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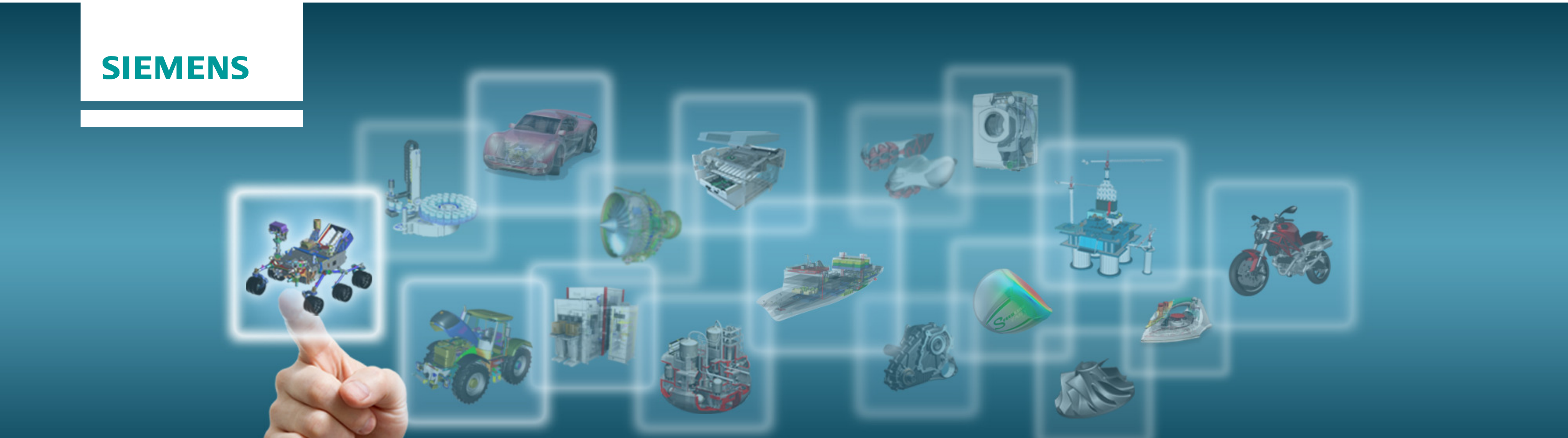

American Society of Composites 29th technical Conf., 16th US-Japan Conf. on Composite Materials, San Diego, USA, September 10, 2014

Reducing overdesign with predictive performance and producibility simulation

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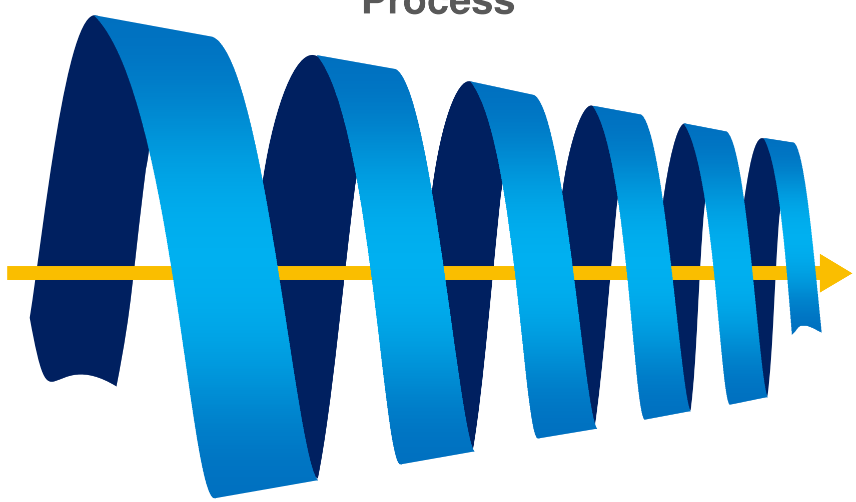
Smarter decisions, better products.

Problem Statement

Inputs

- Idealized fiber orientations
- Simplified draping
- Uniform mechanical properties
- Large material knockdowns

Process



Outputs

- Increased weight
- Increased material cost
- Increase production cost

Overdesign adds weight, cost and structural errors due to stiffness that defeat the rationale for designing with composite materials. Can overdesign of composite products be reduced or eliminated by discontinuing the use of simplifying assumptions in analysis and development?

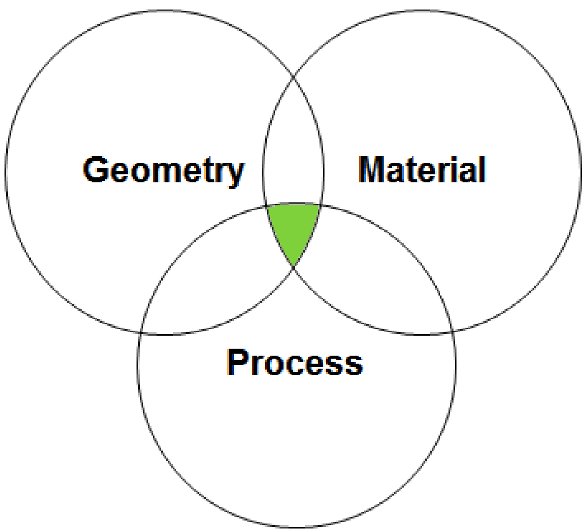
How to reduce overdesign

How to reduce the overdesign of composite structures:

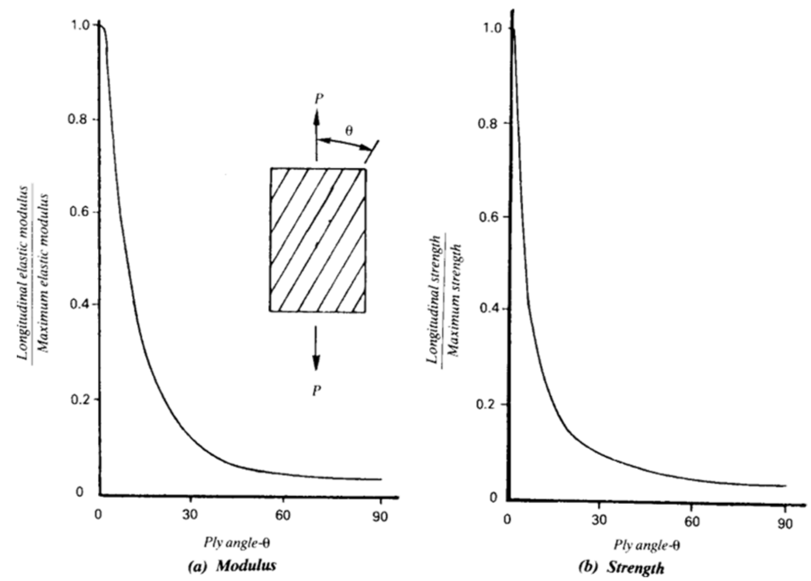
- Be sure about the local fiber orientations, and not just rely on theoretical orientations
- Use optimization methods, in order to minimize the weight while satisfying mechanical performances and manufacturing limitations
- Use accurate and tight safety margins, identified by using non linear analysis in order to reproduce in the the most reliable way the real behavior of the composite structures, including geometric non linearities and damage modes
- Eliminate data exchange interoperability issues between analysis and design to achieve optimization loops that are efficient and cost effective

How to reduce the overdesign of composite structures:

- Be sure about the local fiber orientations, and not just rely on theoretical orientations
  - Combination of geometry, material and production process are required



Fiber misalignment has a significant impact on modulus and strength

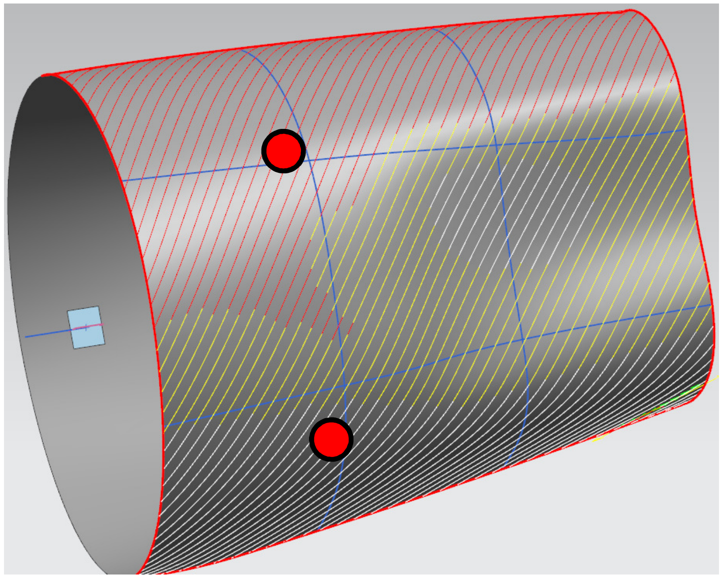


Courtesy Michael Chun-Yung Niu, Lockheed Aeronautical Systems

How to reduce the overdesign of composite structures:

- Be sure about the local fiber orientations, and not just rely on theoretical orientations

Red fibers exceed the maximum fiber misalignment tolerance of 10°, yellow are between 7-10° and white are under 7°



Example: first 8 plies [90/-45/0/-45/-45/-45/90/-45]

Name	Actual Fiber Direction	
	Warp	Weft
P001	86.294620	N/A
P002	-52.024802	N/A
P003	-6.987920	N/A
P004	-52.329214	N/A
P005	-51.729627	N/A
P006	-52.752939	N/A
P007	86.360444	N/A
P008	-51.729627	N/A

How to reduce the overdesign of composite structures:

- Use optimization methods, in order to minimize the weight while satisfying mechanical performances and manufacturing limitations
    - Possibility to determine optimal stacking sequence tables, satisfying the ply continuity constraint over the regions

Composite structure, with regions of different thickness

Optimisation

Corresponding optimal stacking sequence table; for one total thickness the stacking sequence is known

