SAND2015-5055C

Modeling and Measurement of Supersonic Hailstone Impacts

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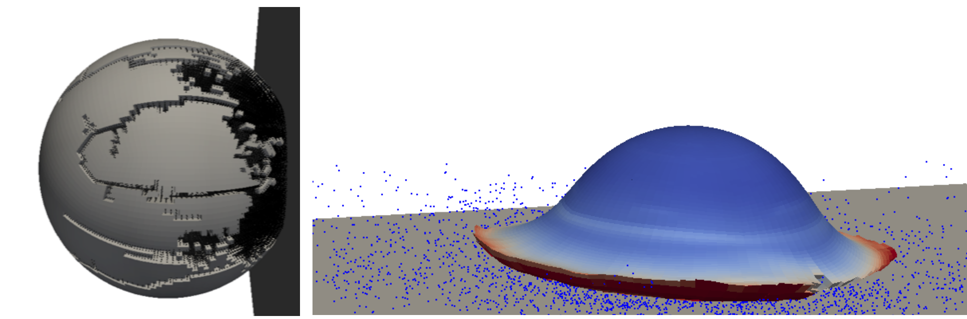

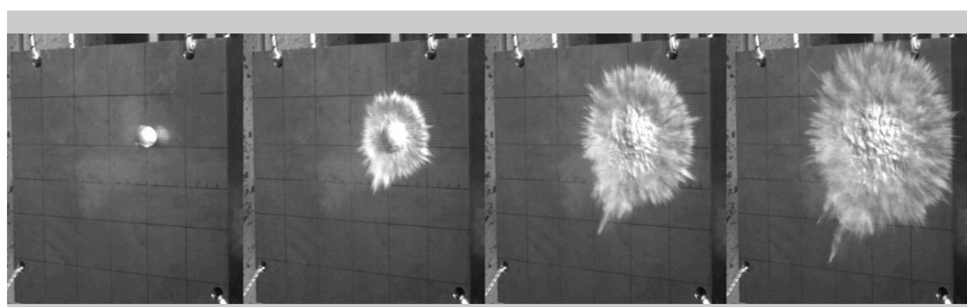

ASME 2015:
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

- Hailstone impacts have the potential to cause significant damage to aircraft and wind turbine blades.

- Hailstone impact tests are costly, time-consuming, and difficult.
  - The ability to model hailstone impacts would provide a better way to explore large parameter spaces and investigate difficult to measure conditions; e.g., high-speeds or simultaneous hailstone impacts.

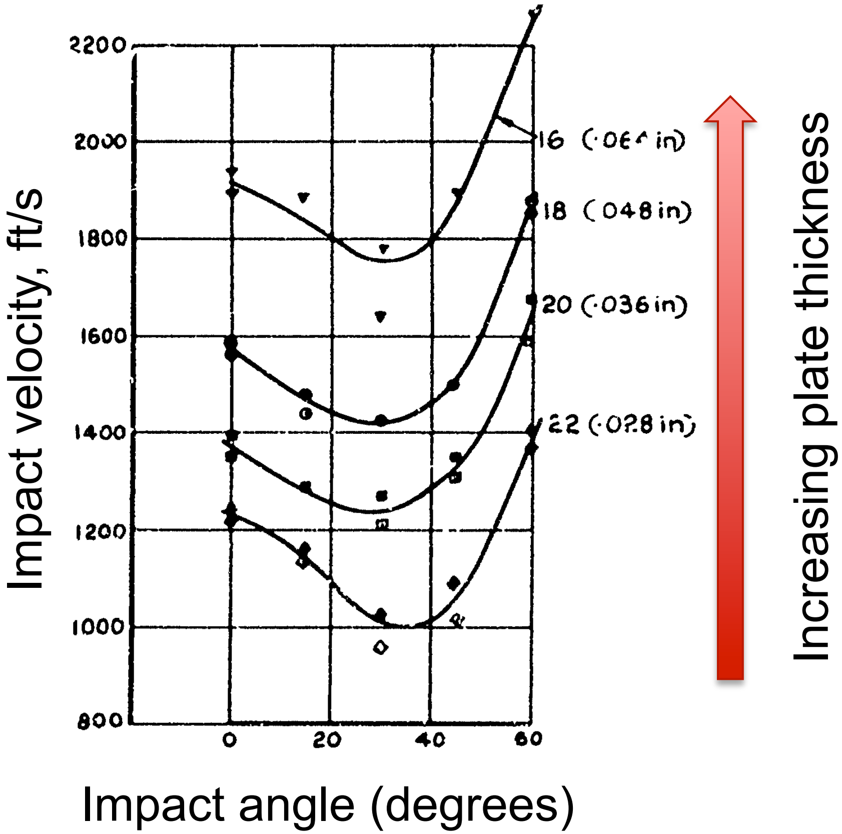
N708AA Hail Damage,
Dave Subelack (Wee in YYC), Flickr.

Background - McNaughtan and Chisman (1969)

- McNaughtan and Chisman (1969) studied supersonic hailstone impacts on thin aluminum plates, but did not measure the impulses imparted by the hailstones.

- Others have since measured impulses from hailstone impacts but have not studied impacts over 720 ft/s (220 m/s).

Penetration thresholds for different thickness aluminum alloy plates impacted by 1 inch diameter hailstones.

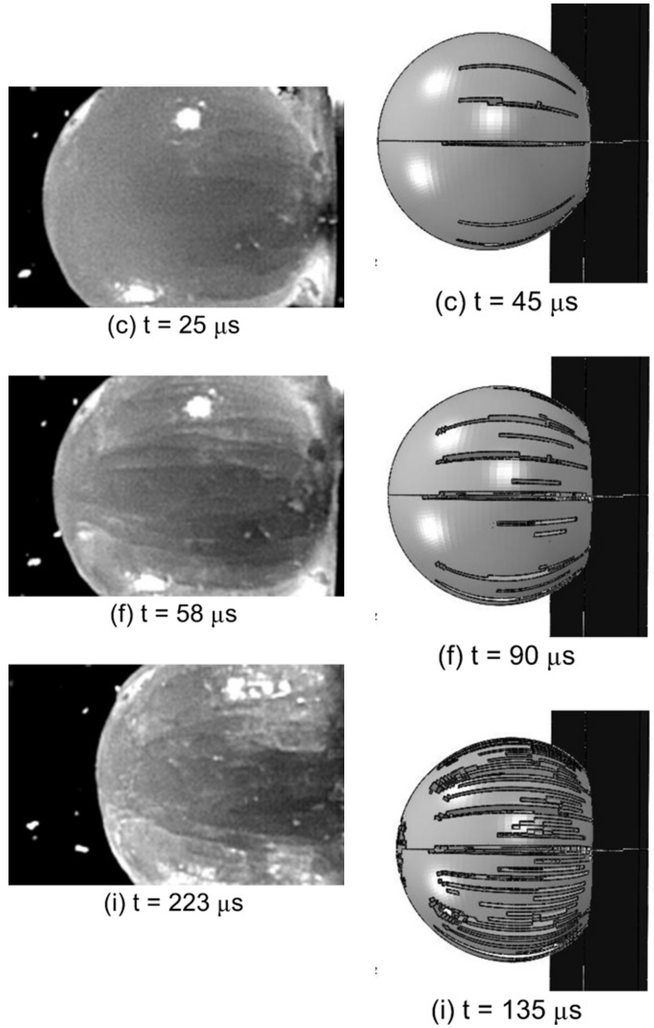


"A Study of Hail Impact at High Speed on Light Alloy Plates"
McNaughtan, I.I., Chisman, S.W., 1969.

Background – Tippmann et al. (2013)

Experiments:

- Measured impulses of hailstones by firing them at a steel bar instrumented with strain gauges.
- Normal impacts up to 194 m/s.
- Captured propagation of cracks with high-speed photography.



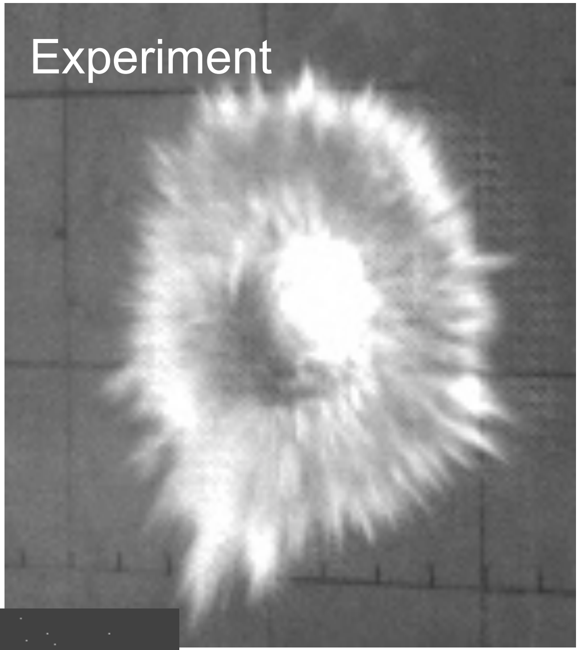
Simulations:

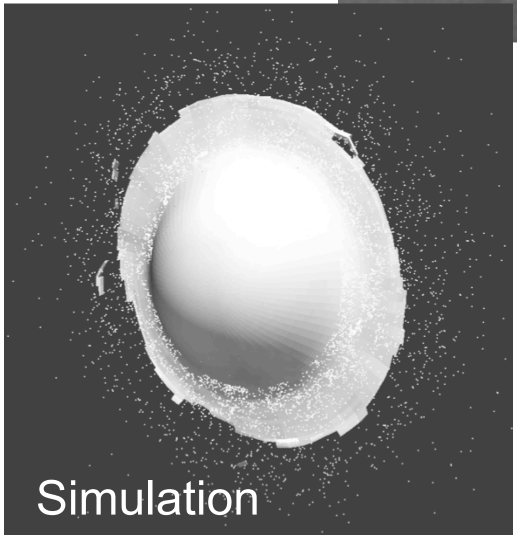
- Similar cracking patterns achieved through tensile pressure failure criterion
- Strain rate sensitivity captures behavior over a range of velocities
- Predict peak impulse but not long-term response

"Experimentally validated strain rate dependent material model for spherical ice impact simulation"
Tippmann, J.D., Kim, H., Rhymer, J.D., 2013.

