Predicting Frictional Properties of Graphene Kirigami Using Molecular Dynamics and Neural Networks

Designs for a negative friction coefficient

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Outline

Thesis overview

1. **Sheet kirigami**: Alter a graphene sheet using atomic scale cuts and stretching
2. **Forward simulation**: Calculate the frictional properties of the sheet using MD simulations
3. **Accelerated search**: Use machine learning to replace the MD simulations and perform an accelerated search for new designs

Can we control the friction of a nanoscale Kirigami sheet through pattern design and straining of the sheet?

Can we control the friction of a nanoscale Kirigami sheet through pattern design and straining of the sheet?

Motivation

- Kirigami: Variation of origami with cuts permitted
- Desgins: Macroscale $\rightarrow$ nanoscale

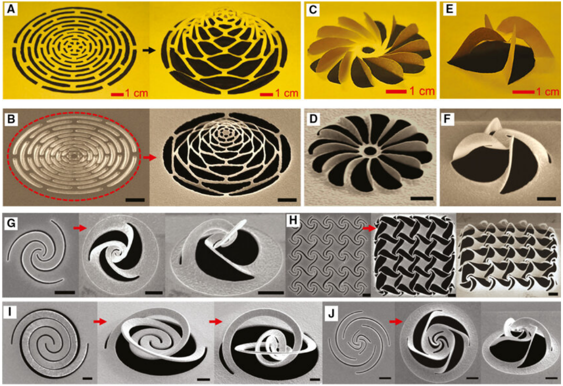
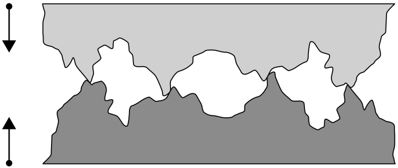


Figure: Example of macroscale Kirigami designs implemented on a nanoscale using a focused ion beam (FIB). Black scale bars: 1 μm. Reproduced from [1].

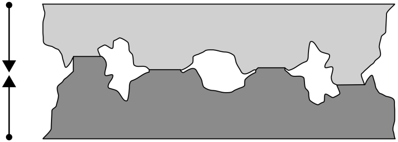
Motivation

Out-of-plane buckling

- Hanakata et al. [2, 3] found out-of-plane buckling with Kirigami designs
- Surface properties are predicted to be important for friction properties
  - Asperity theory: Contact area
  - Frenkel–Kontorova models: Commensurability



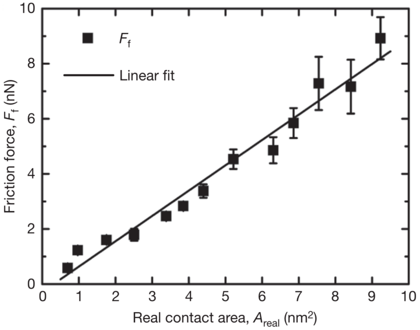
(a) Small load.



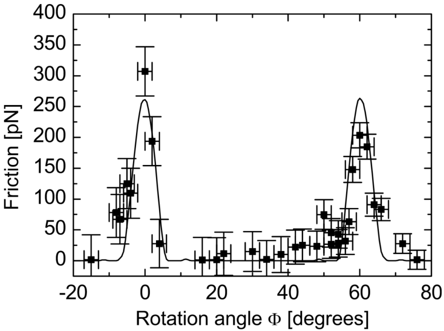
(b) High load.

Figure: Reproduced from [4].

Motivation
Contact area and commensurability



(a) Numerical MD results using an amorphous carbon tip and a diamond sample. Reproduced from [5] with permission from the Springer Nature.



(b) Experimental results of a graphene sheet sliding on graphite. Adapted from [6], reproduced from [7] with permission from the American Physical Society.

Outline

Creating a graphene Kirigami system

System setup

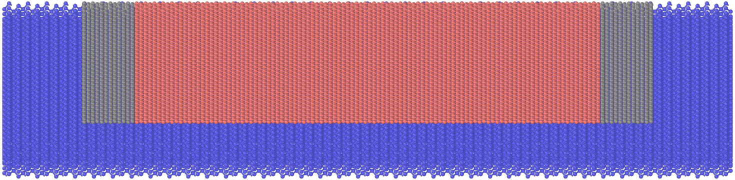
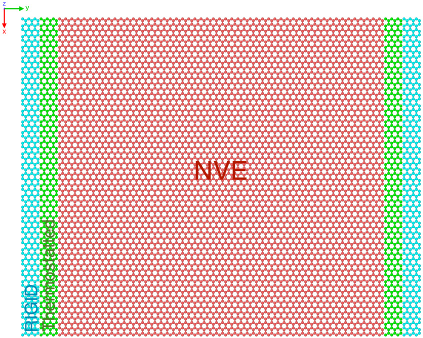


Figure: Graphene sheet on a silicon substrate. Blue: Substrate, Red: Inner sheet, Grey: Pull blocks.

