STRUCTURAL OPTIMIZATION IN THE DESIGN OF A COMPOSITE RAIL CAR BODY

- *Framework : The ULTIMAT project*
- *The engineering problem*
- *The optimization formulation*
- *The cost function formulation*
- *Application to ALSTOM subway car structures*
- *Methodology issues*

Edmondo Di Pasquale, Pascal Ghys, Fevrier 2014

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ULTIMAT

UTILISATION INNOVANTE DES NOUVEAUX MATERIAUX DANS LA CONSTRUCTION FERROVIAIRE

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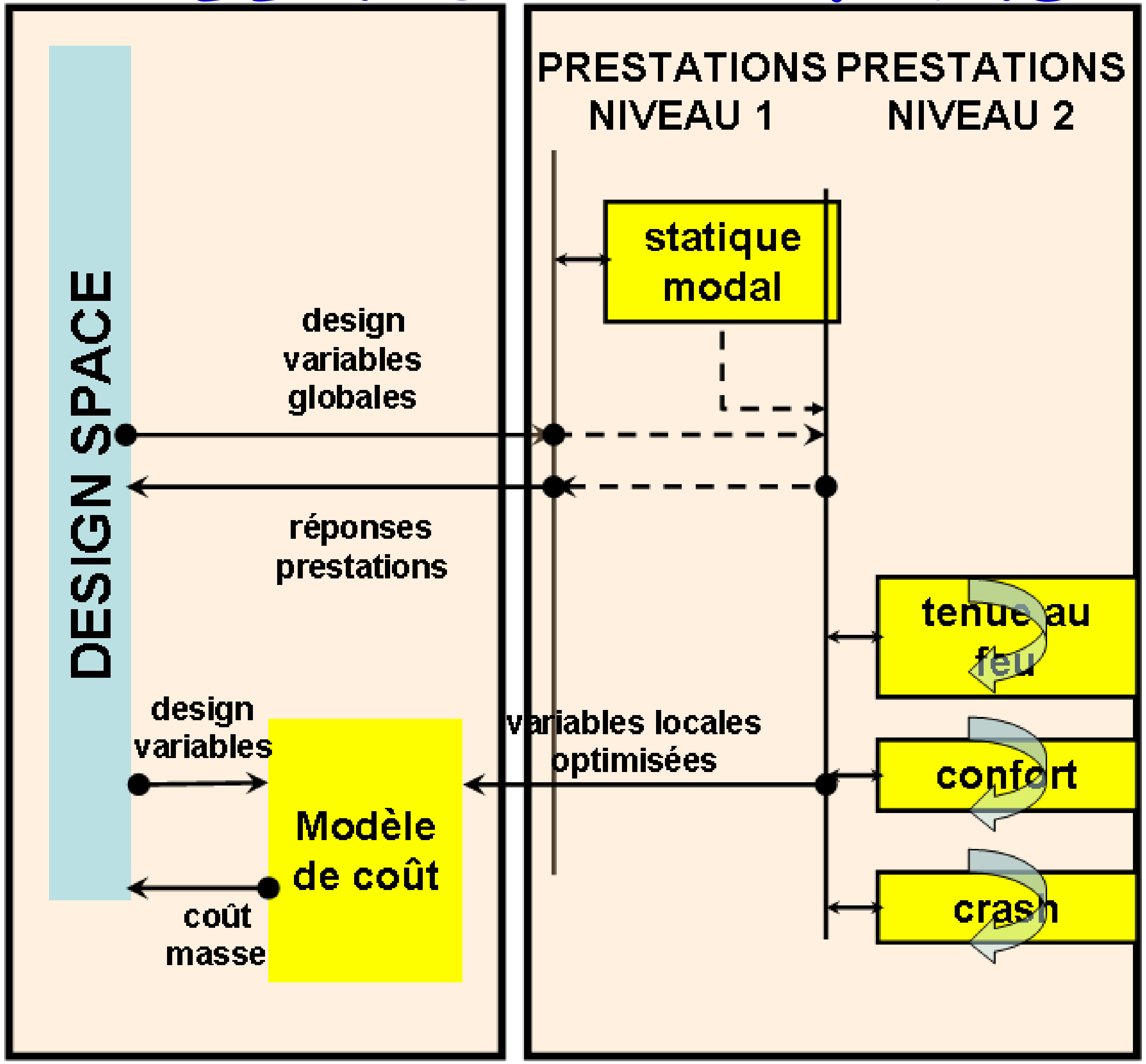
ULTIMAT OBJECTIVES AND RESULTS

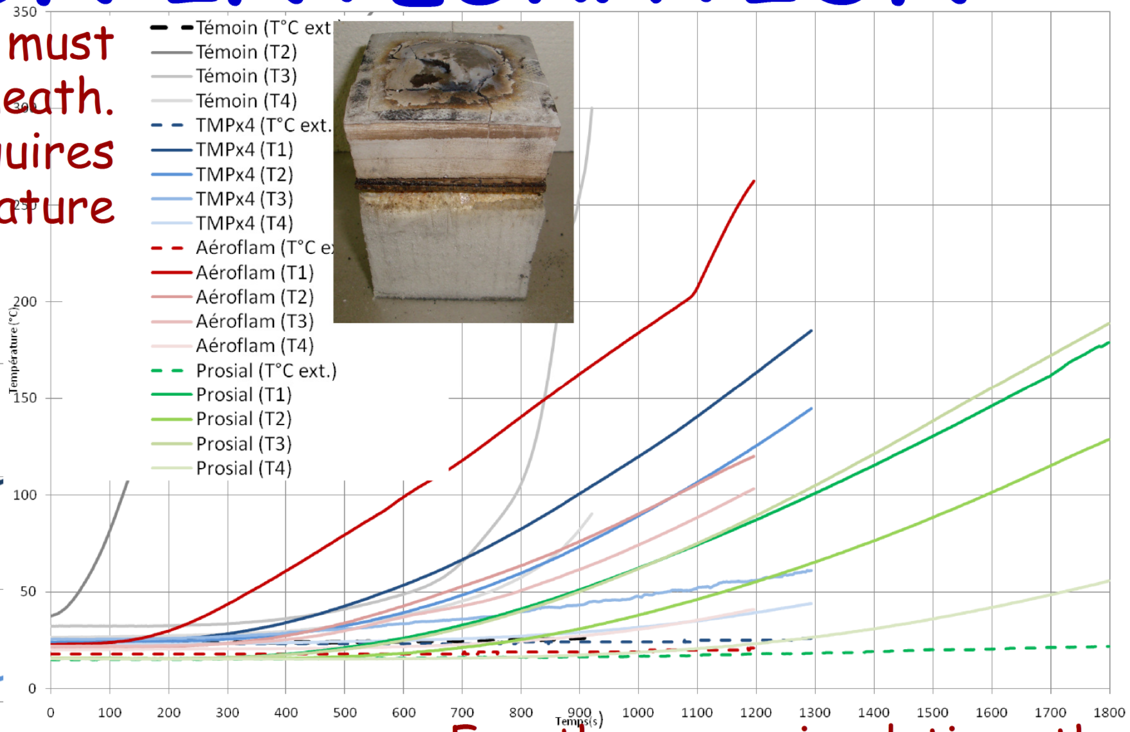
- Use new (composite) materials to build a rolling stock car body
- Significantly decrease :
  - Weight (20%) → 24%
  - Number of parts (20%) → 20%, with feature integration
  - Operating cost (30%) → 30%, thanks to energy savings
  - Assembly time (50%) → 50%
- Integrate multiple functions in single-built components
- Advance understanding of the behavior of composite materials in railway environment
- Validate technological solution via prototype fabrication and testing

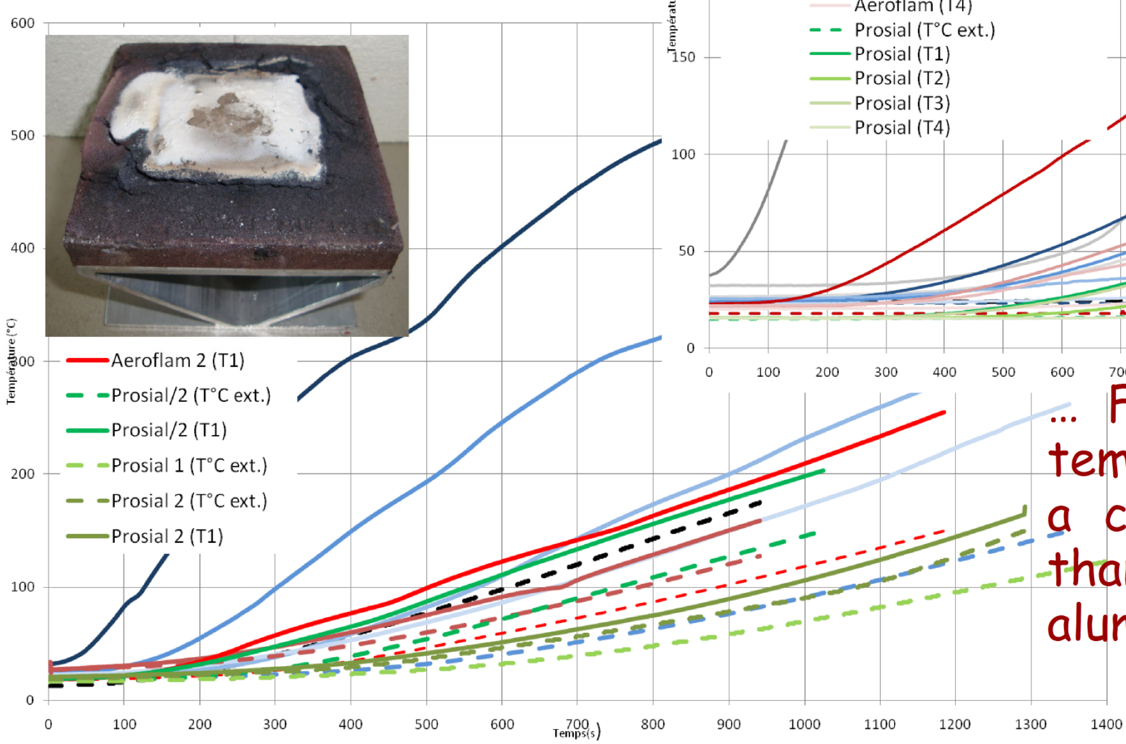
PARALLEL PROJECT ROLLING STOCK MDO



WHY IS MDO IMPORTANT ? FUNCTION INTEGRATION

Rolling stock floorbeds must resist to a fire burst underneath. The experimental set-up requires a controlled temperature increase …





… For the same insulation, the temperature rises much less for a composite sandwich floorbed than for a « traditional » aluminum floorbed.

ULTIMAT TECHNOLOGICAL CHALLENGES

- New, demanding design constraints (rolling stocks)
- Cost constraints (≤ aluminum frame)
- Manufacturing constraints (infusion)
- Production rate (≈300/an)
-
- Component size (13 m span)
- Component aspect ratio (foam/fiber > 20)
- Material anisotropy
- Material property dispersion
-
- Multi-scale problem
- Number of degrees of freedom
- Dependency among degrees of freedom

FACE AND FLOOR PANELS BUILT IN ONE PIECE

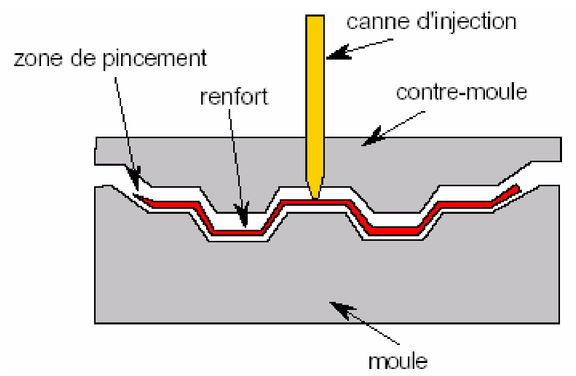
Le RTM (Resin Transfer Moulding) :

Caractéristiques mécaniques garanties.

Surfaces extérieures et surfaces intérieure finies.