Plies orientation

35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
-45																																		
-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45																						
-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45												
-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45																		
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0																				
-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45	-45											
-45	-45																																	
90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90										
45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45									
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0								
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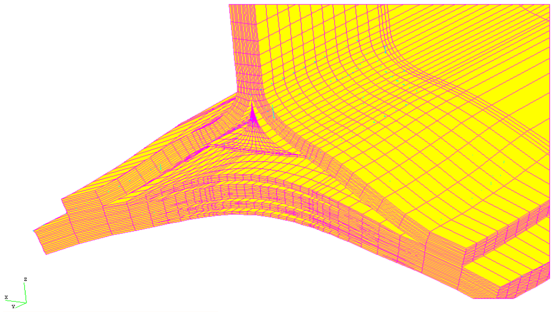
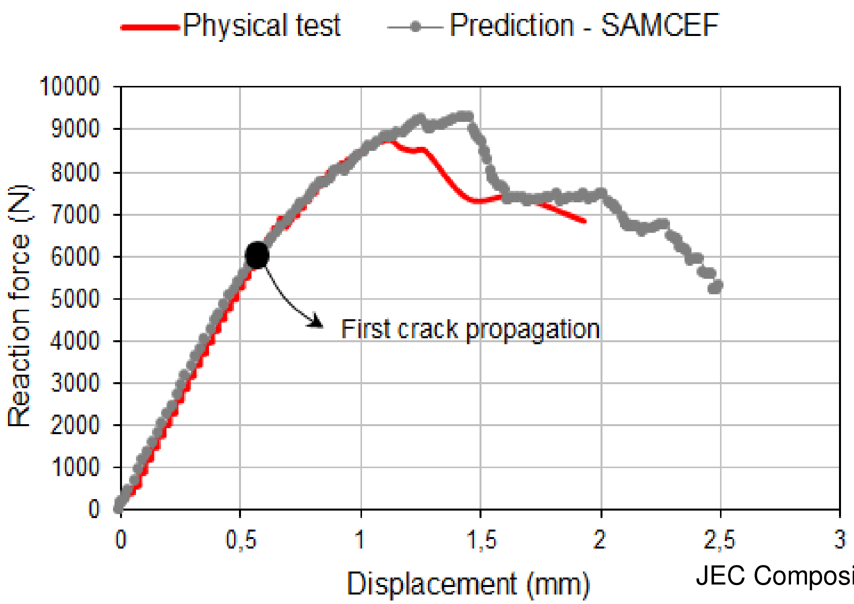
How to reduce the overdesign of composite structures:

- Use accurate and tight safety margins, identified by using non linear analysis in order to reproduce in the the most reliable way the real behavior of the composite structures, including geometric non linearities and damage modes
  - Accurate material allowables determined with non-linear analysis





JEC Composite Magazine, 90, 2014

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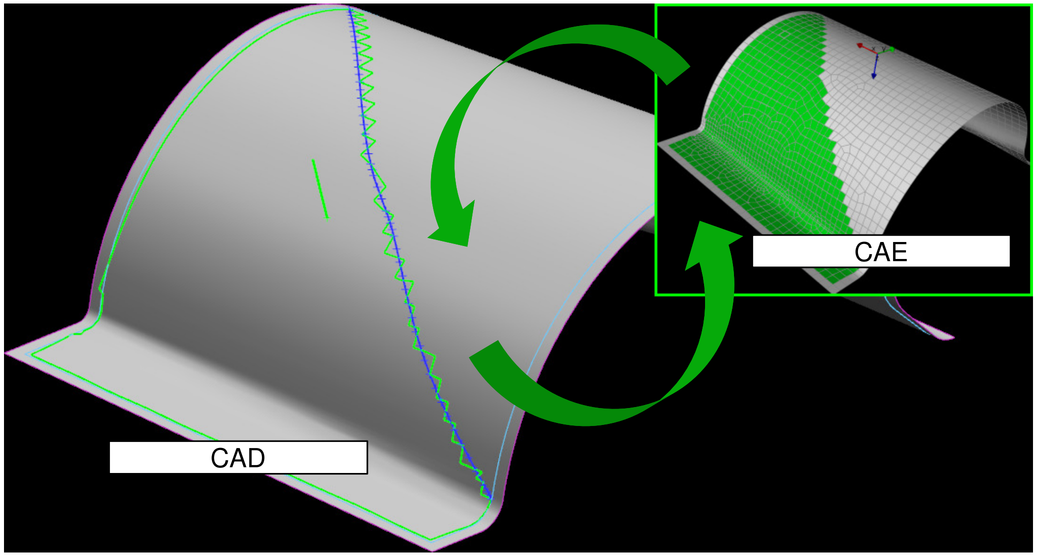
How to reduce the overdesign of composite structures:

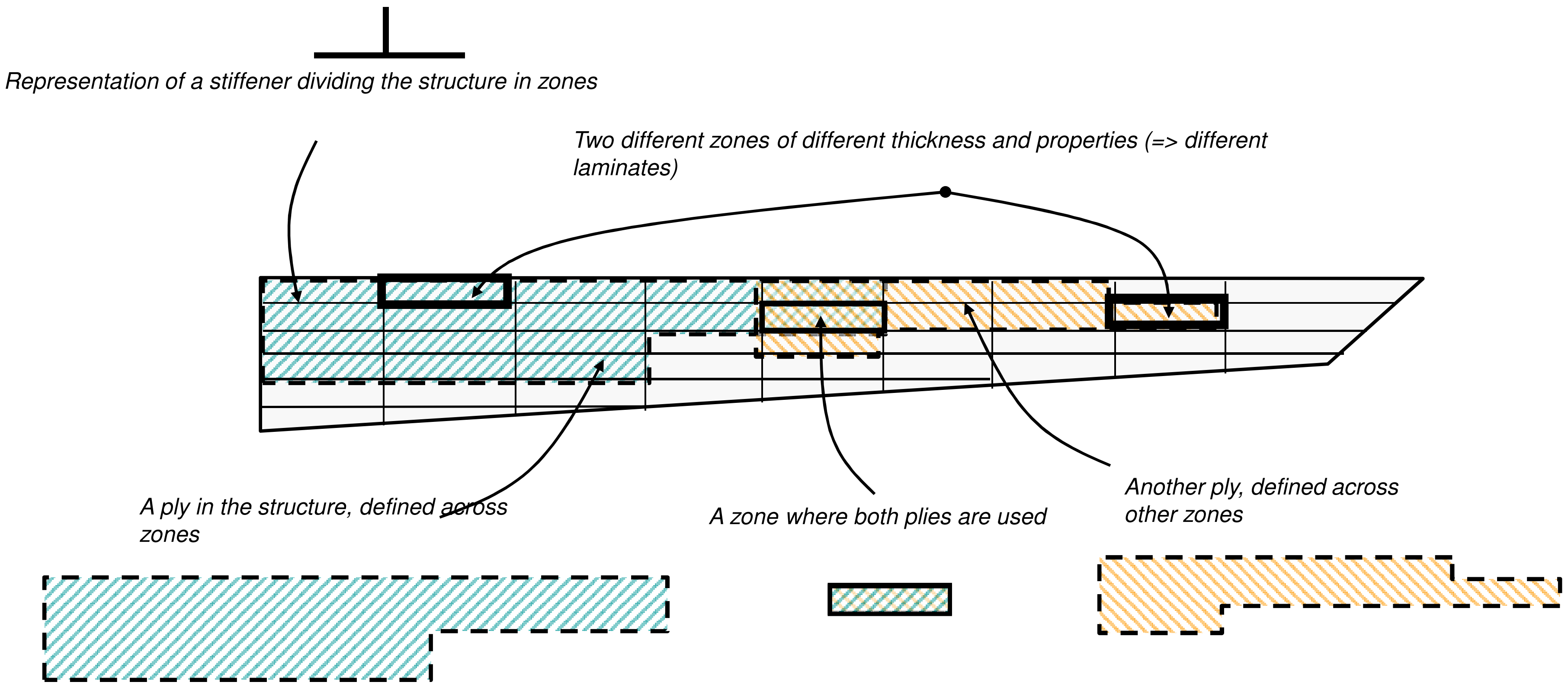
- Eliminate data exchange interoperability issues between analysis and design to achieve optimization loops that are efficient and cost effective
    - Effective data exchange between analysis and design for manufacturing solutions.



JEC Composite Magazine, 90, 2014

Composite structures optimization: problem statement

Stacking sequences optimization with conventional orientation 0, 45, -45 and 90

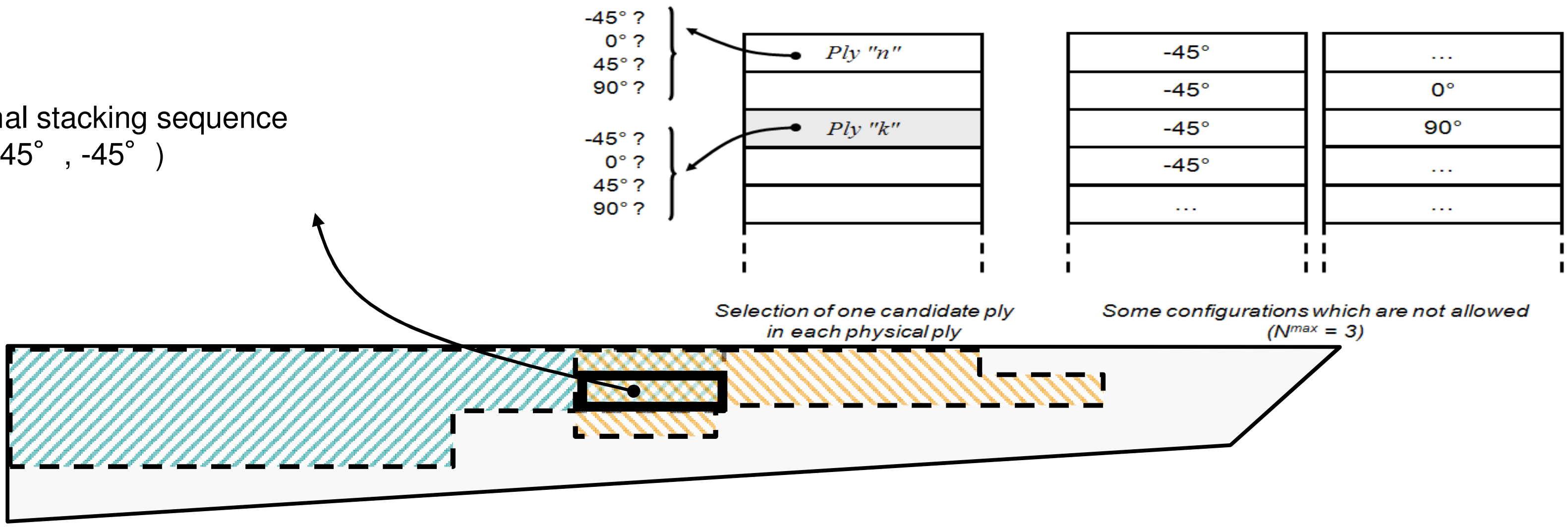


Composite structures optimization: problem statement

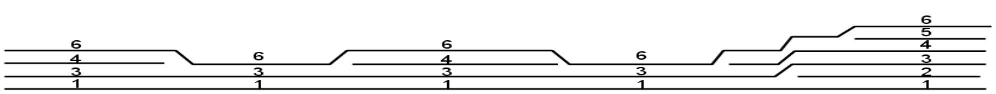
Stacking sequences optimization with conventional orientation 0, 45, -45 and 90

