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Towards an Automated Procedure for High-Quality Conformal Meshes for Complex Woven Composites

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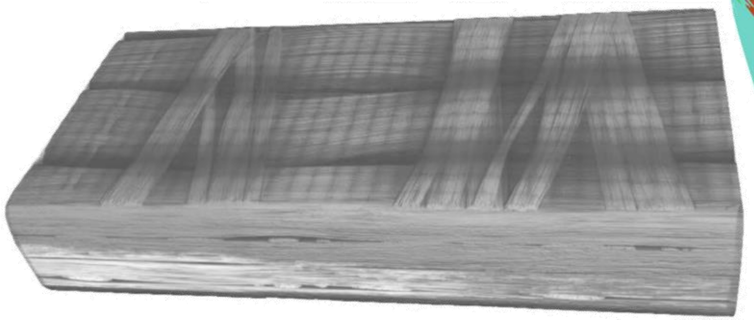
Outline

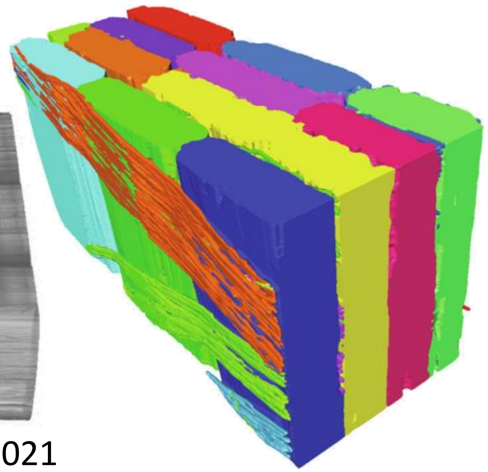
- Why mesh generation remains a challenge
- Methods proposed in the current literature
- Algorithm description
- Case study: angle interlock textile composite
- Outlook and Conclusions

Why Mesh Generation Remains a Challenge

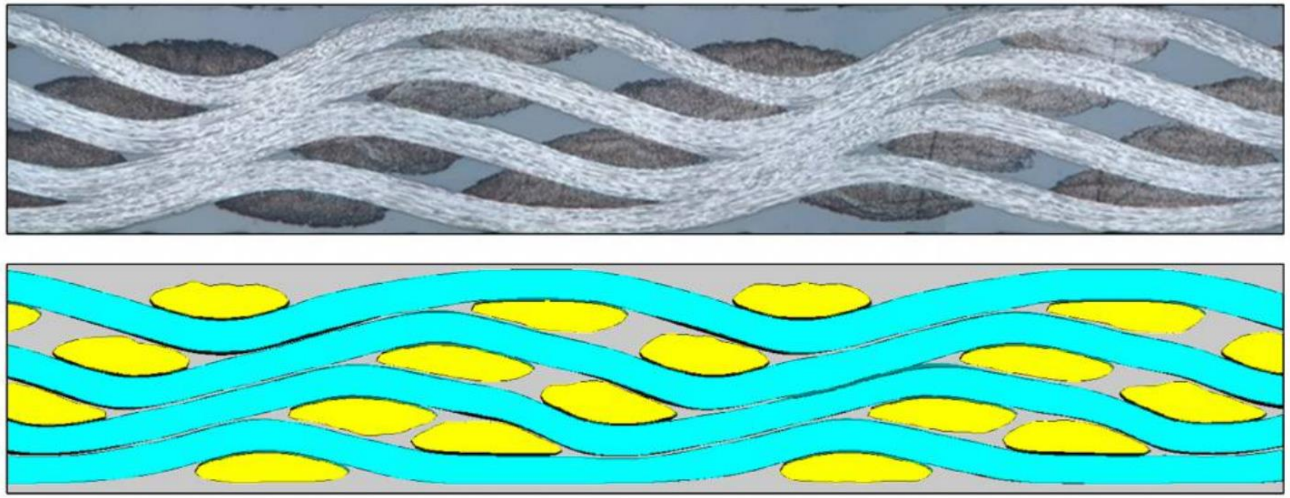
- Performance predictions have often relied on idealized micro/mesostructures
- Stress concentrators (holes, notches, large voids, etc.) increase sensitivity to mesostructure
- Complex geometries (woven near net-shape, joints, etc.) are very difficult to idealize
- Options to create accurate model mesostructures for complex components
  - Destructive analysis (serial sectioning)
  - Non-destructive inspection (X-Ray CT)
  - Process Simulation
- Surface descriptions of tows often result in small resin slivers between tows or overlaps between tow surfaces, which complicates mesh generation
- Researchers have proposed many methods, but all are limited as we continue to pursue more complicated components

Model created directly from X-ray tomography





Auenhammer et al. Composite Structures 2021

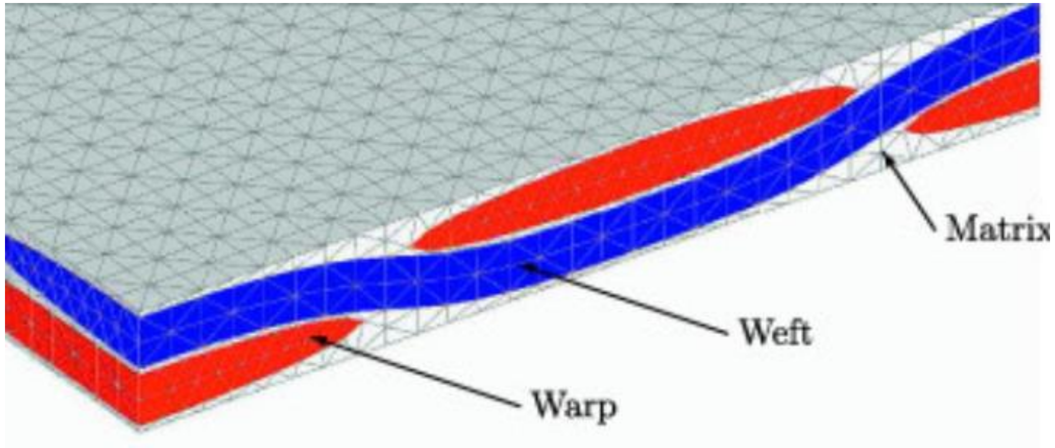


Mollenhauer et al. SciTech 2021

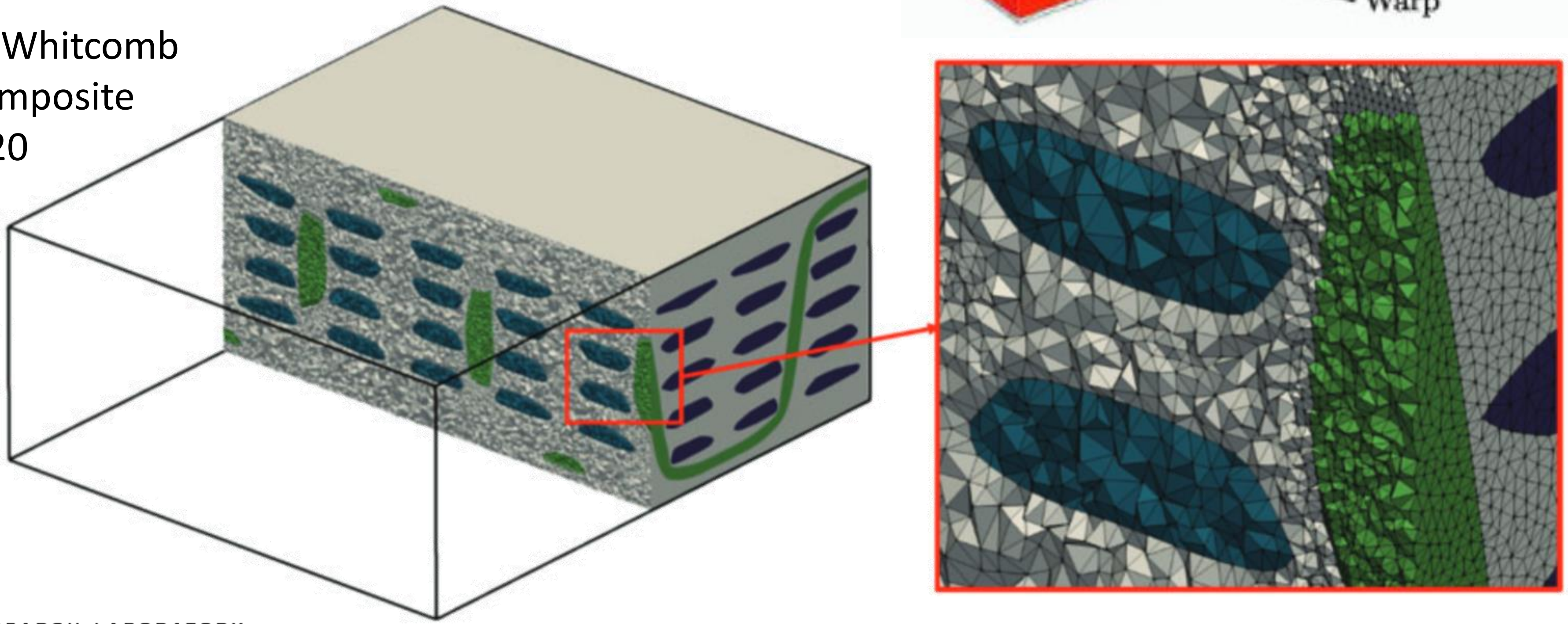
Method: Artificially Insert Matrix Between Tows

- Most common approach used in the literature
- Typically achieved by shrinking tows
- Issues:
  - Modifies fiber volume fraction
  - Leads to unrealistic stresses within sliver of neat resin between tows

A. Melro, P. Camanho, F. Pires, S. Pinho
Computational Materials Science 2012



M. Ballard, J. Whitcomb
Journal of Composite Materials 2020



Method: Detect and Remesh Contact Zones

- Avoids drawbacks of artificially inserting resin
- Implemented for specialized cases
- Ha et al. assumes a parametric form for a tow weave through two other tows
- Grail et al. assumes contact zones are approximately planar
- Issue: generalizing approaches to 3D textiles appears to be very difficult

