On electroadhesive layer jamming structures

Guo J[1], Yuan Y[2], Liu L[2], Liu Y[2], Leng J[2]

[1] School of Science, Harbin Institute of Technology (Shenzhen), Shenzhen, China

[2] Department of Astronautical Science and Mechanics, Harbin Institute of Technology, Harbin, China

Introduction

Variable stiffness is a useful function for living creatures to survive and adapt in unknown and changing environments, and is needed for morphing-load bearing tasks in our daily life. Jamming is a common variable stiffness mechanism and layer jamming is a popular variable stiffness structure. Here we present a fundamental study of parallel electroadhesive layer jamming structures under different loading conditions, and compare the theoretical and experimental deflection–force curves. The results may provide helpful insights towards their practical applications.

Objective

We aim to present a comprehensive and experimentally validated theoretical variable stiffness models of flexible parallel electroadhesive structures.

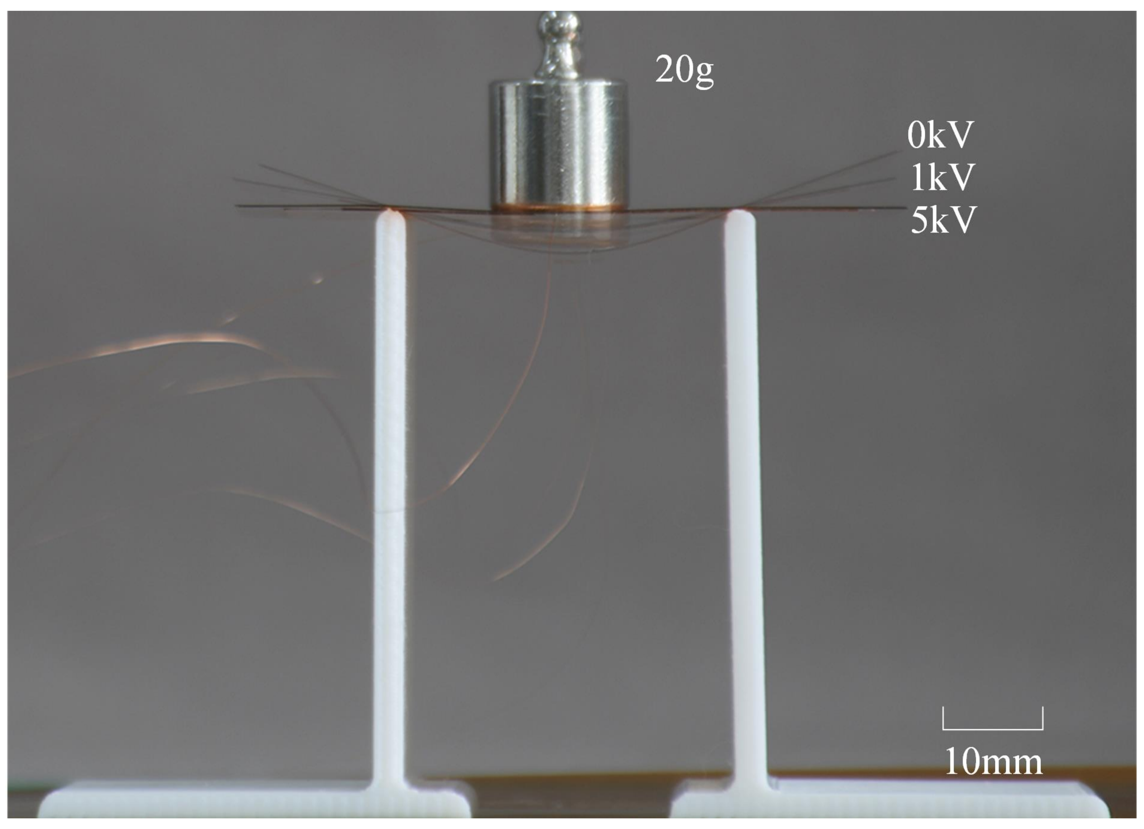
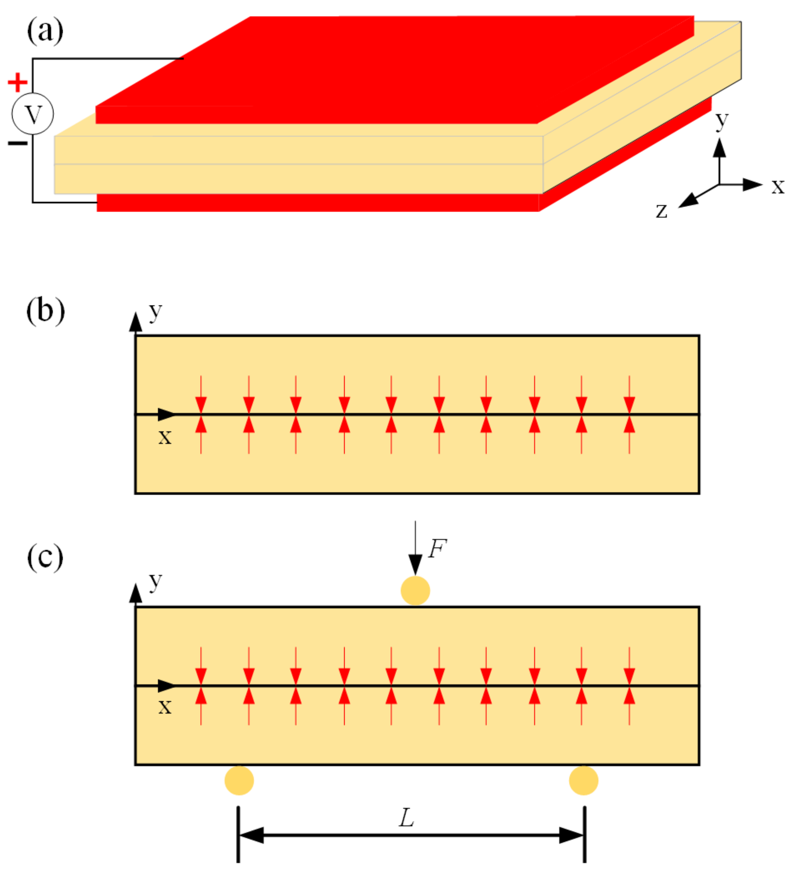


