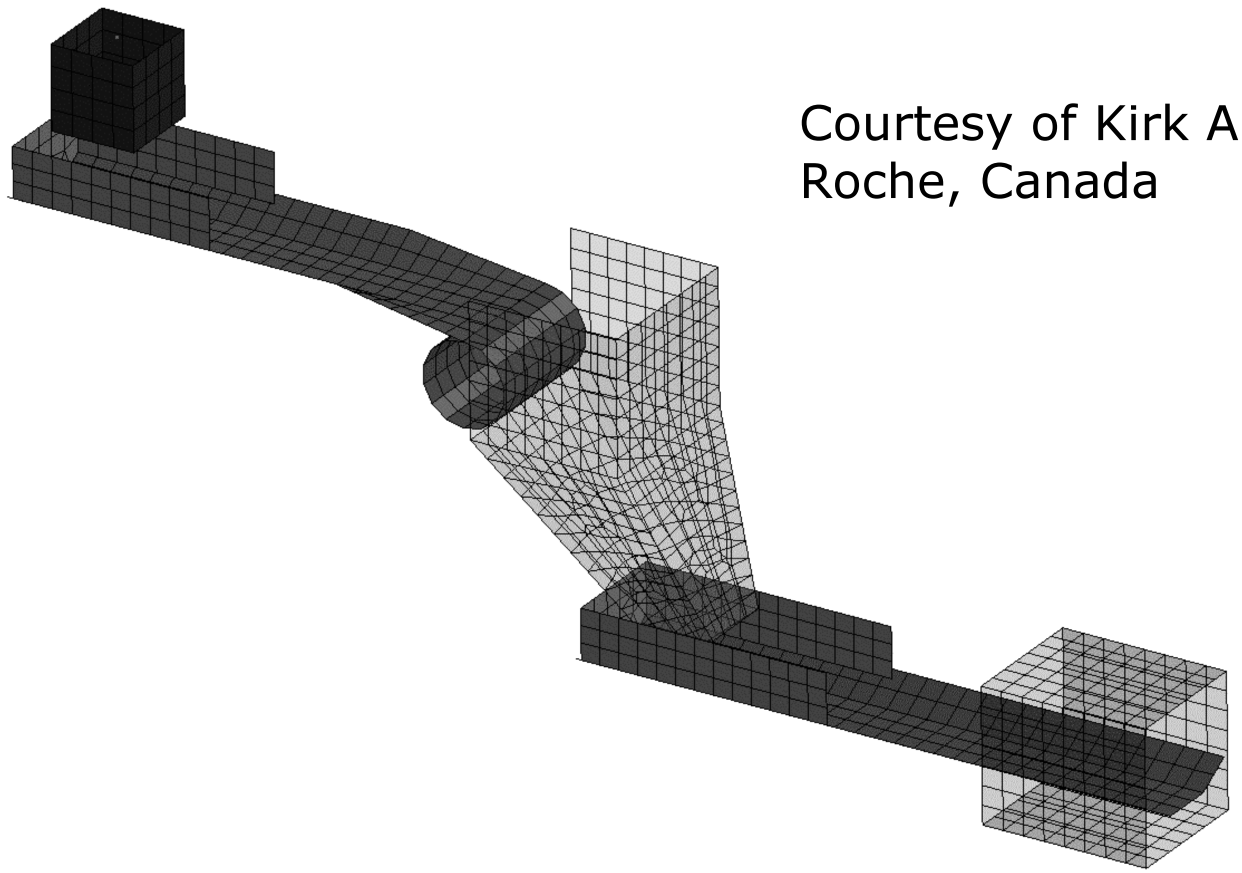
Using DEM Coupling Card

*DEFINE_DE_TO_SURFACE_COUPLING - LCVi

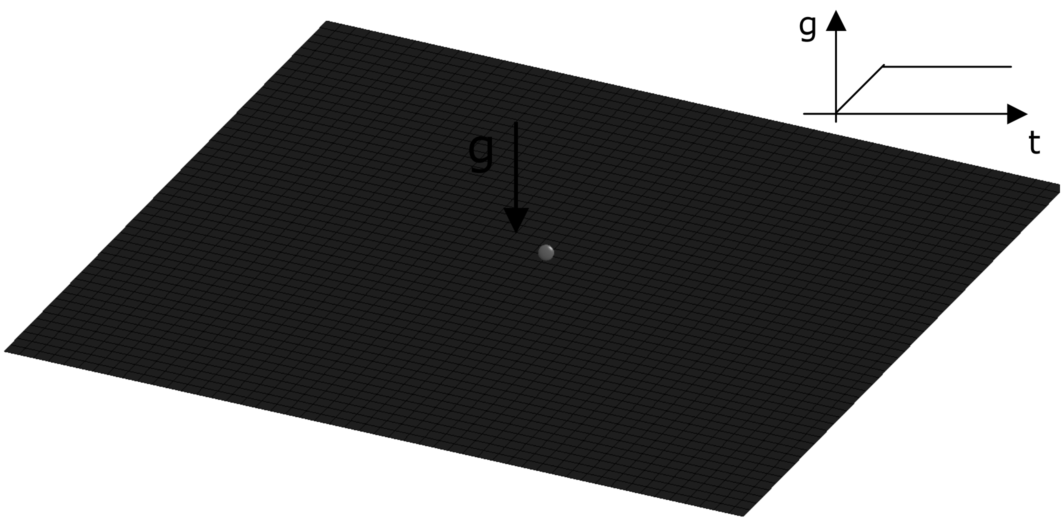


Courtesy of Kirk A. Fraser
Roche, Canada

Example of Interaction

- As an example consider one particle placed on a plate made of shells. The plate is fully constrained around the boundary. A gravity load is applied to the ball and the force in the interface can be calculated and compared to the force in the interface force files.