G. Grail et al. Composites: Part A 2013

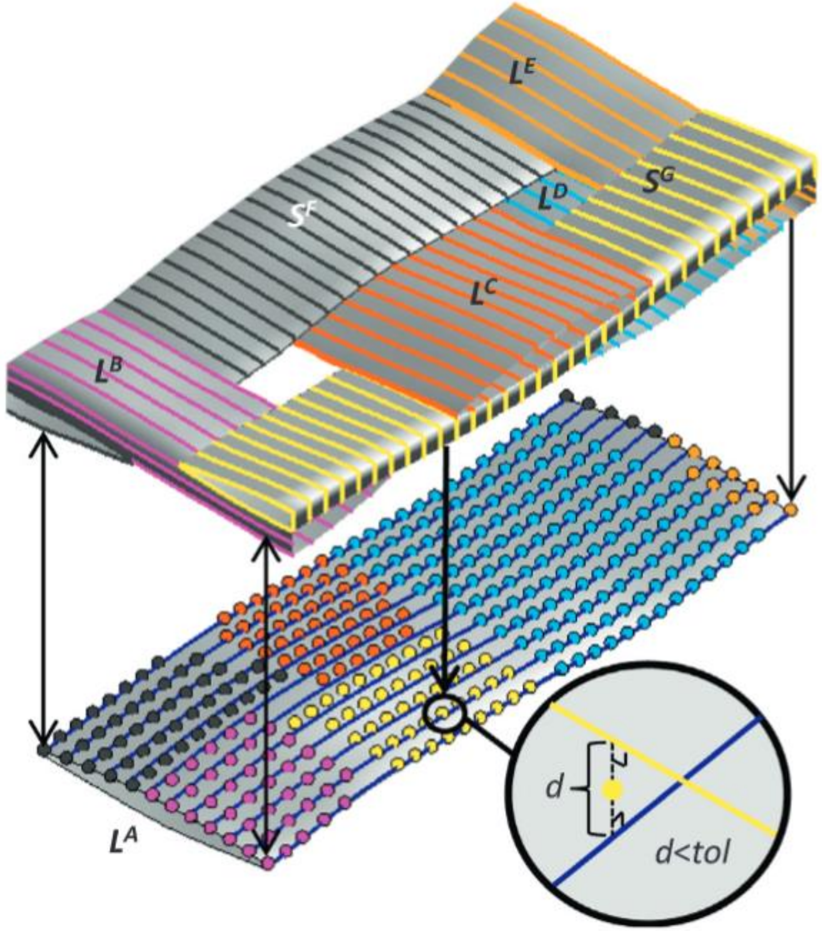
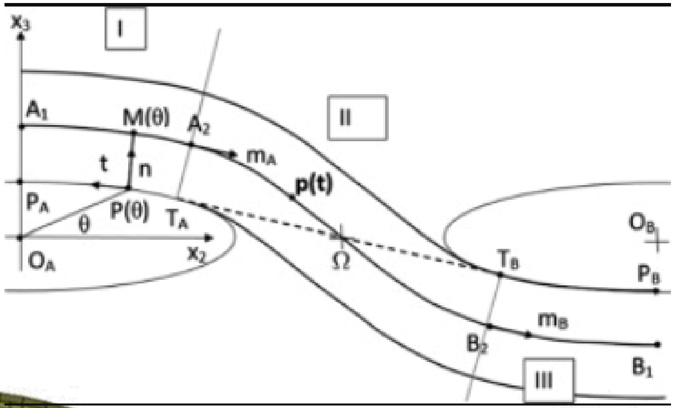
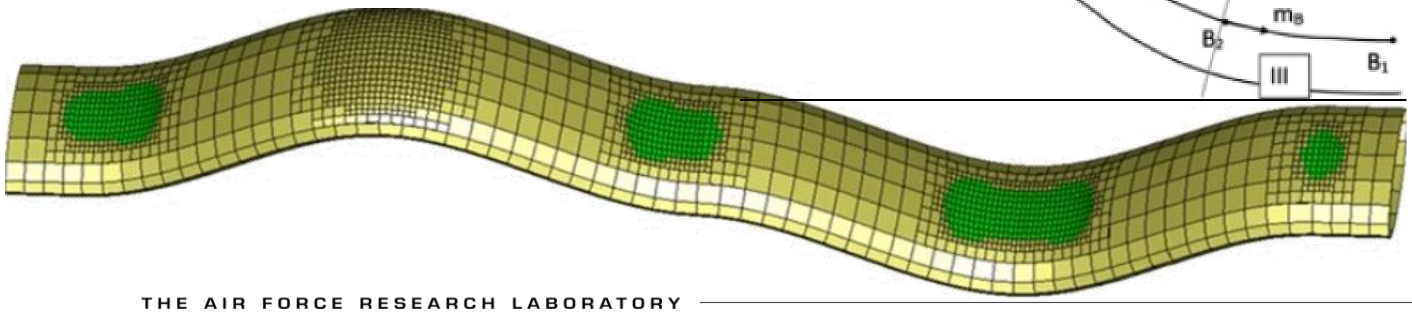


Fig. 3. Detection of contact zones between yarns. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

M. Ha, L. Cauvin, A. Rassineux
Comptes Rendus Mécanique 2016

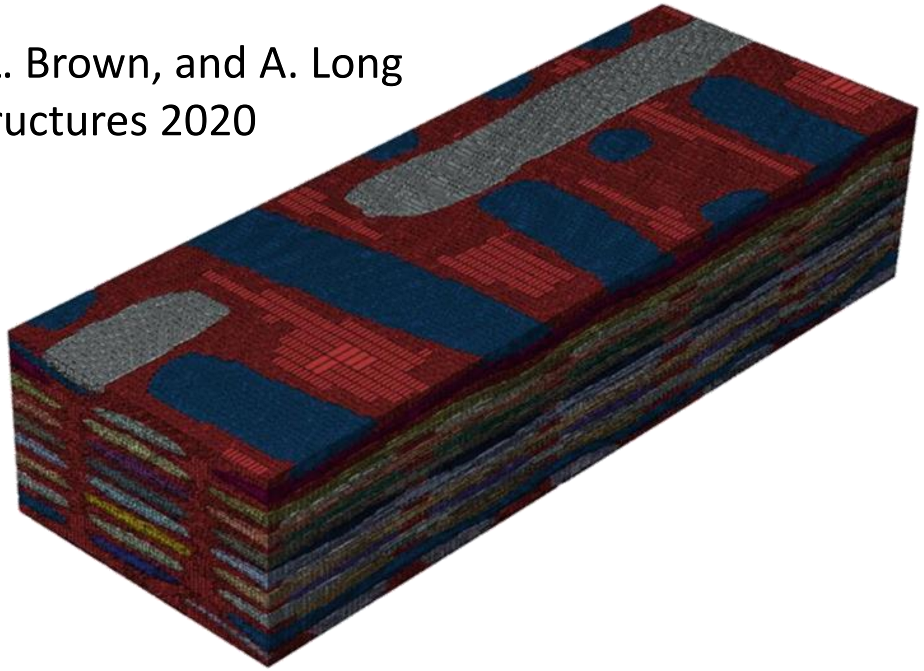


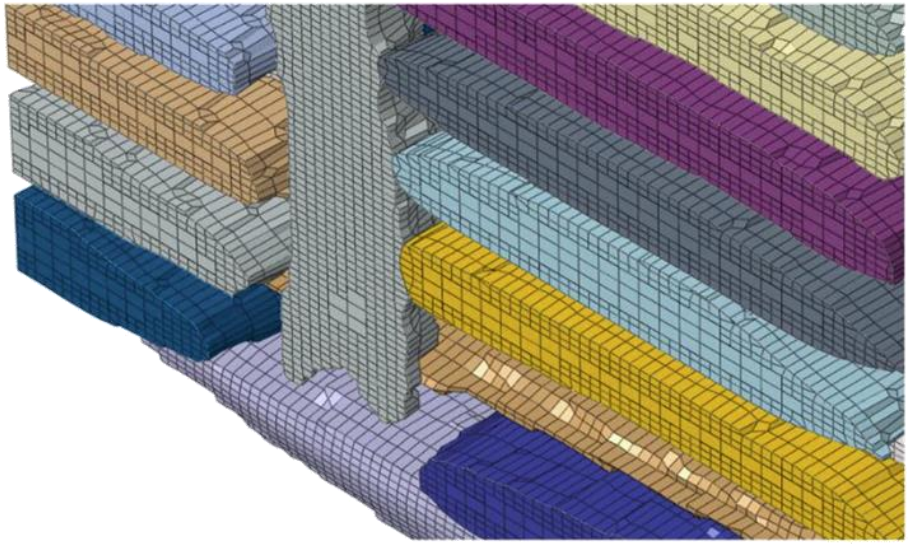


Method: Octree Meshing with Local Refinement

- Must be combined with smoothing to avoid artificial stress concentrations, which does remove the structured octree property
- General approach without any currently known edge cases
- Issues:
  - High refinement near interfaces, which can simply be a product of meshing a curved object with cubes
  - Not readily used by traditional finite element codes

M. Matveev, L. Brown, and A. Long
Composite Structures 2020

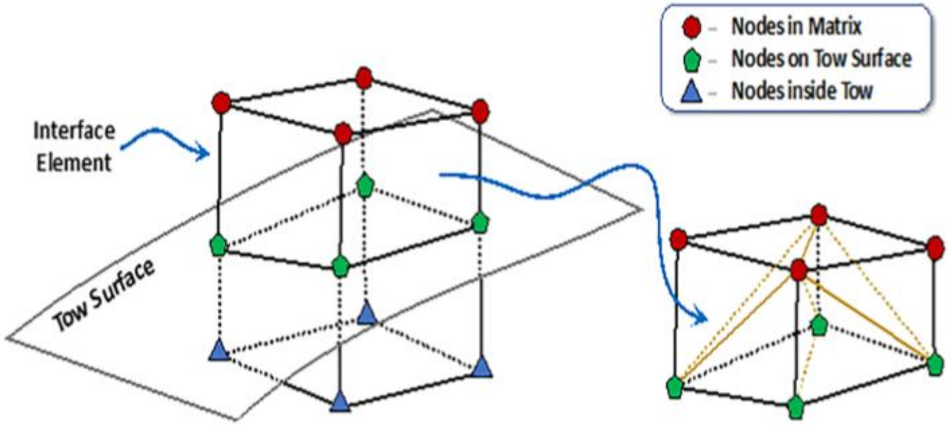




Method: Independent Mesh Method (IMM)

- Tows cut background mesh
- Interfaces connected via penalties or cohesive zones
- Issues:
  - Non-conforming interfaces introduces error at a common failure location
  - Matrix condition number often very high due to small support for cut basis functions
  - Complex components require either a very fine background mesh everywhere or a special mesh that is appropriately refined near interfaces

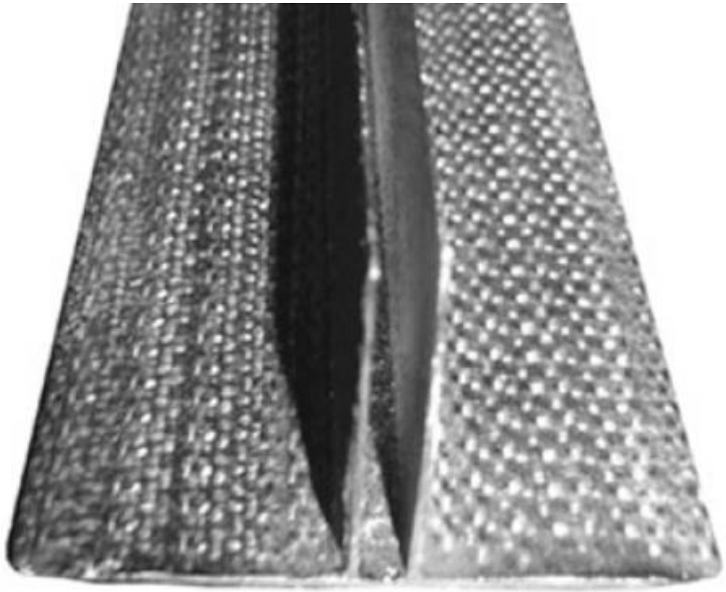
H. Adluru et al. Composites: Part A 2023



Challenges for Advanced Woven Structures

- 3D as-woven components and tailored fiber placement (TFP) components exhibit:
  - Complex mesostructures (tows can follow very tortuous 3D paths)
  - High spatial variation (repeating unit-cell may not exist or be much larger)
- Traditional multiscale strategies do not work
- We are working towards simulating large regions of interest at the mesoscale for these complex components, but we need a general method for creating meshes