System size = ???

(a) Side view.



(b) Top view.

Creating a graphene Kirigami system

Sheet Kirigami

Primitive lattice vectors

$$\mathrm{a}_1 = a\left(\frac{\sqrt{3}}{2}, -\frac{1}{2}\right) \qquad \mathrm{a}_2 = a\left(\frac{\sqrt{3}}{2}, \frac{1}{2}\right), \qquad |\mathrm{a}_1| = |\mathrm{a}_2| = a = 2.46\,\text{Å}.$$

Basis

$$\left\{\left(0, 0\right), \frac{a}{2}\left(\frac{1}{\sqrt{3}}, 1\right)\right\}.$$

Interatomic distance

$$\left|\left|\frac{a}{2}\left(\frac{1}{\sqrt{3}}, 1\right)\right|\right| \approx 1.42\,\text{Å}.$$

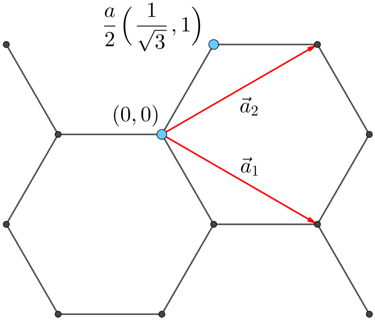


Figure: Graphene crystal structure.

Creating a graphene Kirigami system

Sheet Kirigami

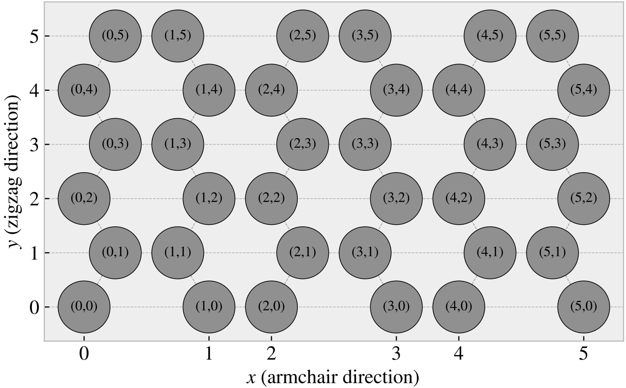


Figure: Graphene atom site indexing.

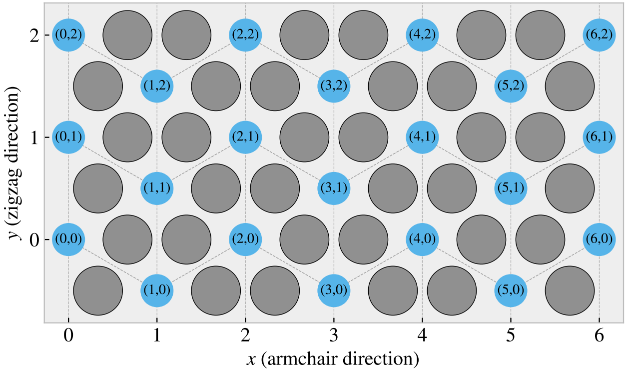
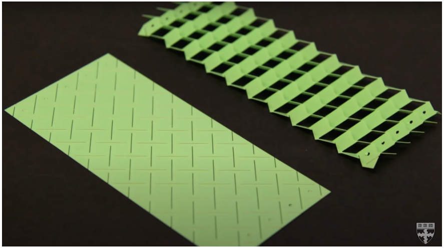


Figure: Graphene center element indexing.

