Programming and Predicting Soft Pneumatic Actuators From Metamaterial Skins to Digital Twins

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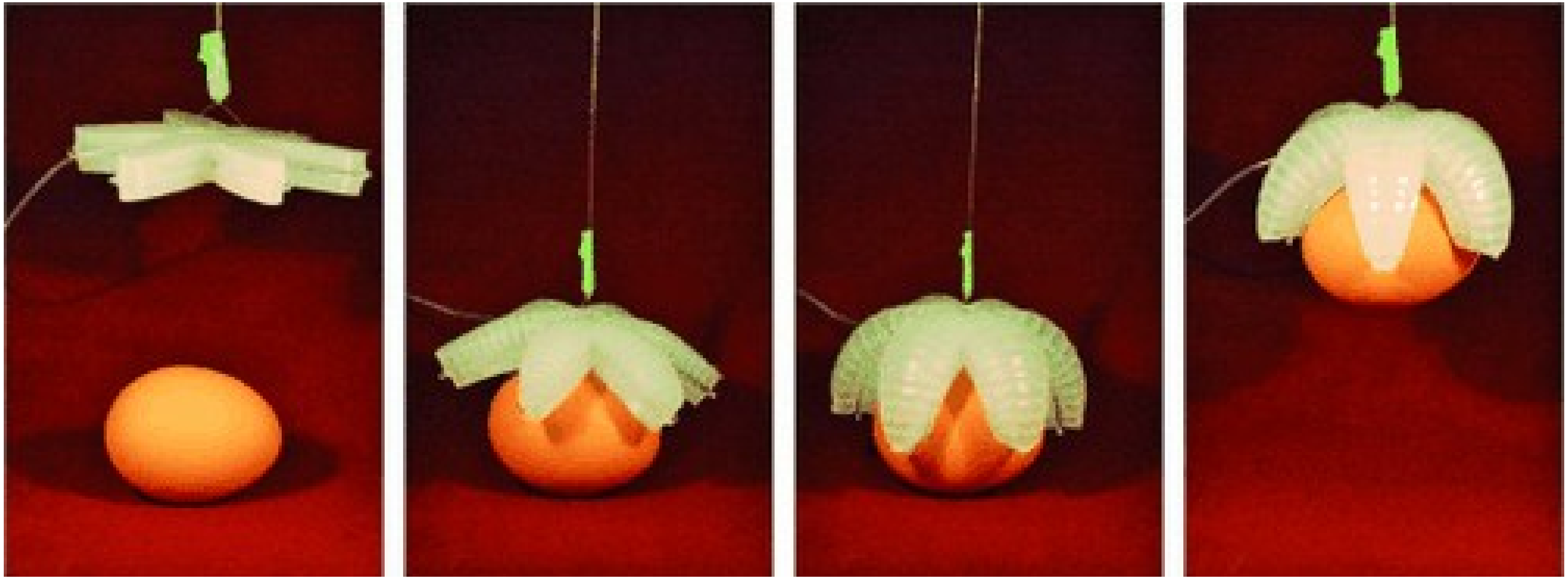
A Seminar at University of Trento, TN, IT, 2026. 7. 28

Roadmap

SICHUAN UNIVERSITY

01	02	03	04
CONTEXT	**PROGRAM**	**PREDICT**	**INTEGRATE**
Why compliant actuators need programmable mechanics	Metamaterial skins encode deformation	Digital twins reconstruct full-field response	Design and prediction enable intelligent actuation

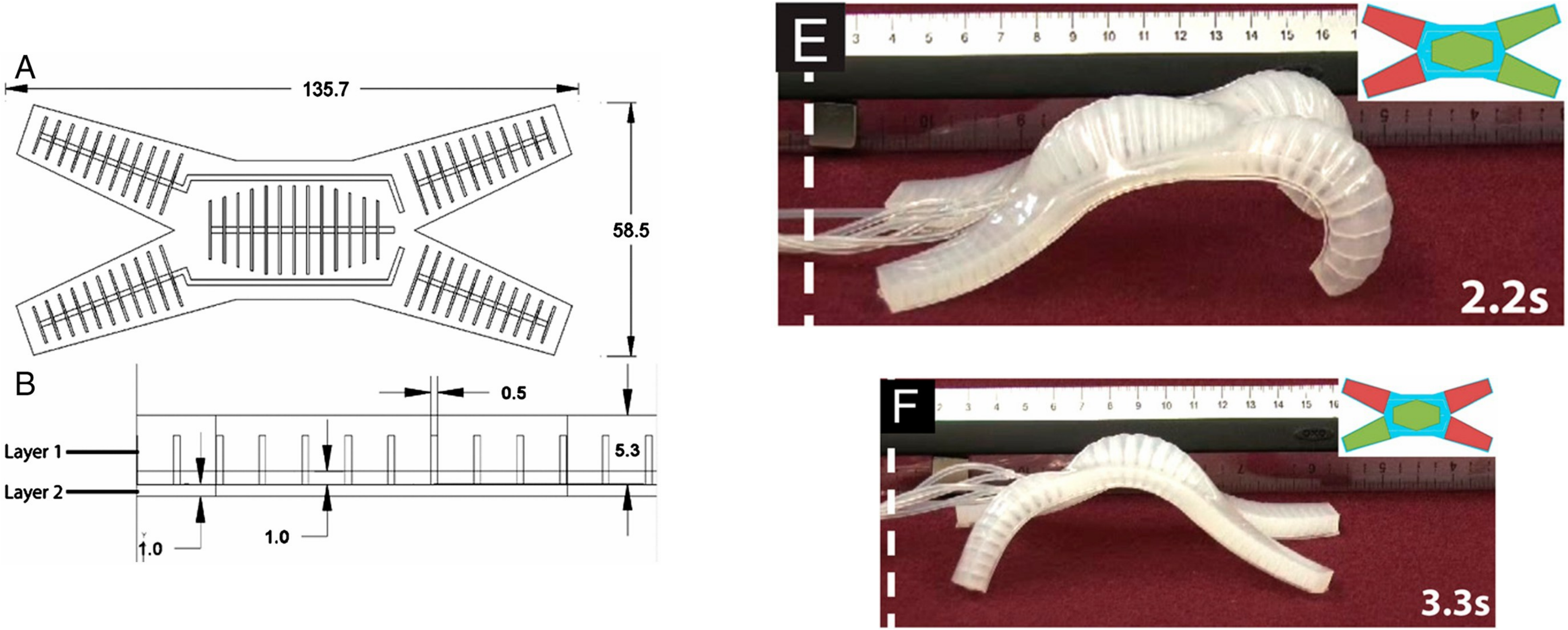
Soft pneumatic actuators enable adaptable motion



Whitesides, Angew. Chem. Int. Ed. 50, 1890-1895 (2011).

Pressure provides input; compliant geometry determines motion.

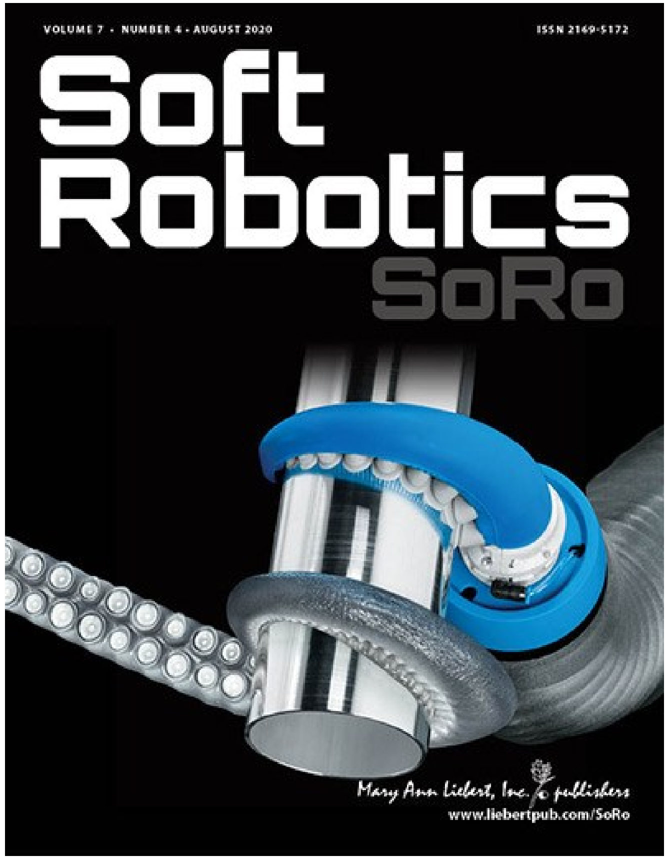
Compliance enables safe interaction

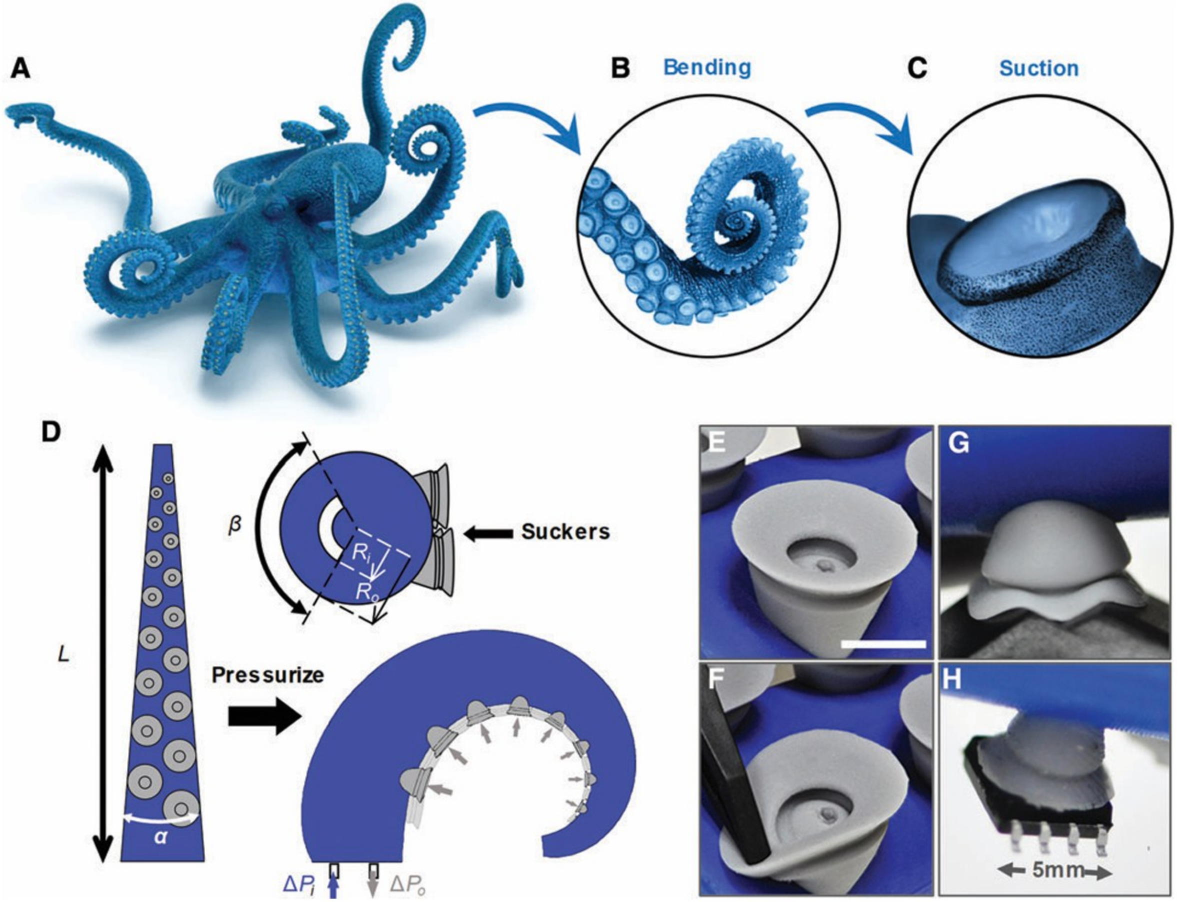


Whitesides, PNAS 108, 18887-18892 (2011).

Softness combines adaptability, safety, and complex interaction.

Mechanical architecture programs motion

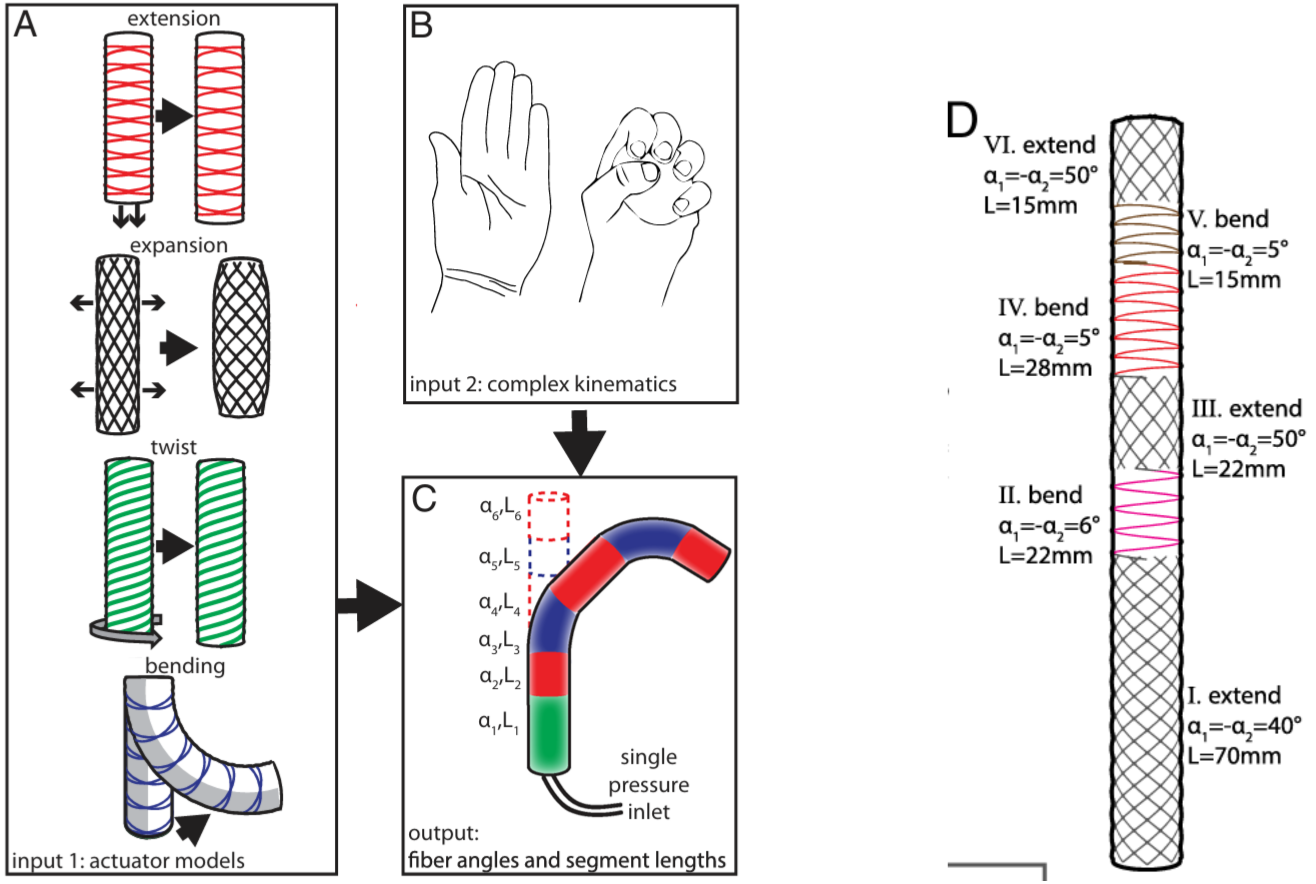


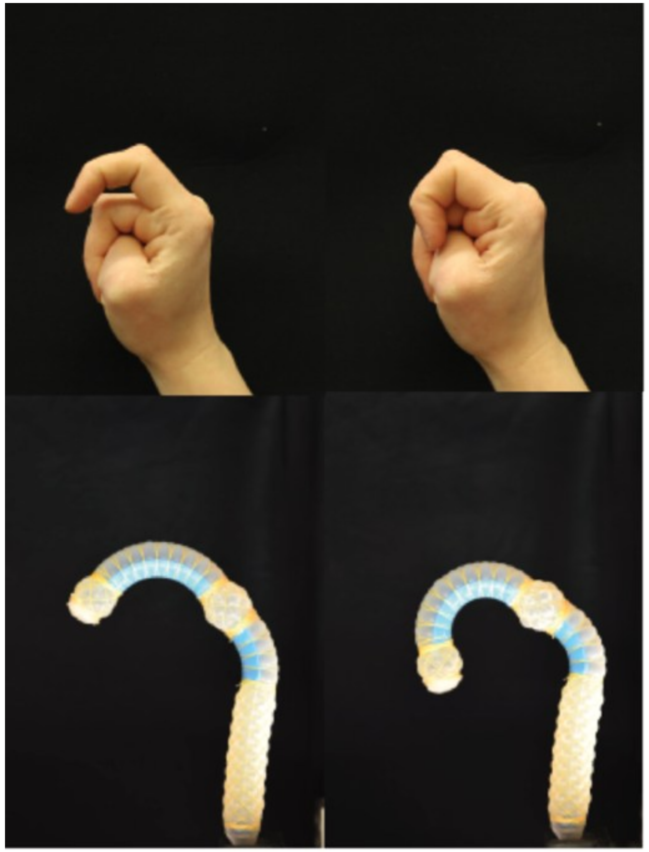


Xie, Z., Domel, A. G., **An, N.**,..., Bertoldi, K.*, Wen, L.*. Soft Robotics 7, 639-648 (2020).

