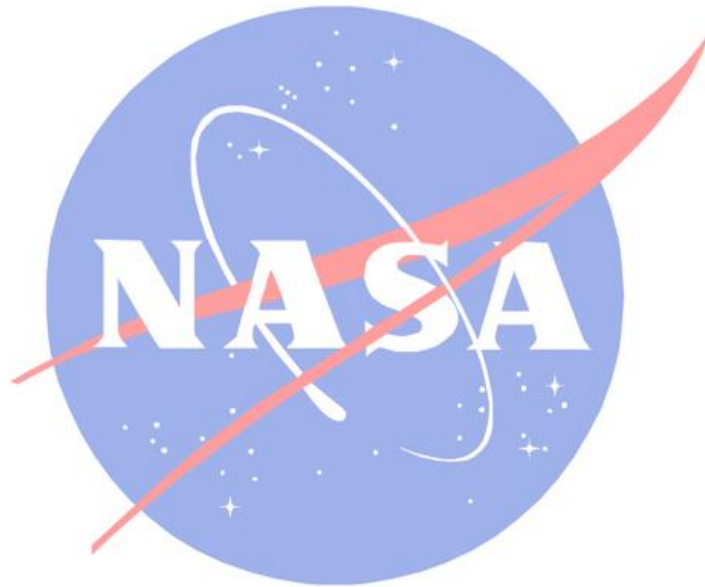
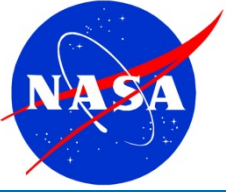


# Aeroelastic Topology Optimization of Wing Structures



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**NASA Langley Research Center**  
**Aeroelasticity Branch**



# NASA's Subsonic Fixed Wing Project



- ◆ Generational improvements in transport aircraft
  - N+1, N+2, N+3
  - Aggressive reductions in noise, emissions, and fuel burn

2008 Vehicle  
Concept Study

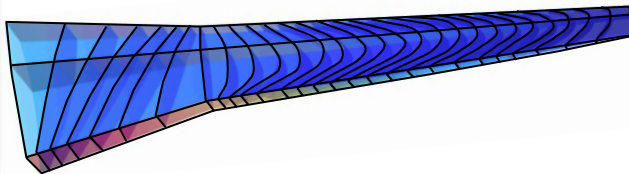


- ◆ Technological advances needed across many fronts
  - Aerodynamics, propulsion, alternative fuels, acoustics, structures
- ◆ Broad structures-centric goals (for wings):
  - Stabilize flexibility in minimum-weight wings
  - Exploit flexibility to reduce wing loading/drag via load redistribution and wing shaping

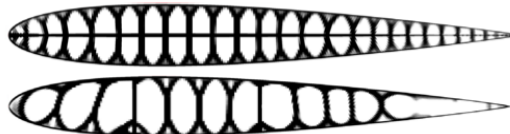
- ◆ Many ways to passively control trade-off between weight and aeroelastic performance
  - One method: identify optimal distribution of support material within a wing box (topology)

## three topology optimization activities:

location, orientation, connectivity, curvilinearity of ribs/spars/stringers?

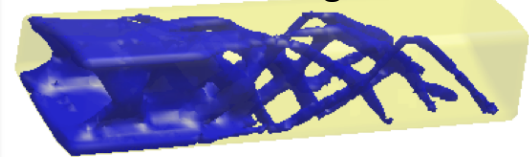


distribution of material within the shell structures?



Oktay et al., 2011

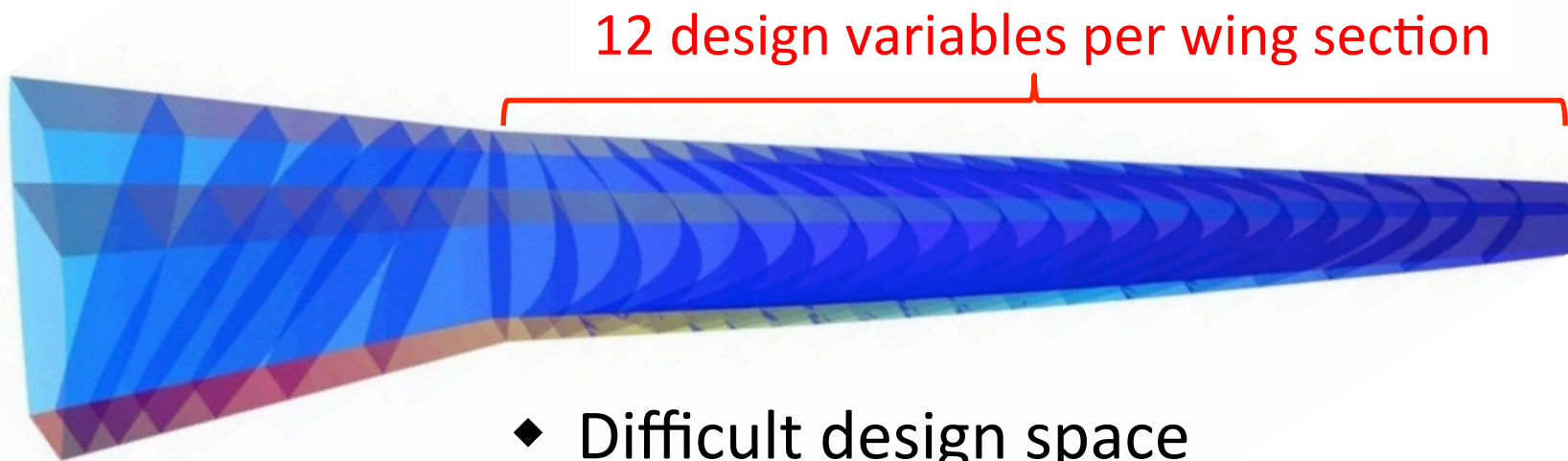
distribution of 3D material within the wing box?



K. James, U of T

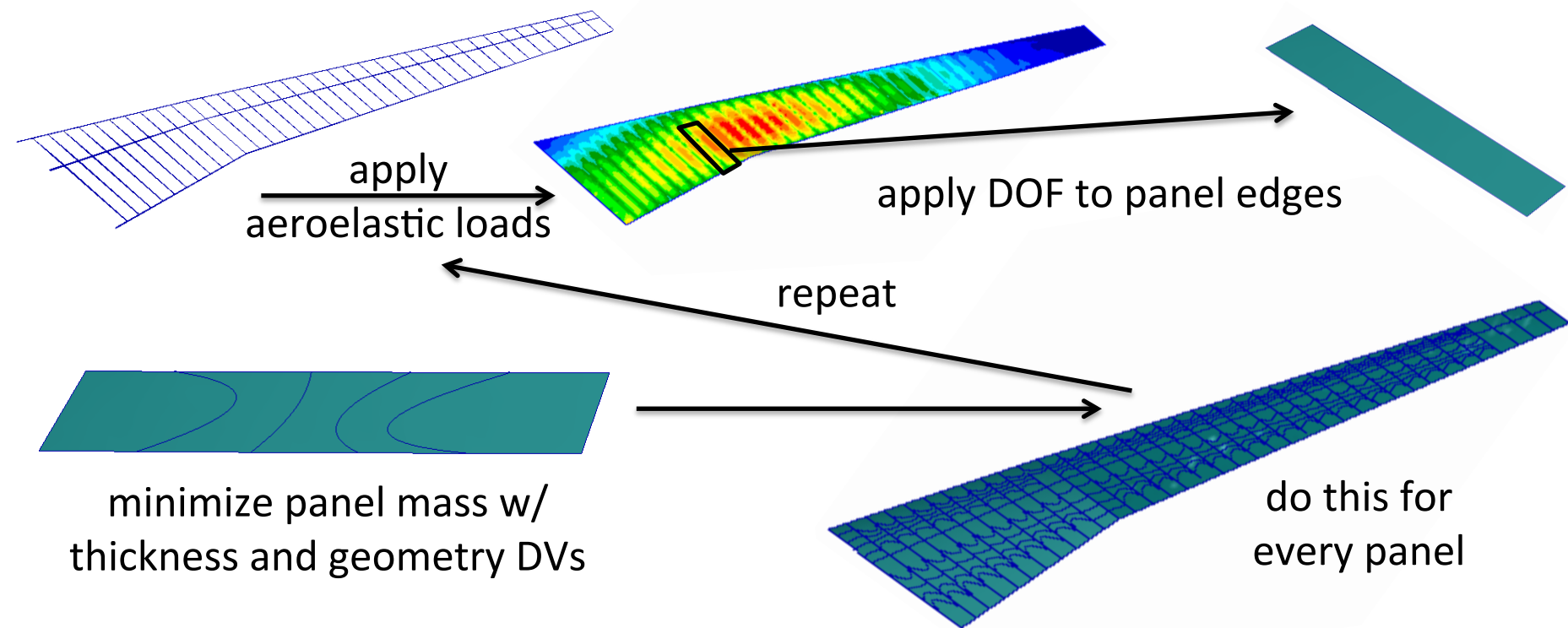
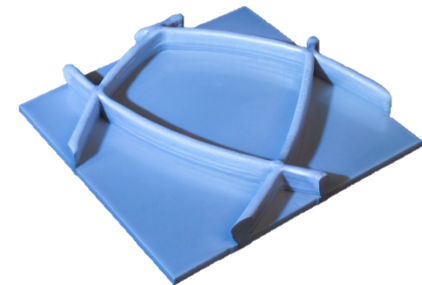
simultaneous or sequential optimization

