



# Modeling real fibers: everything you need to know about the Rocky DEM flexible fiber model

Rocky DEM's flexible fiber model includes **plastic deformation** effects, **anisotropy**, and an integrity **failure model**, which allow you to cover a wider range of fiber materials in more complex equipment and with higher fidelity.

This white paper covers Rocky DEM's flexible fiber model as well as some application examples.

## How does Rocky model flexible fibers?

**Flexible fiber modeling** in Rocky follows the approach described by Guo et al. [1]. In this approach, a flexible fiber is built by connecting **sphero-cylinders** by means of **joints**, as depicted in Figure 1.



Figure 1. Schematic drawing of a fiber composed of several sphero-cylinder elements.

An auxiliary entity with **elastic** and **viscous** properties, a joint connects two adjacent sphero-cylinder elements.

Initially, the centers of the hemispherical ends of adjacent elements coincide, and the joints are undeformed. However, when the elements move, the **relative movement** between them may produce **linear** deformations (**normal** and **tangential**) and/or **angular** deformations (**bending** and **torsion**) on the joints, as shown in Figure 2.

In response to these deformations, **forces** and **moments** are induced and exerted on the adjacent elements to resist these deformations.

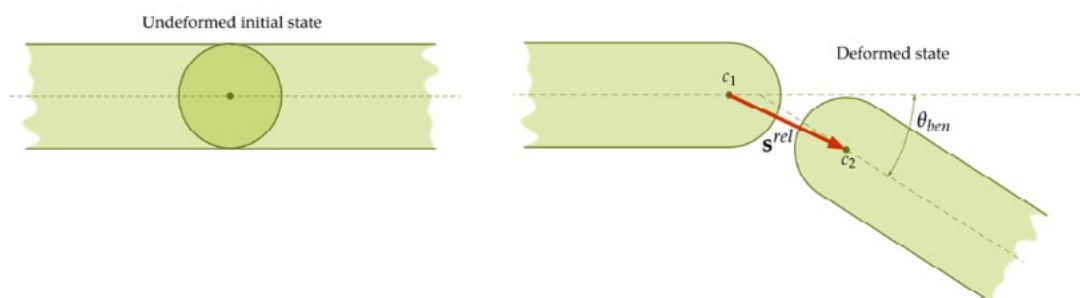


Figure 2. A fiber joint in its undeformed initial state (Left). A fiber joint in a deformed state showing the relative movement between elements and the bending deformation (Right).

## What if the fiber has a complex shape?

Using the Rocky flexible fiber model, you are not limited to **straight fibers**. You can create your own fiber shape using the **custom fibers** option, in which **sphero-cylinder** segments can be arranged to form **complex, multi-branched geometries**, as shown in Figure 3.

Also, the modeled segments can have **different diameters** and **Young's moduli**. This allows you to define a custom fiber with **non-uniform flexibility**.

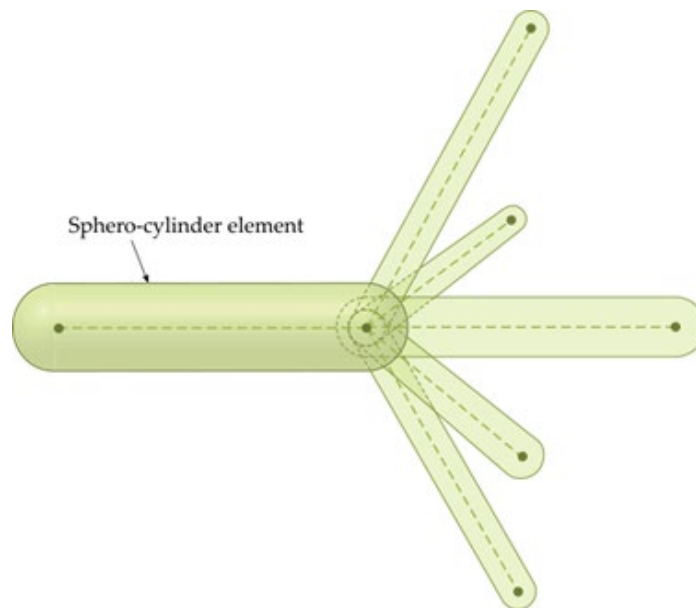
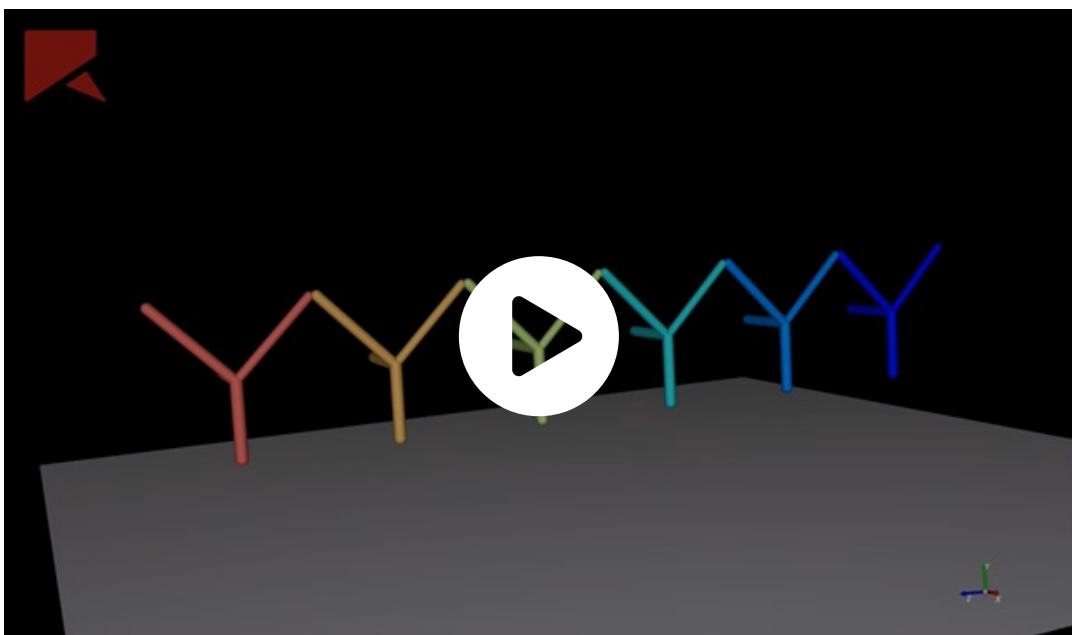


Figure 3. Multi-branched fiber with different diameters and non-uniform flexibility.

