Composite coatings with embedded fibers and particiles for multiple impact protection

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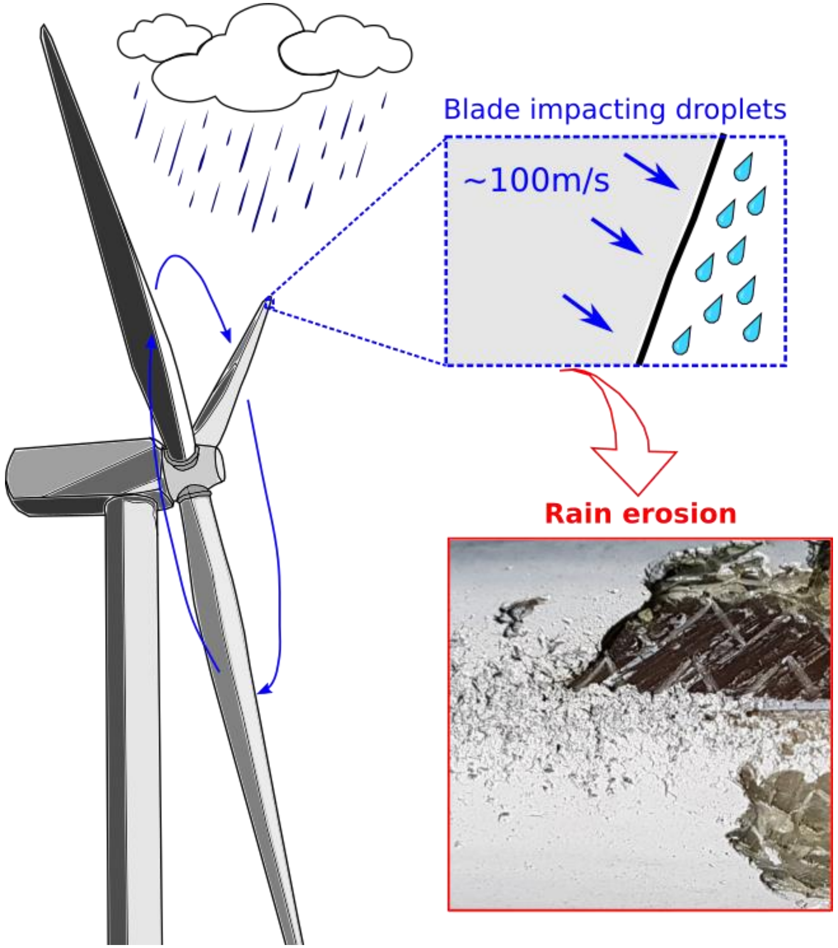
Leading edge erosion of wind turbine blades



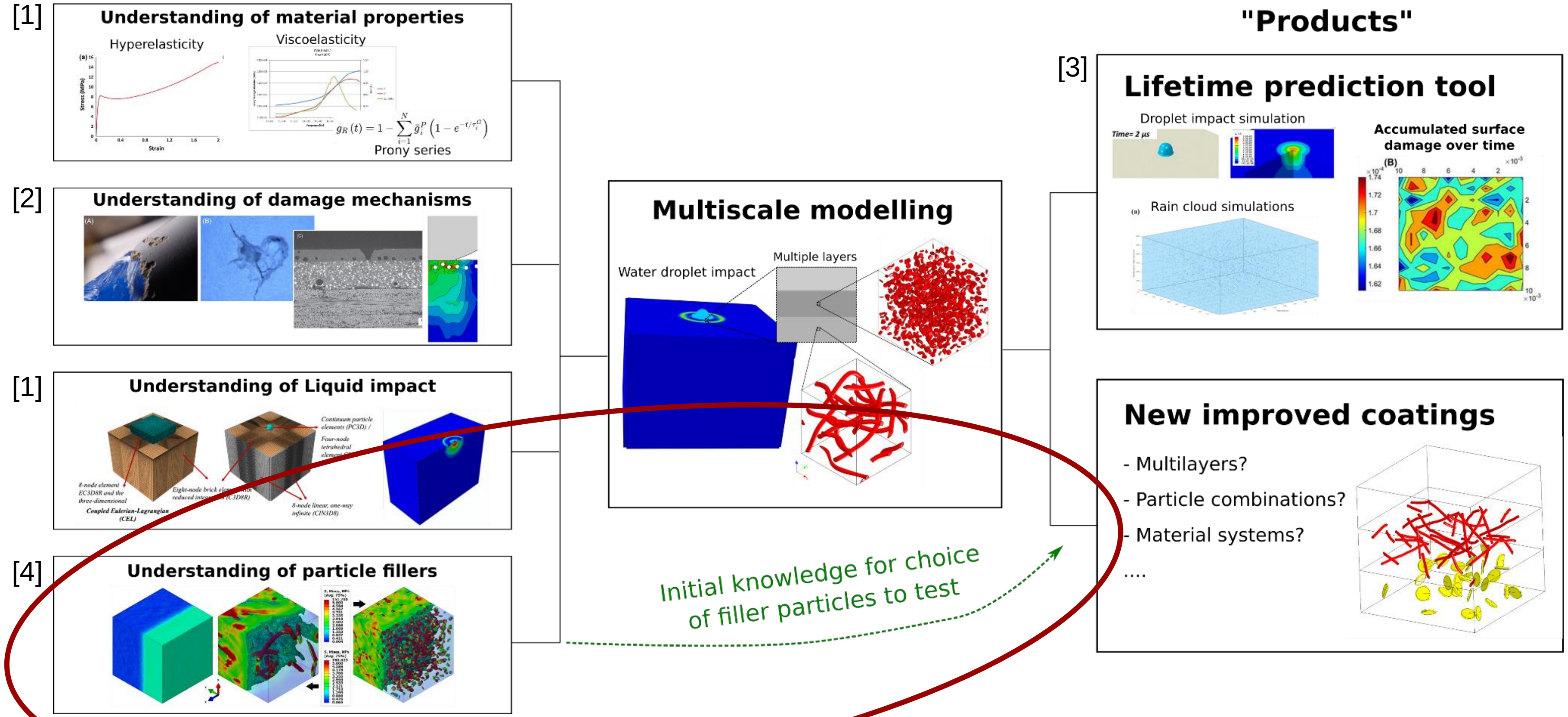
- Wind turbines operate under various weather conditions such as heavy rain and wind, with required lifetimes of around 20-30 years
- With increasing blade length, tip rotation speeds reach velocities as high as 100 m/s
- Blades impacting rain drops and other particles at such speeds lead to erosion of the surface with current coating solutions

→ Develop new erosion resistant coatings

DURALEDGE

Role in the Duraledge project

Some of several focus areas



[1] Doagou-Rad S and Mishnaevsky L 2020 Rain erosion of wind turbine blades: computational analysis of parameters controlling the surface degradation *Meccanica* **55** 725–43

[2] Mishnaevsky Jr. L, Fæster S, Mikkelsen L P, Kusano Y and Bech J I 2020 Micromechanisms of leading edge erosion of wind turbine blades: X-ray tomography analysis and computational studies *Wind Energy* **23** 547–62

[3] Doagou-Rad S, Mishnaevsky L and Bech J I 2020 Leading edge erosion of wind turbine blades: Multiaxial critical plane fatigue model of coating degradation under random liquid impacts *Wind Energy* 1–15

[4] Jespersen K M, Monastyreckis G and Mishnaevsky L 2020 On the potential of particle engineered anti-erosion coatings for leading edge protection of wind turbine blades: Computational studies *IOP Conf. Ser. Mater. Sci. Eng.* **942**

Purpose of current work

Goal: Develop new erosion resistant coatings

Experimental coating development

Possible variations

- Different types of resin
- Different filler particles
- Number and combination of layers
- Layer thicknesses
- ⋮

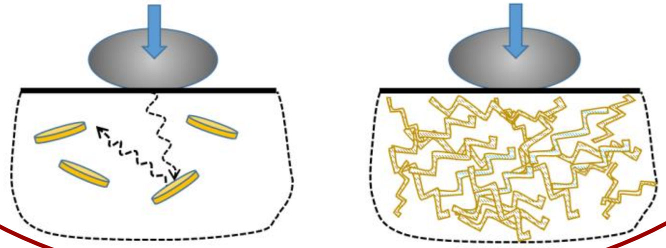
Takes too long time to test all, and choices can for good or bad be biased by previous knowhow

→ Use modelling to reduce the number of cases to be tested experimentally, and reveal new possible improvement combinations one had not imagined

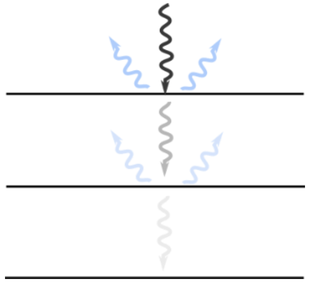
What makes coatings erosion resistant?