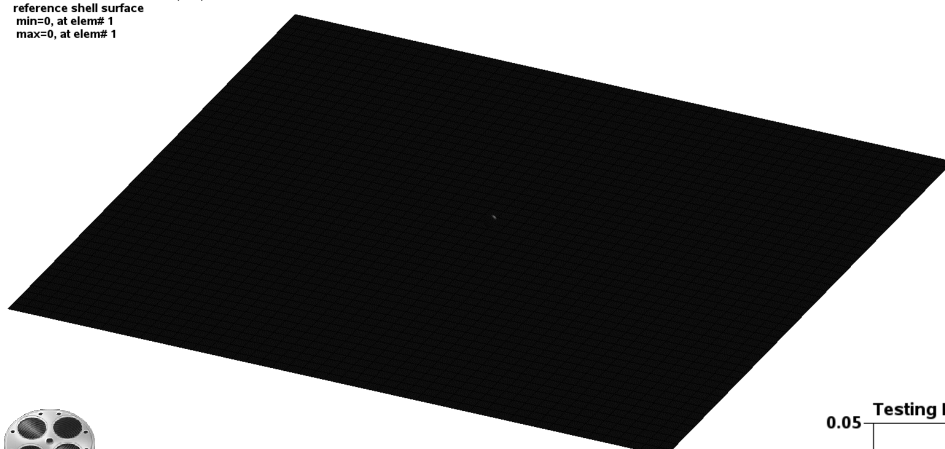
- The force is slowly applied and the maximum value is reached with the first 20% of the simulation time.



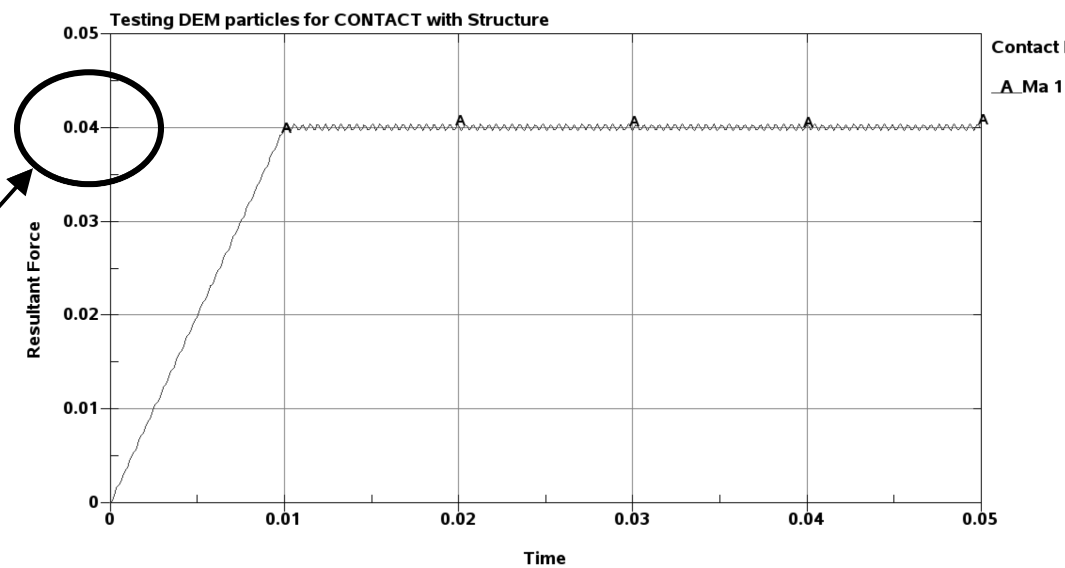
The density of the particle is set to 7.8e-6ton/mm^3 which is rather heavy. The radius is specified to be 0.5mm. The volume is given by :
V=4/3 * ¶ * r^3
which gives a volume of 0.523mm^3 and a mass of 4.084e-6ton. Since the force in the interface is F=M * A one gets that the force is
F=(4.084e-6 * 9820)N = <u>0.04N</u>