The video below shows an example where each particle has a different combination of **bending stiffness** for its branches.



Video 1. Custom flexible fibers with different bending stiffnesses for its branches.

## What if the fiber is anisotropic?

It is possible to define an elastic ratio **individually** for each joint deformation: **normal**, **tangential**, **bending**, and torsion. By defining a ratio that multiplies the stiffness computed from the particle material and geometrical properties, you can tune the **effective stiffness** for one or more directions. Using the anisotropic model, the range of materials that can be modeled is considerably wider.

In the example shown in Figure 4 below, similar flexible fibers are bending due to their own weight. In purple, the fiber is isotropic, i.e., it has the same stiffness for bending as for traction. In yellow, the fiber is anisotropic, and the bending resistance is almost null. The image on the right shows how the yellow fiber's behavior matches an analytical catenary curve.

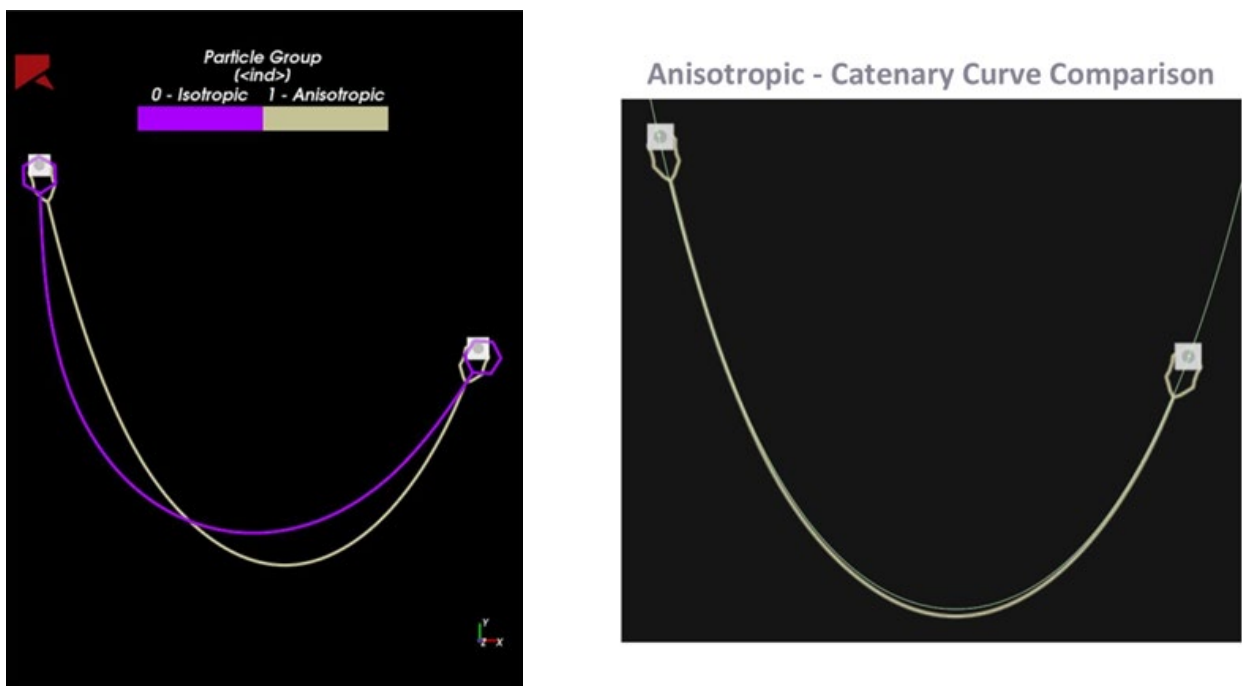


Figure 4. Anisotropy Influence: The purple fiber has the same bending stiffness for all deformations, whereas the yellow fiber has bending stiffness less than other stiffnesses (Left). The yellow fiber anisotropic behavior closely matches a catenary curve (Right).

## How do you compute the forces and moments?

For a flexible fiber, the forces and moments are computed (as is the case for any other particle in Rocky) as functions of the **linear and angular deformations**. The different models available in Rocky are described below.

### The linear elastic model

This is the most basic model in Rocky. In this model, the forces (normal force,  $F_n$  and tangential force,  $F_t$ ) and moments (bending moment,  $M_{ben}$  and torsional moment,  $M_{tor}$ ) are **directly proportional** to the **deformations** (normal deformation,  $s_n^{rel}$ , tangential deformation,  $s_t^{rel}$ , angular bending deformation,  $\theta_{ben}$  and angular torsional deformation,  $\theta_{tor}$ ), as shown in Figure 5.

