



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

Thibaut Métivet, Emile Hohnadel, Tomohiko G Sano, Toshiyuki Kawata,  
Florence Bertails-Descoubes

### ► To cite this version:

Thibaut Métivet, Emile Hohnadel, Tomohiko G Sano, Toshiyuki Kawata, Florence Bertails-Descoubes.  
Investigating the compaction of open ring stacks through real and numerical experiments. HFSS 2023  
- International Conference on Highly Flexible Slender Structures, Sep 2023, Rijeka, Croatia. pp.1-2.  
hal-04225083

**HAL Id: hal-04225083**

**<https://hal.science/hal-04225083>**

Submitted on 2 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

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

Thibaut Metivet<sup>1</sup>, Emile Hohnadel<sup>1</sup>, Tomohiko G. Sano<sup>2</sup>, Toshiyuki Kawata<sup>2</sup>,  
 Florence Bertails-Descoubes<sup>1</sup>

<sup>1</sup> Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, LJK, Grenoble, France, thibaut.metivet@inria.fr  
<sup>2</sup> Department of Mechanical Engineering, Keio University, Yokohama, Japan, sano@mech.keio.ac.jp

**Keywords:** thin elastic rods, frictional contact, 2D open rings, mechanical metamaterials, snap-fits

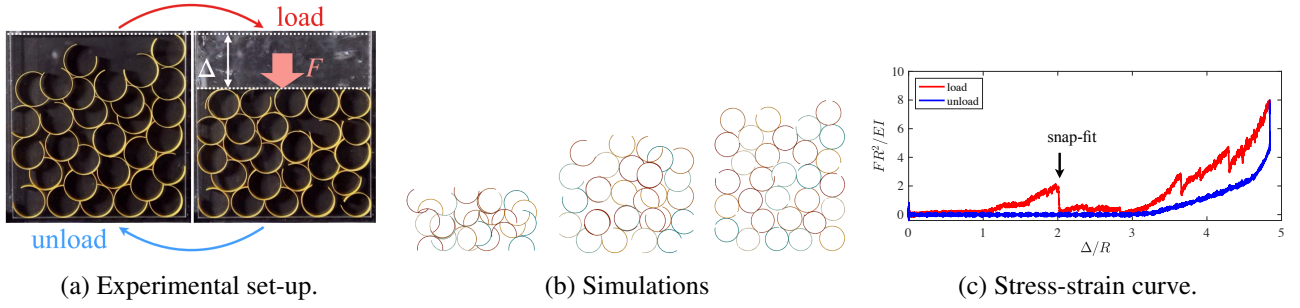


Figure 1: (a) Experimental set-up with 30 open rings. (b) Simulation of 30 rings with different opening angles. (c) Stress-strain curve for one compression cycle, illustrating the shell-shell snap-fit events leading to force drops.

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.

## References

- [1] Sano T. G., Hohnadel E., Kawata T., Metivet T., Bertails-Descoubes F. *Randomly stacked open-cylindrical shells as a functional mechanical device*, arXiv 2301.07867, <https://arxiv.org/abs/2301.07867>, 2023.
- [2] Holmes, D.P. *Elasticity and stability of shape-shifting structures*, Current opinion in colloid and interface science, 40, pp.118-137, 2019.

