

CURVATURE-CONTROLLED MORPHING OF FOLDING WINGTIPS USING HONEYCOMB PLATES

Rui Yang[1,2], Shenghua Li[1,2] & Shiyong Sun[1,2]

[1] School of Mechanical Engineering, Dalian University of Technology, China
[2] State Key Laboratory of High-performance Precision Manufacturing, Dalian University of Technology, China

Abstract

This study proposes a structure-oriented morphing paradigm based on honeycomb plates with programmable bending characteristics. By tailoring the geometric configuration of the honeycomb cells, curvature control is embedded directly into the load-bearing structure. A folding wingtip configuration is developed by coupling a rigid eccentric-rod actuator with the substrate. Numerical analyses indicate that rectangular honeycomb configurations exhibit superior deformation stability and surface smoothness, offering a promising pathway for next-generation morphing aircraft.

Keywords: Honeycomb structures; Morphing wingtip; Curvature control; Programmable bending; Gaussian curvature.

1. Introduction

With the rapid development of morphing aircraft technologies, increasing emphasis has been placed on achieving large, continuous, and smooth shape changes while simultaneously preserving load-bearing capacity and geometric accuracy [1, 2].

Morphing wingtip and folding wing configurations demand precise curvature control to ensure aerodynamic efficiency and structural compatibility.

However, many existing morphing concepts rely on localized compliant regions or highly complex actuation systems, which often introduce surface deviation and limited controllability. To address these challenges, this study explores the use of periodic honeycomb microstructures.

Unlike traditional designs, the proposed approach embeds curvature control directly into the load-bearing structure by tailoring the geometric configuration of the honeycomb cells, making the global bending behavior an intrinsic property of the structure.

2. Methods

2.1 Parametric Analysis and Design Laws

To elucidate the mapping relationship between microscopic geometric features and macroscopic morphing performance, a systematic parametric study was conducted on the honeycomb cells. The investigation focuses on two primary design variables: the cell angle (θ) and the aspect ratio (l/t), with their typical topological configurations illustrated in Fig. 1.

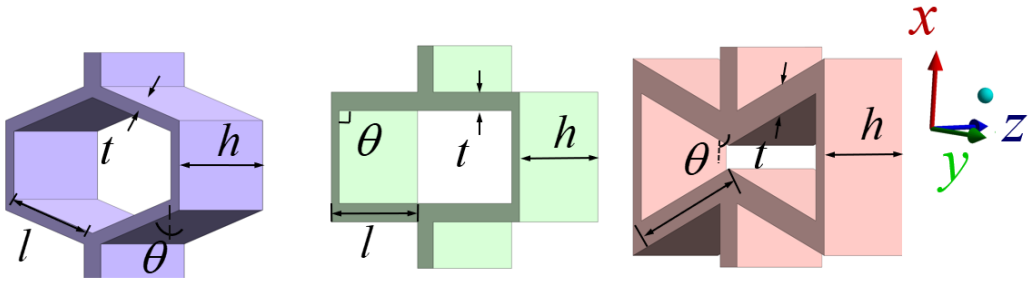


Figure 1 Geometric parameters of the three honeycomb structures.

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The results demonstrate that tailoring the cellular geometry directly induces a reversal of the equivalent Poisson's ratio, which fundamentally dictates the macroscopic three-dimensional curvature profile of the honeycomb plates under out-of-plane bending loads.

Finite element (FE) simulations were performed on three distinct categories of honeycomb structures characterized by positive, negative, and near-zero Poisson's ratios. Figure 2 captures the resulting three-dimensional curvature profiles under out-of-plane bending, confirming that the sign of the equivalent Poisson's ratio uniquely determines the macroscopic bending topology. For conventional hexagonal honeycombs ($\theta < 90^{\circ}$), the substrate exhibits a positive Poisson's ratio (PPR) effect. As depicted in Fig. 2(a), the out-of-plane bending load induces a positive primary curvature ($\kappa_{11} > 0$), while an anticlastic curvature of the opposite sign ($\kappa_{22} < 0$) arises transversely due to the Poisson's ratio effect. The negative product of these principal curvatures yields a negative Gaussian curvature, manifesting as a saddle-shaped surface.