Each proportionality factor (**stiffness,  $K$** ) is computed based on material properties (Young's modulus and Poisson's ratio) and geometrical properties (such as cross-sectional area and moments of inertia).

$$F_n = K_n s_n^{rel}$$

$$F_\tau = K_\tau s_\tau^{rel}$$

$$M_{ben} = K_{ben} \theta_{ben}$$

$$M_{tor} = K_{tor} \theta_{tor}$$

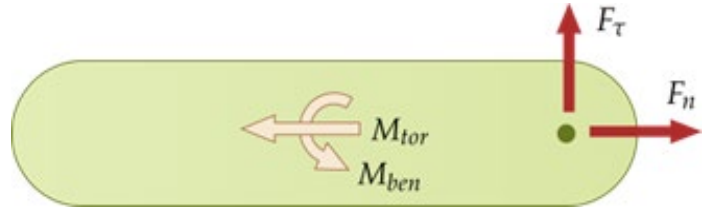


Figure 5. Forces and moments for the linear elastic model, where  $F_n$  is the normal force,  $F_\tau$  is the tangential force,  $M_{ben}$  is the bending moment,  $M_{tor}$  is the torsional moment,  $s_n^{rel}$  is the normal deformation,  $s_\tau^{rel}$  is the tangential deformation,  $\theta_{ben}$  is the angular bending deformation,  $\theta_{tor}$  is the angular torsional deformation,  $K_n$  is the normal stiffness,  $K_\tau$  is the tangential stiffness,  $K_{ben}$  is the bending stiffness and  $K_{tor}$  is the torsional stiffness.

### The linear elastic + viscous damping model

In order to dissipate oscillations, it is possible to add **viscous damping forces** (normal viscous damping force,  $F_n^v$  and tangential viscous damping force,  $F_\tau^v$ ) and **moments** (bending damping moment,  $M_{ben}^v$  and torsional viscous damping moment,  $M_{tor}^v$ ) to the elastic ones. For this model, the damping terms are proportional to the **relative linear velocities** (normal velocity,  $v_n^{rel}$  and tangential velocity  $v_\tau^{rel}$ ) and relative **angular velocities** (bending angular velocity,  $\omega_{ben}$  and torsional angular velocity  $\omega_{tor}$ ).

When using this model, forces and moments are modeled as the sum of two parts: an **elastic** one and a **damping** one, as shown in Figure 6.

$$F_n^v = C_n v_n^{rel}$$

$$F_\tau^v = C_\tau v_\tau^{rel}$$

$$M_{ben}^v = C_{ben} \omega_{ben}^{rel}$$

$$M_{tor}^v = C_{tor} \omega_{tor}^{rel}$$

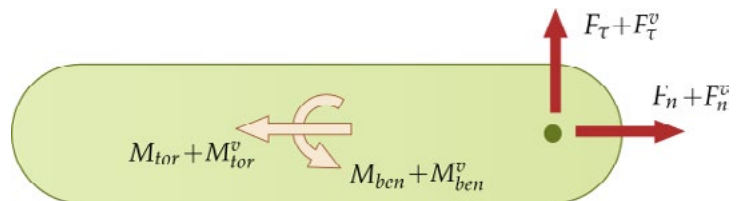


Figure 6. Viscous damping forces and moments for the viscous damping model, where  $F_n^v$  is the normal viscous damping force,  $F_\tau^v$  is the tangential viscous damping force,  $M_{ben}^v$  is the bending damping moment,  $M_{tor}^v$  is the torsional viscous damping moment,  $v_n^{rel}$  is the normal velocity,  $v_\tau^{rel}$  is the tangential velocity,  $\omega_{ben}$  is the bending angular velocity and  $\omega_{tor}$  is the torsional angular velocity.

## The bilinear elastoplastic model

In the same line of modeling different materials, the bilinear elastoplastic model was added as an extra option. This model is applied only to angular deformations (bending and torsion) and includes two linear regimes with different stiffnesses, as shown in Figure 7. The transition between the elastic and elastoplastic regimes occurs at a limiting angle, given by the user.

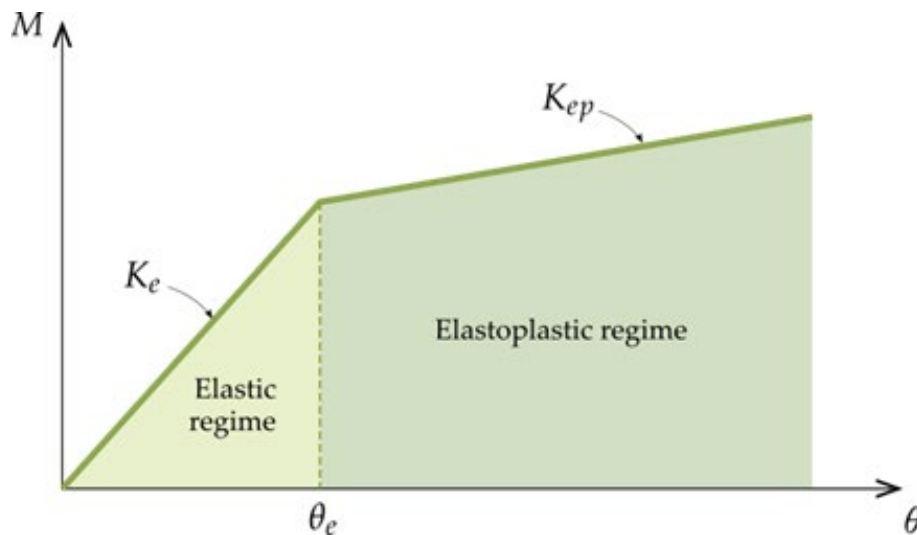
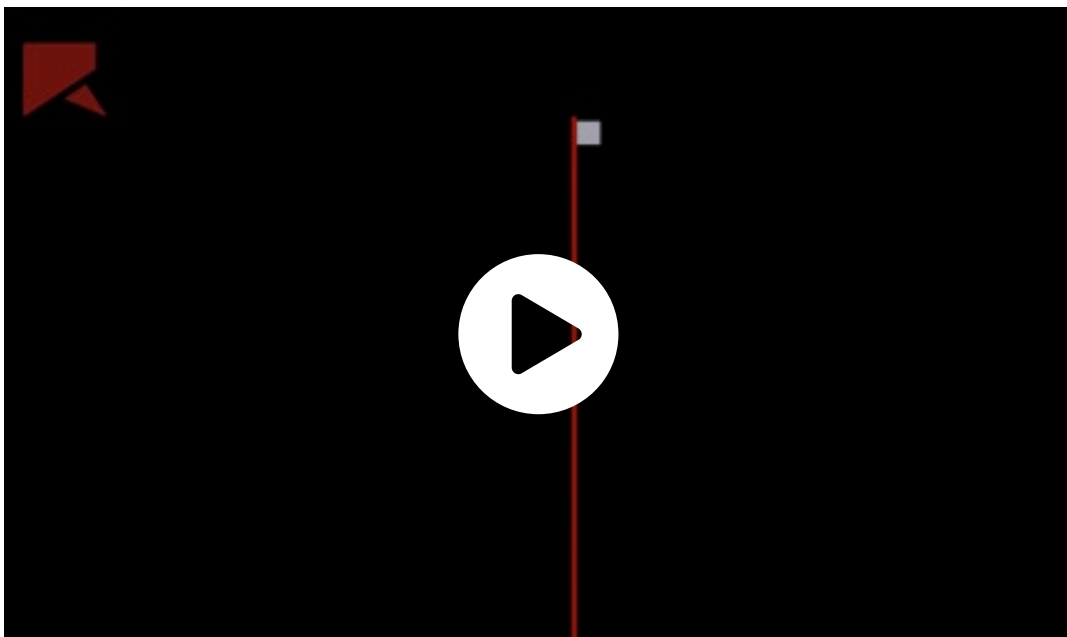