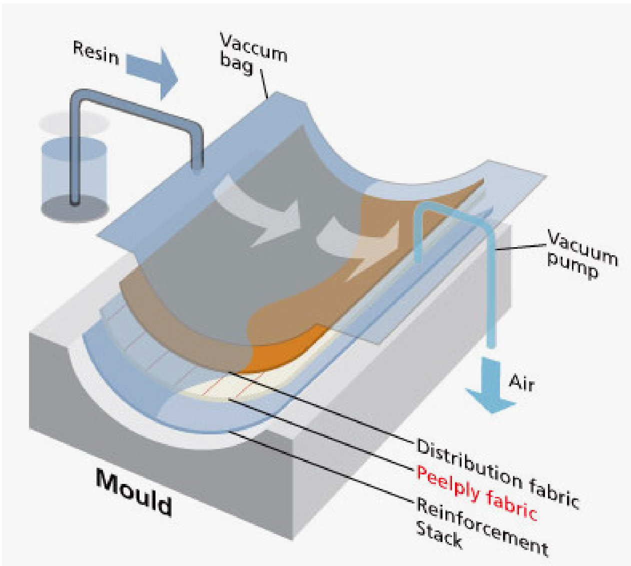
Temps de cycle de fabrication court.

Outillage complexe pour de grandes pièces (supérieur à 5 m²).

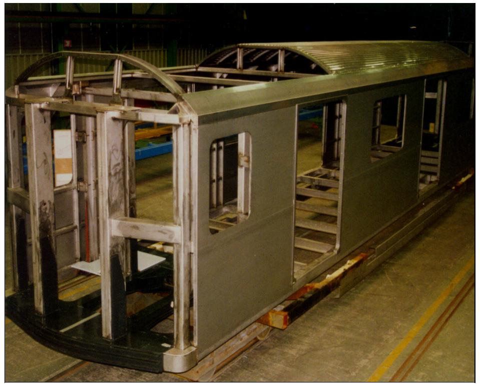


L'infusion :

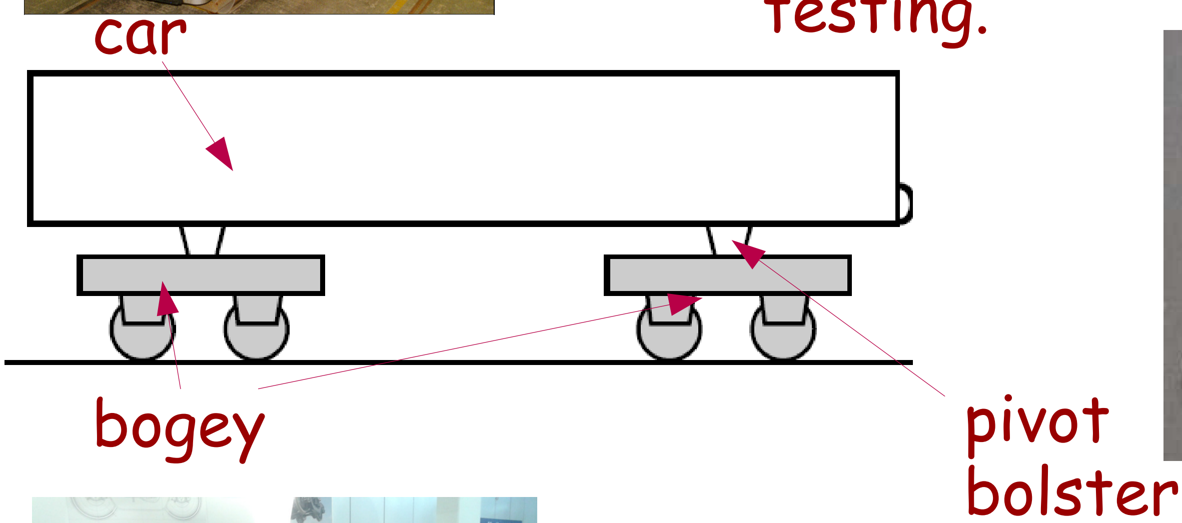
- Bonnes caractéristiques mécaniques.
- Outillage simplifié en comparaison au RTM.
- Une seule face de la pièce est finie.
- Temps de cycle plus long que le RTM.



WHERE DOES THE CAR END ?



The interface between the car and the bogey (pivot bolster) is part of the car design.
It requires specific sizing and testing.

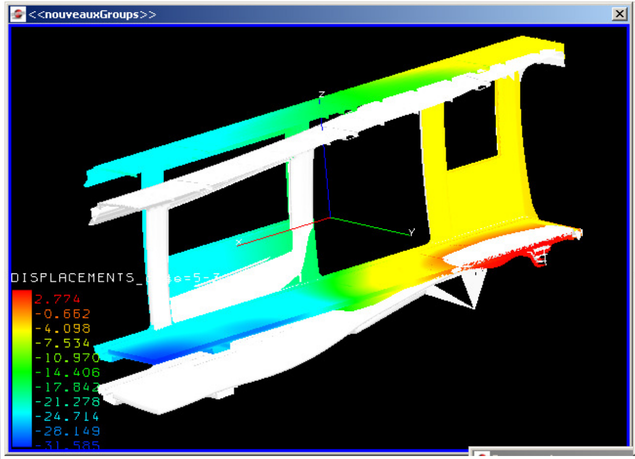


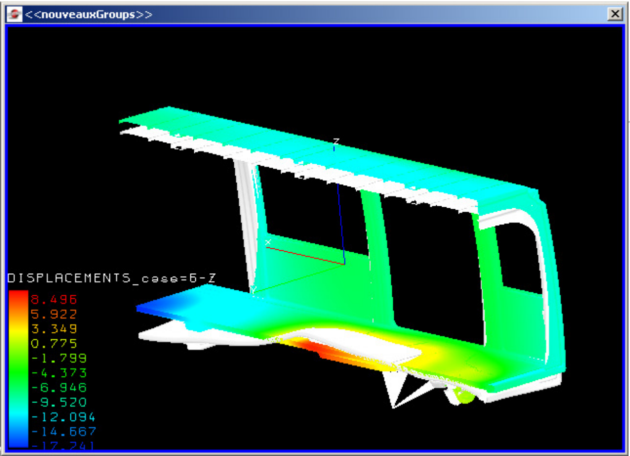
STRUCTURAL MECHANICS PROBLEM FORMULATION

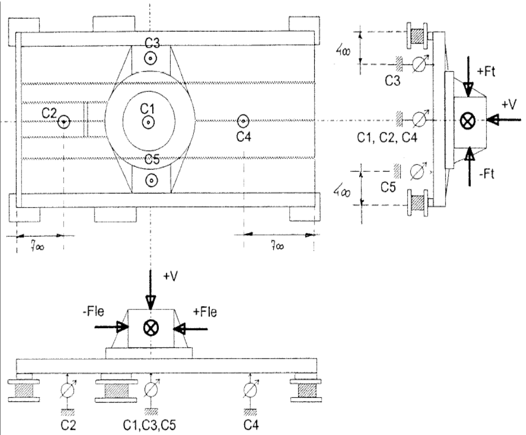
Case Vertical overload :
An acceleration of 1.2 g is applied on the structure, loaded with equipment and passengers

Case 100t compression :
Concentrated load on the bogey pivot. This is the quasi-static equivalent of a crash event

Pivot bolster tests :
8 different load cases including static and fatigue strength







Retained responses :
Side sill deformation (mm)
Floor deformation (mm)

Retained responses :
Front end
vertical deformation (mm)
Foam strain (%)

Retained responses :
Monolith strain (%)