Credit: UDRI Tailored Fiber Placement
https://udayton.edu/udri/capabilities/materials/tailored-fiber-placement2.php



Advanced Weaving Technology, chapter *3D Weaving for Composites* by Islam 2022

Credit: Bally 3-D Composite Structures
https://www.ballyribbon.com/3d-woven-ribbon

Process-to-Performance Analysis Pipeline

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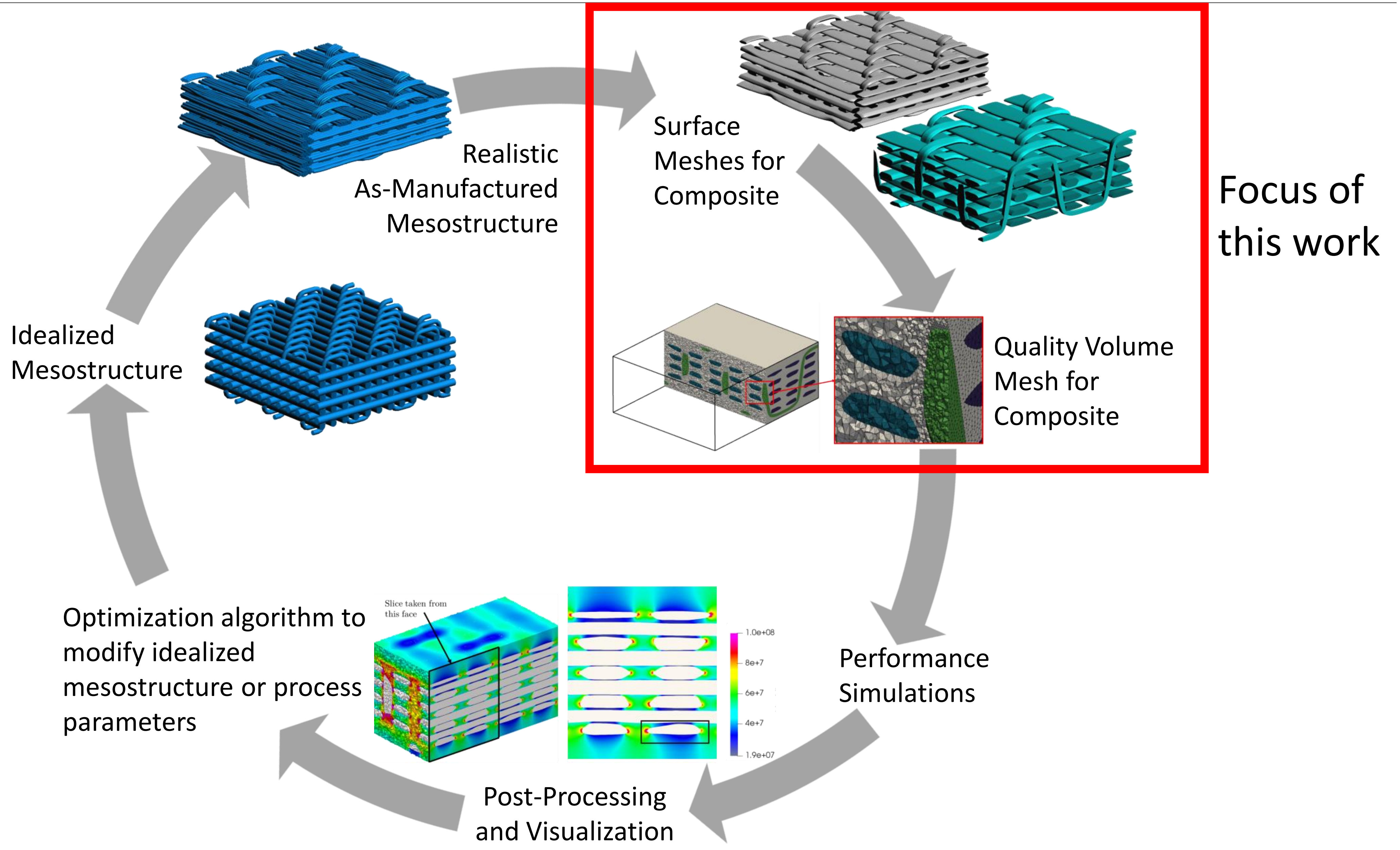
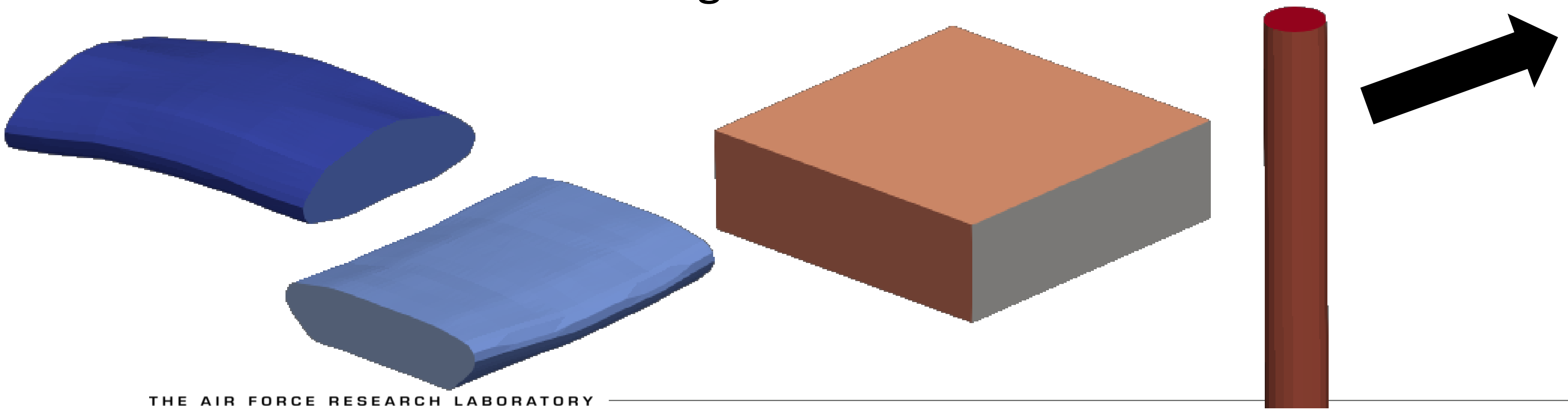
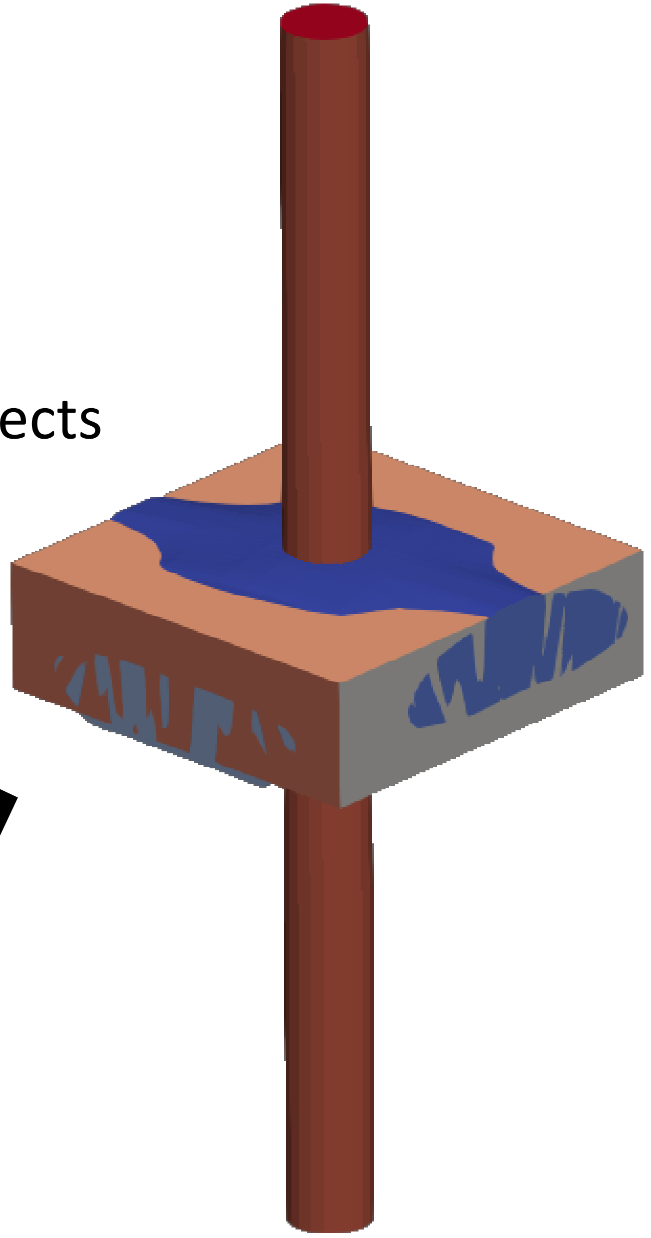


Algorithm Step 1: Combine Surfaces

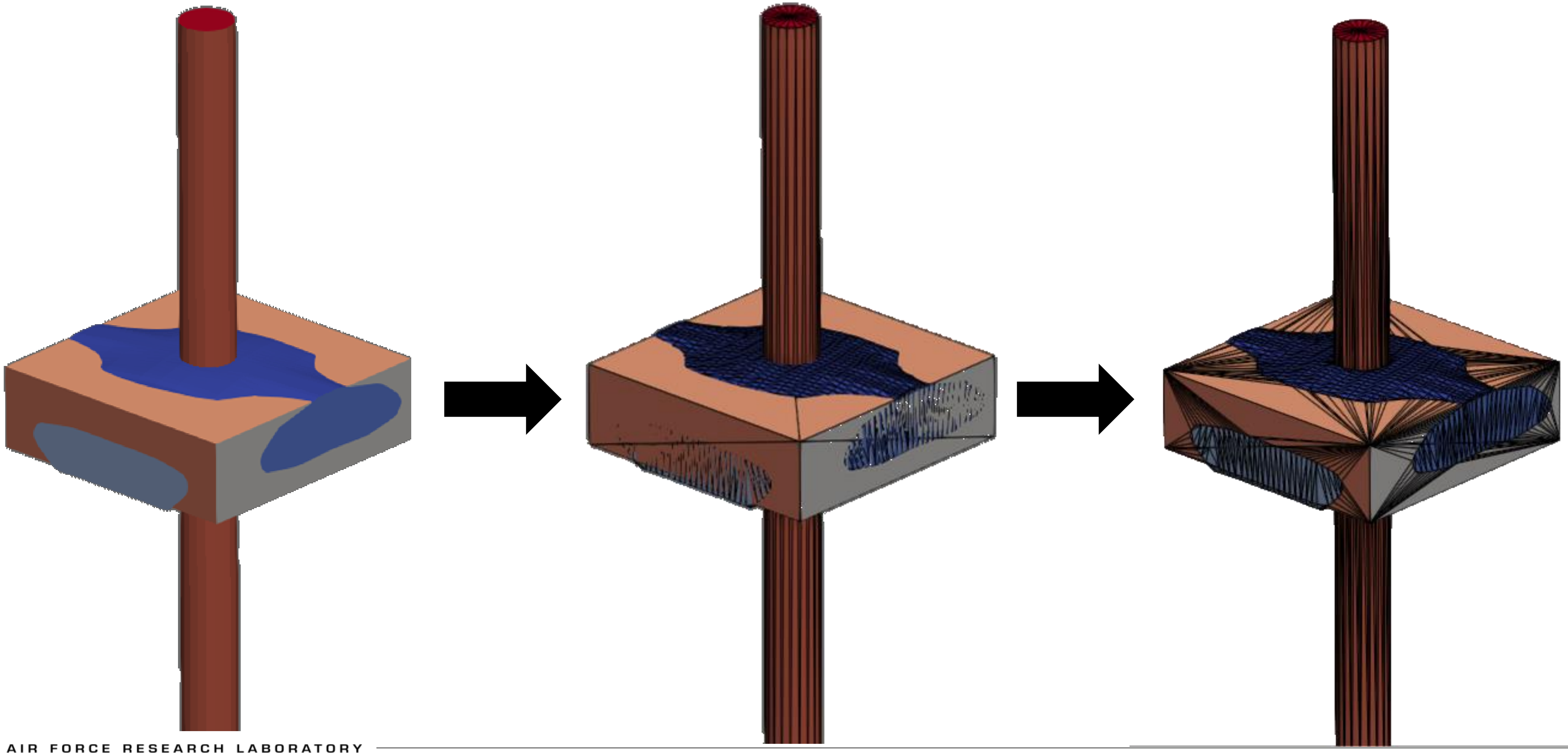
- Input for each *object* (tow, neat resin, hole, notch, void):
  - Surface mesh (polygonal, triangular, quadrilateral)
  - Facets labelled (enables feature preservation)
  - Boolean type (i.e. solid, clip inside, clip outside)
  - Priority (integer)
    - Higher priority objects cut away from lower priority objects
    - Overlaps between objects with the same priority are specially addressed
- Facets renumbered to be unique
- Data combined into single data structure