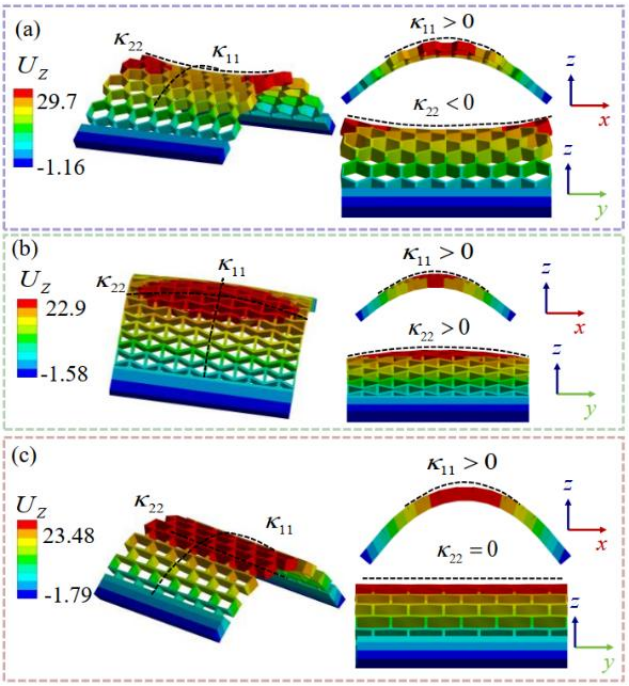


Figure 2 Examples of 3D shapes with Gaussian curvatures generated by three honeycomb bends

(a) Saddle shape with negative Gaussian curvature from positive Poisson's ratio honeycomb

(b) Ellipsoidal shape with positive Gaussian curvature from negative Poisson's ratio honeycomb

(c) Cylindrical shape with zero Gaussian curvature from zero Poisson's ratio honeycomb [3].

Conversely, when the cell angle exceeds $\theta > 90^{\circ}$, the re-entrant hexagonal configuration transitions into a representative negative Poisson's ratio (NPR) auxetic substrate.

As shown in Fig. 2(b), the synchronous and directionally coupled transverse deformation during bending leads to identical signs for both the primary and transverse curvatures ($\kappa_{11} > 0$, $\kappa_{22} > 0$). This synclastic, dual-curvature bending behavior effectively verifies that a negative bending Poisson's ratio inherently corresponds to a positive Gaussian curvature, generating an ellipsoidal profile.

Serving as the critical transition between these two topological regimes, the rectangular honeycomb with a cell angle of $\theta = 90^{\circ}$ exhibits a unique decoupled deformation characteristic associated with a near-zero Poisson's ratio (ZPR). As shown in Fig. 2(c), when the plate undergoes bending in the primary direction ($\kappa_{11} = 0$), virtually no transverse strain coupling is observed, causing the transverse curvature to approach zero ($\kappa_{22} \approx 0$). Consequently, the macroscopic Gaussian curvature degenerates to zero, culminating in a developable cylindrical surface.

Based on the detailed morphing mechanisms identified for each configuration, the multi-dimensional regulatory role of the microscopic geometric parameters can be established. The analysis indicates that the cell angle (θ) serves as the governing mechanism variable that dictates the macroscopic morphing mode and the final Gaussian curvature distribution. Meanwhile, the aspect ratio (l/t) acts as an efficiency variable that regulates the structural stiffness gradient and deformation compliance within the design space.

As illustrated in Fig. 3, these identified kinematic mapping laws provide a rigorous quantitative foundation for the programmable design of cellular substrates. Under pure bending, the PPR, ZPR, and NPR configurations naturally evolve into smoothly continuous surfaces with negative, zero, and positive Gaussian curvatures, respectively. This bridges the gap between the microscopic geometric parameter space of the microstructures and the macroscopic analytical space governed by differential geometry.