PROJECT EVOLUTION

TOPOLOGY OPTIMIZATION

↓

CAD DESIGN

↓

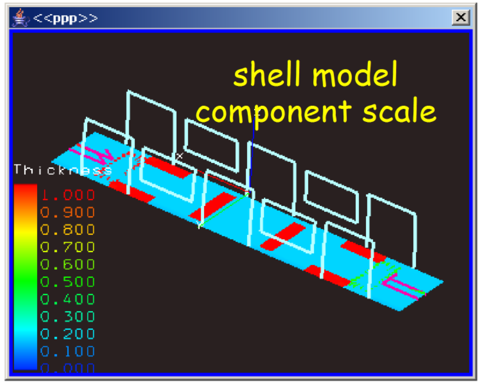
PARAMETRIC OPTIMIZATION

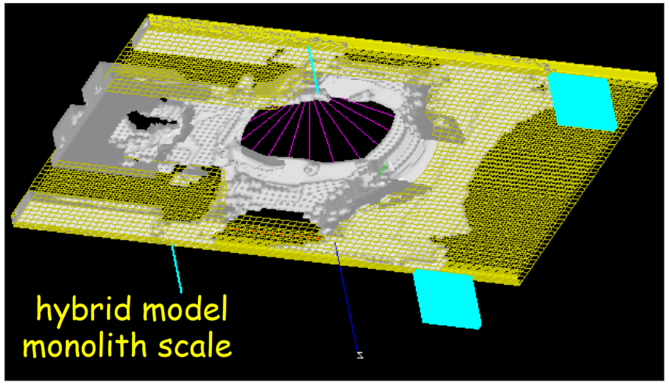
↓

ON THE MESH MODIFICATIONS

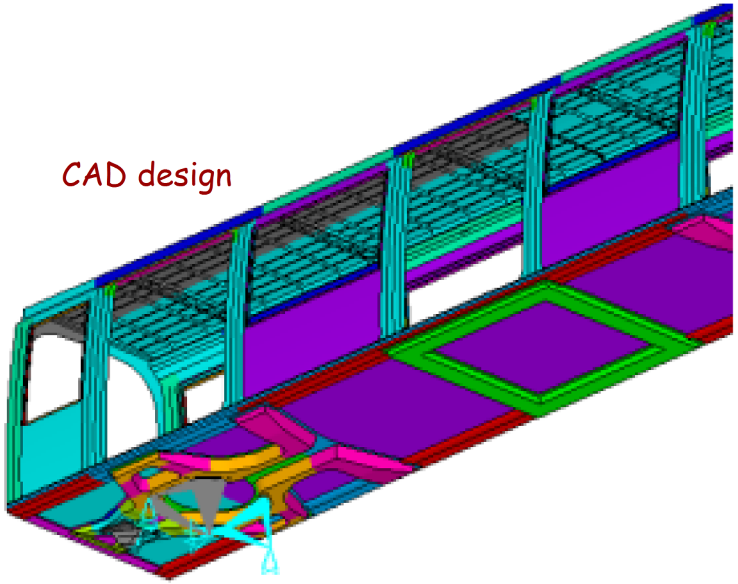
↓

FINAL DESIGN





CAD design



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PROJECT EVOLUTION

TOPOLOGY OPTIMIZATION

↓

CAD DESIGN

↓

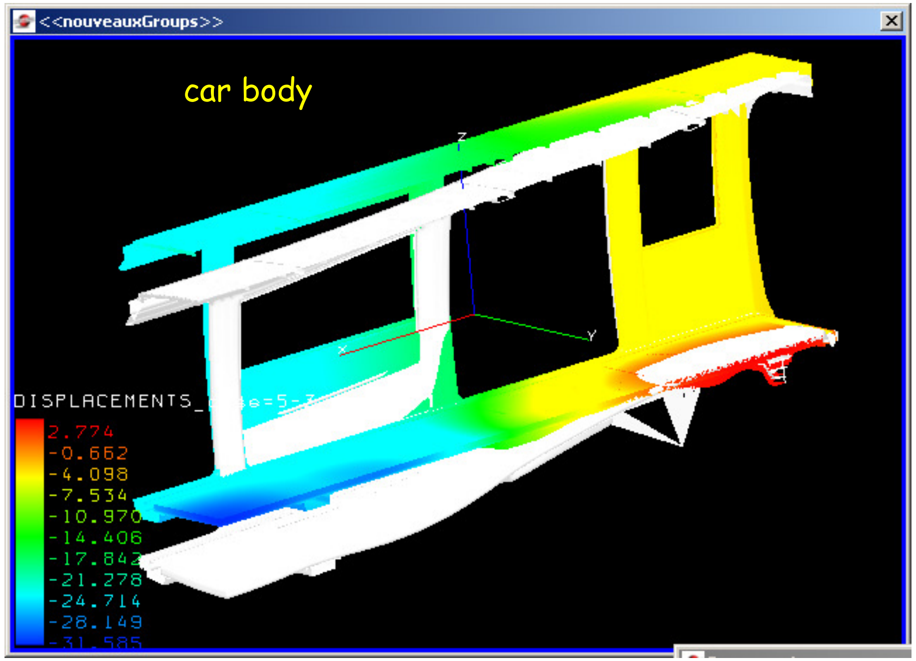
PARAMETRIC OPTIMIZATION

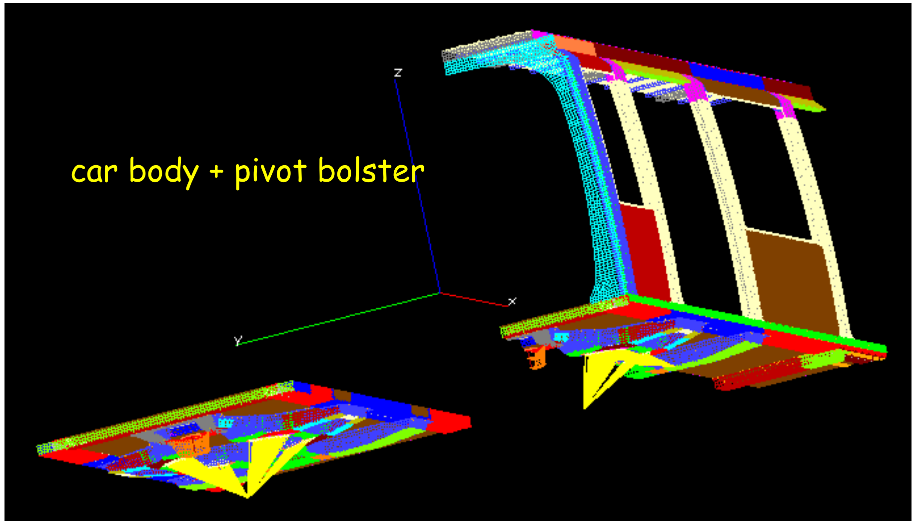
↓

ON THE MESH MODIFICATIONS

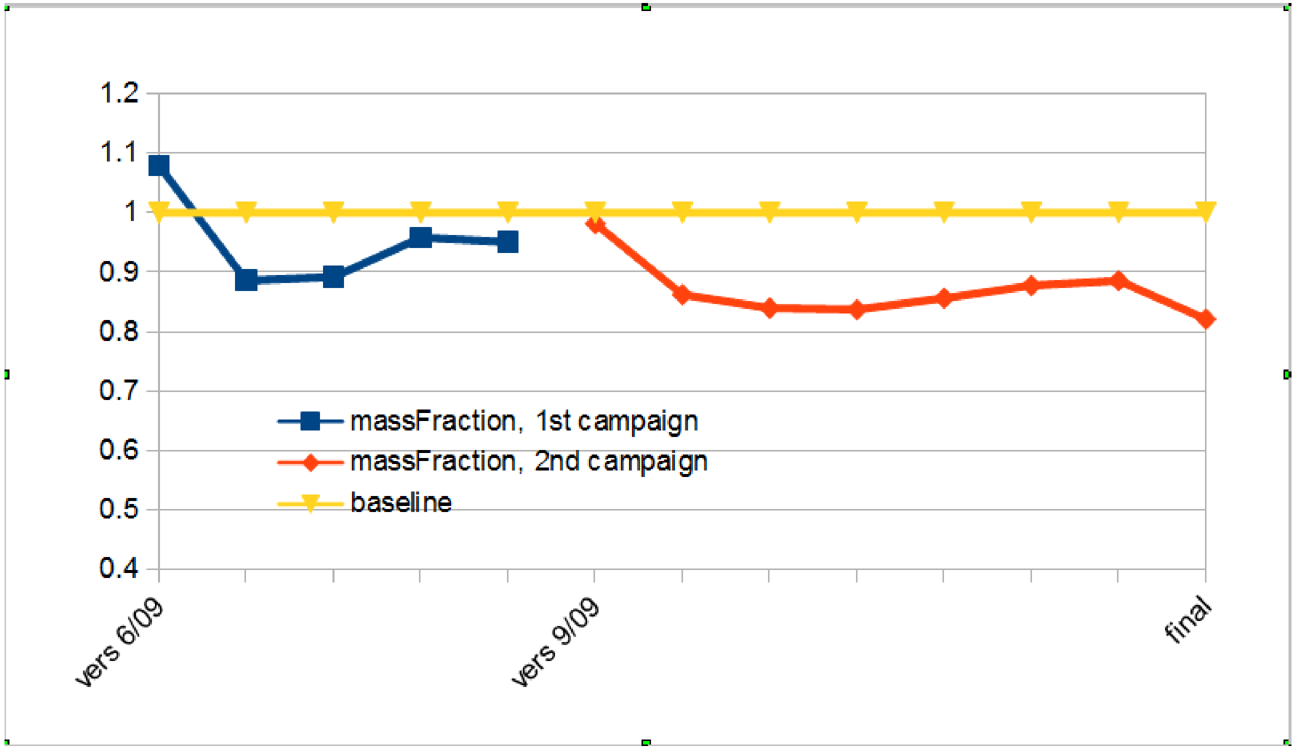
↓

FINAL DESIGN





OPTIMIZATION SUGGESTS/FOLLOWS DESIGN MODIFICATIONS



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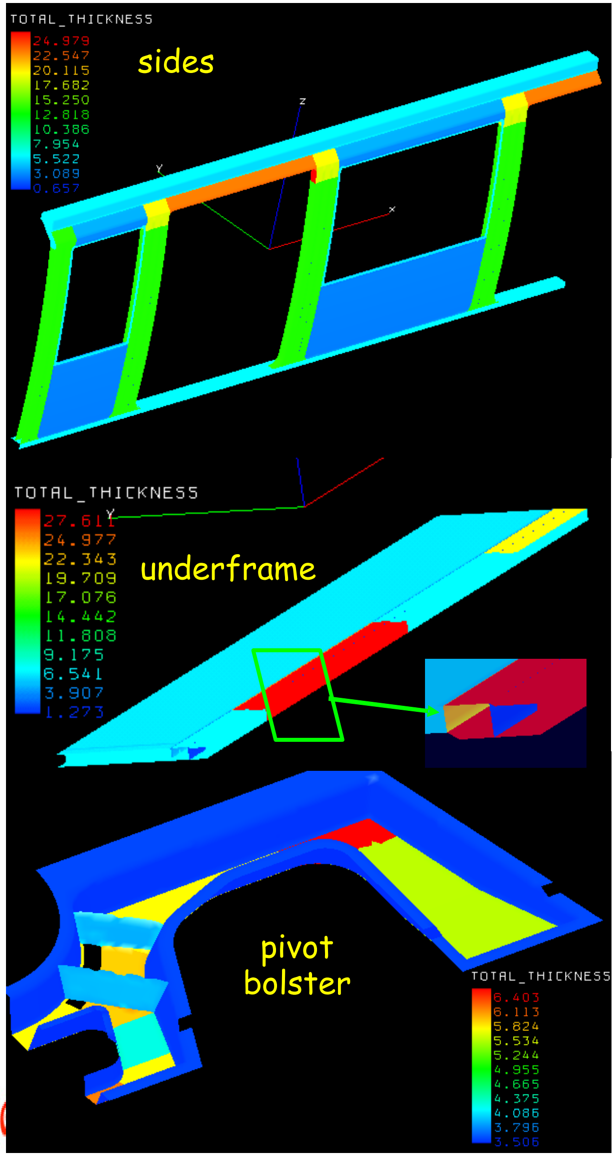
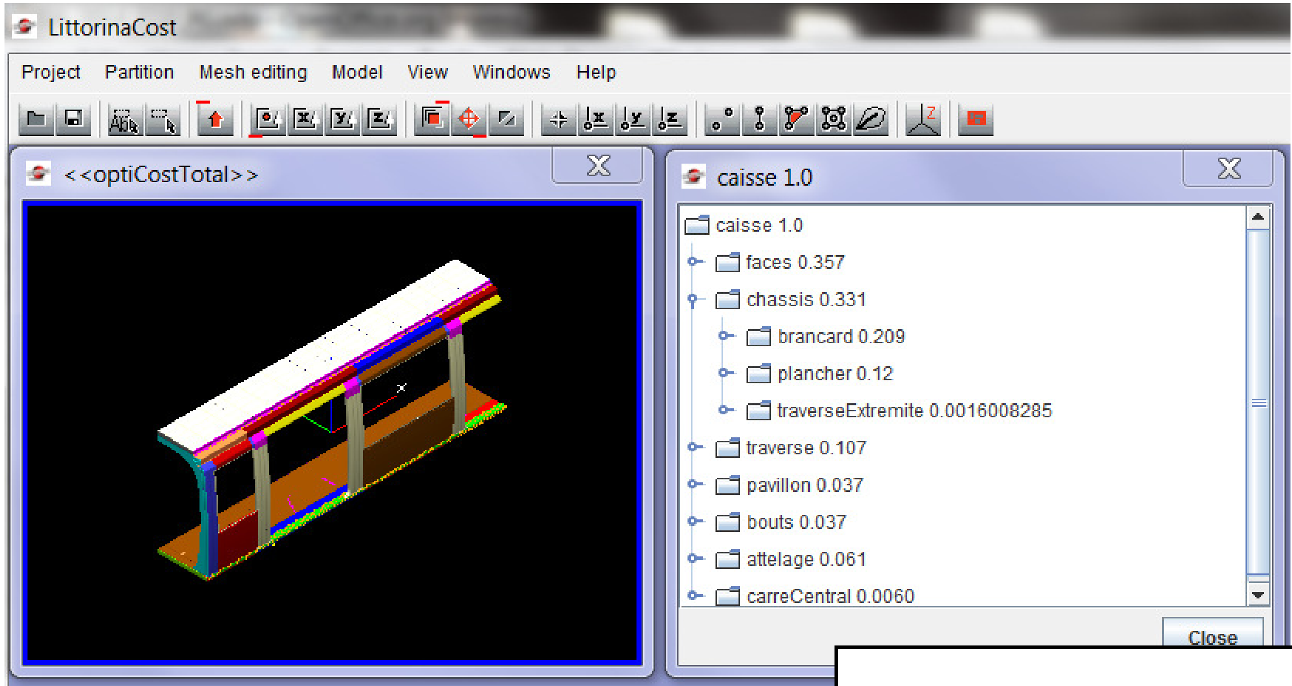
FINAL BODY DESIGN - I



Optimal structure combines glass/carbon fiber monoliths, glass fiber sandwiches and conventional steel and aluminum parts

FINAL BODY DESIGN - II



material	mass fraction
foam	0.08
glass fiber monolith	0.33
carbon fiber monolith	0.30
steel	0.29
aluminum	0.01

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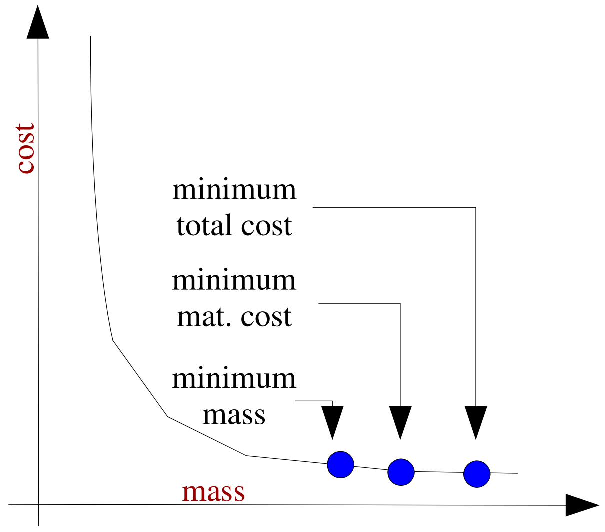
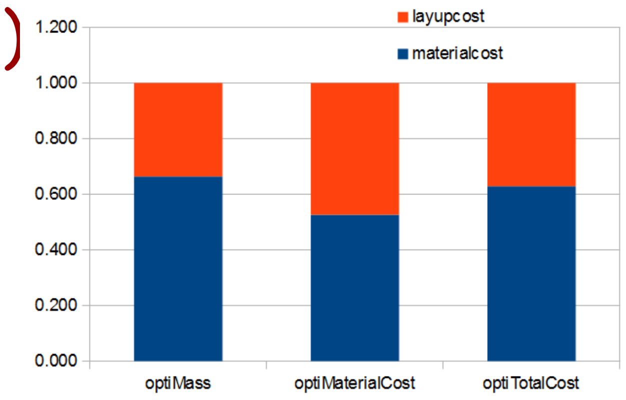
WHICH OBJECTIVE FUNCTION ?