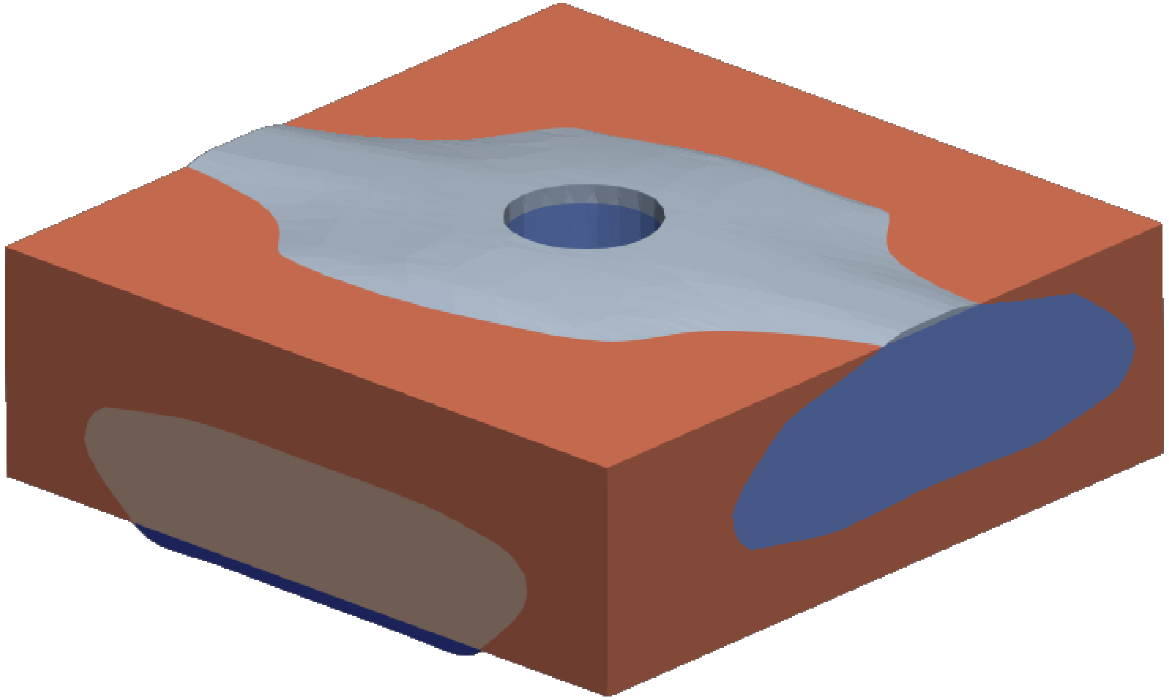
Algorithm Step 2: Create Consistent Triangular Surfaces

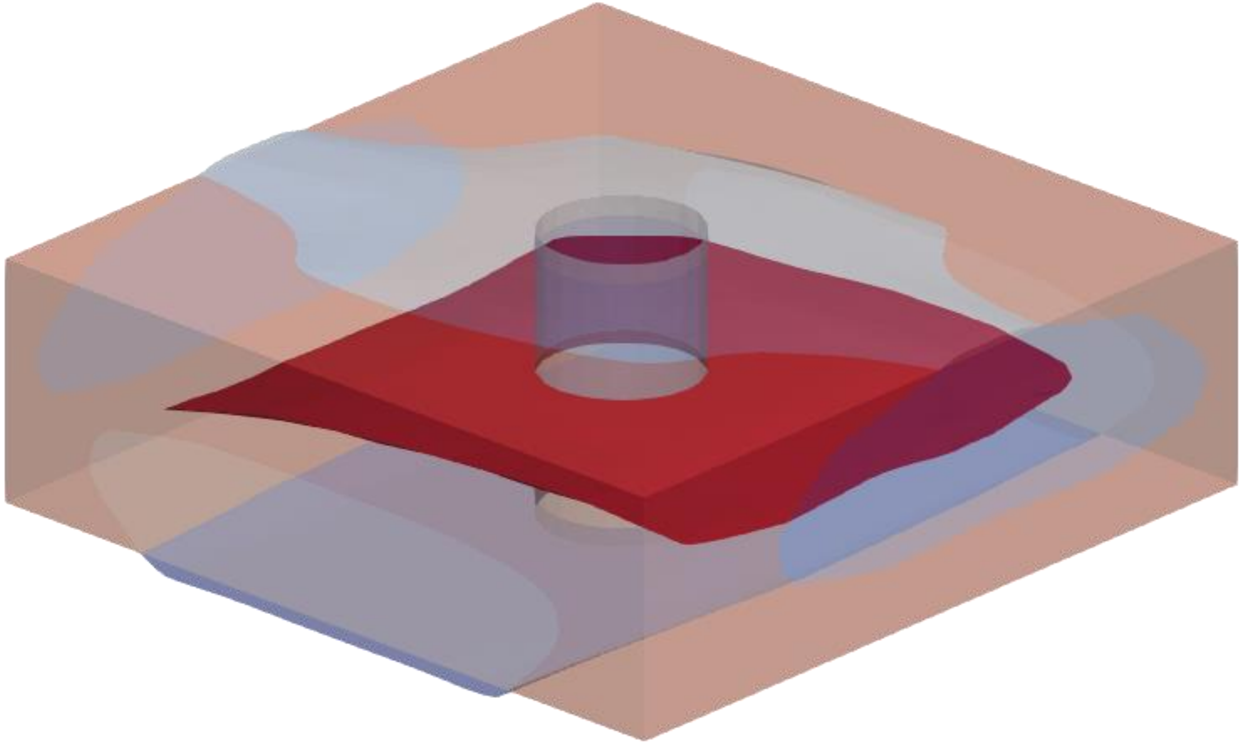
- All surfaces are triangulated
- Any triangle-triangle, triangle-edge, triangle-vertex, and edge-vertex intersections are remeshed such that all intersections occur along an edge or at vertex



Algorithm Step 3: CDT and Segment Regions

- Constrained Delaunay tetrahedralization created (extremely poor quality)
- Flood fill algorithm used to segment region based on consistent triangular mesh from last step
- Each *region* corresponds to a contiguous set of tetrahedra that lie within a unique combination of *objects*
- Triangular faces that correspond to the consistent triangular surface are tracked