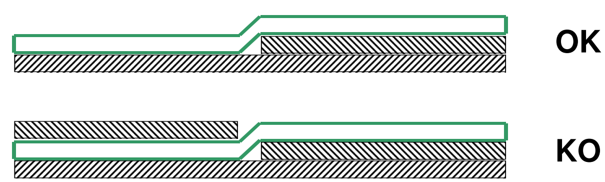
In each zone, optimal stacking sequence (plies at 0° , 90° , 45° , -45°)

Design rules



Across the zones, **manufacturing constraint** (ply continuity,blending)



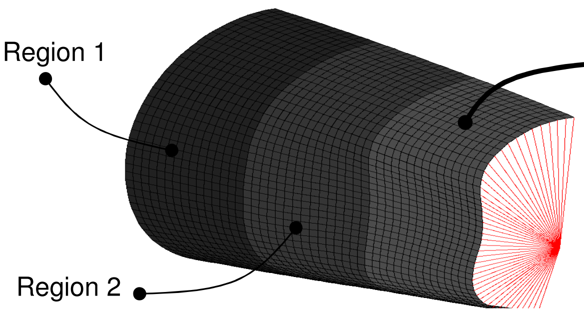


Structural optimization: general methodology

2-step procedure, chaining

- **STEP 1**: optimization with continuous design variables: determine local thickness and optimal proportions of 0, 45, -45, 90 in each region
- Rounding: ply thickness => corresponding number of plies
- **STEP 2**: optimization with discrete design variables: local stacking sequences + blending (ply continuity across the regions)
  - No more than 4 plies with the same orientation
  - Symmetric laminate
  - Keep the imposed proportions of each orientation (input from step 1)
  - 0/90 and 45/-45 sequences forbiden

Design rules



$t_{region3\_0deg}$?
$t_{region3\_45deg}$?
$t_{region3\_90deg}$?

$N_{region3\_0deg}$?
$N_{region3\_45deg}$?
$N_{region3\_90deg}$?

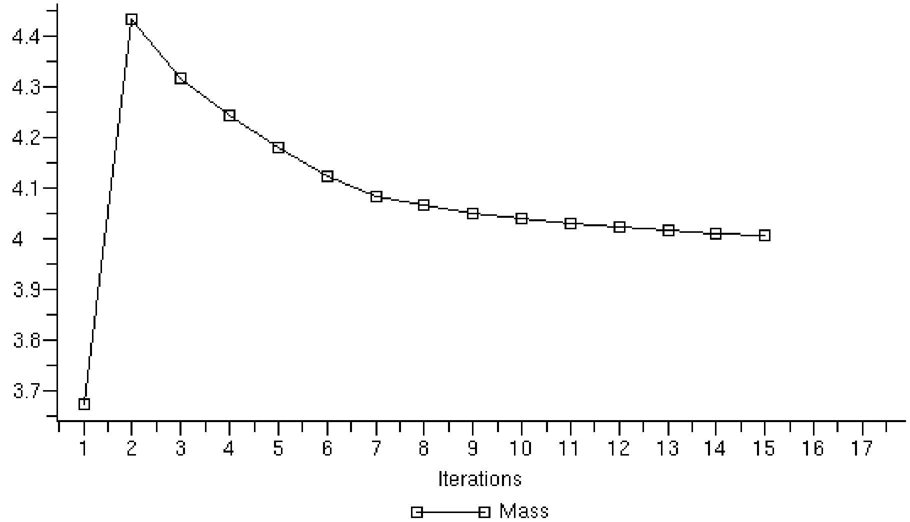
Optimal stacking sequence

90
-45
-45
-45
-45
90
-45
0
45
0
45
0
45
45
0
0
45
0

Application

2-step procedure

- **STEP 1**: optimization with continuous design variables: determine local thickness and optimal proportions of 0, 45, -45, 90 in each region
  - Gradient-based optimizer: Sequential Convex Programming
  - Semi-analytical sensitivity (for linear and non-linear responses)



Optimal number of plies

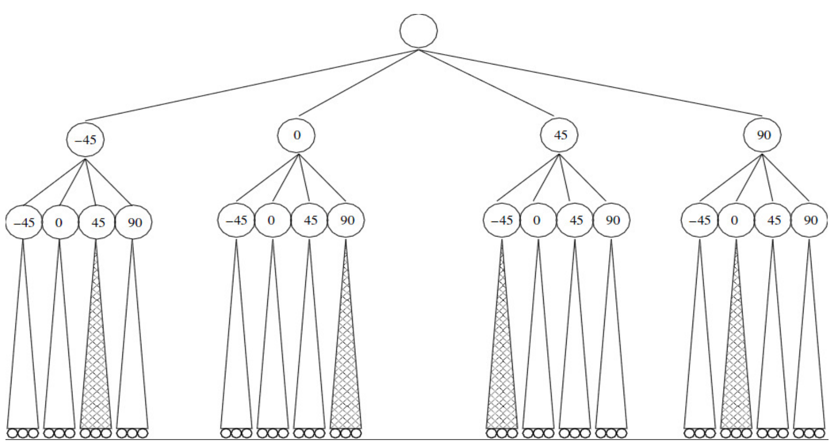
	Region 1	Region 2	Region 3
N plies at 0°	16	12	12
N plies at -45°	10	10	10
N plies at 45°	10	10	10
N plies at 90°	4	4	4
Total number of plies	40	36	36

Application

2-step procedure

- **STEP 2**: optimization with discrete design variables: local stacking sequences + blending (ply continuity accross the regions)
  - Integer programming approach (tree with cut branches corresponding to unfeasible design wrt the design rules)