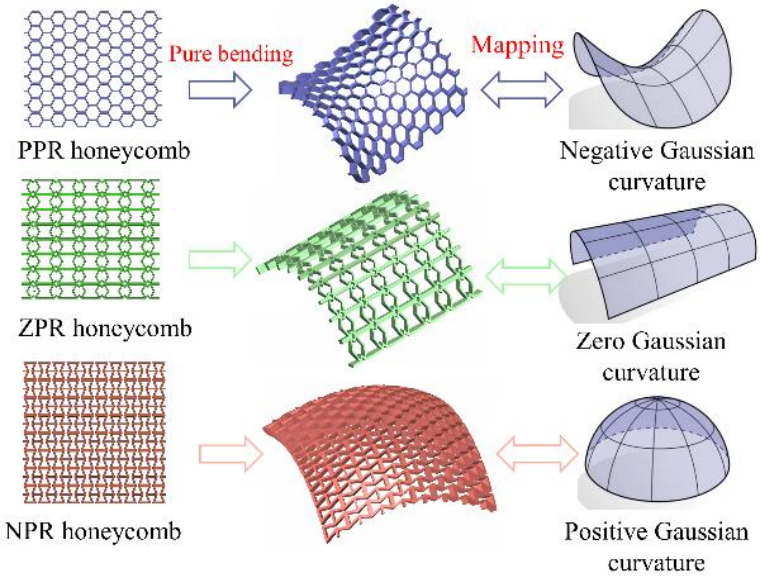


Figure 3 Mapping the relationship between honeycomb micro-architectures (PPR, ZPR, and NPR) and macro-scale deformation modes characterized by distinct Gaussian curvatures under pure bending.

This framework enables an efficient, inverse design paradigm for aircraft structures. In practical engineering applications, it allows designers to strategically screen and optimize the cellular configuration based on specific aerodynamic curvature requirements before the integration and deployment of complex actuation systems. By replacing the conventional, high-cost trial-and-error approach with a predictive, morphology-guided architecture, this framework offers a highly viable design solution for next-generation aerospace morphing structures, such as continuous-variable-camber wings and folding wingtips.

2.2 Actuation Trade-offs and Transverse Constraint Analysis

In the design of aerospace morphing structures such as continuous-variable-camber wingtips, balancing the macroscopic morphing profile control with the characterization accuracy of the intrinsic material deformation is a critical consideration for actuation mechanism selection. To accurately capture the three-dimensional deformation states of honeycomb substrates under out-of-plane bending, a weakly constrained cable-driven folding section was developed in this study.

The experimental configuration, as illustrated in Figs. 4 and 5, comprises an aerodynamic airfoil frame, an embedded flexible honeycomb substrate, alignment holes, and high-strength actuation cables. Under the cable-driven boundary condition, the actuation force delivered by a linear motorized stage is applied eccentrically and symmetrically to the end face of the wing segment.

Because the flexible cables only sustain unidirectional tension, they introduce no parasitic out-of-plane bending stiffness or transverse displacement constraints.

This significantly mitigates interference from transverse boundary constraints, allowing the in-plane shear and transverse expansion/contraction behaviors of the honeycomb plate during bending to be

governed entirely by its cellular microstructure.

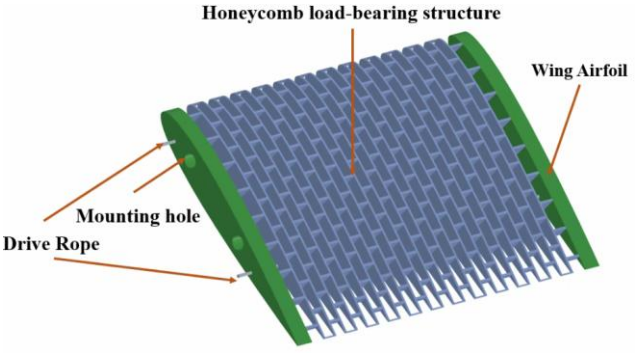


Figure 4. Schematic design of the cable-driven folding/turning region in the honeycomb structure.

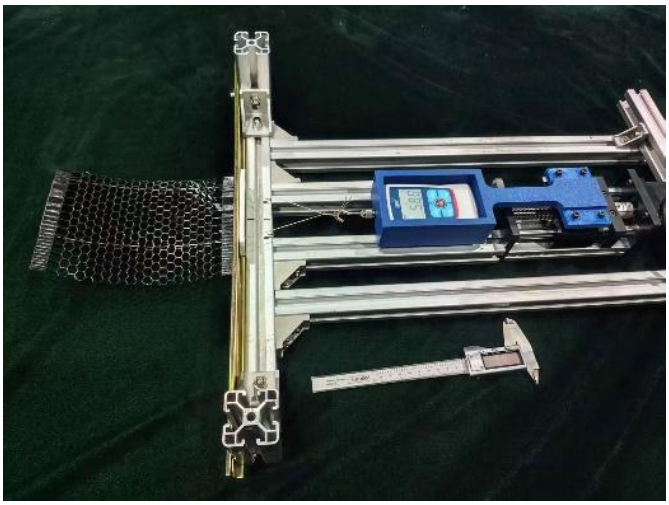


Figure 5. Preliminary experimental test rig for characterizing the intrinsic bending deformation of honeycomb substrates using a cable-driven actuation method.

