In-Situ Monitoring of Geometric Drift and Thermo-Mechanical Modeling Toward a Digital Twin for Thin-Wall Fused Filament Fabrication

Digambar Killedar[a], Emmanuel Ogunniyi[a,b], Yanzhou Fu[c], Austin Downey[a,d], Lang Yuan[a], Matthew D. Folsom[e]

[a]Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA
[b]Engineering and Computer Science Department, Benedict College, Columbia, SC, USA
[c]Department of Ocean and Mechanical Engineering, Florida Atlantic University, Boca Raton, FL, USA
[d]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC, USA
[e]Interactive Aptitude LLC, Tyngsboro, MA, USC

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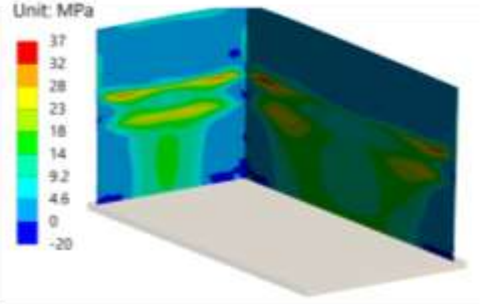
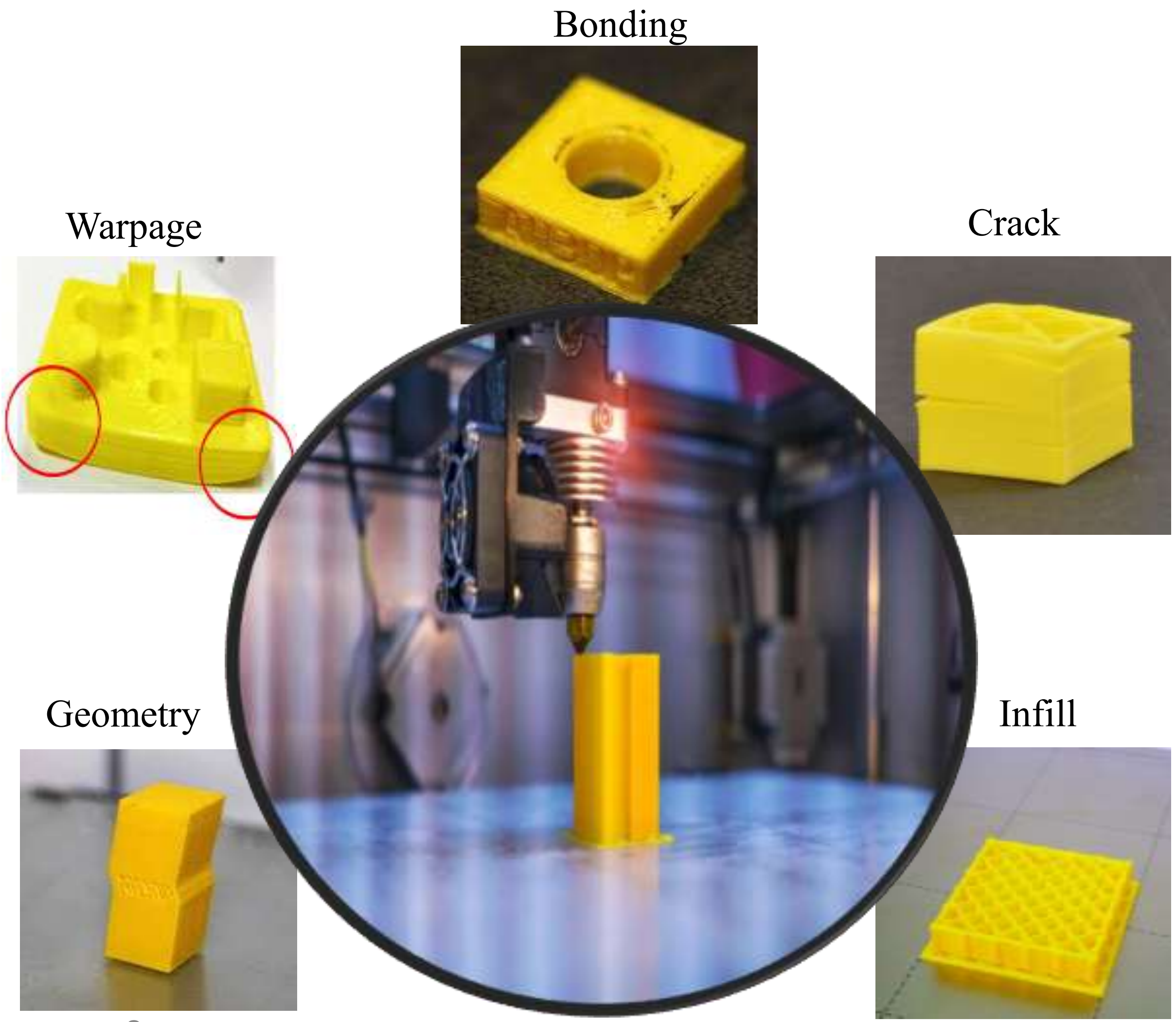


Fused Filament Fabrication (FFF)

- Layer-by-Layer Finite Element Model Development in Additive Manufacturing
- Digital Twin: Concept and Framework
- Driving Challenge: Thin-Wall Structures
- This Study: In-Situ Monitoring of Geometric Drift in Thin Walls



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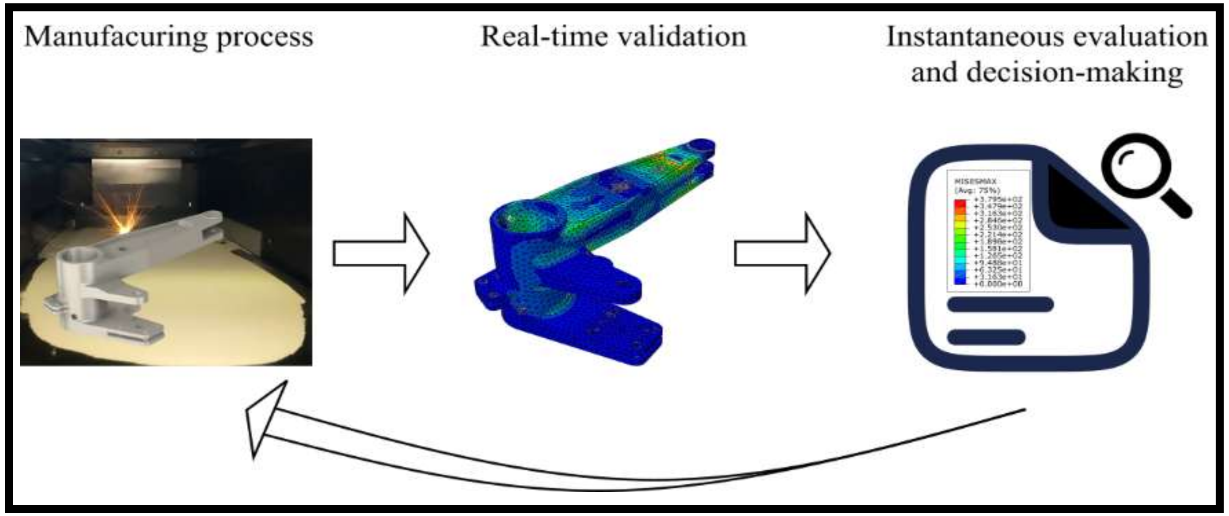
Goal: Parts Ready for Use After Printing