- Tree with cut branches: limited enumeration



- Initial solution (non feasible)

	40	38	36	34	32	30
90	1					
90	1	1				
90	1	1	1			
90	1	1	1	1		
45	1	1	1	1	1	
45	1	1	1	1	1	1
45	1	1	1	1	1	1
45	1	1	1	1	1	1
-45	1	1	1	1	1	1
-45	1	1	1	1	1	1
-45	1	1	1	1	1	1
0	1	1	1	1	1	1
0	1	1	1	1	1	1
0	1	1	1	1	1	1
0	1	1	1	1	1	1
90	1	1	1	1	1	1
90	1	1	1	1	1	1
90	1	1	1	1	1	1
0	1	1	1	1	1	1
0	1	1	1	1	1	1

Optimisation

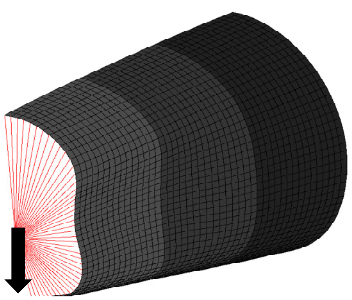
- Selection of the orientation (1st column)
- Permutation of the plies (rows)

	40	38	36	34	32	30
90	1	1	1			
-45	1	1	1	1	1	1
0	1	1				
-45	1	1	1	1	1	1
-45	1	1	1	1	1	1
-45	1	1	1	1	1	1
90	1	1	1	1	1	1
-45	1	1	1	1	1	1
0	1	1	1	1	1	1
45	1	1	1	1		
0	1	1	1	1	1	
45	1	1	1	1	1	1
0	1	1	1	1	1	1
45	1	1	1	1	1	1
45	1	1	1	1	1	1
0	1	1	1	1	1	1
0	1	1	1	1	1	1
45	1	1	1	1	1	1
0	1	1	1	1	1	1
0	1					

Application

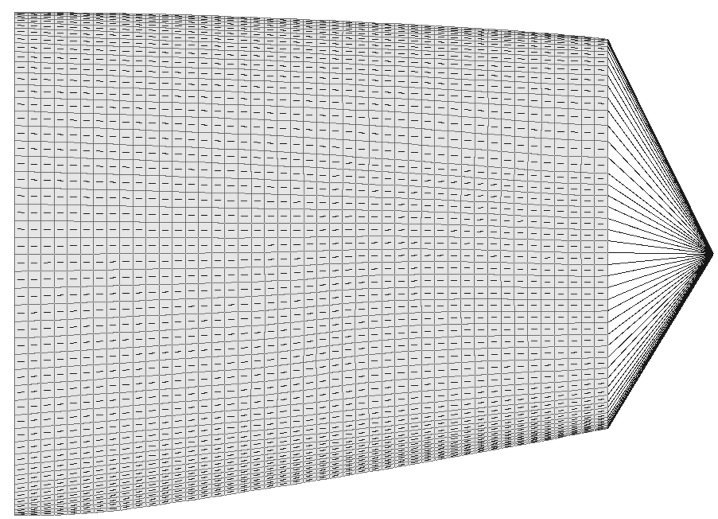
Final solution

- Composite structure (aft fuselage) divided in 3 zones
- Balanced laminate/sym.
- Min weigth, with buckling and stiffness restrictions
- Result of optimization: zone 1 has 40 plies; zones 2 and 3 have 36 plies