Figure 7. Bilinear elastoplastic model regimes.

Video 2 below shows how the fiber bends differently before and after reaching this limiting angle.

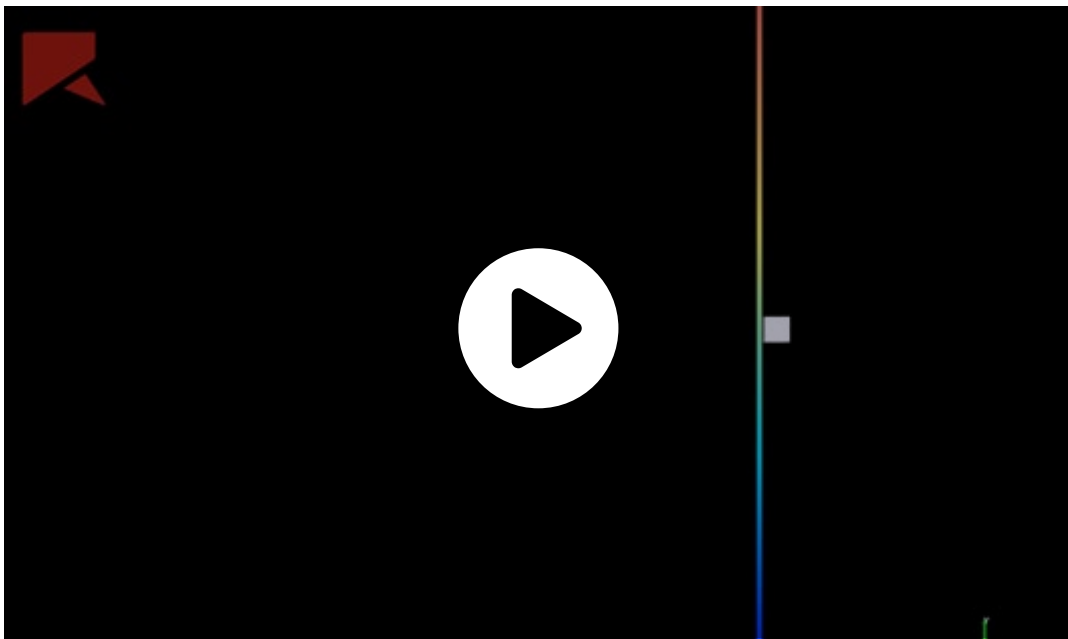


Video 2. Fiber bending before and after reaching the limiting angle for the bilinear elastoplastic model.

## The bilinear elastoplastic model with failure

When using the **bilinear elastoplastic** model, you can add a **failure criterion**. When the failure option is enabled, a **sudden drop** on the moment value happens when the angular deformation reaches the limiting value that controls the elastic-elastoplastic regime transition.

The **bilinear elastoplastic** model allows you to model the loss of joint stiffness without rupture, i.e., without element separation. This model can be used, for example, to model green tree twigs or branches. The behavior of the fiber before and after failure can be seen in Video 3 below.



Video 3. Fiber modeled using the bilinear elasto-plastic model with the failure criterion.

## What if you want the flexible fibers to break?

In Rocky DEM, flexible fibers can break according to two different criteria, as explained below.