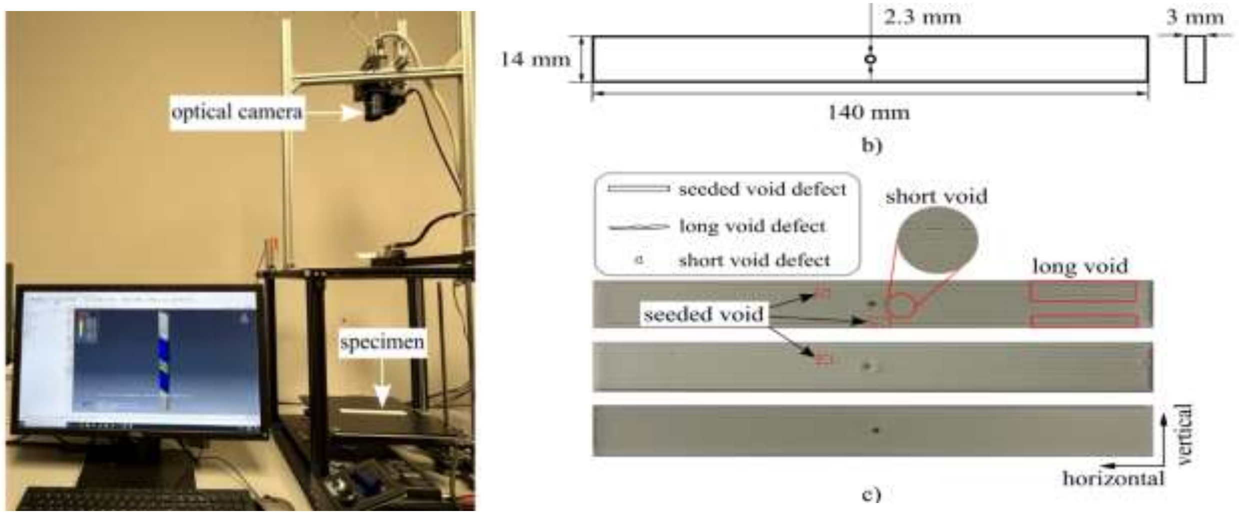
- Enable parts to be ready for use immediately after printing
- Eliminate reliance on post-process testing
- Detect defects and assess impact as they occur
- Move toward in-process validation and certification

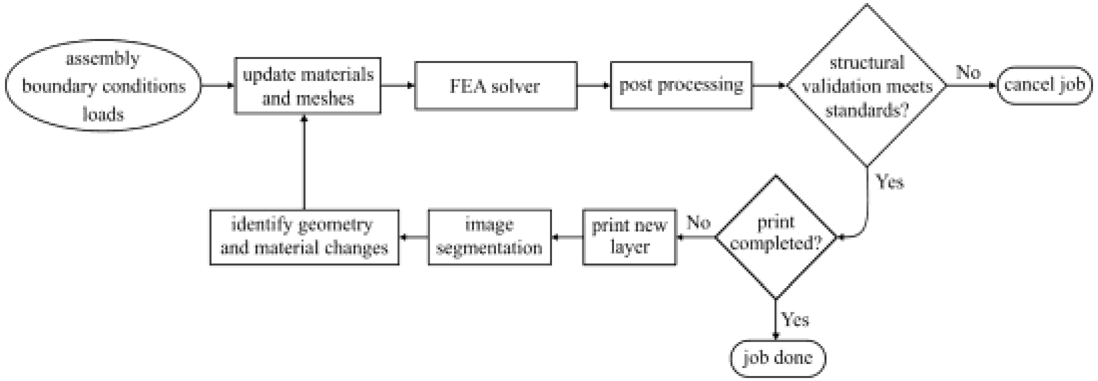


Layer-by-Layer Finite Element Model Development in Additive Manufacturing

Motivation for Layerwise FEA

- AM builds parts layer by layer
- Defects occur during fabrication, not just after
- Structural integrity evolves with each deposited layer
- Traditional FEA:
    - pre-process (design)
    - post-process (validation)
- Cannot capture in-process defect accumulation

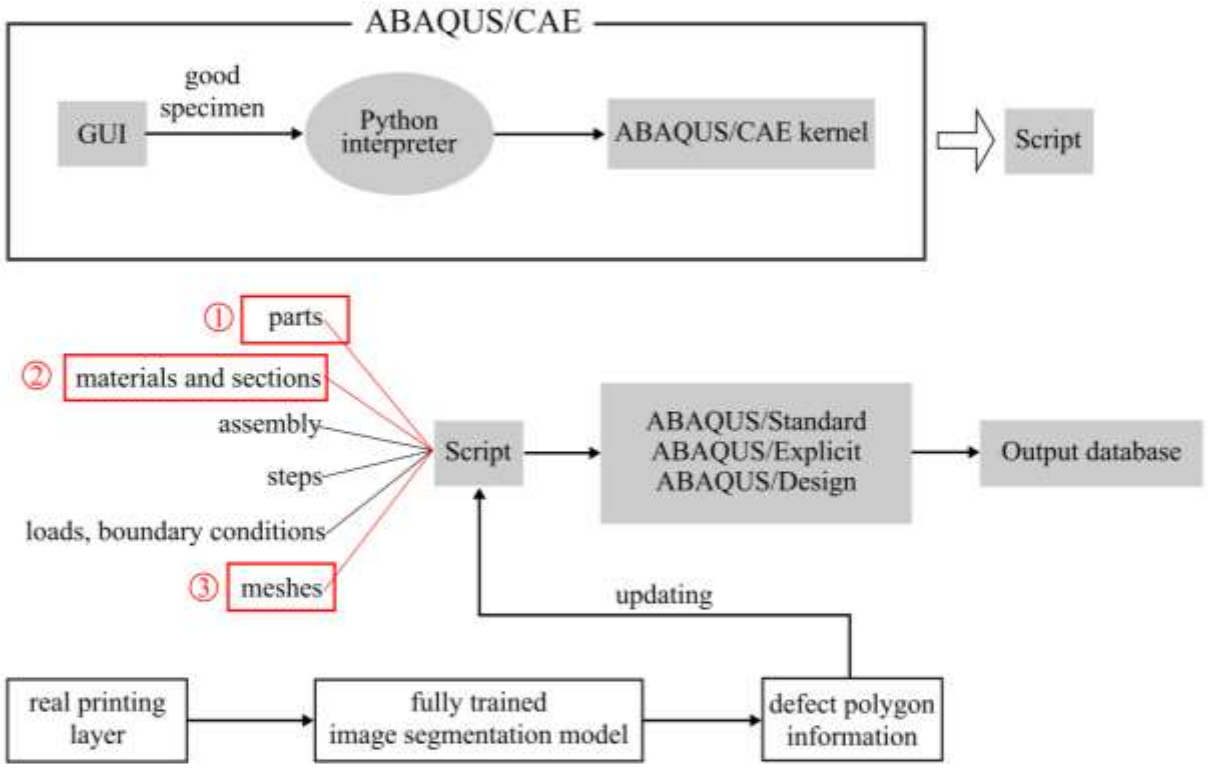




Yanzhou Fu, Austin R.J. Downey, Lang Yuan, Hung-Tien Huang, and Emmanuel A. Ogunniyi. Simulation-in-the-loop additive manufacturing for real-time structural validation and digital twin development. Additive Manufacturing, 98:104631, January 2025. doi:10.1016/j.addma.2024.104631