Hypothesis 1: Scattering of stress waves can improve the erosion resistance

Scattering on particles



Reflection on interfaces (multiple layers)



Hypothesis 2: A network of fibers can improve the damping properties and thus the erosion resistance

Coating damping properties
(energy dissipation)

Resin induced damping properties
(E.g. viscoelastic properties)

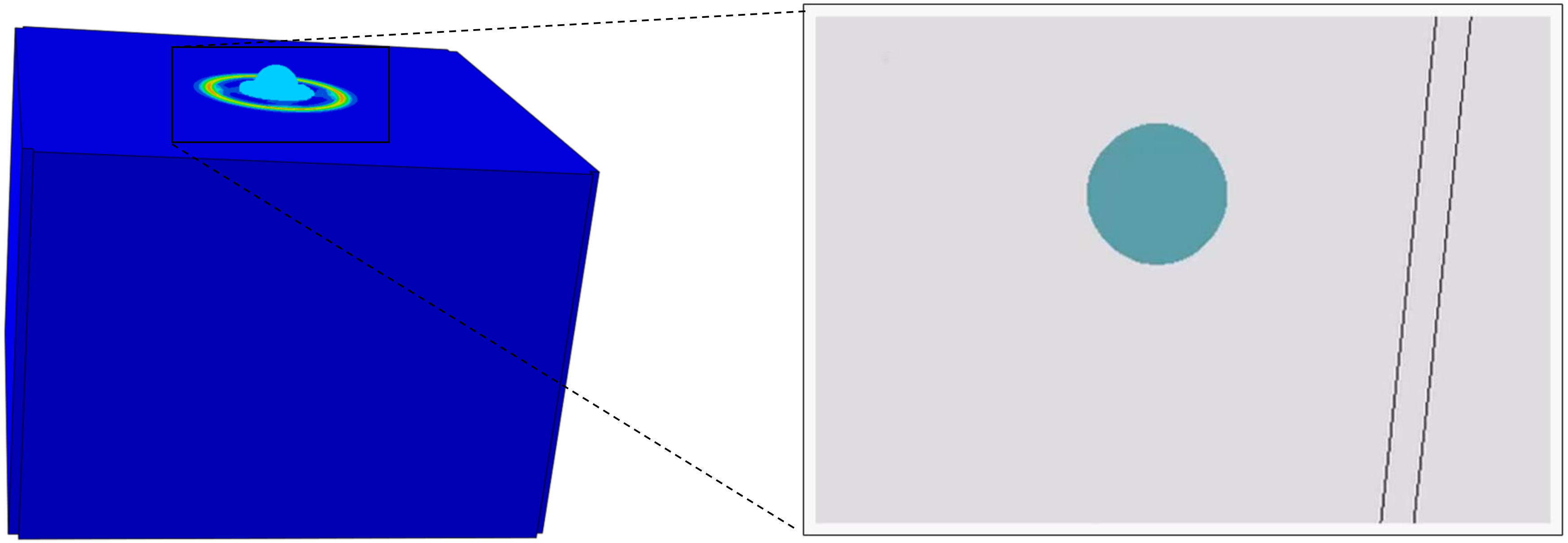
Interface damping/damage

Filler induced damping properties
(E.g. network of fibers)

Modelling of water droplet impact

- Water droplet impact has been modelled e.g. by SPH impacting a solid

Highest stresses below droplet



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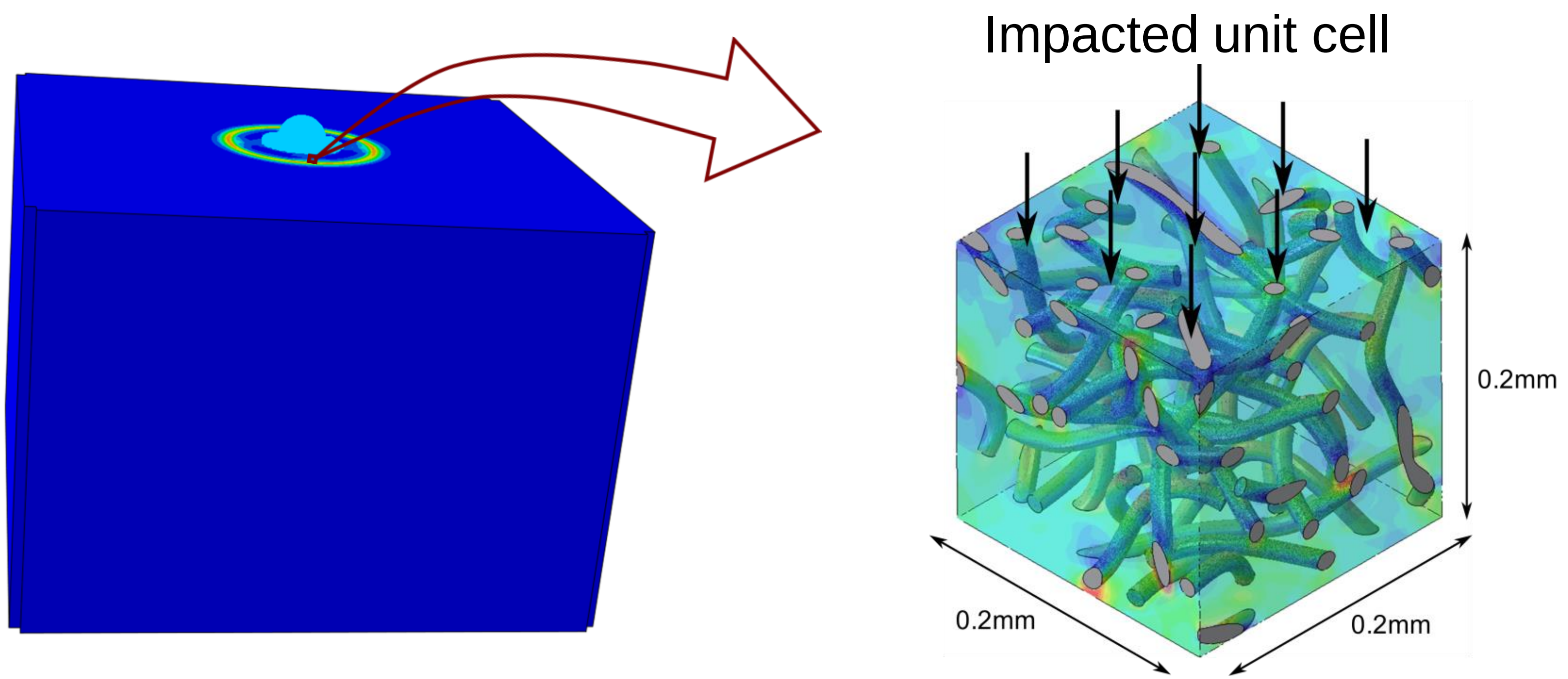
Simplification of impact for particle comparison