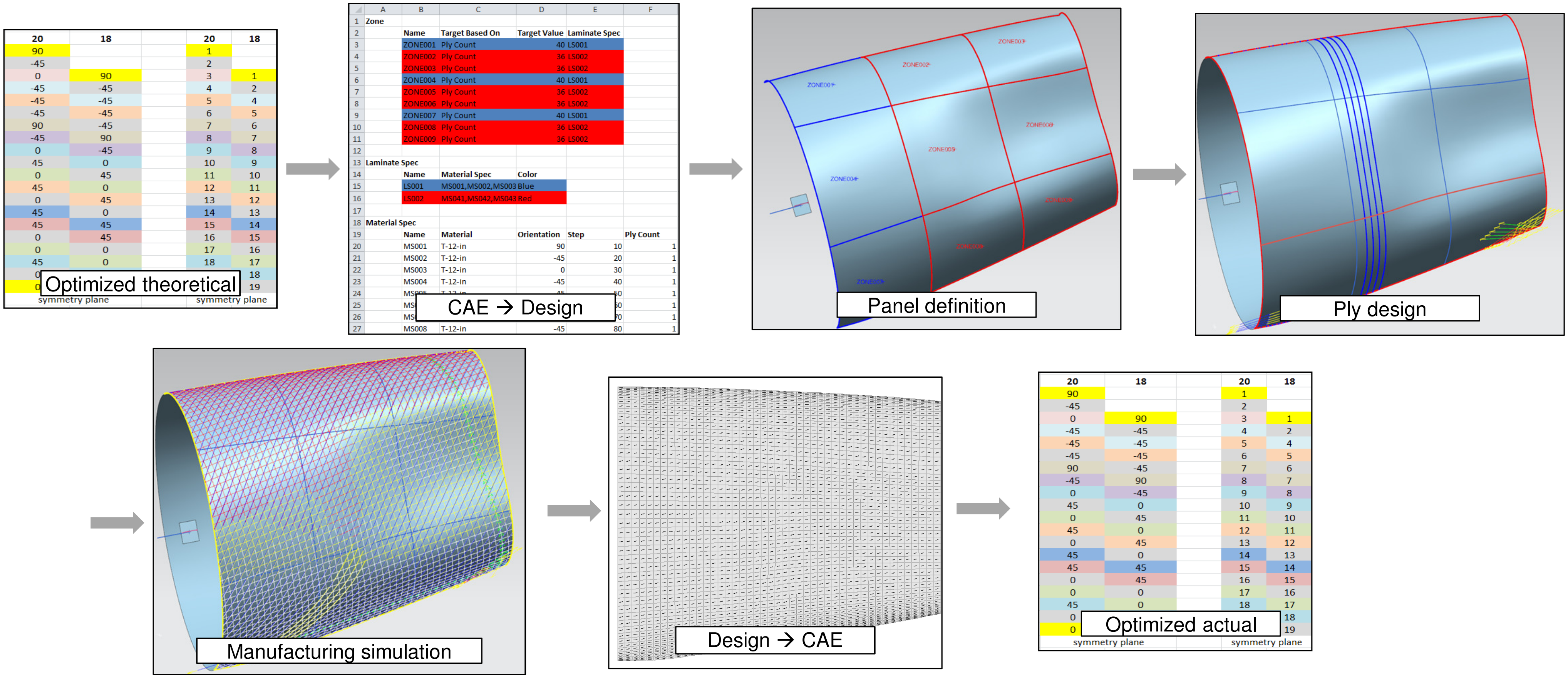


20	18		20	18
90			1	
-45			2	
0	90		3	1
-45	-45		4	2
-45	-45		5	4
-45	-45		6	5
90	-45		7	6
-45	90		8	7
0	-45		9	8
45	0		10	9
0	45		11	10
45	0		12	11
0	45		13	12
45	0		14	13
45	45		15	14
0	45		16	15
0	0		17	16
45	0		18	17
0	45		19	18
0	0		20	19
symmetry plane			symmetry plane	

Theoretical optimal orientations for ply 1
(draping method = simple projection)
Example: ply at 0deg