Creating a graphene Kirigami system

Sheet Kirigami



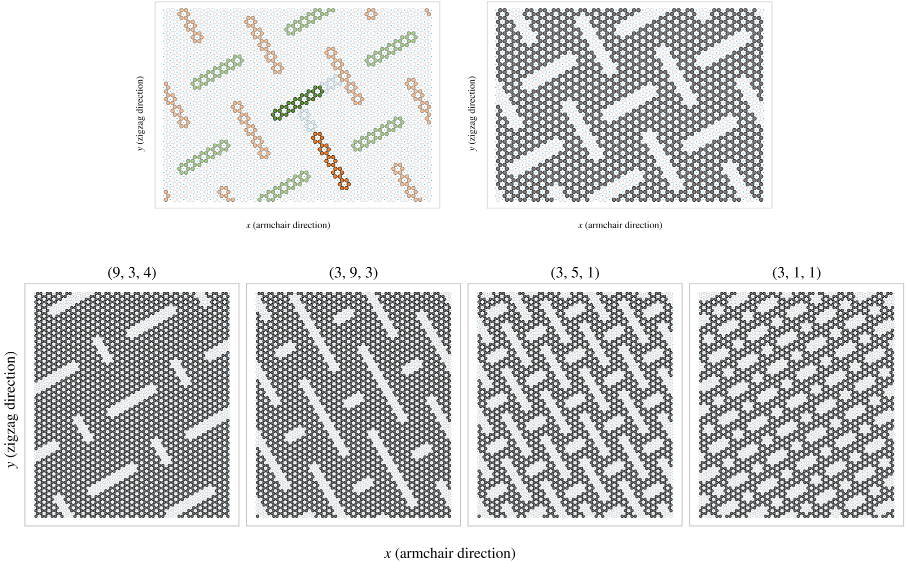
(a) Tetrahedron: Alternating perpendicular cuts producing a tetrahedron-shaped surface buckling when stretched. Reproduced from [8].

(b) Honeycomb: Scotch$^{\text{TM}}$ Cushion Lock$^{\text{TM}}$ [9] producing a honeycomb-shaped surface buckling when stretched. Reproduced from [9].

Figure: Macroscale kirigami cut patterns used as inspiration for the nanoscale implementation.

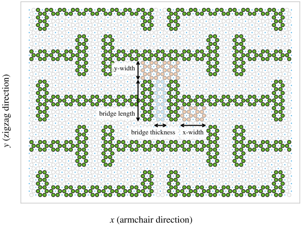
Creating a graphene Kirigami system

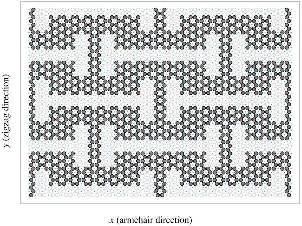
Sheet Kirigami

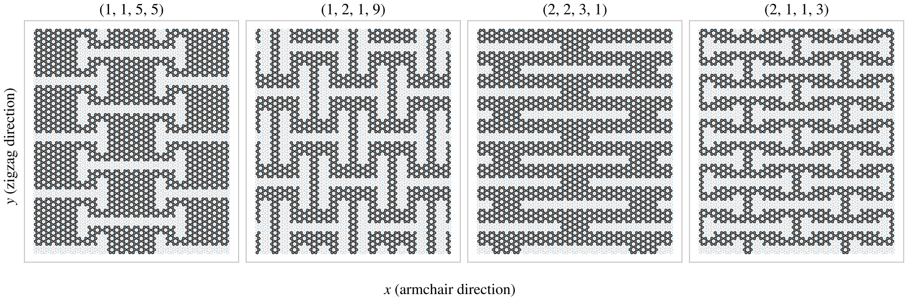


Creating a graphene Kirigami system

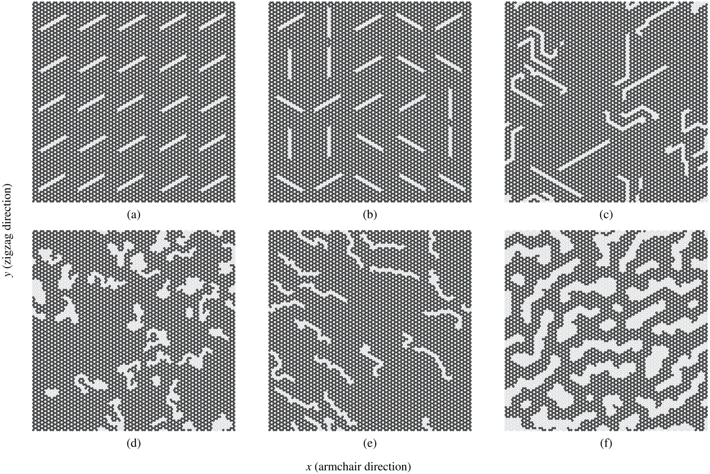
Sheet Kirigami







Random walk



Integration. Newtons equation (NVE)

$$m_i \frac{d^2 \mathrm{r}_i}{dt^2} = \mathrm{F}_i = -\nabla U_i,$$

Introducing the temperature (canonical ensemble: NVT) with the Langevin equation

$$m_i \frac{d^2 \mathrm{r}_i}{dt^2} = \underbrace{-\nabla U_i}_{F_i} \underbrace{-\alpha \mathrm{v}_i}_{\text{Drag}} + \underbrace{\mathrm{R}_i}_{\text{Fluctuation}},$$

$$\langle R \rangle = 0, \qquad \langle R^2 \rangle = 2\alpha k_B T.$$

Outline

Pilot study
Friction metrics

- Friction metrics?
- Stick slip?