Example of Interaction

- One approach for this set-up is to use *CONTACT_AUTOMATIC_NODES_TO_SURFACE where the DEM particles are the slave side.

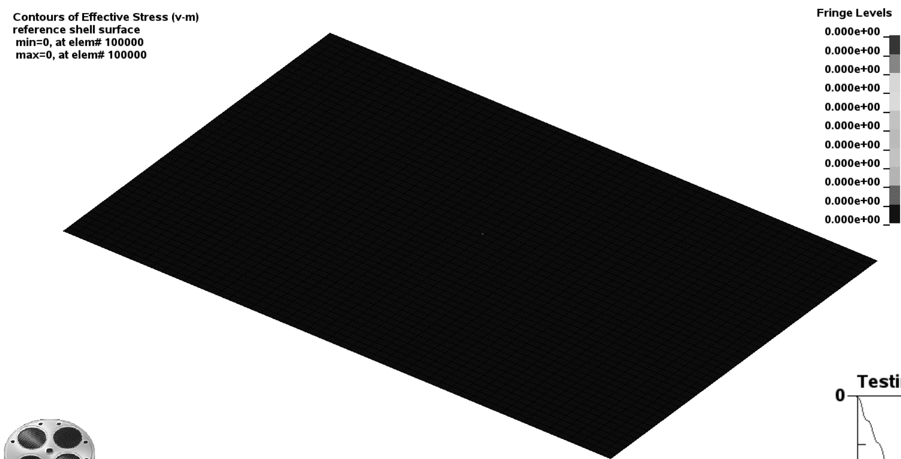


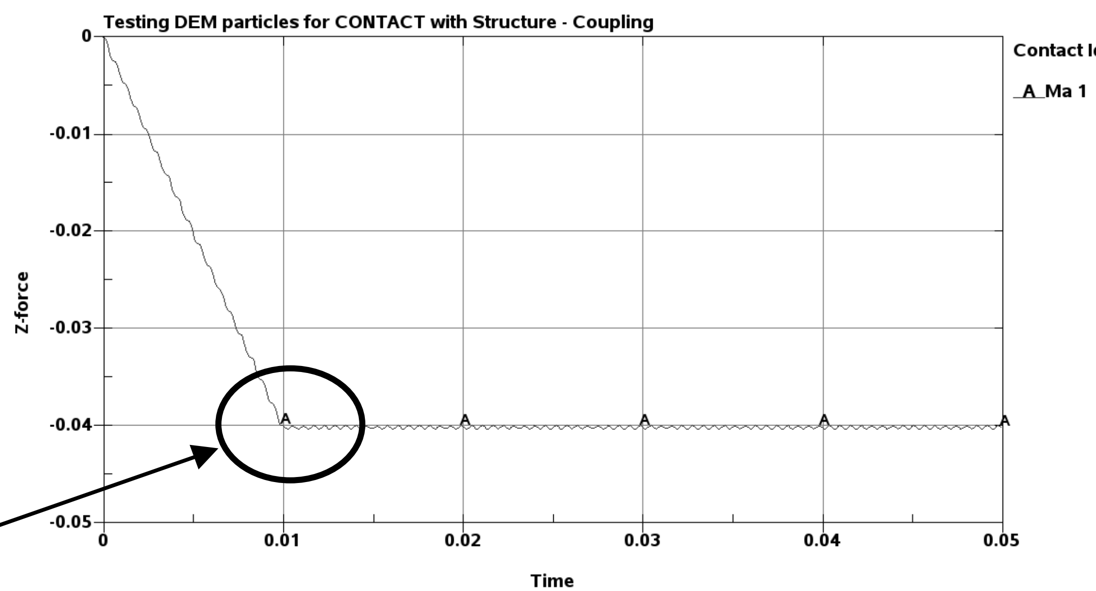
- The force should be 0.04N so very good results are obtained for this small example when the contact approach is used. The is from the *rcforc* file.