Present work

- Used a different technique (SWAT-TEEM) to measure:
  - Higher velocities
  - Oblique impact angles
- Added mass particles and an additional failure criterion to simulation in order to:
  - Model full impulse of impact
  - Capture secondary impacts
  - Model low angle and large deformation impacts

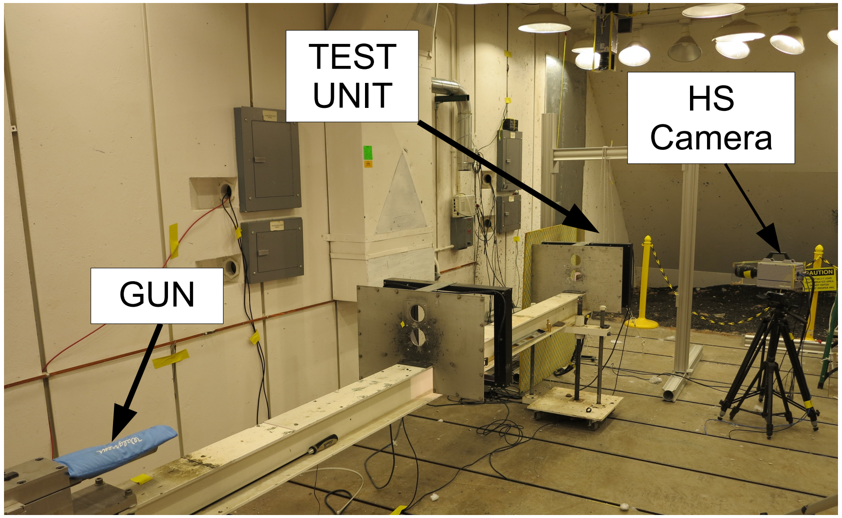


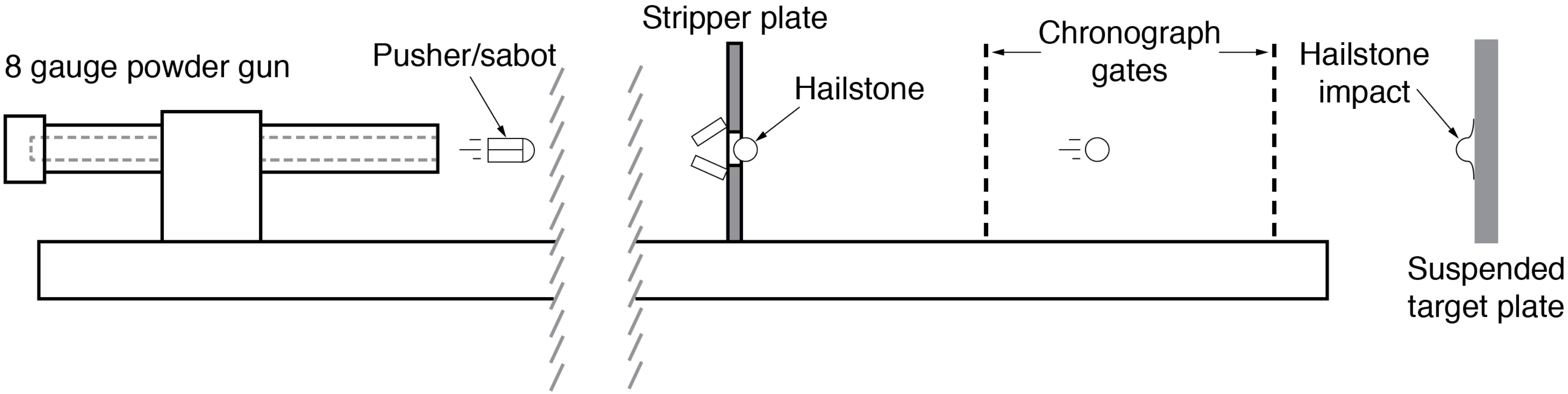


A 'hailstone' (4.41g, 20.45mm) impacting plate at 366 m/s.

Experiments

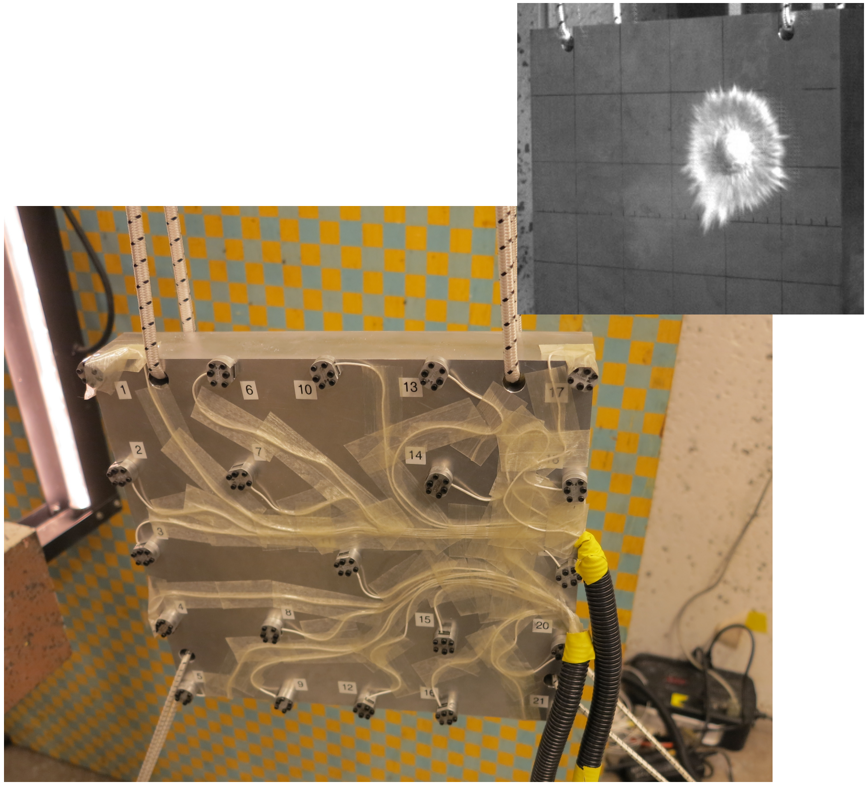
- Experimentalists:
  - Ballistics by Lee Stauffacher and Bob Jones
  - SWAT-TEEM analysis by Tyler Schoenherr
- 8 gauge powder gun
  - Velocities from 150 to 675 m/s
  - Used a pusher/sabot to propel hailstone
- Hailstone
  - Molded, cotton-reinforced ice ball
  - 0.81 inch diameter





Sum of Weighted Accelerations Technique using Time-Eliminated Elastic Modes (SWAT-TEEM)

- SWAT-TEEM[1] can predict forces acting on a body by separating the rigid body accelerations from those due to vibrational modes.
- Advantages
  - Measure off-axis forces
  - Increased target size/ complexity
  - Predicts impact location that can be checked with high-speed video