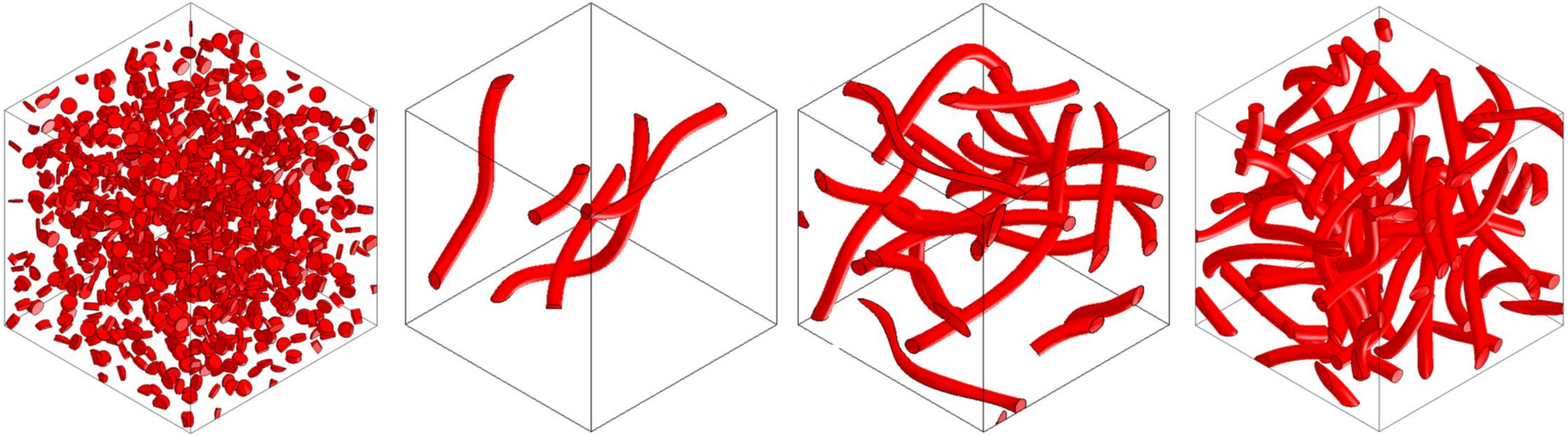
- Assumed that a small unit cell will be subject to approximately homogeneous impact load



Considered particles

- Unit cells generated by Digimat software

4 vol% discs | 1 vol% fibers | 4 vol% fibers | 8 vol% fibers

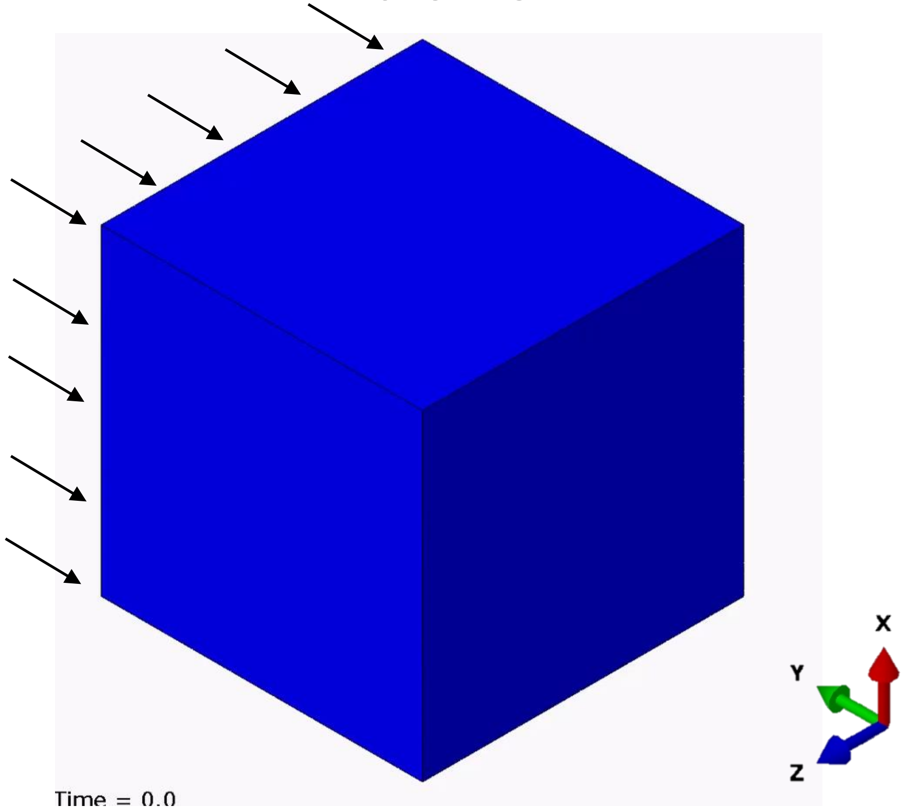


Hypothesis 1

Scattering of stress waves

Studying first stress wave after impact

Pure PU

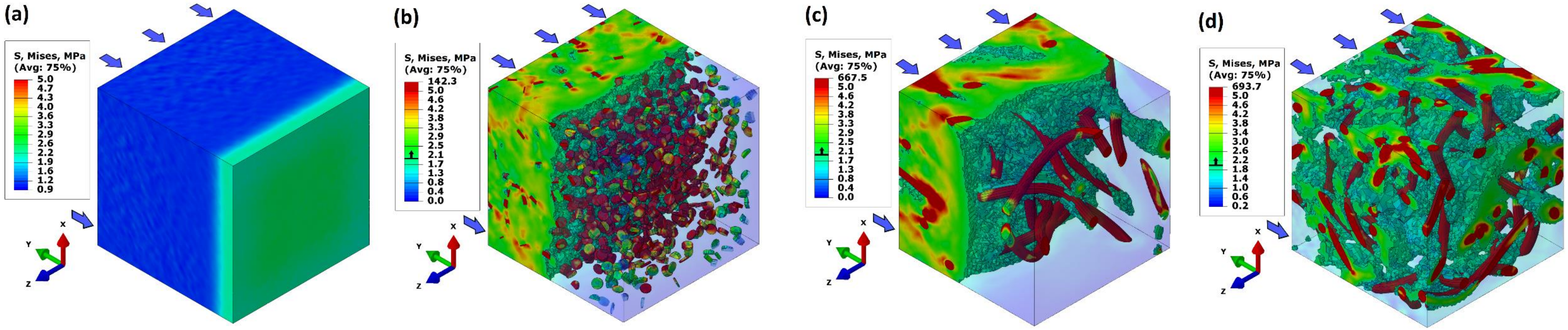


(video)

- Impacted 0.005mm over 0.001ms (5 m/s)
- Linear elastic materials
- Symmetry boundary conditions
- First stress wave compared for
  - Pure PU
  - 4 vol% discs
  - 4 vol% curves fibers
  - 8 vol% curved fibers

Scattering of the first stress wave

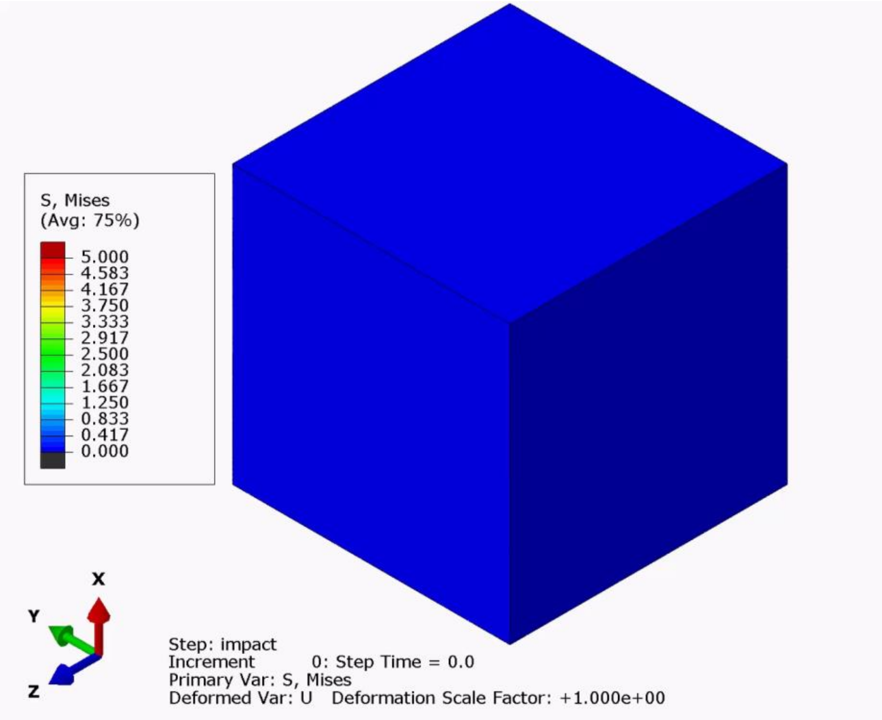
Pure PU | 4 vol% discs | 4 vol% fibers | 8 vol% fibers



