

Air-induced defect formation during powder compaction

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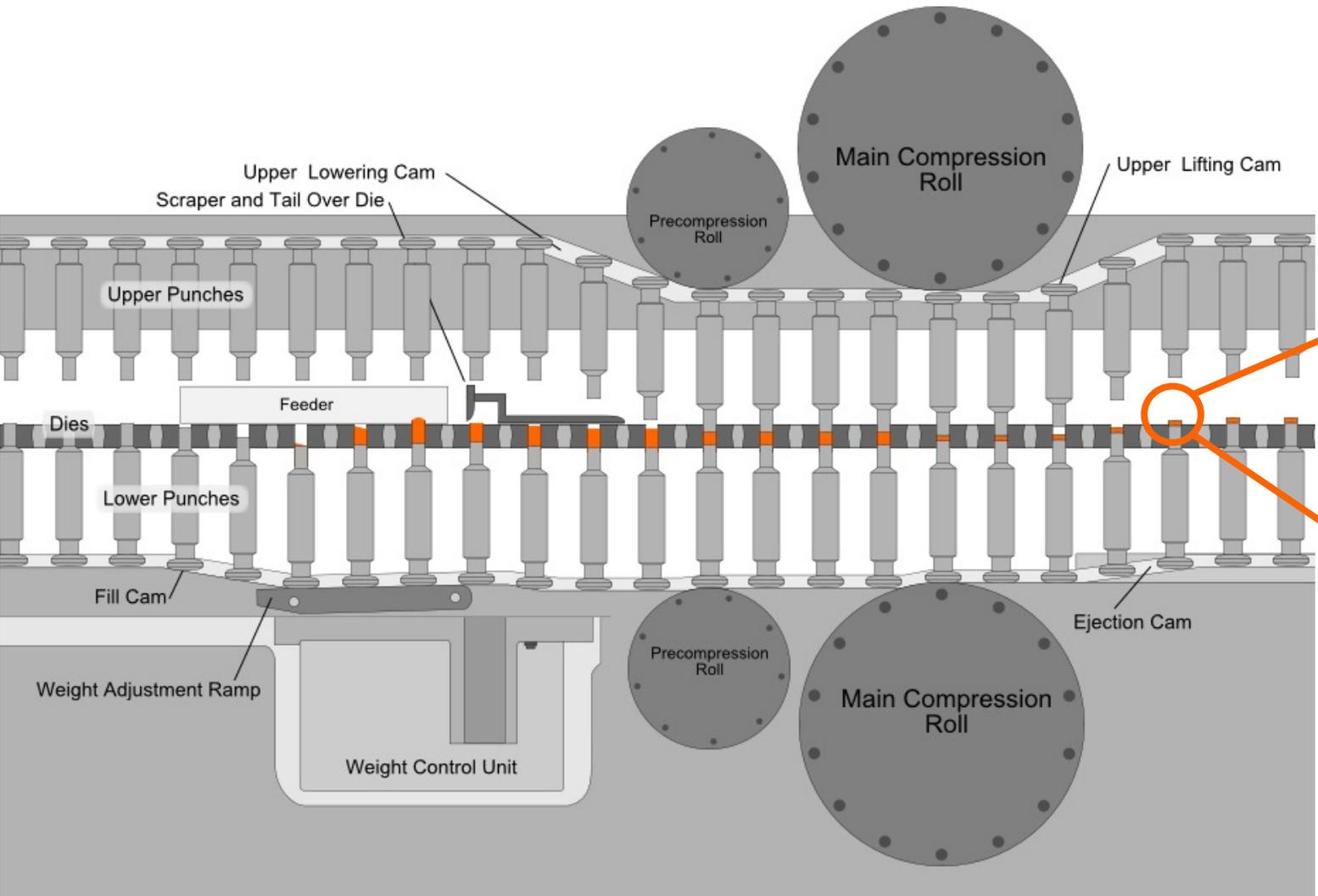
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Project Motivation

Entrapped air causes defect formation upon ejection from die



Use mechanics-based approach to predict defect formation to reduce waste material