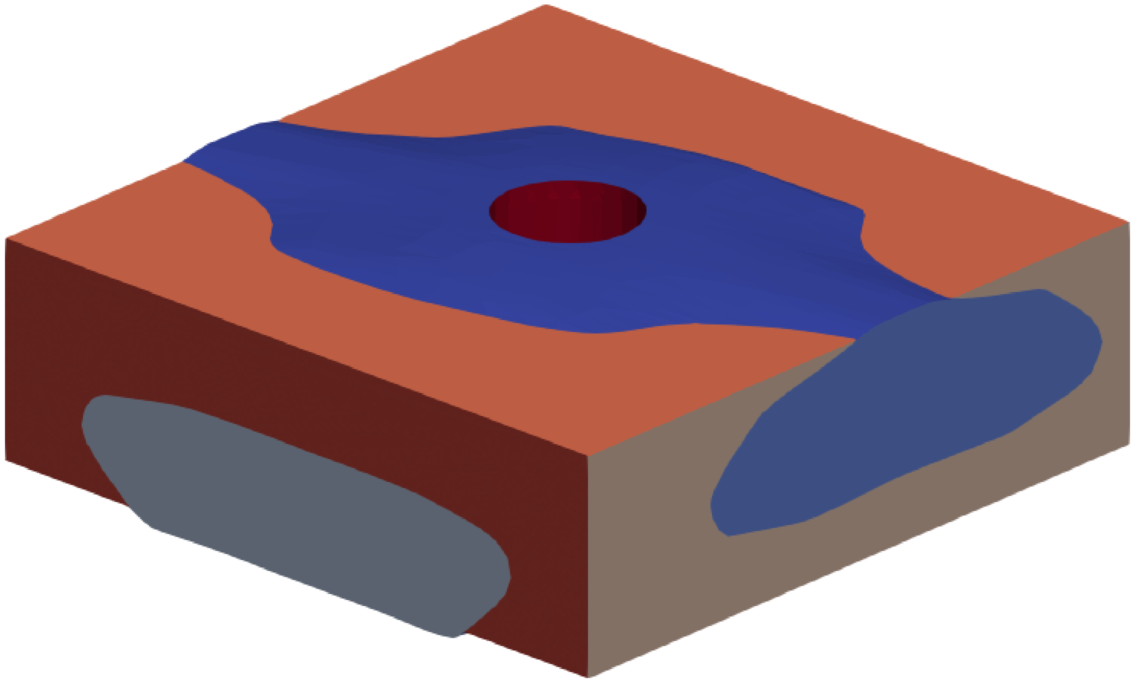




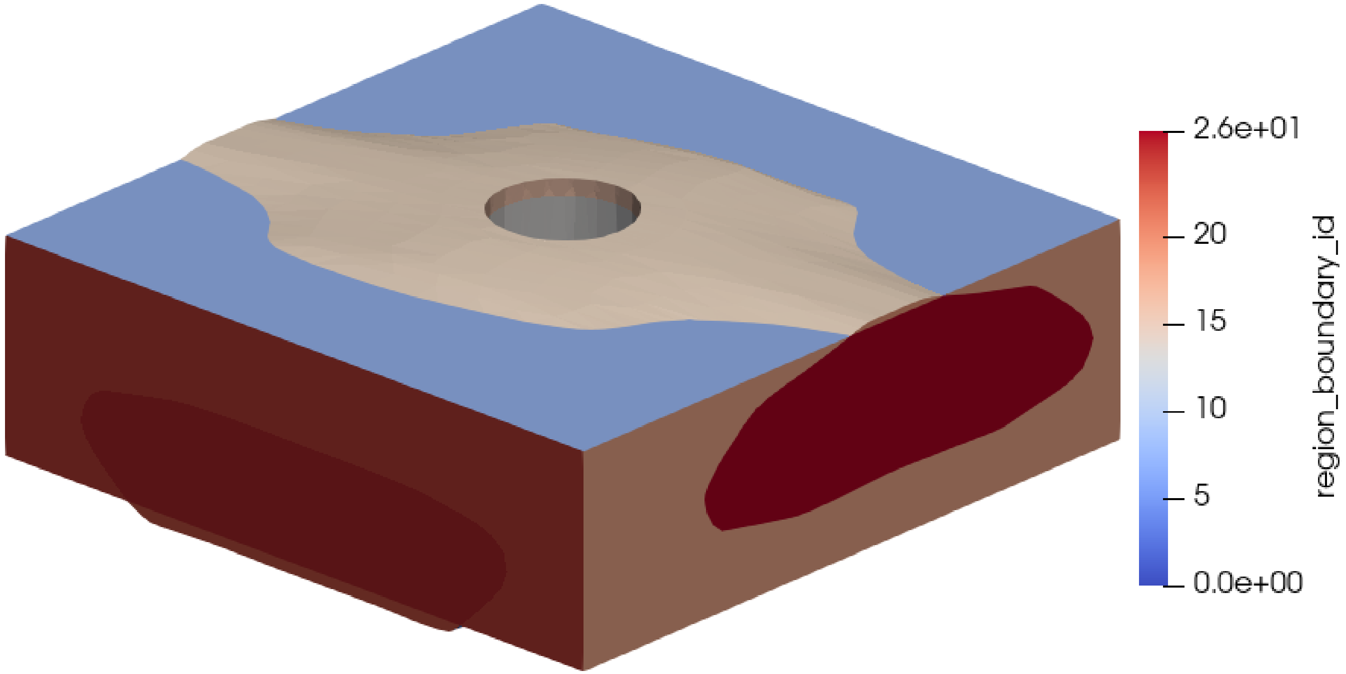
Algorithm Step 4: Segment Region Boundaries

- Boundaries of regions are uniquely enumerated for each tracked triangle
- Each *region boundary* corresponds to a unique combination of the facet and adjacent regions

Facet ID from step 1 for reference



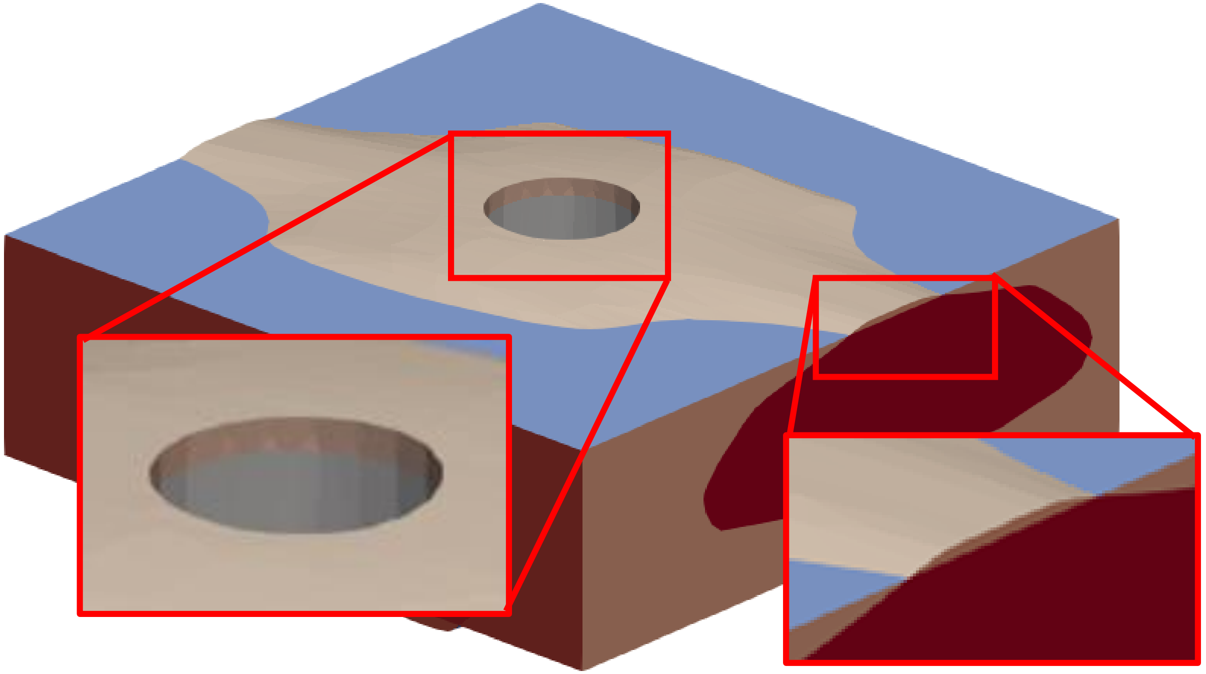
Region Boundary ID



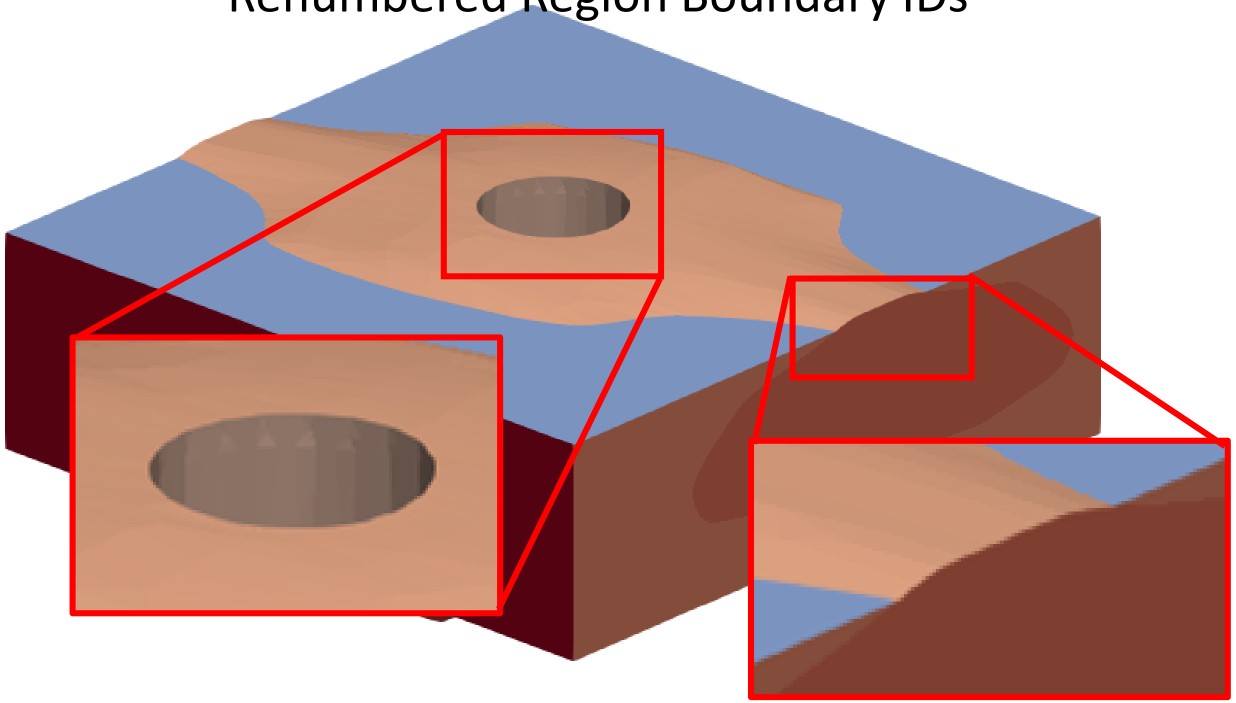
Algorithm Step 5: Merge Regions

- Boundaries belonging to a object with a lower priority that are inside objects with a higher priority are unnecessary and lead to poor mesh quality
- Renumber regions to remove these boundaries
  - Regions of overlap between objects with same priority are not merged
- Remove tracked triangular faces on removed region boundaries