Structure can replace complex control.

Anisotropy converts inflation into bending

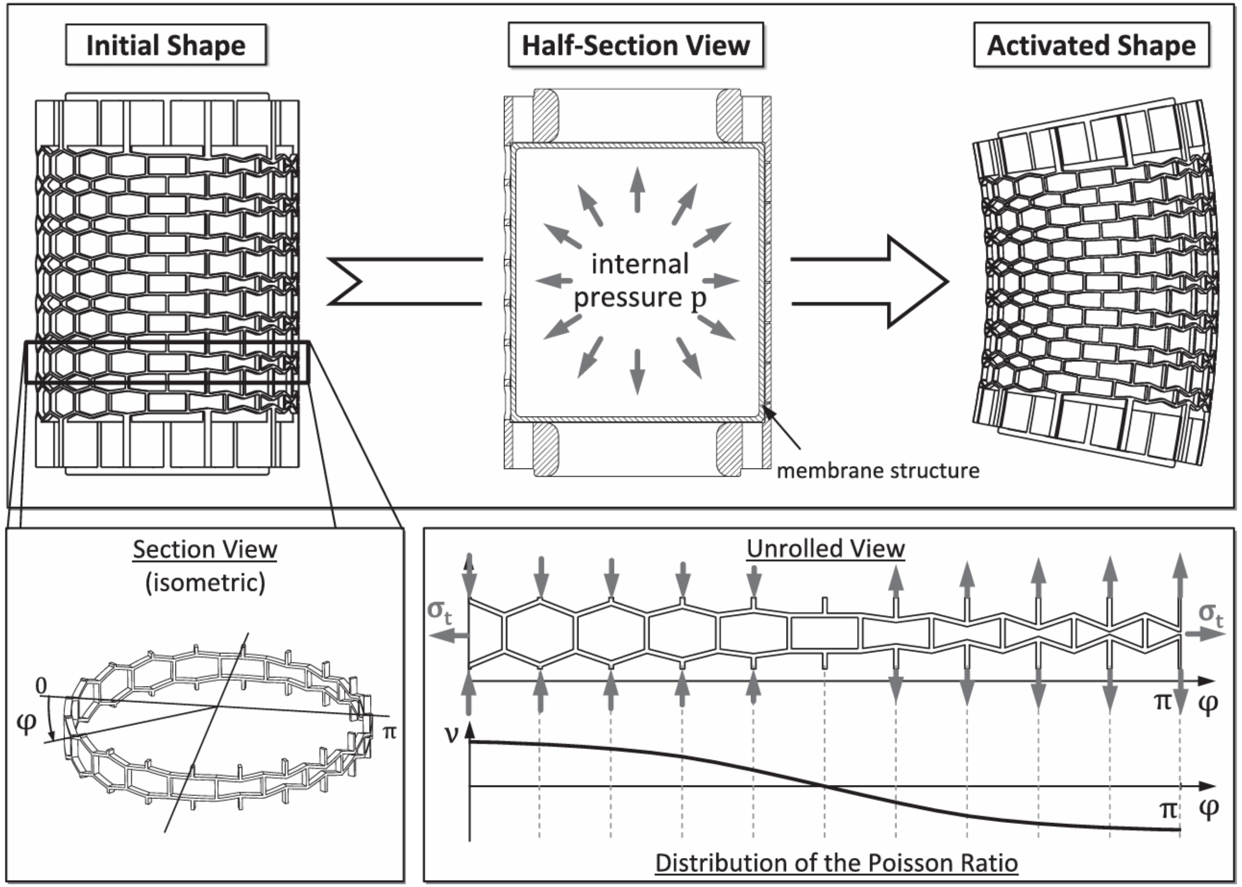


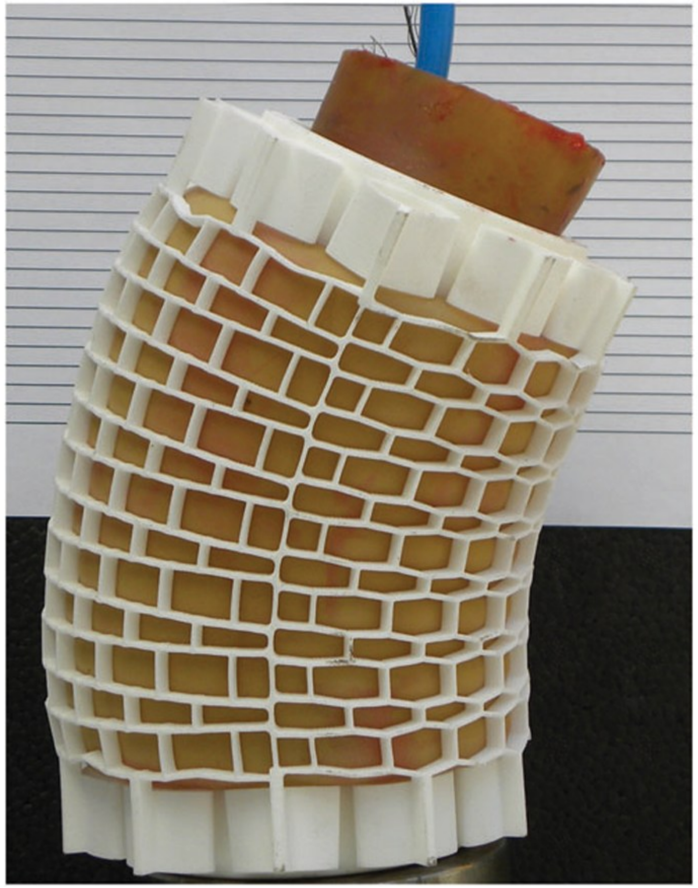


Connolly et al., PNAS 114, 51-56 (2017).

Directional stiffness converts expansion into curvature.

Metamaterials provide a scalable design language

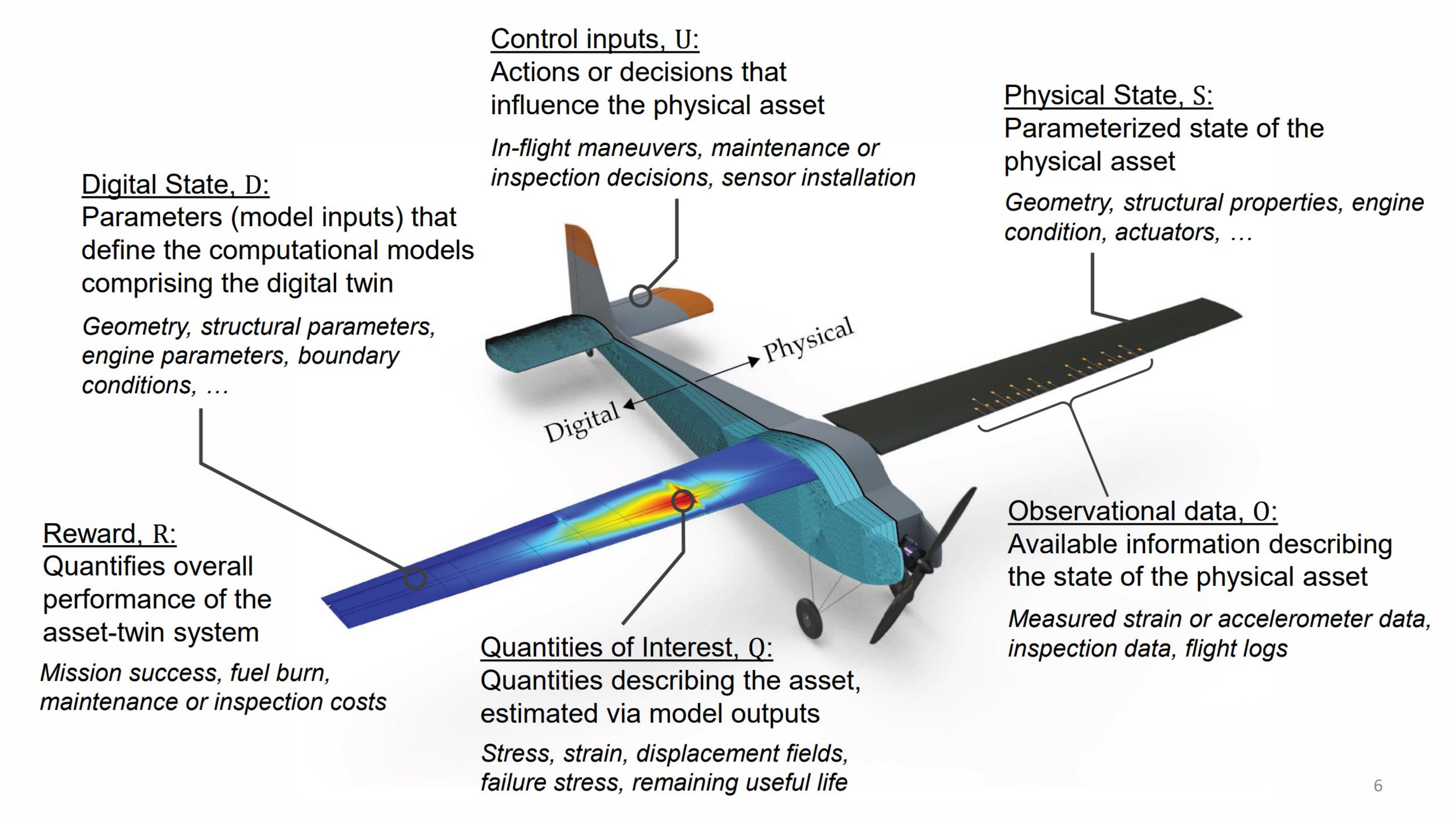




Hasse & Mauser, Soft Robotics 7, 155-167 (2020).

Patterned skins make deformation programmable.

A digital twin links actuator, data, and model

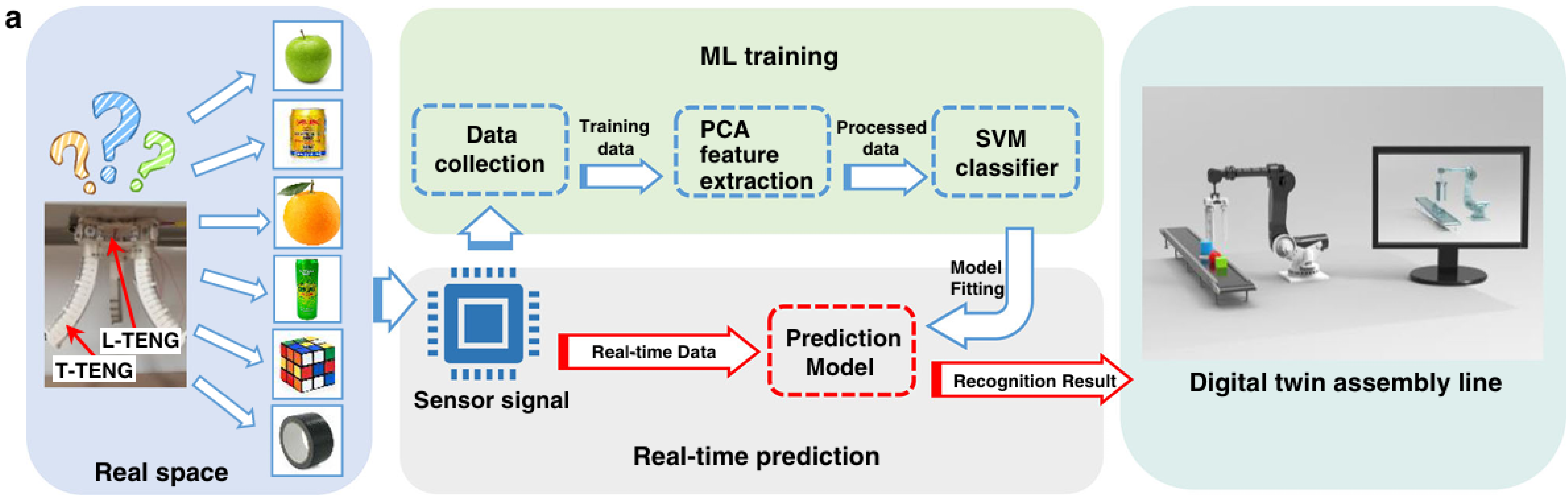


A useful twin links inputs, models, and observable outputs.

Real-time prediction closes the digital loop

Near-real-time inference turns simulation into an operational model.

Digital twin of soft robots



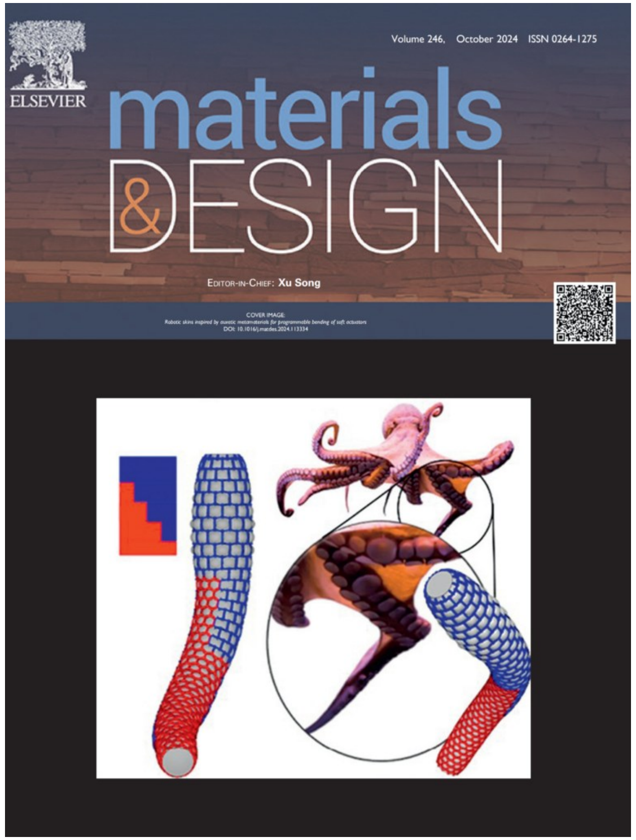
Jin et al., Nature Communications 11, 5381 (2020).

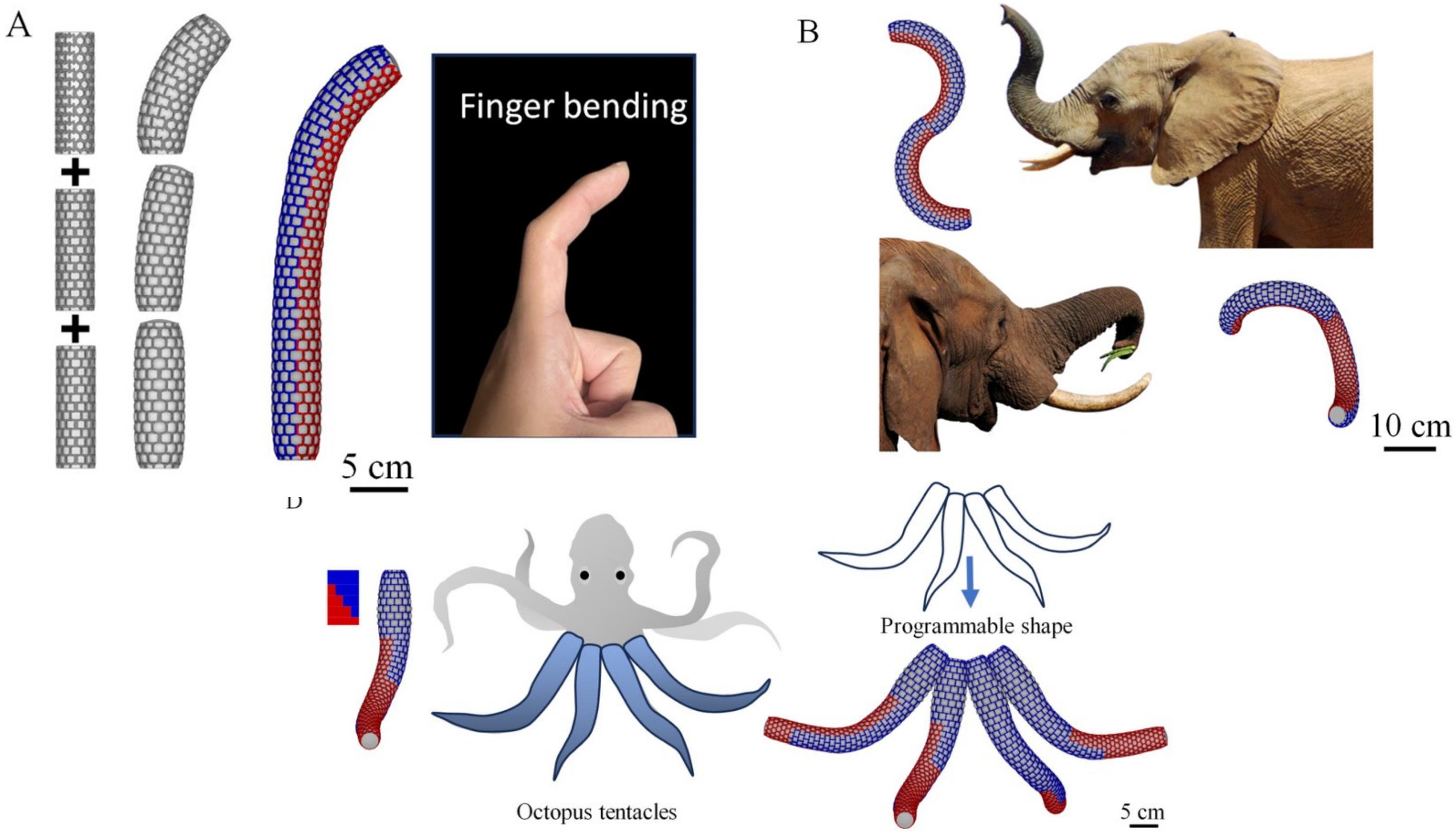
PART I

Programming motion with metamaterial skins

Geometry becomes a mechanical instruction set for bending, expansion, twisting, and morphing.