### Griffith surface energy criterion for breakage

With the Griffith surface energy criterion, **rupture** occurs when the **tensile stress** at the joint is greater than the **fracture stress**,  $\sigma_n^f$  (as shown in Figure 8). The **fracture stress**, by its turn, is related to the **surface energy**.

$$\frac{F_n}{A} \geq \sigma_n^f$$

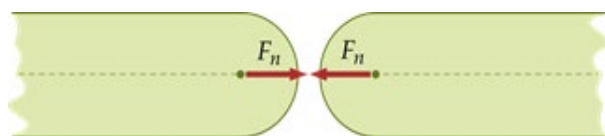
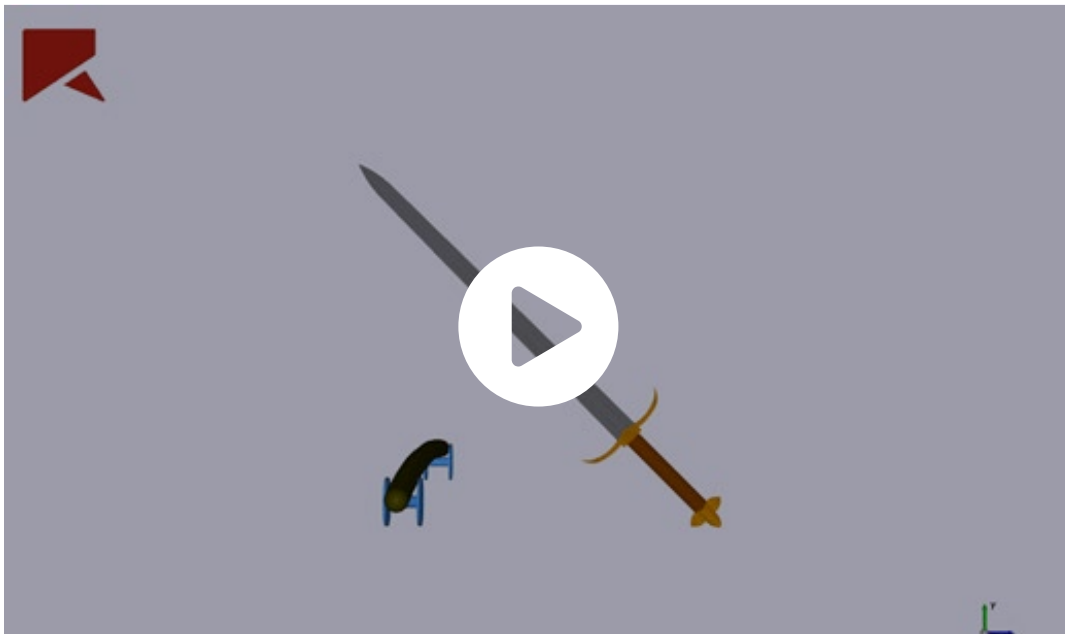


Figure 8. Griffith surface energy criterion for breakage.

Video 4 below shows an example of fiber breakage using the shear stress criterion.



Video 4. Fiber breakage using the shear stress breakage criterion.

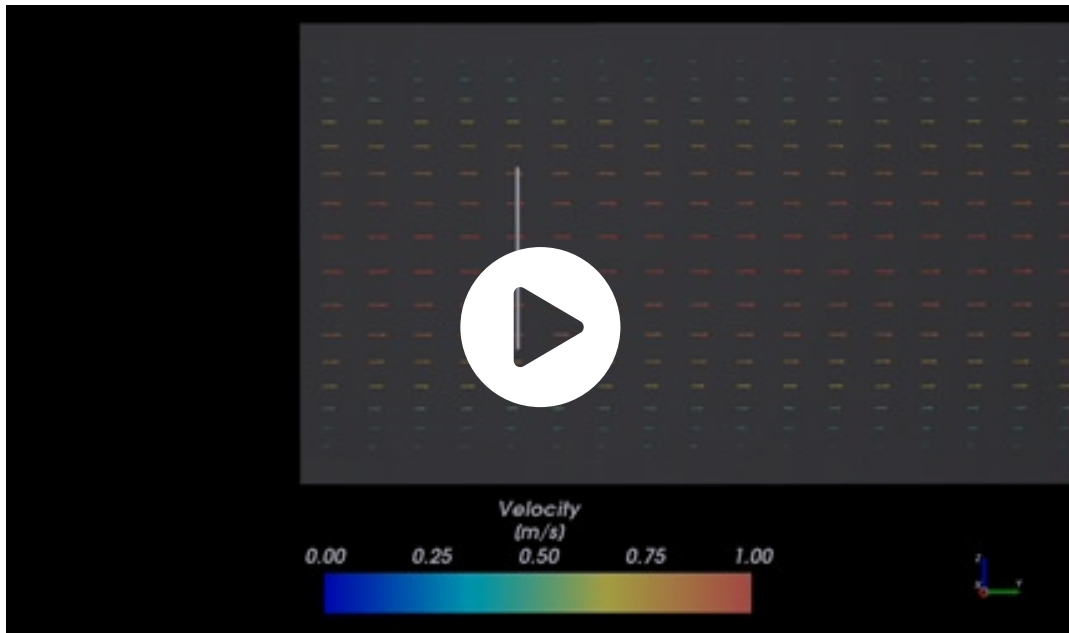
## What if it is a fluid-driven problem?

In many cases, in order to predict the particle trajectory, it is important to consider the **fluid forces** acting on particles. For many applications, the fluid drag is the driving force for the fibers in the system.

For fibers, Rocky uses the **Marheineke & Wegener drag model** [2] that was developed for **long slender fibers** immersed in turbulent dilute flows. This model decomposes the force into normal and tangential components and is uniformly valid for all Reynolds number regimes. By taking into account the **fiber orientation** and **alignment** with the incident flow, the the drag coefficient estimate is more accurate.

