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To cite this article: K M Jespersen *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **942** 012027

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On the potential of particle engineered anti-erosion coatings for leading edge protection of wind turbine blades: Computational studies

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Abstract. The potential of particle and fiber reinforced anti-erosion coatings for the protection of wind turbine blades is explored through computational modelling. A hypothesis that stiff disc-shaped particle or fiber reinforcements embedded in viscoelastic coatings ensure better erosion protection is validated numerically, and mechanisms of this effect are analyzed. A computational unit cell model of coatings with embedded fibers (fiber pulp) or disc particles subject to rain droplet impact is developed, and series of computational experiments is carried out. The distribution and scattering of stress waves from the rain droplet impact and damping properties are analyzed for homogeneous viscoelastic polyurethane coatings, coatings with disc-shaped particles, and fiber pulp. It is shown that the stress waves are increasingly scattered, and the damping is increased with higher volume percentage of the fibers. The mechanism of such increased energy dissipation is found to be related to the high local viscoelastic deformation in the regions between closely located fibers and the higher stiffness of the unit cell. The current work demonstrates the high potential of fiber engineered coatings for the improvement of anti-erosion protection of wind turbine blades.

1. Introduction

Leading edge erosion of wind turbine blades is one of the most common mechanisms of the blade degradation. The repair of eroded wind turbine blades, especially off-shore, is a quite expensive and labour consuming process [1]. With the blades becoming longer to increase the power output, the tip speeds increase and as a consequence, rain droplets and particles hit the blades at higher speeds. Significant efforts were put into developing new leading edge protection technologies to reduce the need for repair. Ideas have ranged from applying metal shields [2] and protective tapes [3] on the blade to developing advanced multi-layer coatings with particles [4]. Protective coatings can be applied in-mold and have practically no negative impact on the aerodynamic properties of the blade [2]. However, coatings which can last the entire 20-30 years of life of wind turbine blades have yet to be developed, and pushing the blade length to new limits will require even stronger erosion-resistant coatings in the future. Therefore, it is of great importance to continuously improve the coating solutions for wind turbine blades.

In [4], different effects and mechanisms to enhance the erosion resistance of blade coatings are reviewed, among them, the damping effect caused by the viscoelasticity of coatings, attenuation,



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dispersion and scattering of stress waves by inhomogeneities, mode conversion at interfaces, redirection, and conversion of deformation energy to heat by molecular relaxation processes. Dissipation of stress waves in composite materials can be caused by the viscoelastic nature of the resin and by scattering on inclusions. At high frequencies, the wavelength is not very large compared to the reinforcements size, and thus, the wave propagation can be influenced by particles. Multiple scattering of waves on particles lead to frequency-dependent velocity and attenuation of coherent waves. Several approaches and estimations were developed to model the wave scattering on the particles: scattered field expressions and quasi-crystalline approximation, models based on the causal differentiation method and Kramers-Kronig expressions between phase velocity and attenuation [5], the generalized self-consistent model by Christensen and Lo [6], and others [7, 8, 5, 9].

An interesting type of coating materials is the materials with Interpenetrating Polymer Networks (IPN). For instance, the damping properties of polyurethane can be improved by introducing epoxy to form a polyurethane/epoxy interpenetrating polymer network. The advantages of IPN as compared with pure polyurethane include better heat resistance, higher strength, and extension of the temperature range with sufficiently high damping peaks [10, 11]. Bicontinuous materials with high specific area and interlocked topology can make the material system defect-insensitive and enhance energy absorption of the materials. In several works, the optimization of IPN structures has been carried out to achieve the best damping properties [10, 11, 12]. Following [4], the assumption was formulated that the stiff distributed particles embedded in the coatings can enhance the erosion protection by scattering the impact wave from the rain droplet. Further, it is assumed that the embedded interconnected fibers (pulp) can also enhance the erosion resistance by creating an additional wave propagation mechanism (along the interfaces), additional damping mechanisms (pulp deformation) and also wave scattering. These assumptions are explored in this work using computational simulations.