- For 4 vol% particles, the stress waves travels quite similar for discs and fibers, but stresses are locally near fibers transferred further into the depth
- For 8 vol% fibers, the stress waves are additionally scattered and faster reaches the bottom of the unit cell

Effect of fiber volume fraction on stress waves

4 vol% fibers



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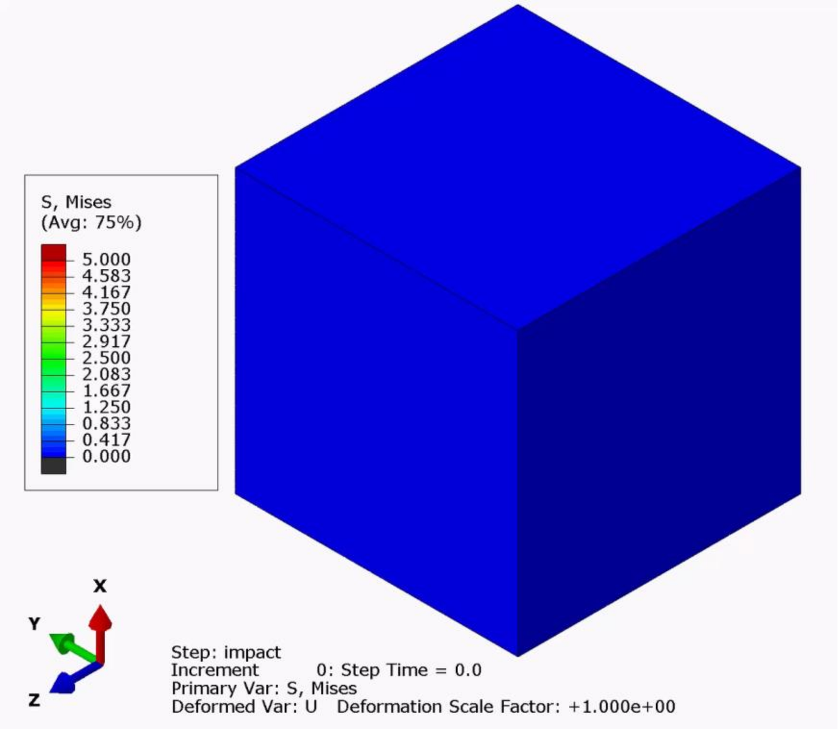
8 vol% fibers



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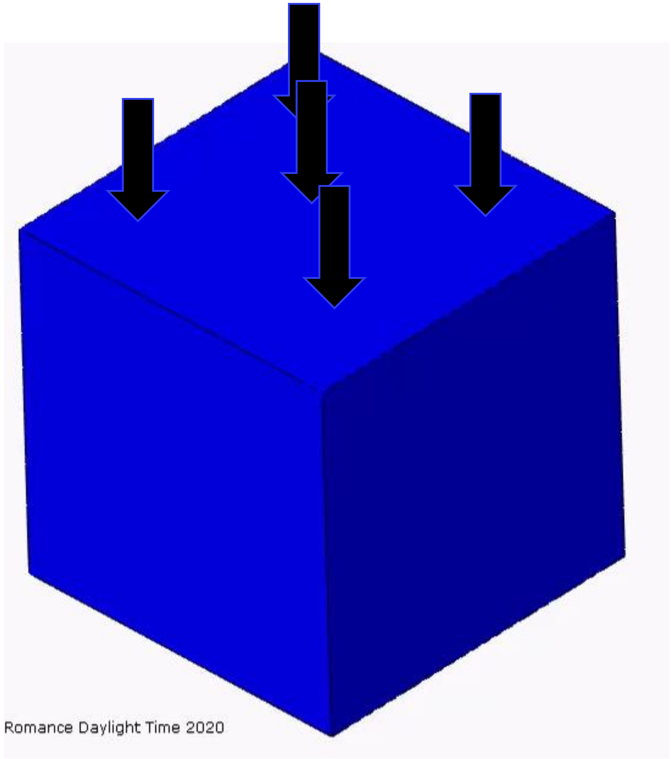
Hypothesis 2

Damping induced by fibers

“Bouncing” of unit cell to simulate damping



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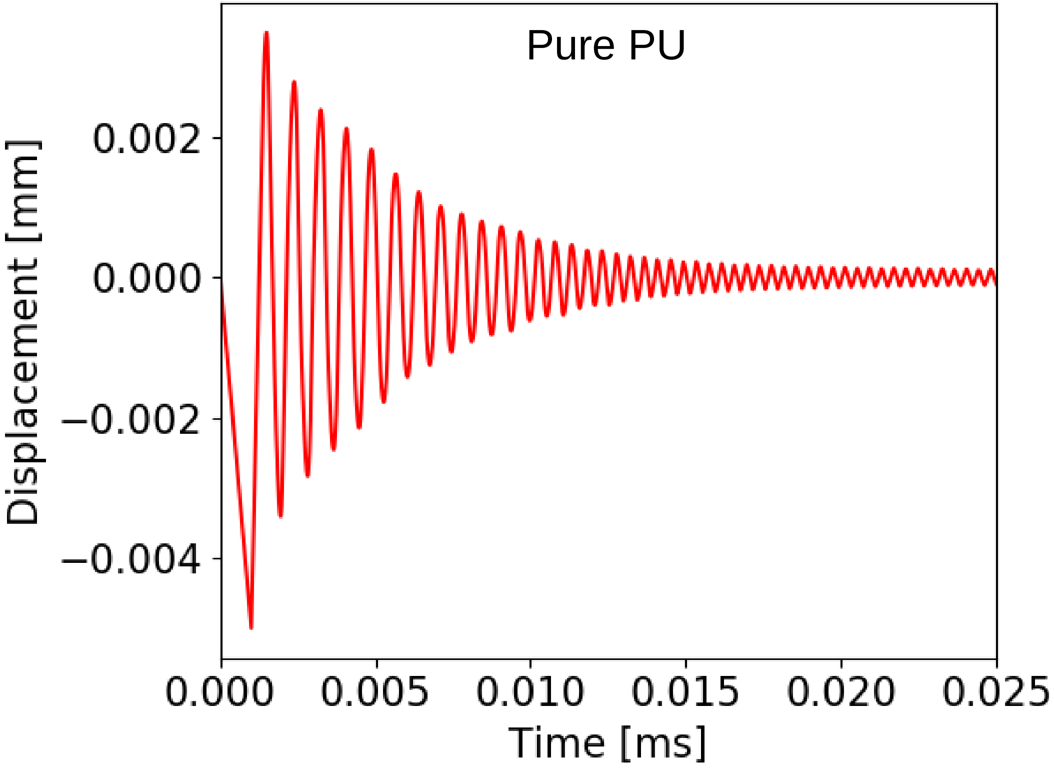
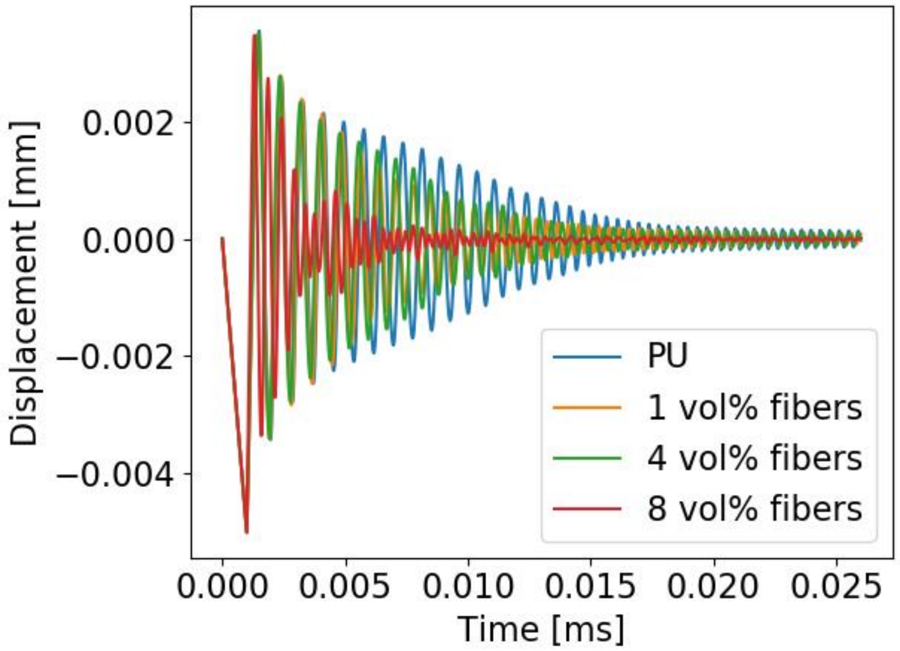
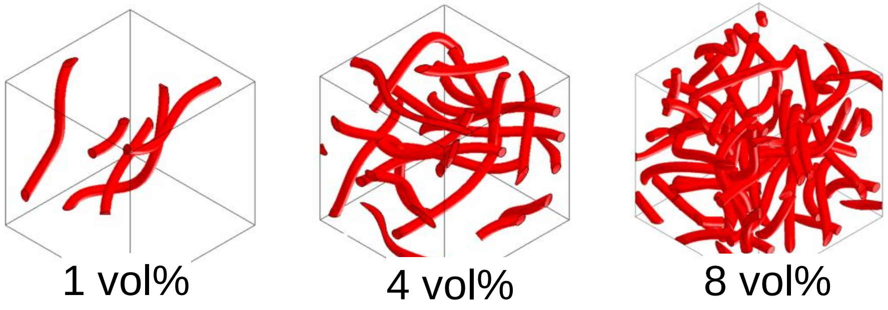
Average displacement of impacted surface