Auxetic skins program pneumatic deformation



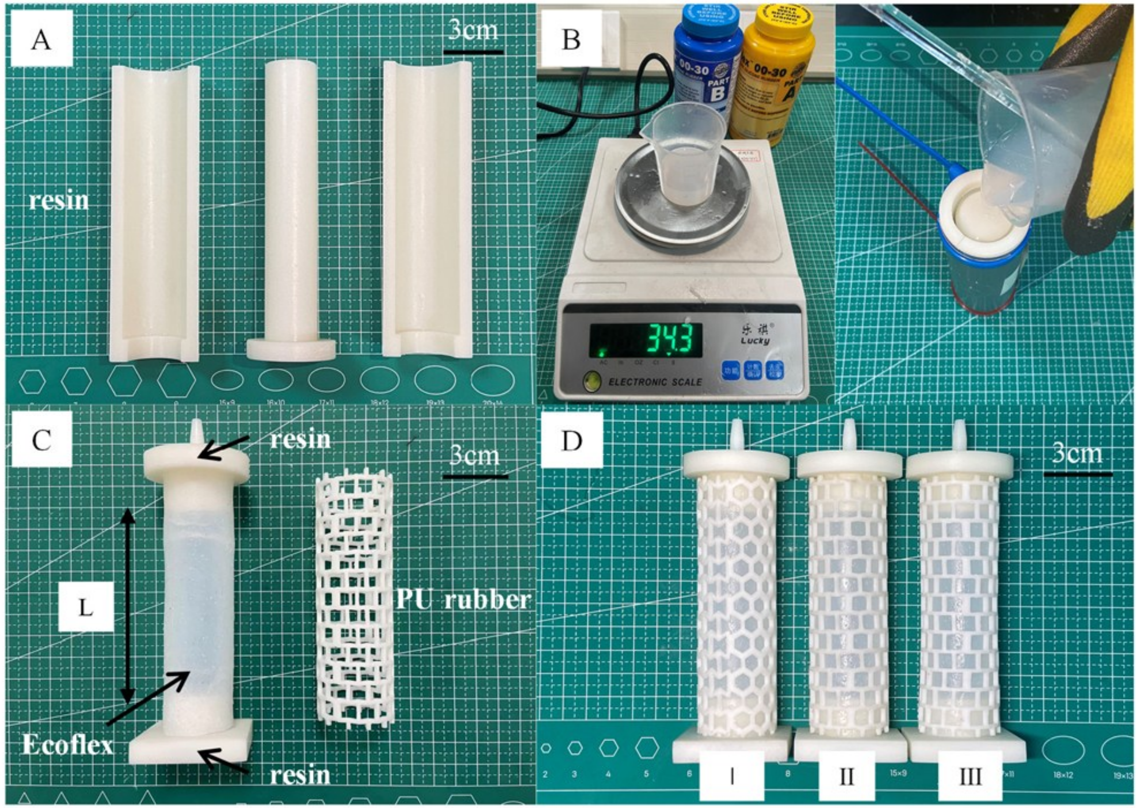


Pu, Y., Zheng, S., Hu, X., Tang, S., & **An, N.***, Materials & Design 246, 113334 (2024).

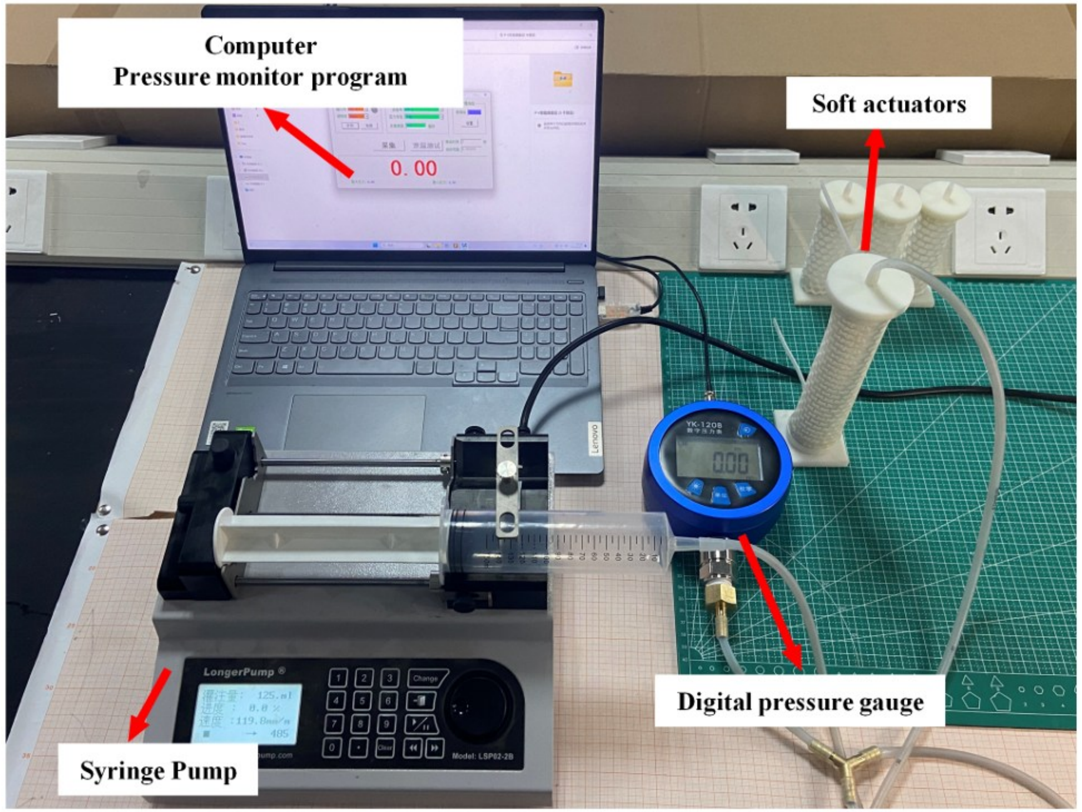
Auxetic and conventional cells form a mechanical code.

Experiments connect fabrication to response

Fabrication

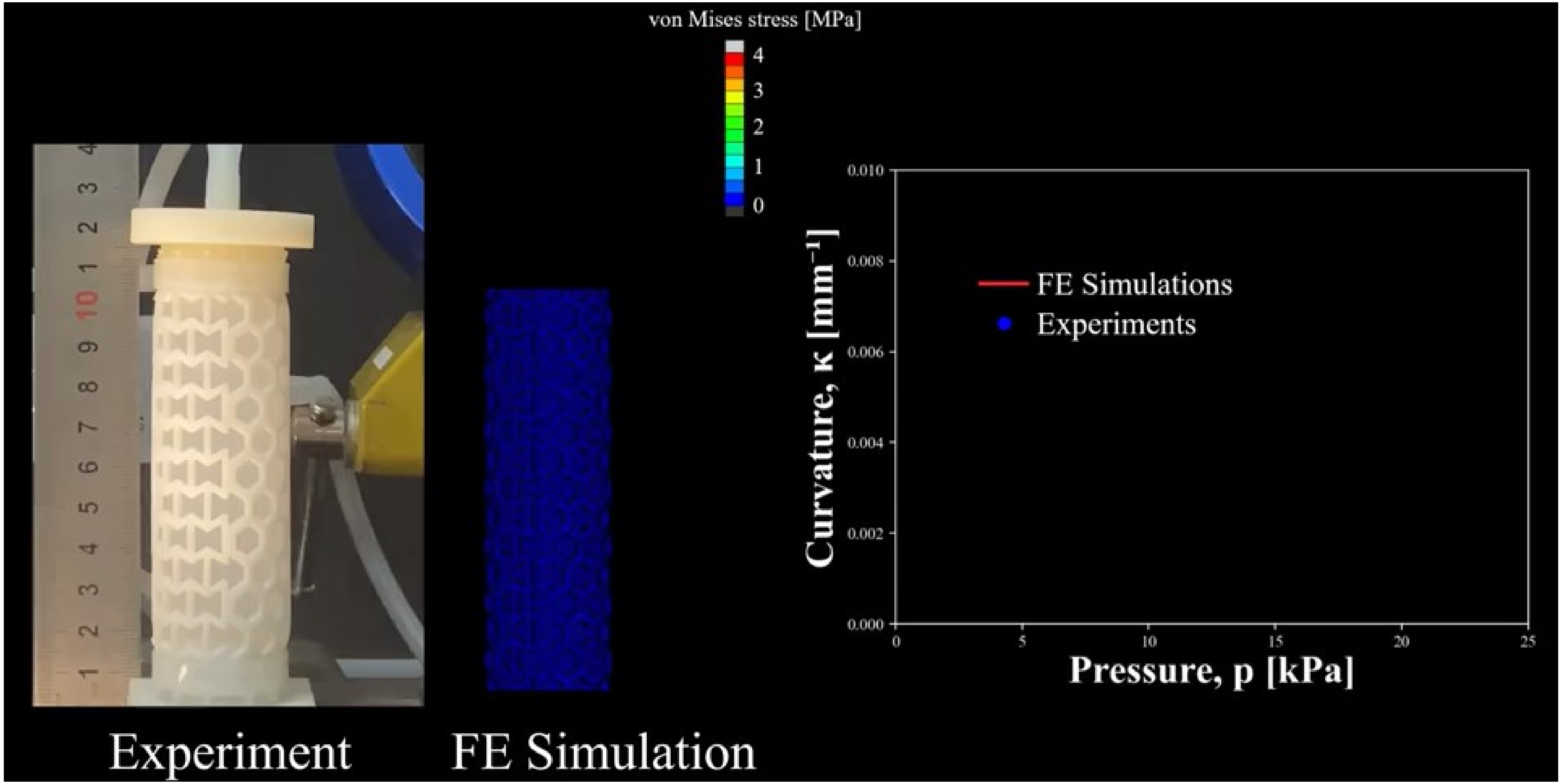


Testing Set-up



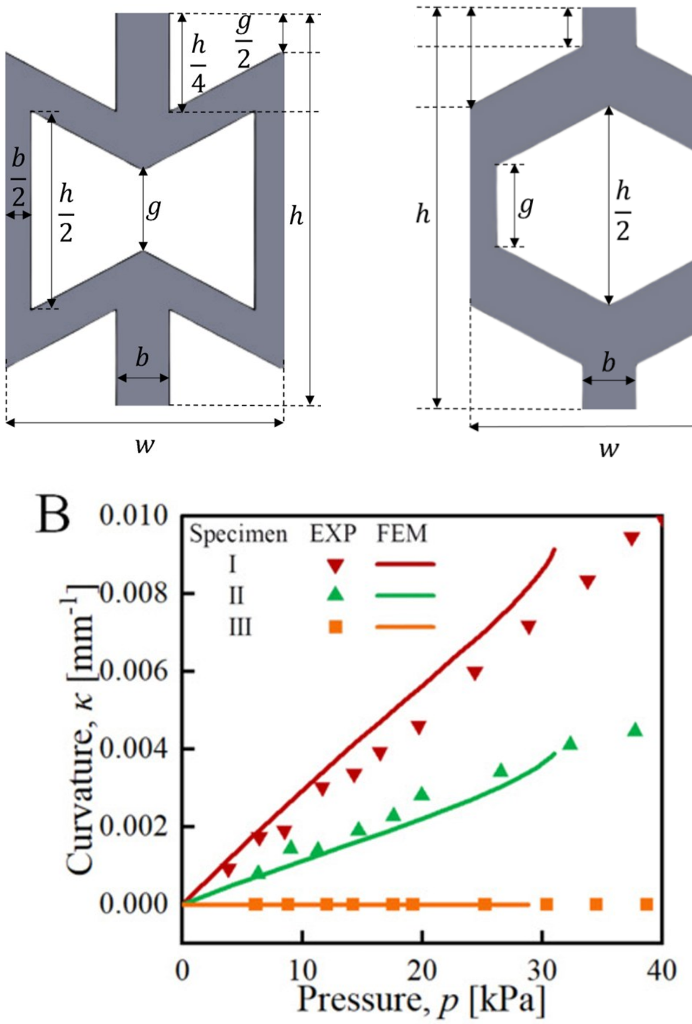
Fabrication and testing connect geometry to response.

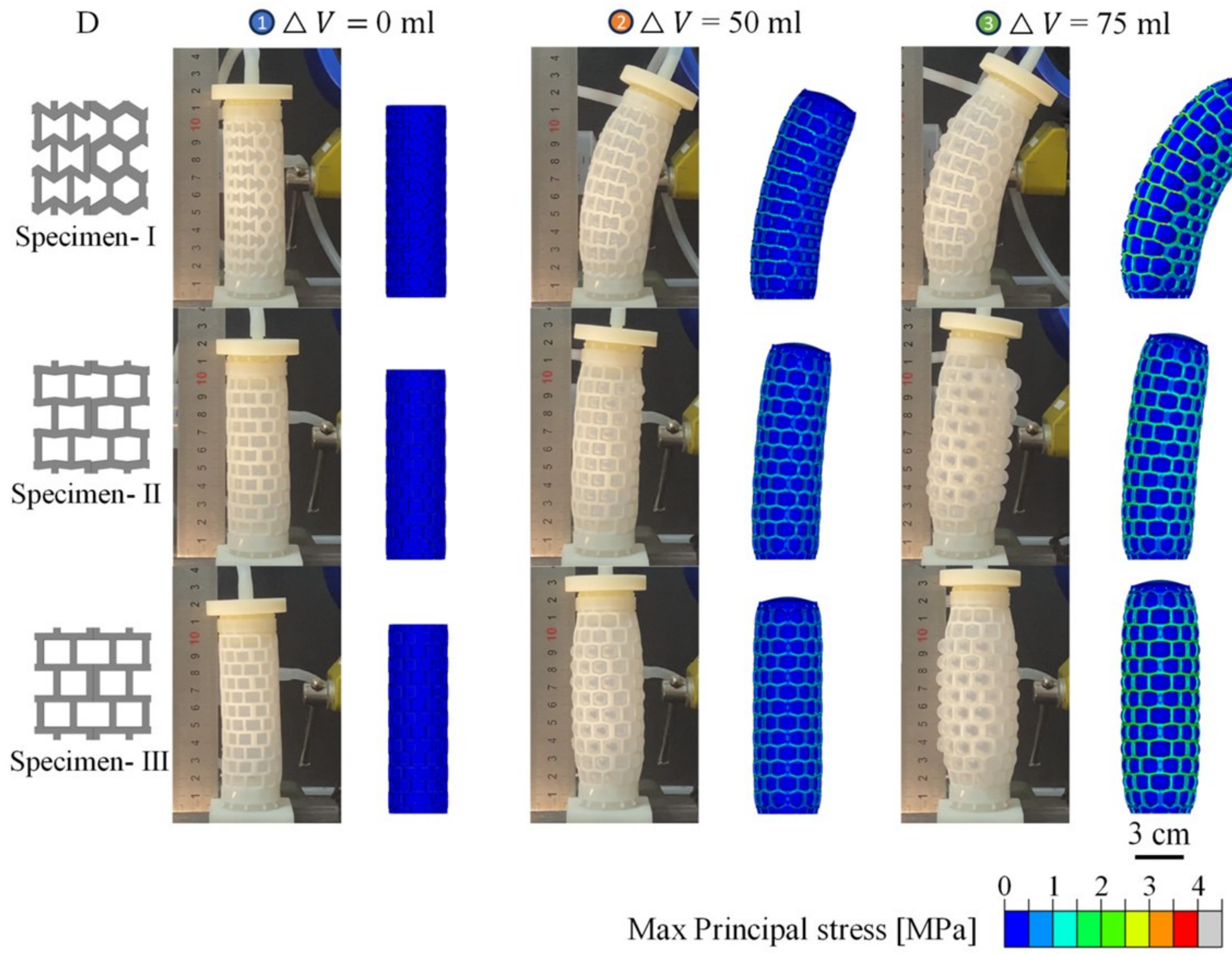
Experiments validate the FE model



Validated simulation enables efficient design exploration.