Fig. 1 A flexible parallel electroadhesive that can change its bending stiffness under different voltages (such as 1 and 5 kV).

Method

We use the Euler–Bernoulli beam theory and consider slip between layers by integrating the Maxwell stress tensor into the model.



There are three phases during the structural bending:

1) pre-slip or adhesion phase: the whole structure is electrically bonded in a stable way when $\tau_{max}(x,y) \le \tau_f$;

2) partial-slip or transition phase: the whole structure has partial layer slips when $\tau_{min}(x,y) < \tau_f \le \tau_{max}(x,y)$;

3) full-slip phase: layer slip occurs in the whole structure when $\tau_{min}(x,y) > \tau_f$.

τ_f is the electroadhesive shear stress between layers. $\tau_{min}(x,y)$ and $\tau_{max}(x,y)$ represent the maximum and minimum shear stress at the position where the layers are in contact with each other respectively, when we assume that the multilayer structure is a whole.

Fig. 2 Schematic diagram of the variable stiffness flexible parallel electroadhesive physical model: (a) 3D configuration under no load, (b) 2D configuration under no load (red arrows denote electroadhesive forces), and (c) 2D configuration under a central concentrated force (*F* is the load and *L* is the three-point bending support span length).

Analytical modelling

We derive variable stiffness models of three three-point bending, cantilever beam bending under tip concentrated forces, and cantilever beam bending under uniformly distributed forces.