Pilot study
Out-of-plane buckling

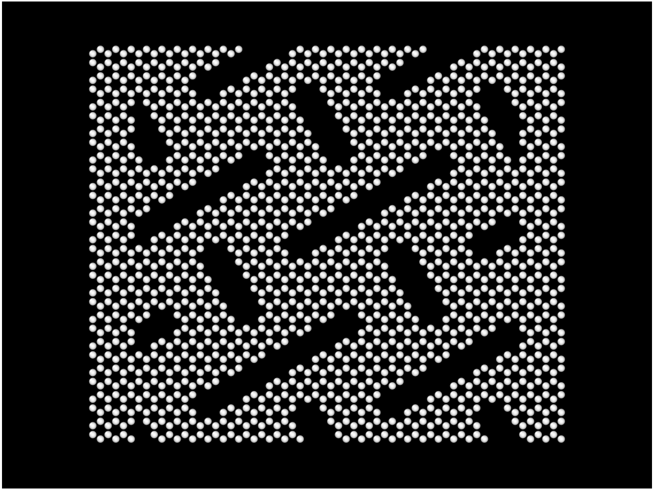


Figure: Kirigami sheet stretch in vacuum. Small tetrahedron pattern.

Pilot study
Out-of-plane buckling

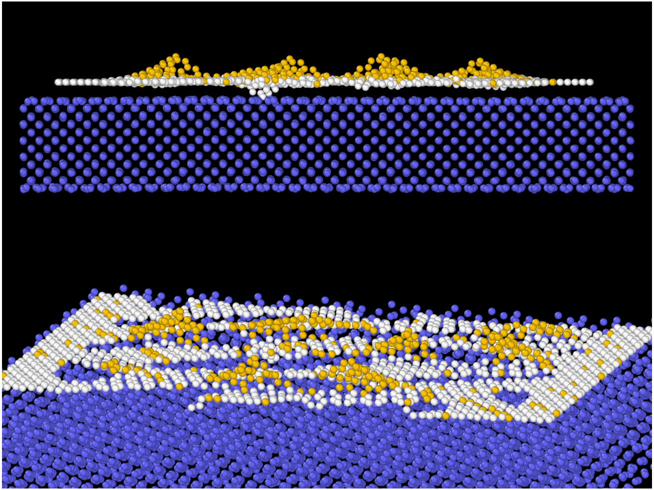


Figure: Kirigami stretch in contact with Si-substrate.

Pilot study

Out-of-plane buckling

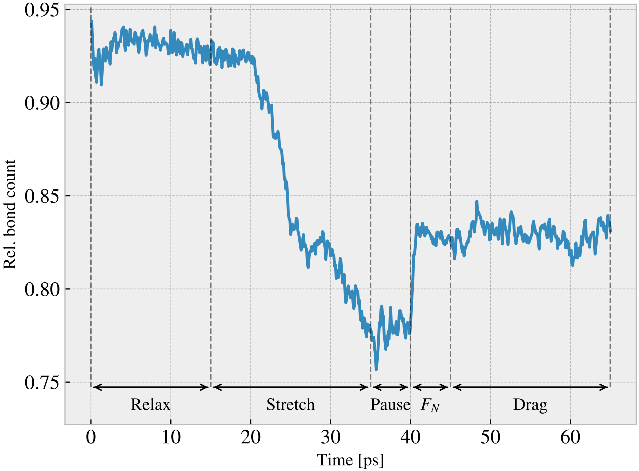
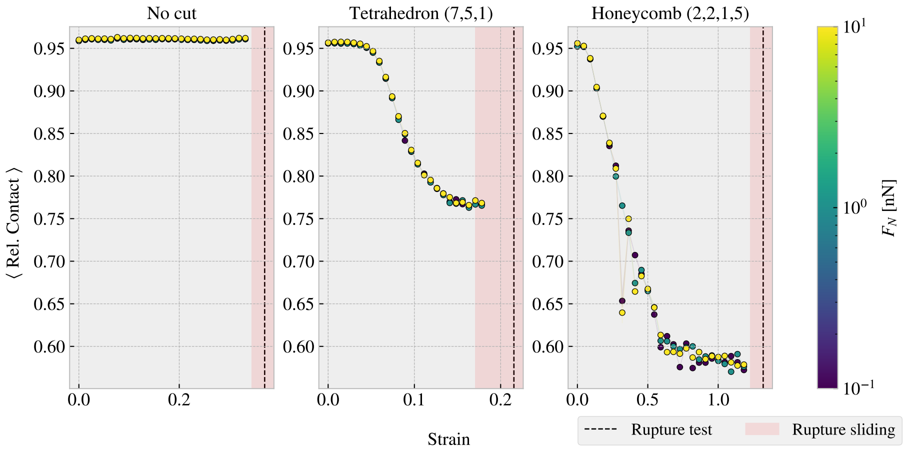