Experimental and finite element results indicate that this minimally constrained actuation configuration successfully captures the three-dimensional morphing surfaces dictated entirely by the cellular geometry. Specifically, conventional hexagonal honeycomb plates deform into a saddle-shaped surface with a negative Gaussian curvature due to the positive Poisson's ratio effect. Re-entrant hexagonal plates evolve into an ellipsoidal surface with a positive Gaussian curvature owing to their synclastic transverse contraction, whereas rectangular plates exhibit decoupled single-curvature behavior, deforming into a cylindrical surface with zero Gaussian curvature.

However, this cable-driven approach inherently introduces excessive physical compliance out of plane. When subjected to large-stroke morphing, the high compliance makes it challenging to maintain the prescribed geometric profile, which limits its direct applicability in standard wing operational environments. Consequently, while the cable-driven scheme offers exceptional accuracy for intrinsic mechanism characterization, a more deterministic boundary condition is required for practical geometric contour control.

To ensure precise geometric contour retention during large-angle folding and effectively suppress out-of-plane structural instability, a rigid eccentric-rod actuation mechanism featuring a deterministic kinematic path was introduced. The overall assembly and structural details of this transmission system are depicted in Fig. 6. By passing the eccentric shaft through the designated routing holes within the honeycomb, the rigid mechanism provides robust out-of-plane kinematic guidance, significantly enhancing the profile stability of the morphing surface during actuation.

Nevertheless, as a dominant displacement boundary condition, the rigid rod demands a highly compatible deformation mode from the cellular substrate; otherwise, severe transverse boundary constraint stresses and localized geometric distortions will be induced within the structure.

To address this challenge, a systematic evaluation and selection of the substrate configurations were conducted based on the specific kinematic requirements of the folding wingtip. As illustrated in Fig. 6, aerodynamic and kinematic constraints mandate that the transition region of the folding wing tip forms an ideal single-curvature geometric surface. Utilizing positive Poisson's ratio (PPR) or negative Poisson's ratio (NPR) honeycombs with strong transverse coupling would create a fundamental topological conflict with the target shape, inevitably leading to severe skin wrinkling or internal geometric locking.

In contrast, the comparative results in Fig. 6 clearly demonstrate that the near-zero Poisson's ratio (ZPR) rectangular honeycomb spontaneously and stably transforms into a developable cylindrical surface with zero Gaussian curvature under out-of-plane bending. This unique deformation characteristic yields an exact geometric and kinematic match with the desired single-curvature target profile of the folding wingtip. Consequently, configurations prone to coupled transverse distortion (PPR and NPR) were deliberately excluded, and the rectangular honeycomb was established as the optimal morphing substrate topology. This selection ensures a smooth kinematic path for the actuation mechanism and lays the physical foundation for precise aerodynamic shape control.