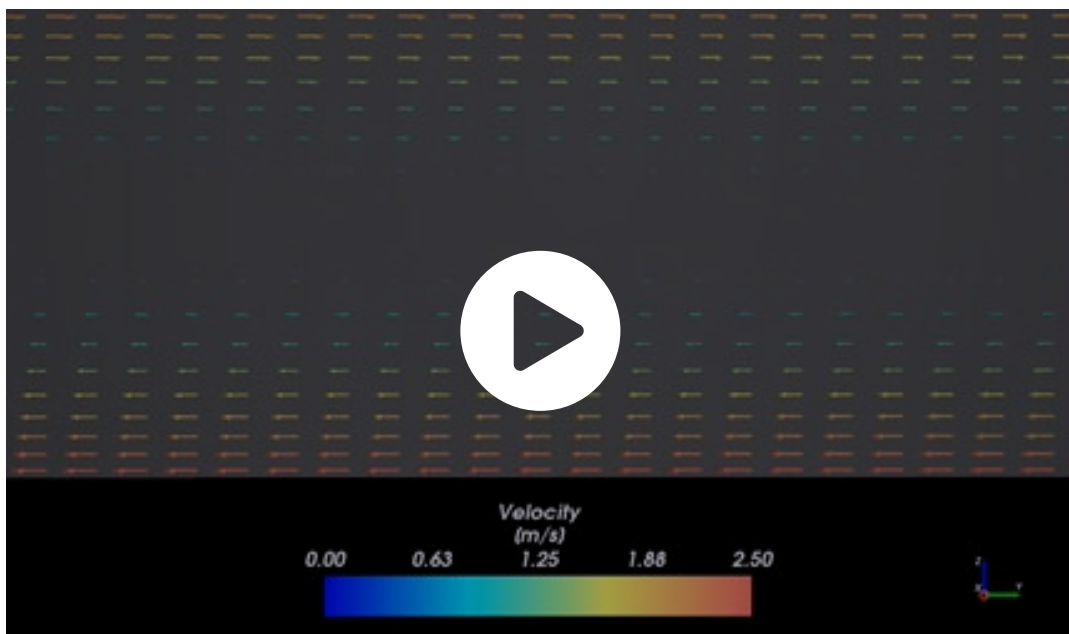
It is also important to note that the drag is computed **per element**. This is important for fibers with **large aspect ratios**, as the fiber can span different fluid cells, and therefore cross regions with different velocities. Using this approach, the **drag force** for each **segment** is calculated based on the fluid velocity at the centroid of that segment.

The videos below show two cases in which this effect can be clearly seen. In Video 5, the fiber is injected on a **parabolic** flow. If the drag were computed based on the centroid of the fiber, the fiber would move to the right keeping the same shape. But given the drag is computed per segment and as the velocity is higher for the center region, this fiber bends and flows to the right, forming a C shape.



Video 5. Flexible fiber injected in a parabolic flow.

In Video 6, the fiber is placed between two plates, each one moving in a different direction. If the drag were computed based on the centroid of the fiber, it would not move, as the fluid velocity is zero at the center. But as the drag is computed per segment, the fiber rotates.



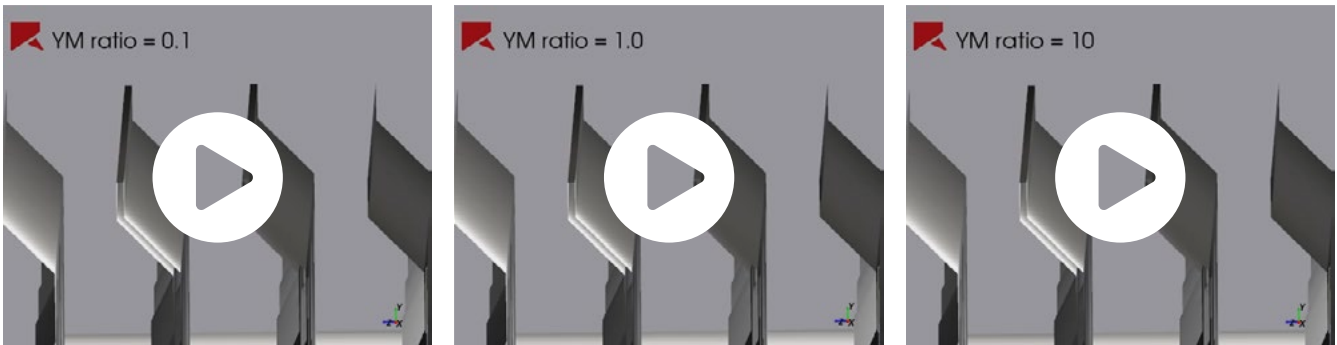
Video 6. Flexible fiber injected in between two plates moving in opposing directions.



## Model your own flexible fiber

Given all the models available, you can pick the model and calibrate its coefficients so that your fiber mimics the behavior of your particular material.

In Video 7 below, you can see how fibers with different joint stiffnesses behave differently when impacting the surface while driven by the airflow.

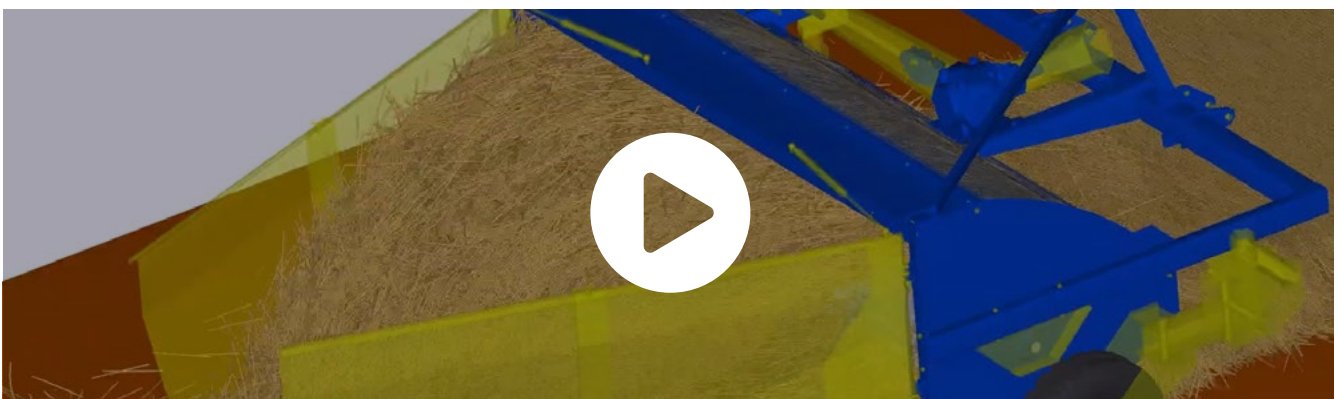


Video 7. Flexible fibers with different joint stiffness behaving differently when impacting the surface while driven by the airflow.