Previous Region Boundary IDs



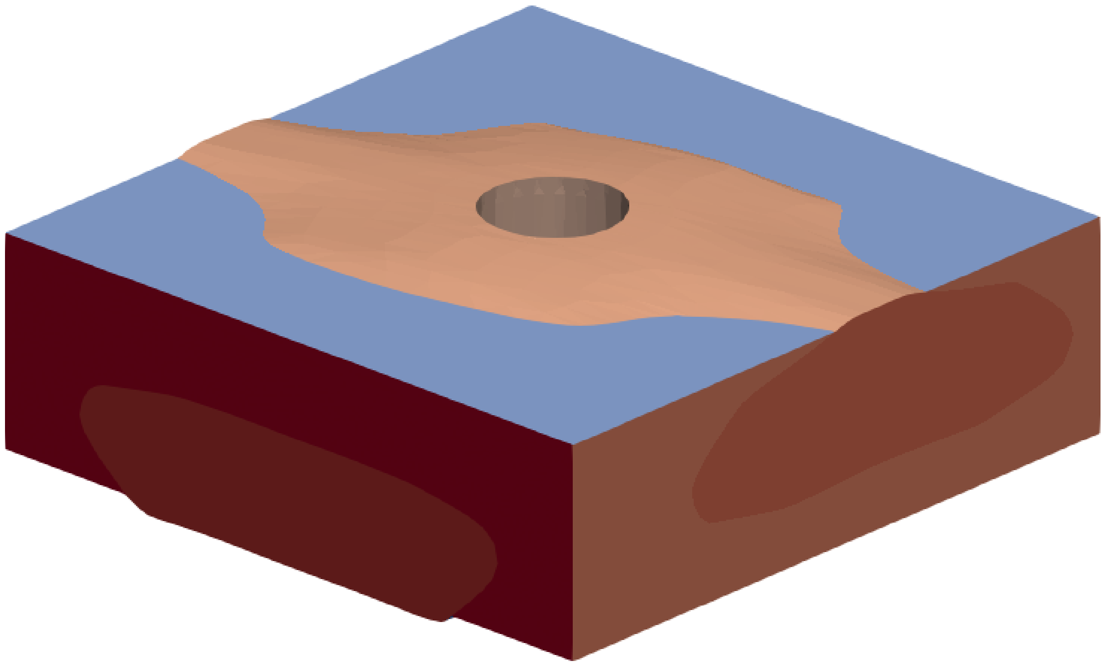
Renumbered Region Boundary IDs



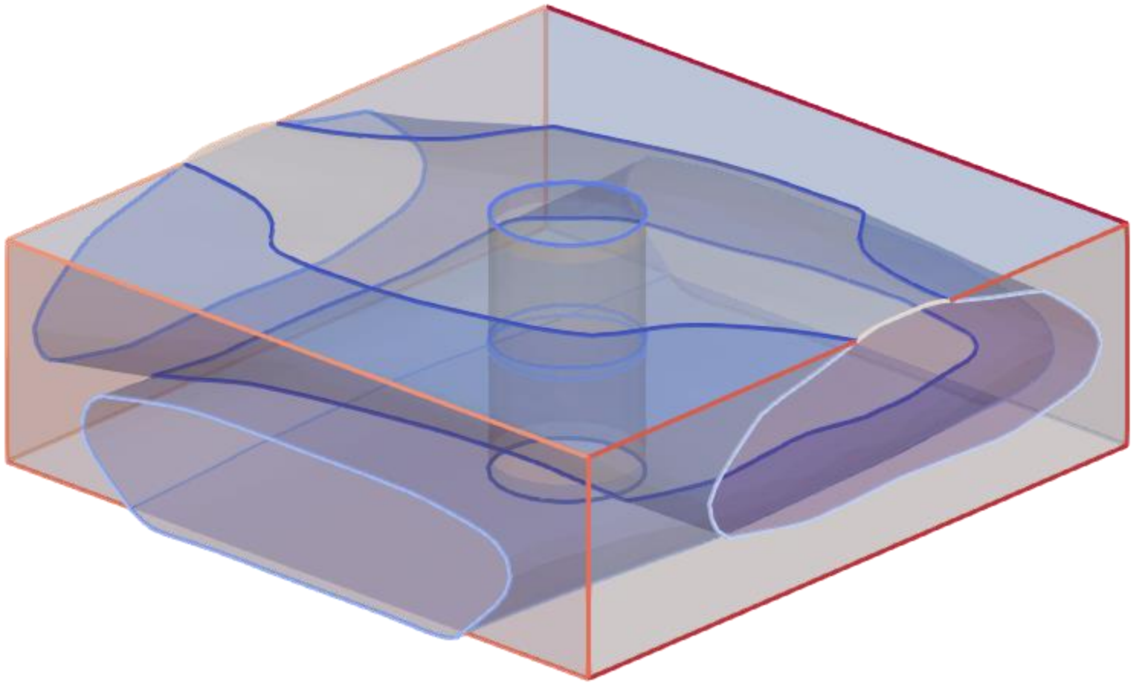
Algorithm Step 6: Segment Seams

- Sets of edges that lie along a unique combination of region boundaries are enumerated
- Each unique set of edges is referred to as a *seam*
- Seams are preserved during mesh optimization in later steps (edge flips, moving vertices, etc.)

Region Boundary IDs for Reference

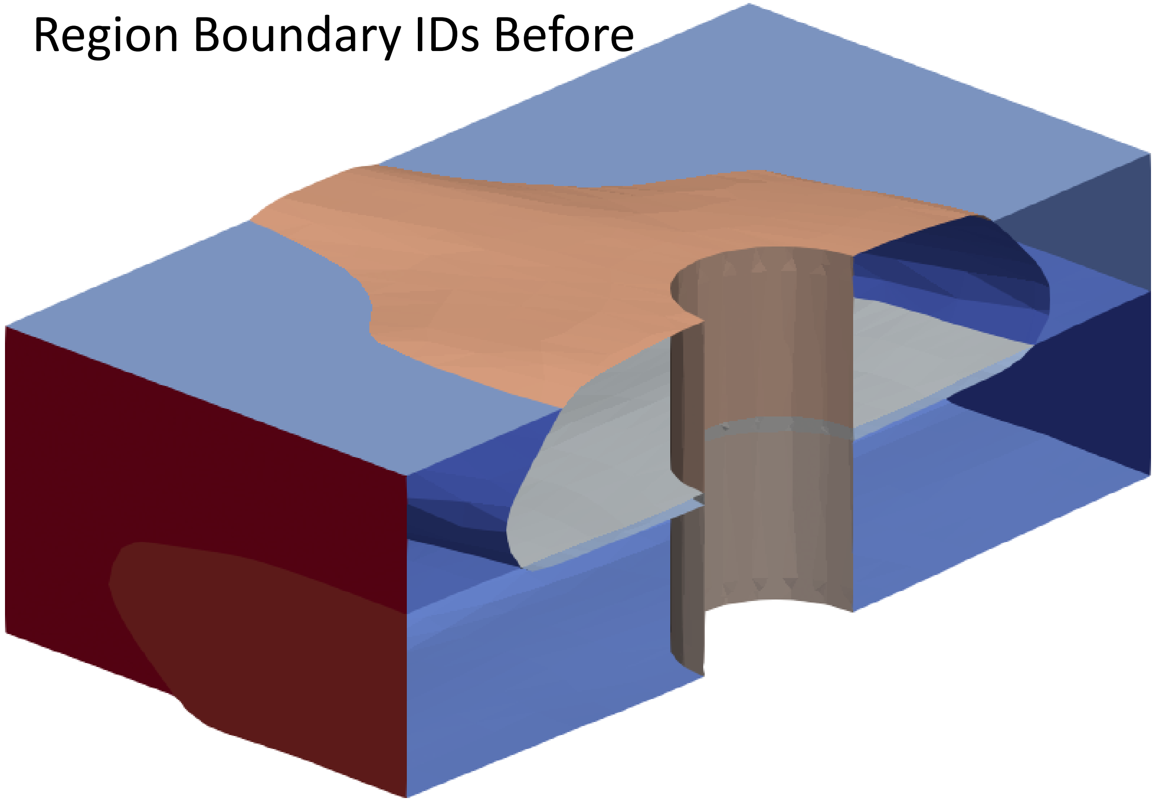


Seam IDs

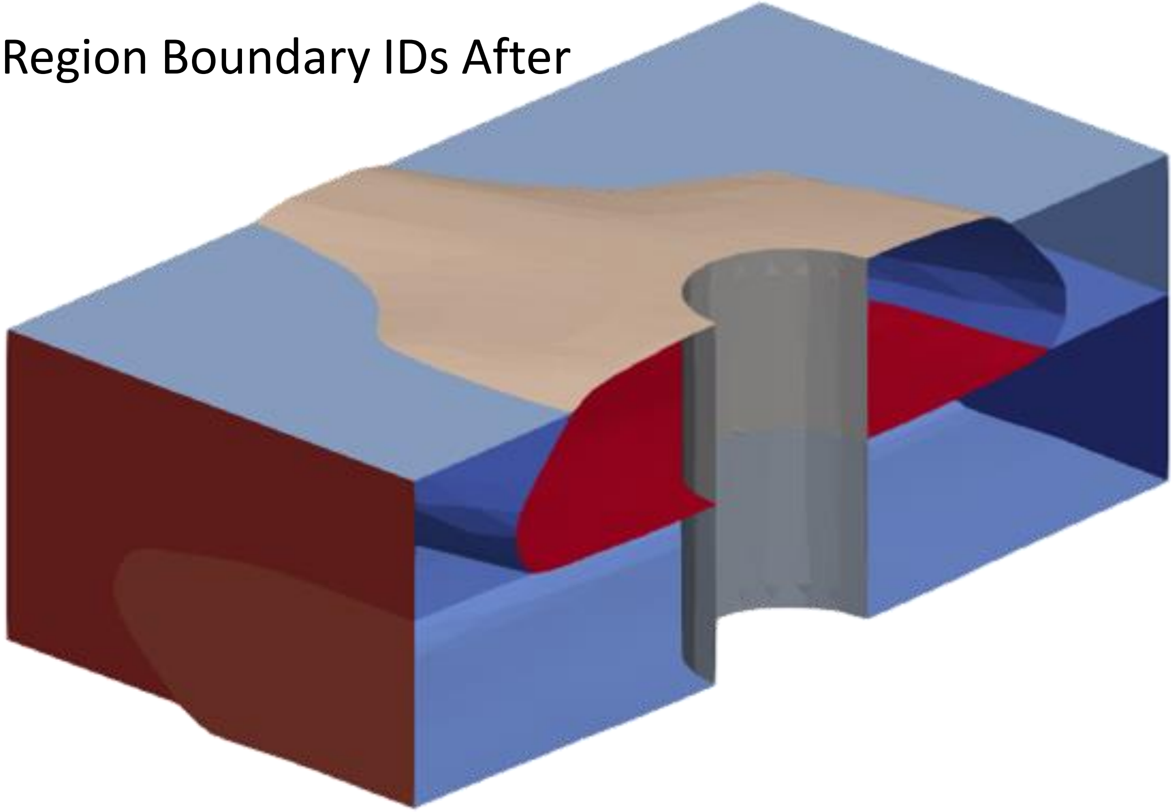


- Regions of overlap between objects with same priority are replaced with new surfaces
- Level-set method is used to find new conforming surfaces (Ballard et al. ASC 2020)
- All features (regions, region boundaries, and seams) are renumbered appropriately