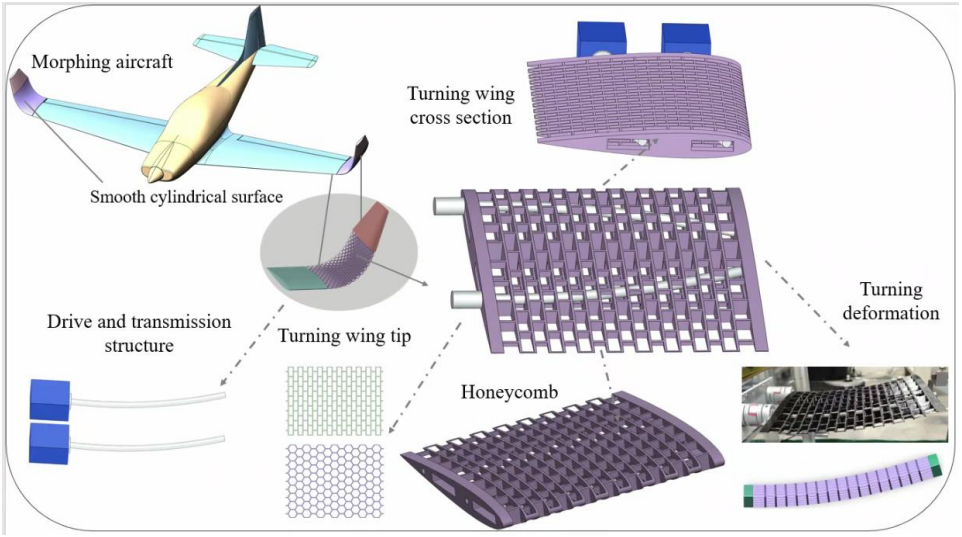


Figure 6. Conceptual design of a morphing aircraft folding wing based on deformable honeycomb structures.

3. Results and Discussions

Based on the experimental boundary conditions and constraint mechanisms established previously, a systematic numerical simulation was performed and compared with physical experimental results to evaluate the deformation behavior of different honeycomb configurations during the morphing process. First, regarding the selection of the macroscopic deformation topology, the full-field morphing characteristics obtained from numerical simulations are illustrated in Figs. 7 and 8.

The results indicate that, compared with conventional positive Poisson's ratio (PPR) hexagonal honeycombs and negative Poisson's ratio (NPR) re-entrant honeycombs, the near-zero Poisson's ratio (ZPR) rectangular configuration exhibits superior structural developability and cylindrical morphing characteristics. Due to the intrinsic in-plane Poisson's ratio effect, conventional PPR and NPR honeycombs feature a strong strain coupling between the transverse and longitudinal directions. Consequently, under large-angle out-of-plane bending, a pronounced transverse principal curvature develops (e.g., yielding a positive Gaussian curvature ellipsoidal surface for NPR where $\kappa_{11} > 0$, $\kappa_{22} > 0$, and a negative Gaussian curvature saddle surface for PPR where $\kappa_{11} > 0$, $\kappa_{22} < 0$).

Conversely, the transverse principal curvature (κ_{22}) of the rectangular honeycomb remains approximately zero under forced bending, and its overall deformed shape closely matches a developable cylindrical surface with zero Gaussian curvature. This morphing characteristic validates the configuration selection analysis presented earlier, demonstrating that the rectangular honeycomb ensures a smooth and continuous transition from the main wing to the wingtip, fundamentally

eliminating aerodynamic efficiency degradation caused by undesired transverse non-zero curvature distortions.

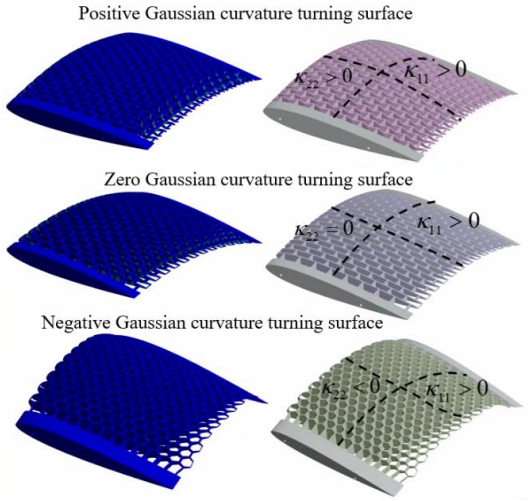


Figure 7. Comparison of generated surfaces for wings with three different Poisson's ratios under out-of-plane deformation.

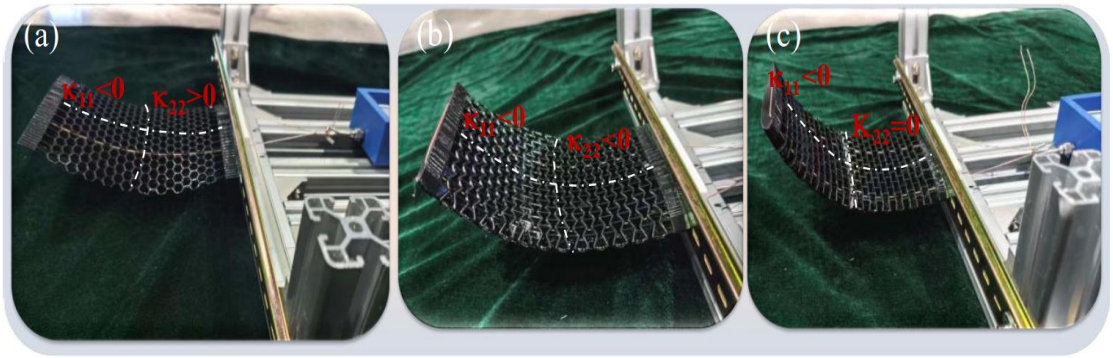


Figure 8. Experimental results of out-of-plane deformation for three types of honeycombs (a) regular hexagonal (b) re-entrant hexagonal (c) rectangular.