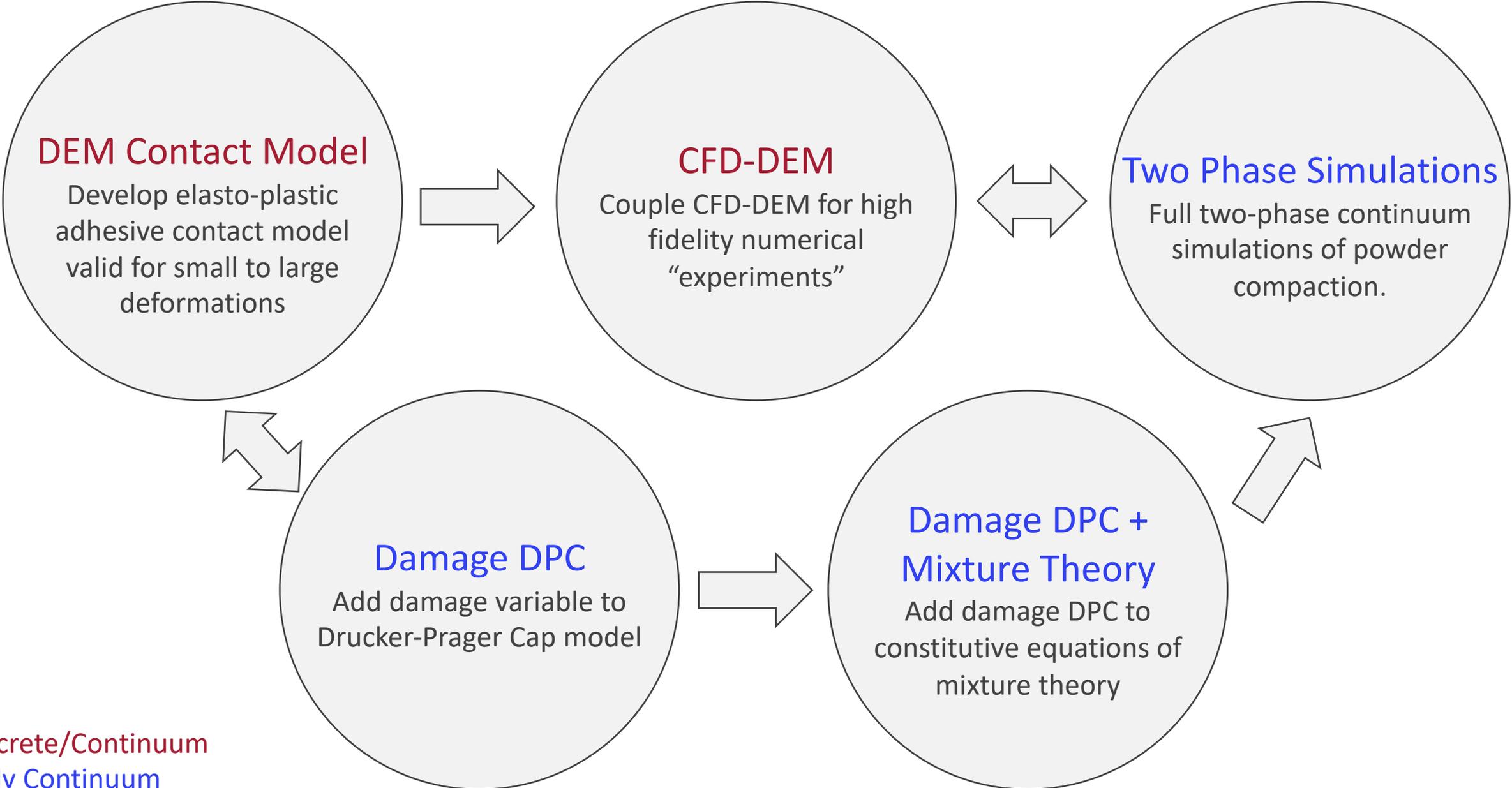


Capping/lamination



Cracking

Project Workflow