## Flexible fiber application examples: Expanding the types of problems that DEM can now solve

### Hay Tedder Performance

In the case study shown in Video 8 below, the goal was to model a **hay tedder** and compare different **operating conditions** to ensure proper material handling. Flexible fibers were used to model the hay, and the multi-GPU capability allowed the customer to simulate a large number of fibers.



Video 8: Hay tedder performance analysis using flexible fibers to model the hay.

## Harvester Performance

Video 9 shows simulation a combine harvester header simulation, including hay **breakage** and **plastic deformation** of the stems. Particles were modeled using Rocky DEM custom flexible fiber particle type to model the crop.

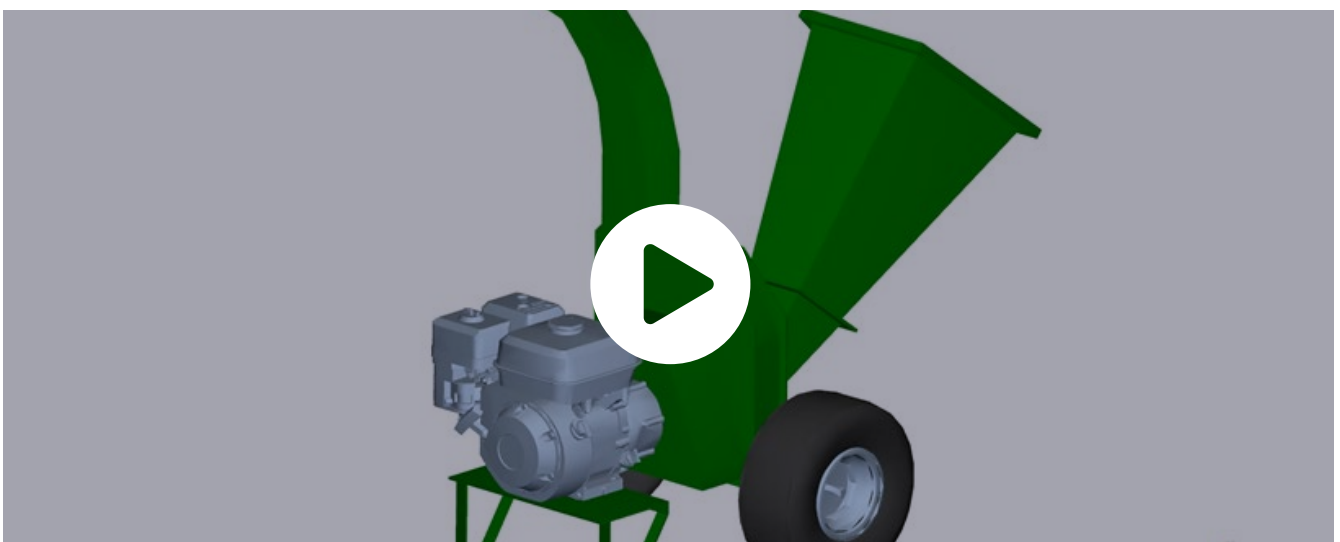


Video 9: Combine harvester header simulation including hay breakage and plastic deformation of the stems.

## Wood Chipper Efficiency

In the example shown in Video 10 below, the goal was to evaluate the **chipping efficiency** for different **disk rotational speeds** as well as to assess if **clogging** would happen when changing the **wood tonnage**.

Wood branches were modeled using **custom flexible fibers**, and the **wood chopping** was modeled using the **fiber breakage model**.

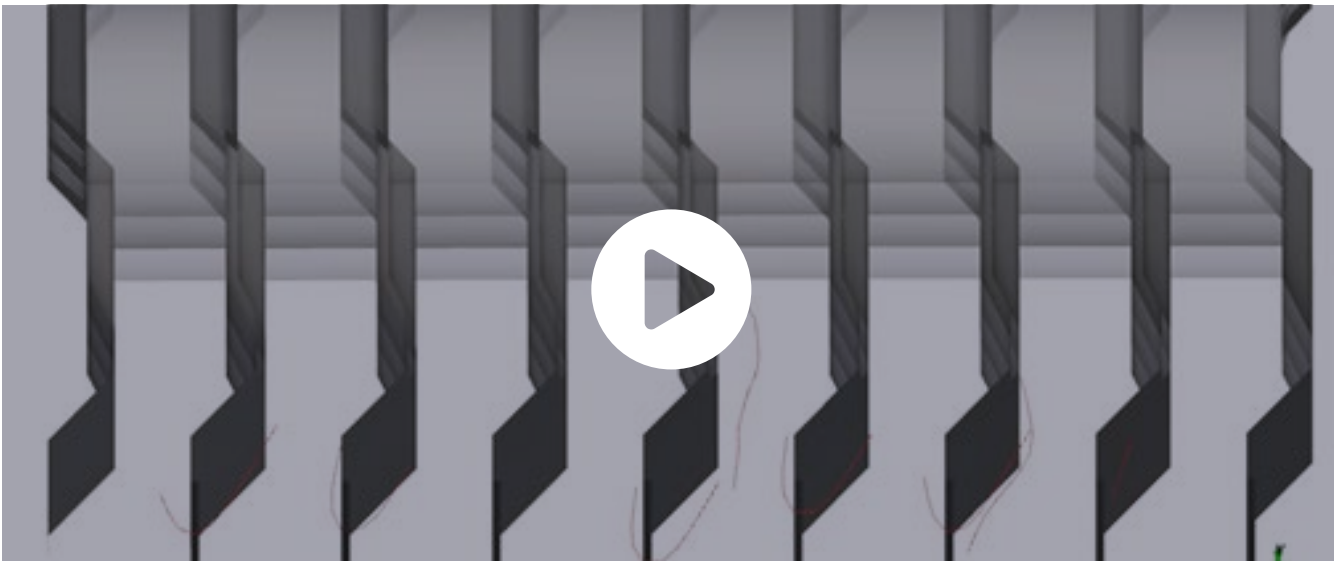


Video 10. Wood chipper efficiency analysis for different rotational speeds using flexible fibers to model the wood branches