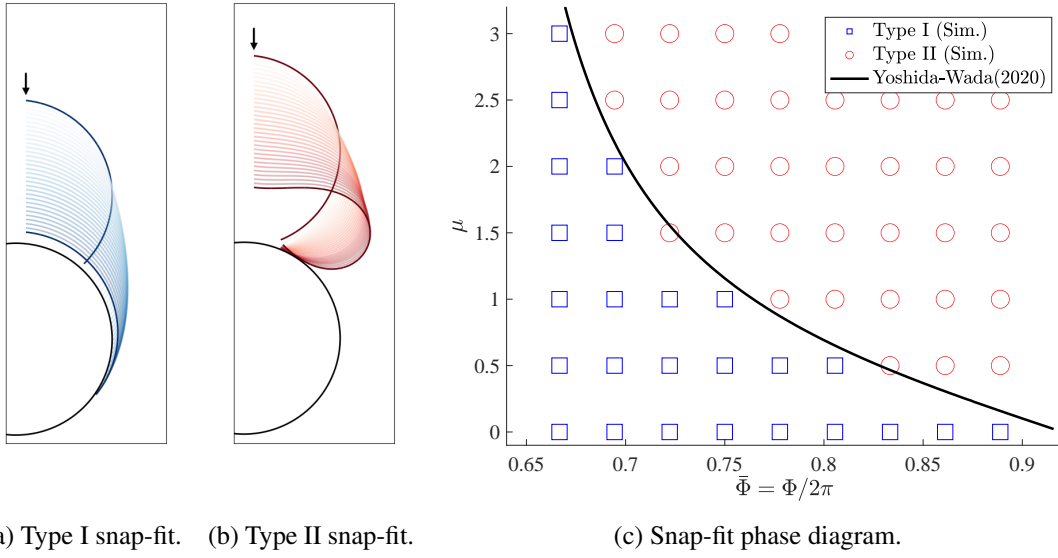


Figure 2: (a,b) Simulations of sliding (type I) or sticking (type II) snap-fit of a 2D cylindrical shell onto a rigid cylinder. The snap-fit regime depends on the opening angle of the ring  $\Phi$  and the friction coefficient  $\mu$  between the ring and the cylinder. (c) Simulated and theoretical phase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

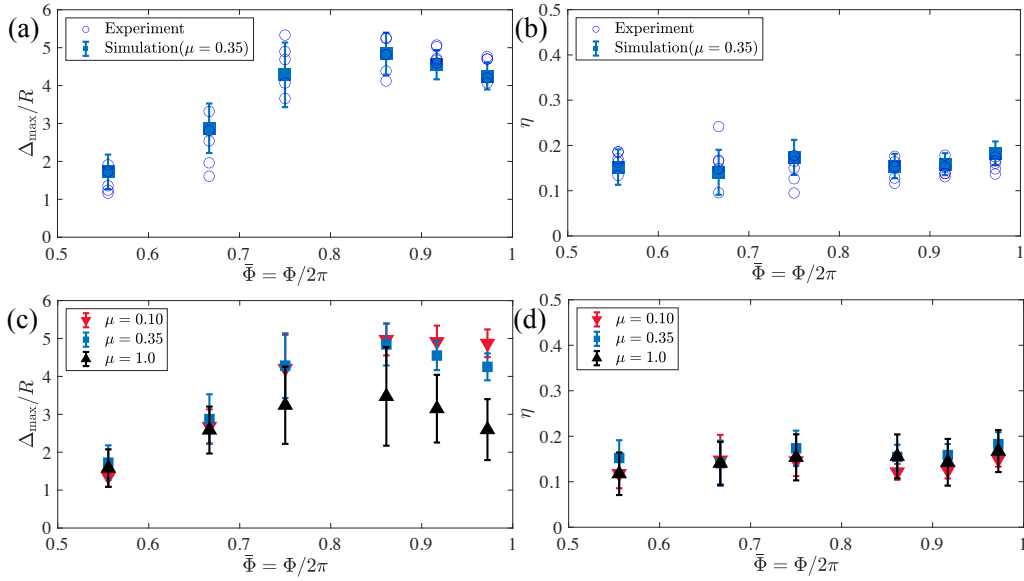


Figure 3: The maximum relative displacement  $\Delta_{\max} \equiv \frac{H_0}{H_f}$  (with  $H_0$  and  $H_f$  the initial and final heights of the stack during the compression cycle) and energy absorption ratio,  $\eta \equiv \frac{f_{\text{cycle}} F d \Delta}{F_{\max} \Delta_{\max}}$  as a function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

- [3] Reis, P.M. *A perspective on the revival of structural (in) stability with novel opportunities for function: from buckliphobia to buckliphilia*, Journal of Applied Mechanics, 82(11), p.111001, 2015.
- [4] Bertails F., Audoly B., Cani M.-P., Querleux B., Leroy F., L  v  que J.-L.. *Super-Helices for Predicting the Dynamics of Natural Hair*, ACM Transactions on Graphics, 25:3: 1180-1187, 2006.
- [5] Daviet G., Bertails-Descoubes F., Boissieux L.. *A hybrid iterative solver for robustly capturing Coulomb friction in hair dynamics*, ACM Transactions on Graphics, 30, Article 139: 1-12, 2011.
- [6] Yoshida K., Wada H.. *Mechanics of a Snap Fit*, Physical Review Letters, 125, 194301, 2020.