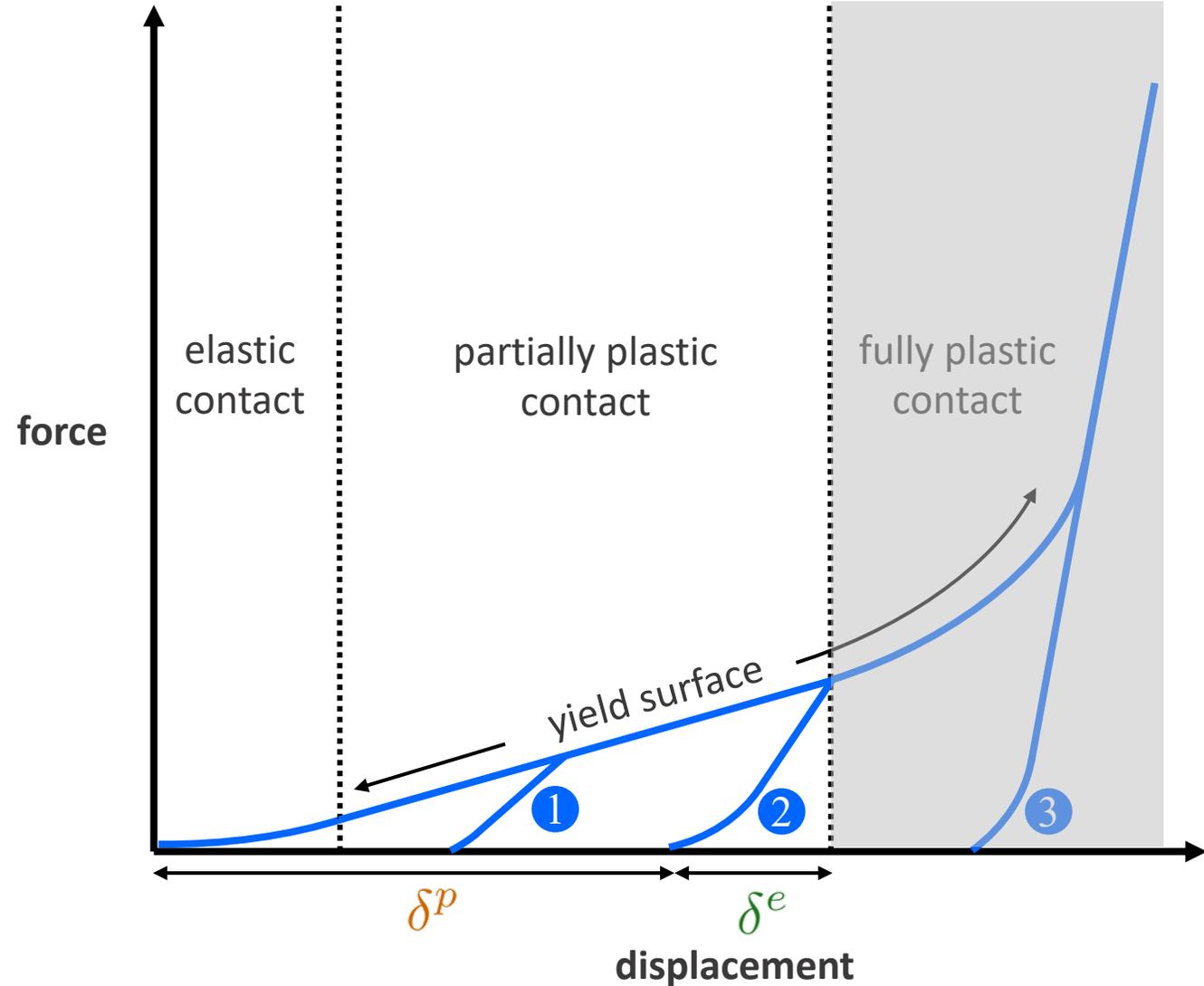
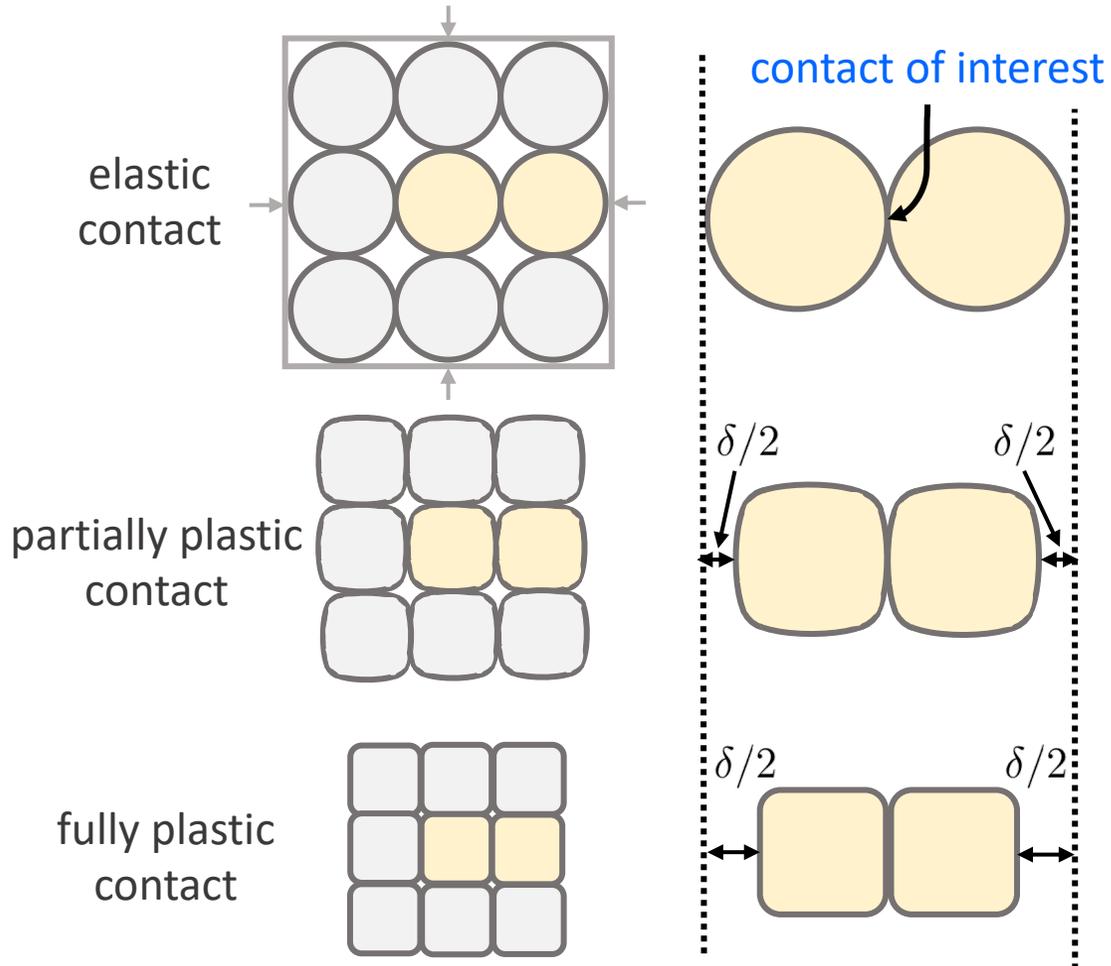
Discrete/Continuum
Fully Continuum