Next, to evaluate the continuous deformation behavior of the folding rectangular honeycomb over the full actuation cycle, both a refined model and an equivalent solid model were developed to predict the response of the eccentric-rod transmission system driven by a stepper motor. The response of the rectangular honeycomb under continuous eccentric-rod actuation is shown in Fig. 9. As the stepper motor drives the eccentric rod through rotation angles of 20° (Fig. 9(a)), 40° (Fig. 9(b)), up to a maximum large-stroke angle of 90° (Fig. 9(c)), the flexible substrate exhibits highly smooth, continuous, and lock-free cylindrical bending, which aligns with the zero Gaussian curvature analysis. Furthermore, no localized deformation discontinuities resulting from microscopic strain concentrations are observed, nor is there any unexpected local curvature reversal caused by instability in regions with high deformation gradients.

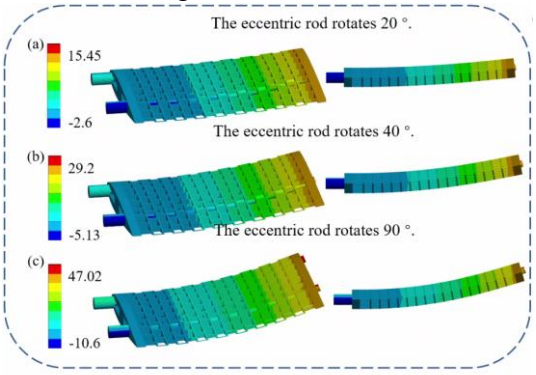


Figure 9. Continuous deformation states of the folding honeycomb: (a) 20° (b) 40°(c) 90°.

To quantitatively verify the shape-control accuracy under eccentric-rod actuation, the finite element (FE) predictions were compared with the experimental data. The full-field displacement profiles and the three-dimensional scanning results of the key characteristic points during continuous actuation are presented in Fig. 10. A global comparison between the 3D point cloud obtained via the scanner and the FE contour plots (Fig. 11) reveals that, guided by the rigid eccentric shaft, the flexible honeycomb substrate undergoes smooth, continuous, and uniform cylindrical deformation along the spanwise direction without localized strain discontinuities. The maximum relative error remains well within engineering tolerances, directly demonstrating that the mechanism-structure coupling of the eccentric rod driving the rectangular honeycomb successfully achieves smooth and continuous morphing for folding wingtips under large-angle, large-stroke conditions.

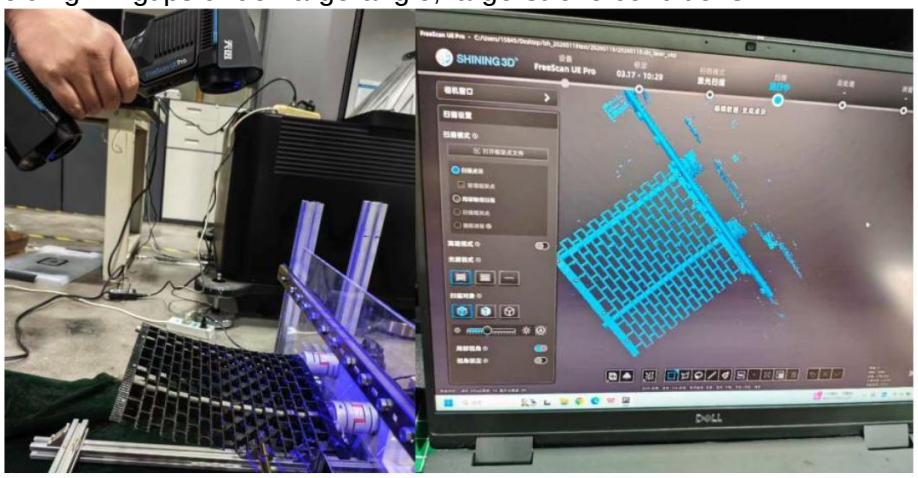


Figure 10. 3D scanning process and the corresponding software interface.