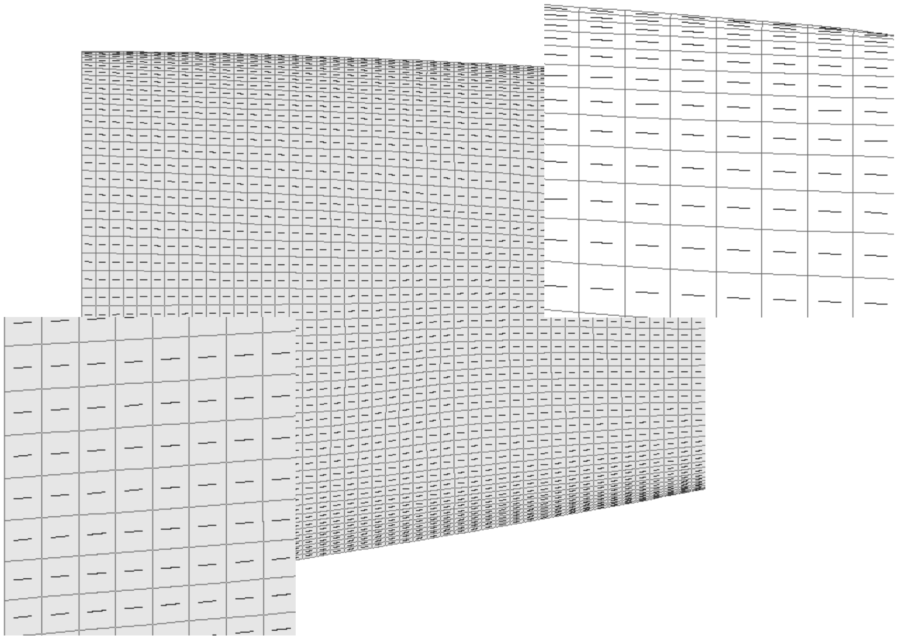


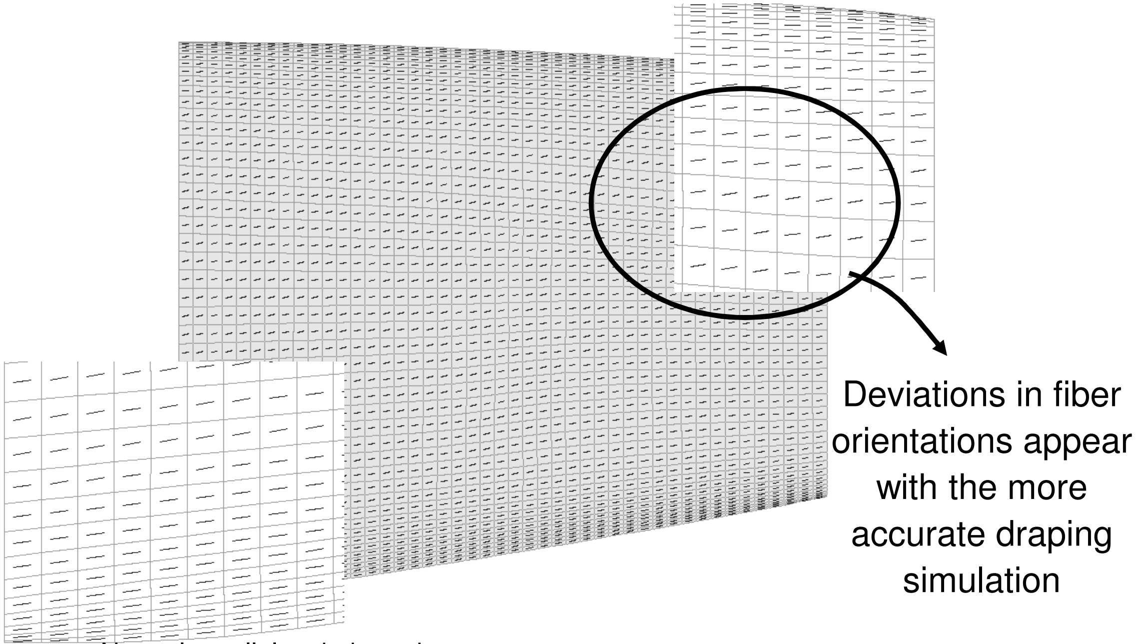
Validation and Feedback



Comparison between the two draping simulations, based on the optimal solution

- Optimal orientations for ply 3 (draping method = simple projection) compared to the Fibersim solution
- Fibersim identifies the deviation between desired and actual orientations of the plies (non developable surface)

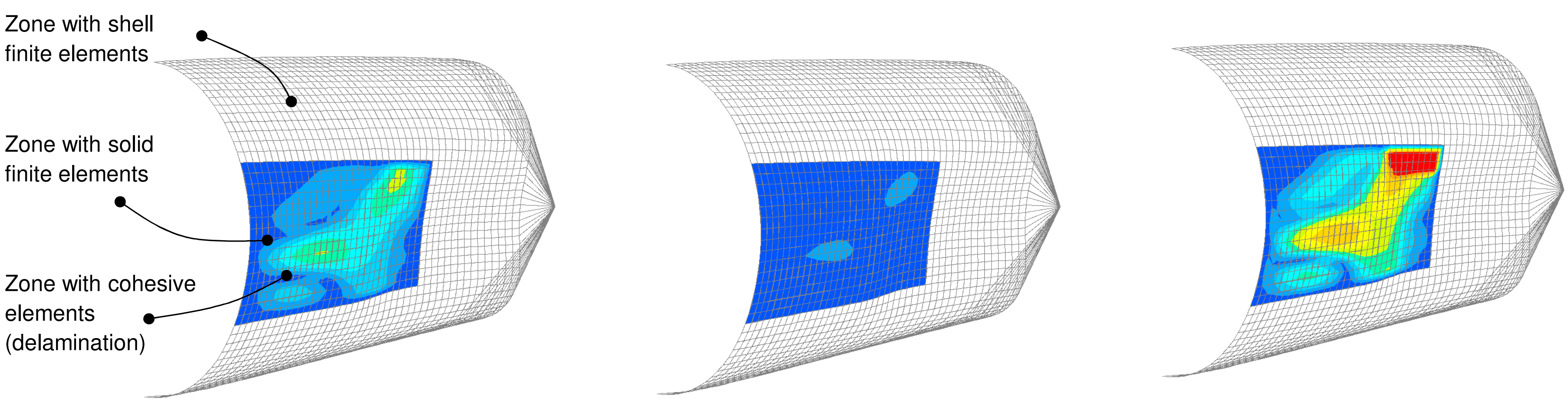




Natural parallel path, based on automated deposition machine head start location

Use of non linear analysis on the optimal solution, draped with Fibersim

- Starting with the optimal "theoretical" orientations obtained with the optimization approach
- Accurate draping simulation obtained with Fibersim, based on the previously identified optimal orientations, is used here
- Mix of shell and solid elements mesh
- Cohesive elements defined between some plies, to simulation possible delamination
- Non linear analysis with SAMCEF, to check some delamination propagation inside the optimized structure
  - Check that delamination will appear above the nominal loading

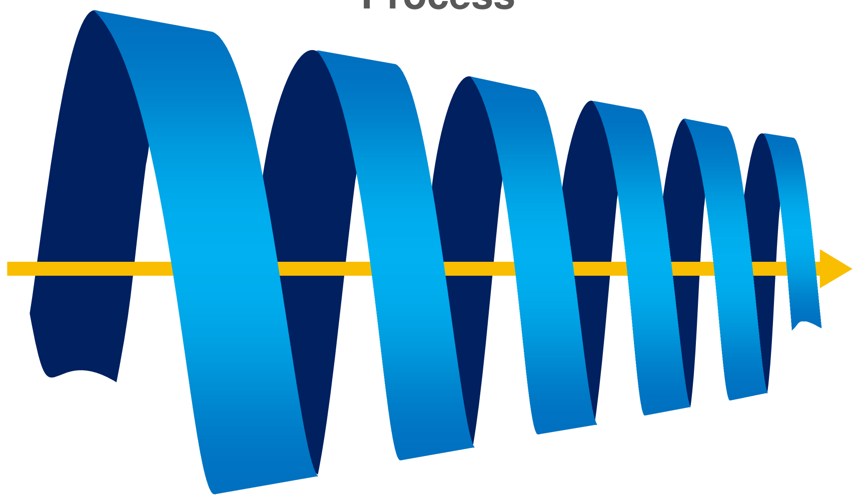


Reducing overdesign

Inputs

- True fiber orientations
- As-manufactured draping
- Accurate material behavior
- Tighter safety margins

Process



Outputs

- Optimal weight
- Optimal material usage
- Decreased material and product costs

Cost effective communication between analysis and design solutions are the basis for interative loops that lead to optimization. Predictive performance using linear and non-linear analysis with as-manufactured fiber orientation eliminate ambiguity for optimal use of materials reducing weight and cost.