Contact Model: Building a Strong Foundation

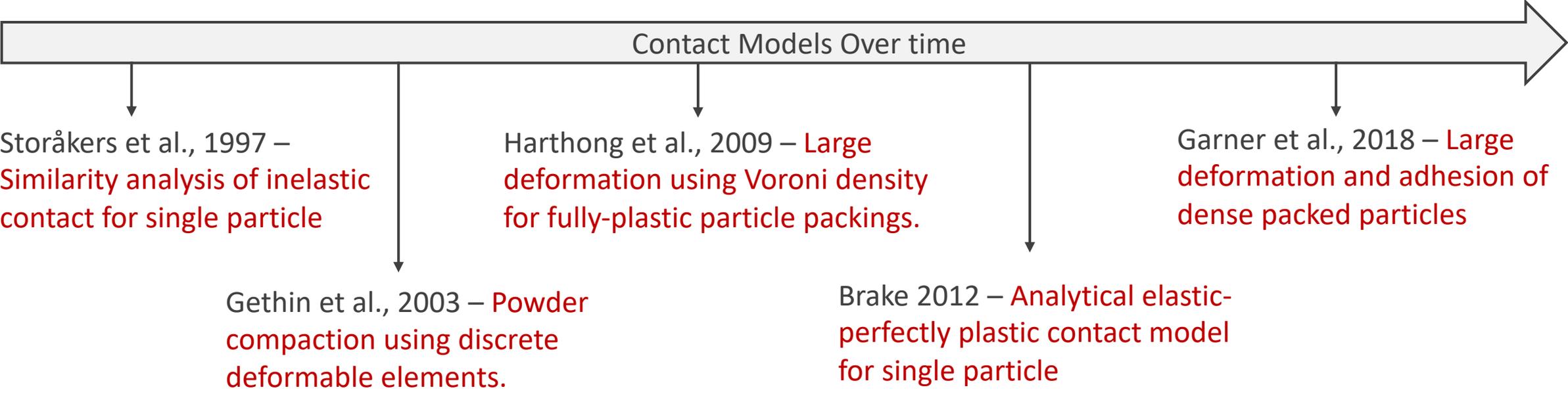
Contact model underlies all numerical “experiments” used to validate continuum models