- ◆ Parameterize number, location, and curvilinearity of ribs and spars within each wing box section
- ◆ Basic code developed by R. Kapania's group at VPI
  - Aeroelasticity added to framework by LaRC

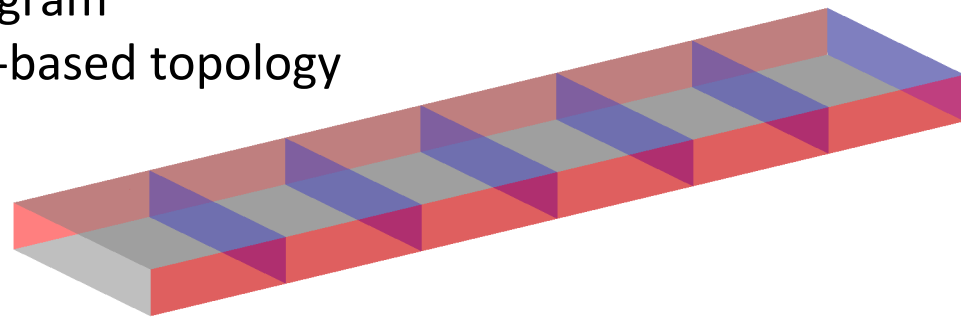


- ◆ Difficult design space
- ◆ Anything gained from curvilinearity?
  - Enabled by EBF<sup>3</sup>

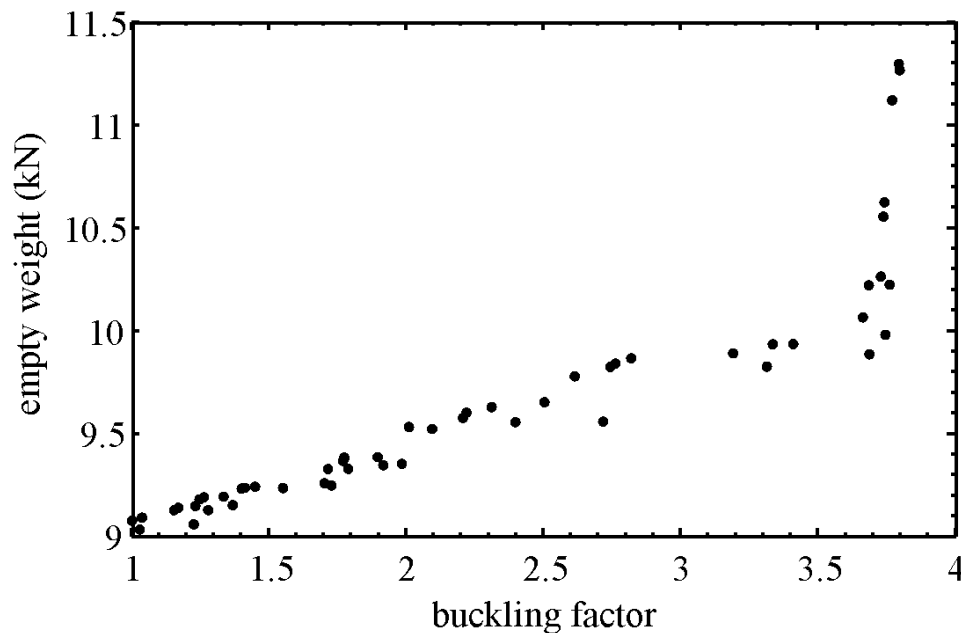
- ◆ R. Kapania's group at VPI: curvilinear stiffener placement for minimum-mass panel strength/buckling/cripling
  - Extend to entire wing?



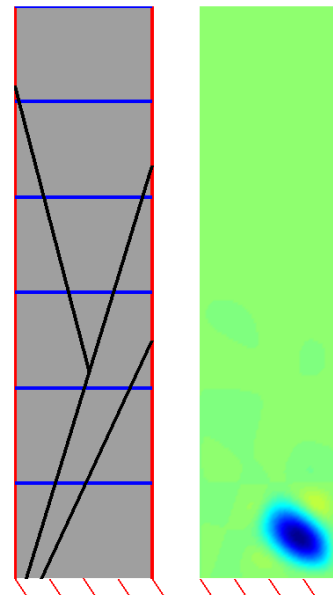
- ◆ Implicit parameterization, don't optimize topology directly
  - Optimize a “developmental program”
  - Program then creates a cellular-based topology
  - M. Kobayashi, U. Hawaii
- ◆ Use to create skin stringers