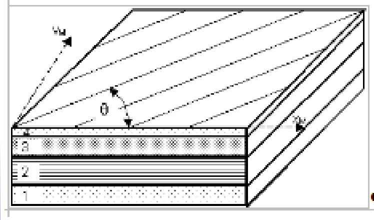
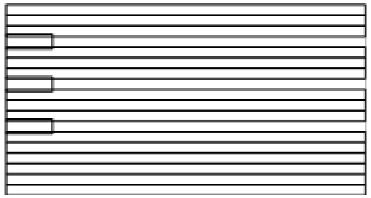
- Mass
- Material cost
- Production (lay-up) cost
  - Hourly operator rate
  - Lay up total thickness
  - Part surface
  - Part geometry
- Total cost (Material + Production)

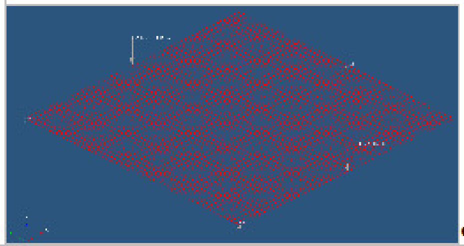
	optiMass	optiMaterialCost	optiTotalCost
mass	1.000	1.369	1.216
totalcost	1.000	0.988	0.987

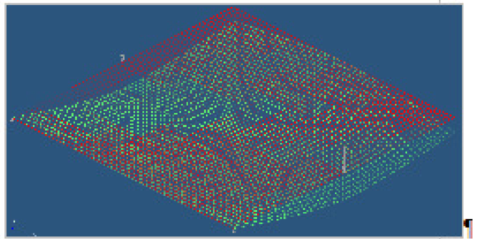




WHICH COMPOSITE MODEL ?

layer model used	actual layer distribution
	

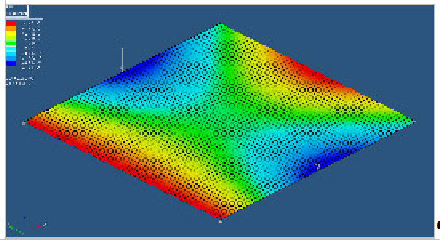
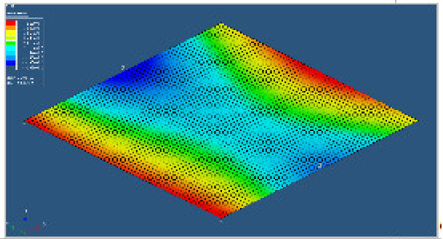
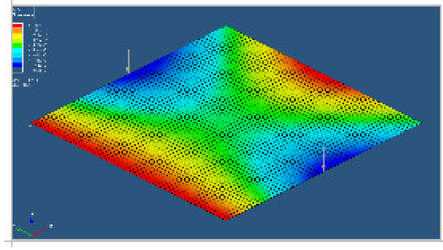
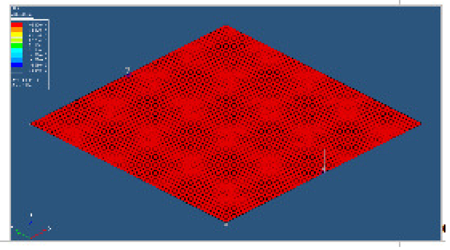




In early design, we do not have nor seek a detailed lay-up.

Our objective is to identify how much monolyth we have to put at a given orientation.

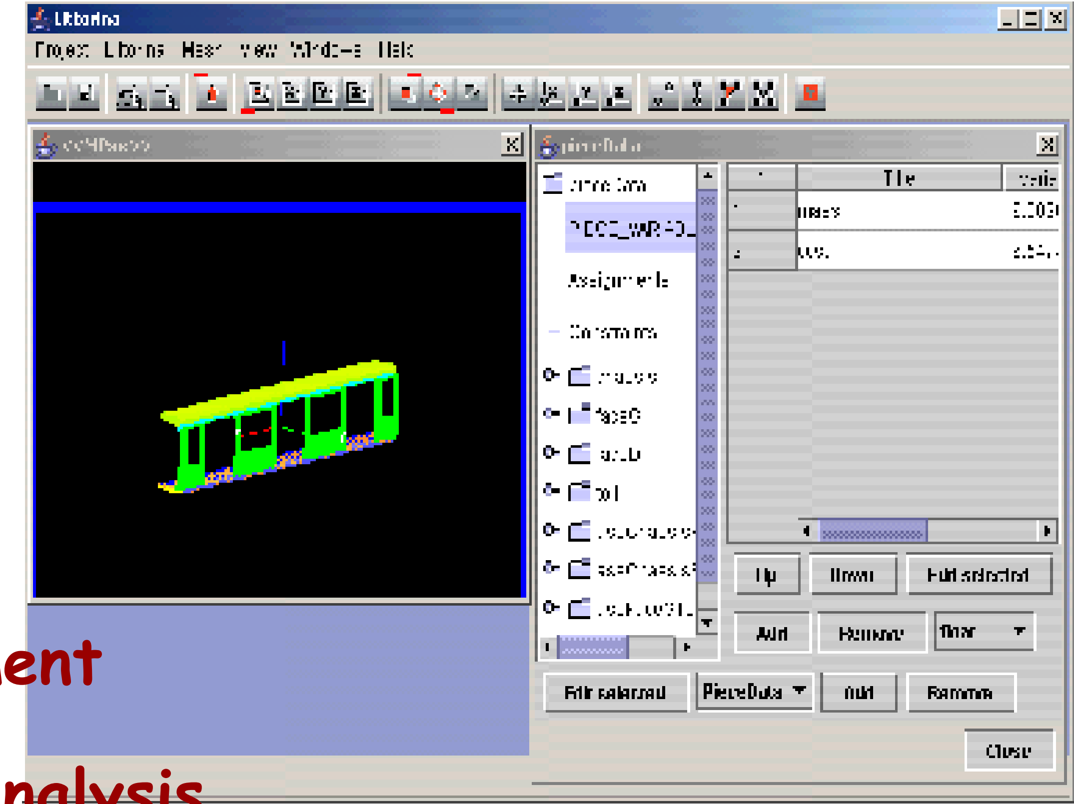
Which model should we use when we have only a few layers ?

actual layer - DEFAULT	4 layers - DEFAULT
	
4 layers - SMEAR	**4 layers - MEM**
	

METHODOLOGY ISSUES

- Littorina software
- Lay-up modeling : numerical models
- Actual lay-up
- Assembly feature generation

LITTORINA : AN ENKIDOU APPLICATION



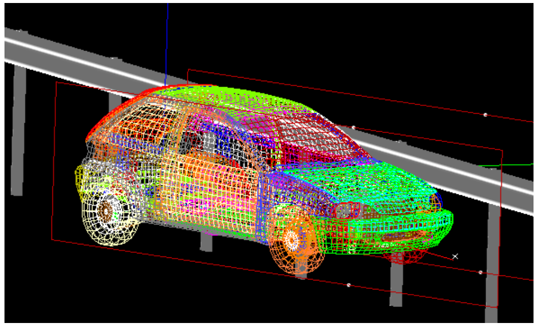
- Architecture
- Databases
- Assembly modeling
- Cost estimation
- Multi-solver environment
- Link generation and analysis
- Layup modeling and optimization
- Layer definition (optimal from supplier catalog

What is ENKIDOU® ?

Java-based library for the development of custom software

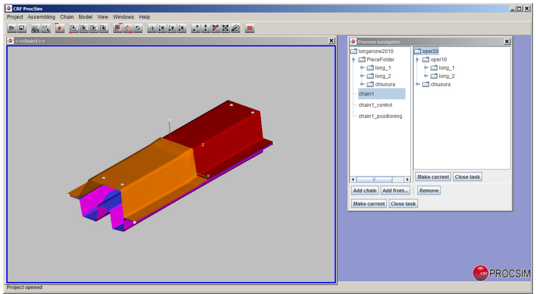
ANALYSIS
- PARAMETRIC
- TOPOLOGY
- ANALYSIS

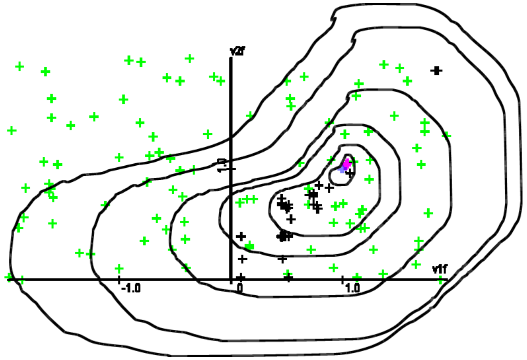
OBJECT ORIENTED DATA STRUCTURES



CAE MODEL EXT. SOLVERS

OPTIMIZATION (VARIABILITY)





PROCESS AUTOMATION

2D – 3D GRAPHICS GUI

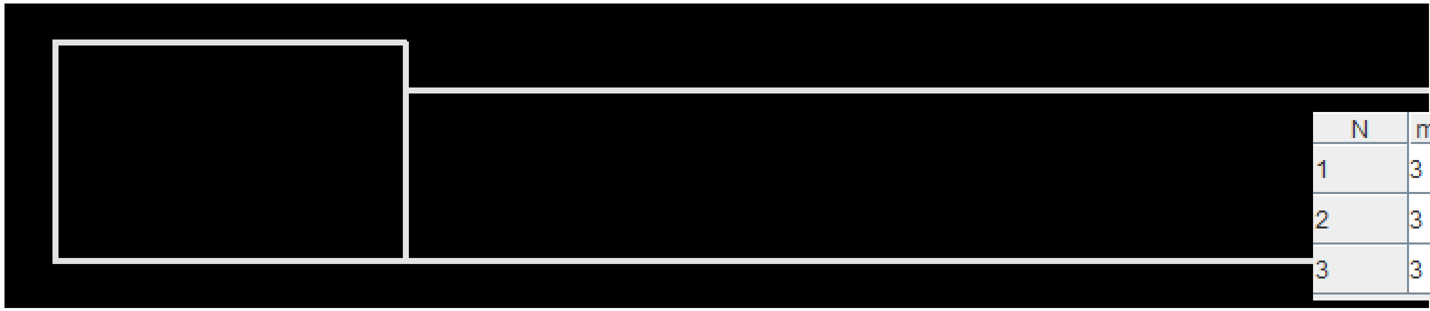
LAYUP MODELING AND OPTIMIZATION - I

Layup is the process of deposing the (pre-cut) fiber sheets in the mold before infusion or RTM (or others ...).