2. Computational models

In order to explore the potential of structural modifications of anti-erosion coating materials, a series of computational studies have been carried out. Figure 1 shows examples of three considered damping mechanisms: (a) viscoelasticity, (b) disc-shaped particle reinforcement, (c) pulp (multiple elastic fibers) induced damping of the engineered coatings. Small unit cells models similar to that presented in Figure 2(b) were established. This section describes the materials and particle structures used for the modelling, along with the details of the modelling approaches.

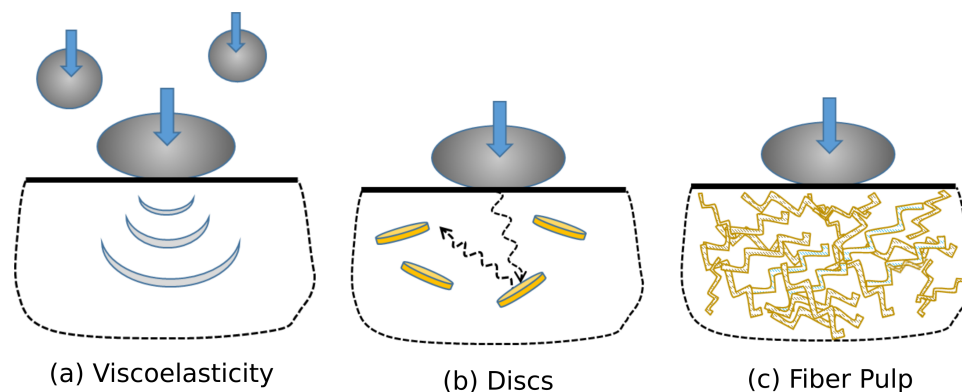


Figure 1: Considered damping mechanisms: (a) viscoelastic damping, (b) disc particle reinforcement induced damping, (c) fiber pulp enhanced damping.

2.1. Simplification of 3D model droplet impact

In the previous work by Doagou-Rad et al. [13, 14] the rain droplet impact on a polyurethane (PU) coated surface was simulated, however without taking the particles distributed in three dimensions (3D) into account. Figure 2(a) shows a droplet impact model similar to that presented in [13]. The material below the water droplet is subjected to stress waves travelling away from the impact location, and therefore the loading of a given material point will be different depending on location and time. To study the scattering of stresses, energy dissipation, and similar mechanisms that can improve the erosion resistance of coatings for different particles in detail while still keeping the problem relatively simple, small volumes (unit cells) were considered. Figure 2(b) shows one of the unit cells studied in this paper with 8 volume percentage (vol%) fibers. It is assumed that the considered volume is sufficiently small so that the impact load would be nearly homogeneously distributed on the surface.