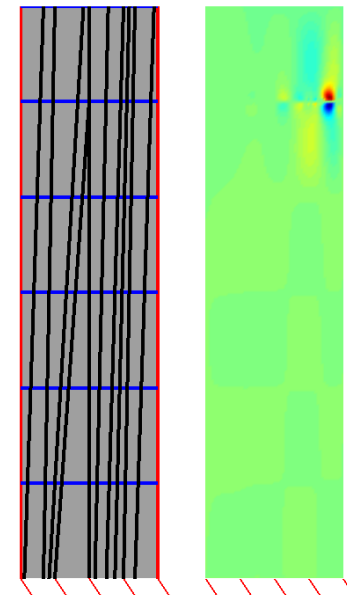
roll maneuver

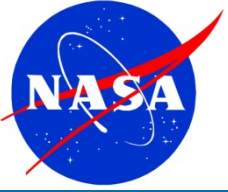


min. weight

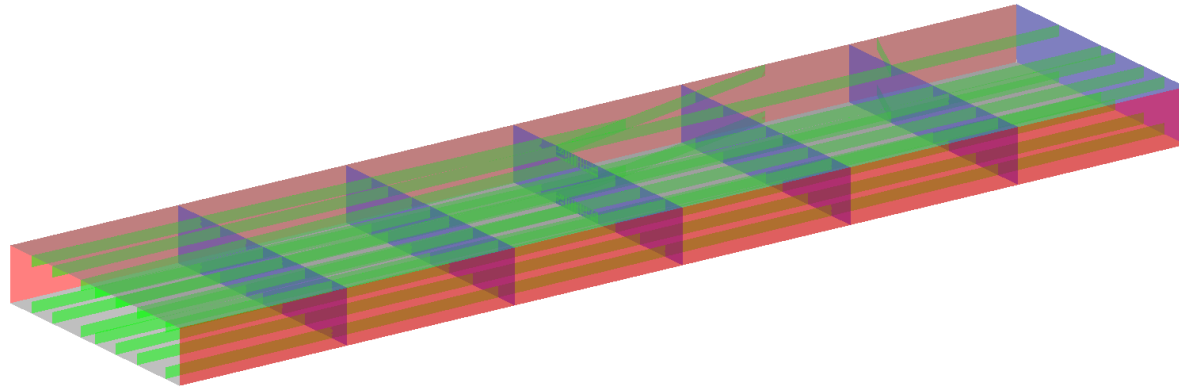


max. buckling

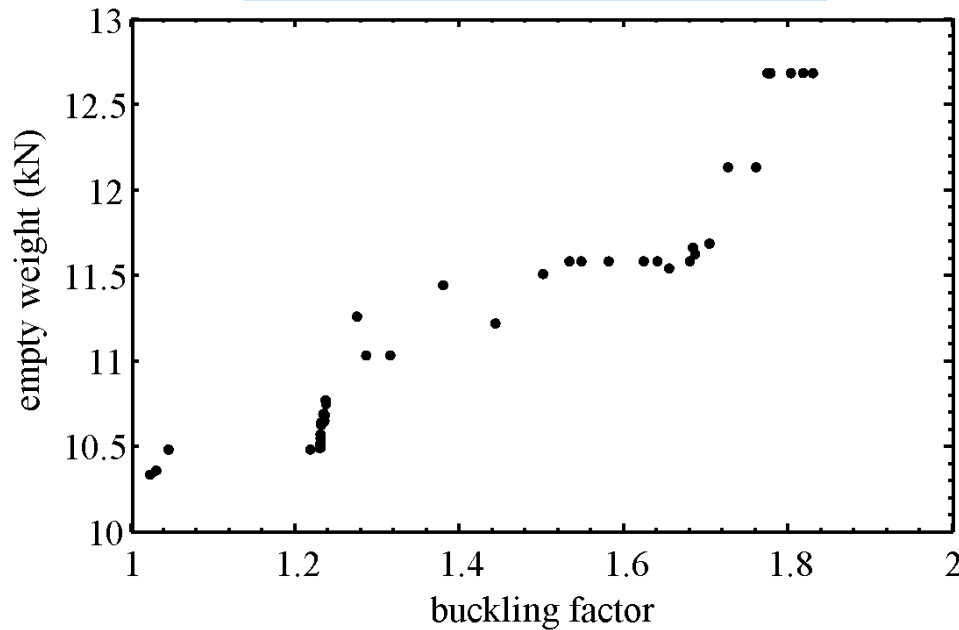




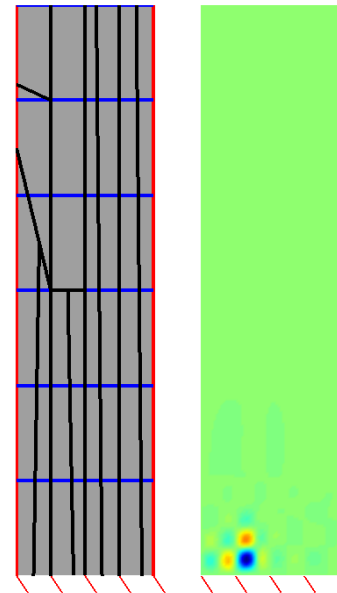
# Cellular-Based Stringer Topologies (2)



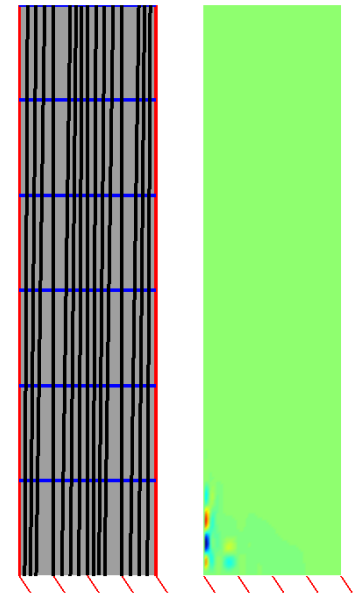
pull-up maneuver



min. weight



max. buckling





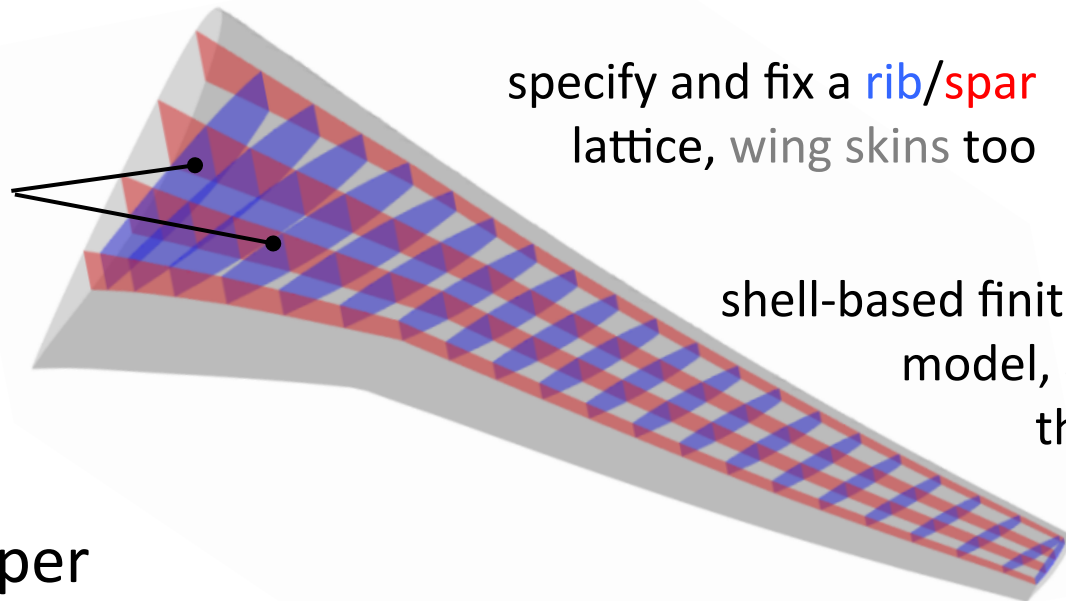
# Topology Optimization within Ribs/Spars



Conduct topology optimization within the **rib** and **spar** shell structure

specify and fix a **rib**/**spar** lattice, wing skins too

shell-based finite element model, aluminum throughout



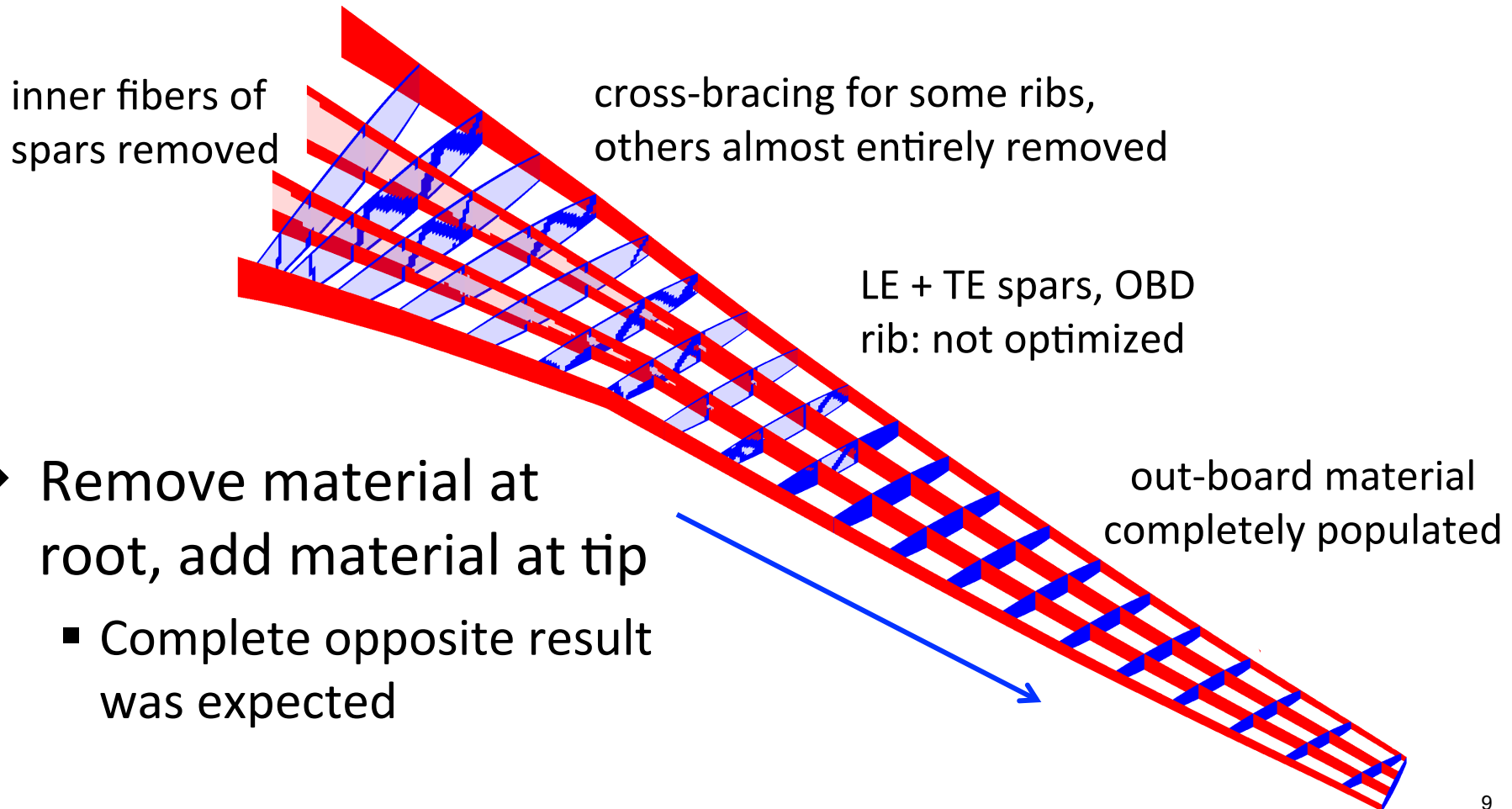
- ◆ One density DV per shell finite element
  - 0 (void) to 1 (solid)
  - Continuous design variables
  - Implicit penalty on intermediate densities