Layup can be very complex, but follows some general rules:

- for each mold, there is one base (master) layer pattern
- patches with different patterns are deposed over the base; any number of patches can be deposed, but we must avoid sharp discontinuities in patterns

In a typical example of layup, we set up a base uxing a triaxial glass fiber
Part of the volume is filled with foam
Upper part of the end rail is reinforced with a glass/carbon mixture
Finally, a steel plate is deposed on the extremity



N	materi...	thickne...	thetas	p
1	3	0.6084...	45.0	Y
2	3	0.6084...	-45.0	Y
3	3	0.6626...	90.0	Y

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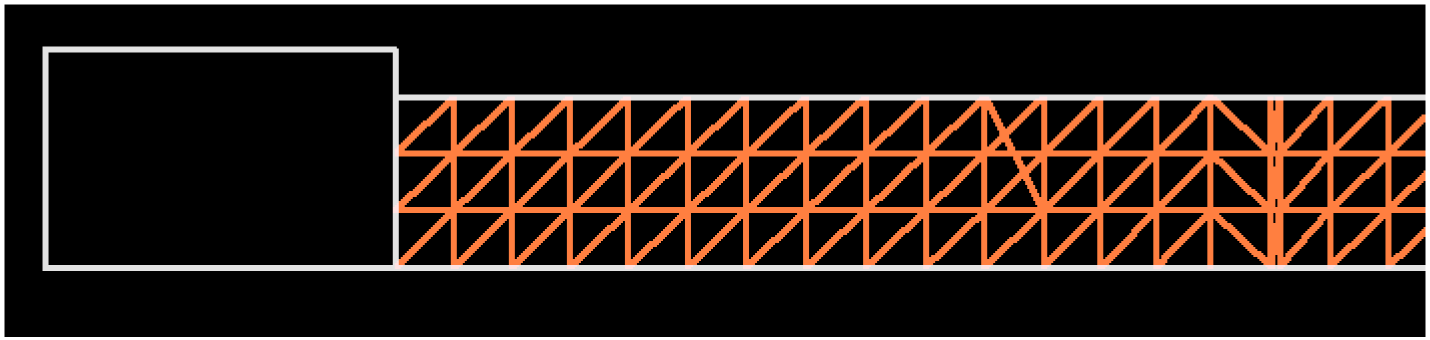

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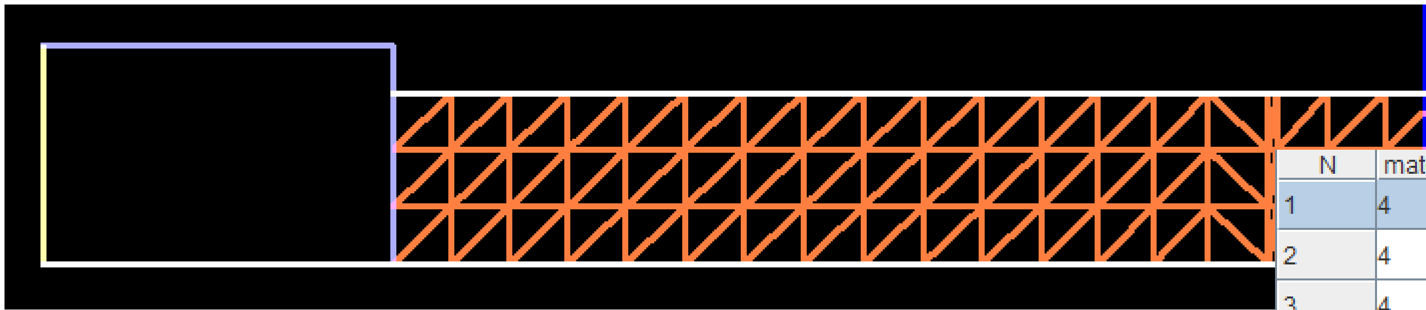

N	materi...	thickne...	thetas	pco
1	4	0.6476...	45.0	YES
2	4	0.4717...	-45.0	YES
3	4	0.4717...	90.0	YES

LAYUP MODELING AND OPTIMIZATION - I

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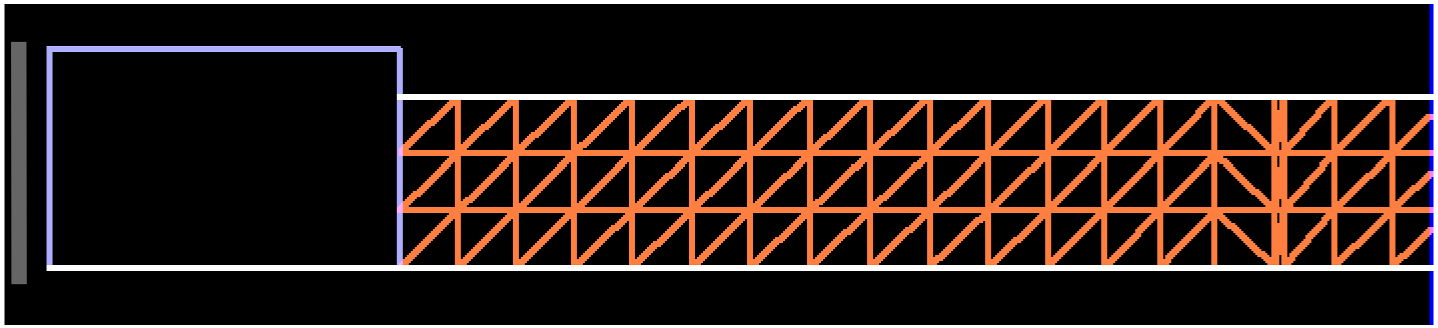
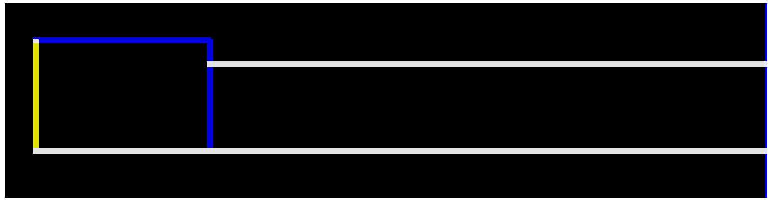


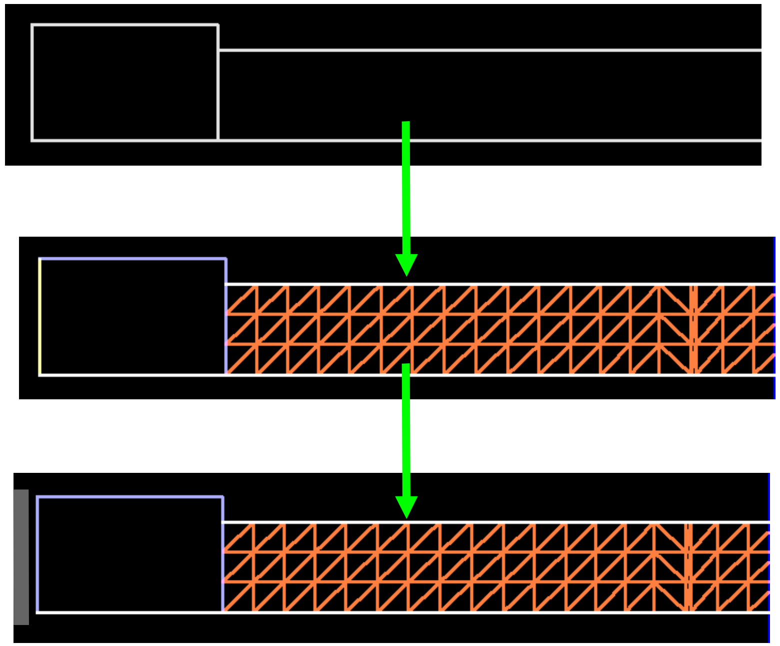
LAYUP MODELING AND OPTIMIZATION - II

SIMULATION MODEL
(components – PID -parts -sections)



PCOMP	2						
	13	3.7	45.0		13	2.0	90.0
	13	3.7	-45.0		13	2.0	0.0

LAYUP MODEL
(component groups)



One component for each *final* layer pattern

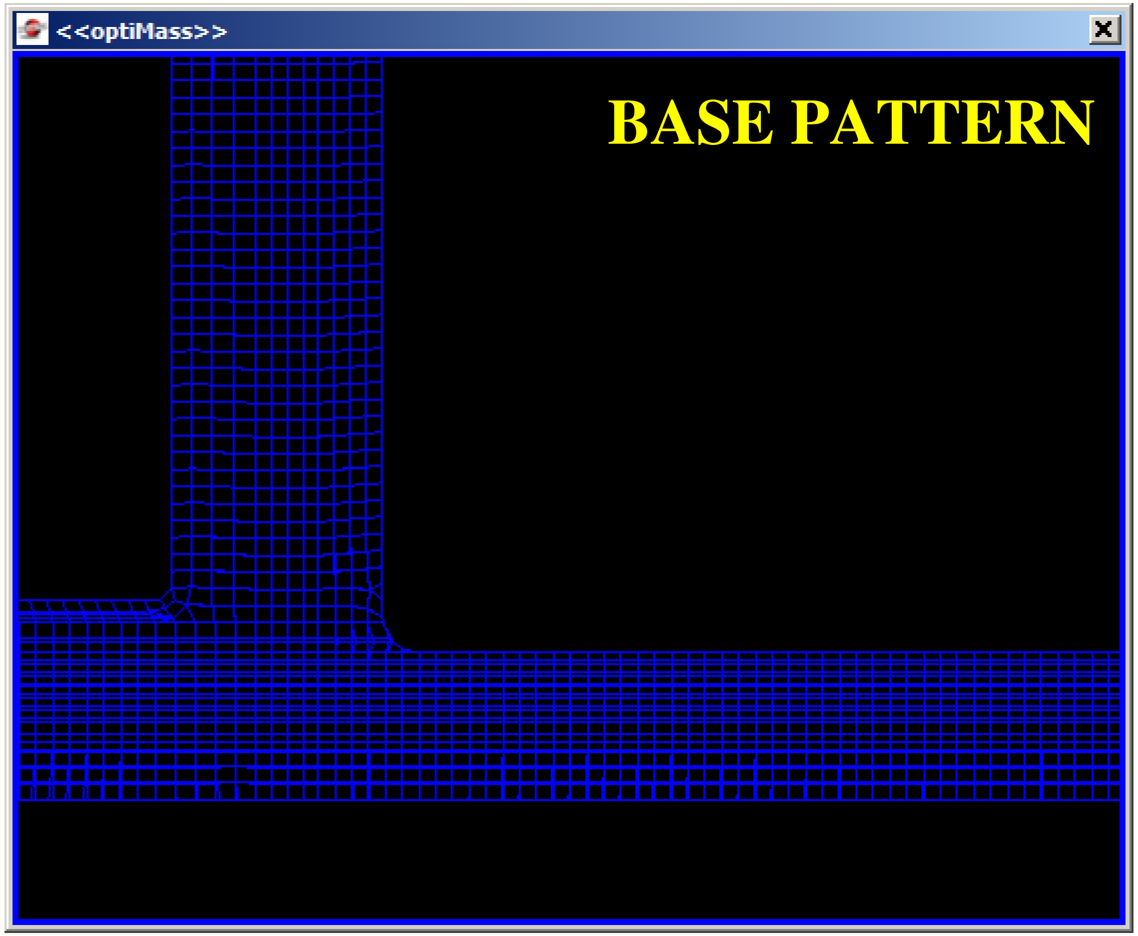
One component group for each *incremental* layer pattern

THIS APPROACH IS COMPATIBLE WITH MOST CAE CODES
(NASTRAN/OS/GENESIS – DYNA/RADIOSS/PAM – ANSYS – ABAQUS ...)

LAYUP MODELING AND OPTIMIZATION - III

OVERLAP OF DIFFERENT LAYER PATTERNS ARE HANDLED THROUGH DESIGN VARIABLES:

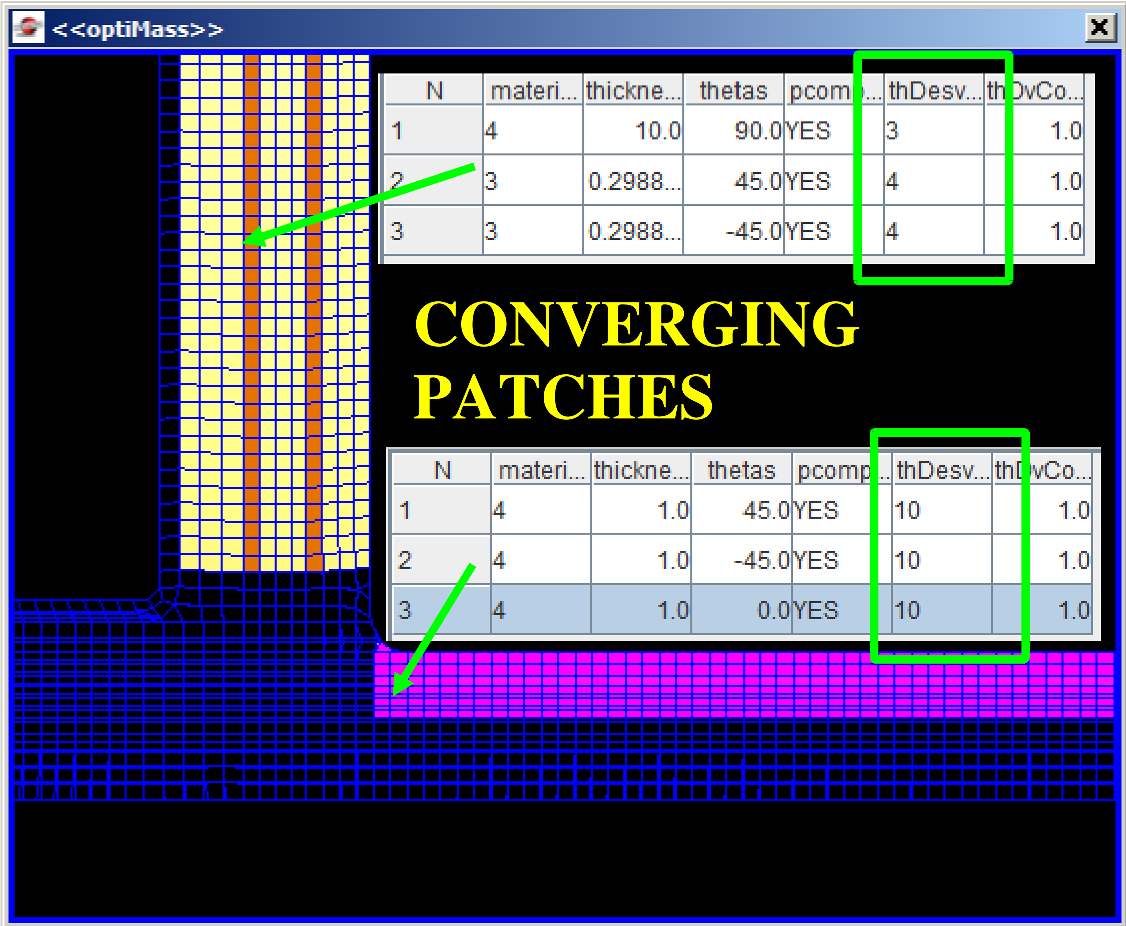
- DESIGN DEFINITION
- INTERFACE TO STRUCTURAL OPTIMIZATION



LAYUP MODELING AND OPTIMIZATION - III

OVERLAP OF DIFFERENT LAYER PATTERNS ARE HANDLED THROUGH DESIGN VARIABLES:

- DESIGN DEFINITION
- INTERFACE TO STRUCTURAL OPTIMIZATION



LAYUP MODELING AND OPTIMIZATION - III

OVERLAP OF DIFFERENT LAYER PATTERNS ARE HANDLED THROUGH DESIGN VARIABLES:

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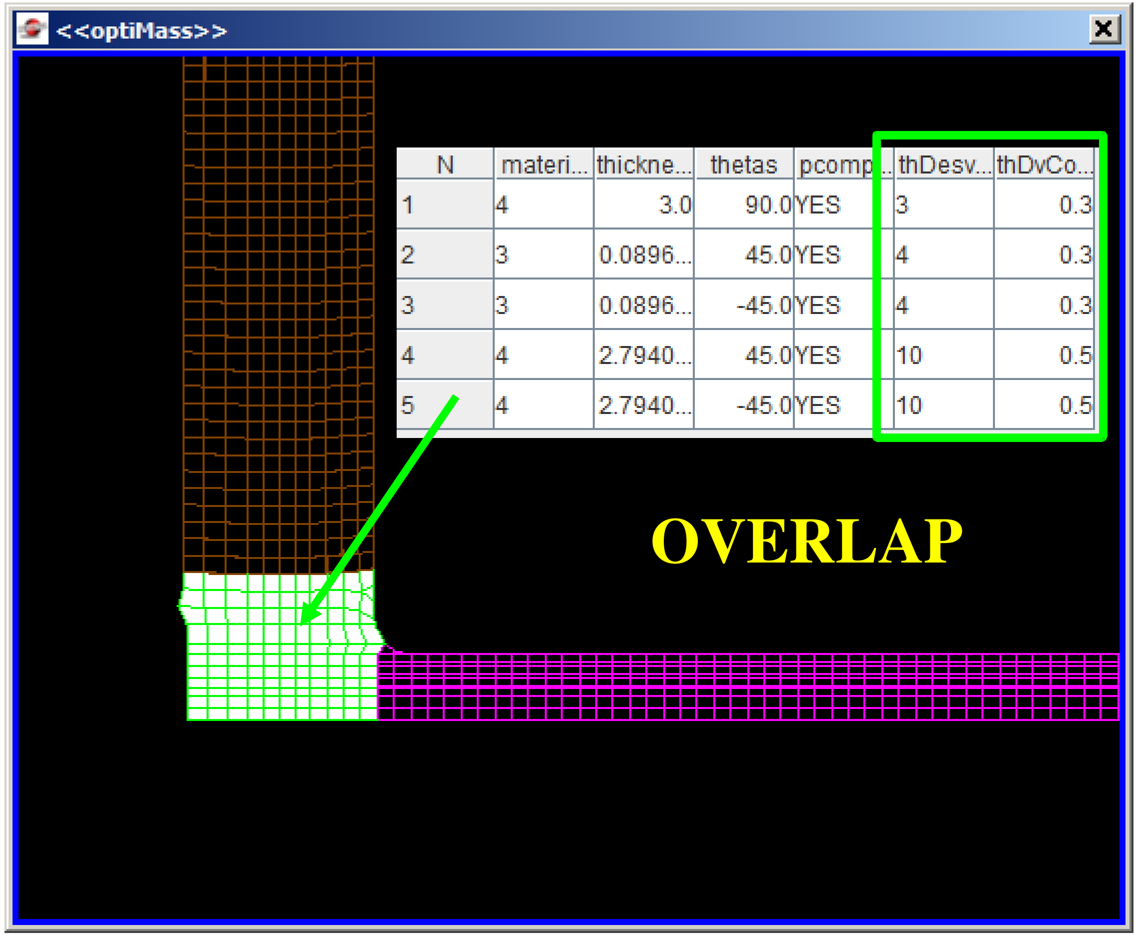

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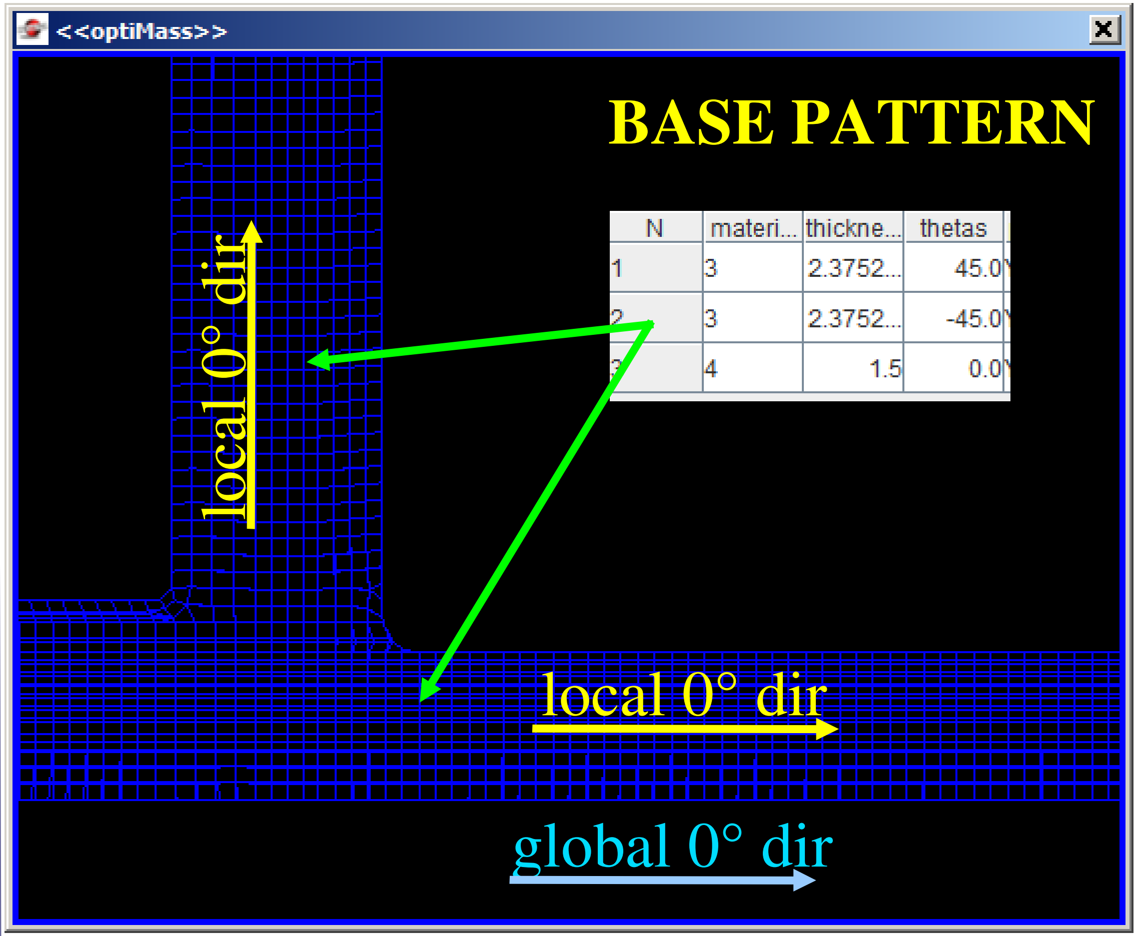
LAYUP MODELING AND OPTIMIZATION - IV

Fiber orientation issues



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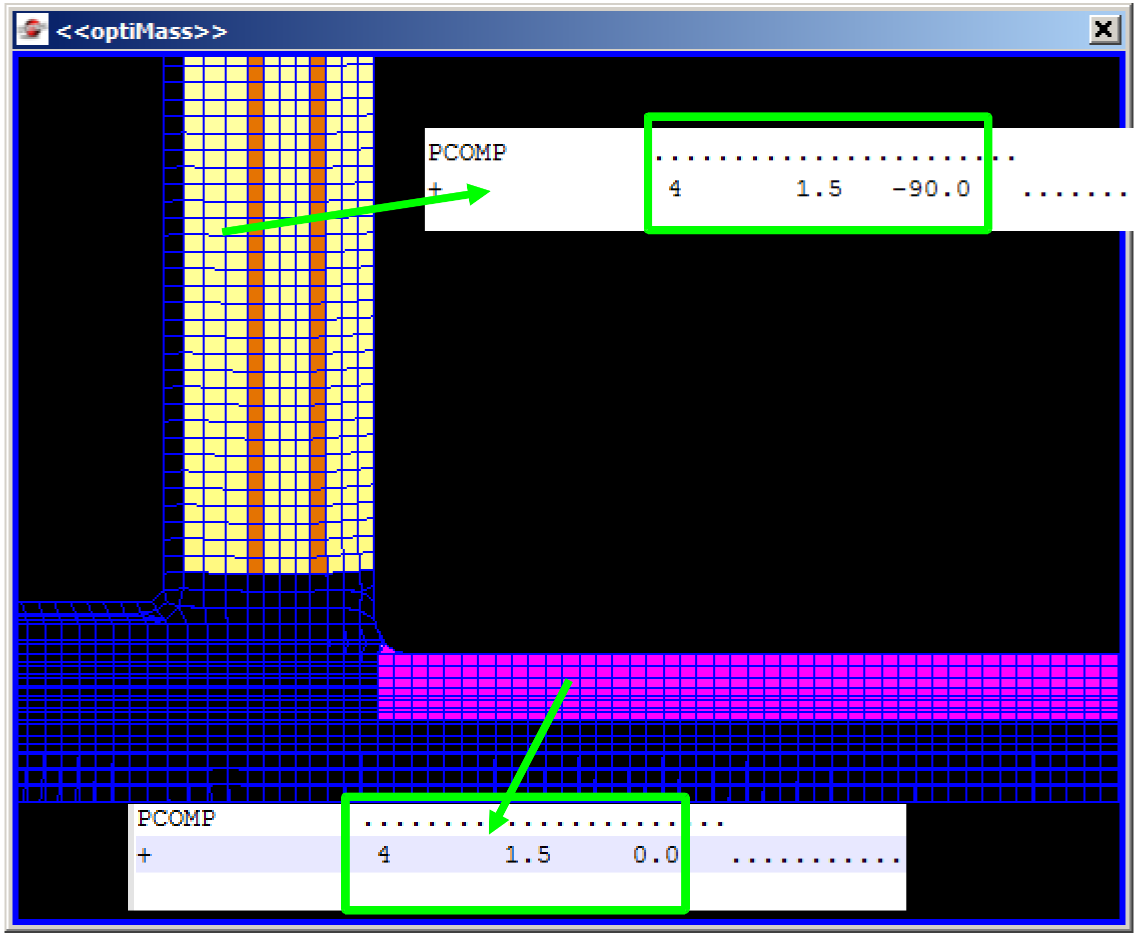
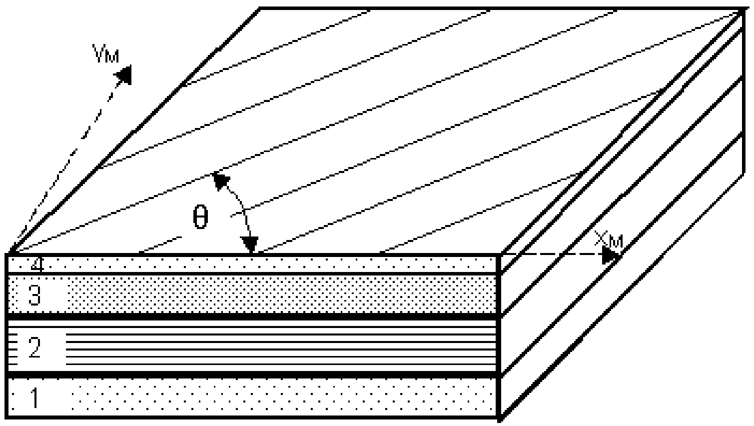
LAYUP MODELING AND OPTIMIZATION - IV