Region Boundary IDs Before

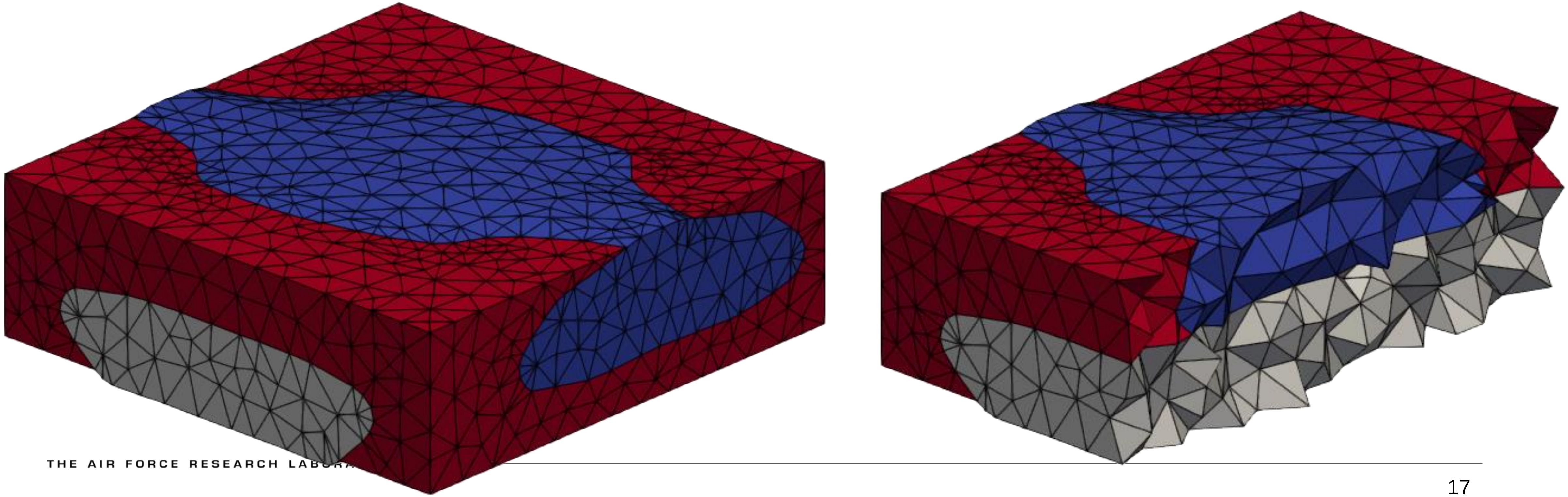


Region Boundary IDs After



Algorithm Step 8: Mesh Improvement

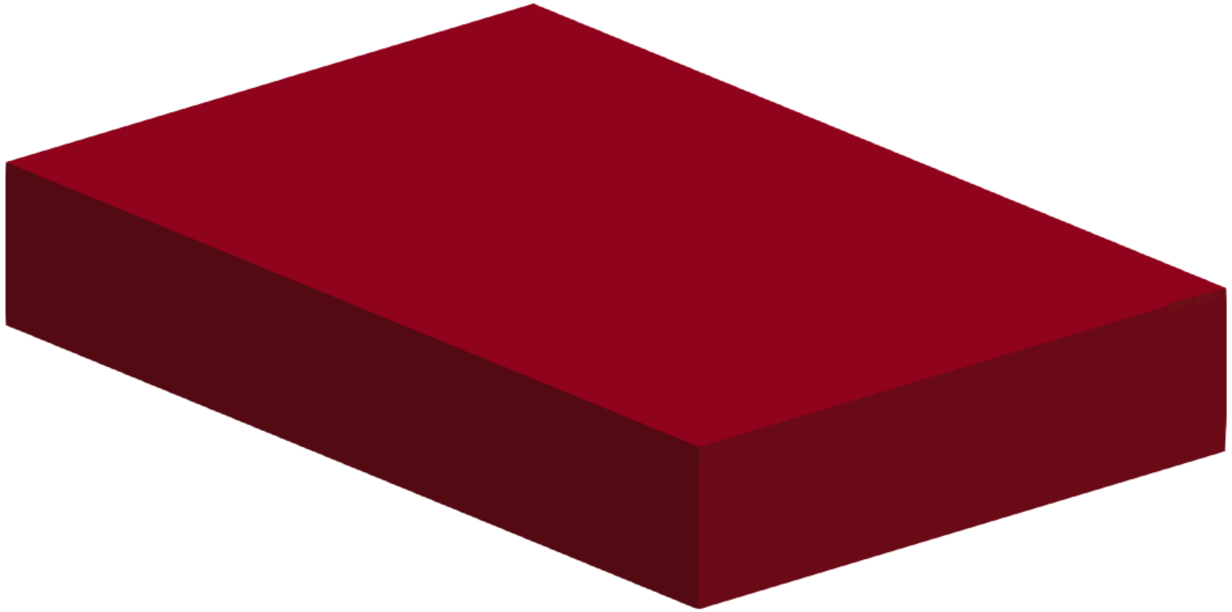
- Surfaces corresponding to tracked triangles are improved through standard procedures (edge flips, edge splits, tangential vertex smoothing)
  - Features are preserved throughout surface mesh improvement and tetrahedralization remains valid (though poor quality)
- Available libraries used to improve volume mesh (TetGen, Stellar, fTetWild)
  - fTetWild yields best results but moves surfaces within a defined (sometimes creates artifacts that is corrected after)



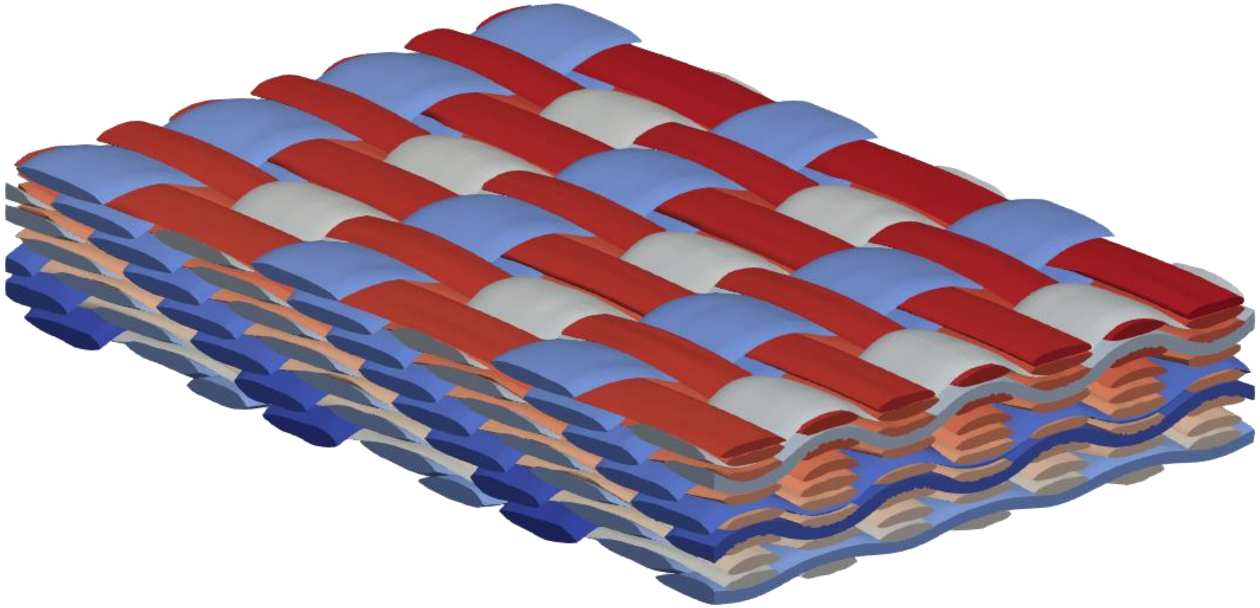
Case Study: Angle Interlock Textile

- Process simulation used to predict an as-woven angle interlock tow architecture
- Tows described as spline surfaces with caps
- Neat resin idealized as rectangular prism (though it leaves some tows exposed)
- Numerous regions of overlap (nearly between every close tow)

Neat Resin



Tow Surfaces



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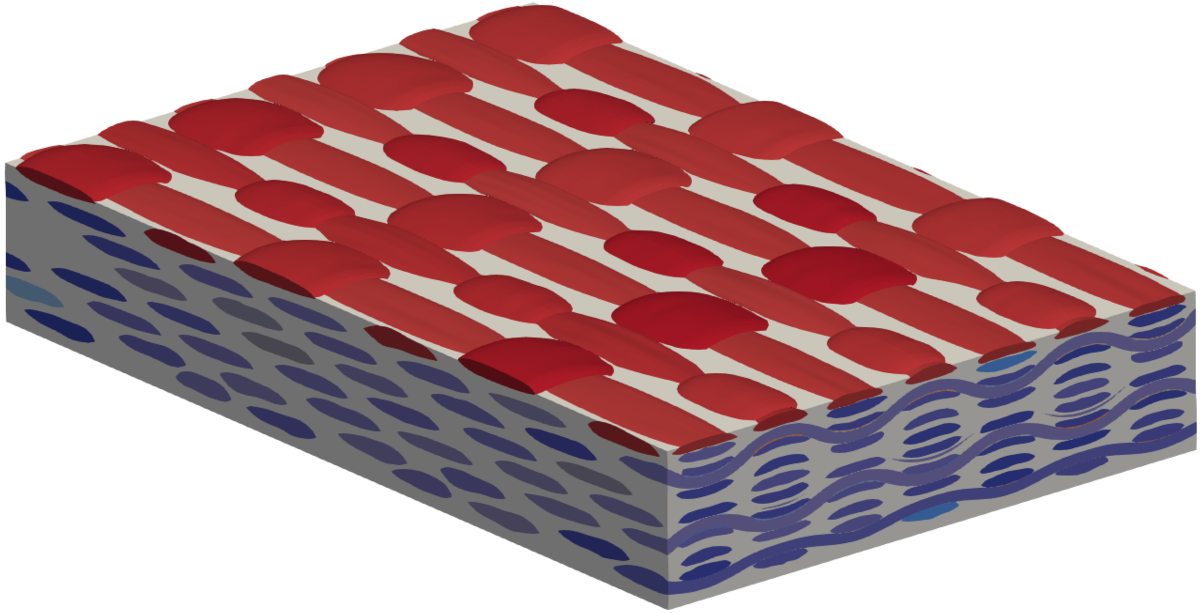
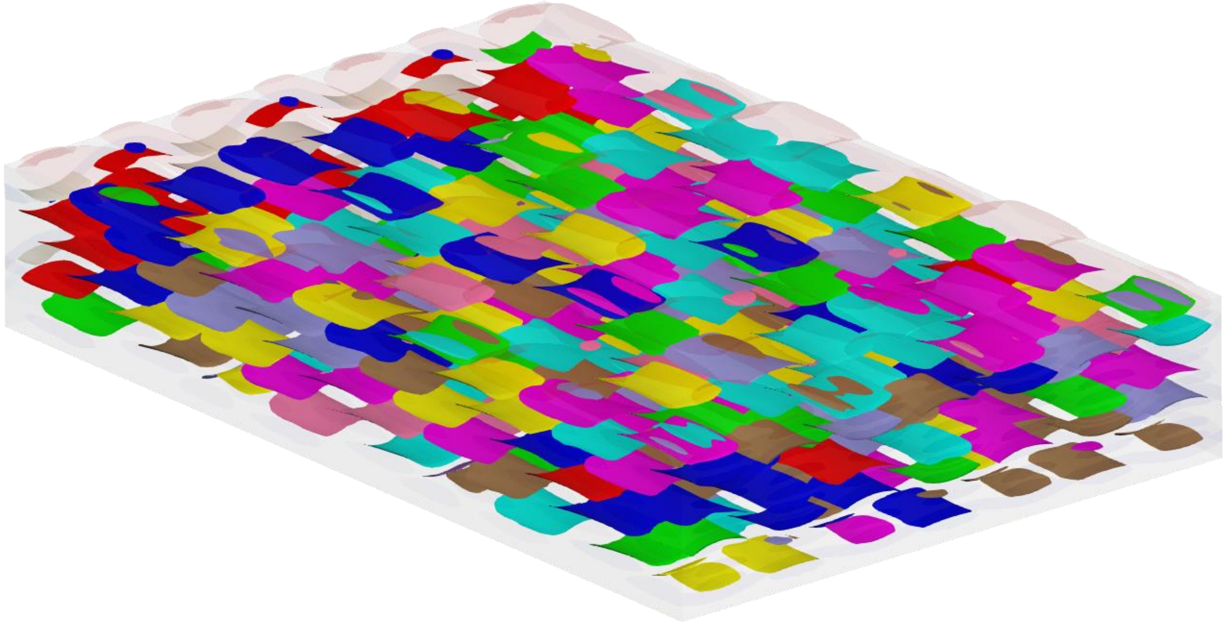
Region IDs