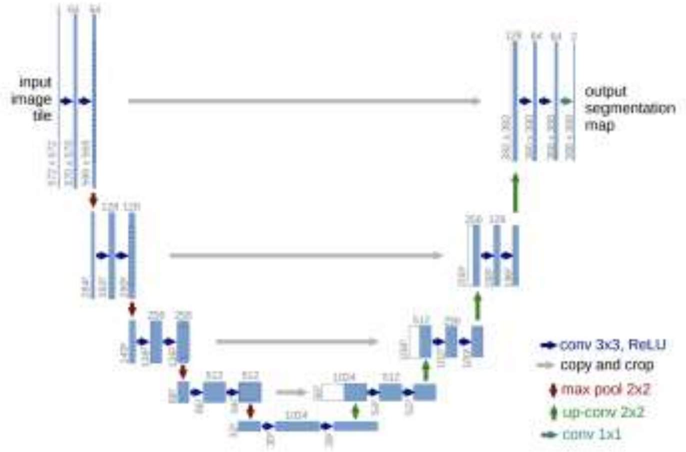
Simulation-in-the-Loop Concept

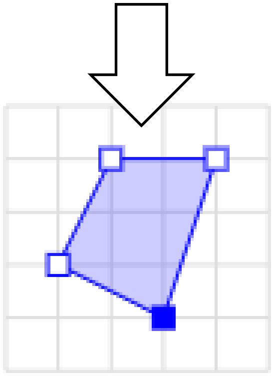
- Build a live FEA model during printing
- Start with ideal (defect-free) geometry
- Update model using in-situ measurements
- Run FEA after each layer
- Enable real-time structural assessment

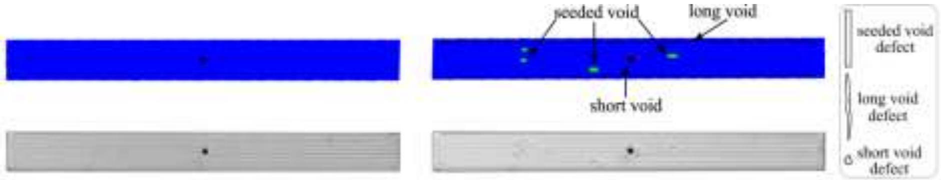


Defect Detection and Data Input

- Capture layer images during printing
- Apply image segmentation (U-Net)
- Detect:
  - seeded voids
  - long / short voids
- Extract:
  - defect location
  - defect size and shape
- Provide inputs for FEA model updating