Oktay et al., 2011

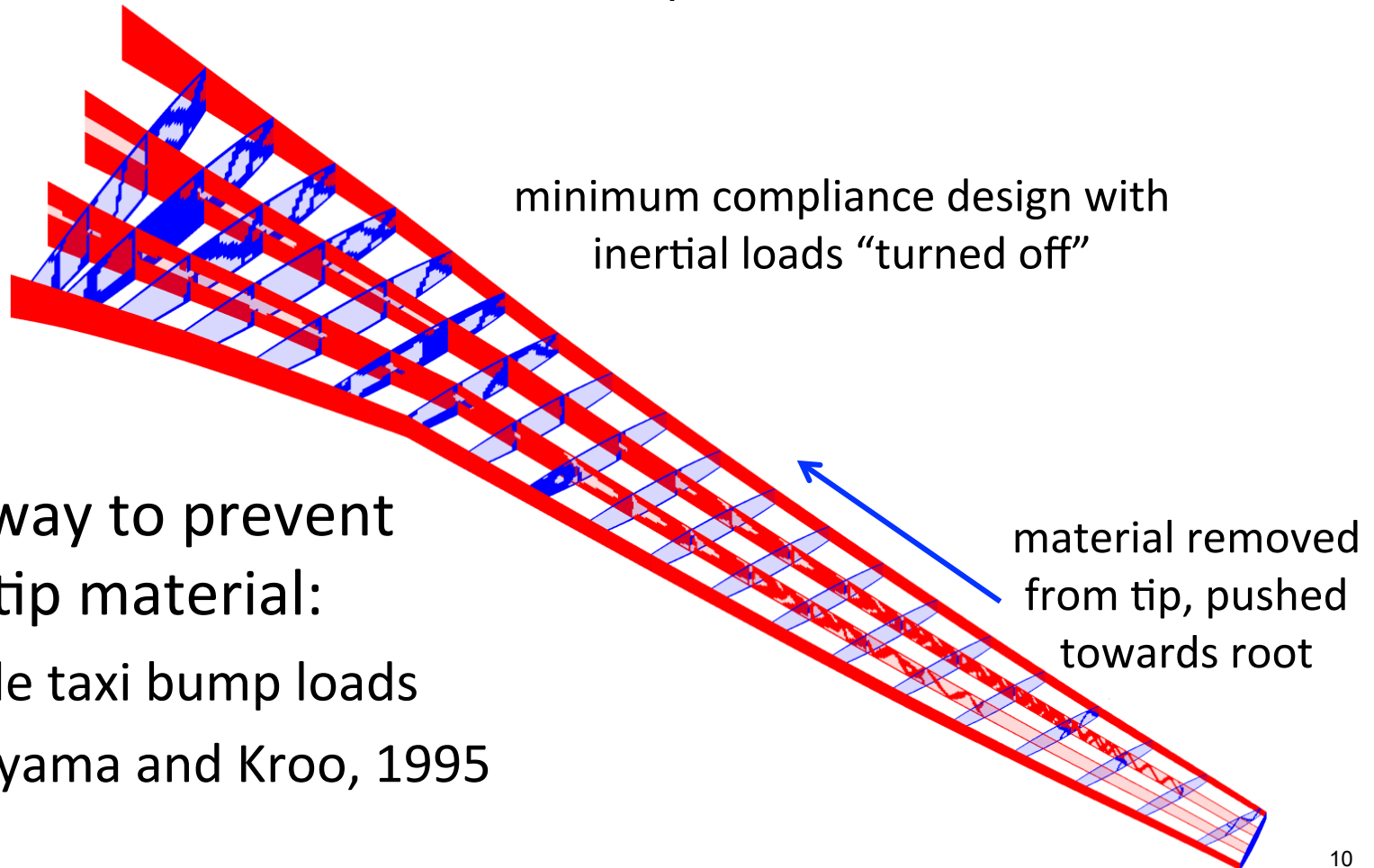


- ◆ Minimize work done by external loads: easy
  - Volume fraction = 50%



- ◆ Remove material at root, add material at tip
  - Complete opposite result was expected

- ◆ Adding mass at tip: downward inertial loads oppose upwards aero loads
  - Total load is reduced, and so is compliance



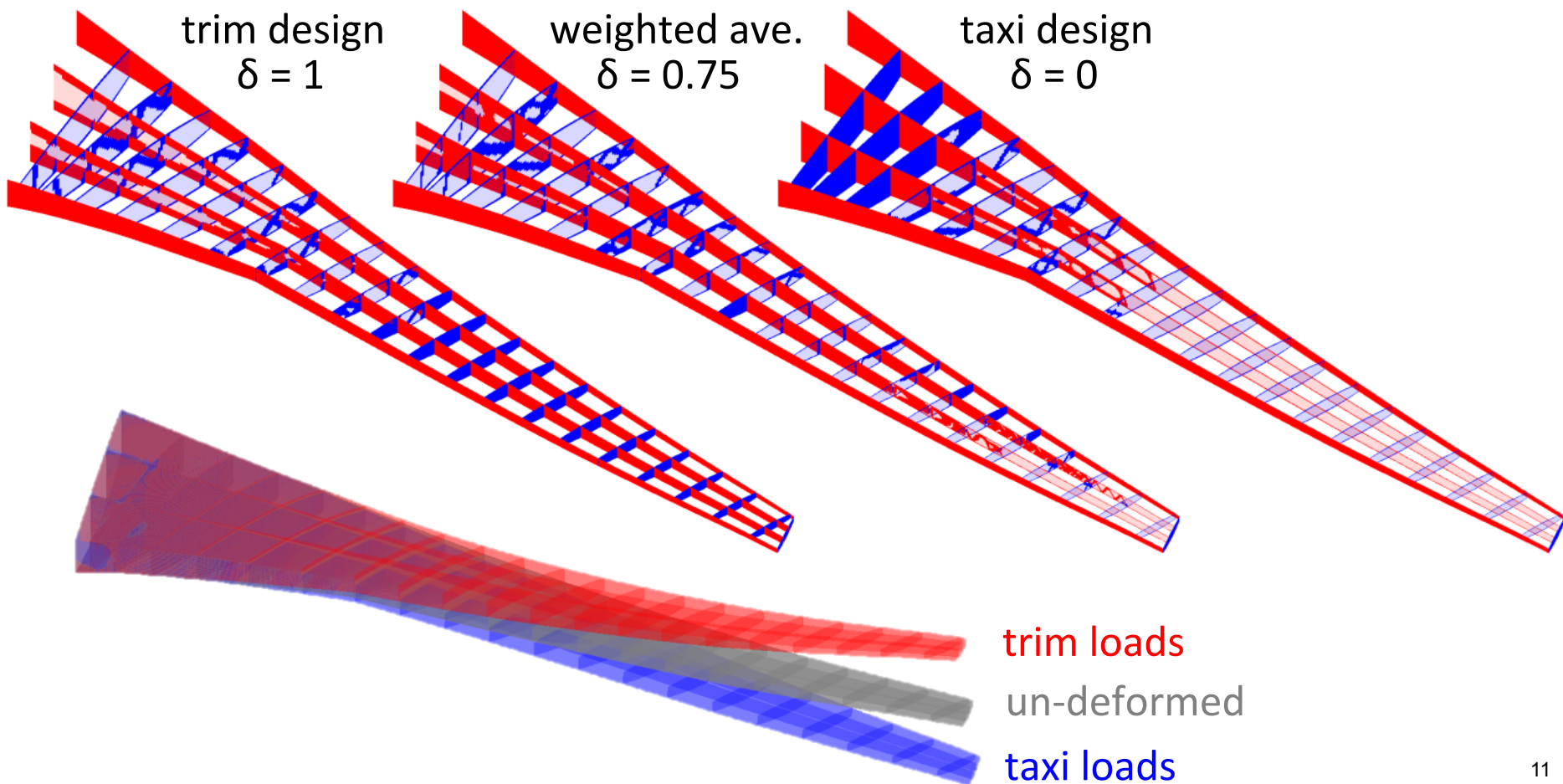
- ◆ Better way to prevent excess tip material:
  - Include taxi bump loads
  - Wakayama and Kroo, 1995