Regions of Overlap



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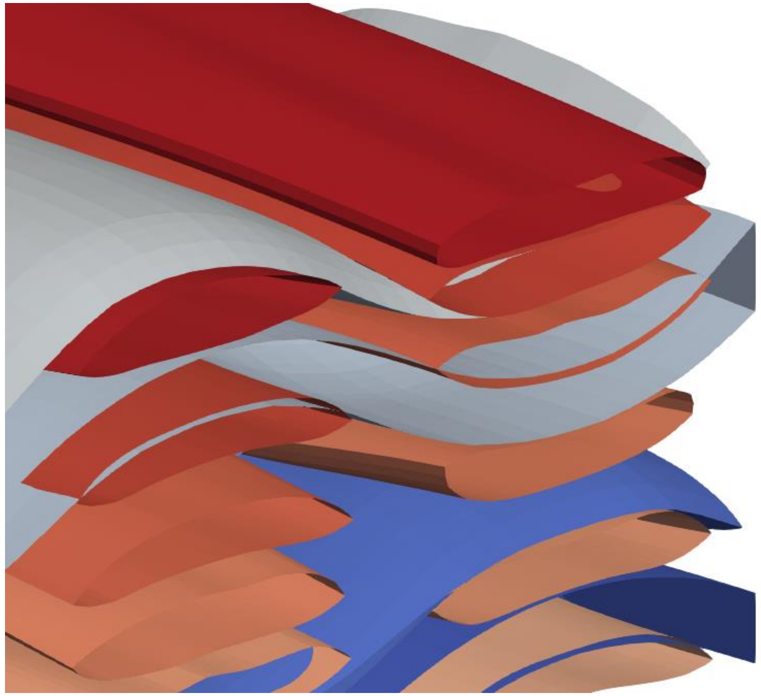
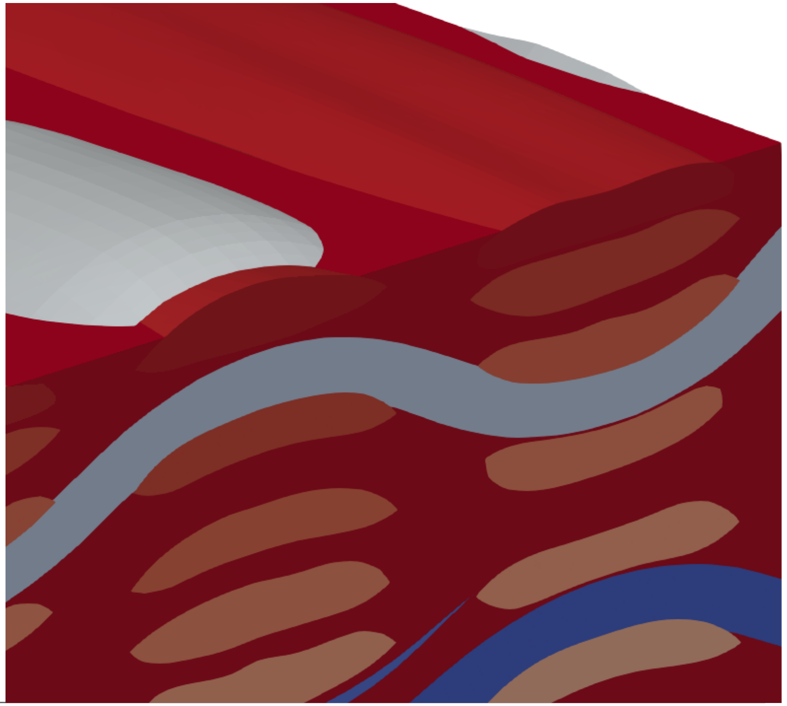
- Tows described as spline surfaces with caps
- Neat resin idealized as rectangular prism (though it leaves some tows exposed)
- Numerous regions of overlap (nearly between every close tow)
  - A few regions of overlap revealed edge case for level-set method
  - Consequently, each tow is assigned unique priority for this case study



Unique priorities result in tows cutting away from other tows



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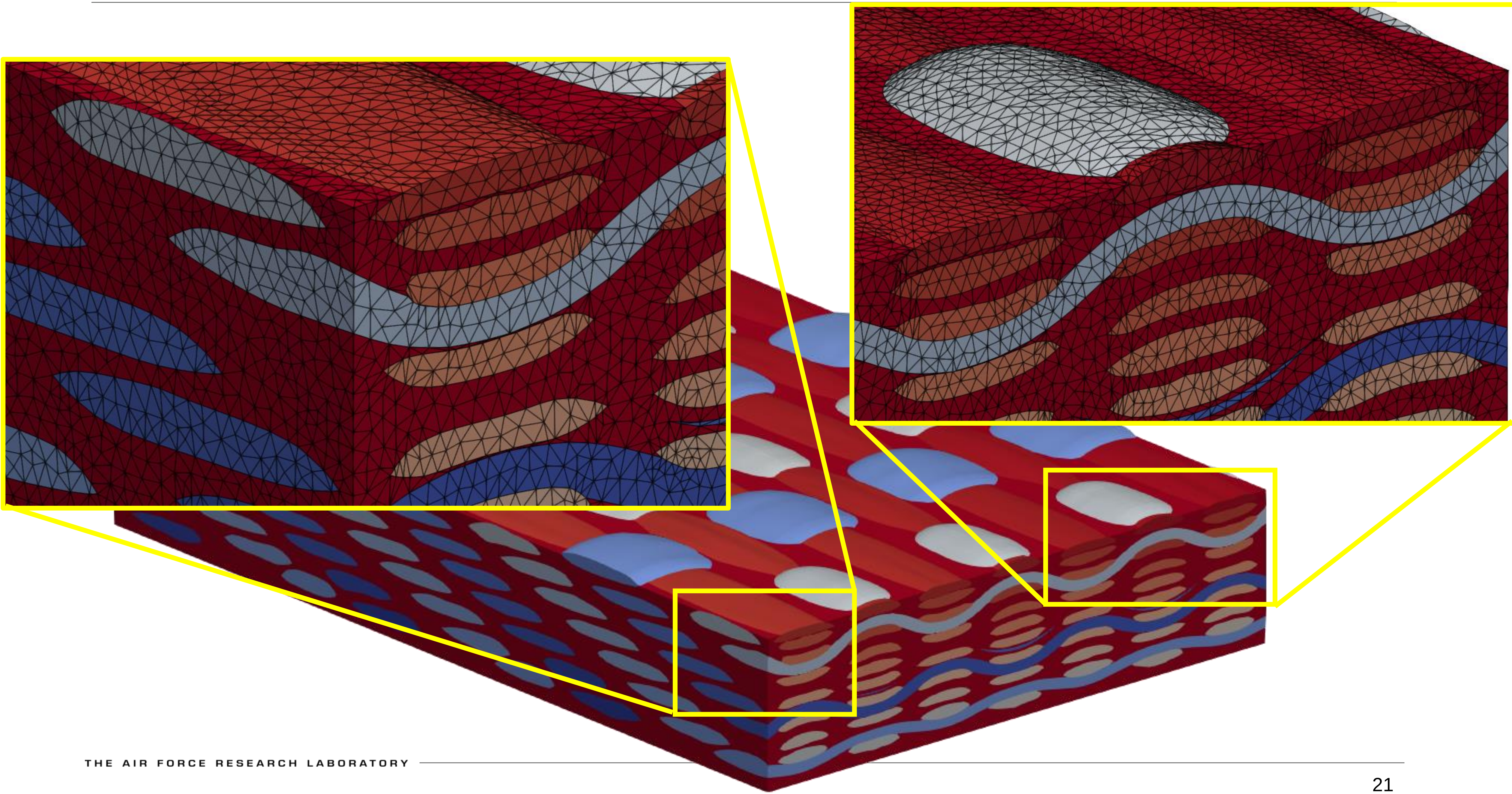
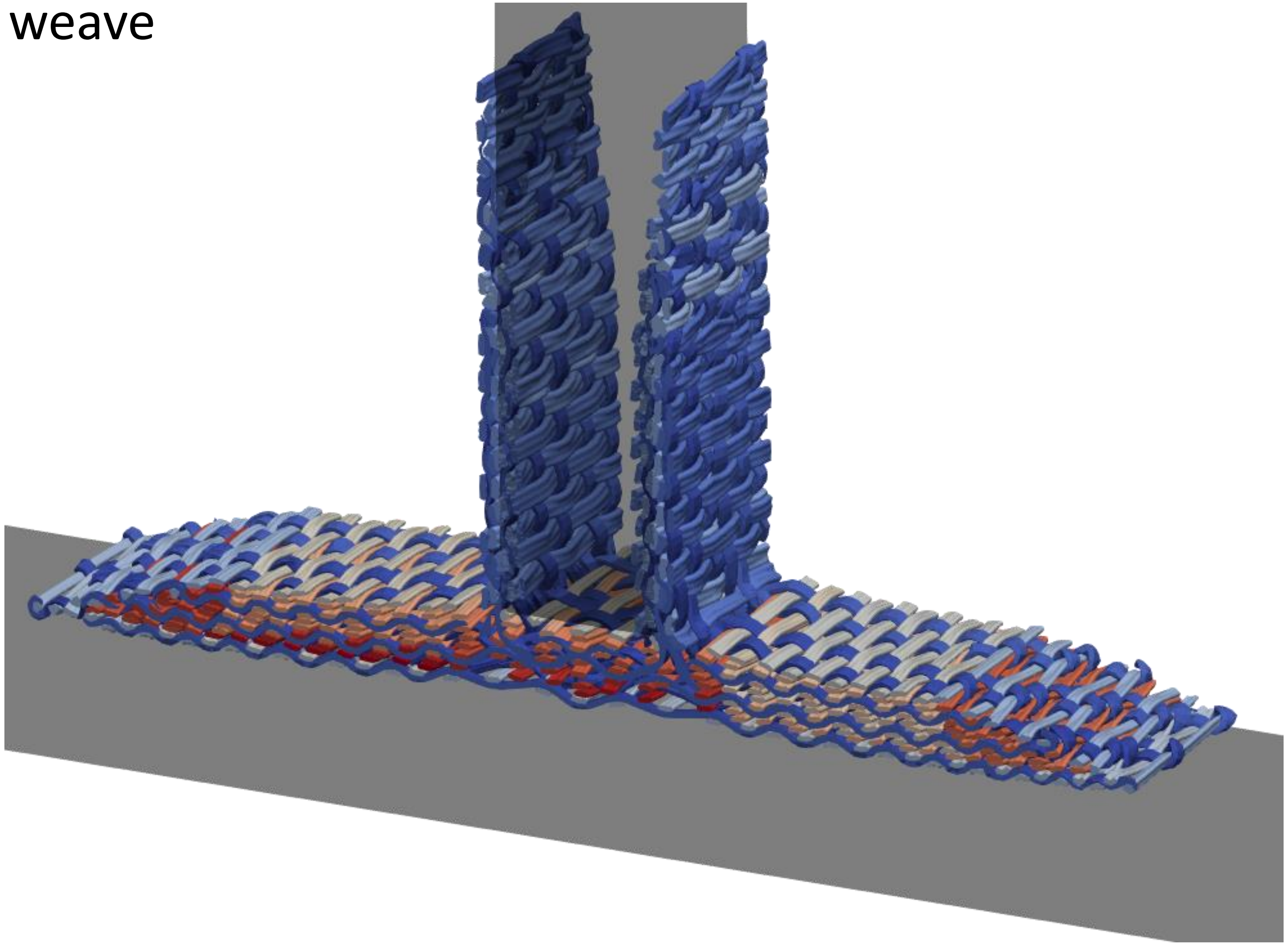


Final Thoughts

- Simulating more complex mesostructures requires advances in mesh generation, performance prediction, visualization, and post-processing
- Algorithm presented here provides a near complete step towards automated generation of high-quality, conforming tetrahedralizations
- Implementation is partially parallelized and tractable (a few hours for case shown on a single workstation)
- Gaps in technology that need to be addressed
  - Edge cases for method used to create conforming shared surfaces in regions of overlap (allowing tows to cut away from other tow is current workaround)
  - Edge cases for curvilinear higher order tetrahedra for curved surfaces
  - Artifacts introduced by fTetWild
- Ready to distribute tool to users within the next year
  - Still deciding if how we want to license it given dependencies
- We are aiming to simulate far more complex components than have been considered before…

Current Target Problem: 3D Woven Joint

- Process simulation used to predict the tow architecture of a 3D woven joint
- Extreme number of overlapping tows
- Complex weave



Questions?