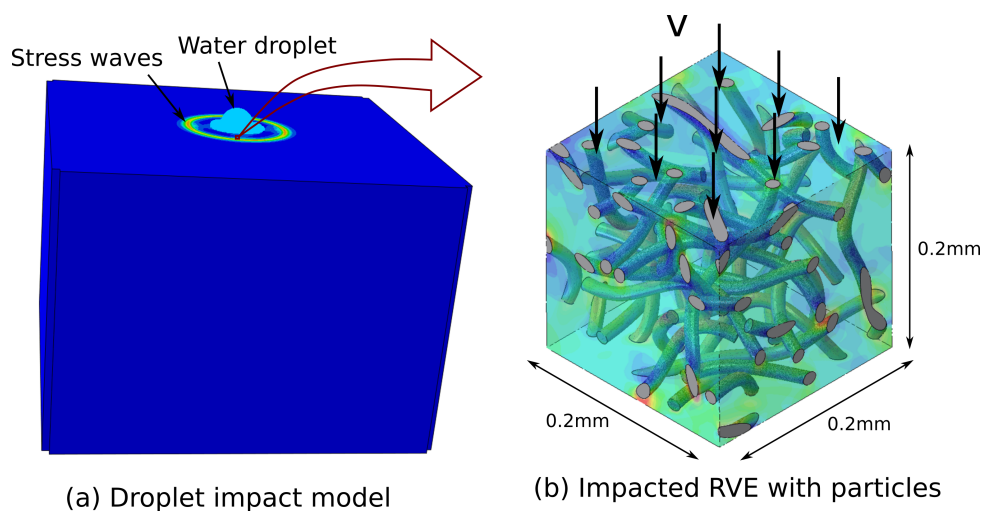


Figure 2: Principle of modelling simplification where a small material point of the full droplet model (a) is considered as a separate unit cell (b) with applied homogenized impact load.

2.2. Materials

Two different types of particles; discs with varying thickness and curved fibers (pulp) are modelled in this paper. Nepheline Syenite particles and Kevlar pulp were used as an example in this study. However, as several other types of particles with similar properties could be used as well, the names "discs" and "fiber pulp" will be used in the rest of the paper. The fiber pulp is modelled with a length of 0.5 mm and a constant diameter of $d = 12\mu\text{m}$. The discs were modelled with a diameter of $12\mu\text{m}$ and varying thickness of 1-6 μm , giving 2-12 aspect ratio values, respectively. PU was used as the matrix in the models and depending on the analysis was modelled as either linear elastic or hyper- and viscoelastic behaviour. The elastic material properties used for the particles and matrix are summarized in Table 1. The hyper- and viscoelastic behavior of the PU matrix used in this work was the same as that presented by Doagou-Rad et al. [13].

2.3. Explicit finite element impact models

Two types of models (A & B) utilizing different meshing approaches and workflow were used in the present work as listed below.

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

(A) Model with high time-resolution of initial impact (0-0.001ms)

(B) Model of over-time behaviour including damping from viscoelasticity (0-0.025ms)

For both model A and B, the model geometry was generated using the software Digimat. Figure 3 shows examples of the unit cells considered in the current study. The finite element modelling was carried out using Abaqus Explicit with an initial mass scaling factor of 2. All models were done with X, Y and Z-symmetry conditions applied to the unit cell sides and using 4-node tetrahedral elements (C3D4). Doagou-Rad et al. [13] reported that the von Mises stresses reached a maximum at approximately 0.001ms after droplet impact, and this was applied as the impact time for all the unit cell models. It was chosen to use a maximum deformation of 0.005 mm, giving a maximum strain of $\varepsilon = 0.025$ for all the modelled unit cells.

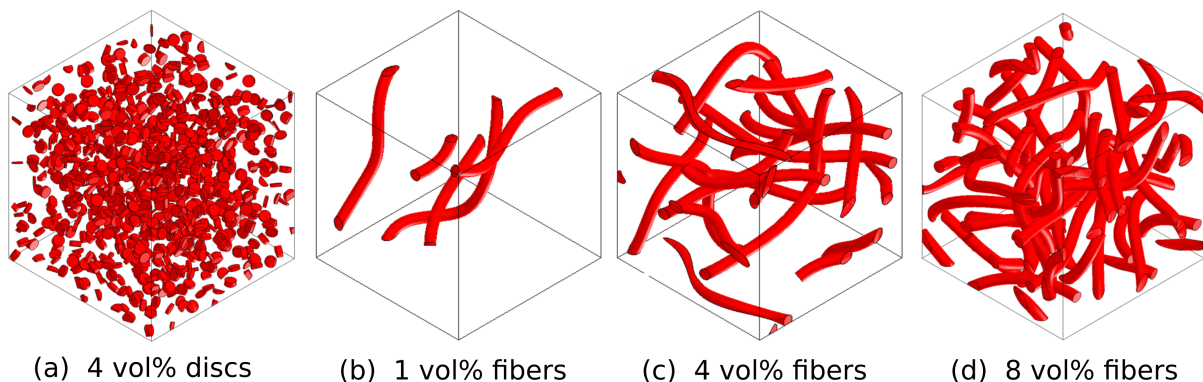


Figure 3: Examples of unit cells generated in Digimat used in the current study.