Critical to model the complex force-displacement curve accurately



Prior Inelastic Contact Models



Continuum Models

Reduced-Continuum Models

“Classical” Contact Model

Full field solutions

- Stresses/Total force
- Strains
- Displacements

High resolution at high computational cost

Partial field solutions

- Stresses/Total force at contact
- Surface displacements at contact

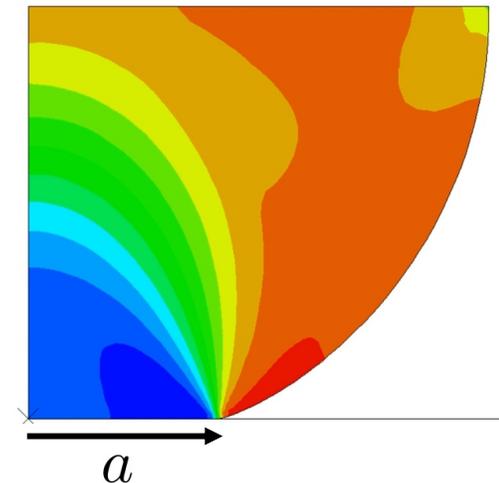
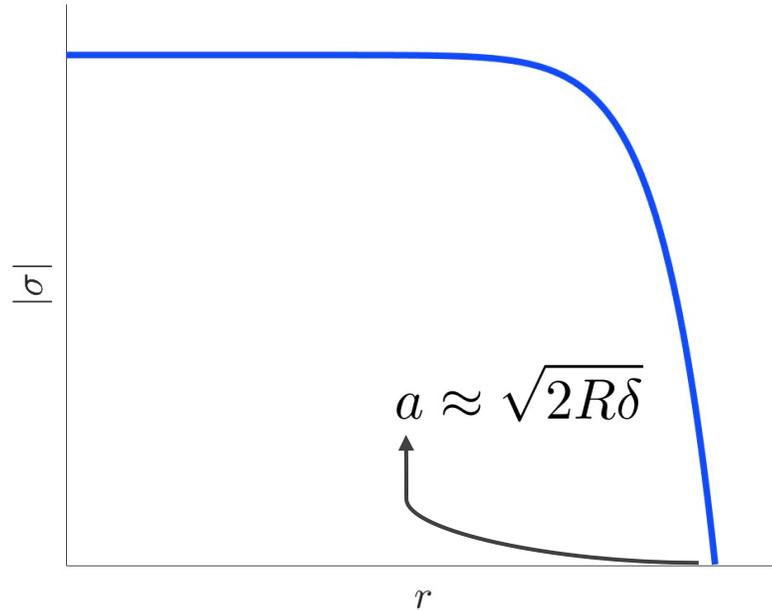
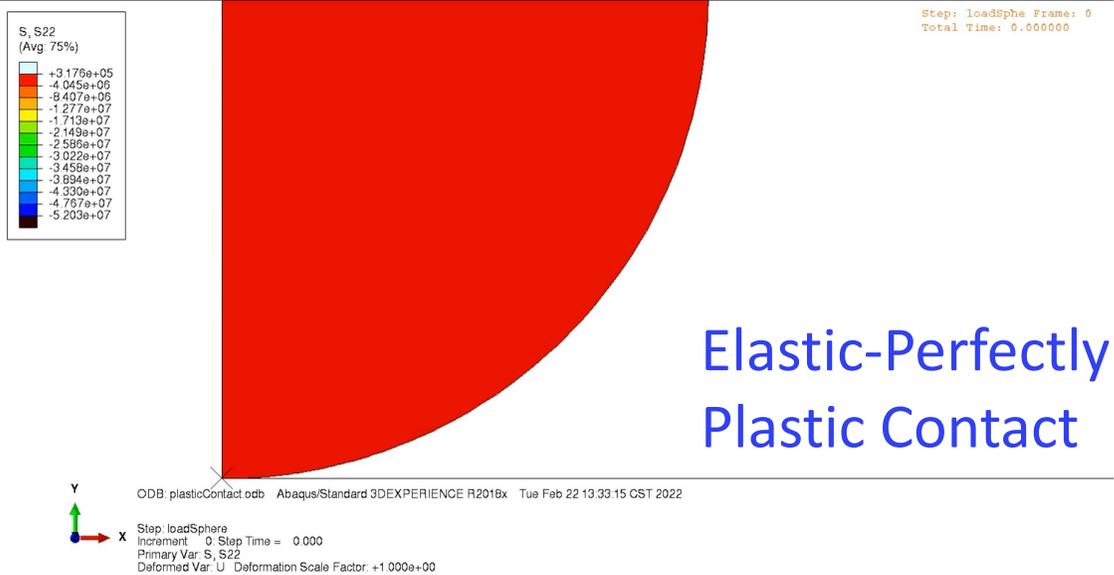
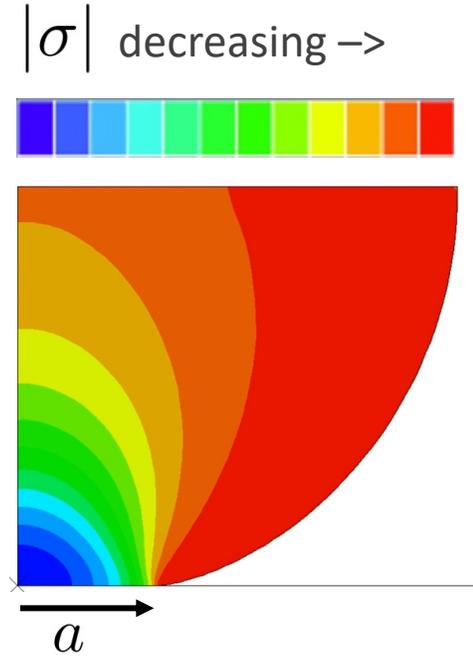
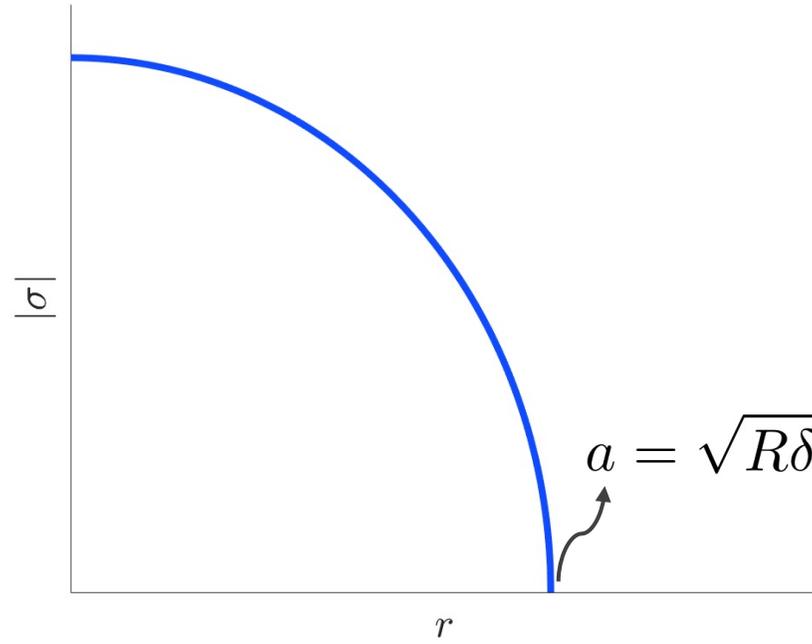
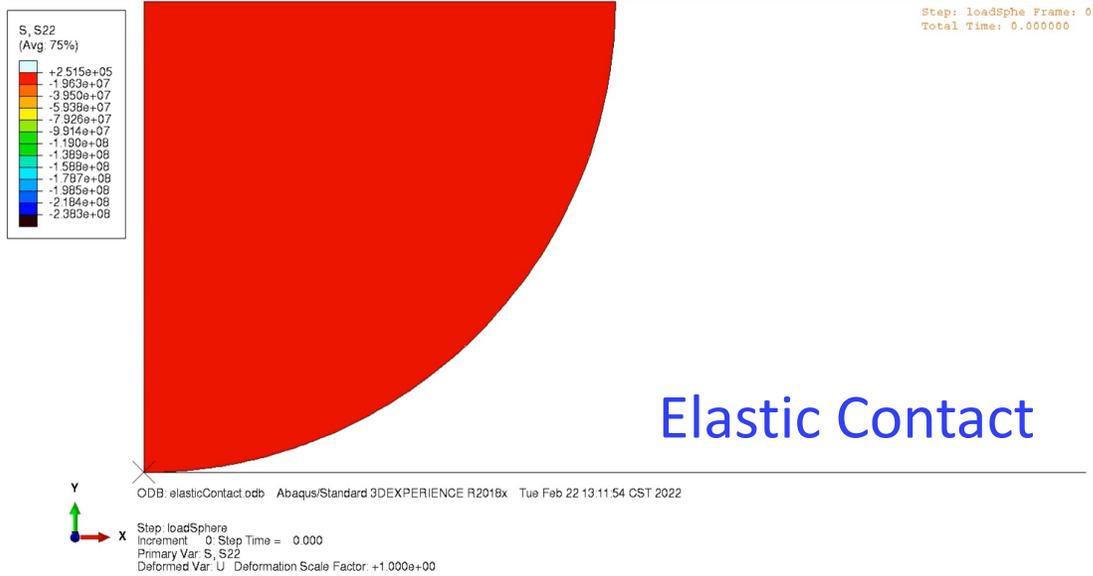
Moderate resolution at moderate/low computational cost