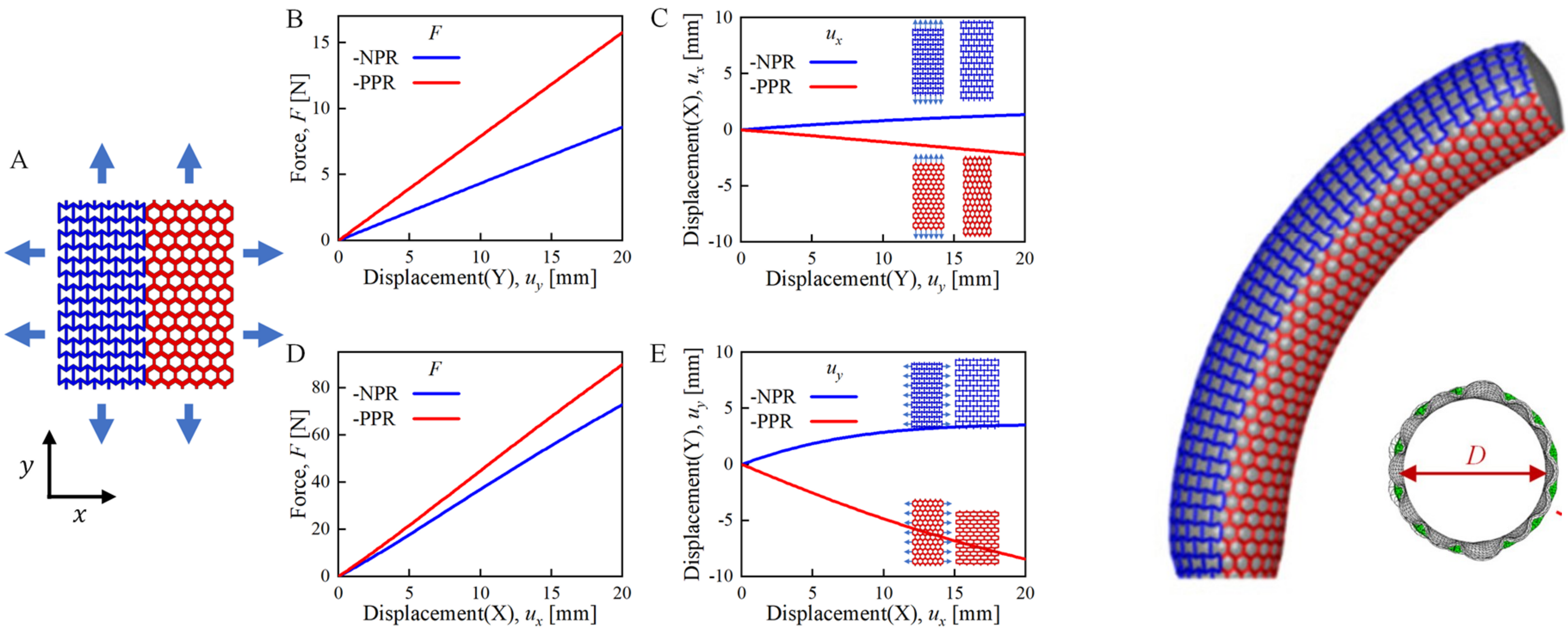
Unit-cell geometry sets the deformation mode





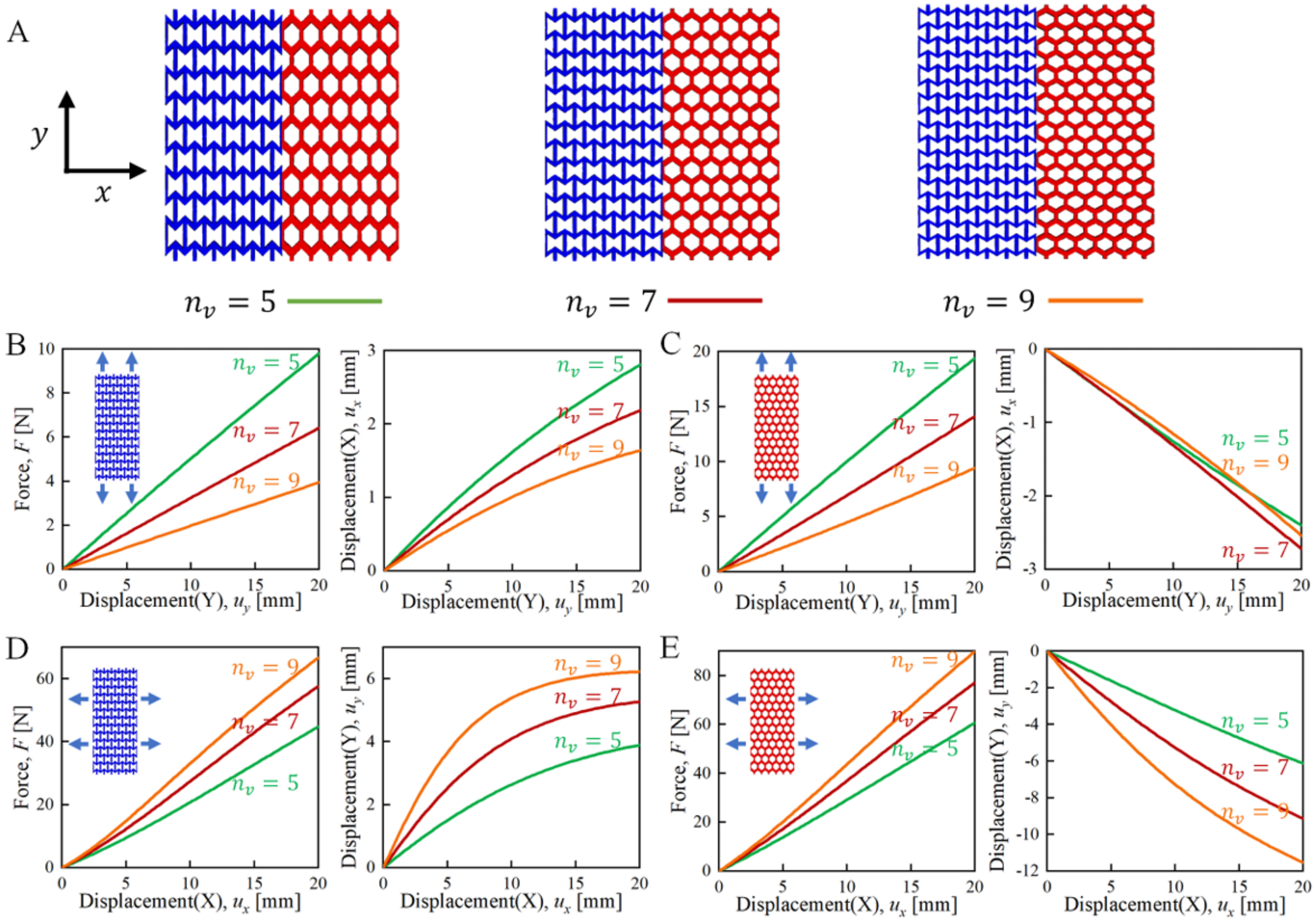
Cell geometry determines the deformation mode.

Skin layout couples expansion and bending



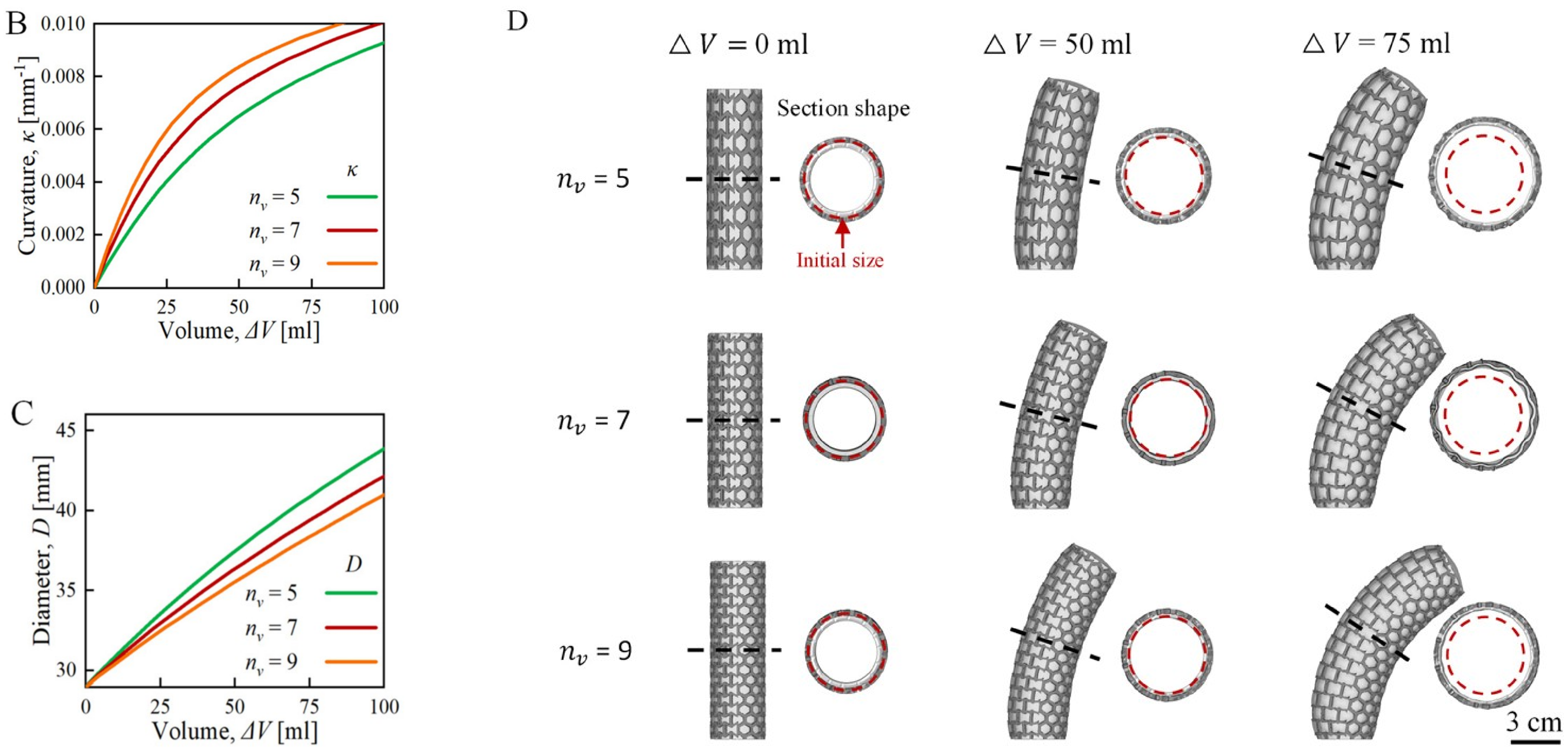
Skin layout converts local expansion into global bending.

Vertical cell count tunes actuator response



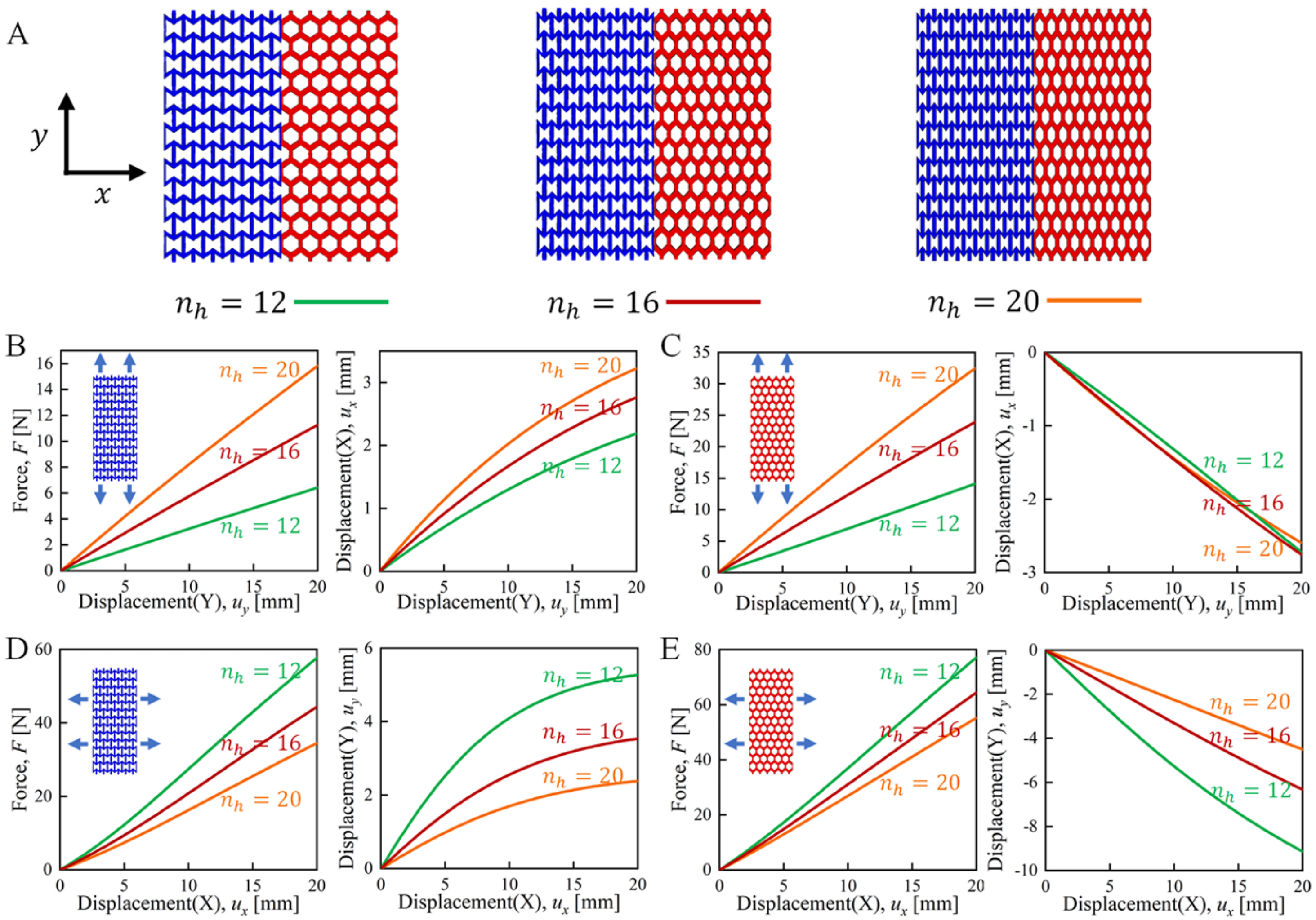
Axial patterning controls curvature and expansion.

More vertical cells favor bending



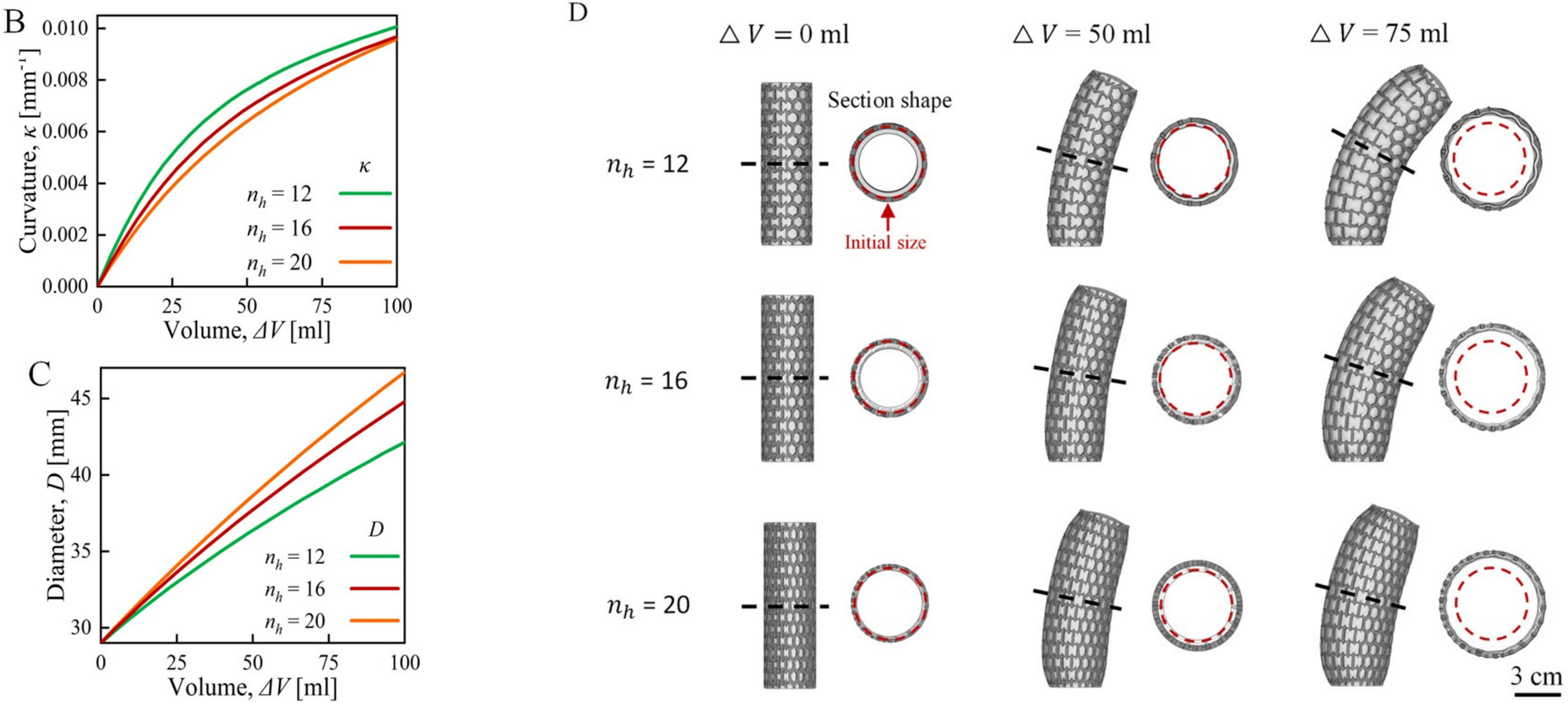
More vertical cells favor bending over radial expansion.