Fiber orientation issues



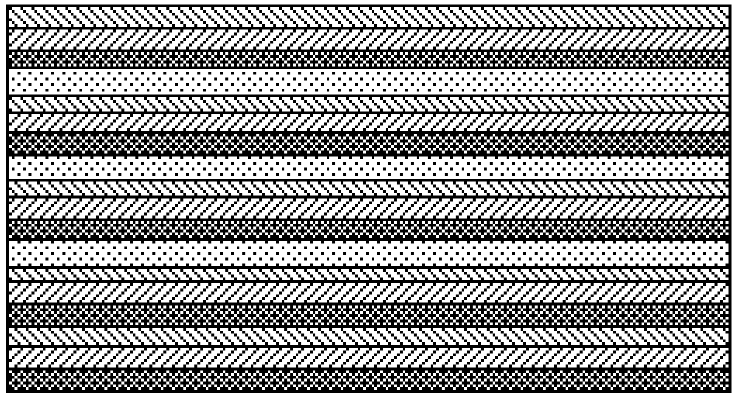
INDUSTRIAL LAYUP (RESHUFFLE) - I

FIRST - OPTIMIZED NUMERICAL MODEL



N	materi...	thickne...	thetas	pcomp...	thDesv...	thDvCo...
1	3	2.3752...	45.0	YES	32	1.0
2	3	2.3752...	-45.0	YES	32	1.0
3	4	1.5	0.0	YES	33	0.15

ACTUAL LAYUP



N	materi...	thickne...	thetas	pcomp...	thDesv...	thDvCo...
1	3	0.8	45.0	YES	32	1.0
2	3	0.8	-45.0	YES	32	1.0
3	4	0.5	0.0	YES	33	0.15
4	3	0.8	0.0	YES	<none>	1.0
5	3	0.8	0.0	YES	<none>	1.0
6	4	0.5	0.0	YES	<none>	1.0
7	3	0.8	0.0	YES	<none>	1.0
8	3	0.8	0.0	YES	<none>	1.0
9	4	0.5	0.0	YES	<none>	1.0

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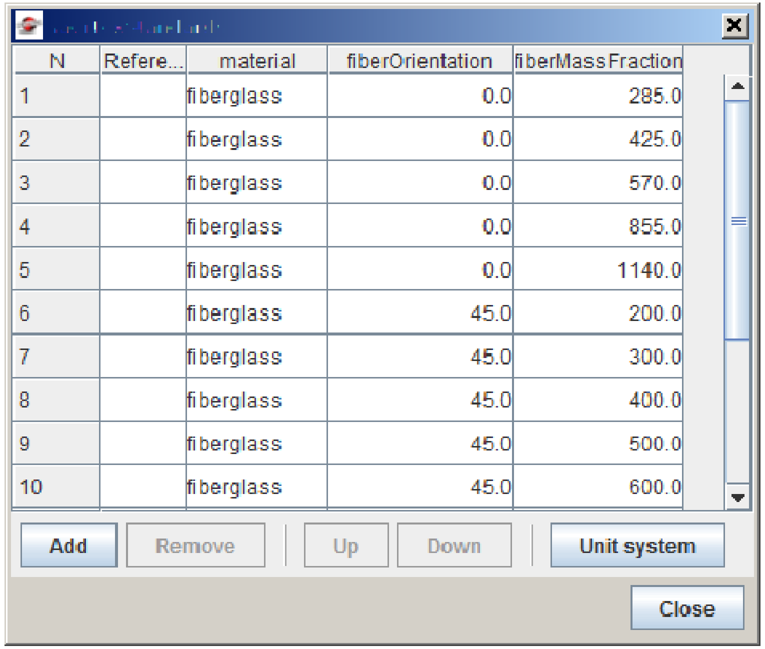
INDUSTRIAL LAYUP (RESHUFFLE) - II

Starting point: supplier catalogue, contains all the different sheet type and unit weights

From the catalog, we build up a table of references, generating :

- -Uniaxial 0 90
- -Biaxial 0/90 45/-45
- -Triaxial 0/45/-45 90/45/-45
- -Quadriaxial

We find the optimal combination of the references (which one and in how many replications) using ENKIDOU design space and genetic optimization



N	Refere...	material	fiberOrientation	fiberMassFraction
1		fiberglass	0.0	285.0
2		fiberglass	0.0	425.0
3		fiberglass	0.0	570.0
4		fiberglass	0.0	855.0
5		fiberglass	0.0	1140.0
6		fiberglass	45.0	200.0
7		fiberglass	45.0	300.0
8		fiberglass	45.0	400.0
9		fiberglass	45.0	500.0
10		fiberglass	45.0	600.0

ALSTOM

INDUSTRIAL LAYUP (RESHUFFLE) - II

Starting point: supplier catalogue, contains all the different sheet type and unit weights

From the catalog, we build up a table of references, generating :

- -Uniaxial 0 90
- -Biaxial 0/90 45/-45
- -Triaxial 0/45/-45 90/45/-45
- -Quadriaxial

We find the optimal combination of the references (which one and in how many replications) using ENKIDOU design space and genetic optimization

references0.5

N	type	referen...	thickne...	thickne...	thickne...
1	uniDire...	[redacted]	2.28E-1	0.00E0	0.00E0
2	uniDire...	[redacted]	3.40E-1	0.00E0	0.00E0
3	uniDire...	[redacted]	4.56E-1	0.00E0	0.00E0
4	uniDire...	[redacted]	6.84E-1	0.00E0	0.00E0
5	uniDire...	[redacted]	9.12E-1	0.00E0	0.00E0
6	biAxial...	[redacted]	2.28E-1	0.00E0	1.07E0
7	biAxial...	[redacted]	2.28E-1	0.00E0	2.28E-1
8	biAxial...	[redacted]	2.28E-1	0.00E0	3.40E-1
9	biAxial...	[redacted]	2.28E-1	0.00E0	4.56E-1
10	biAxial...	[redacted]	2.28E-1	0.00E0	6.84E-1
11	biAxial...	[redacted]	2.28E-1	0.00E0	9.12E-1
12	biAxial...	[redacted]	3.40E-1	0.00E0	1.07E0
13	biAxial...	[redacted]	3.40E-1	0.00E0	2.28E-1
14	biAxial...	[redacted]	3.40E-1	0.00E0	3.40E-1
15	biAxial...	[redacted]	3.40E-1	0.00E0	4.56E-1
16	biAxial...	[redacted]	3.40E-1	0.00E0	6.84E-1
17	biAxial...	[redacted]	3.40E-1	0.00E0	9.12E-1
18	biAxial...	[redacted]	4.56E-1	0.00E0	1.07E0
19	biAxial...	[redacted]	4.56E-1	0.00E0	2.28E-1
20	biAxial...	[redacted]	4.56E-1	0.00E0	3.40E-1

Close

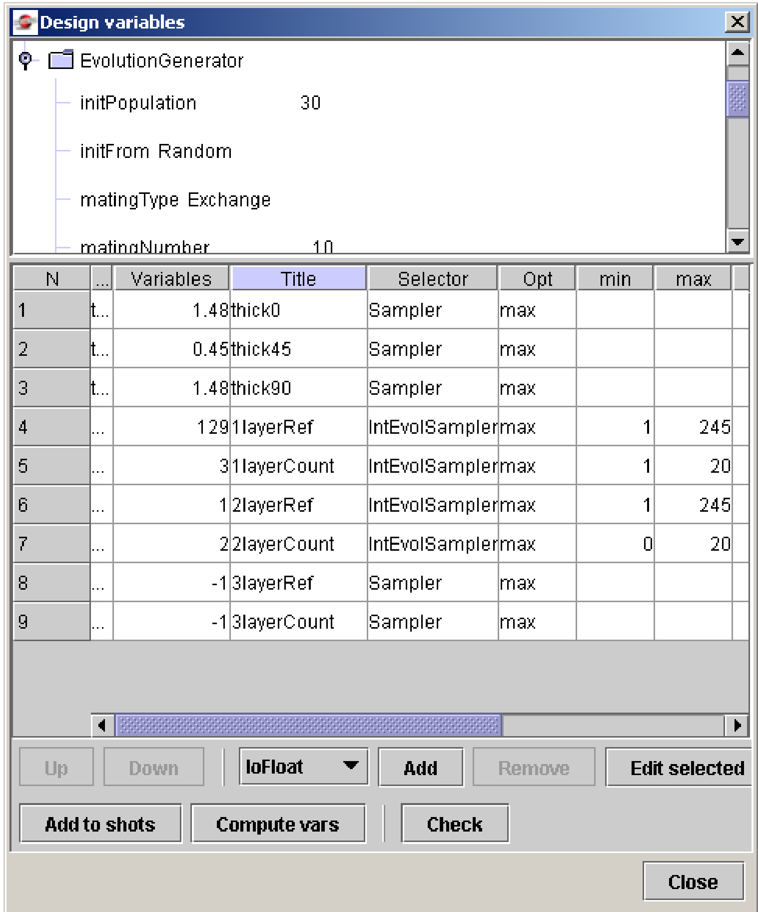
INDUSTRIAL LAYUP (RESHUFFLE) - II

Starting point: supplier catalogue, contains all the different sheet type and unit weights

From the catalog, we build up a table of references, generating :

- -Uniaxial 0   90
- -Biaxial 0/90   45/-45
- -Triaxial 0/45/-45   90/45/-45
- -Quadriaxial

We find the optimal combination of the references (which one and in how many replications) using ENKIDOU design space and genetic optimization



N	...	Variables	Title	Selector	Opt	min	max
1	t...	1.48	thick0	Sampler	max		
2	t...	0.45	thick45	Sampler	max		
3	t...	1.48	thick90	Sampler	max		
4	...	129	1layerRef	IntEvolSampler	max	1	245
5	...	3	1layerCount	IntEvolSampler	max	1	20
6	...	1	2layerRef	IntEvolSampler	max	1	245
7	...	2	2layerCount	IntEvolSampler	max	0	20
8	...	-1	3layerRef	Sampler	max		
9	...	-1	3layerCount	Sampler	max		

INDUSTRIAL LAYUP (RESHUFFLE) - II

Starting point: supplier catalogue, contains all the different sheet type and unit weights

From the catalog, we build up a table of references, generating :

- -Uniaxial 0   90
- -Biaxial 0/90   45/-45
- -Triaxial 0/45/-45   90/45/-45
- -Quadriaxial

We find the optimal combination of the references (which one and in how many replications) using ENKIDOU design space and genetic optimization

	target thickness	reshuffled thickness
0°	1.48	1.37
+/- 45°	0.45	0.48
90°	2.45	2.48
Total	4.83	4.81