Single valued solutions

- Total force at contact
- Displacements at point of first contact

Low resolution and limited robustness at low computational cost

Finite Element Contact Simulations



Demands of Model

Force-Displacement ✓

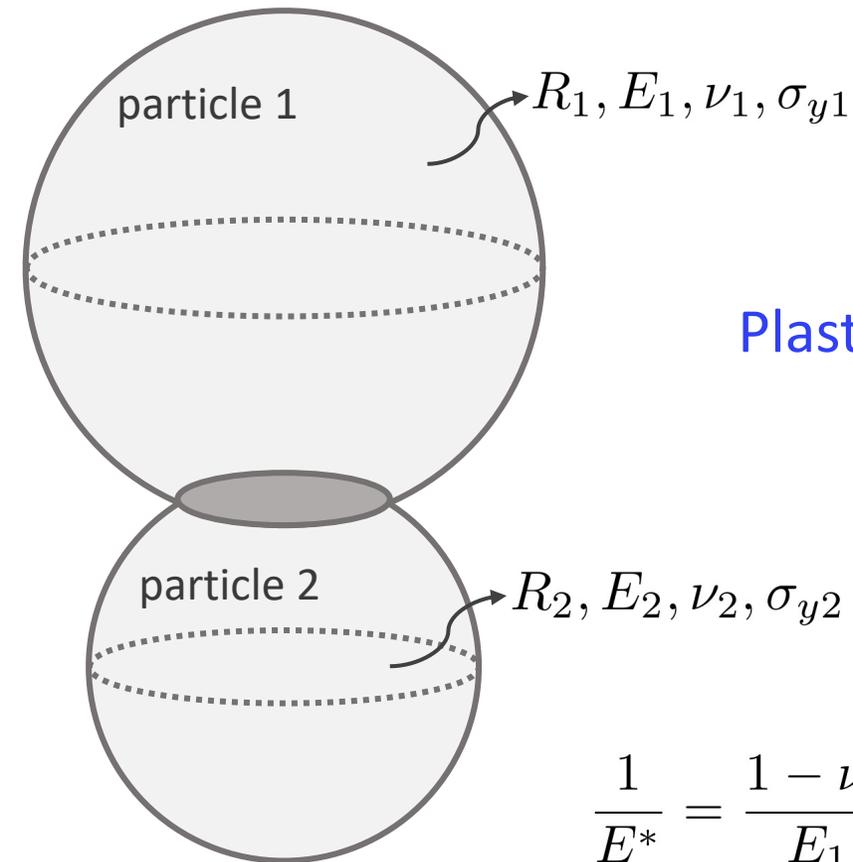
- Hertz in elastic limit
- Linear force displacement in partially plastic contact

Stress-Profile ✓

- Pointwise contact stress profile
- Hertz profile in elastic limit
- Flattened profile in partially plastic limit

Plastic Displacement ✓

- Pointwise plastic surface displacement
- Predict reasonable blunted shape upon unloading.



Hertz:

$$\sigma = \frac{2E^*}{\pi\sqrt{R}} \left(\delta - \frac{r^2}{R} \right)^{1/2}$$

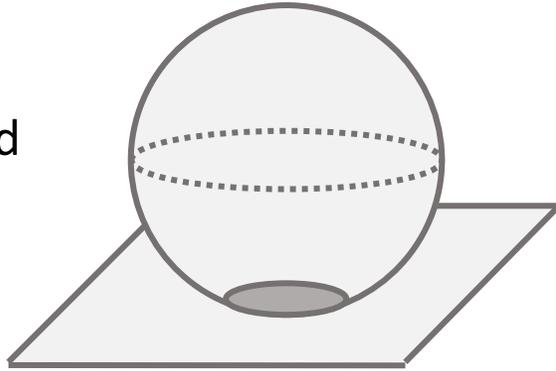
Plasticity changes curvature \Rightarrow Blunted profile is a new circular arc?