Hoop cell count redistributes deformation



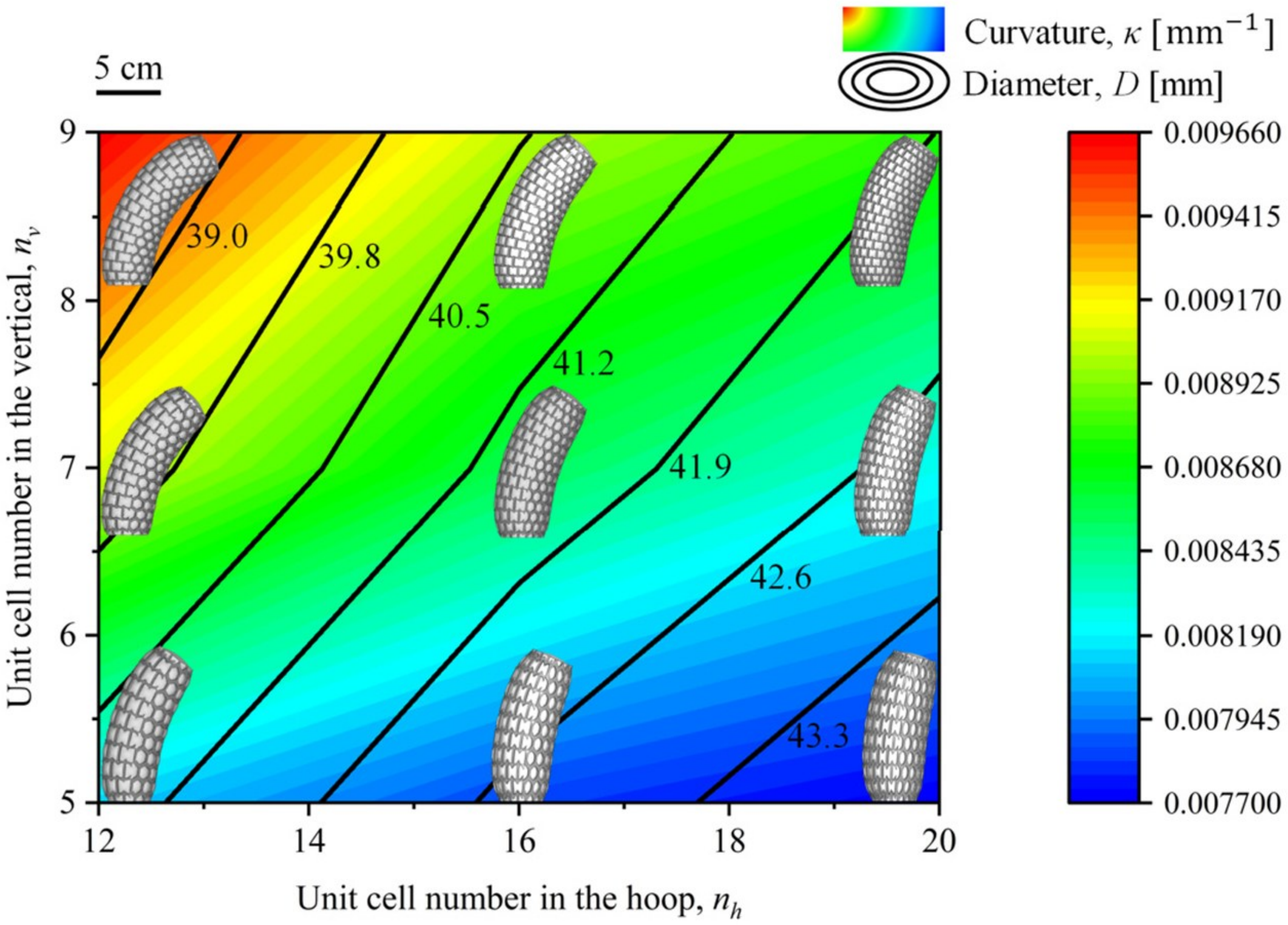
Hoop patterning controls circumferential compliance.

More hoop cells favor expansion



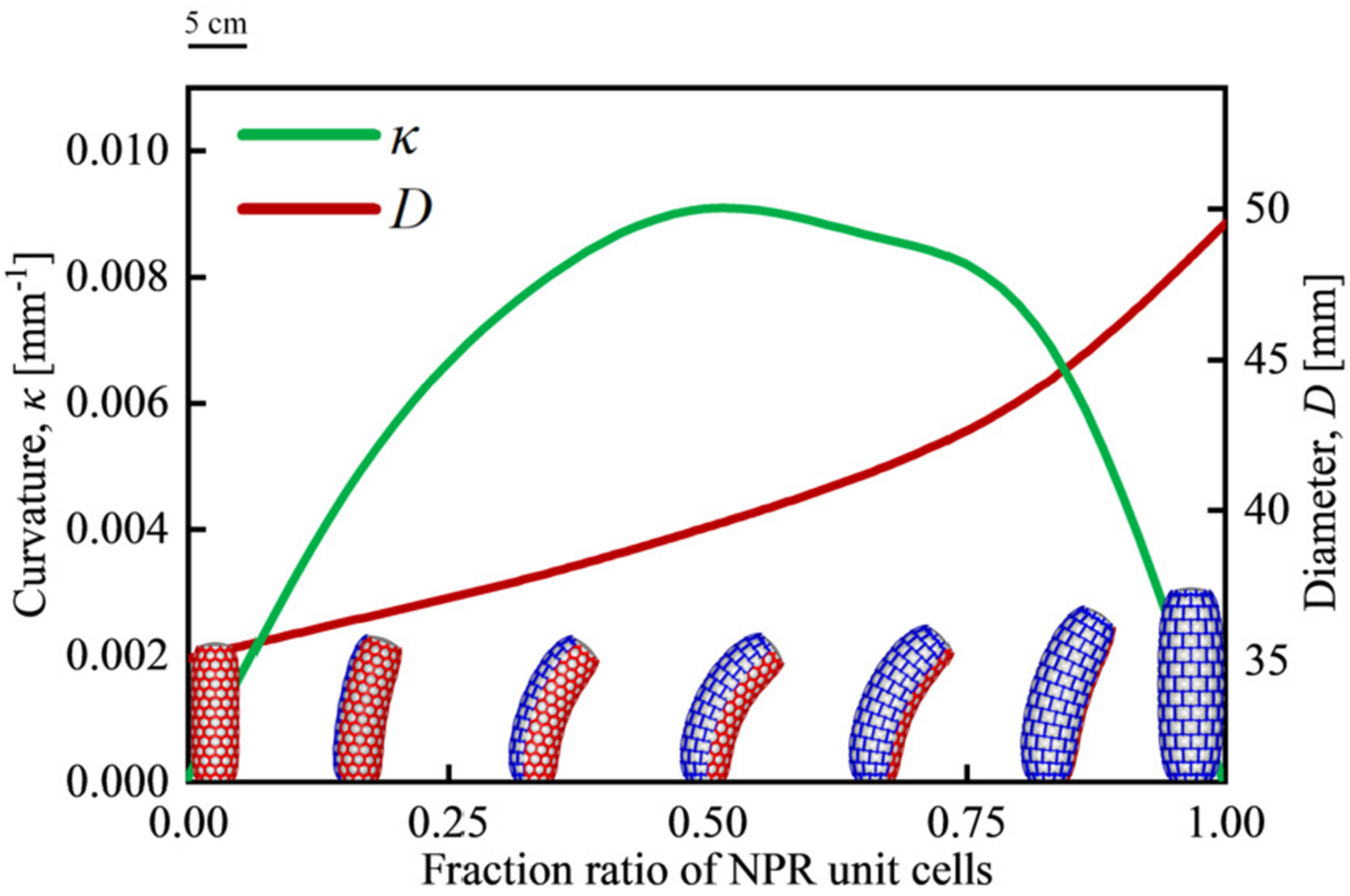
More hoop cells favor expansion over bending.

Design maps reveal coupled deformation



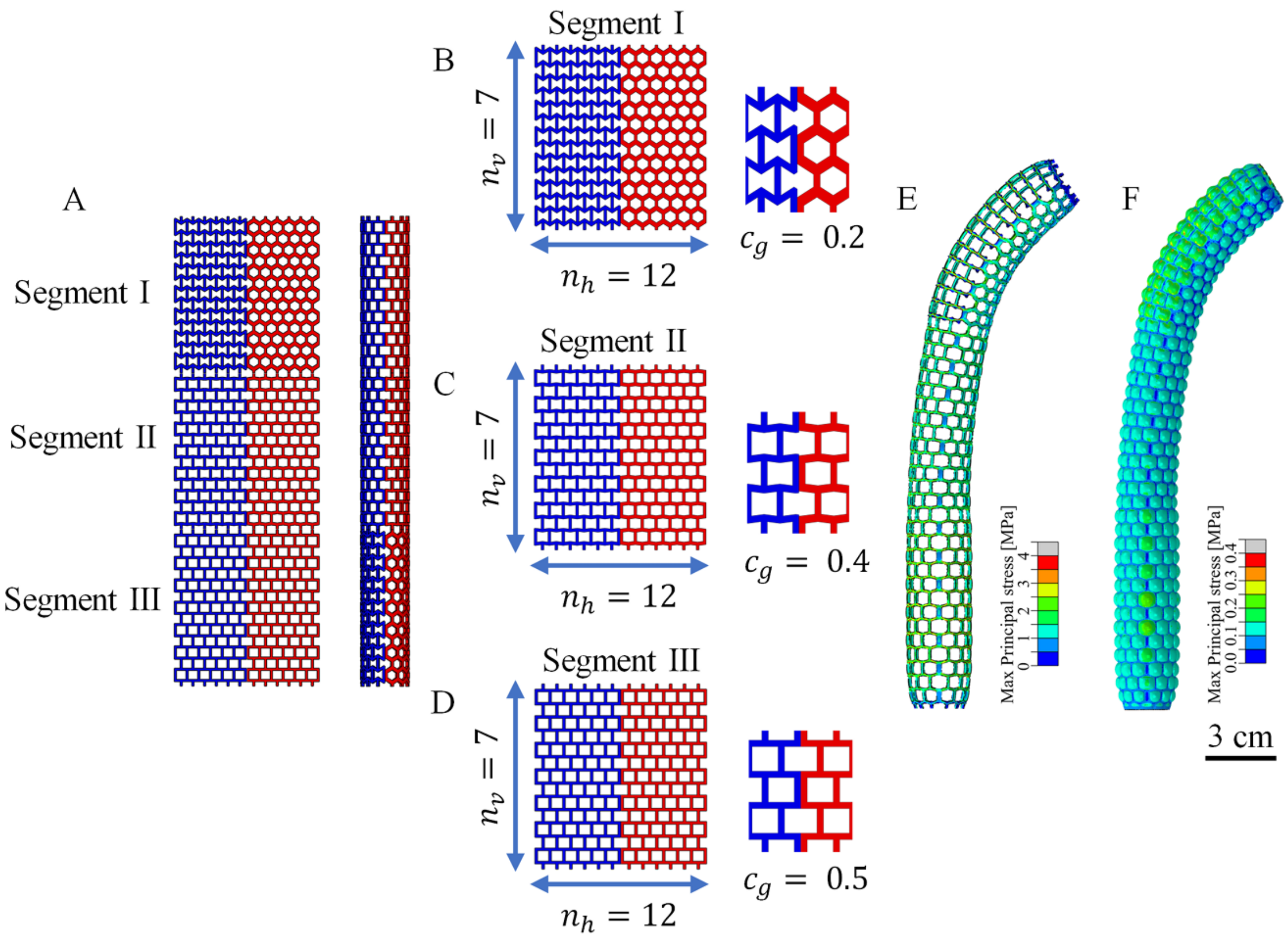
Design maps reveal coupled bending-expansion regimes.

Graded skins trace a performance envelope



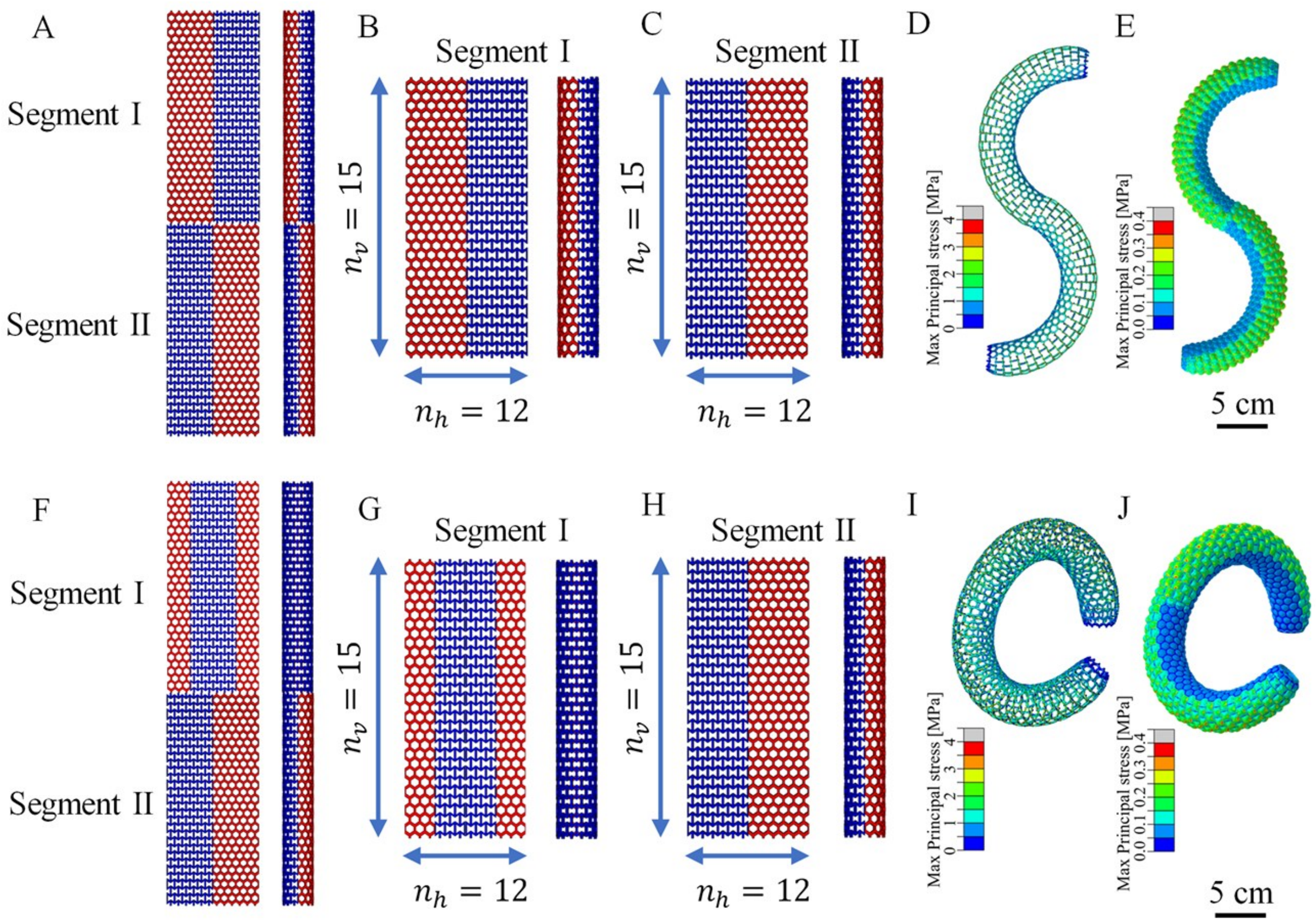
Graded skins balance curvature and diameter change.

Segmented skins reproduce finger bending



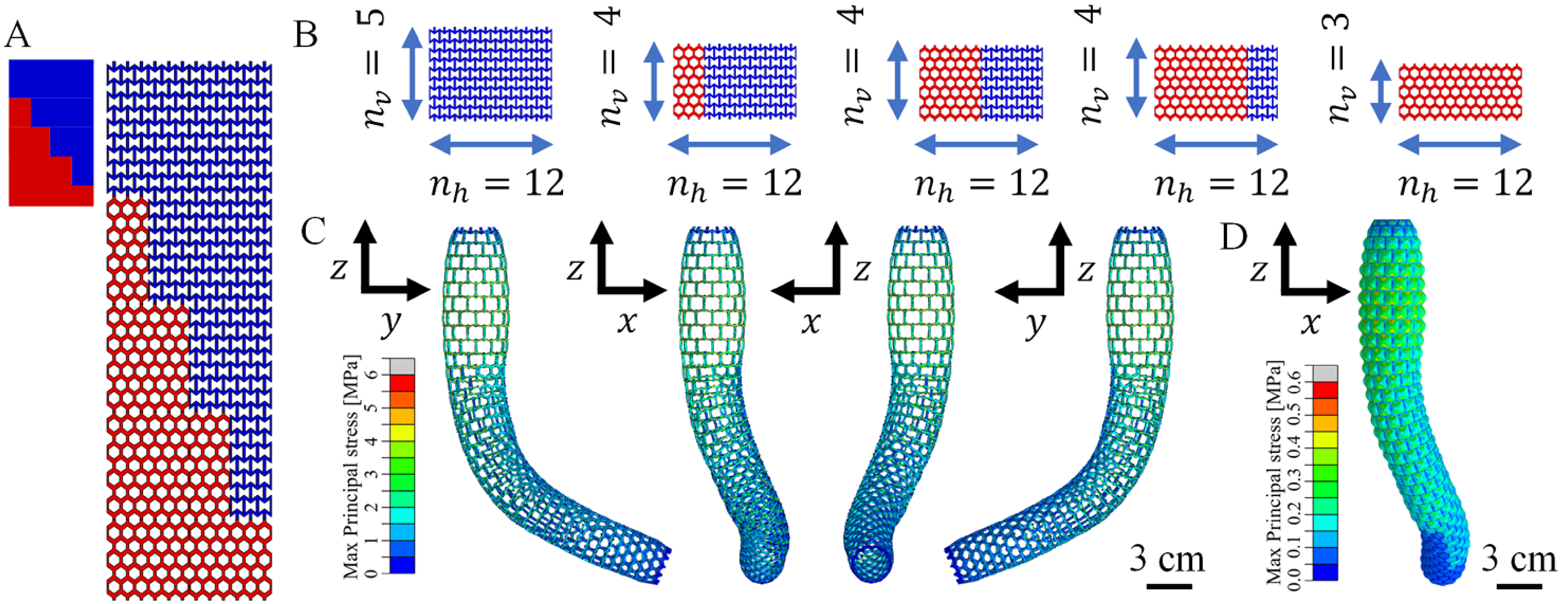
Segmented skins produce distributed finger-like bending.

Patterning adds twisting to bending



Asymmetric patterns add torsion without extra actuators.