For model A, the model geometry generated in Digimat was imported as a step file into Abaqus where linear elastic material properties, boundary conditions and mesh were applied. The geometry was meshed in Abaqus which gave an overall number of elements ranging between 1.5-2.5 million, with a size of around 3 μm .

For model B, the unit cells were both generated and meshed in Digimat to be able to study a range of different fiber structures and volume percentages. After generating and meshing the unit cell in Digimat, the input file for Abaqus was exported. The input file was then changed into an explicit impact model by modifying the material properties, step, boundary conditions, history and field output directly in the file. This approach gives less freedom when meshing than using Abaqus as for model A, however it requires less manual work, making it suitable for parametric studies with focus on the overall behaviour.

Model B was carried out using visco- and hyperelastic material behavior for the PU introducing damping into the system. The fibers were modelled as linear elastic. The unit cells were impacted (pressed) and then released using a separate load step in Abaqus. The average displacement of the impacted surface of the unit cell was measured to be able to compare the damping of the different unit cells. The number of elements was up to around 2,500,000 and

down to 230,000 depending on the internal structure of the unit cell. For model B, all the analyses were carried out on a computer cluster, where a single model took up to 12 hours using 200 cores.

3. Results and discussion

3.1. Particle/impact wave interaction

In order to understand the stress distribution inside PU coatings reinforced by fiber pulp and discs, a high-resolution impact model (model A) was performed with a step time of 0.001 ns. Unit cell models of pure PU, 4 vol% discs, along with 4 and 8 vol% fibers were compared at the time of 0.2 ns, where the first stress wave was observed. Figure 4(a) shows the pure PU model with an average stress of 1.1 MPa, while the model with 4 vol% discs (b) shows much higher average stress values of 3.8 MPa and maximum stress peak of 142.3 MPa. The model with 4 vol% fibers (c) shows a similar average stress of 4.1 MPa, but the maximum stress peak reaches up to 667.5 MPa. The model with 8 vol% fibers (d) has stresses distributed throughout the whole unit cell model, an average stress of 6.7 MPa, and a stress peak of 693.7 MPa.

To further discuss the micromechanical stress-transfer mechanism, one can notice from Figure 4 that for both discs and fibers the stress is transferred from particle to particle, with higher stresses at shorter neighbor particle distances. The stresses build up inside the matrix in the range of 20-30 μm around the fibers (pulp diameter - 12 μm), while the stress around the discs