# Taxi Bump Loads



- ◆ Taxi loads: pure downward static inertial load, no aero
- ◆ Minimize weighted compliance:  $\delta \cdot C_{\text{trim}} + (1-\delta) \cdot C_{\text{taxi}}$





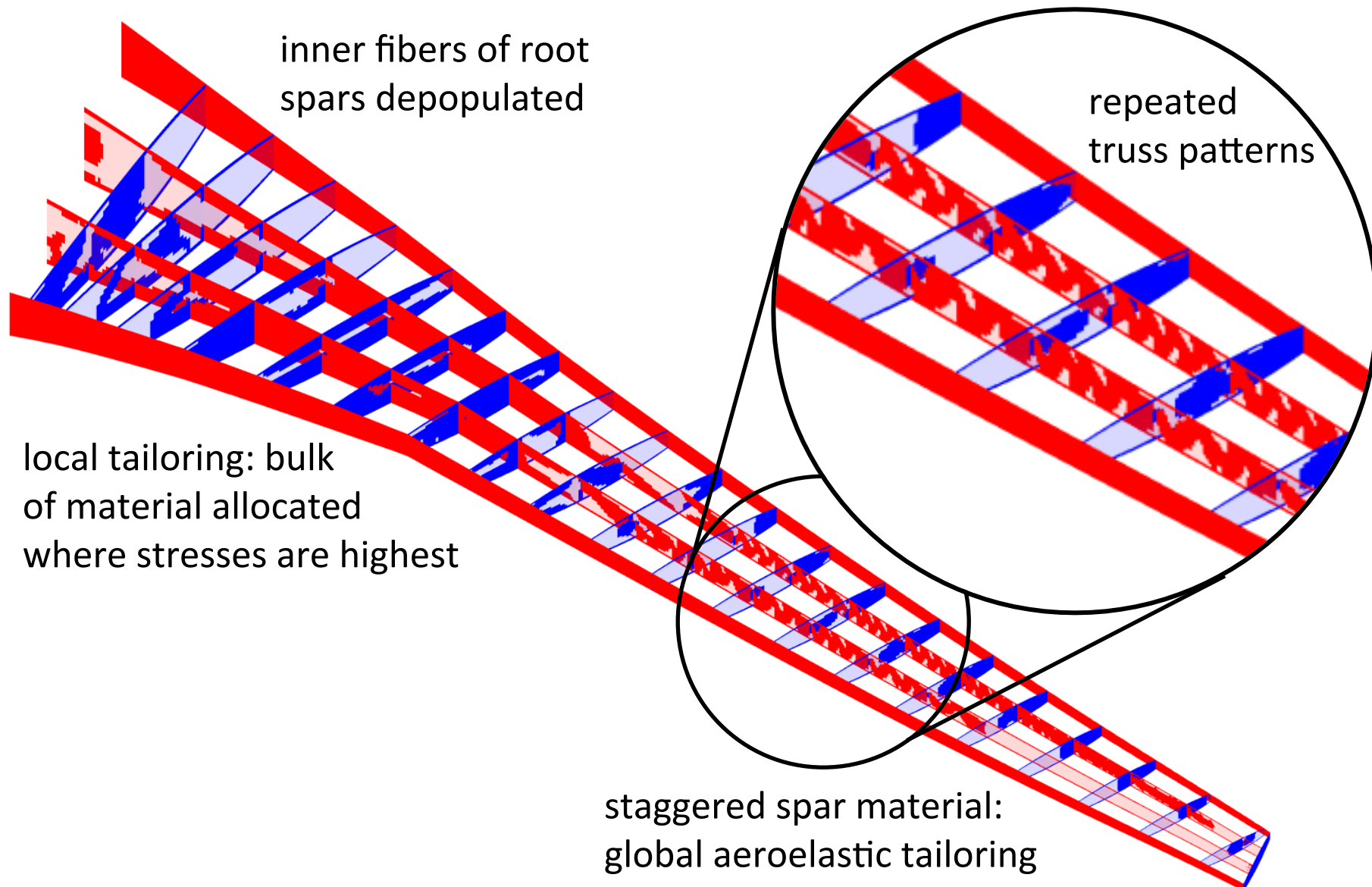
- ◆ Elastic compliance: convenient, generally gives stiff structures...
- ◆ ...but we really care about stresses
- ◆ Challenging problem:
  - Stress in each finite element needs to be monitored
  - Element with critical stress can change identity during optimization

Le et al., 2010

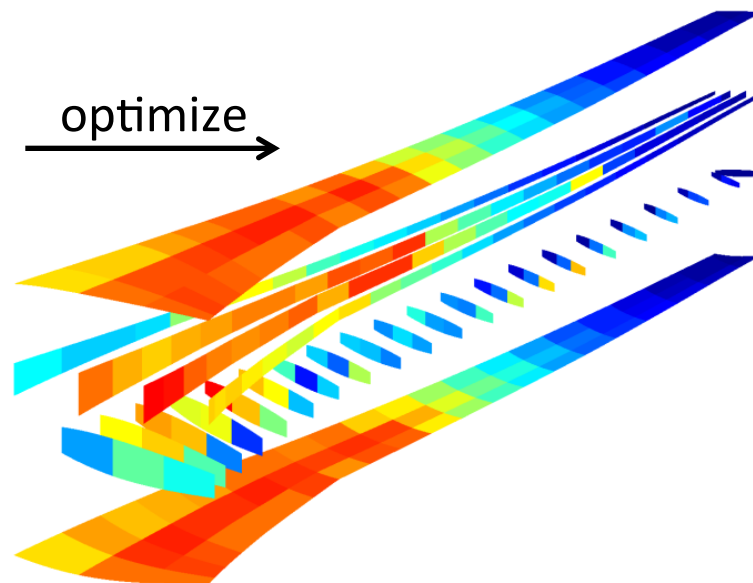
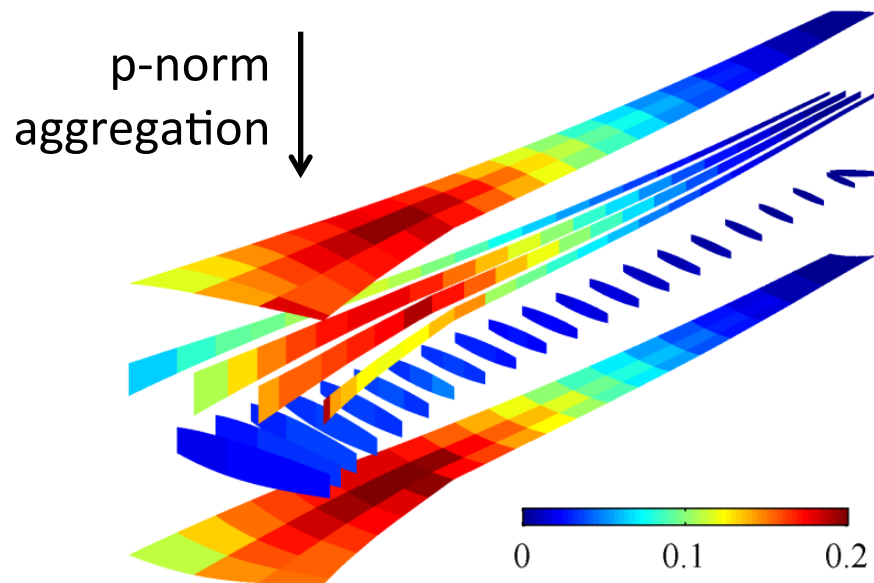
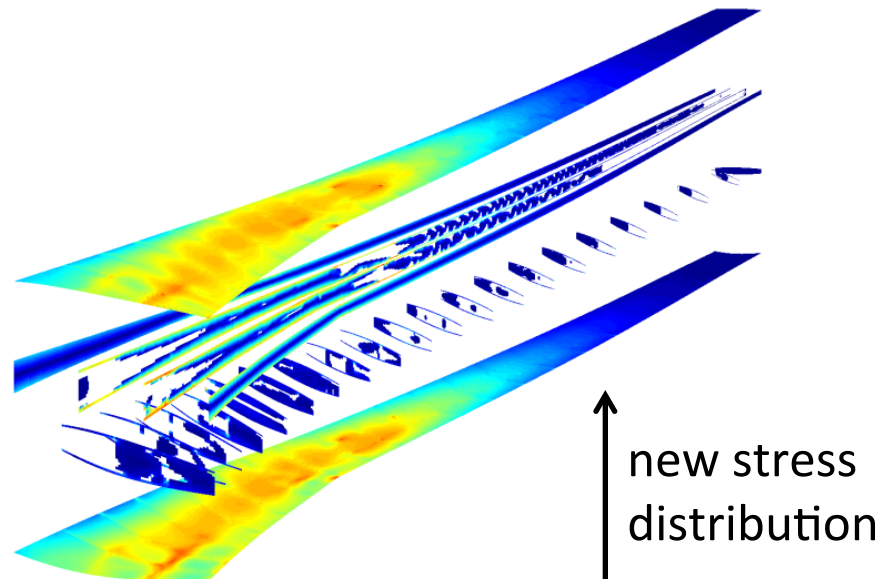
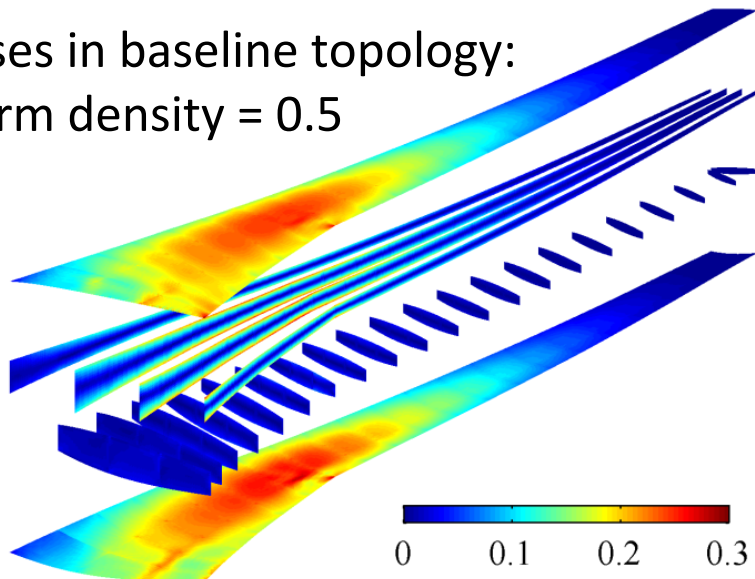
1. relax element stresses  
based on density:  
 $f = VM * \text{density}^{0.5} / \text{yield}$