Example of Interaction

- An other approach for this set-up is to use *DEFINE_DE_TO_SURFACE_COUPLING where the DEM particles are the slave side.

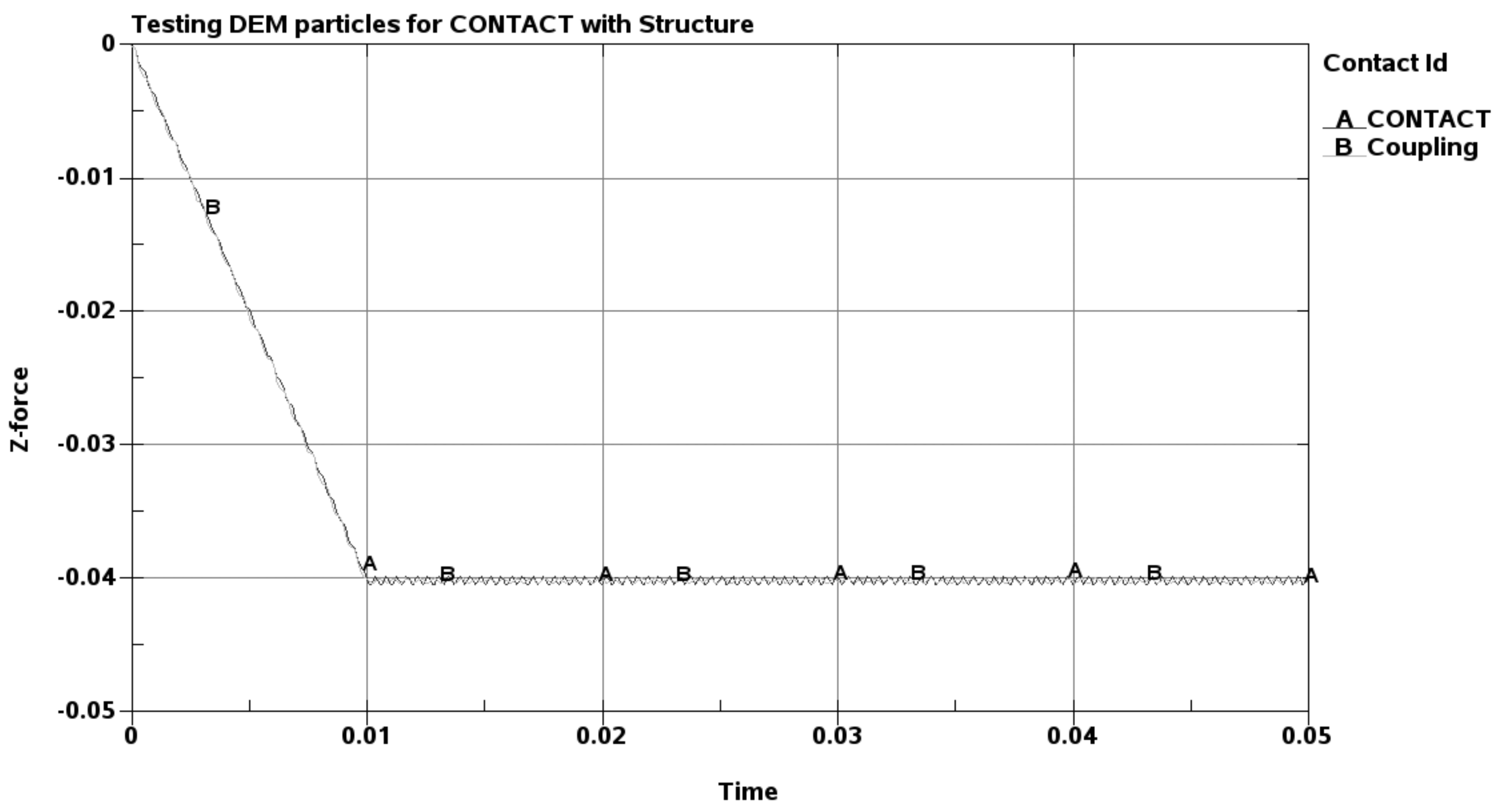




- The force should be 0.04N so very good results are obtained for this small example when the contact approach is used. The is from the *demrcf* file.

Example of Interaction

- One can compare the force from the *rcforc* file and the one obtained in the *demrcf* file. They should be very similar for these two approaches.