Cell combinations enable complex morphing



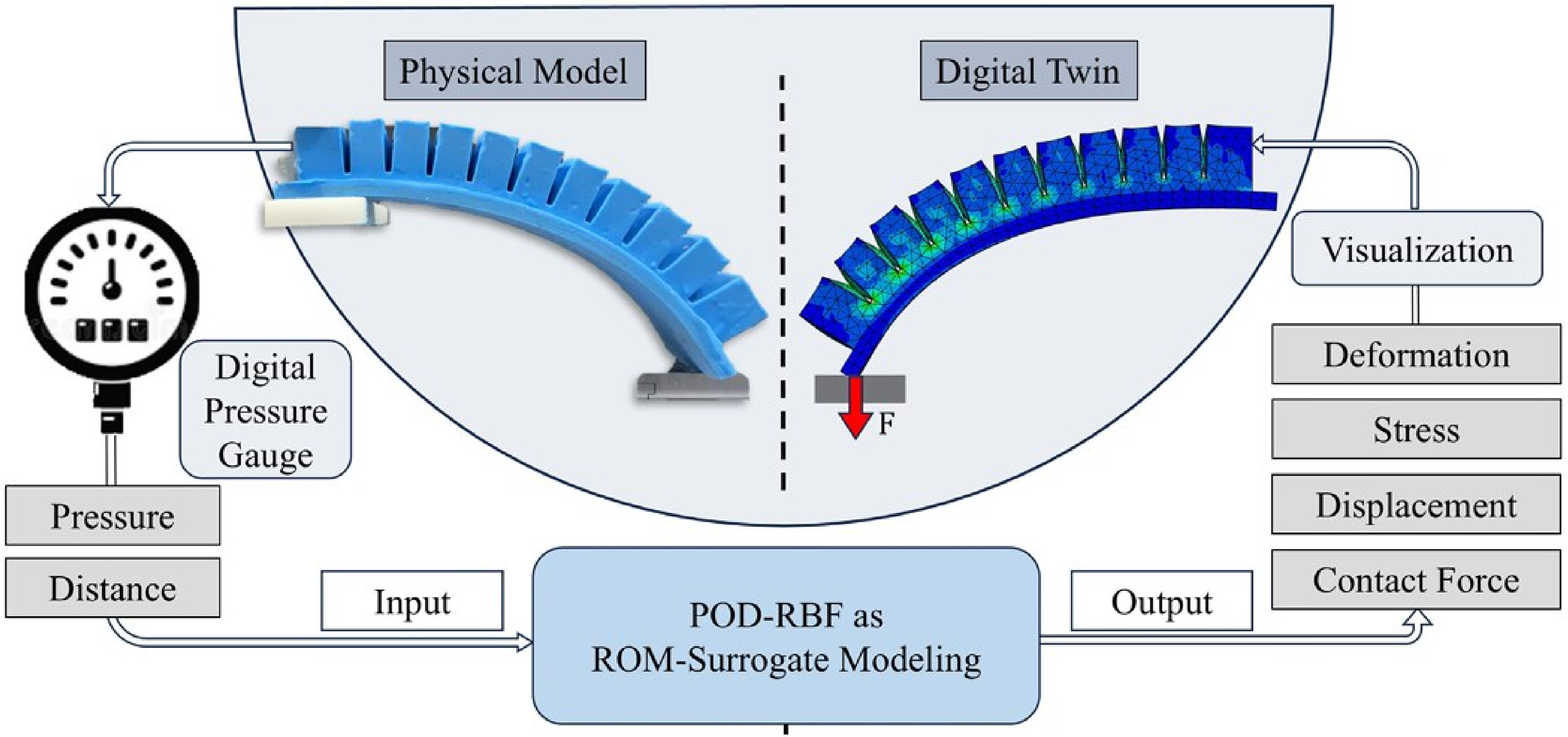
A small cell library generates diverse shapes.

PART II

Predicting behavior with digital twins

Reduced-order modeling transforms high-fidelity simulation
into rapid full-field prediction.

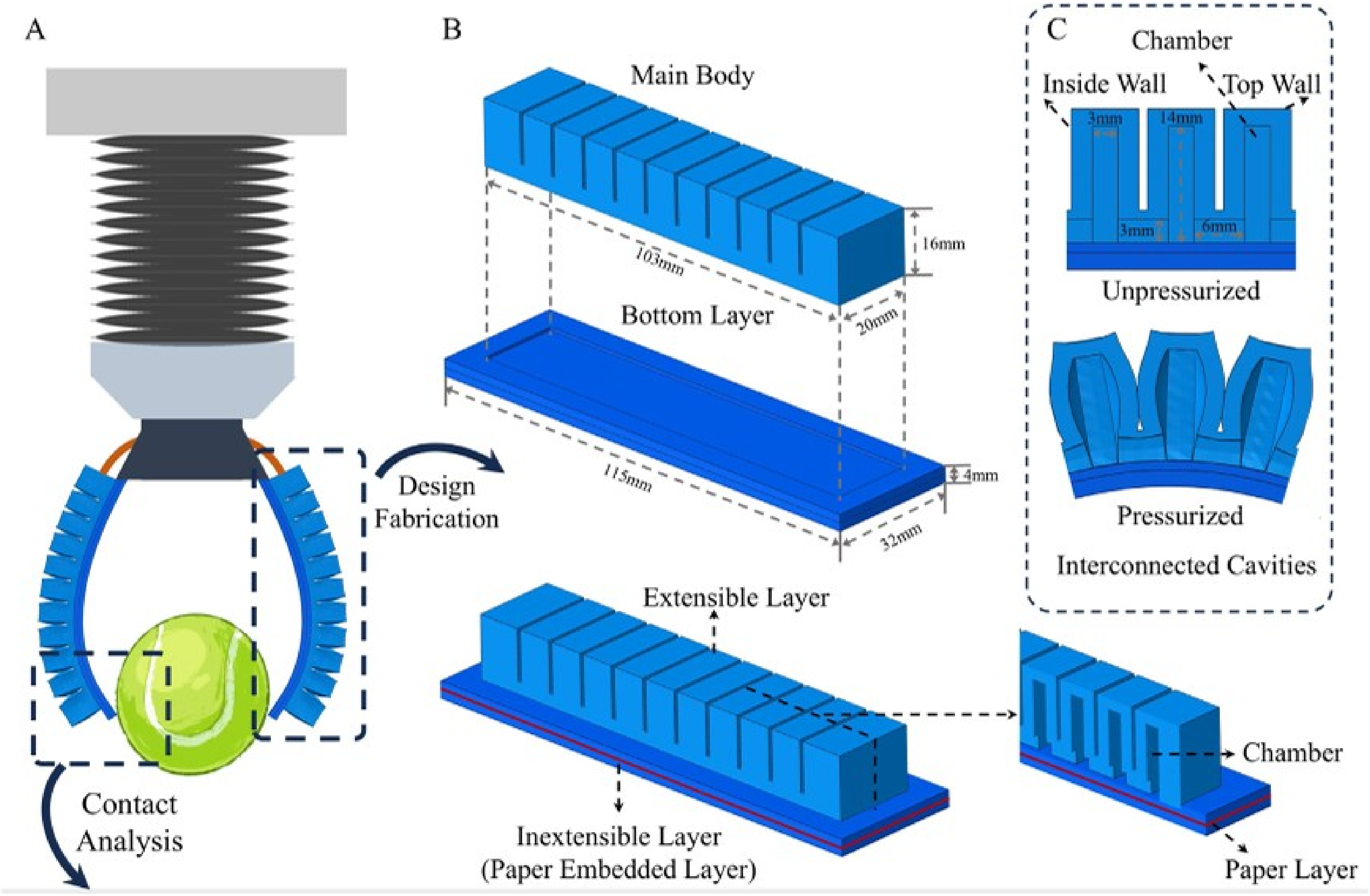
The POD-RBF twin predicts full-field response

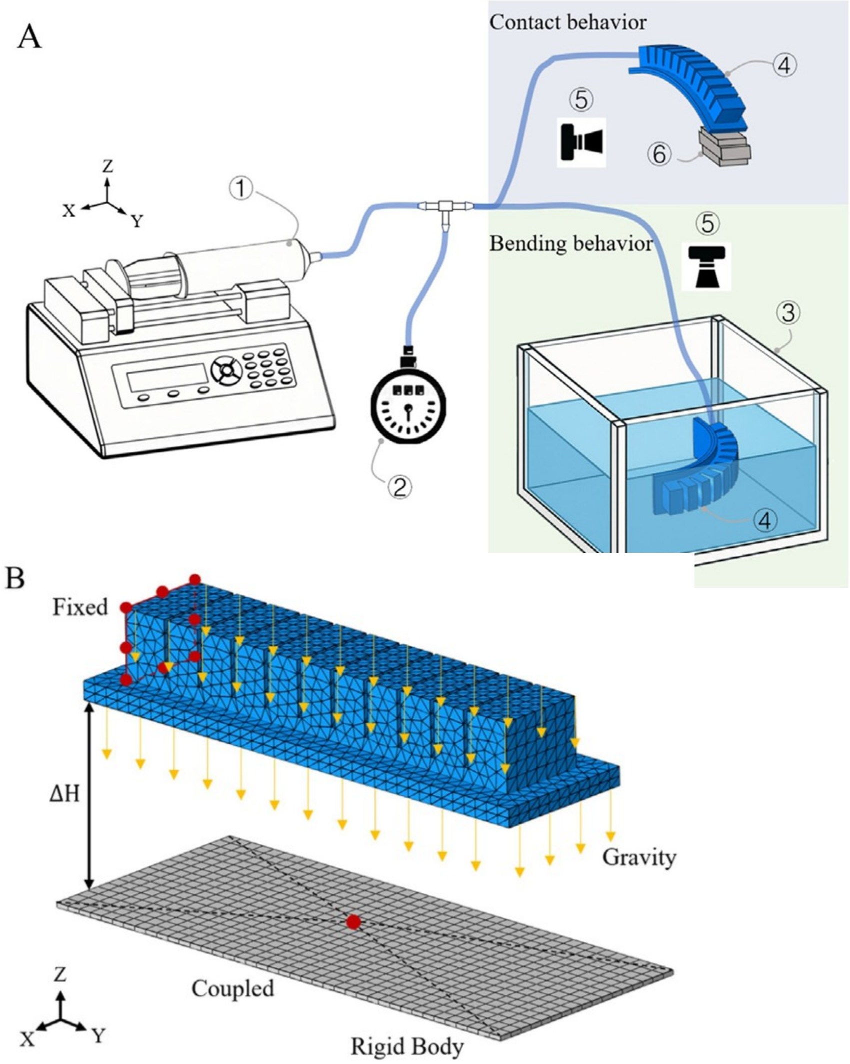


Pu, Y., …& **An, N.*** (2026). *International Journal of Solids and Structures,* 339, 114190.

The twin predicts fields and contact from a small parameter set.

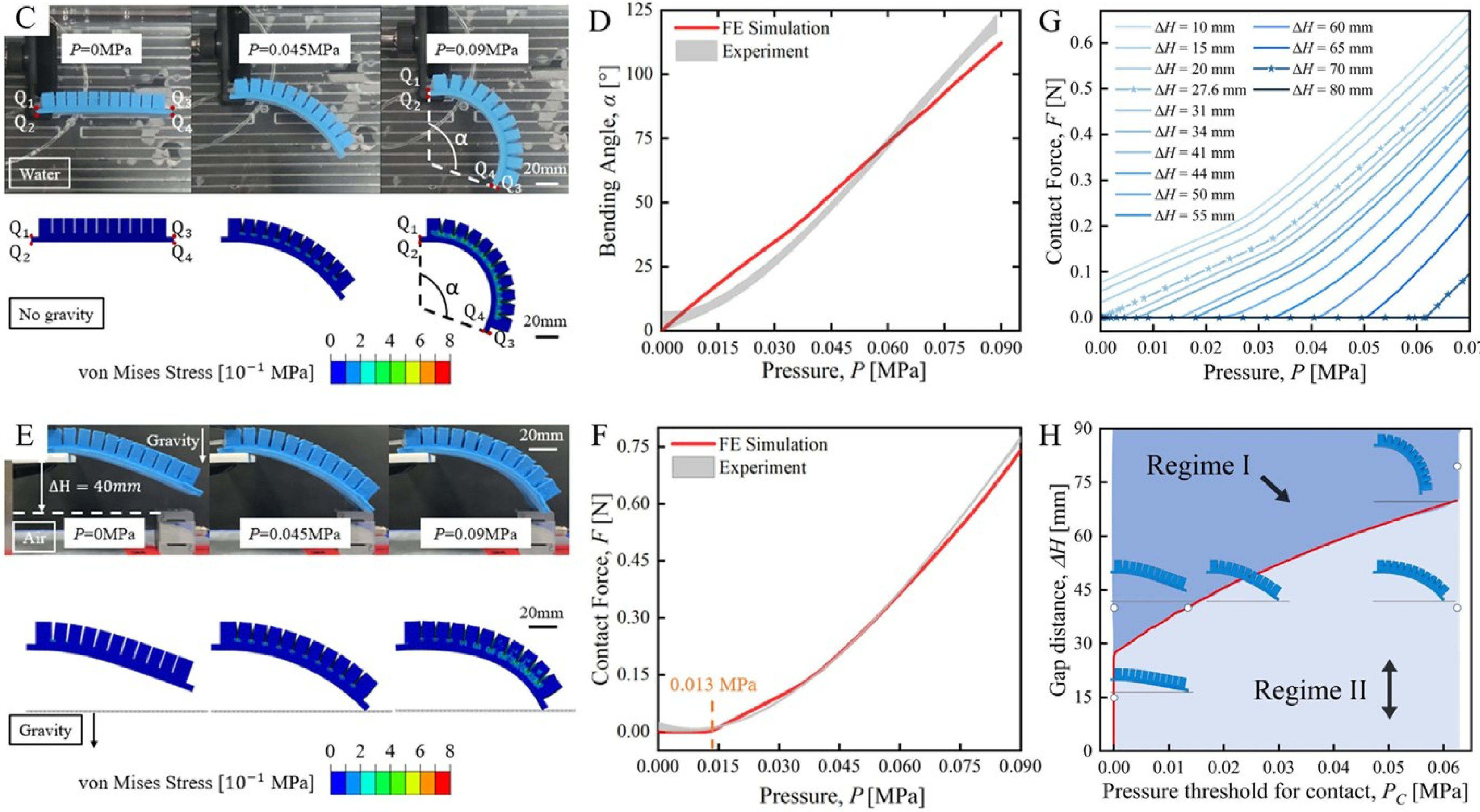
Simulations supply the training snapshots





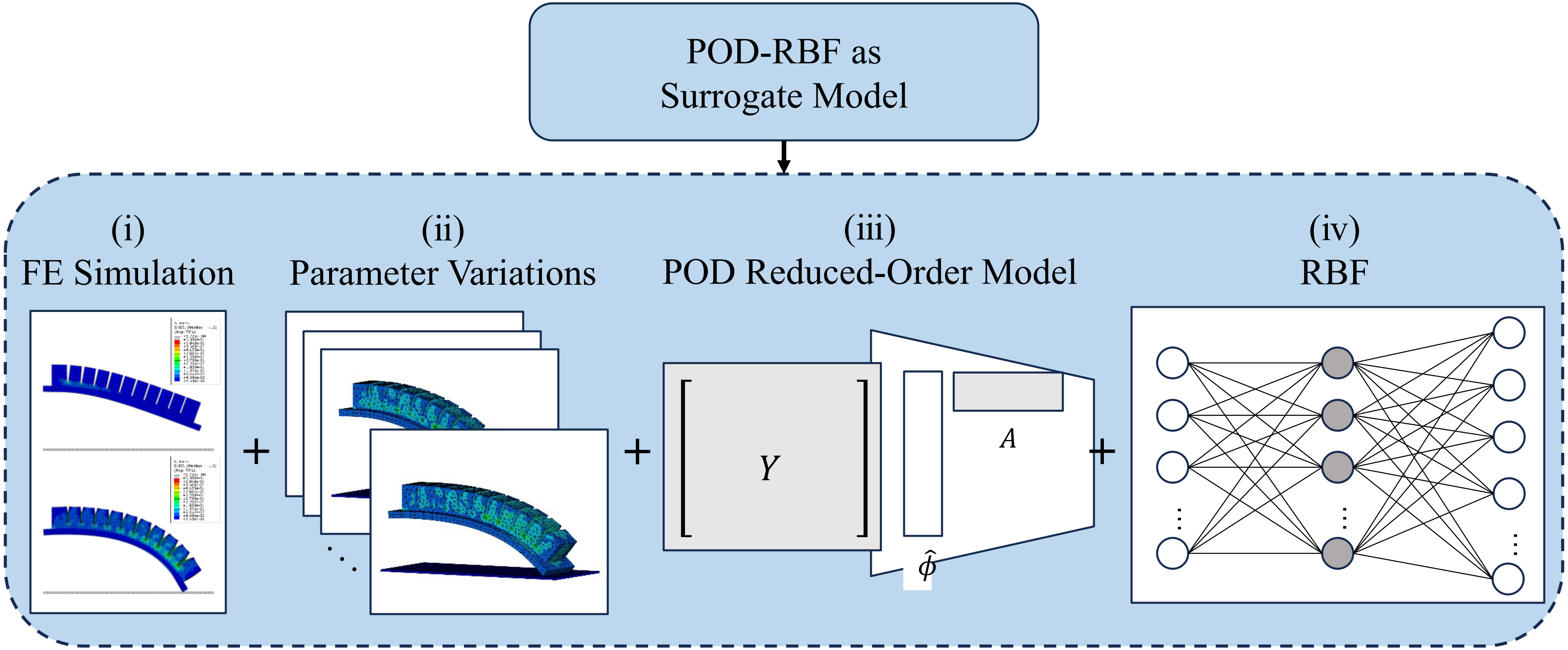
Offline simulations create the data for fast online prediction.

Experiments anchor the numerical model



Experiment-FEA agreement establishes a credible full-order model.