Inspired by vibrations theory the damping of the system can be estimated by how quickly the unit cell stops moving

Effect of fiber volume percentage on “damping”

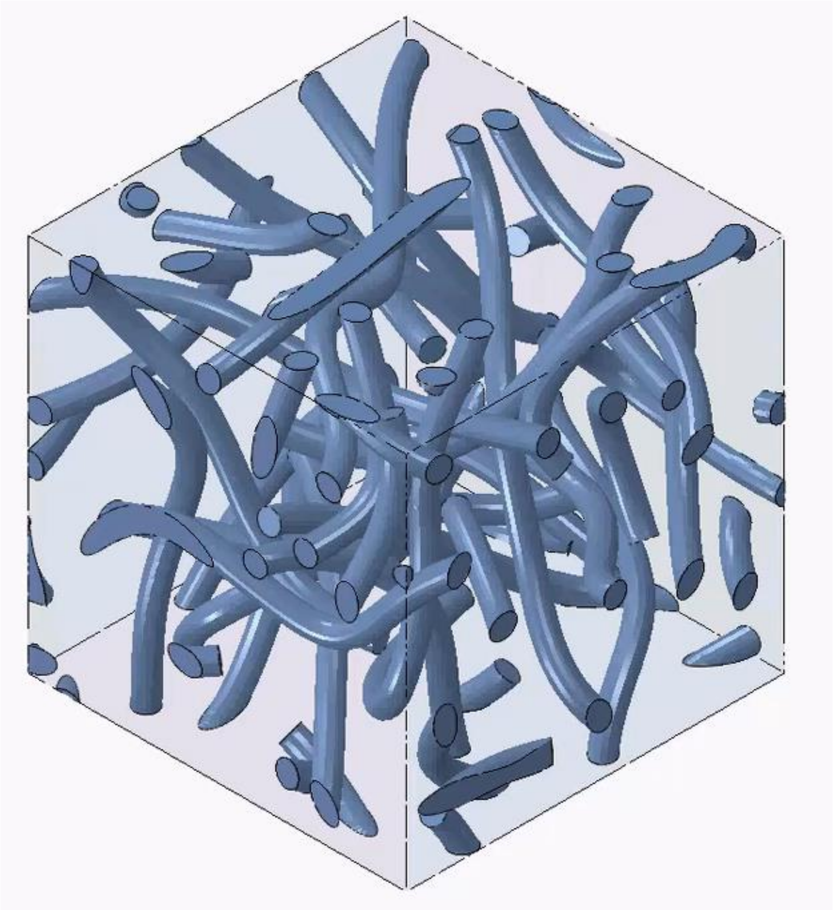




- Pure PU bounces with higher average amplitude and lower frequency than all fiber cases
- Not much difference between 1 vol% and 4 vol%
- For 8 vol% significantly different behavior is observed