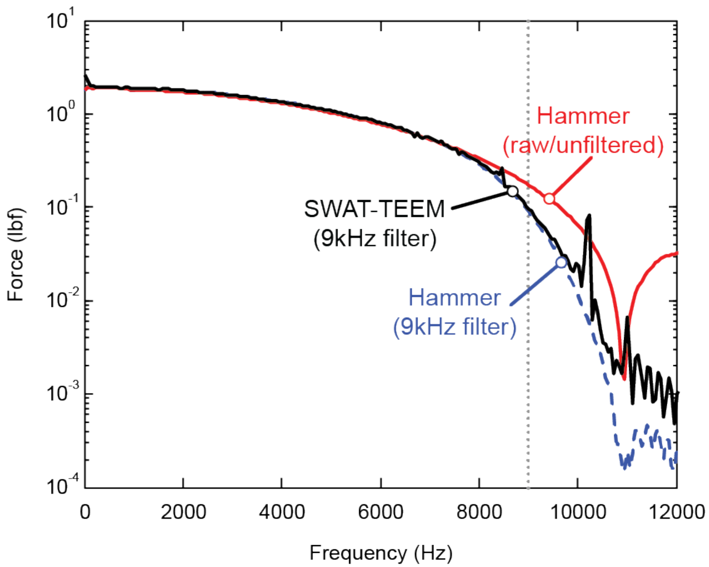


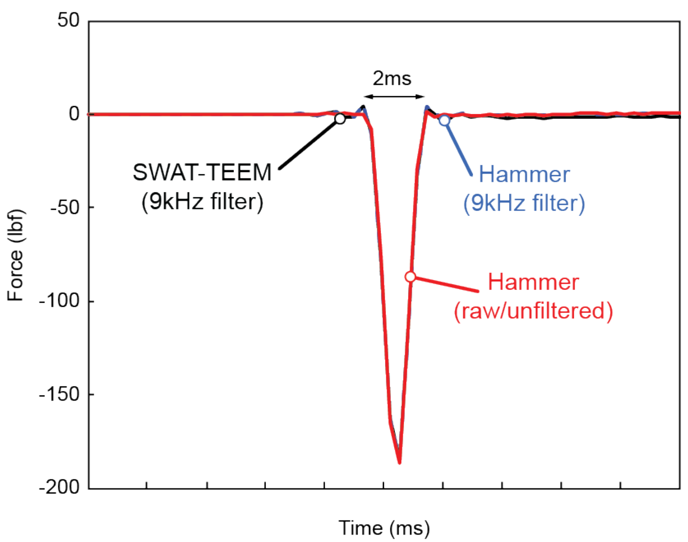
Aluminum plate (11x12x2 inches) instrumented with 21 accelerometers for SWAT-TEEM analysis.

[1]Mayes, R. L., 1994, "Measurement of Lateral Launch Loads on Re-Entry Vehicles Using SWAT," Proceedings of the 12th International Modal Analysis Conference, Honolulu, HI, pp. 1063–1068.

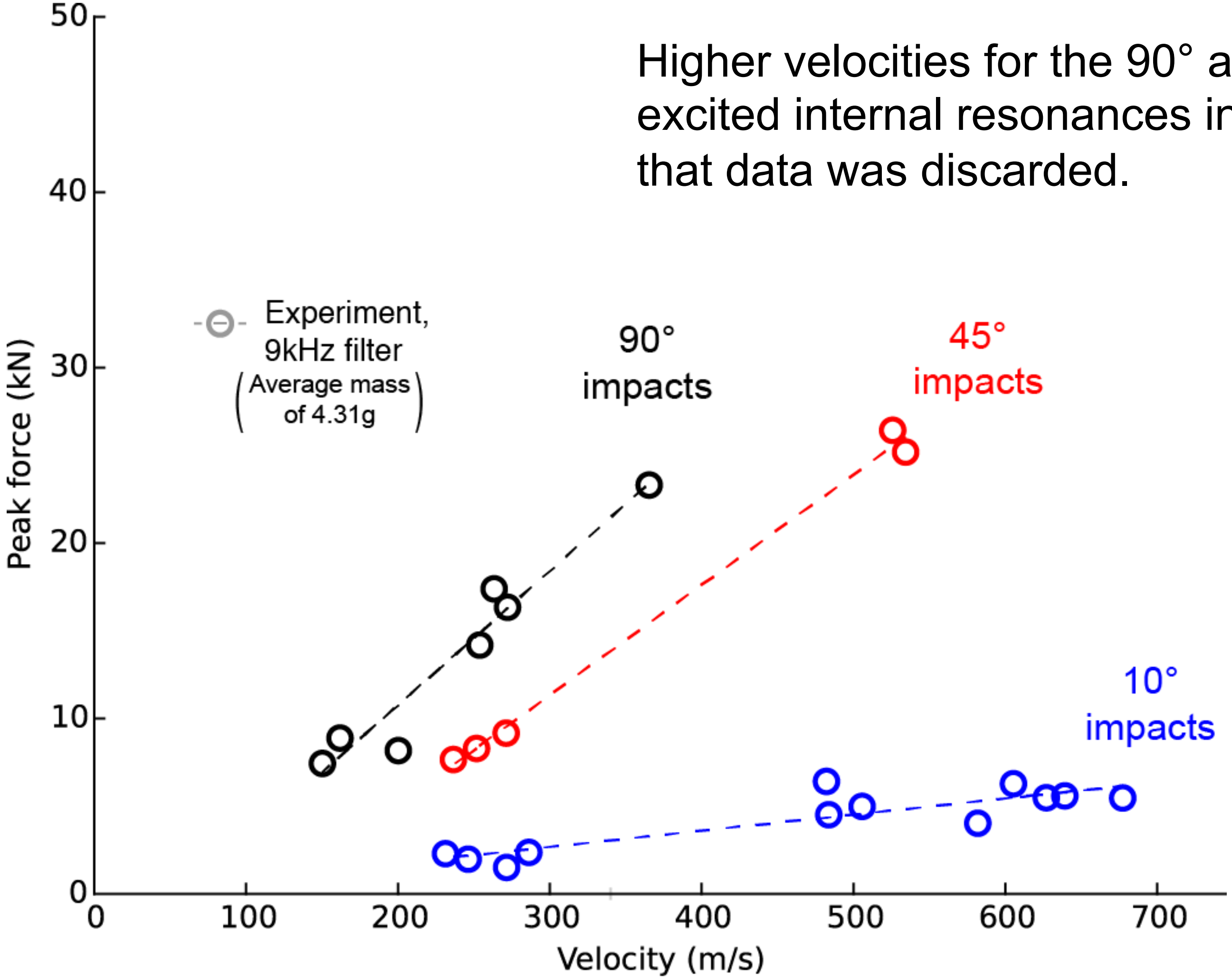
Experiments – SWAT-TEEM calibration

- An instrumented hammer applies a known force to the plate.
- **Limited to 9kHz by the coarseness of our accelerometer array- cannot resolve higher-order mode shapes of the plate.**
- Filtering data at 9kHz, we obtain an excellent prediction of the force from SWAT-TEEM.





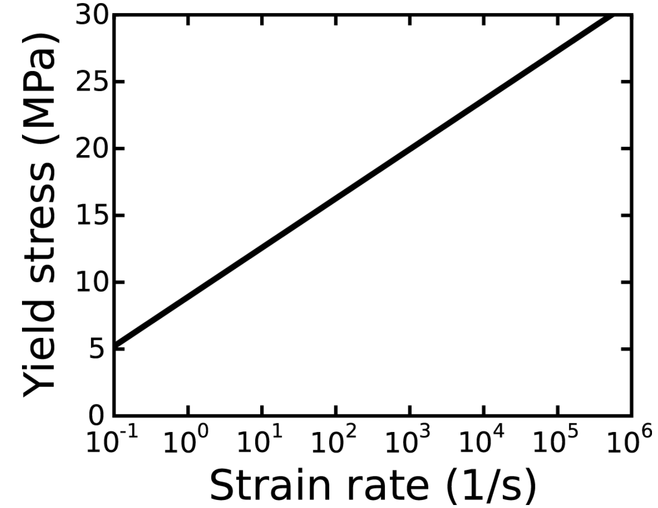
Experiments – Hailstone impacts



Higher velocities for the 90° and 45° degree cases excited internal resonances in the gauges and so that data was discarded.