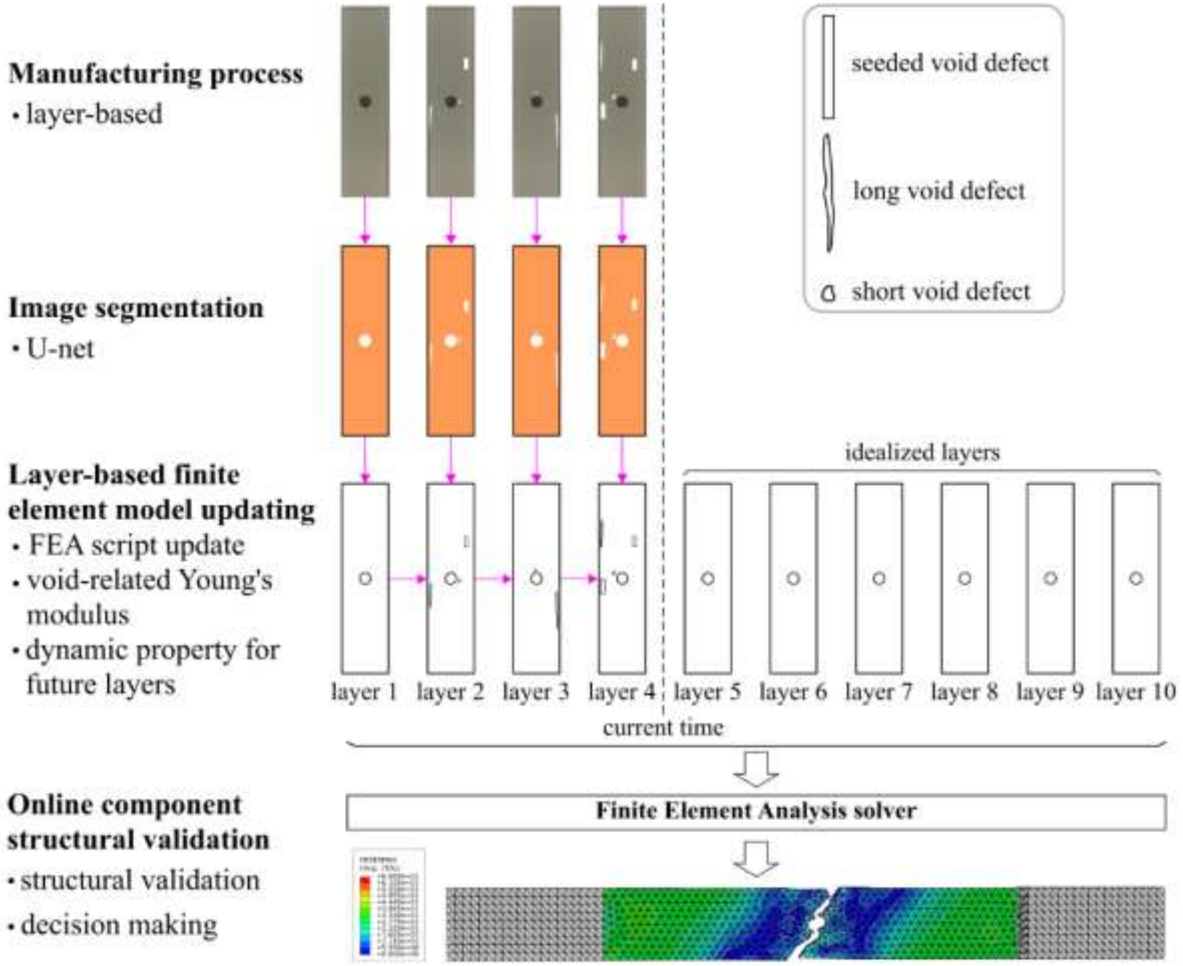






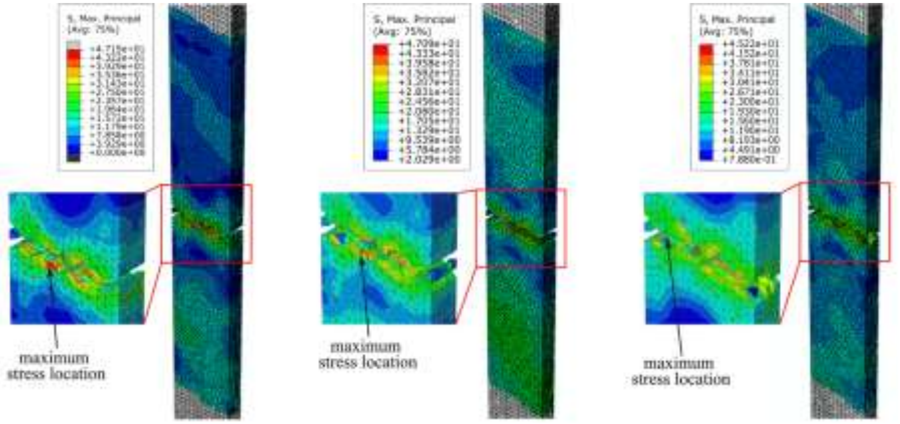
Layerwise FEA Model Updating

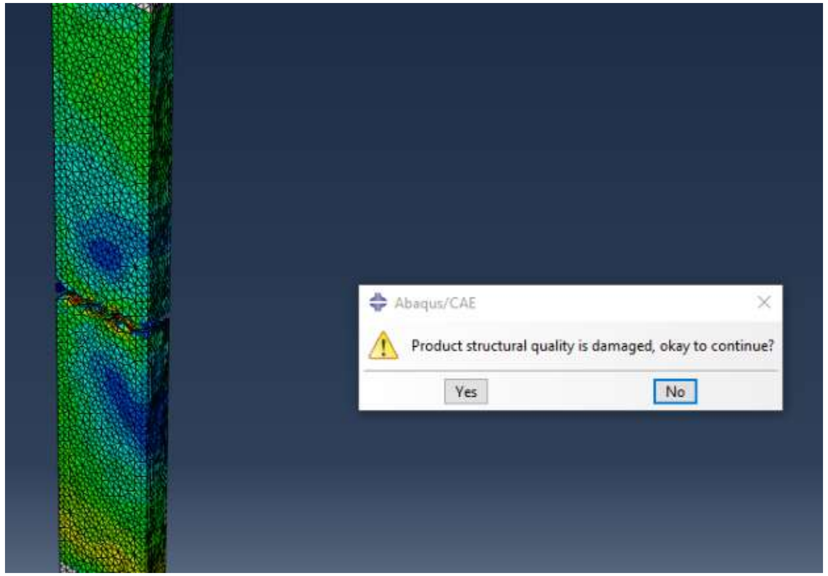
- Update model after each printed layer
- Defects incorporated as:
  - geometry changes (voids)
  - material changes (porosity → reduced modulus)
- Maintain evolving mechanical state
- Model reflects printed part



Structural Validation and Decision-Making

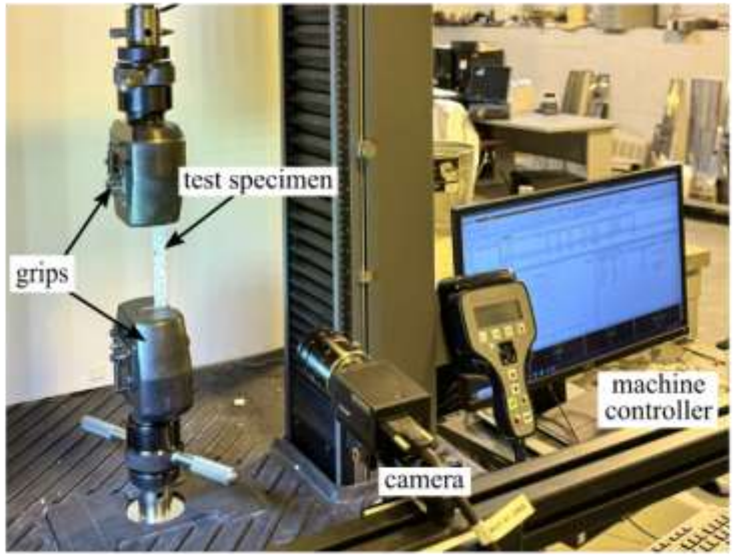
- Compute:
  - maximum principal stress
  - strain distribution
- Compare against failure thresholds
- Track defect accumulation across layers
- Enable:
  - continue printing
  - cancel print if integrity is compromised
- Achieves in-process structural validation

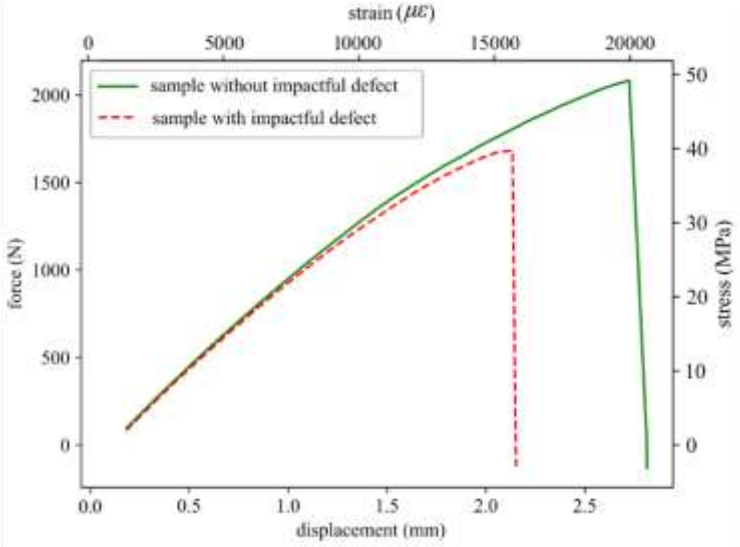




Model Accuracy and Validation

- FEA predictions agree with experiments within ~5% error
- U-Net defect detection achieves ~92.8% IoU accuracy
- Model captures strength reduction due to defects
- Validated against tensile testing and DIC measurements
- Accurately identifies stress concentration and failure regions