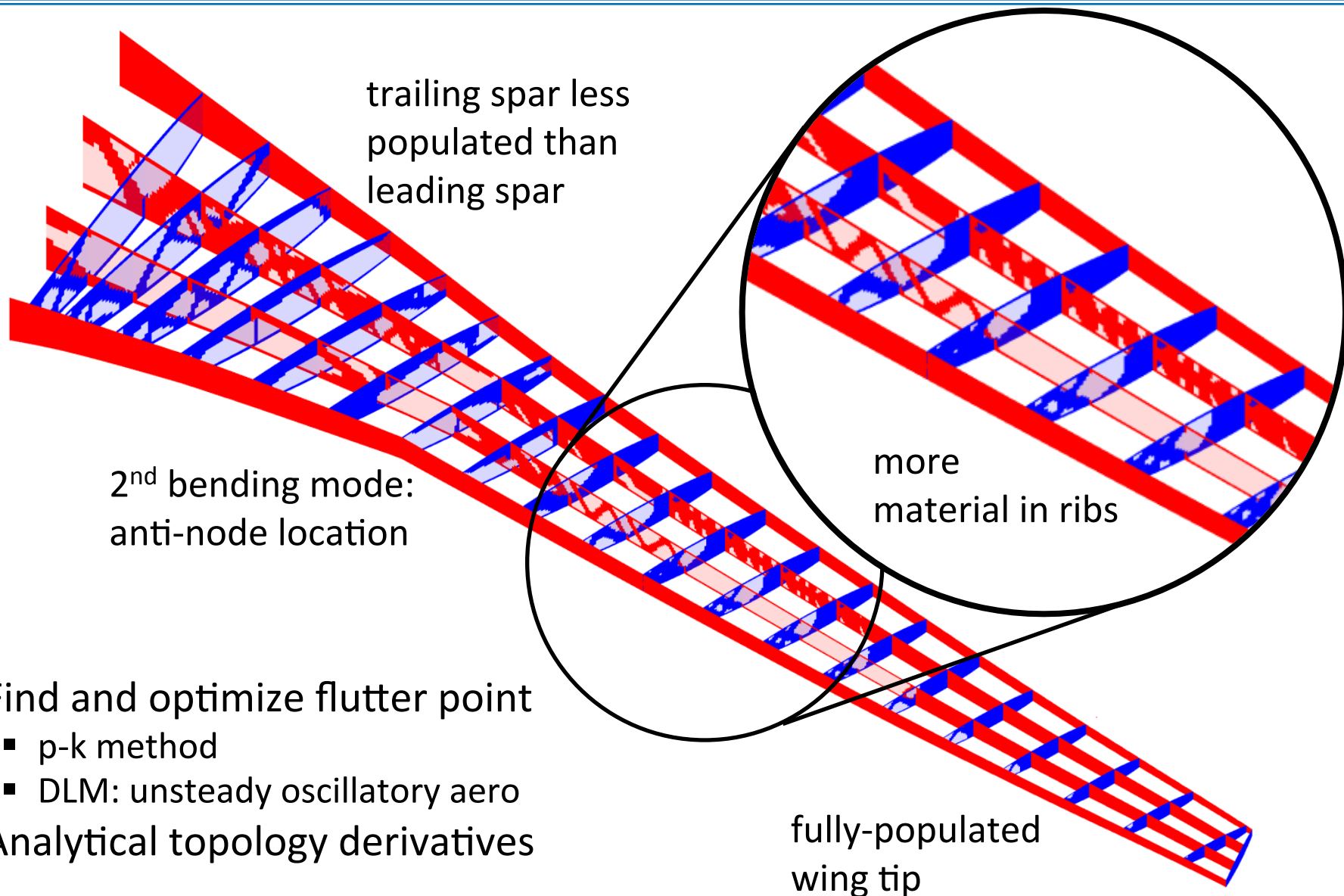
2. group finite elements  
into zones: p-norm stress  
aggregate for each

3. bound method: minimize the maximum  
p-norm (with volume constraint)