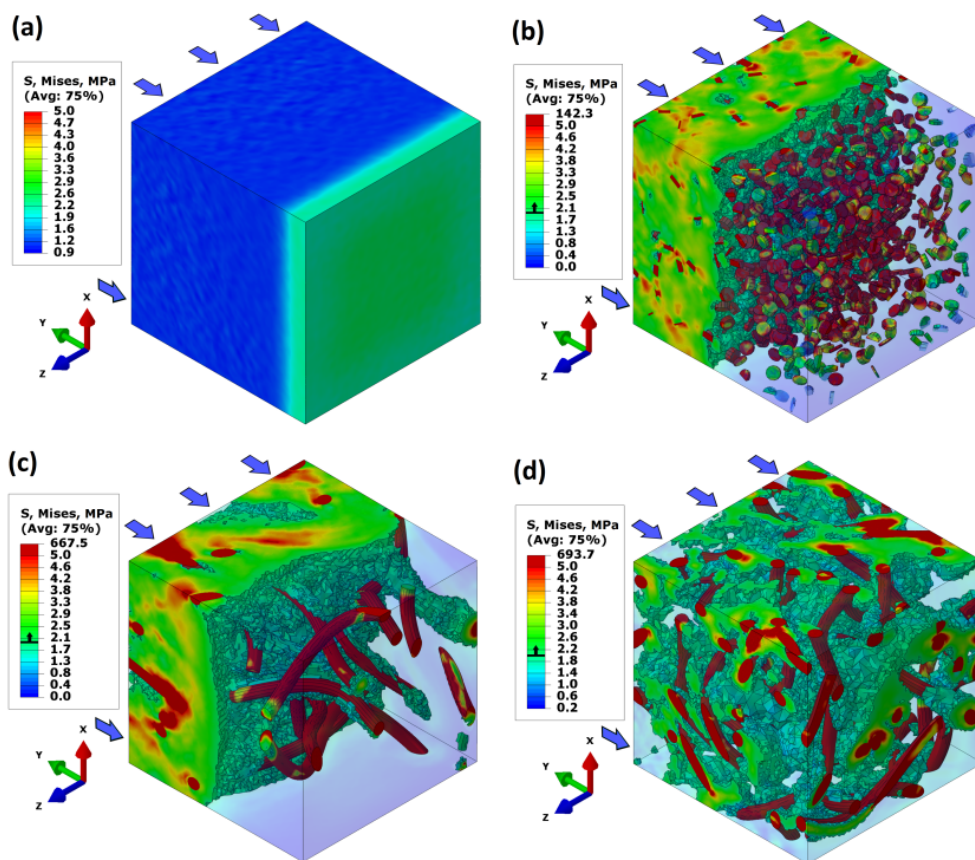


Figure 4: Initial impact models at the same time step ($t=0.2$ ns). (a) Pure PU, (b) 4 vol% discs, (c) 4 vol% fiber pulp, (d) 8 vol% fiber pulp. Stresses below 2 MPa have been hidden for clarity in (b)-(d).

penetrates only up to 5-10 μm . Additionally, as a single particle of the fiber pulp penetrate far into the depth of the unit cell, they transfer the stresses into the matrix further down at a shorter time than for the discs. In other words, although the overall stress wave is similar, the stresses are locally transferred into the matrix faster for the fibers than for the discs. As stresses are building up in a larger region for the fiber pulp than for discs, one can also expect an increased energy dissipation due to local viscous effects.

3.2. Effect of fiber pulp volume percentage on energy dissipation

To study the damping properties of the fiber pulp in more details, the movement (bouncing) of each unit cell after impact was modelled considering a longer time frame (0-0.025ms) including viscoelastic material properties (model B). Figure 5(a) shows the average displacement of the impacted surface as a function of time for different volume percentages of fibers compared to pure PU. Considering the average displacement, an increasing volume percentage seems to increase the damping and frequency of the unit cell. Increasing the volume percentage of stiff fibers also increases the overall stiffness of the unit cell, which according to vibrations theory will increase the damping and oscillation frequency. Additional local viscous effects are discussed in the following.

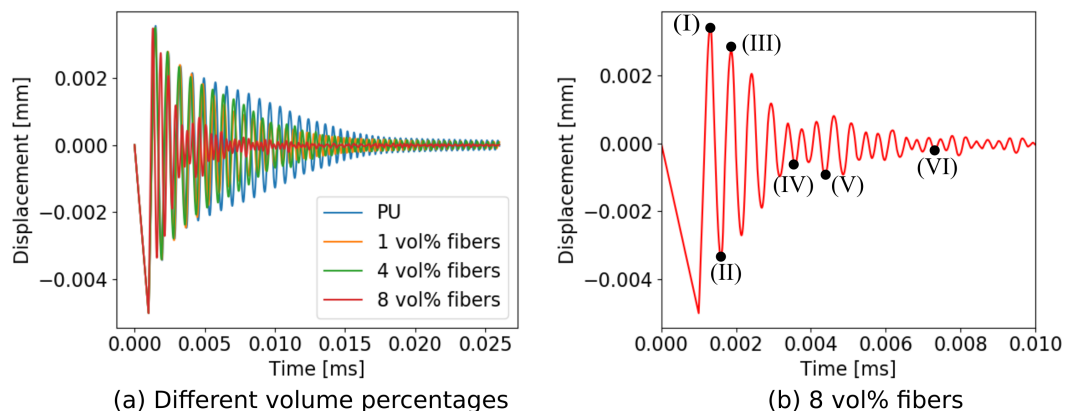


Figure 5: Average displacement of the impacted surface over time for (a) different volume percentage and (b) 8 vol%.

