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# Investigating the compaction of open ring stacks through real and numerical experiments

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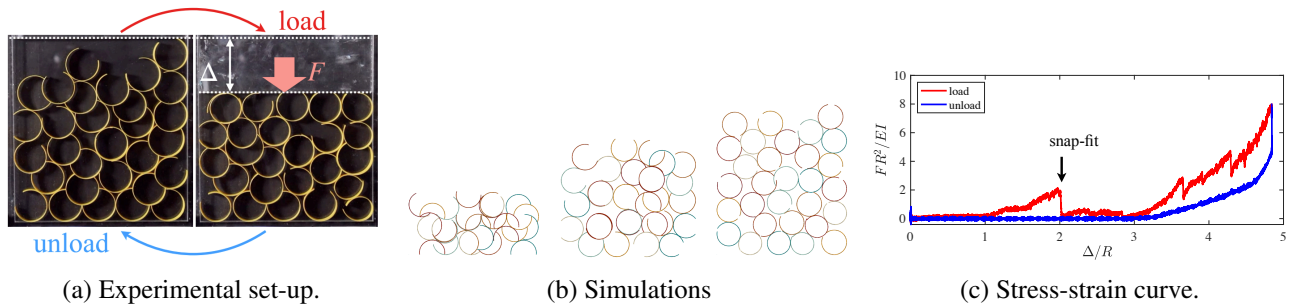


Figure 1: (a) Experimental set-up with 30 open rings. (b) Simulation of 30 rings with different opening angles. (c) Stress-strain curve for one compression cycle, illustrating the shell-shell snap-fit events leading to force drops.

Mechanical metamaterials remarkably exploit large-displacement phenomena, such as the buckling instabilities of slender structures or the coupling between elasticity and friction, as mechanical energy transducers able to achieve designed functionalities [2, 3]. While such systems have recently met large interest owing to the progress in fabrication technology and computational modelling, they often rely on the careful manufacturing of controlled structures, and the effect of randomness or defects in the components are seldom quantified nor accounted for.

This work investigates the mechanical response of a random stack of bidimensional flexible open rings 1a subject to compression cycles, by the means of experiments and simulations [1]. We leverage the curvature-based super-helix [4] numerical model to simulate the open rings as two-dimensional Kirchhoff rods, and fully account for frictional interaction between the rings with a geometrically-exact contact detection algorithm coupled to frictional contact constraints [5]. This fully high-order framework allows for robust and scalable simulations, notably removing the spurious discretisation-based artefacts in the force response that occur with low-order models.

Our numerical model is carefully validated against theoretical predictions for the snap-fit of a single ring onto a cylinder [6], demonstrating the particularly accurate account of Coulomb friction with our non-smooth approach 2. The excellent agreement obtained between our simulations and experiments for the 30 rings assembly compression cycles, in particular regarding the snap-fit force drops and cycle hysteresis, allows to rely on the numerical model to further investigate the impact of the friction coefficient and the opening angle of the rings 1b on the mechanical behaviour of the system. In particular, we find that such a system, which acts as a disordered mechanical metamaterial, can absorb and store mechanical energy upon compression in a controlled way by exploiting large displacement and relocation of rings, snap-fits, and friction 3.