Figure: Contact area approximation: Number of C-Si bonds within a threshold distance of 110% the LJ interaction equilibrium distance.

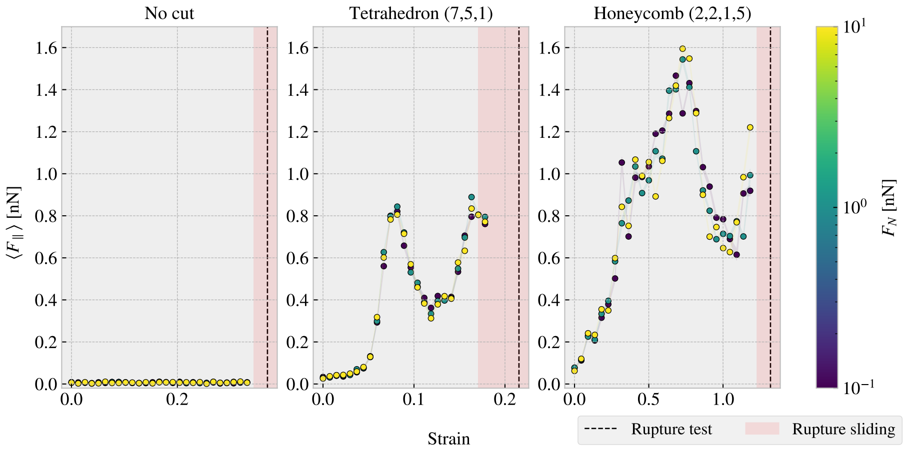
Pilot study

Friction-strain profiles



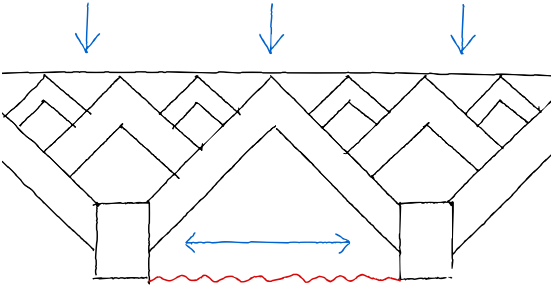
Pilot study

Friction-strain profiles



Load to sheet tension coupling

$$F_t = TF_N, \qquad T = 6$$



Pilot study

Negative friction coefficient

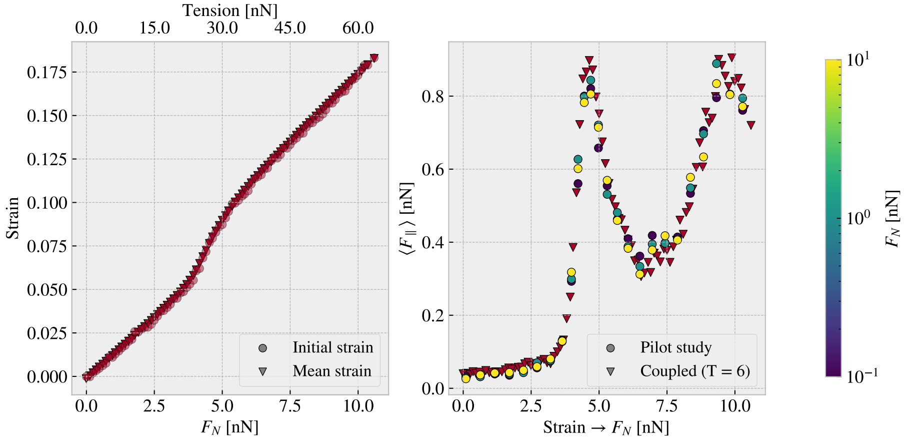


Figure: Tetrahedron $(7, 5, 1)$

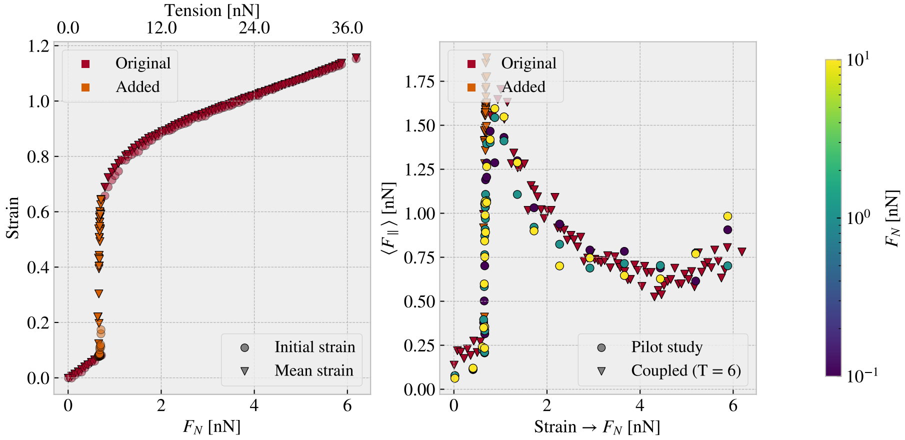


Figure: Honeycomb $(2, 2, 1, 5)$