stresses in baseline topology:  
uniform density = 0.5

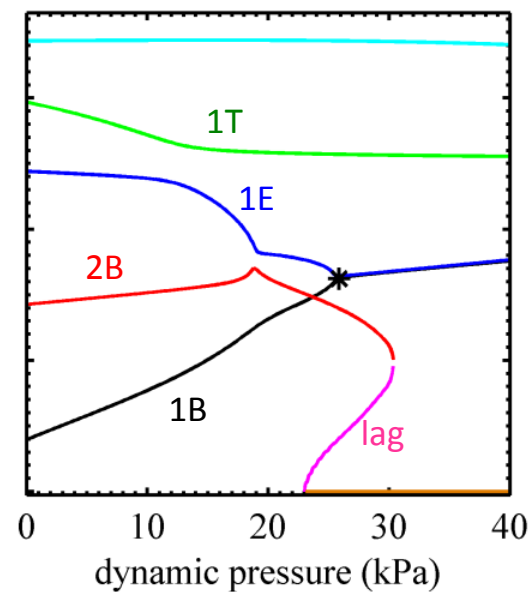
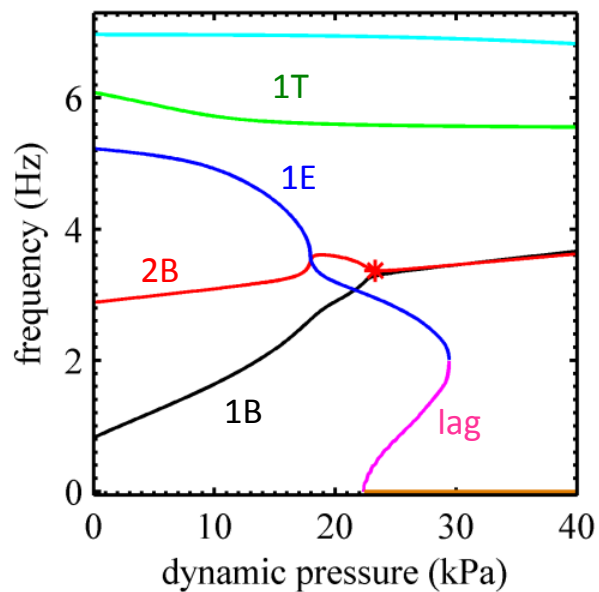
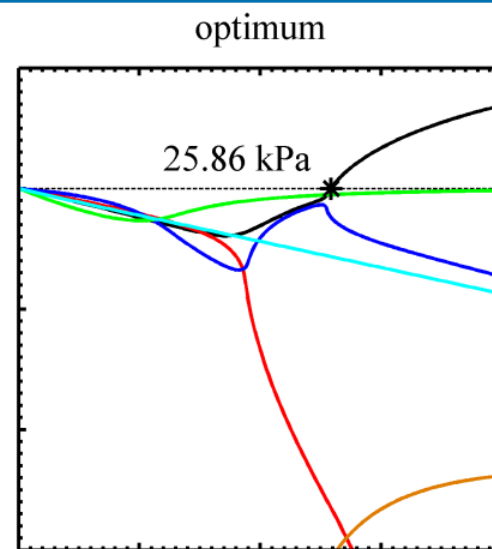
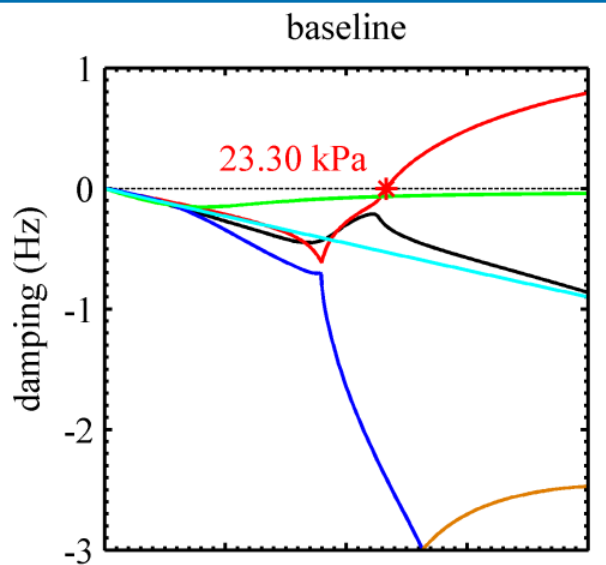




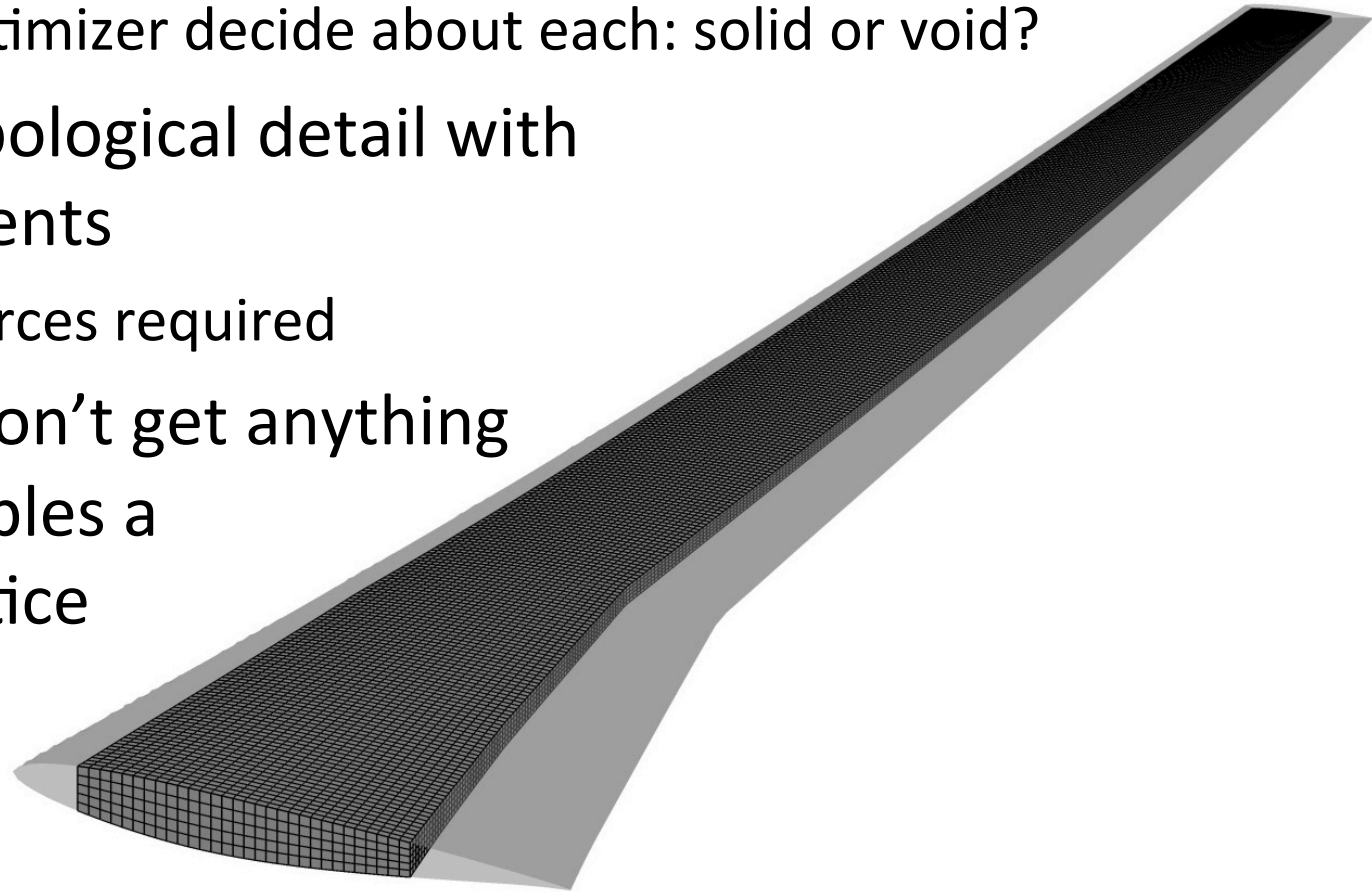
- ◆ Find and optimize flutter point
  - p-k method
  - DLM: unsteady oscillatory aero
- ◆ Analytical topology derivatives



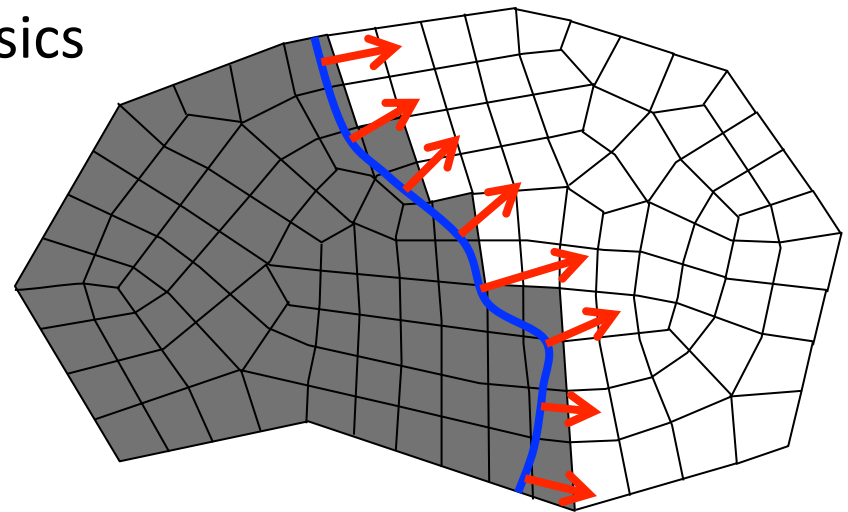
# Eigenvalue Migration



- ◆ Remove the underlying spar-rib concept
- ◆ Fill the wing box with tiny brick elements
  - Let the optimizer decide about each: solid or void?
- ◆ Greater topological detail with more elements
  - HPC resources required
- ◆ Probably won't get anything that resembles a spar-rib lattice
  - Why?