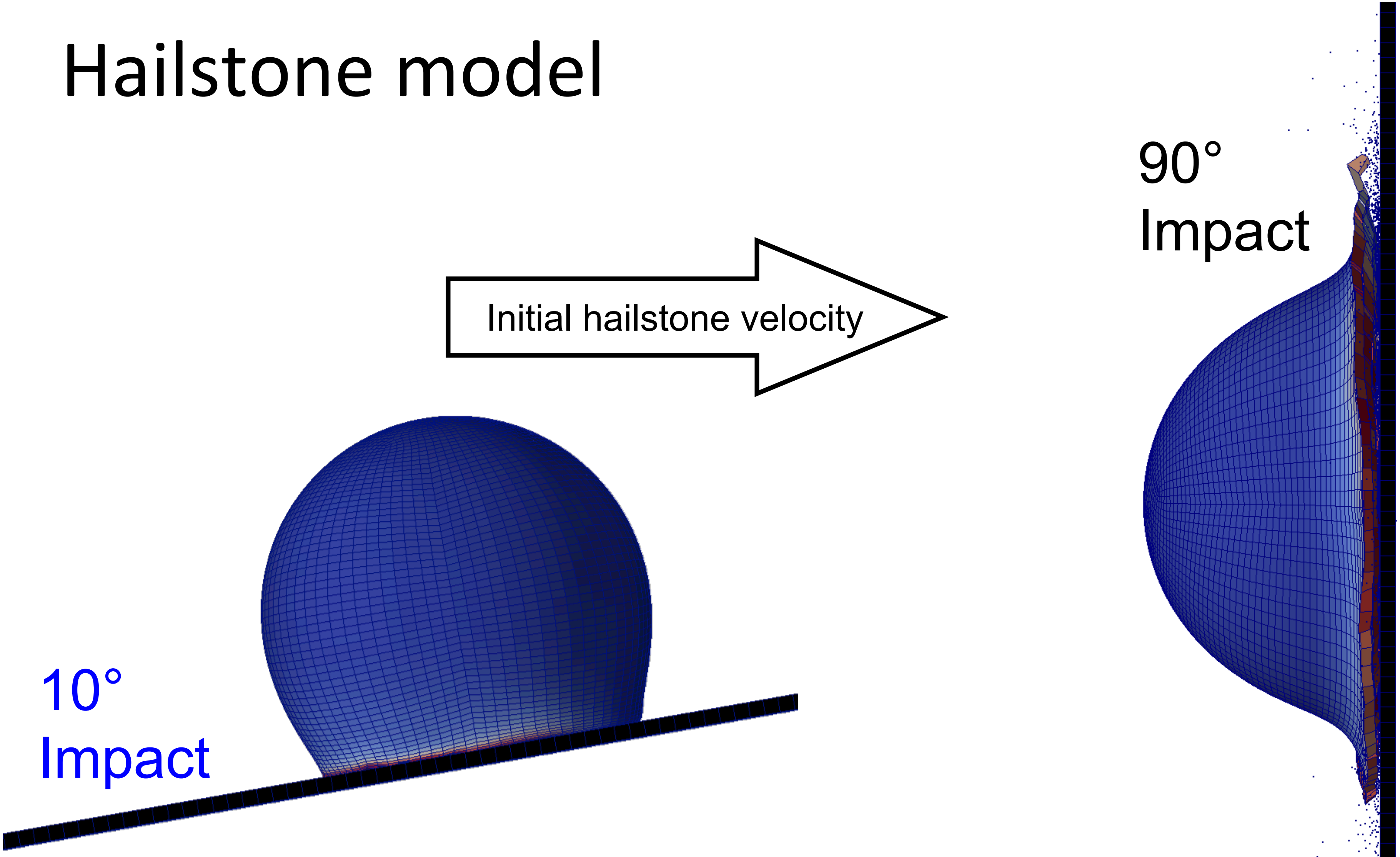
Hailstone material model

- Tippmann et al. model:
  - Elastic-perfectly plastic material
  - Rate sensitive yield (like Johnson-Cook)
  - Tensile pressure failure criterion
    - On failure, zero-out shear stiffness (fluid like behavior)
- Added:
  - Rigid mass particles
    - Helps capture full impulse of the initial impact and any subsequent impacts.
    - Converted to once elements are too deformed.
  - Critical crack opening strain (CCOS)
    - Controls strain over which elements fail
    - A good fit of experimental data was obtained over all angles and velocities for a CCOS = 0.3



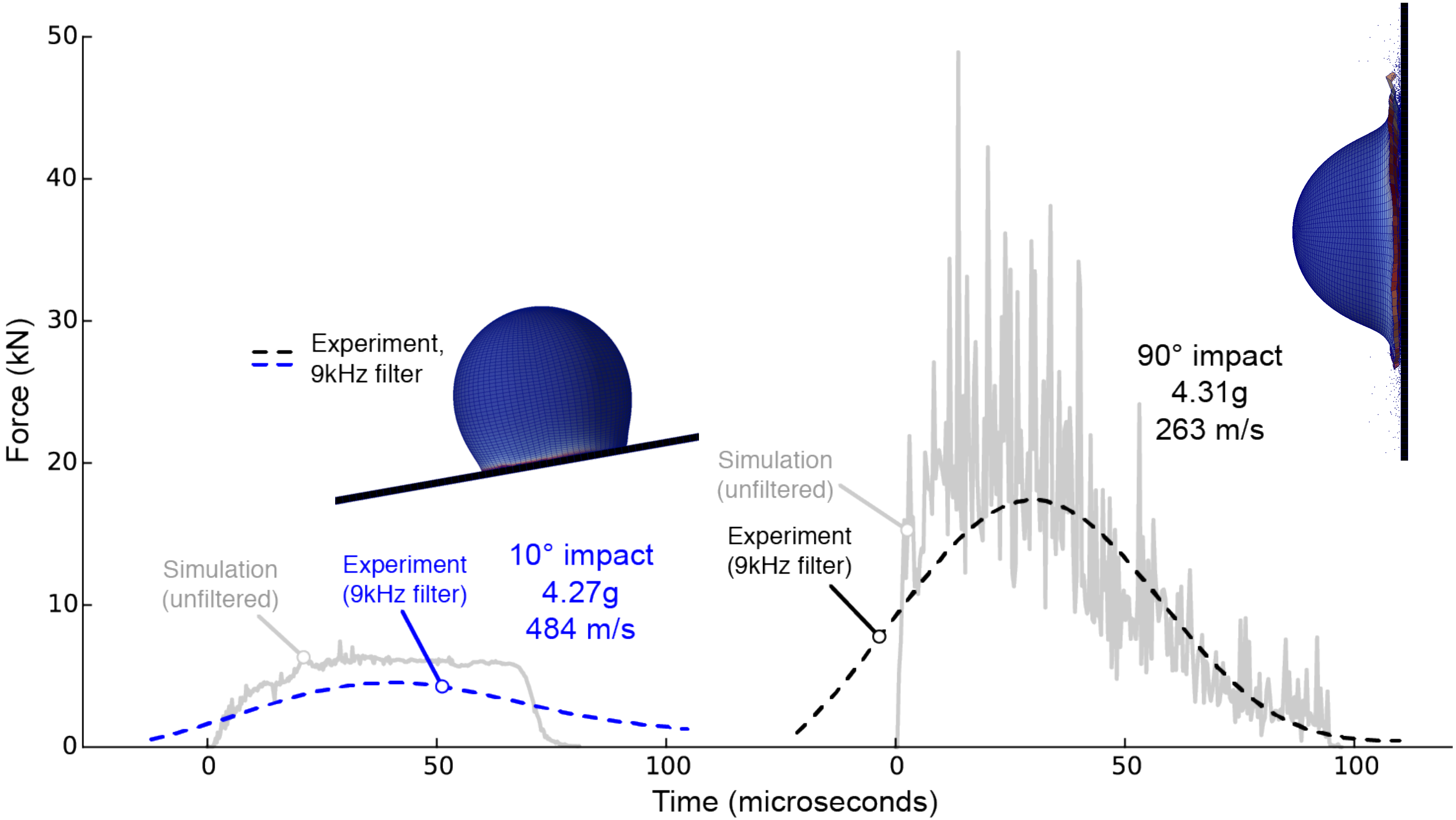
Hailstone material model inputs	
Young's modulus	9.38 GPa
Poisson's ratio	0.33
Density	960 kg/m^3
Tensile failure pressure	0.517 MPa
Quasi-static (<10^{-1}/s) yield stress	5.2 MPa