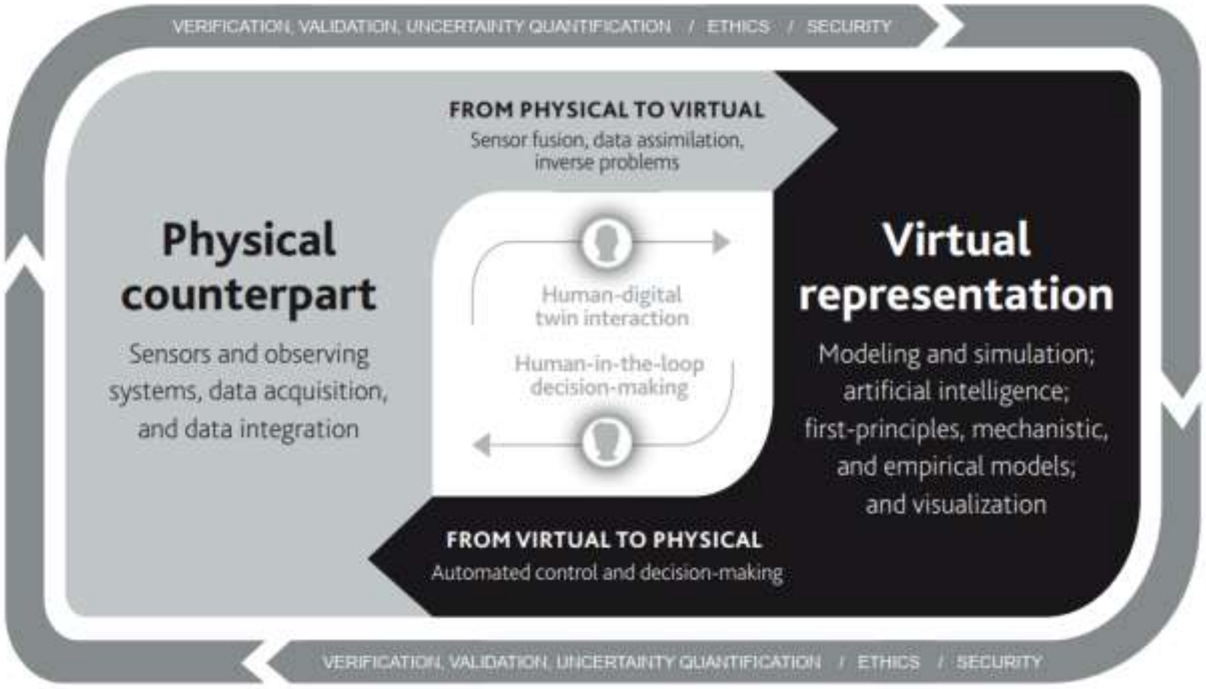




Digital Twin: Concept and Framework

Digital Twin: Concept and Vision

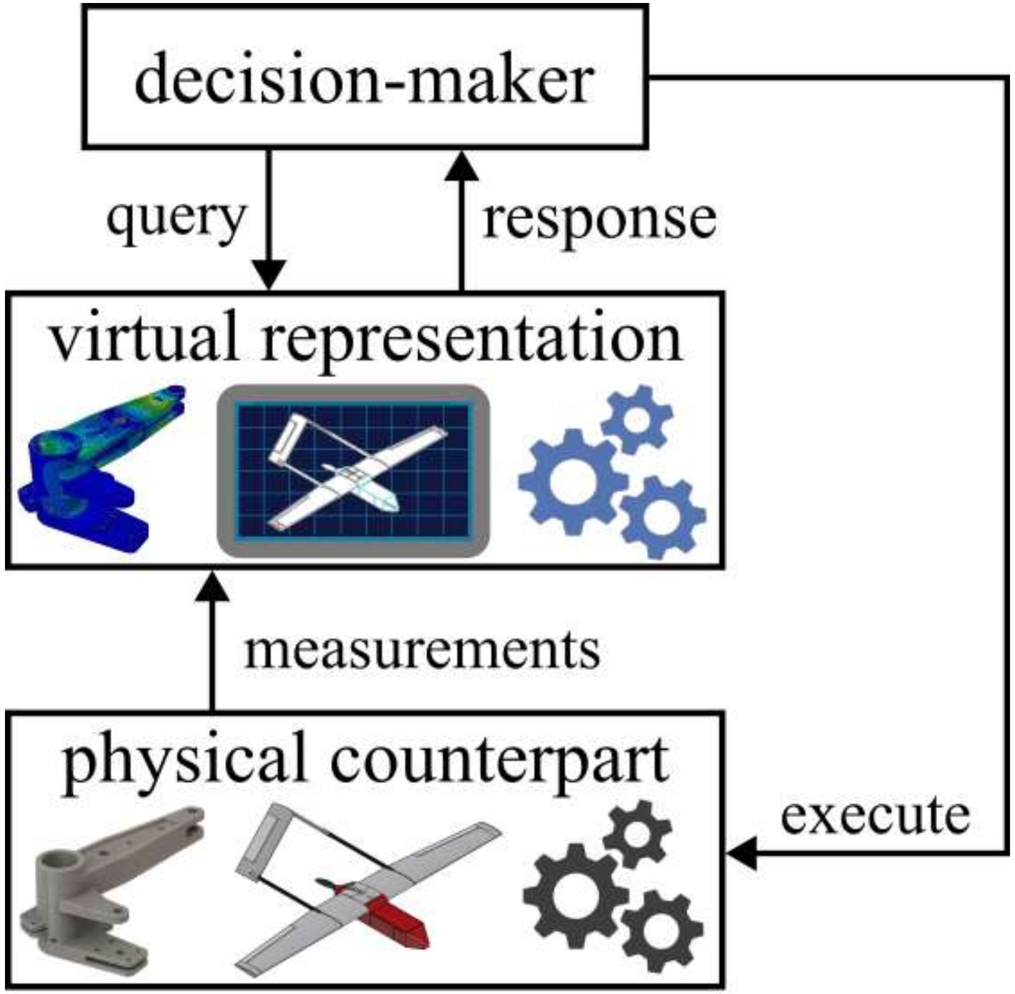
- Virtual representation of a physical counterpart
- Updated using data from the physical counterpart
- Enables prediction, monitoring, and decision-making
- Information flows between physical and virtual systems
- Supports decisions on system performance



Willcox, K., Bingham, D., Chung, C., Chung, J., Cruz-Neira, C., Grant, C., ... & Ye, X. (2023). Foundational research gaps and future directions for digital twins. Washington, DC, USA: National Academies Press.

Interacting with the Digital Twin

- Enables a query–response interaction
- Physical counterpart provides measurements
- Queries probe the virtual representation
- Virtual representation returns predictions
- Responses guide actions on the physical counterpart



Kerry Sado, Jarrett Peskar, Austin R.J. Downey, Herbert L. Ginn, Roger Dougal, and Kristen Booth. Query-and-response digital twin framework using a multi-domain, multifunction image folio. *IEEE Transactions on Transportation Electrification*, pages 1-1, 2024. doi:10.1109/tte.2024.3425276