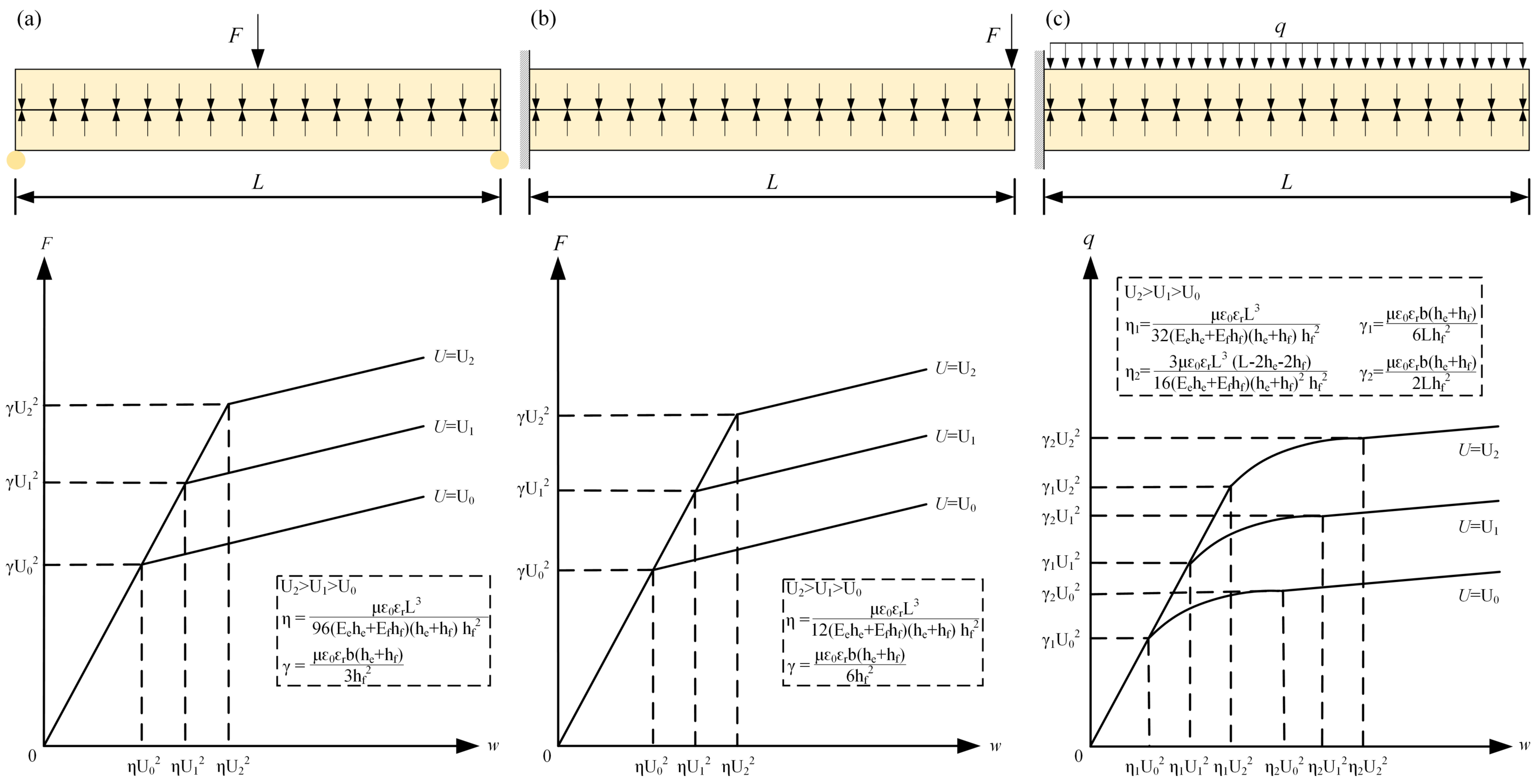


Fig. 3 Deflection-force curves under three different loading conditions: (a) the deflection-force curve of the three-point bending model, (b) the deflection-force curve of cantilever beam bending under tip concentrated forces model, (c) the deflection-force curve of cantilever beam bending under uniformly distributed forces model, where γU_i^2 is the critical load between the pre-slip stage and full-slip stage at different voltages and ηU_i^2 is the corresponding deflections.

Experimental validation

The theoretical deflection–force curves of three-point bending and cantilever beam bending under tip concentrated force all agreed relatively well with the experimental curves.