POD compresses fields; RBF maps parameters

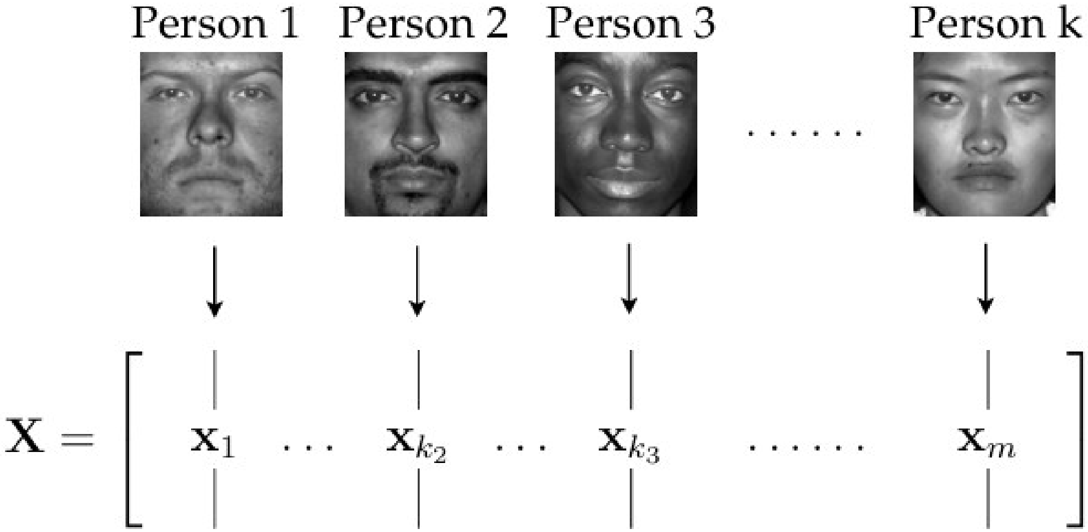


POD separates spatial complexity from parameter interpolation.

POD represents snapshots in a common basis

➢ Face Image Representation

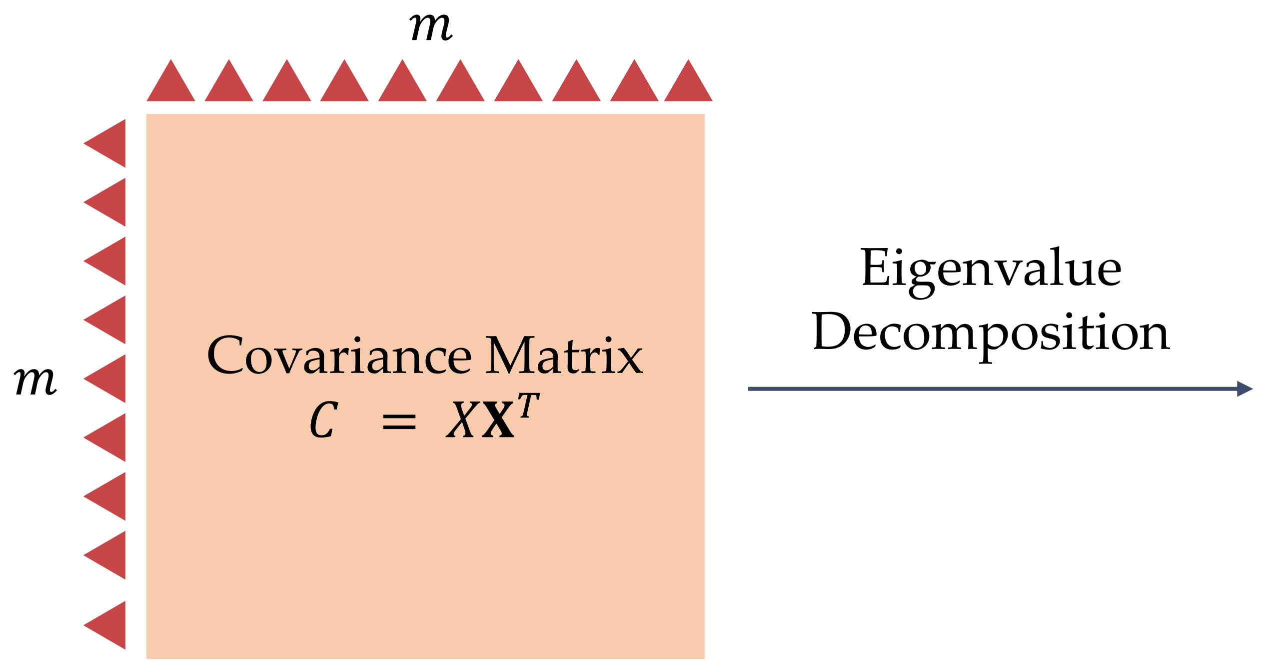
- Each face image is treated as a m-dimensional vector (flattening the 2D image into a 1D array of pixel values).
- A dataset of n face images forms **a data matrix of $\mathbf{X}_{m\times n}$** where each column represents an individual person.

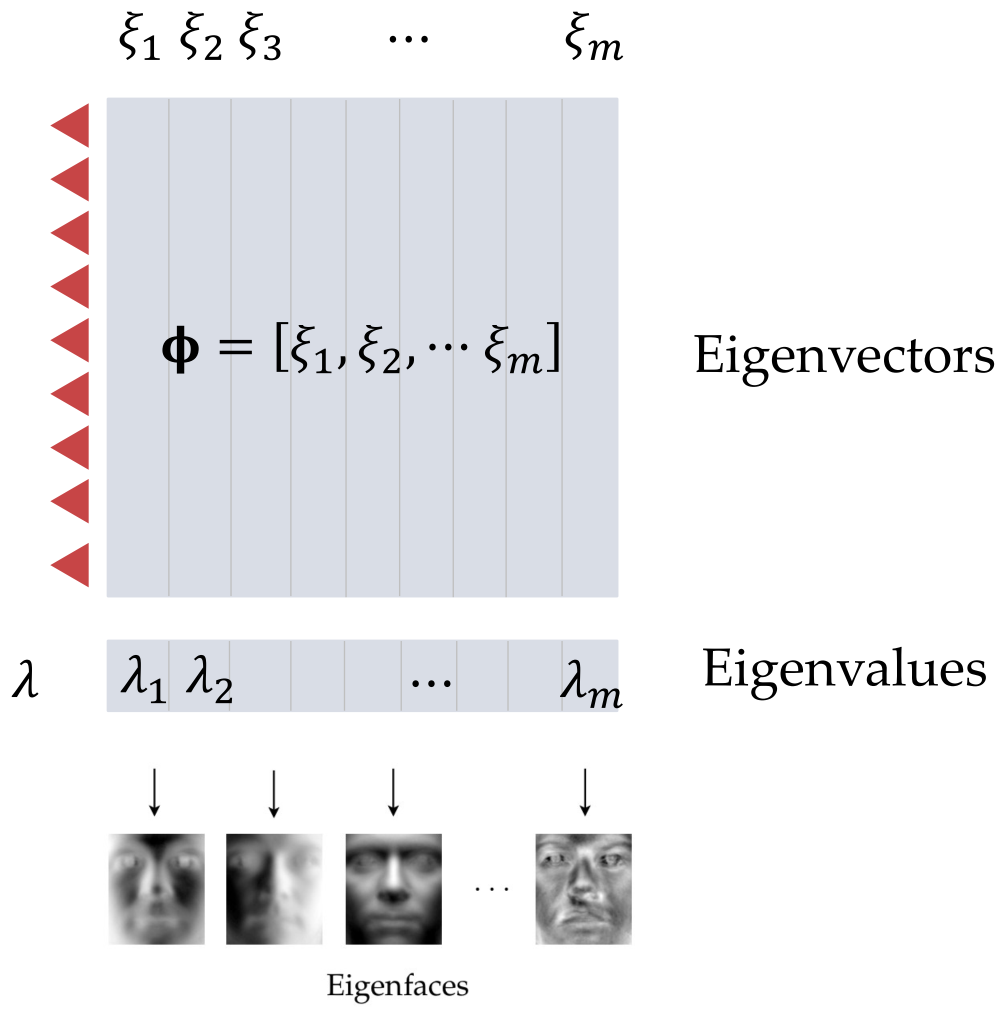


Snapshot organization bridges full fields and reduced coordinates.

Dominant modes retain deformation patterns

- **POD Process**

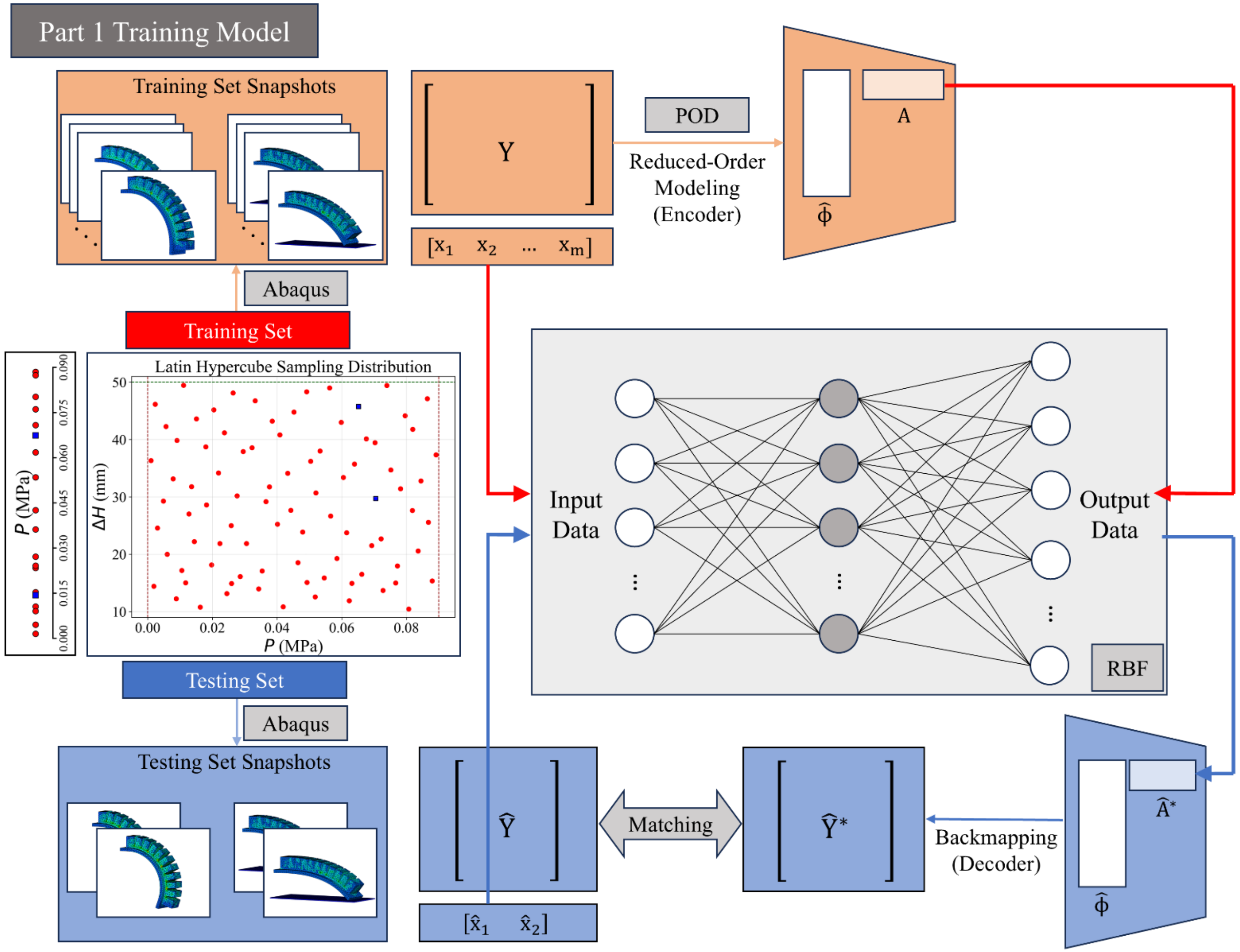




- POD identifies dominant orthogonal patterns, or eigenfaces, ranked by their contribution to the dataset's variance.

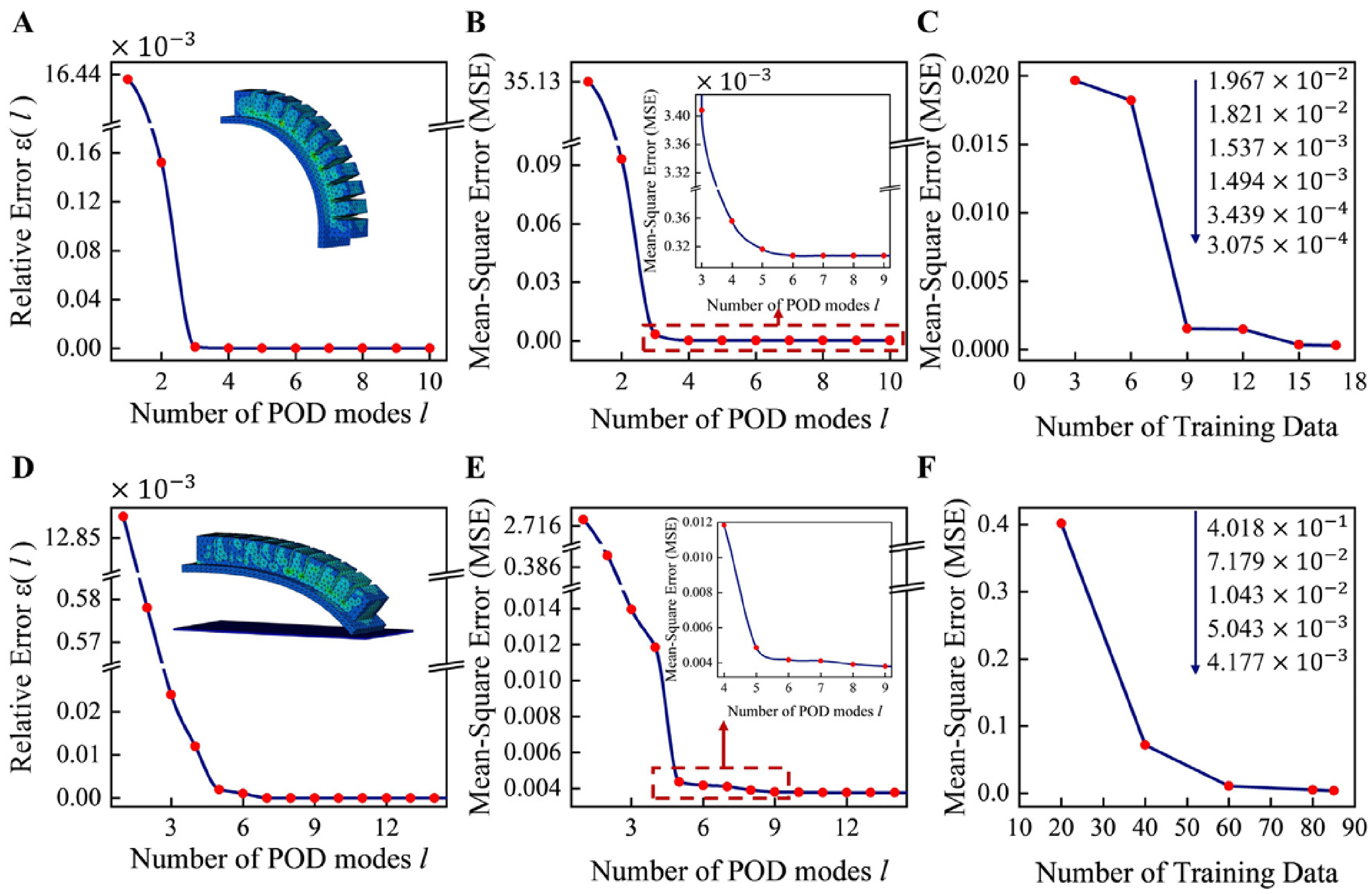
Dominant modes remove redundancy while preserving mechanics.