Hailstone model

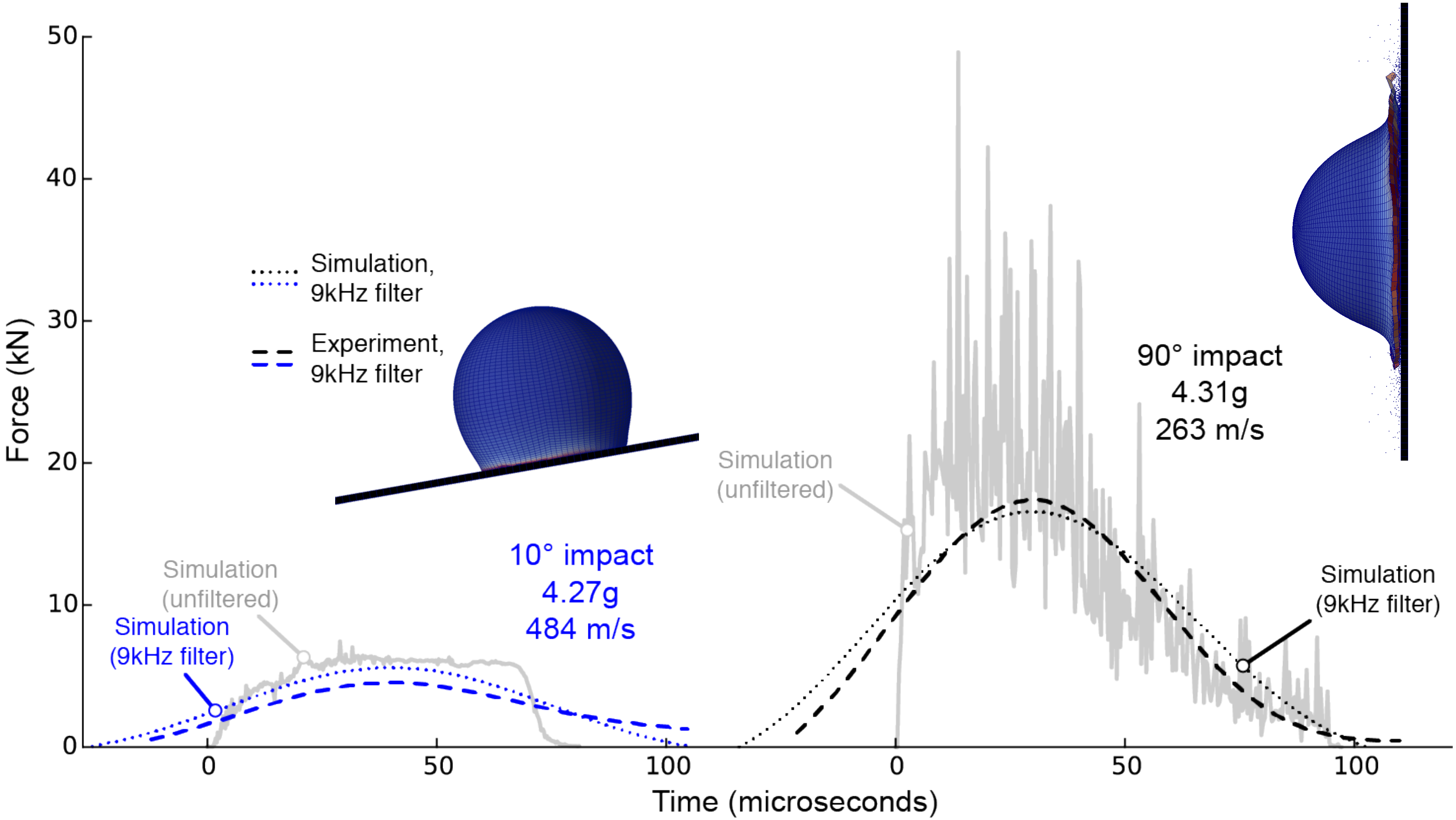


Deformed meshes shown near time of peak impact force.

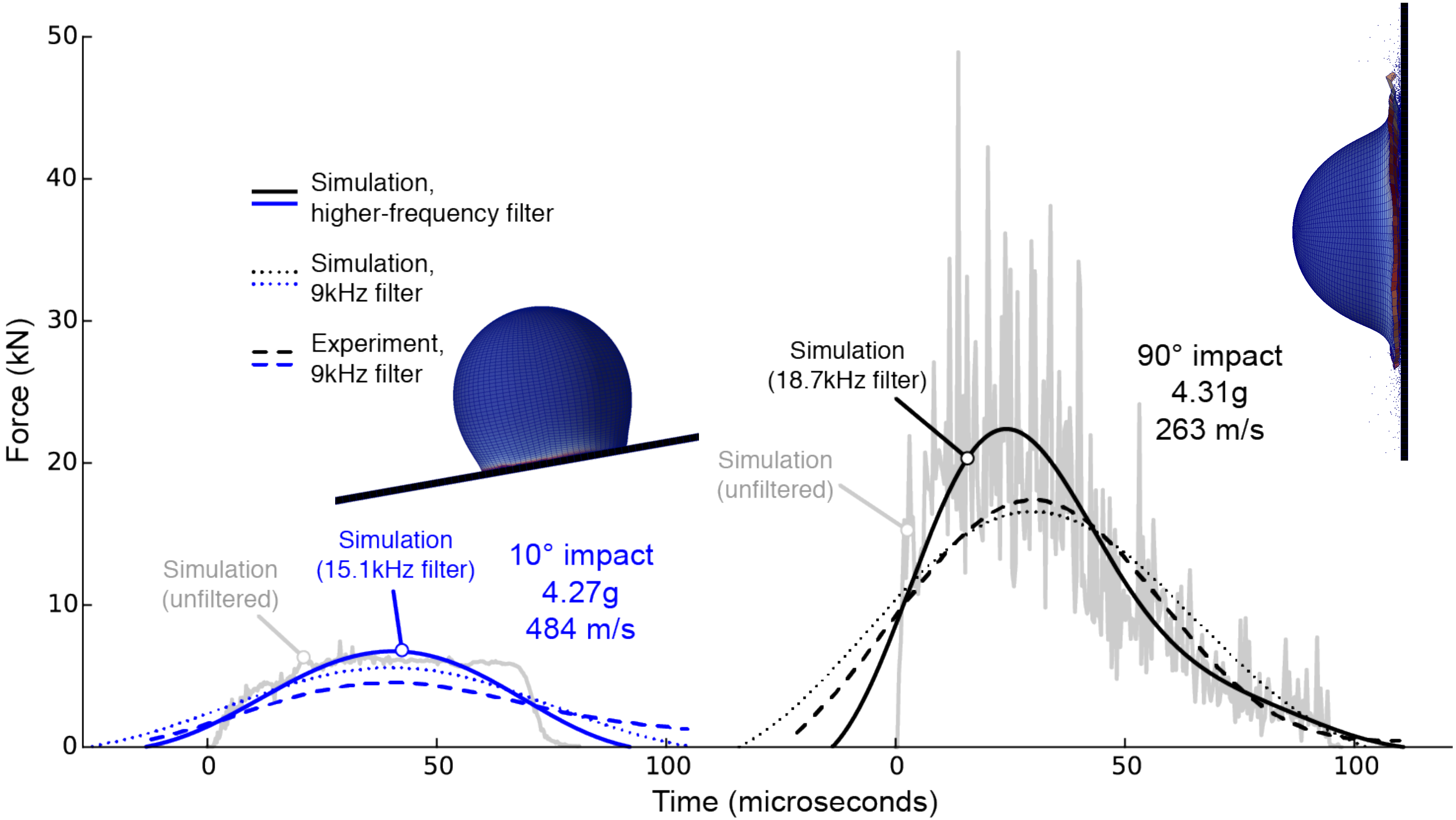
Modeling vs. Experiment - Impulse comparison



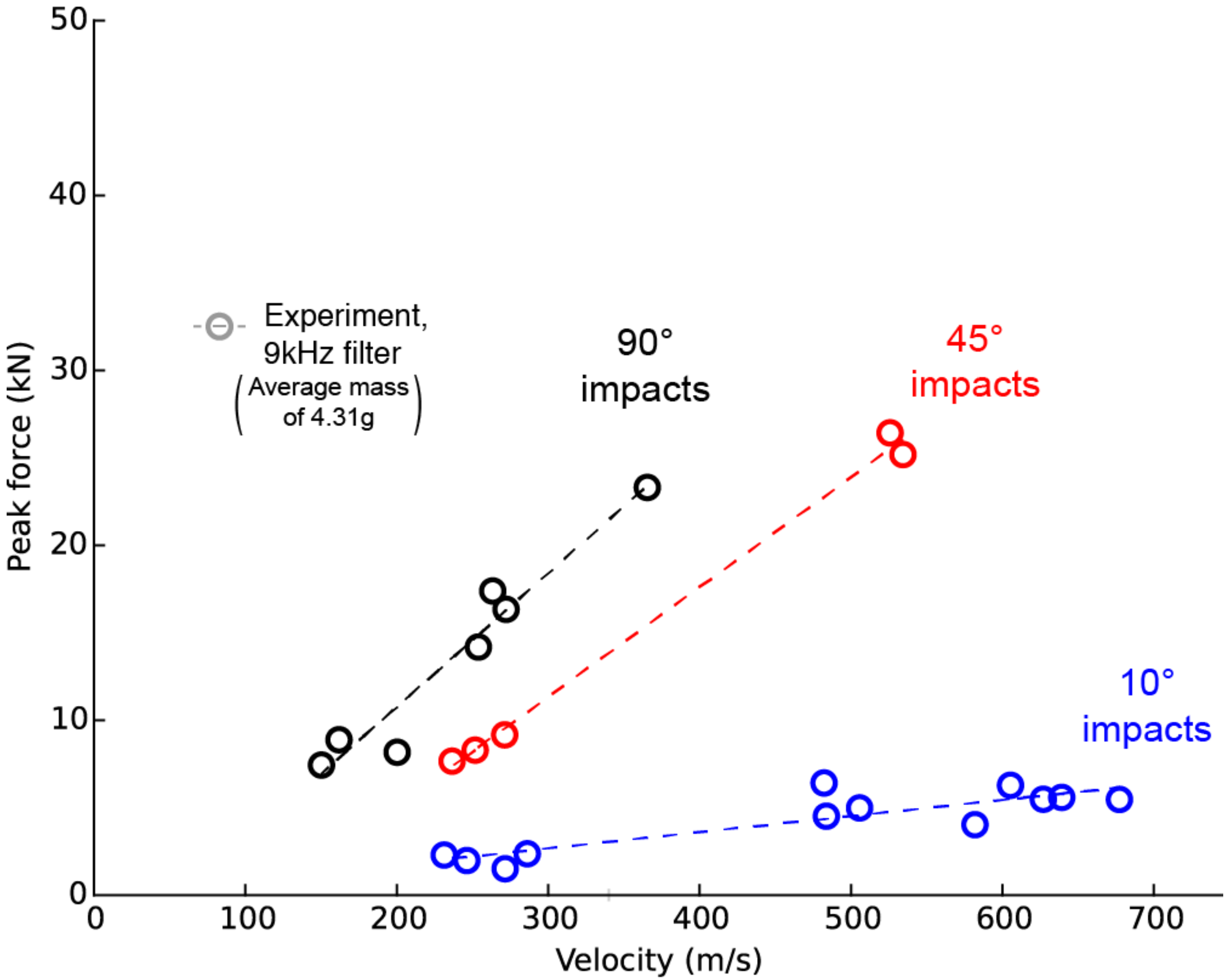
Modeling vs. Experiment - Impulse comparison