Pilot study

Negative friction coefficient

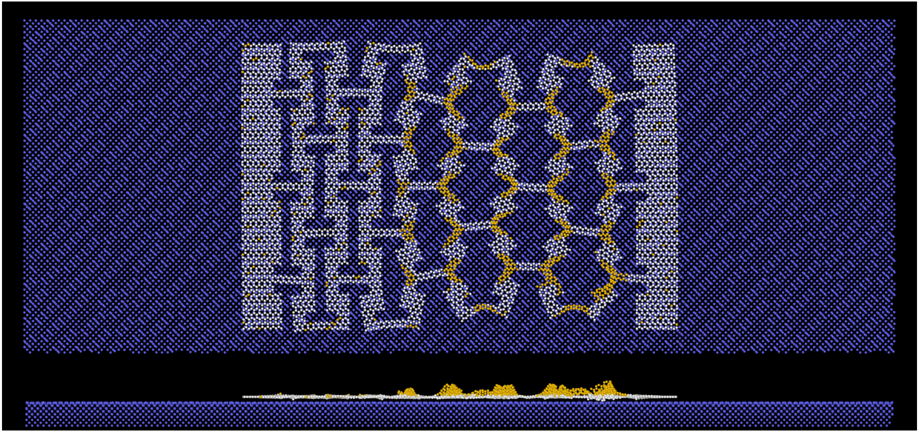


Figure: Honeycomb $(2, 2, 1, 5)$ stretch.

Outline

Table: Summary of the generated data points in the dataset.

Type	Configurations	Submitted	Final	Ruptures
Pilot study	3	270	261	25 (9.58 %)
Tetrahedron	68	3060	3015	391 (12.97 %)
Honeycomb	45	2025	1983	80 (4.03 %)
Random walk	100	4500	4401	622 (14.13 %)
Total	214 (216)	9855	9660	1118 (11.57 %)

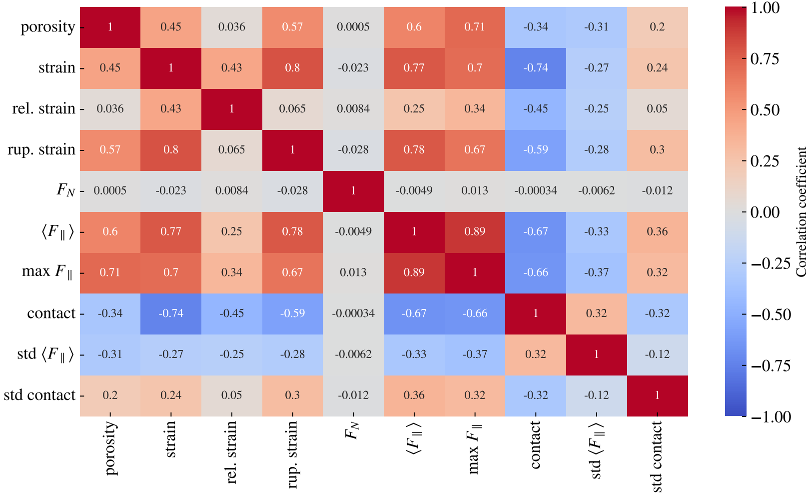


Figure: Pearson product-moment correlation coefficients.