- VERY good agreement!!

Chapter 9

Coupling to New Blast Particle Method

Draft

Coupling to new Particle Blast Method

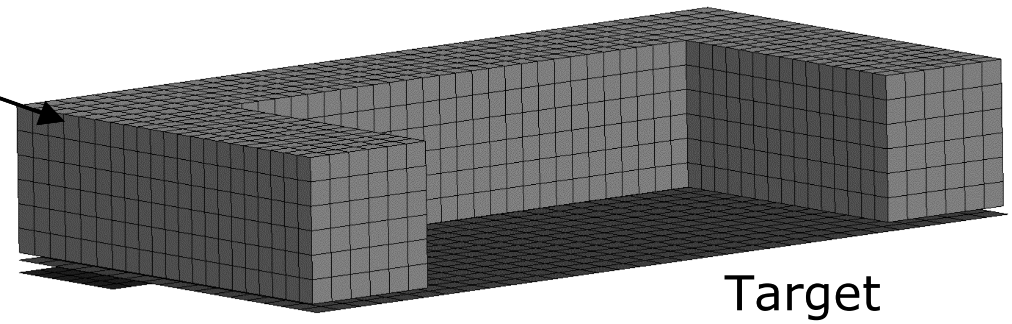
- The card to be used is *PARTICLE_BLAST. This option is under development and not released to the public yet. It is expected it should be ready within the next 6-12 months depending on the beta testing results.

- Currently the option is only implemented in SMP, not in MPP. However, this will hopefully be done by the end of the year.

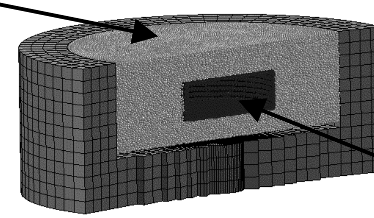
- The method can be coupled with particles modeling sand and be used for simulations of buried land mines. This is very important since this type of simulation has been difficult to model correctly using *LOAD_BLAST since that is for developed for air blasts. And the ALE method is very CPU intensive to use and requires a good understanding of the ALE modeling technique.

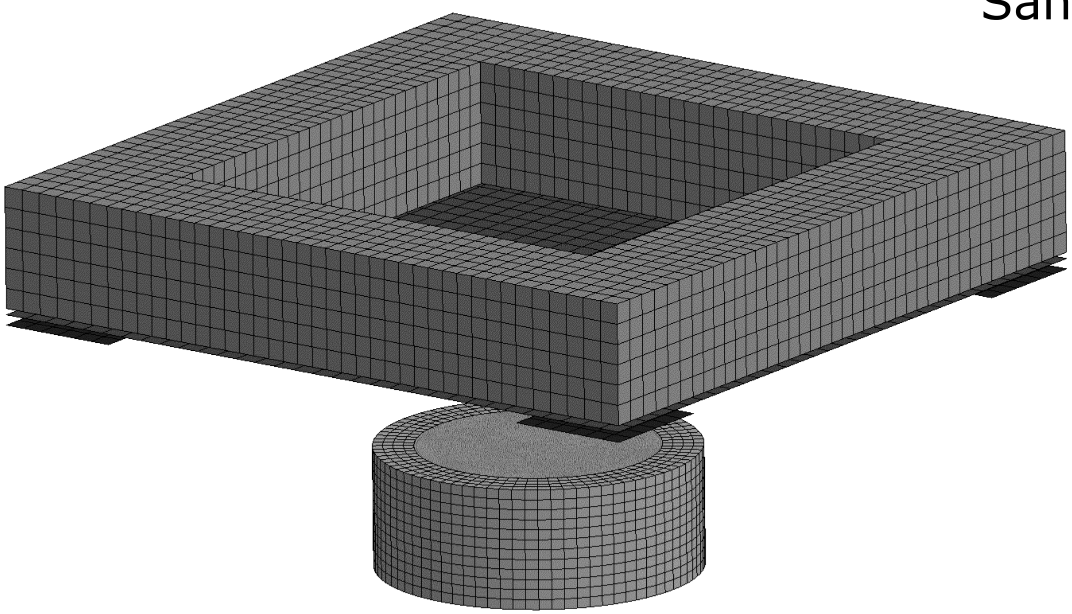
Example

Buried Land Mine



- An explosive is buried into sand. The explosive is modeled with *PARTICLE_BLAST and the sand is using DEM.





- Notice how the sand and explosive mix together during the impact.

Chapter 10

References

Draft

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