This design methodology based on precise geometric and structural matching demonstrates that targeted tailoring of the microscopic cell parameters of a 2D honeycomb substrate enables smooth and continuous deformation of folding wings. Under the displacement boundary conditions enforced by the rigid linkage mechanism, the cylindrical morphing capability of the rectangular honeycomb inherently maintains excellent out-of-plane shape retention and geometric profile stability, while enabling precise aerodynamic contour matching post-deformation. By replacing the conventional trade-off between structural stability and deformability with a predictive, compliant-architecture paradigm, this methodology offers a highly viable and scientifically advanced inverse-design pathway for next-generation aerospace adaptive control surfaces requiring exceptional morphing precision.

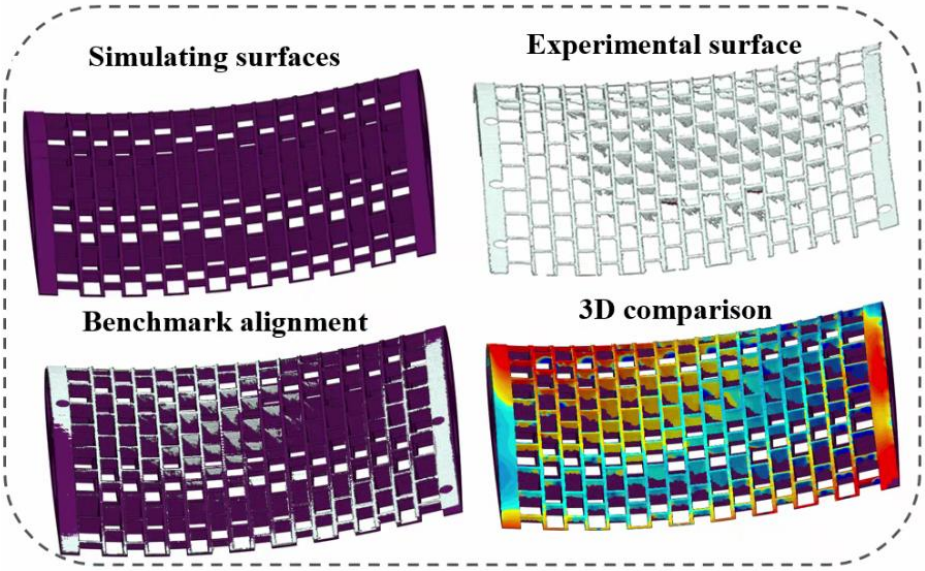


Figure 11. 3D comparative validation between the refined model and the experimental model

4. Conclusion

This study demonstrates that adaptive surface morphing design based on cellular honeycomb substrates provides a viable engineering pathway for shape-adaptive aerospace structures with stringent curvature requirements. The distinct intrinsic Gaussian curvature characteristics of different honeycomb topologies endow the structure with a deterministic and highly repeatable deformation response, thereby significantly reducing the dependence of adaptive morphing systems on complex actuation mechanisms.

By systematically analyzing the kinematic mapping between microscopic geometric parameters and macroscopic three-dimensional morphed surfaces, the deformation behaviors under a weakly constrained cable-driven system and a highly rigid eccentric-rod mechanism were successfully elucidated. To satisfy the specific demand of large-angle wingtip folding for a single-curvature developable surface, configurations with positive or negative Poisson's ratios were deliberately excluded due to their undesired chordwise coupling distortions. Consequently, the near-zero Poisson's ratio (ZPR) rectangular honeycomb was established as the optimal morphing substrate, achieving an exact geometric match between the structural deformation profile and the target aerodynamic shape.

Global quantitative comparisons between full-scale physical prototype experiments and finite element simulations demonstrate that under large-stroke non-linear morphing conditions, the flexible substrate exhibits exceptional surface profiles precision and smoothness, fundamentally eliminating unexpected localized warping. The multiscale architecture design and validation methodology proposed in this study lays a solid theoretical and experimental foundation for the precise shape-matching of next-generation aircraft adaptive morphing surfaces.

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Contact Author Email Address

sunshy@dlut.edu.cn

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