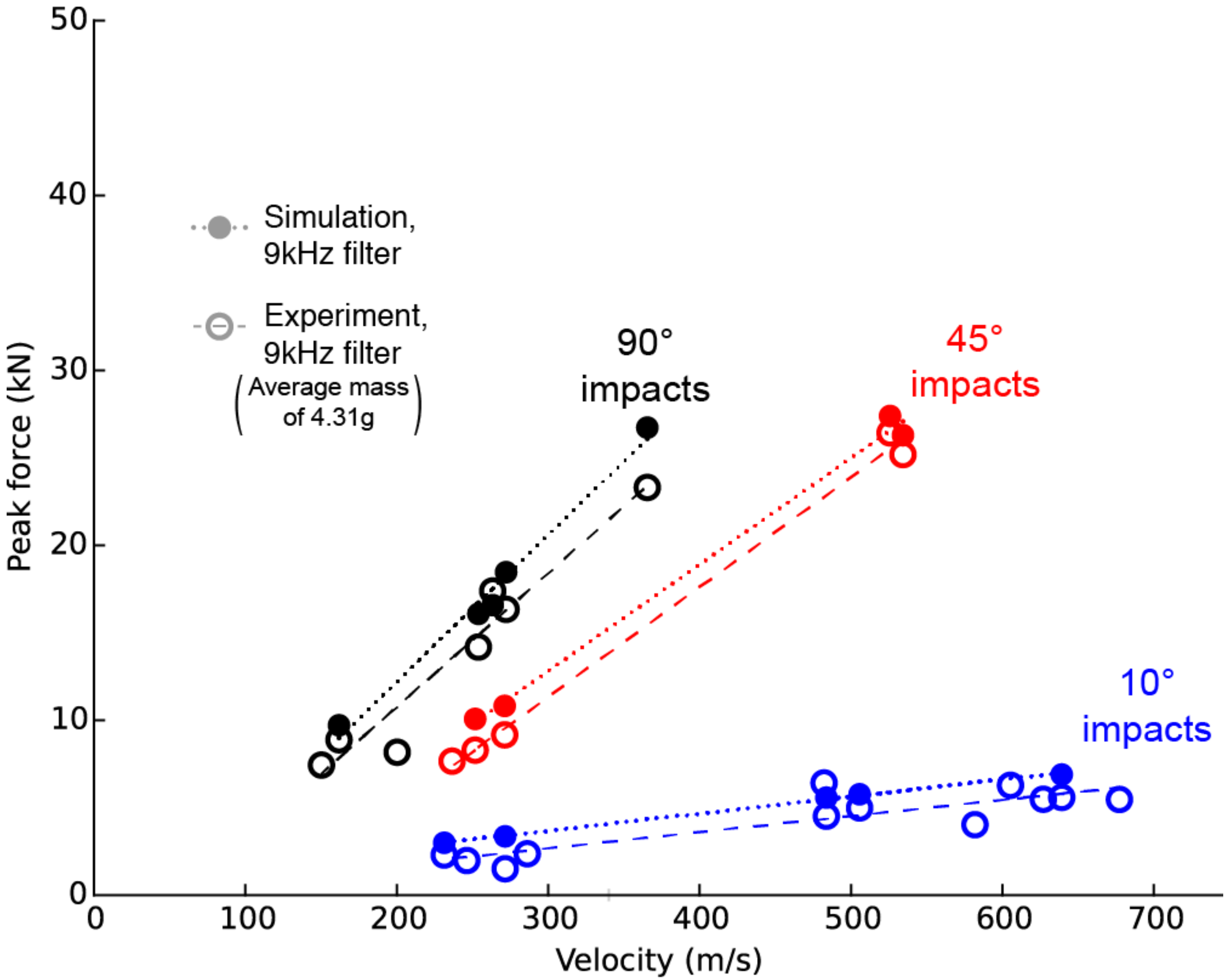
Modeling vs. Experiment - Impulse comparison



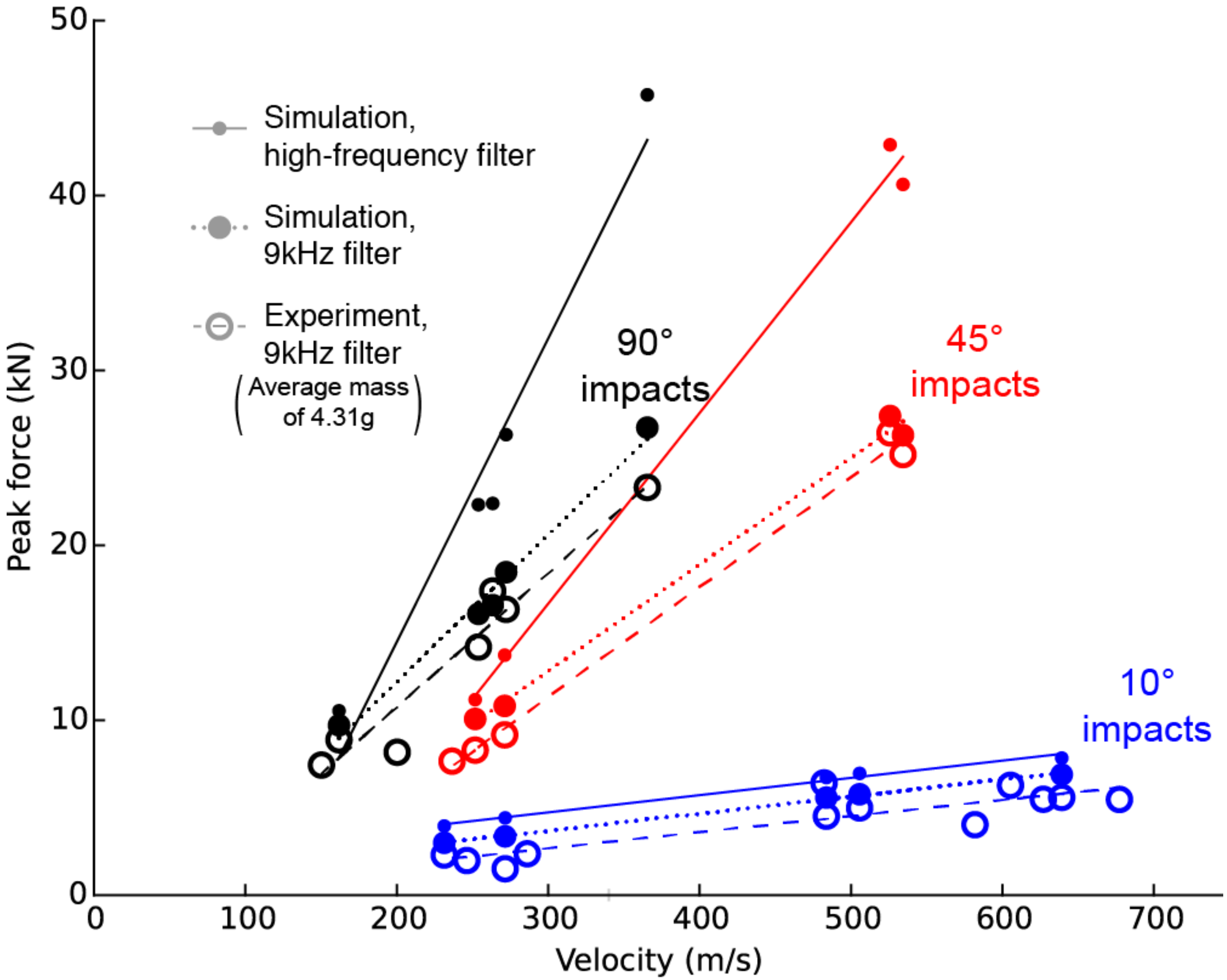
Modeling vs. Experiment – Peak force comparison