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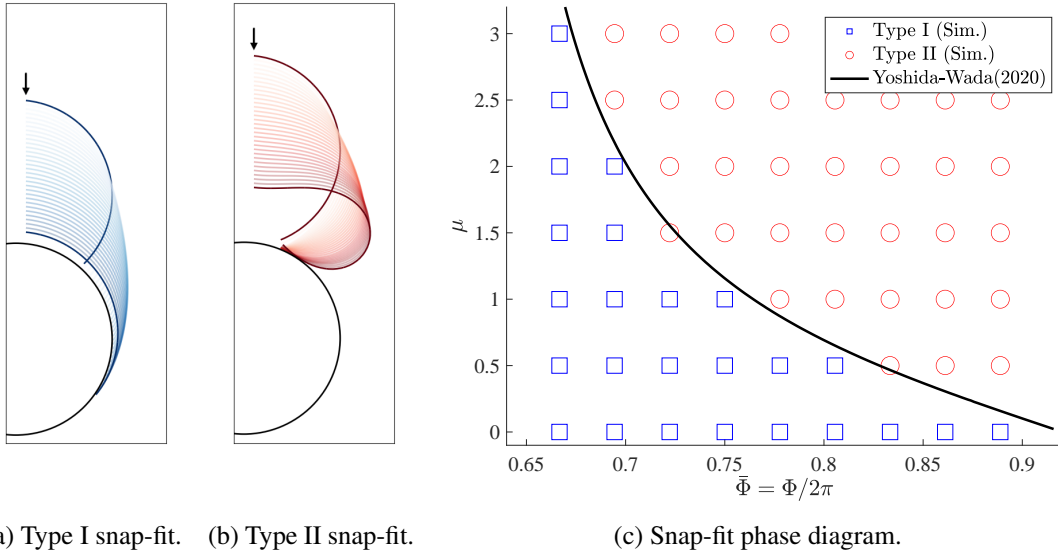


Figure 2: (a,b) Simulations of sliding (type I) or sticking (type II) snap-fit of a 2D cylindrical shell onto a rigid cylinder. The snap-fit regime depends on the opening angle of the ring  $\Phi$  and the friction coefficient  $\mu$  between the ring and the cylinder. (c) Simulated and theoretical phase diagram for type I or II snap-fitting in  $(\Phi, \mu)$  space.

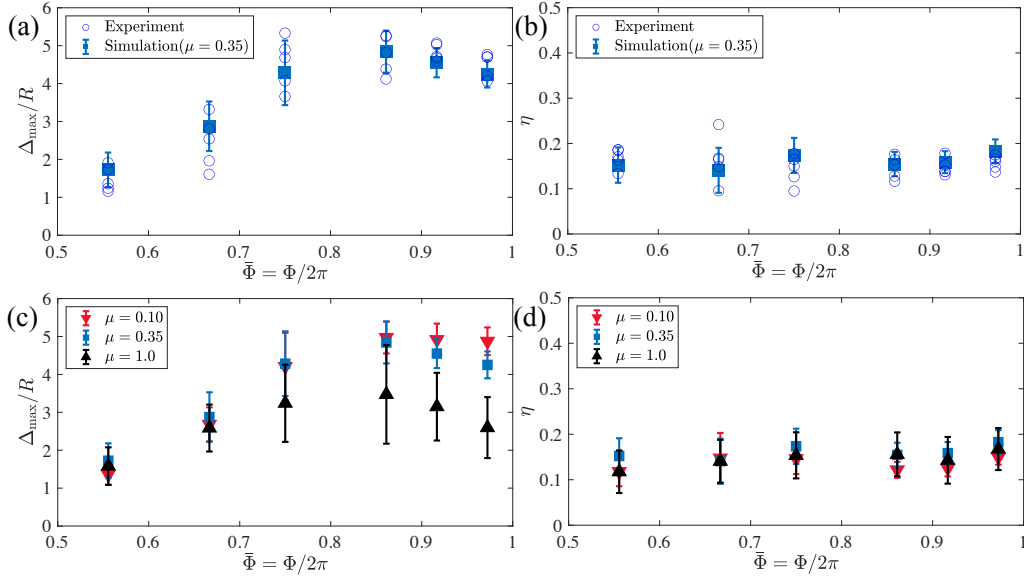


Figure 3: The maximum relative displacement  $\Delta_{\max} \equiv \frac{H_0}{H_f}$  (with  $H_0$  and  $H_f$  the initial and final heights of the stack during the compression cycle) and energy absorption ratio,  $\eta \equiv \frac{\int_{\text{cycle}} F d\Delta}{F_{\max} \Delta_{\max}}$  as a function of the ring opening  $\Phi$  and the friction coefficient  $\mu$ .

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