2*

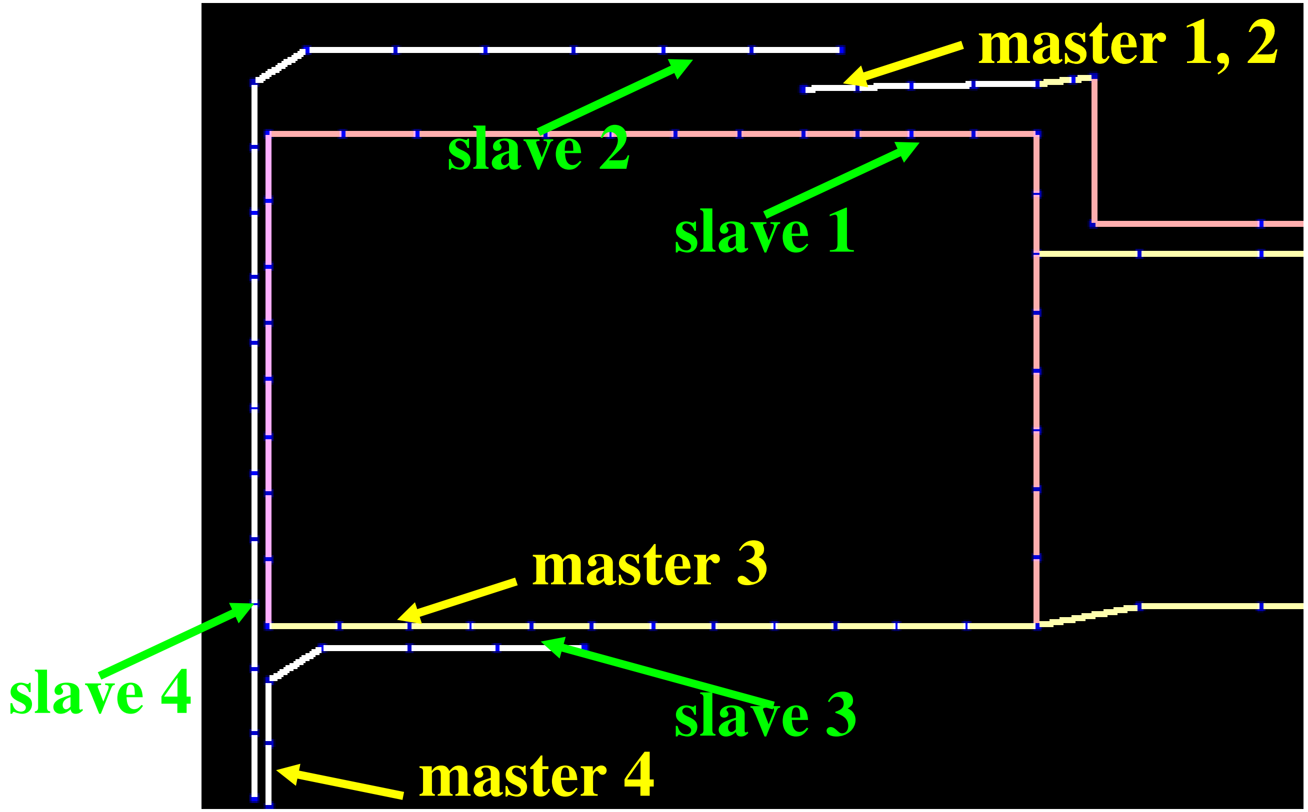
N	type	referen...	thickne...	thickne...	thickne...
102	quadriAxial	[redacted]	2.28E-1	2.40E-1	1.07E0

1*

N	type	referen...	thickne...	thickne...	thickne...
32	biAxial0-90	[redacted]	9.12E-1	0.00E0	3.40E-1

ASSEMBLY TOOLS - I

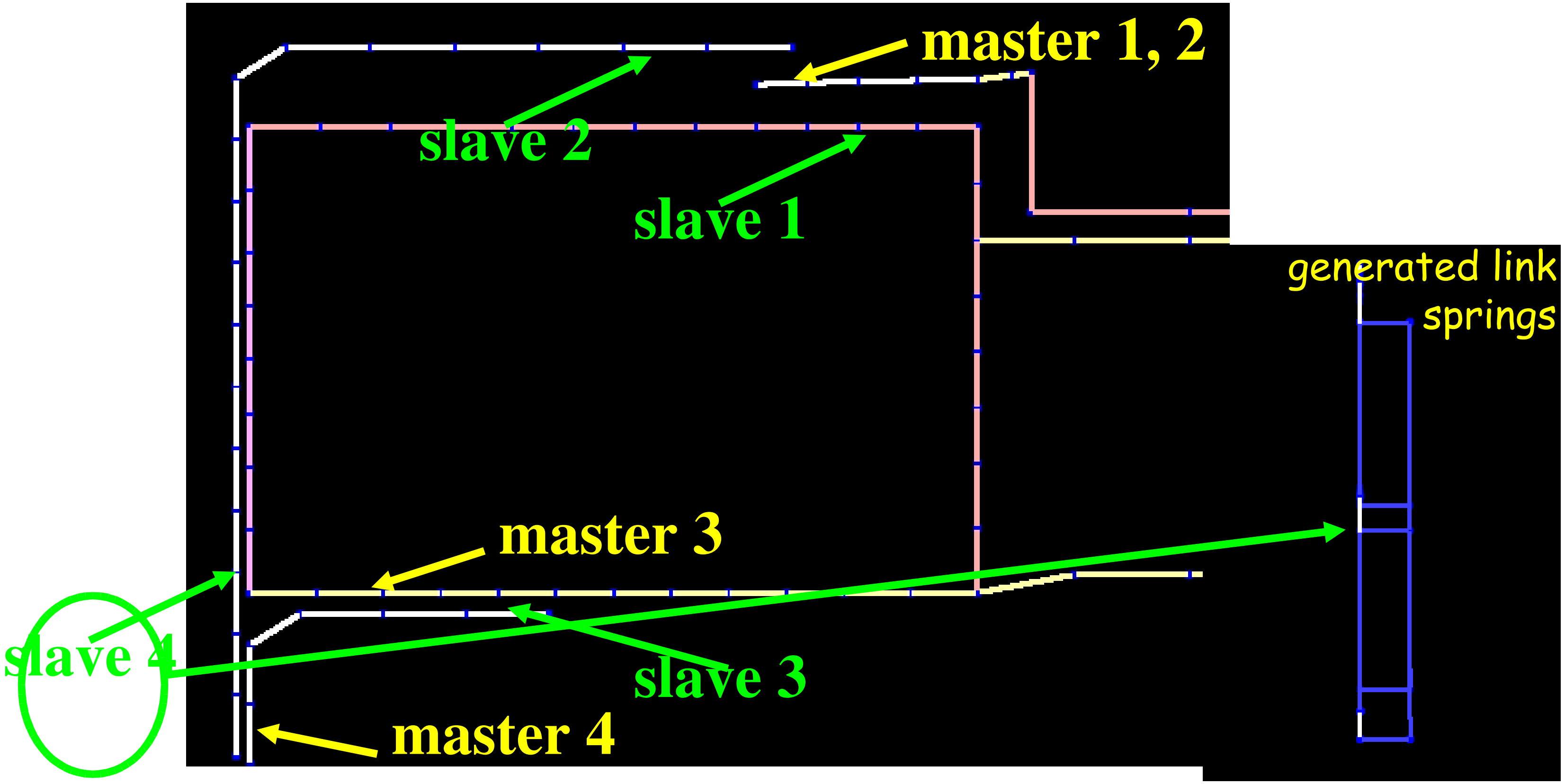
GLUE LAYER GENERATION



1. Master and slave surface definition (NB: meshes are NOT coherent)
2. Extrusion from master to slave (glue generation)
3. Link of glue to slave surface
   - spring elements
   - MPC or equivalent constraints

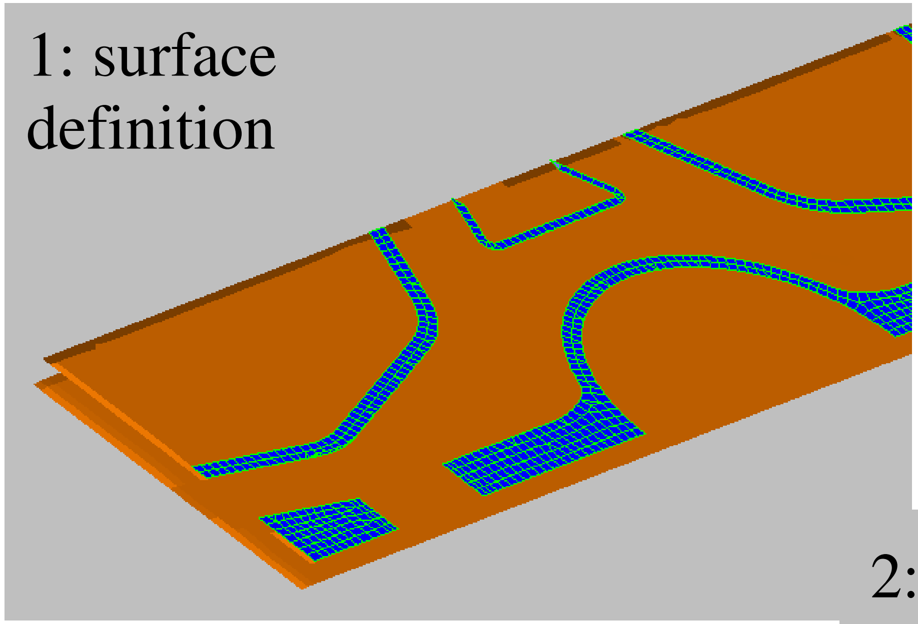
ASSEMBLY TOOLS - I

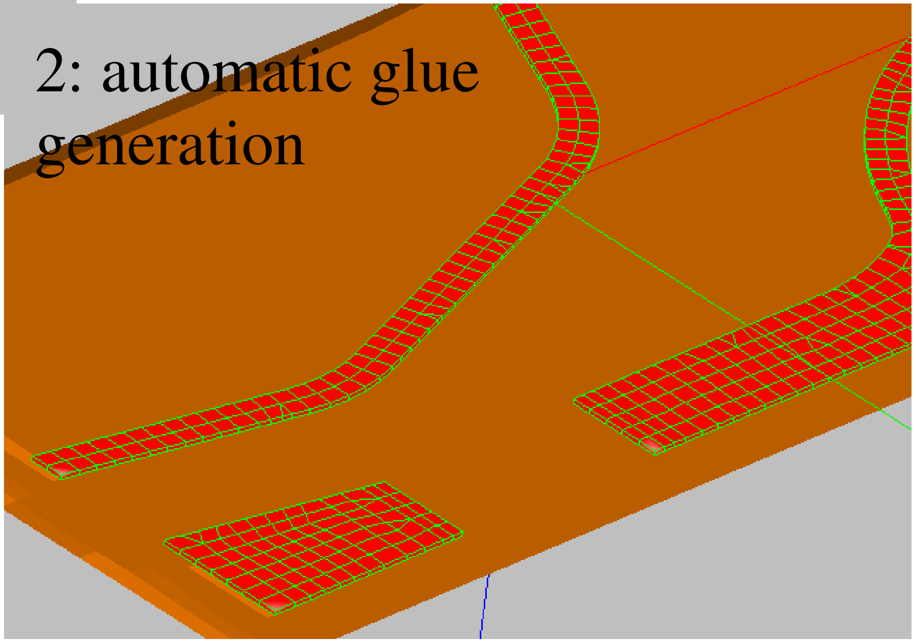
GLUE LAYER GENERATION



1. Master and slave surface definition (NB: meshes are NOT coherent)
2. Extrusion from master to slave (glue generation)
3. Link of glue to slave surface
   - spring elements
   - MPC or equivalent constraints

GLUE LAYER GENERATION WORKS ON COMPLEX GEOMETRIES





COST ANALYSIS

- The cost of the assembled structure is composed of:
  - Raw material cost
  - Fabrication cost
  - Assembly cost
- A cost model is implemented in the prototype, yielding cost estimation
- The user can add/modify the model using expressions
- Different models can be implemented

CONCLUSIONS

- We have used optimization to identify the best lay-up (material, orientation, thickness and location) wrt structural performances
- We have integrated industrial lay-up process in the modeling and optimization procedure
- The use of (Euro) cost as an objective function makes it easier to take into account the effect of manufacturing in the optimization