→ Look into more details of the mechanisms of 8 vol% case

High stresses in matrix for 8 vol% fibers



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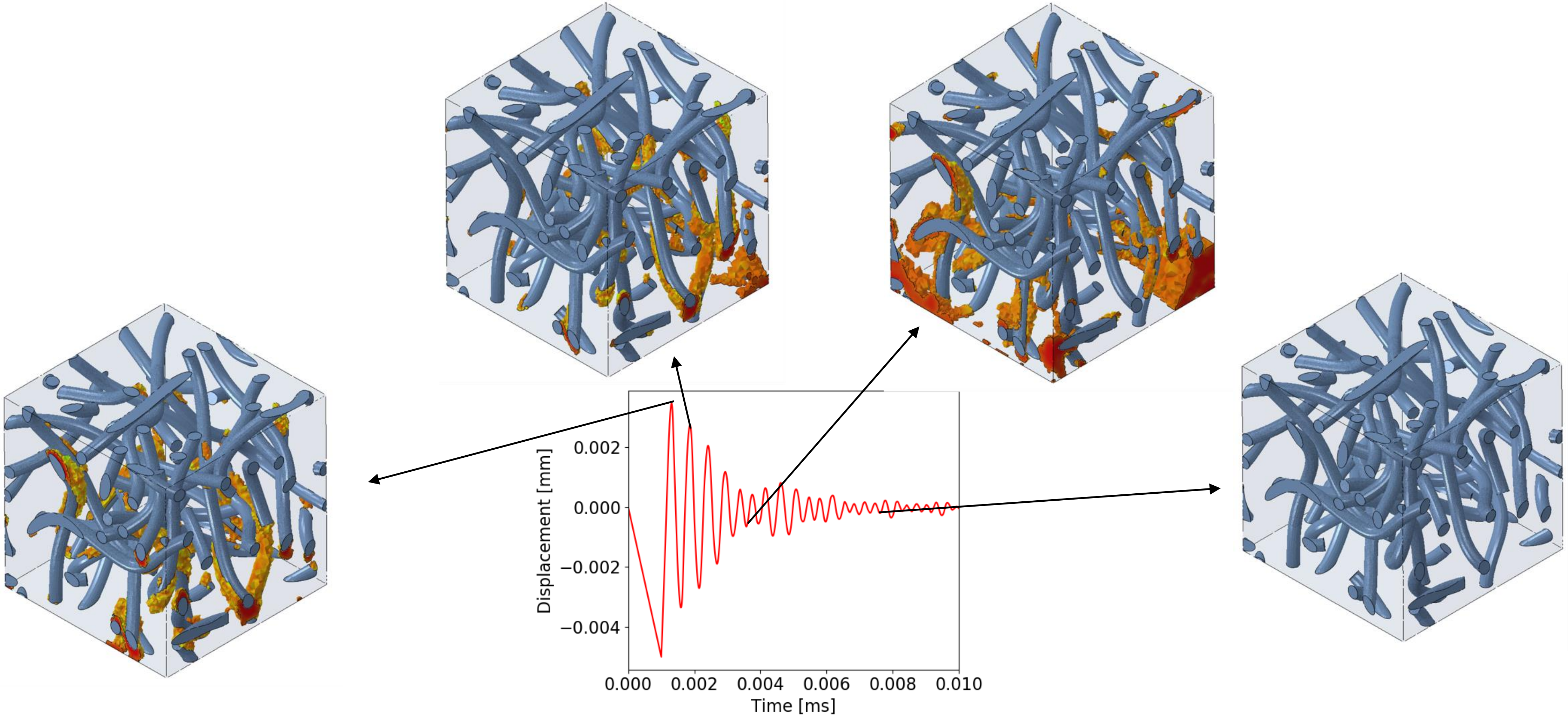
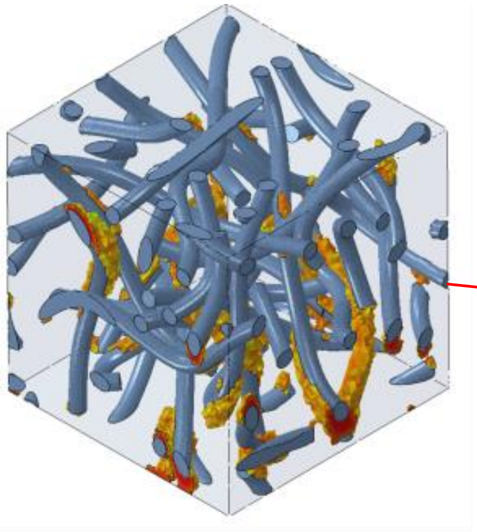
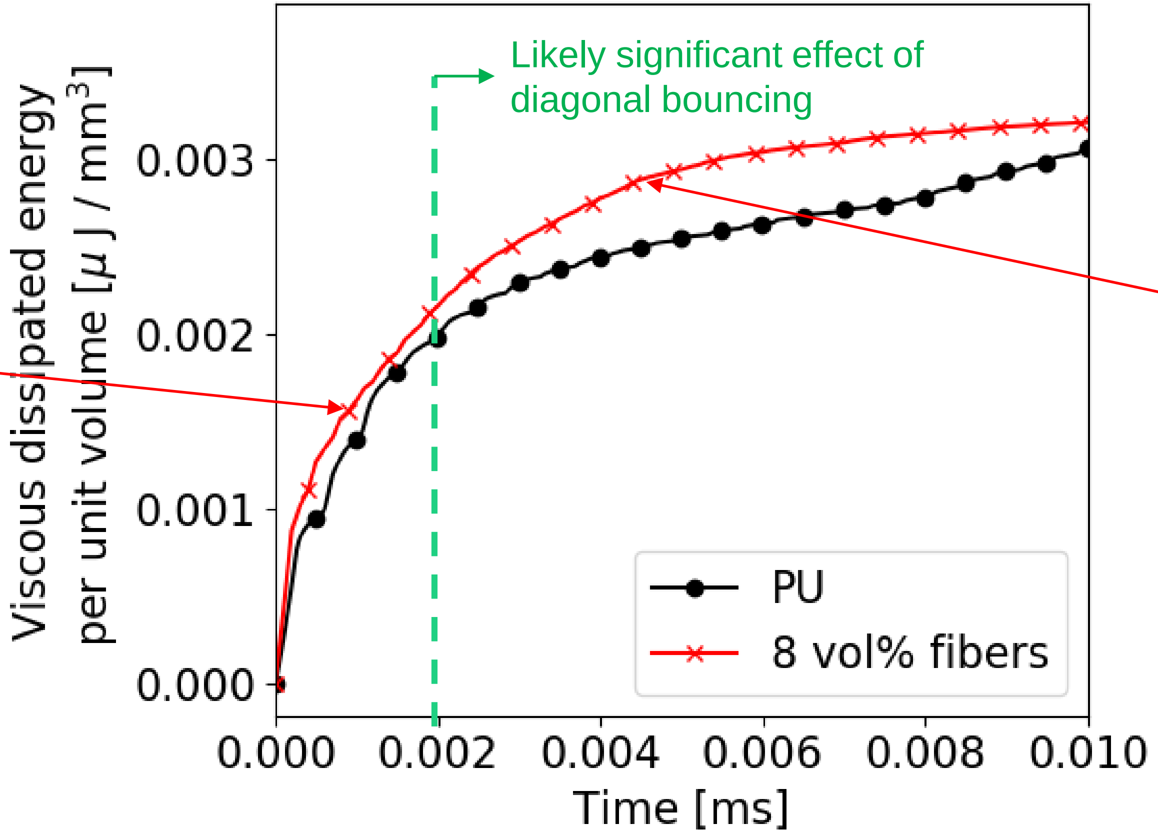
High stresses in matrix for 8 vol% fibers



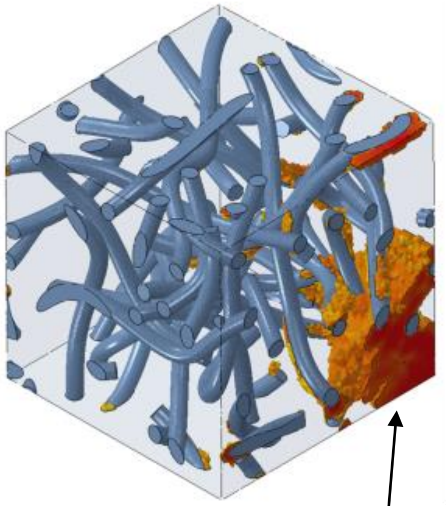
Viscoelastic damping of the unit cell

Uniform deformation of unit cell





Significant diagonal bouncing of unit cell



Energy dissipated due to boundary conditions rather than fibers

Considering larger volume and periodic boundary conditions could possibly fix this issue

Conclusions and outlook

On the potential of particles for erosion protection

- Presence of particles scatters the stresses – more pronounced for higher vol%
- Presence of fibers dissipates more viscous energy - more pronounced for higher vol%
- Additional viscous dissipated energy in high stressed regions could in turn also lead to crack initiation points if weak interfaces
- However, a highly interconnected network of pulp could potentially work as crack progression stoppers
  – Further work includes combined experimental trials and expanded models

Acknowledgements

- The authors gratefully acknowledge the financial support of the Innovation Foundation of Denmark in the framework of the Grand Solutions project DURALEDGE, Durable leading edges for high tip speed wind turbine blades, File nr.: 8055-00012A.

Extra

Duraledge project

- A total of six work packages, where the first three are:

WP1: Understanding of the leading edge erosion

- E.g. establish test and characterization methods to understand the behavior of existing coatings

WP2: Multiscale computational modelling and numerical simulation of leading edge erosion