“This treatment of the unloading process is only approximate... since it tacitly assumes that the pressure distribution before unloading is Hertzian... The actual pressure distribution is flatter than that of Hertz [after plastic deformation]”. – K.L. Johnson

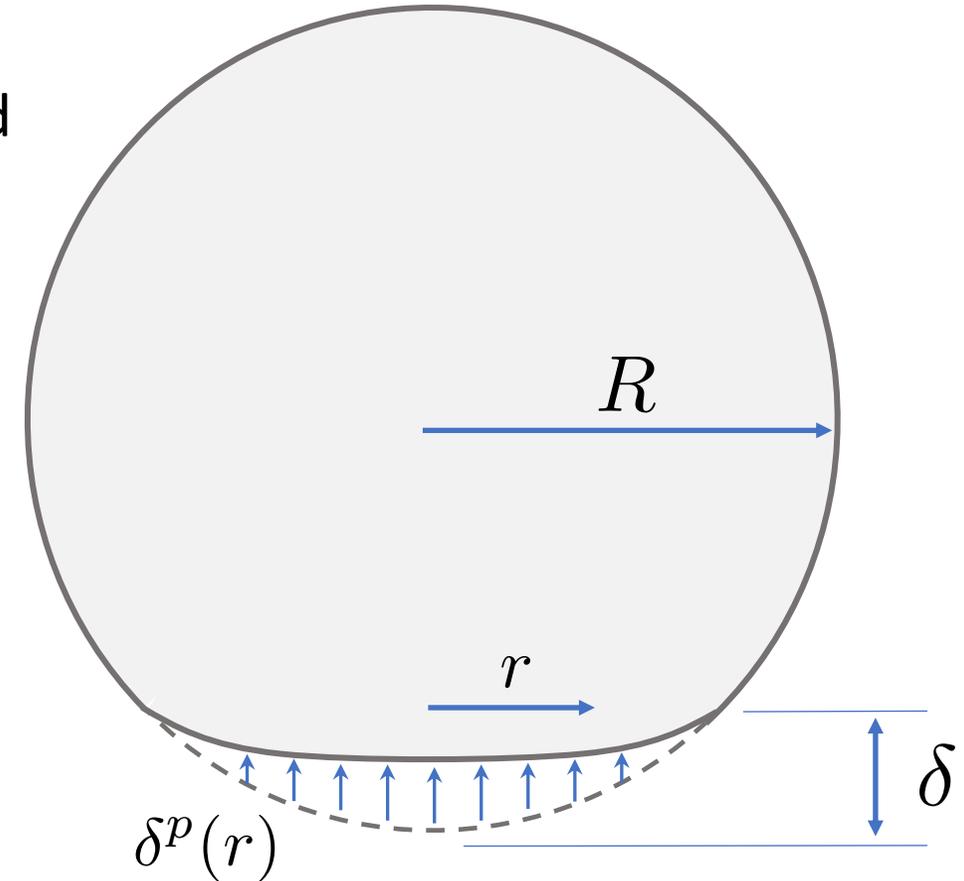
$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Merging 1D Plasticity into Hertzian Contact

Loaded
body:



Unloaded
Shape:



- Keep $\delta_0^p = \delta_0^p(r = 0)$ as a *state variable* on the contact.
- Use δ_0^p to reconstruct an estimate of $\delta^p(r)$.
- Enforce a *plasticity-modified Hertzian relation* to model the pressure distribution on the contact patch.
- Sum the pressure to obtain the force, giving

$$F = F(\delta, \delta_0^p).$$

- Enforce yield condition $\sigma(r = 0) = Y$ to update δ_0^p .

Plasticity-Modified Hertzian Relation

Classic Hertz Law:

$$\sigma = \frac{2E^*}{\pi} \sqrt{\frac{1}{R}} \left(\delta - \frac{r^2}{R} \right)^{1/2}$$

Curvature Overlap Gap function
2

Modified Hertz Law:

$$\sigma = \frac{2E^*}{\pi} \sqrt{\frac{1}{R} + \frac{d^2 \delta^p(r)}{dr^2}} \left((\delta - \delta_0^p) - \left(\frac{r^2}{R} - \frac{\delta^p(r) - \delta_0^p}{2} \right) \right)^{1/2}$$

Curvature Overlap Gap function
2

Plastic Displacement Profile

Hertz



Large Deformation

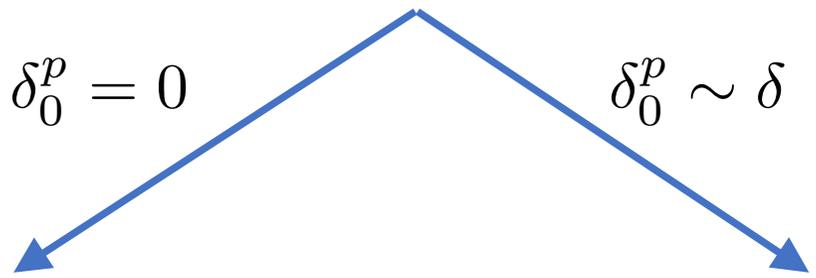
$$\sigma = \frac{2E^*}{\pi\sqrt{R}} \left(\delta - \frac{r^2}{R}\right)^{1/2}$$