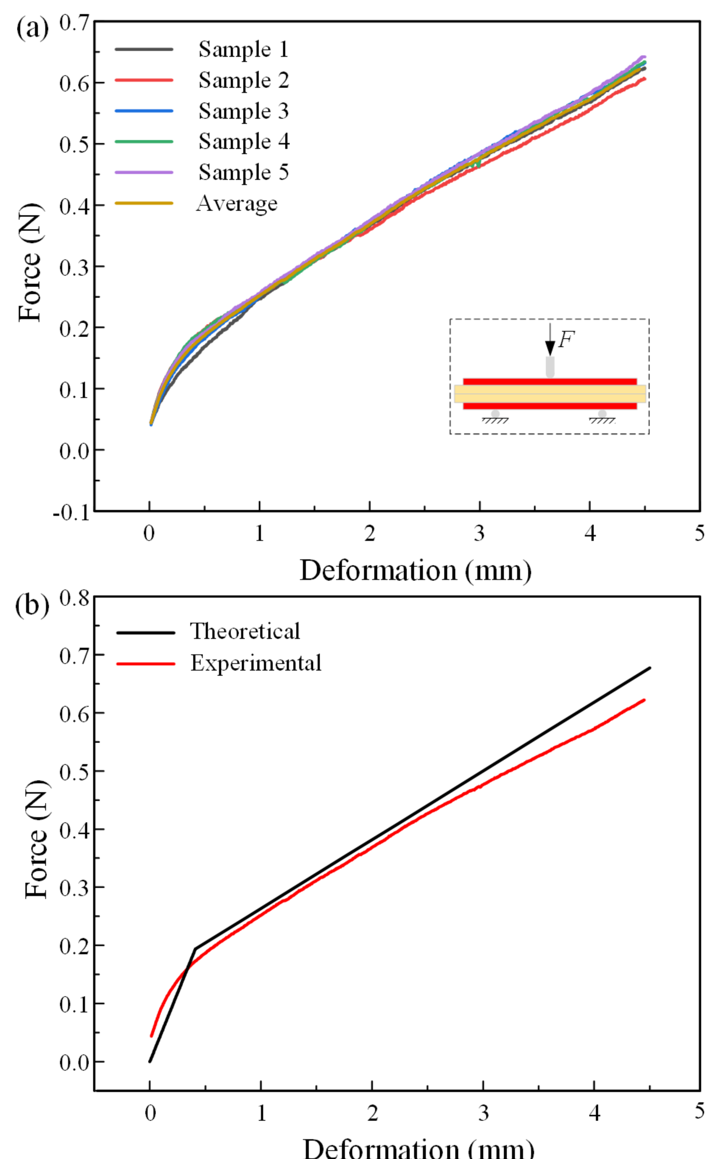


Fig. 4 Three-point beam bending model validation: (a) Experimental data of five different samples and (b) Comparison between the theoretical and experimental deflection-force curve of the three-point beam bending case.

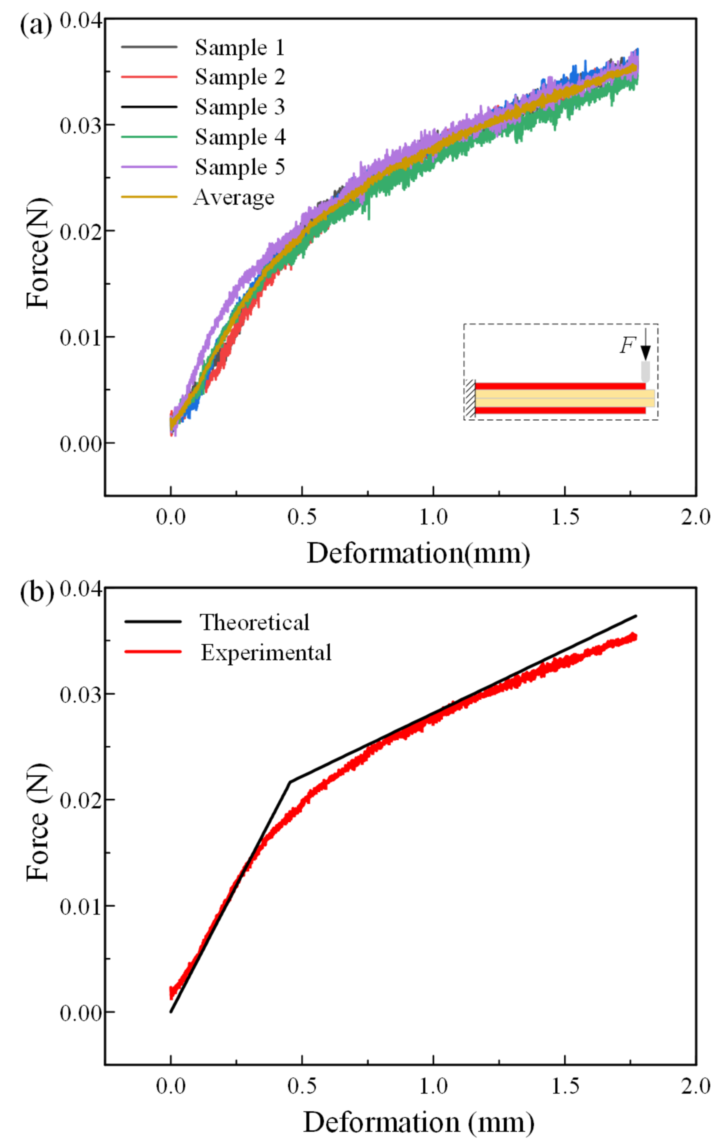


Fig. 5 Cantilever beam under tip concentrated forces bending model validation: (a) Experimental data of five different samples and (b) Comparison between the theoretical and experimental deflection-force curve of the cantilever beam bending under tip concentrated forces case.

Conclusion

- three-point bending and cantilever beam bending under tip concentrated forces only have pre-slip and full-slip, whereas cantilever beam bending under uniformly distributed forces has an additional partial-slip which can be used for stiffness modulation;
- the reason leads to partial-slips comes from changed shear force distributions inside structures; so for any electrostatic jamming structures that are subjected to area loads, partial-slips will occur;
- the stiffness during the pre-slip stage is four times larger than the stiffness in the full-slip stage;
- increasing the voltage, dielectric permittivity and coefficient of friction can elongate the pre-slip stage, thus enhancing the structural load capability.

Future work

- experimental validation of the variable stiffness model of cantilever beam bending under uniformly distributed forces;
- variable stiffness modeling of multi-layer flexible electro-adhesive jamming structures.

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