Modeling vs. Experiment – Peak force comparison



Modeling vs. Experiment – Peak force comparison



Analytical model

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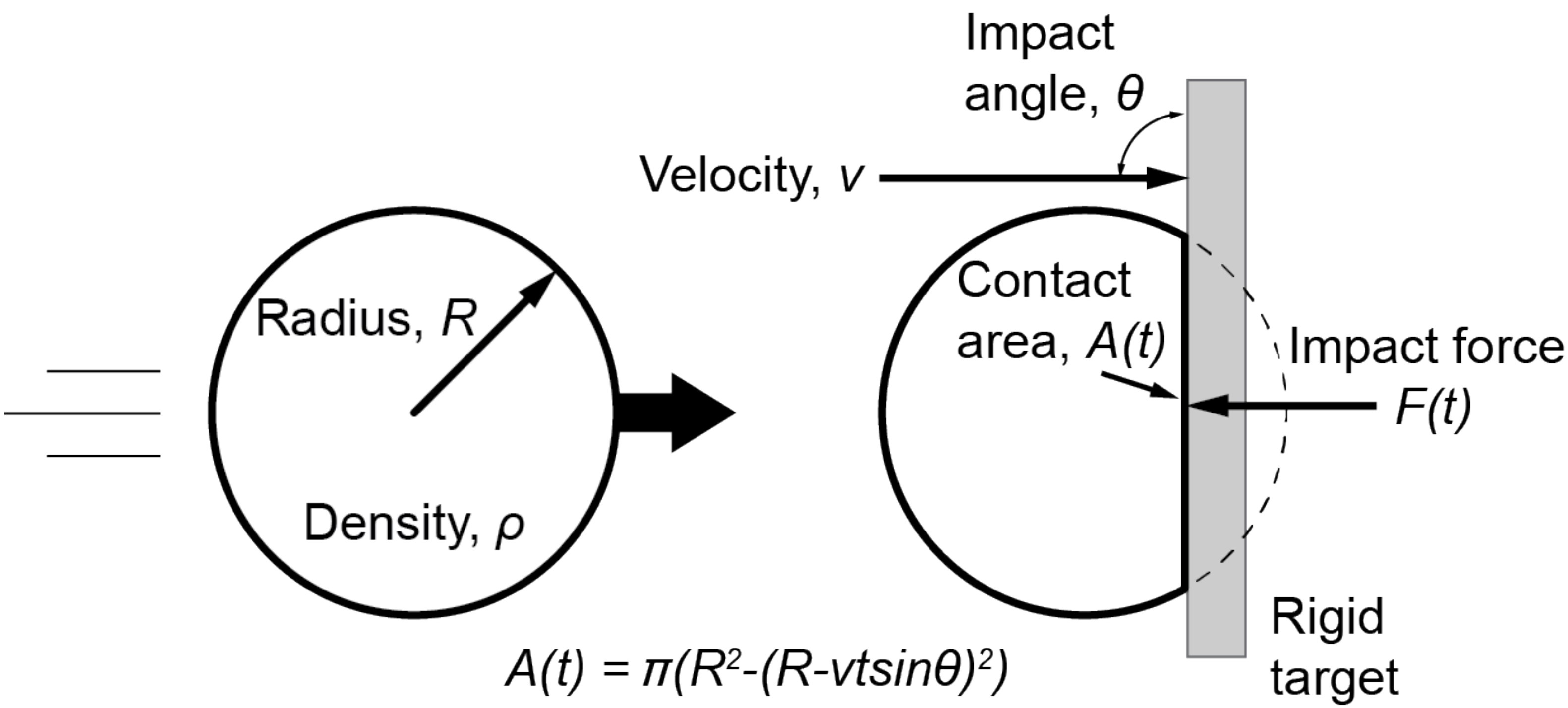
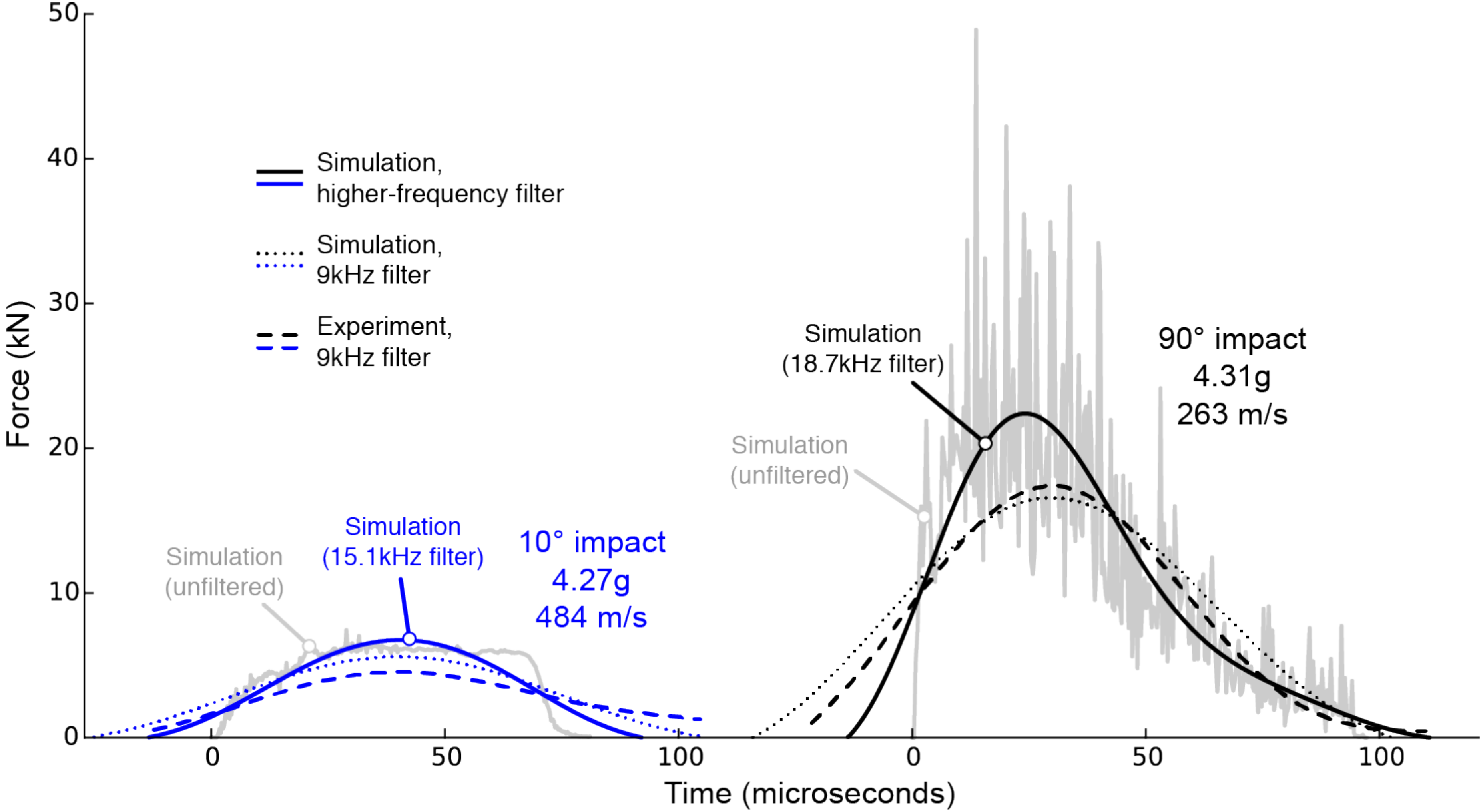