Properties of interest

$$\min F_{\text{fric}}, \qquad \max F_{\text{fric}}, \qquad \max \Delta F_{\text{fric}}, \qquad \max \text{drop}.$$

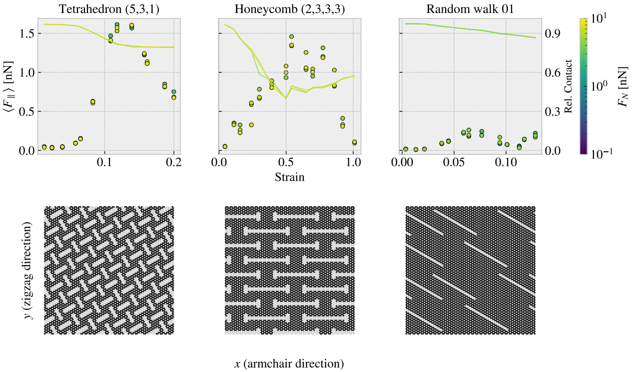


Figure: Max drop property. Best candidates in the dataset.

- Convolutional neural network
- Input: Configuration, strain and load
- Output: <u>Mean friction</u>, maximum friction, contact area, porosity, <u>rupture</u>, rupture strain

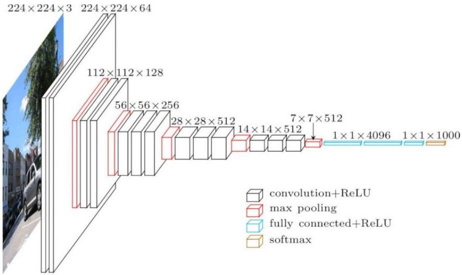


Figure: Illustration of the convolutional network architecture for the VGGNet-16 network. Reproduced from [10].

Table: Evaluation of the final model performance.

	R^2 $[10^2]$			Abs. $[10^2]$	Rel. $[10^2]$	Acc. $[10^2]$
	Mean F_f	Max F_f	Contact	Porosity	Rup. Strain	Rupture
Validation	98.067	93.558	94.598	2.325	12.958	96.102
Tetrahedron	88.662	85.836	64.683	1.207	5.880	99.762
Honeycomb	96.627	89.696	97.171	1.040	1.483	99.111

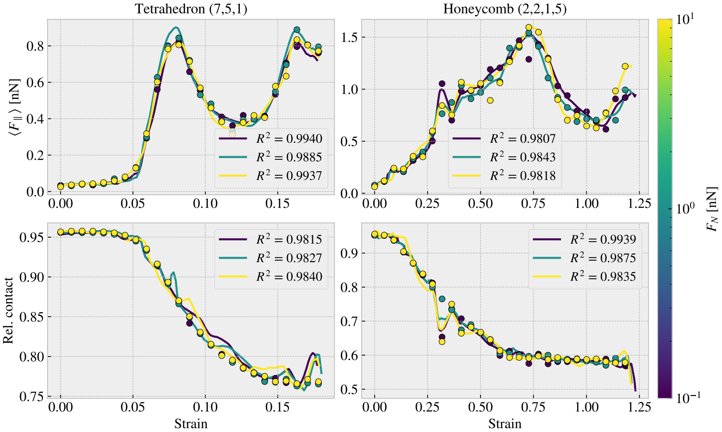
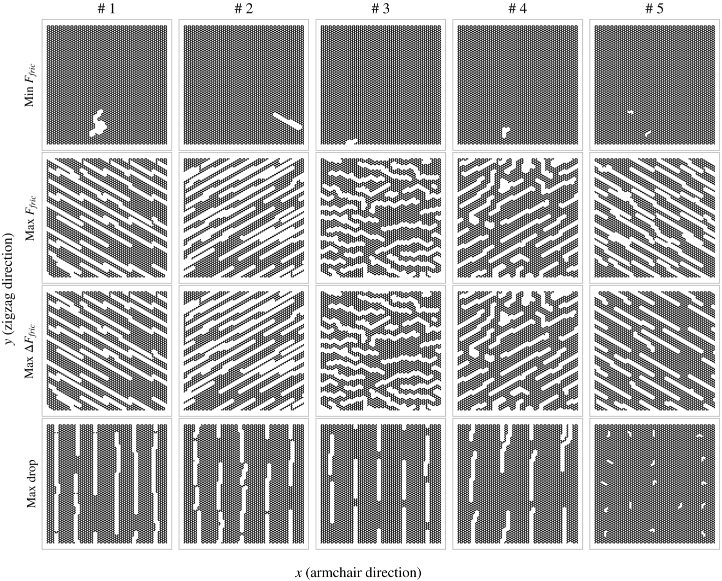


Figure: Visual evaluation of the final model predictions on the Tetrahedron $(7, 5, 1)$ and Honeycomb $(2, 2, 1, 5)$ used in the pilot study.