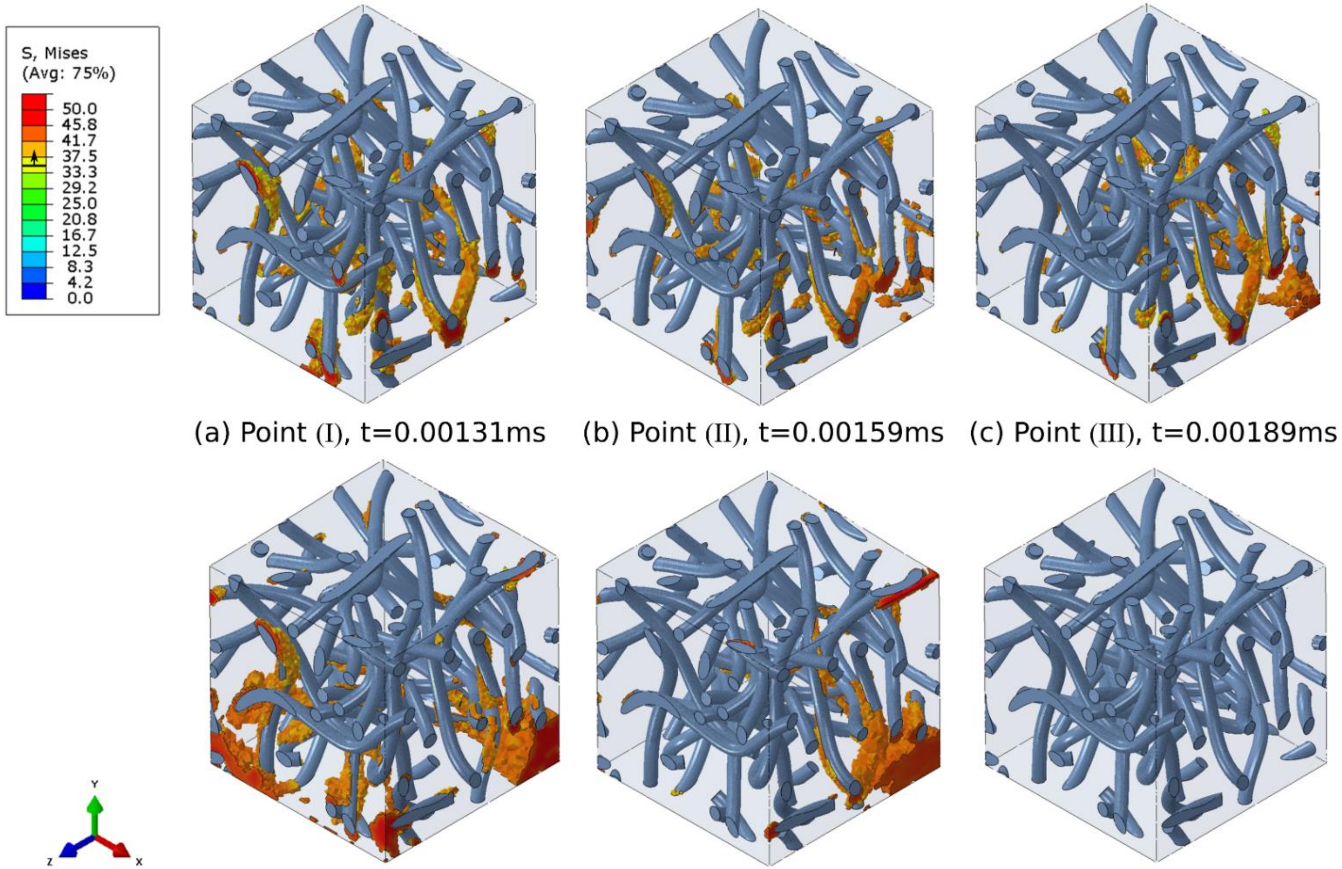
- Develop tools for numerical testing and optimization leading edge protection solutions

WP3: Optimized protective solutions with engineered coatings

- Develop new erosion resistant coating solutions

- Highly interconnected

Highest stresses in bouncing unit cell (8 vol% fibers)

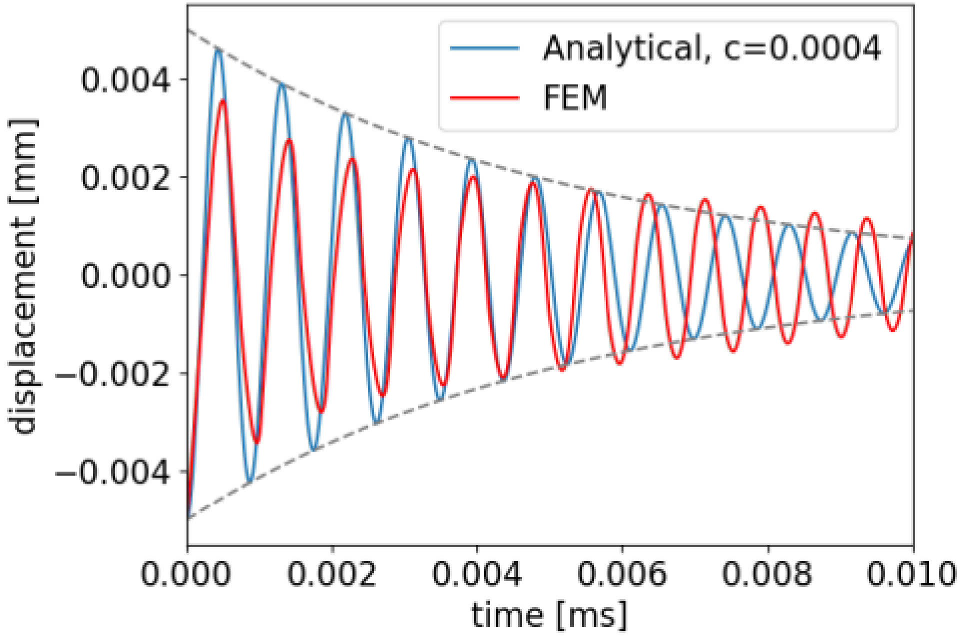


(a) Point (I), t=0.00131ms (b) Point (II), t=0.00159ms (c) Point (III), t=0.00189ms

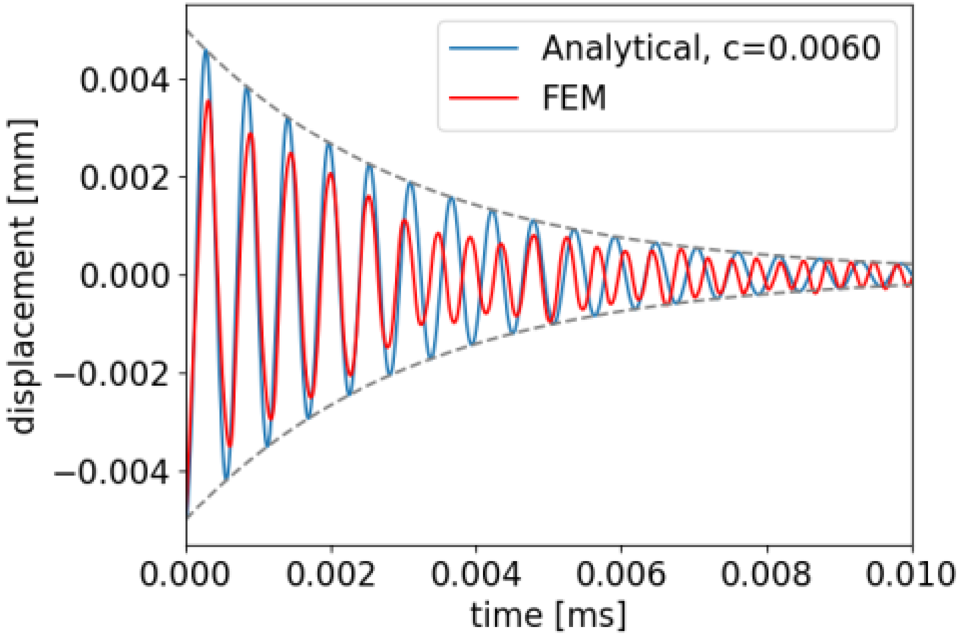
(d) Point (IV), t=0.00357ms (e) Point (V), t=0.00437ms (f) Point (VI), t=0.00732ms

[4] Jespersen K M, Monastyreckis G and Mishnaevsky L 2020 On the potential of particle engineered anti-erosion coatings for leading edge protection of wind turbine blades: Computational studies *IOP Conf. Ser. Mater. Sci. Eng.* **942**