Figure 5(b) shows the time-displacement response for 8 vol% fibers with six marked points in time (I, II, III, IV, V, VI) and Figure 6 shows the highest matrix stresses in the unit cell for each of these time points. In Figure 6, all regions with stresses below 35MPa have been hidden, thus showing only the most stressed regions. Note that compared to Figure 4 which also included the fiber stresses, Figure 6 includes only the matrix stresses. It is seen that at the early stage ((a) and (b)) high stresses are present mainly between fibers located close to one another and along some specific fibers. The regions showing high stresses are relatively similar for when the unit cell is in tension (a) and compression (b). Shortly after impact, the unit cell starts to bounce diagonally as can be seen from the slightly increased stresses in the corners of the unit cell already in (c) and later more significantly in (d) and (e). After some time, the high-stress regions decreases significantly as shown in (f) indicating that most energy has been dissipated. Compared to pure PU where the stresses are evenly distributed, the presence of the fibers lead to regions with more localized stresses where additional energy is dissipated due to the viscoelastic properties of the PU matrix. This is also supported by Figure 7 which shows the energy dissipated by viscous effects for the whole model over time extracted from Abaqus for 8 vol% fibers and pure PU. The fiber case is seen to faster dissipate energy than pure PU.

In other words, the improved damping properties seem to be both a result of the increased unit cell stiffness and due to local viscous energy dissipation from the fiber structure.