## Fouling of Heat Exchangers

Video 11 shows a study performed by **Sub-Zero** [3]. Rocky DEM was used combined with Ansys Fluent to understand **heat exchanger** robustness to **fouling**. This understanding is important in that it gives Sub-Zero more freedom to design more compact refrigerating systems with higher energy efficiency and carefree products.

In this case, the **cotton linter fibers** were modeled using flexible fibers. The fluid forces were taken into account using Rocky's one-way coupling with Ansys Fluent, and an adhesion model was added to mimic the electrostatic force acting on the fibers.



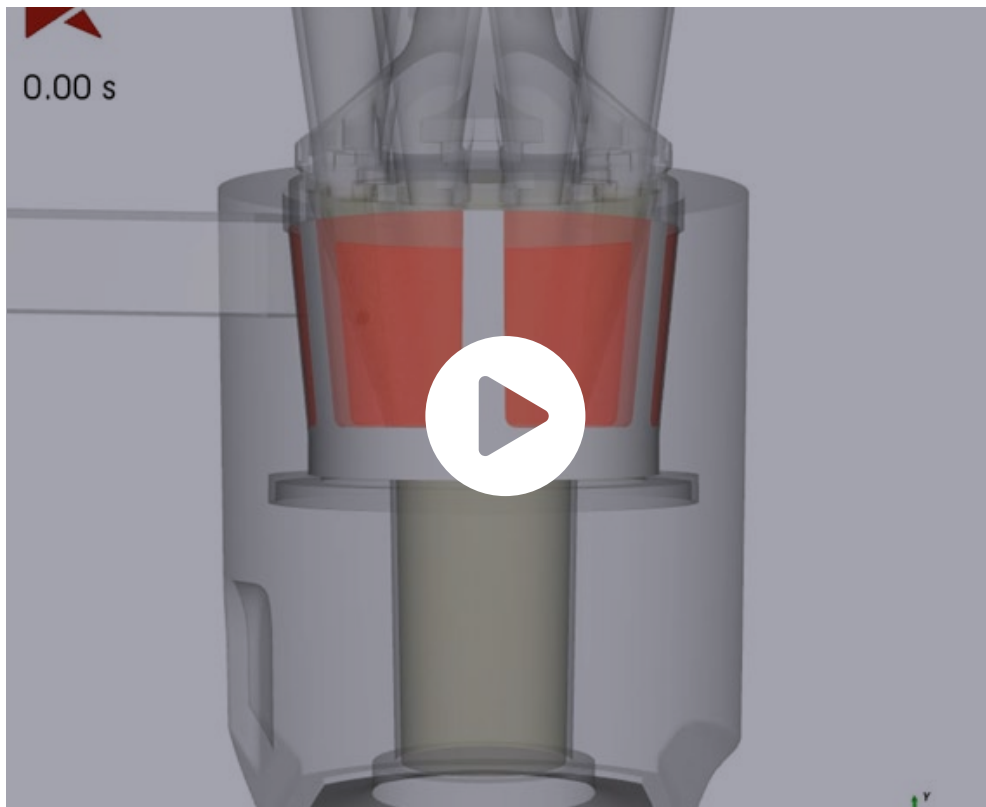
Video 11. Understanding fouling on heat exchangers using flexible fibers to model cotton linter fibers.

If you want more details, you can access the full case study [here](#).

## Pet Hair Vacuum Cleaner

Video 12 below shows a study performed by **BISSELL** [4] of a pet hair vacuum cleaner. Their goals were to evaluate the performance of geometric design variations, and to reduce the cost of new prototypes and experimental testing.

The simulation shows a **one-way DEM-CFD coupled simulation** of a large number of **pet hair strands** inside a **vacuum cleaner**, depicting behaviors such as **flexibility** and **inter-fiber interactions**. The hair strands were modeled using **flexible fibers** with different diameters, and the fluid field, obtained in Ansys Fluent, was taken into account when solving the particle trajectory inside this multi-cyclonic device.



Video 12: pet hair vacuum cleaner study using flexible fibers to model the hair strands and 1-way coupling with Ansys Fluent.

If you want more details, you can access the full case study [here](#).

## References

- [1] Guo, Y., C., W., Curtis, J. S., and Xu, D. (2018). A bonded spherocylinder model for the discrete element simulation of elastic-plastic fibers. *Chemical Engineering Science*, 175:118–129
- [2] N. Marheineke, R. Wegener, Modeling and validation of a stochastic drag for fibers in turbulent flows, *Berichte des Fraunhofer ITWM*, Nr. 172, 2009
- [3] A. Bortoletto, L. Almeida, Using Rocky DEM to Understand Fouling of Heat Exchangers, *Ansys Innovation Conference - Minneapolis*, Sep 17, 2019
- [4] L. Almeida, R. Bharadwaj, K. Leung, CFD-DEM coupled simulation of hair flow inside a cyclone device, *Ansys Innovation Conference - Minneapolis*, Oct 02, 2018



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[www.rocky-dem.com](http://www.rocky-dem.com)