Signals fitted to free vibration theory



(a) Pure PU



(a) 8% fibers

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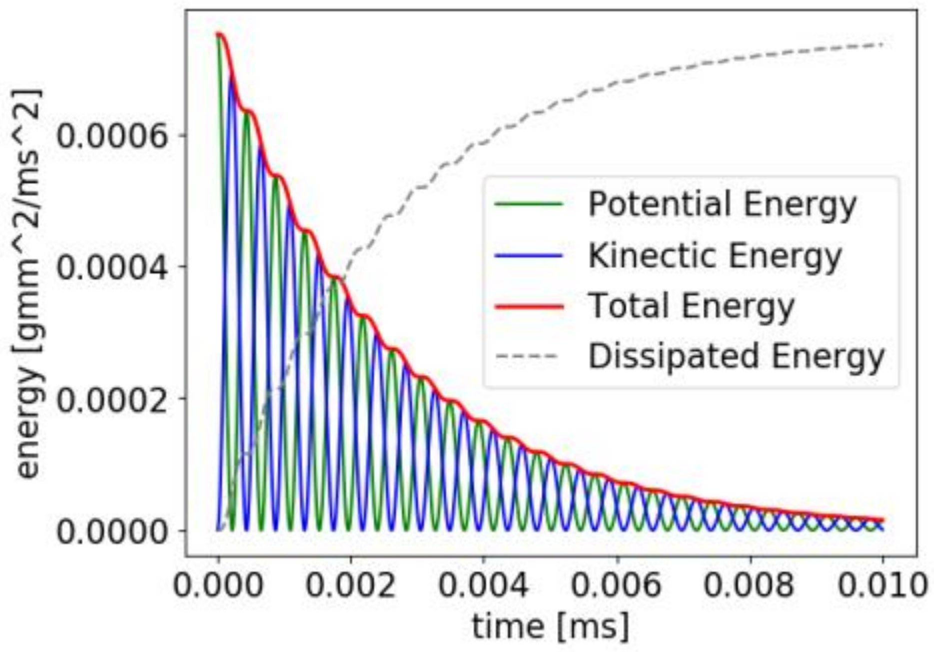
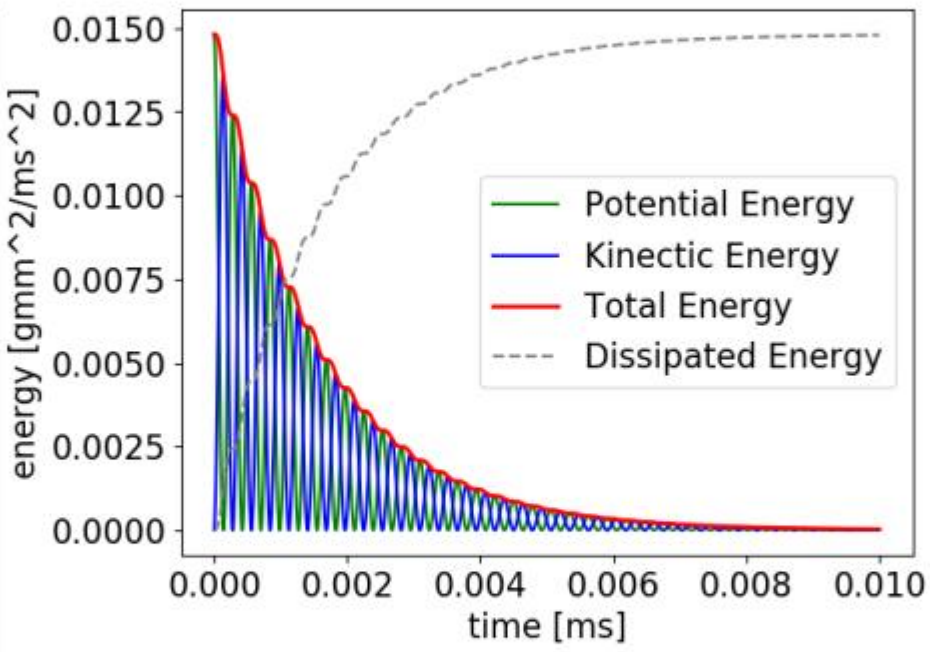
Signals fitted to free vibration theory (energy)



(a) Pure PU



(a) 8% Kevlar

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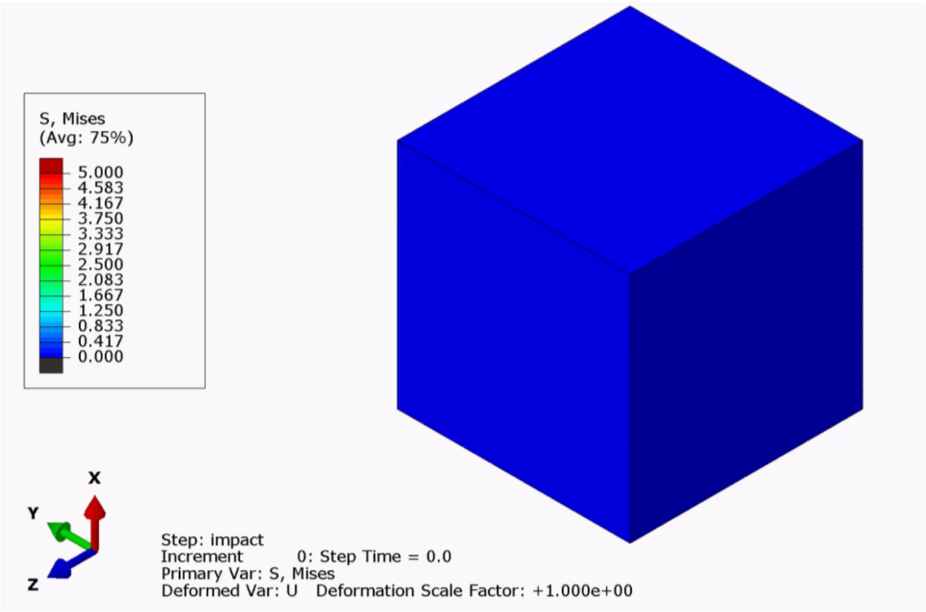
Material properties

Table 1: Elastic material properties and density

	Young's modulus [MPa]	Poisson's ratio [-]	Density [g/mm^3]
Polyurethane	300	0.475	0.00118
Kevlar	70500	0.36	0.00144
Nepheline Syenite	150000	0.2	0.0026

Effect of particles on stress waves

Pure PU



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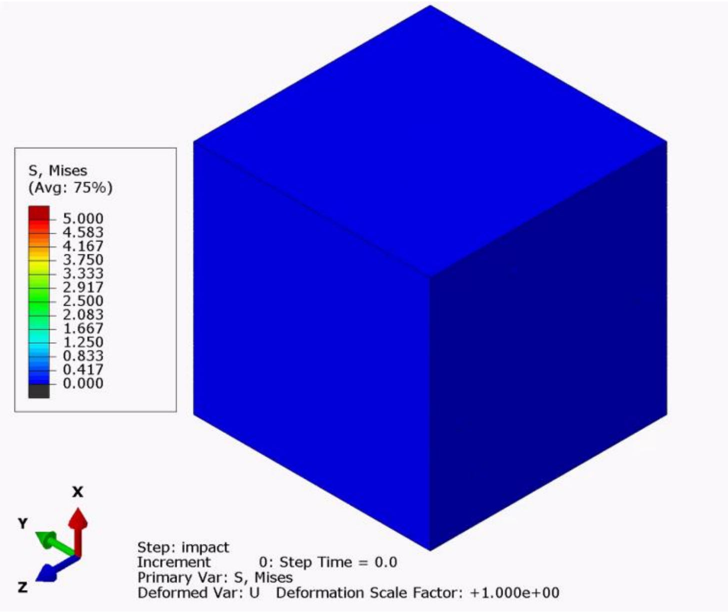
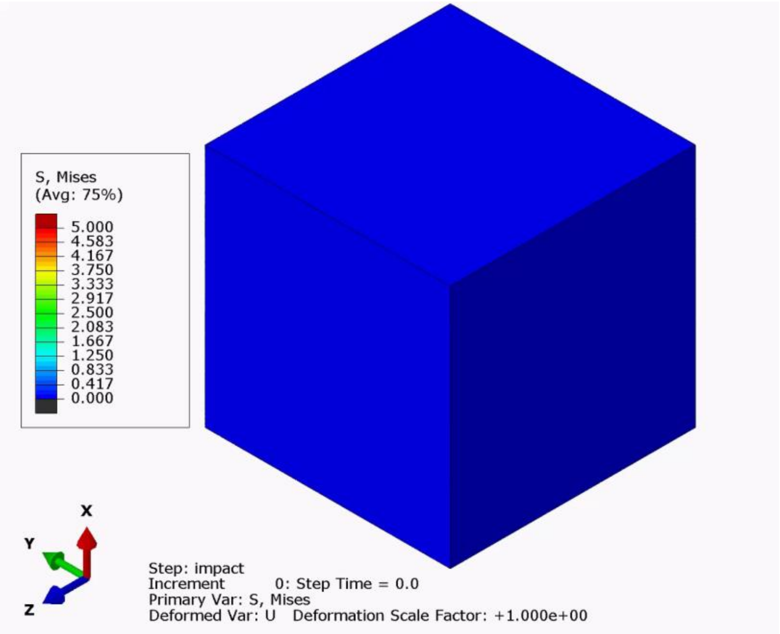
4 vol% discs



(video)

4 vol% fibers



(video)