We generate an extended dataset.

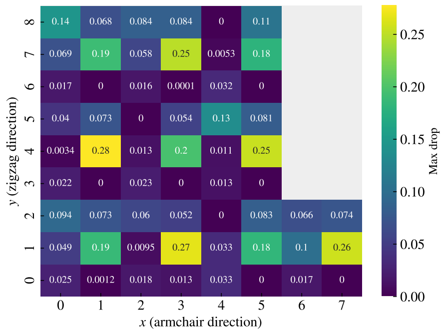
- Tetrahedron: 1.35×10^5 configurations
- Honeycomb: 2.025×10^6 configurations
- Random walk: 10^4 configurations

Kirigami configuration search
Accelerated search

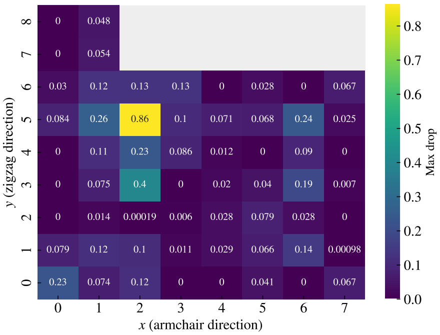


Kirigami configuration search
Accelerated search

Translational variance



(a) Tetrahedron $(1, 7, 1)$ (60). Std $= 0.08$, Rel. Std $= 1.13$



(b) Tetrahedron $(5, 3, 1)$ (60). Std $= 0.13$, Rel. Std $= 1.61$

Figure: Prediction of the max drop property for selected patterns using the machine learning model for all unique reference positions.

Kirigami configuration search

Accelerated search

Genetic algorithm based on Markov chain probability.

1. Rank configurations by fitness score.
2. Assign a mutation probability based on the ranking.
3. Calculate target states from the best candidates.
4. Mutate and repeat.

Poor convergence on the mac drop property optimization

Kirigami configuration search

Accelerated search

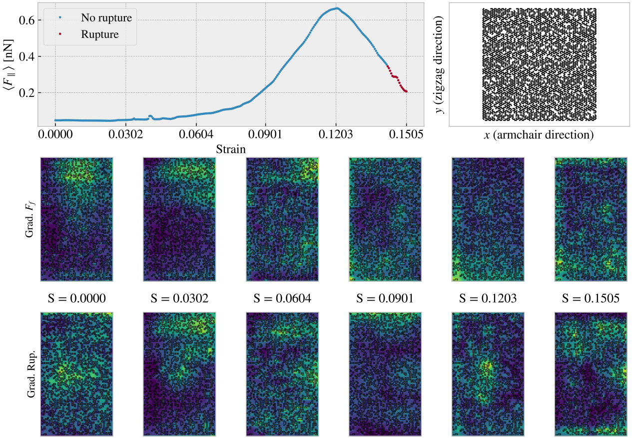


Figure: Genetic algorithm suggestion from a mixed porosity start. Top: Friction-strain curve and configuration. Bottom: Grad-CAM analysis

Grad-CAM

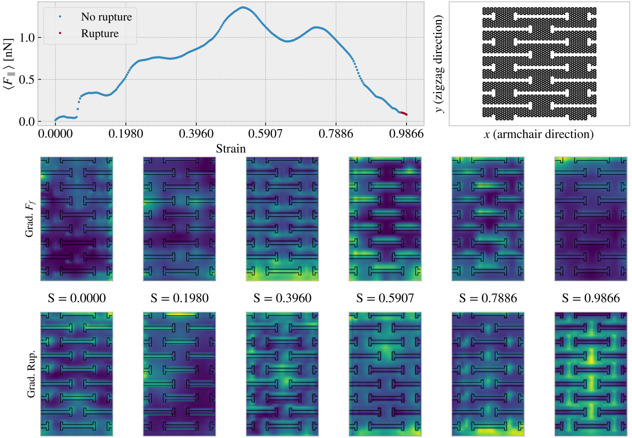


Figure: Honeycomb $(3, 3, 5, 3)$, ref $= (12, 0)$.

Outline

Summary and outlook

Key findings

- Non-monotonous relationship between friction and strain
- Coupled system can be exploited to achieve a negative friction coefficient
- Machine learning is feasible but more data is needed

Further studies:

- Investigation of the underlying mechanism
  - Commensurability hypothesis can be investigated by varying scan angle
- Friction-strain relationship at different physical conditions: temperature, sliding speed, spring stiffness.
- Edge and thermostat effects.
- Improve dataset with active learning

References I

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References II

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