Driving Challenge: Thin-Wall Structures

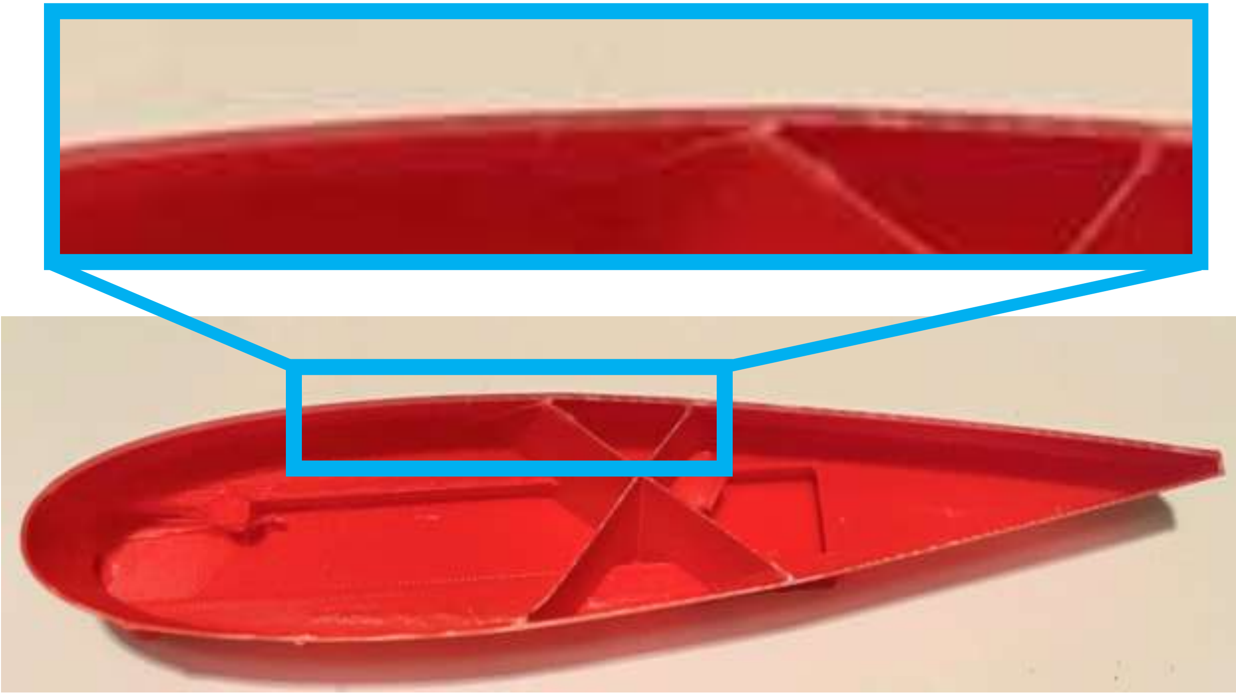
SWIFT-UAV Platform

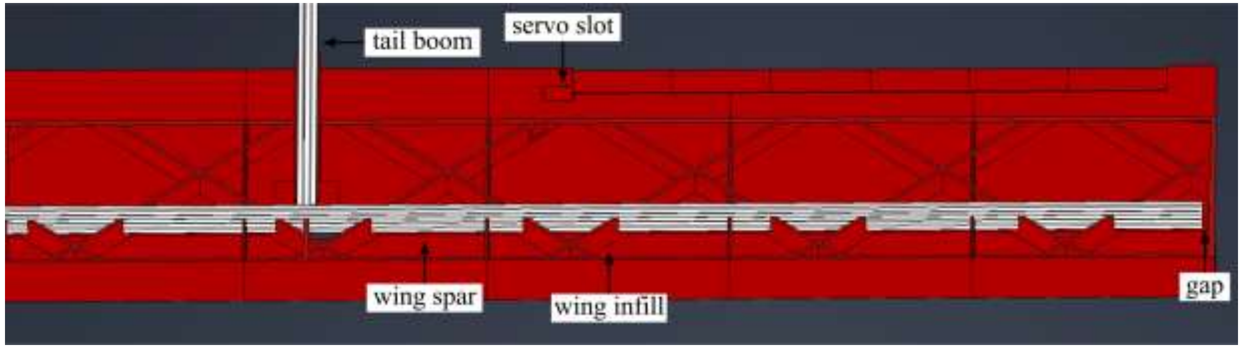
- Modular, 3D-printed UAV for research and testing
- Designed for rapid fabrication and iteration
- Supports integration of sensing and digital twins
- Used for studies in structures, propulsion, and autonomy
- Serves as a testbed for advanced manufacturing concepts

Mateo E. Garcia-Sandoval, Korebami O. Adebajo, Matthew Burnett, and Austin R. J. Downey. Progress towards digital twin integration for online battery health estimation in the swift-uav platform. In Proceedings of the 2026 AIAA Region II Student Conference, Columbia, South Carolina, USA, March 2026. American Institute of Aeronautics and Astronautics

Thin-Wall Wing Structures

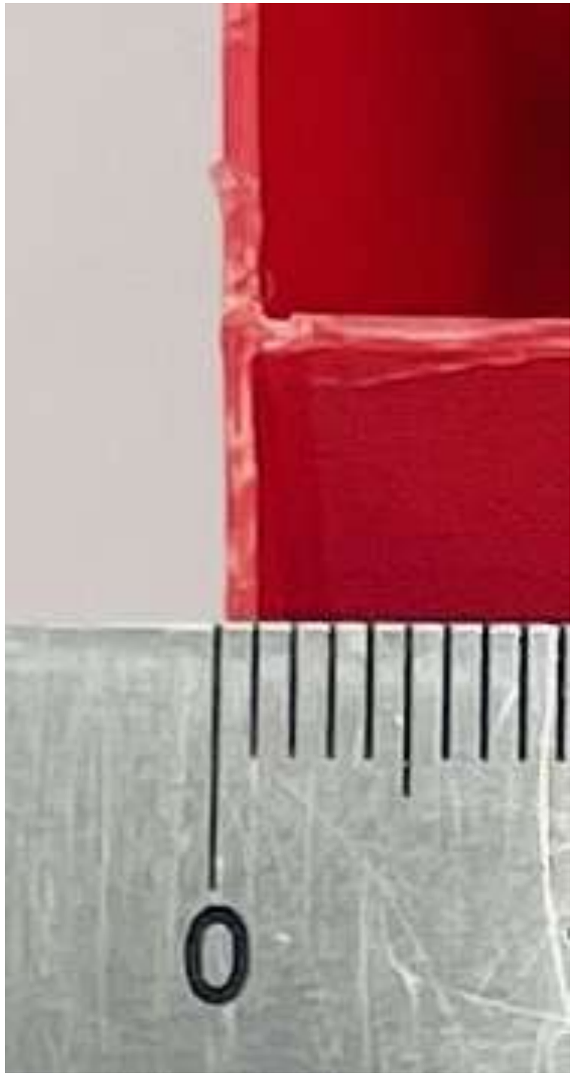
- UAV wings rely on thin-wall geometries to reduce weight
- Thin walls provide high stiffness-to-weight efficiency
- Structural performance depends on layer bonding quality
- Small geometric deviations can affect load paths
- Thin walls are critical to overall aircraft performance





Challenge: Printing Thin Walls

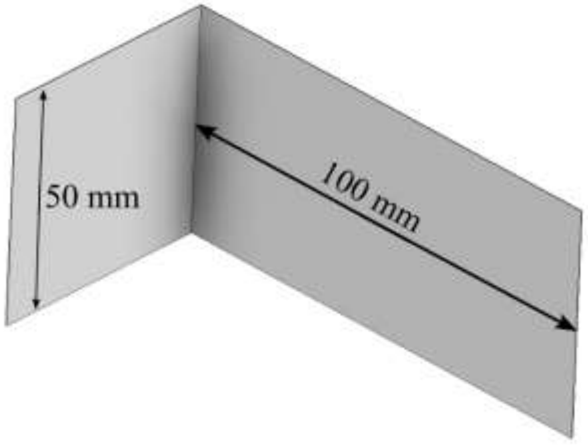
- Low stiffness makes structures prone to buckling
- Thermal gradients induce residual stress and distortion
- Layer-by-layer deposition leads to error accumulation
- Weak interlayer bonding can cause debonding and failure
- Small defects can significantly impact structural integrity