Modified Hertz Law

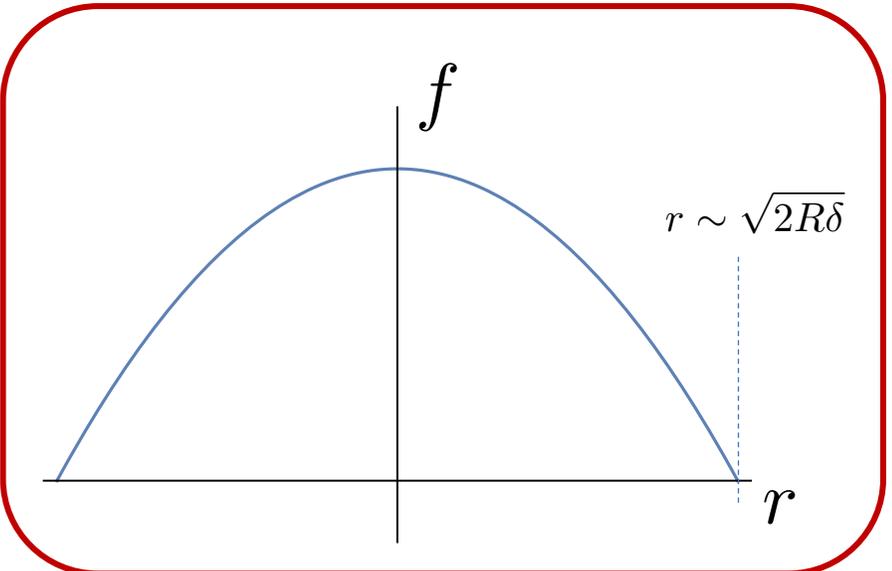
$$\sigma = \sigma_y \left(1 - \left(\frac{r}{\sqrt{2R\delta}}\right)^n\right)$$

$n \in 2, 4, 6, 8, \dots$

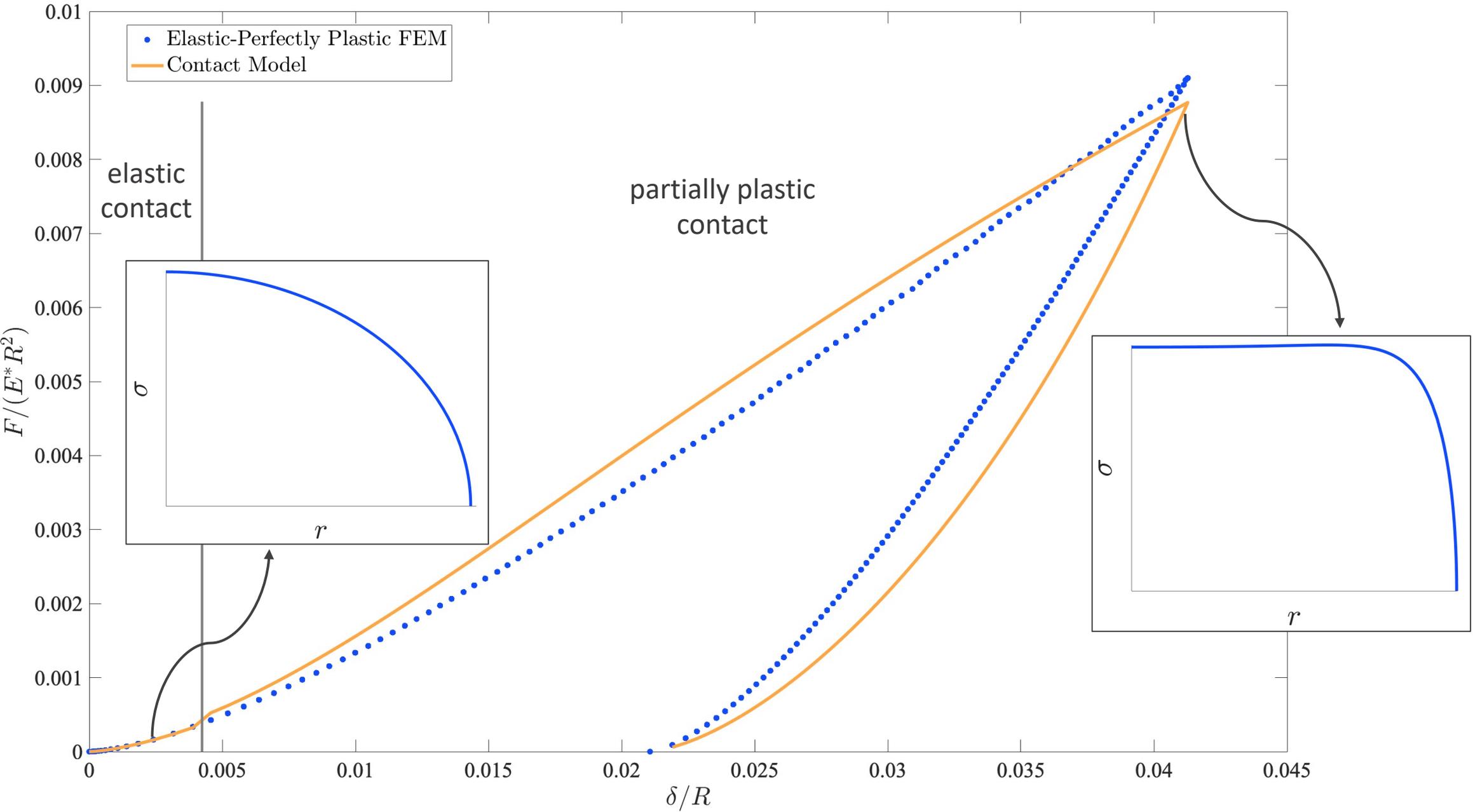
$$\delta^p(r) = \delta_0^p \times f(r, \delta_0^p)$$



$$\delta^p(r) = 0$$



Model Verification



Next Steps

Extend normal contact model to large plastic regime



Implement contact model in LIGGGHTS and run CFD-DEM compaction simulations.



Develop continuum models



Include cohesion, tangential contact model, and rolling resistance.