Reduced models replace full-order solves



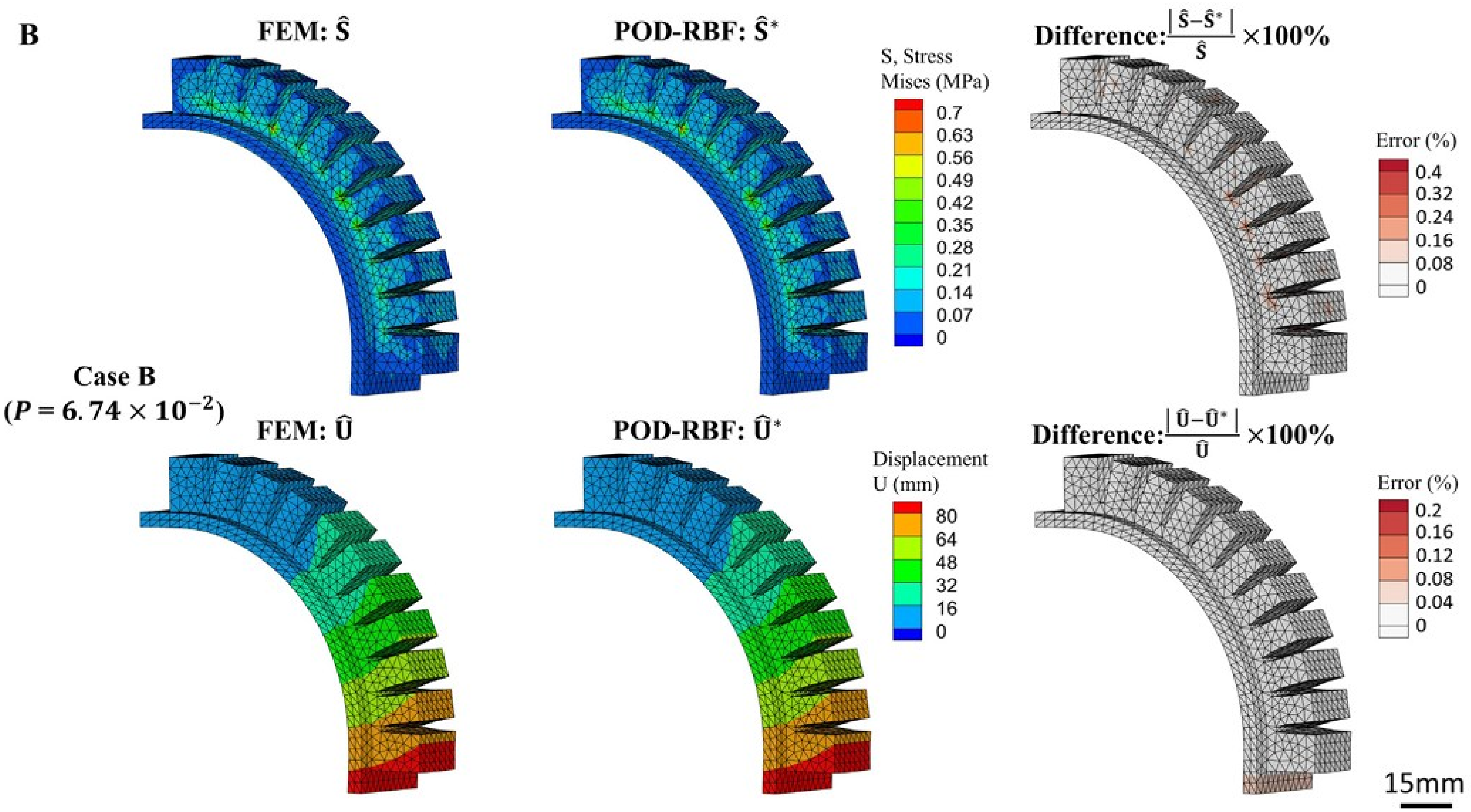
The online stage replaces repeated full-order simulations.

A compact basis converges rapidly



Few modes capture most response variation.

The surrogate reproduces full-field response



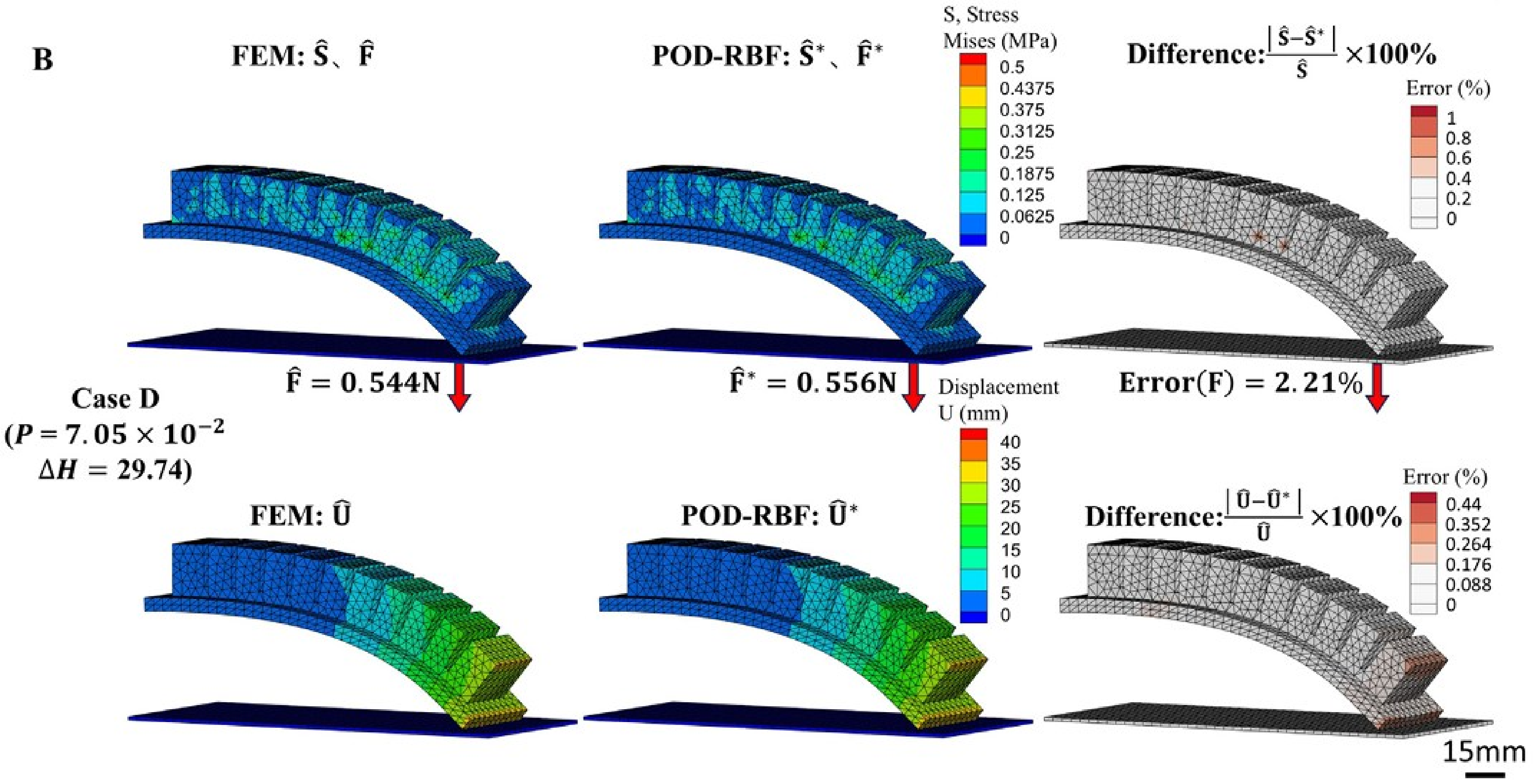
REGIME I · NON-CONTACT

Conventional FEM ≈30 min

POD–RBF online 0.94 s

≈1,900× faster

Prediction errors remain small



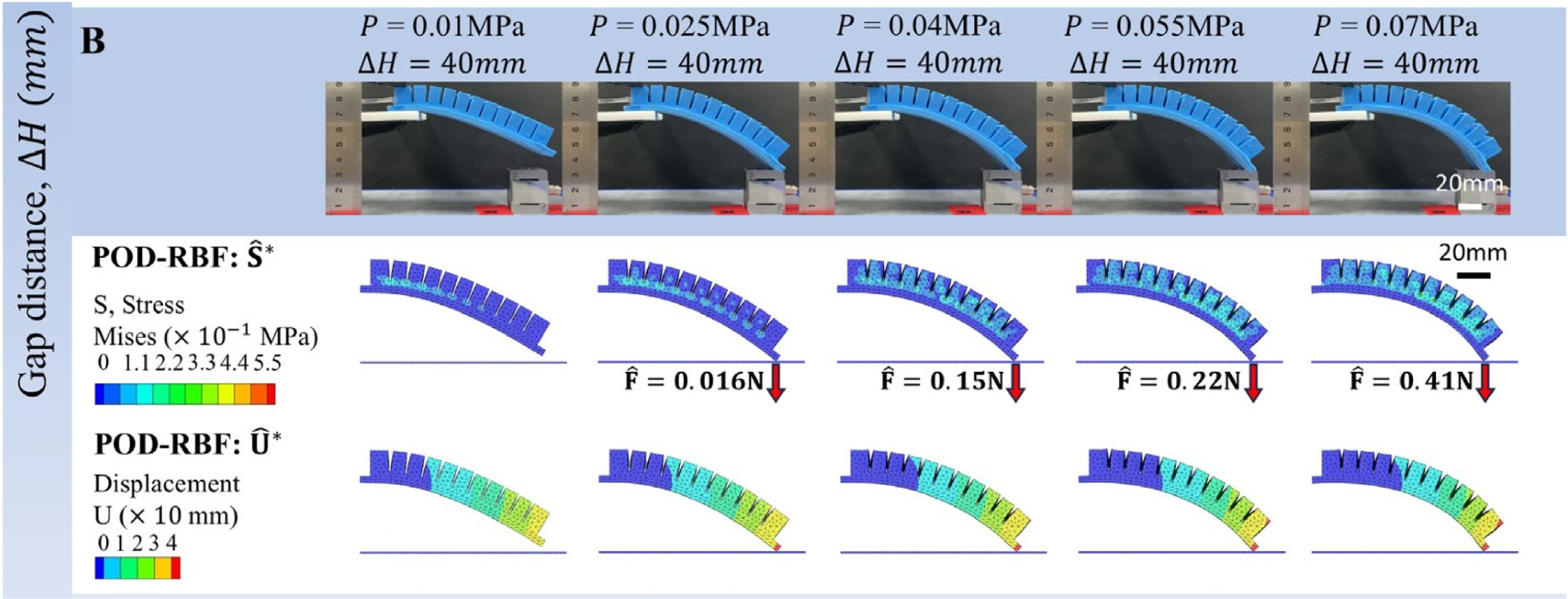
REGIME II · CONTACT

Conventional FEM ≈40 min

POD–RBF online 0.96 s

≈2,500× faster

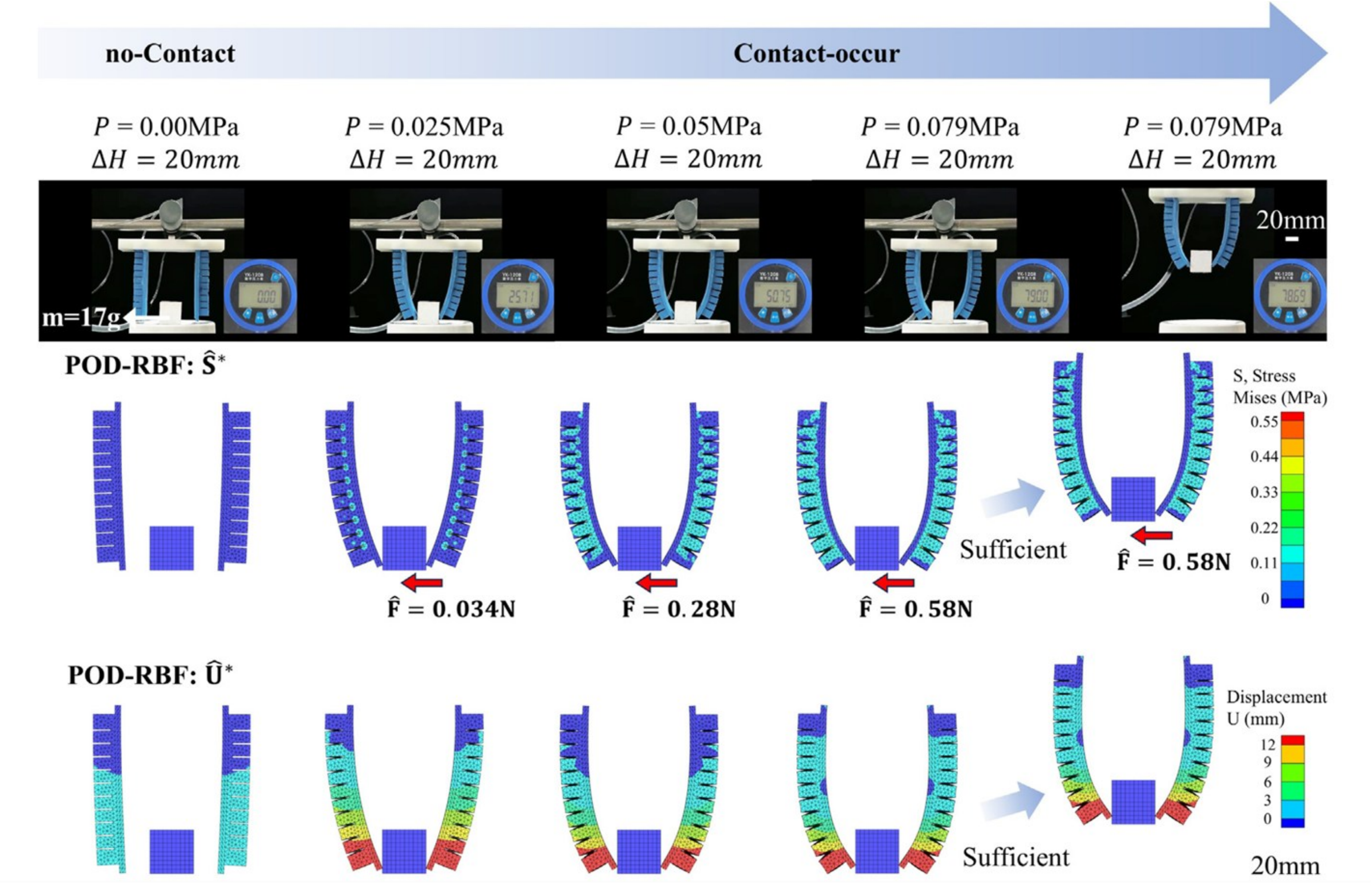
The twin tracks response across pressure



ONLINE DIGITAL TWIN

Conventional FEM 30–40 min   POD–RBF online 0.94–0.96 s   Near-real-time full fields

The framework predicts gripper contact



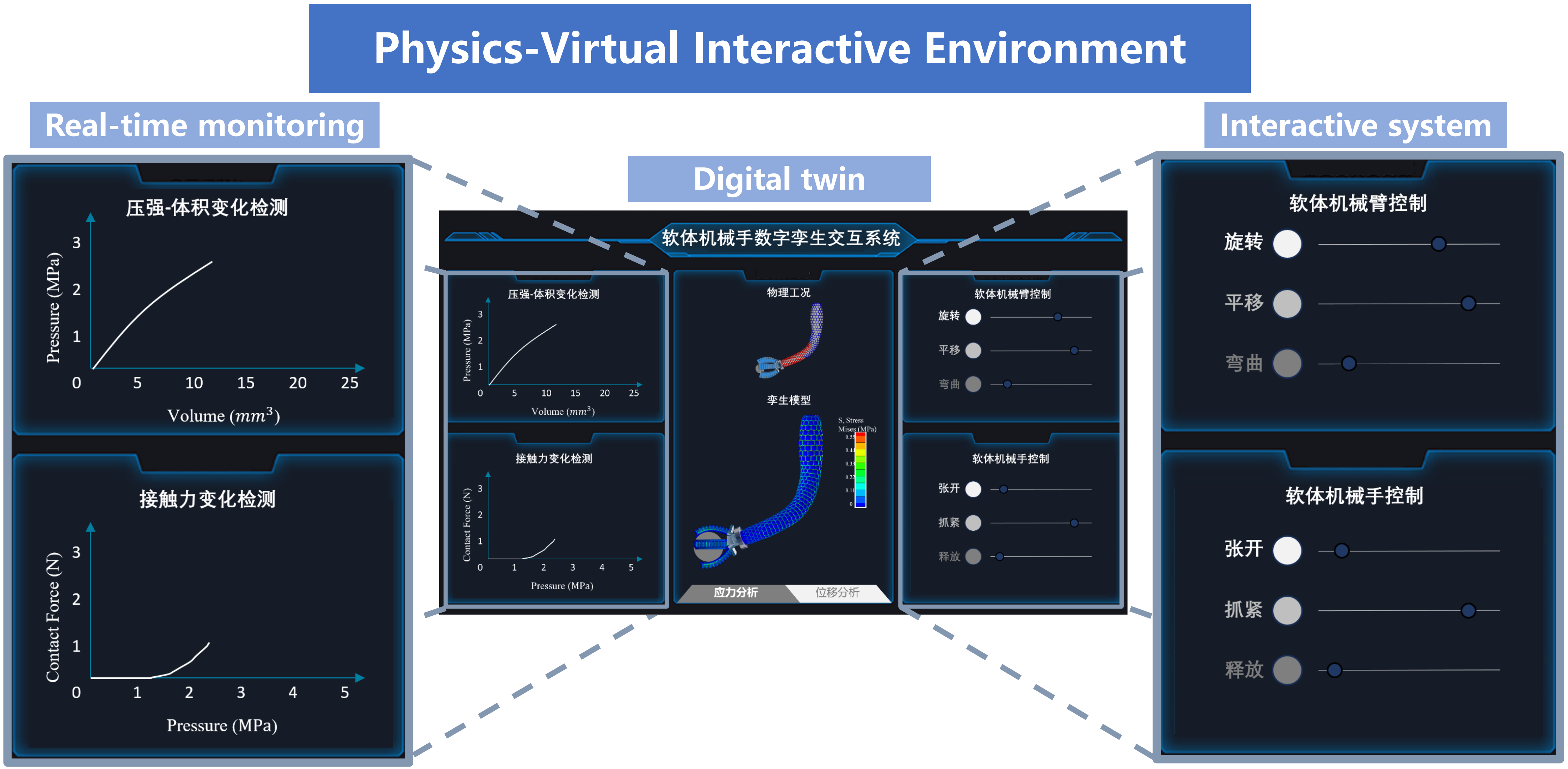
CONTACT / GRIPPER

Conventional FEM ≈40 min

POD–RBF online 0.96 s

≈2,500× faster

Mechanical programming complements digital twins



Two complementary contributions

WORK I

Metamaterial robotic skins

• Programs bending, expansion, twisting, and morphing through unit-cell geometry and layout.

• Validated through experiments and finite-element simulations.

• Establishes a reusable mechanical design strategy for pneumatic actuators.

WORK II

POD–RBF digital twins

• Compresses full-field FEM data into a low-dimensional representation.

• Predicts deformation, stress, and contact quantities in less than one second.

• Accelerates repeated online evaluation by approximately 1,900–2,500×.

Together: program actuator behavior mechanically, then predict and monitor it digitally.