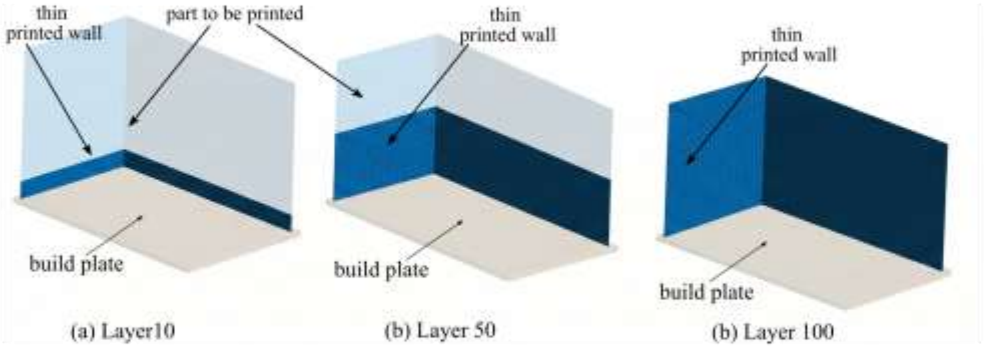


This Study: In-Situ Monitoring of Geometric Drift in Thin Walls

Experimental System

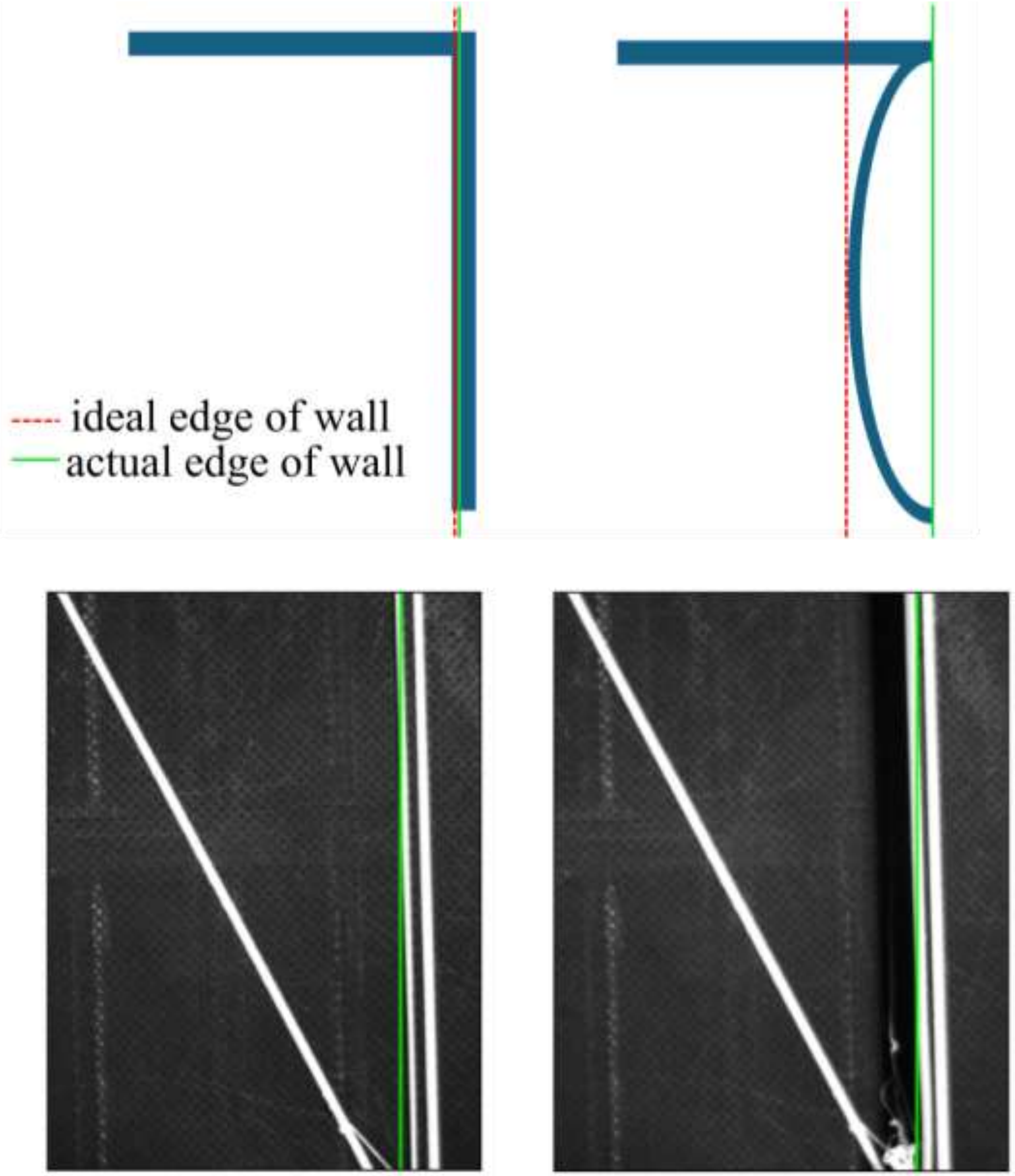
- Thin-wall L-shaped geometry designed to amplify deformation
- Fabricated using FFF with controlled process parameters
- Fixed camera captures images after each printed layer
- Open cross-section increases sensitivity to thermal effects
- Enables measurement of layer-by-layer geometric evolution





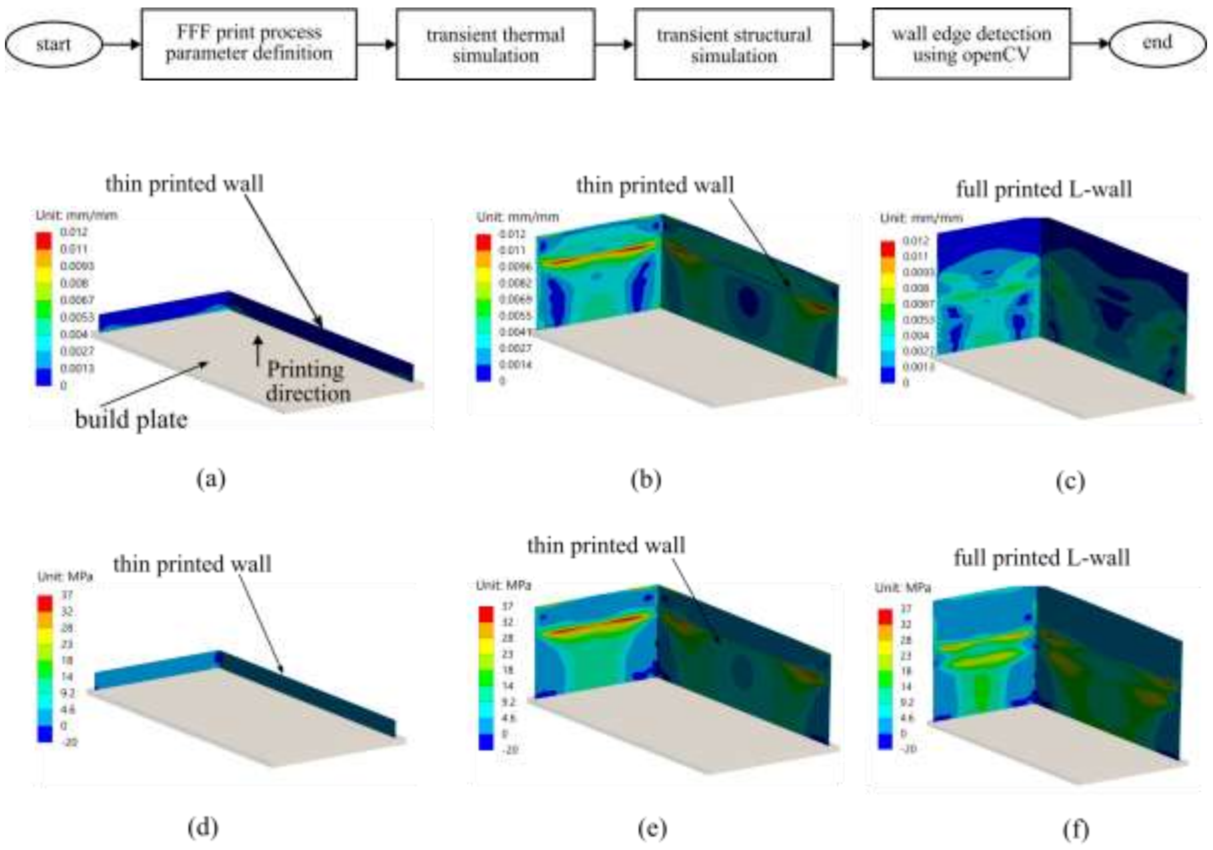
In-Situ Measurement

- Use first printed layer as reference geometry
- Detect wall edge after each new layer
- Compute drift relative to baseline
- Track cumulative deformation with build height
- Captures instability before visible failure



