Supplementary information

I. Supplementary figures and figure captions

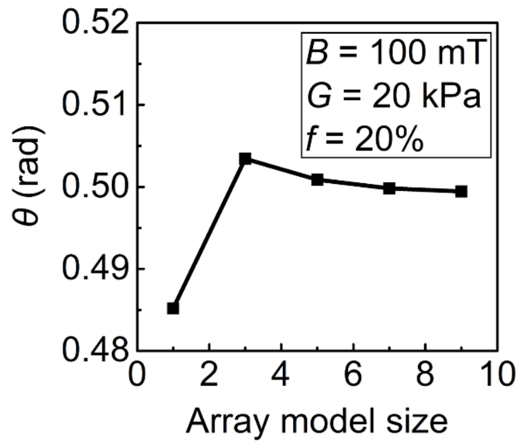

Figure S1. Particle rotation of RVE models with different particle array sizes. The array size is the number of single-particle RVE on one direction of the array model. In these high-volume fraction cases, the rotation of the central particle approaches to a certain value as the model size increases. The error between 5×5 (0.50087 rad) and 9×9 (0.49945 rad) model is smaller than 0.3%, indicating that the results of 5×5 array RVE model is accurate enough to evaluate particle rotation of high-volume fraction cases.

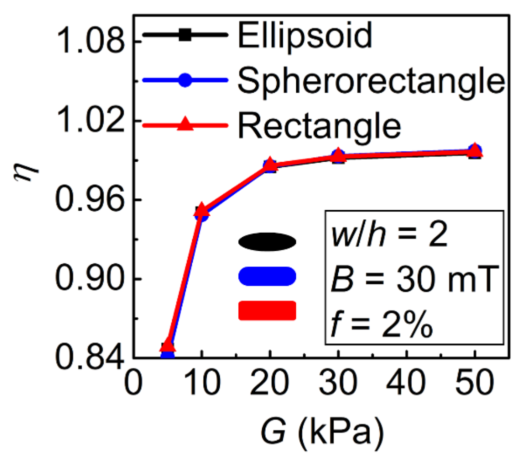

Figure S2. Torque transmission efficiency as a function of matrix shear modulus for different particle shapes. To further explore the effect of particle shape, three different particle shapes with the same aspect ratio are created as shown in the figure. The curves are all overlapped, indicating the main factor that affects the torque transmission efficiency is the aspect ratio.

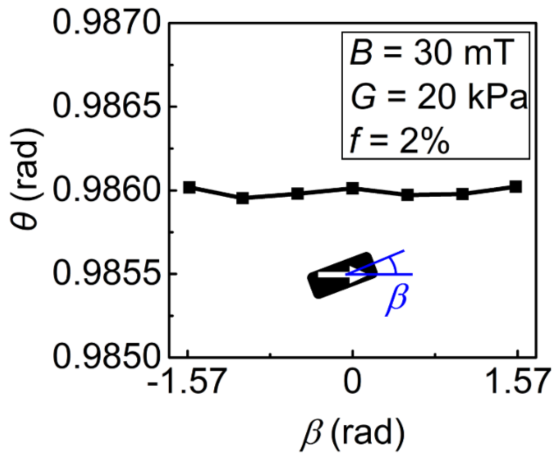

Figure S3. Particle rotation as a function of the particle original orientation. As shown in the figure, the angle between particle magnetization and the long axis of the rectangle particle is defined as β. As β varies from -2/π to 2/π, the particle rotation remains almost the same with the difference less than 0.001 rad).

II. Homogenized model equation solution

For the simplified model, as shown in Figure 6a, the particle volume fraction f is

$$f = \left(\frac{R_1}{R_2}\right)^2 . \tag{S1}$$

As indicated in Figure 3f and discussed in the text, the torque transmission efficiency is

$$\eta = \cos\theta . \tag{S2}$$

Upon the application of a magnetic field, the torque on the particle is

$$m = \pi R_1^2 MB . \tag{S3}$$

To balance this torque, the shear stress at the material point at a distance R from the particle center is

$$\tau = -\frac{m}{2\pi R^2} . \tag{S4}$$

The negative sign is because m is acting on the inner face of the matrix ring. The shear strain is

$$\gamma_{r\theta} = -\frac{m}{2\pi R^2 G} . \tag{S5}$$

Here, to simplify the problem, we consider the cases with small deformation, even though the shear strain can be relatively high under large magnetic fields. Under the polar coordinate, the shear strain is defined as

$$\gamma_{r\theta} = \frac{1}{2}\left(\frac{1}{R}\frac{\partial u_r}{\partial R} + \frac{\partial u_\theta}{\partial R} - \frac{u_\theta}{R}\right). \tag{S6}$$

In our case, the boundary conditions are $u_r\,(R,\theta) = 0$, $u_\theta\,(R,\theta) = u_\theta\,(R)$. Therefore

$$\gamma_{r\theta} = \frac{1}{2}\left(\frac{\mathrm{d}u_\theta}{\mathrm{d}R} - \frac{u_\theta}{R}\right). \tag{S7}$$

Finally, we have the 1st order ODE,

$$\frac{\mathrm{d}u_\theta}{\mathrm{d}R} - \frac{u_\theta}{R} = -\frac{m}{\pi R^2 G}. \tag{S8}$$

This equation can be solved easily as

$$\theta = (1-f)\frac{MB}{2G}. \tag{S9}$$

Since the model geometry used for developing this simple theory is different from the RVE model, the volume fraction should be corrected. Therefore, we have

$$\theta = \left(1-\frac{\pi}{4}f\right)\frac{MB}{2G}. \tag{S10}$$

The above model is developed under the assumption of small deformation. However, when the applied magnetic field is large, the rotation angle should asymptotically approach $\pi/2$. Therefore Eq. (S10) is further modified to

$$\theta = \frac{\pi}{2}\left(1-\frac{\pi}{4}f\right)\left[1-\exp\left(-\frac{MB}{G}\right)\right]. \tag{S11}$$

To further include the finite deformation and the interaction between particles, we introduce a fitting parameter k and revise Eq. (S11) as

$$\theta = \frac{\pi}{2}\left(1 - \frac{\pi}{4} f\right)\left[1 - \exp\left(\frac{kMB}{G}\right)\right]. \tag{S12}$$