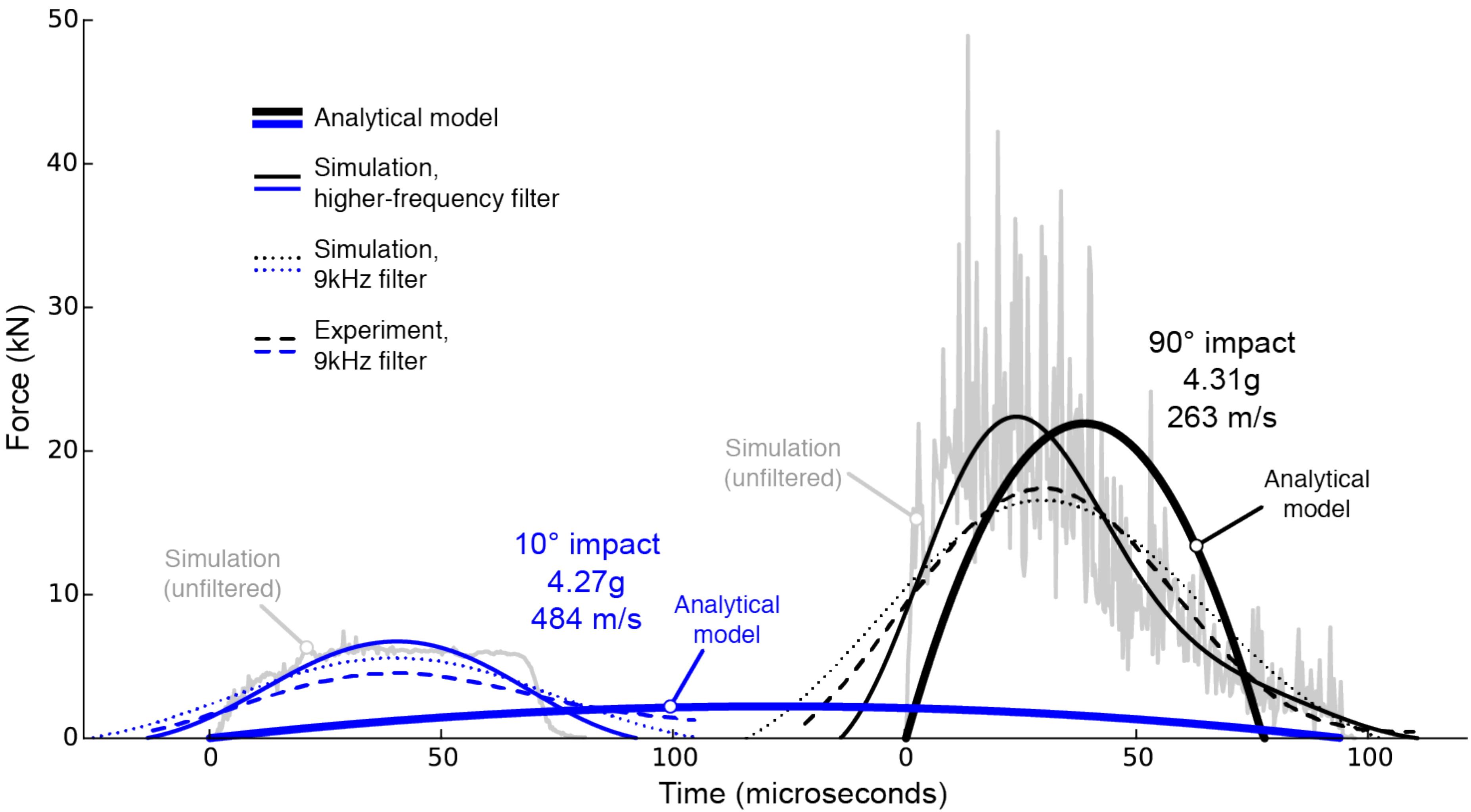
$$A(t) = \pi(R^2-(R-vt\sin\theta)^2)$$

$$F(t) = \rho(v\sin\theta)^2A(t)$$

Modeling vs. Experiment - Impulse comparison



Modeling vs. Experiment - Impulse comparison



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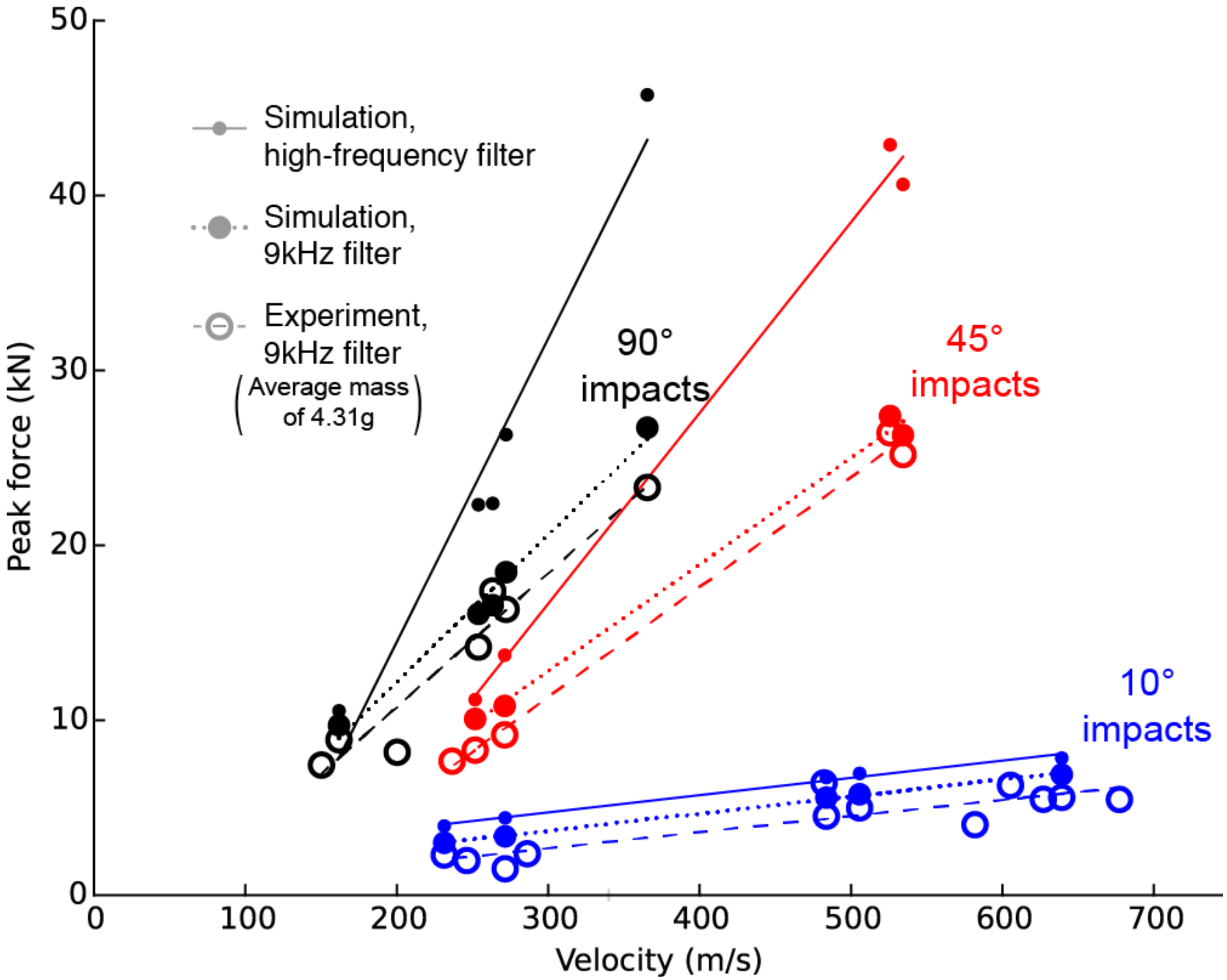
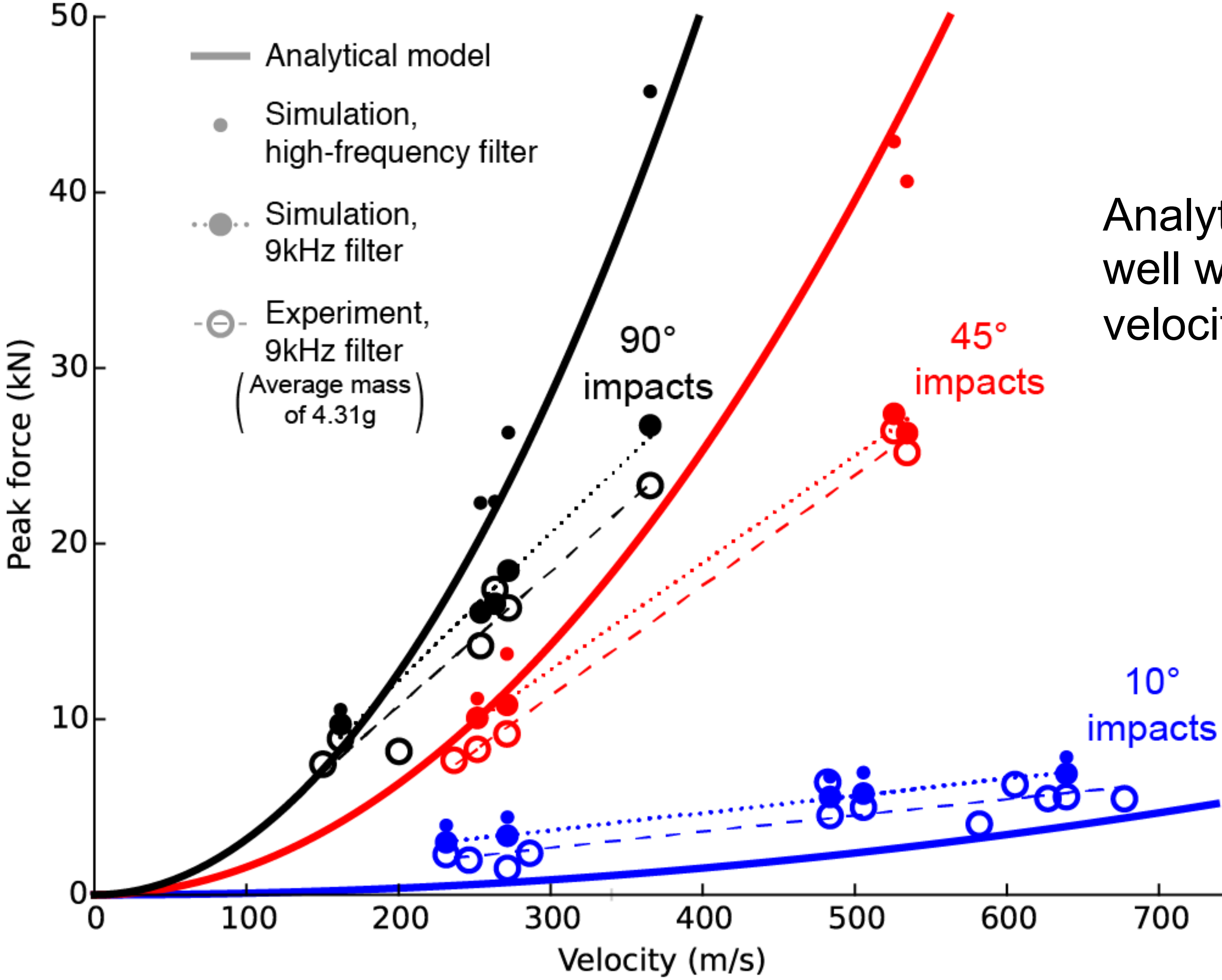


Modeling vs. Experiment – Peak force comparison



Analytical model compares well with FEA model at high velocities and impact angles.

Summary

- Used a different technique (SWAT-TEEM) to measure hailstone impacts at higher velocities and oblique angles.
- Built upon existing hailstone model, adding mass particles and adjusting failure to capture entire impulse of normal and oblique impacts.
- Agreement between the finite element model and analytical and experimental results gives confidence in using the model to study hailstone impacts on other structures and/or under other conditions.