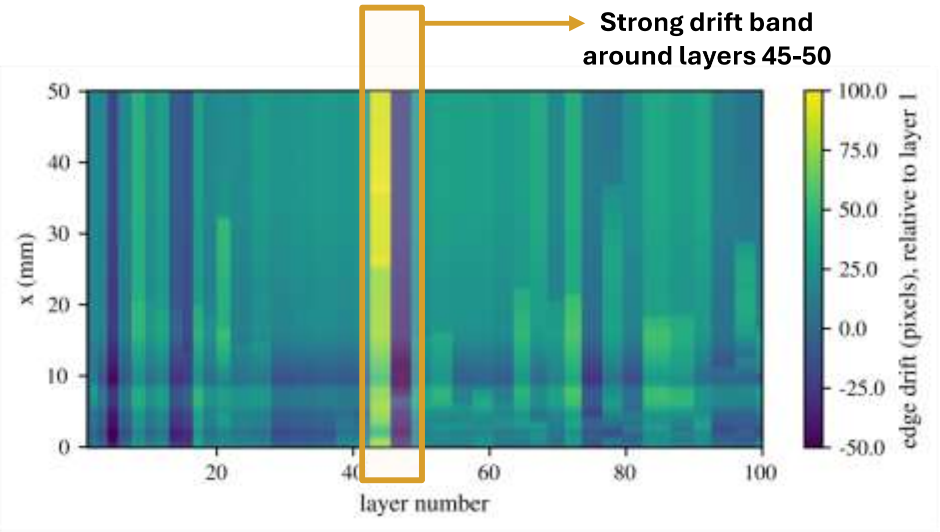
Modeling Approach

- Layer-by-layer element activation driven by print sequence
- Transient thermal analysis captures heat history
- Structural model includes thermal strain coupling
- Predicts stress and strain evolution during printing
- Enables comparison with measured geometric drift

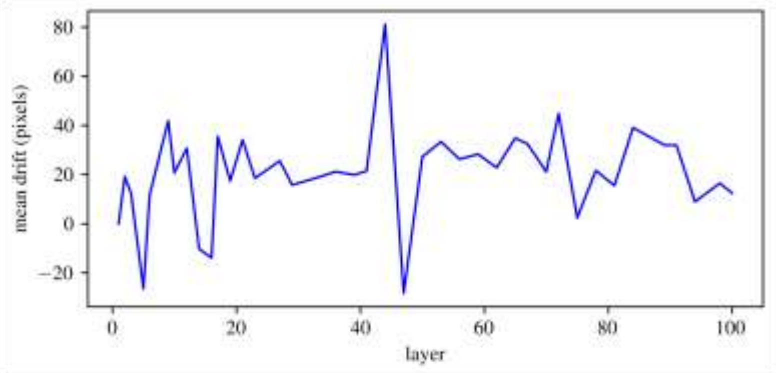


Geometric Drift Reveals Structural Instability

- Cumulative drift develops as layers are deposited
- Deformation trends inward with increasing build height
- Instability emerges near a critical height (~20–25 mm)
- Drift patterns indicate nonuniform, height-dependent behavior
- Geometric measurements reveal onset of failure

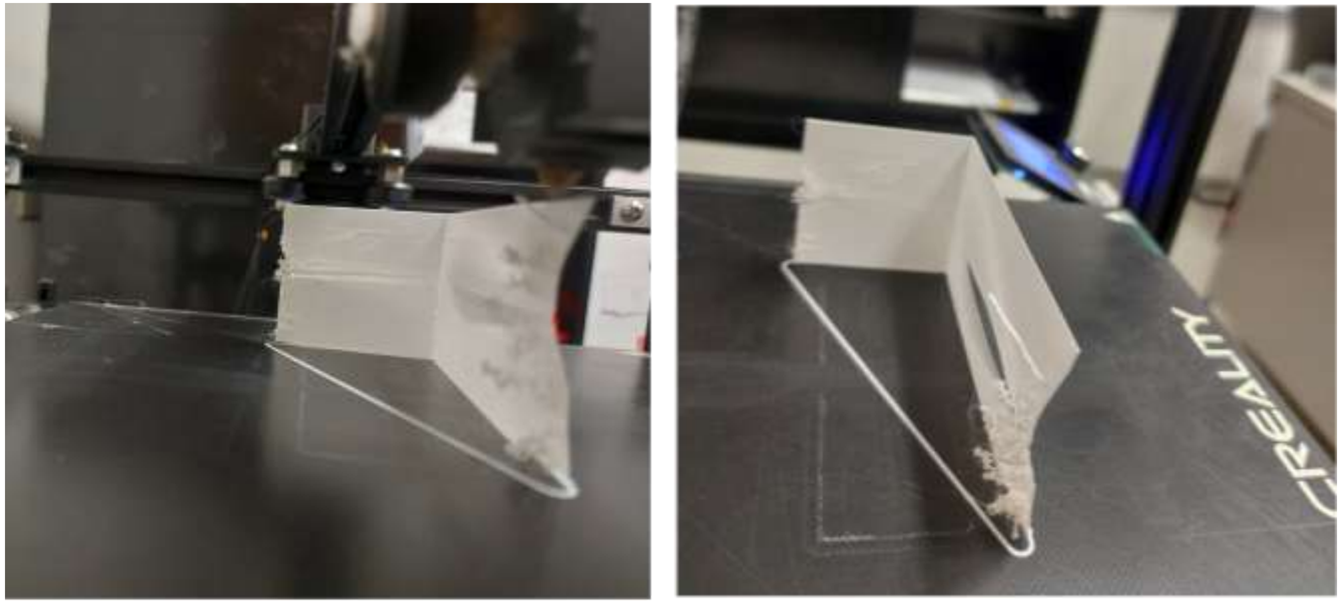


Heatmap of cumulative wall-edge drift



Observed and Predicted Failure Mechanism

- Asymmetric cooling induces thermal shrinkage
- Residual strain leads to cumulative wall bending
- Stress concentrates near a critical height
- Interlayer bonding weakens under tensile loading
- Bending progresses to debonding and failure



Experimental evidence: inward bending followed by interlayer debonding

Conclusion & Future Work

- A low-cost side-view camera can quantify layer-wise geometric drift rather than only flagging visible defects
- Measured drift aligns with simulated strain/stress concentration at the same instability zone.
- That linkage is a practical foundation for calibrating a physics-based digital twin of thin-wall FFF.

Next steps toward a closed-loop digital twin

- Update model parameters with measured drift
- Add damage and debonding physics
- Use real-time data for model updating
- Improve reliability of FFF

Acknowledgement

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Discussion

SWIFT-UAV: Scientific Workhorse for In-flight Field Tests – UAV

github.com/ARTS-Laboratory/SWIFT-UAV

Author Information
Name: Austin R.J. Downey
Email: austindowney@sc.edu
Lab GitHub: github.com/arts-laboratory

Molinaroli College of Engineering and Computing
UNIVERSITY OF SOUTH CAROLINA