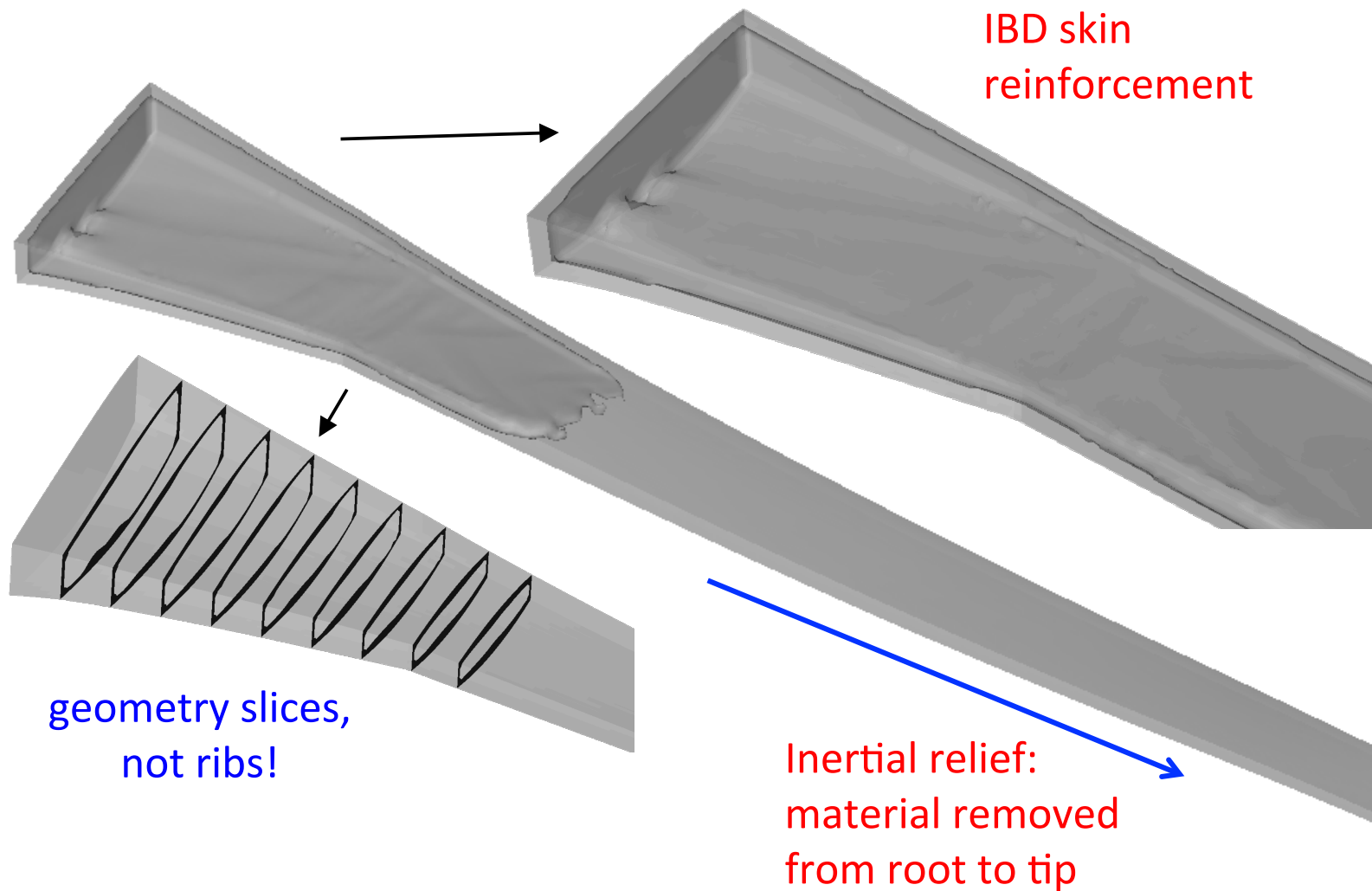


- ◆ Two approaches to this problem:
  1. One DV-per-FE method (voxels, rather than pixels)
  2. Level set methods: topological boundary “flows” through design domain
    - Pseudo-time: optimization iteration number
    - Velocity along the propagating front driven by aeroelastic physics
    - Resulting topology has no intermediate densities (all 0’s and 1’s)
- ◆ Peter Dunning (NIA),  
Alicia Kim (U. Bathe)





# Aeroelastic Trim Results

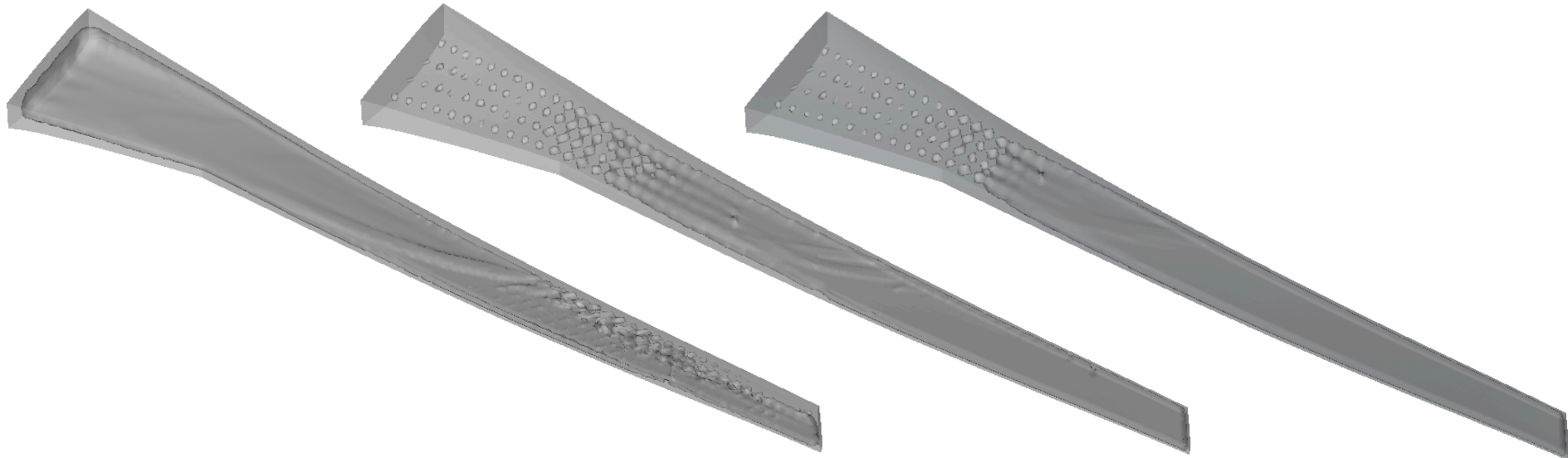


- ◆ Minimize weighted compliance:  $\delta \cdot C_{\text{trim}} + (1-\delta) \cdot C_{\text{taxi}}$
- ◆  $C_{\text{trim}}$ : compliance during aeroelastic trim
- ◆  $C_{\text{taxi}}$ : compliance during taxi bump

$\delta = 0.75$

$\delta = 0.50$

$\delta = 0.25$





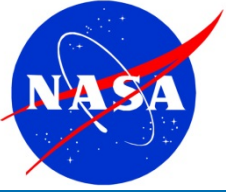
- ◆ Topology optimization: most hands-off method of structural design
  - For better or worse
- ◆ Non-conventional structural reinforcement within wing box:

interesting new  
direction for optimal  
aeroelastic wings?



optimizer exploiting  
gaps in physics/fidelity/  
problem definition?

- ◆ Improve quality of results by:
  1. Consider numerous aeroelastic/performance metrics, all at once
  2. Consider numerous load cases, all at once
  3. Consider numerous tailoring/optimization schemes, all at once
- ◆ Current work:
  - Identified several promising topological parameterizations
  - Obtained cleanly-resolved (but preliminary) topologies driven by complex aeroelastic physics



# Questions?



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