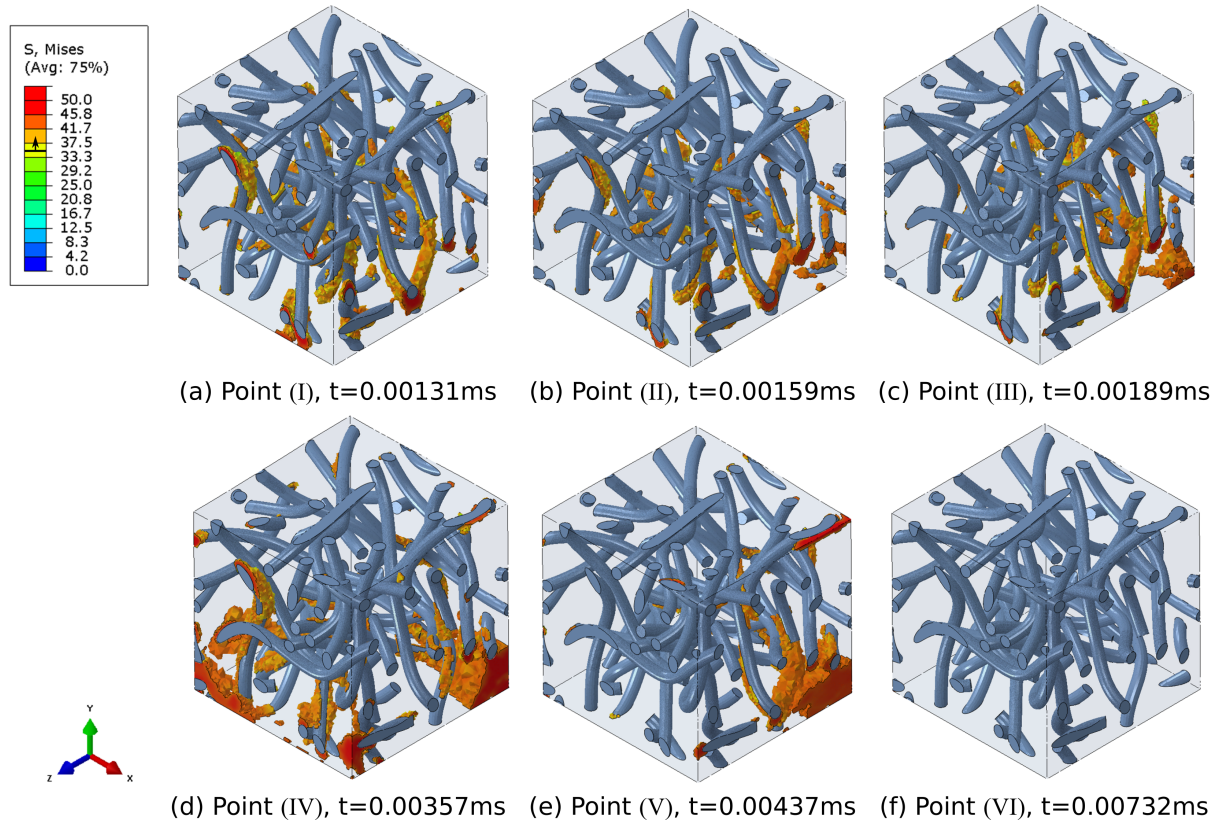


Figure 6: Von Mises stresses in the matrix above 35 MPa for different time points referring to Figure 5(b) after impact on the top surface in the negative Y-direction.

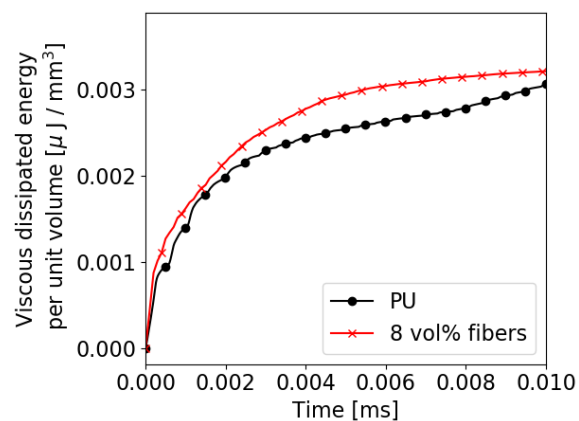


Figure 7: Energy dissipated by viscous effects per element volume in Abaqus models for 8 vol% fibers and pure PU.

3.3. Potential of fiber engineered coatings

As discussed in the introduction, the erosion resistance of blade coatings can be improved by exploiting the viscoelastic damping effect and scattering of stress waves by inhomogeneities. The current work has shown that the presence of fiber pulp (elastic curved fibers) in a viscoelastic resin leads to enhanced scattering of the stress waves, which in turn increases with higher volume percentages (Figure 4(d)). Furthermore, studying the time-displacement response of the unit cells after impact revealed locally higher energy dissipation in regions where stresses build up, particularly near fibers and in regions where the fibers lie close to one another. In addition, even further energy dissipation effects are expected when considering larger network of clustered fibers and the effect of interface behavior between the fiber and matrix. Therefore, the results show good potential of fiber engineered coatings as playing an important role in new future erosion-resistant coating systems for wind turbine blades.

4. Conclusion

In this study, the potential of particle engineered reinforcement of anti-erosion polyurethane coatings for better protection of wind turbine blades against rain erosion was investigated. In a series of computational studies, the effect of discs and fiber pulp reinforcements on the stress wave propagation, wave scattering, and damping in the coating under rain droplet impact was studied. It was demonstrated in the numerical experiments that the coating with an embedded network of stiff elastic curved fibers show enhanced damping and energy dissipation, and therefore better erosion protection can be expected. The embedded particles cause additional wave scattering mechanisms, and viscoelastic energy dissipation was observed in highly stressed regions between closely located fibers. Therefore, particularly for higher volume percentage of fibers, the impact energy of a rain droplet is expected to be dissipated faster for the particle reinforced coatings than for pure polyurethane coatings. Scattering of stresses and increased damping properties serve to improve the erosion resistance of coatings and therefore it was concluded that fibers or similar particles have great potential as a part of new improved leading edge erosion solutions.

Acknowledgments

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

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