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
ULTIMAT

Utilisation innovante des nouveaux matériaux dans la construction ferroviaire

ALSTOM
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
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.
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 (%)
TOPOLOGY OPTIMIZATION

CAD DESIGN

PARAMETRIC OPTIMIZATION

ON THE MESH MODIFICATIONS

FINAL DESIGN
TOPOLOGY OPTIMIZATION

CAD DESIGN

PARAMETRIC OPTIMIZATION

ON THE MESH MODIFICATIONS

FINAL DESIGN
OPTIMIZATION SUGGESTS/FOLLOWS DESIGN MODIFICATIONS
Optimal structure combines glass/carbon fiber monoliths, glass fiber sandwiches and conventional steel and aluminum parts
FINAL BODY DESIGN - II

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass Fraction</th>
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<tr>
<td>foam</td>
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<tr>
<td>glass fiber monolith</td>
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<tr>
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<td>0.29</td>
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<tr>
<td>aluminum</td>
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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)
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?
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 using 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.

<table>
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<tr>
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<td>3</td>
<td>0.6626</td>
<td>90.0</td>
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</tbody>
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**LAYUP MODELING AND OPTIMIZATION - II**

**SIMULATION MODEL**
(components - PID - parts - sections)

**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 ...)
OVERLAP OF DIFFERENT LAYER PATTERNS ARE HANDLED THROUGH DESIGN VARIABLES:

- DESIGN DEFINITION
- INTERFACE TO STRUCTURAL OPTIMIZATION
LAYUP MODELING AND OPTIMIZATION - III

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CONVERGING PATCHES
OVERLAP MODELING AND OPTIMIZATION - III

OVERLAP OF DIFFERENT LAYER PATTERNS ARE HANDLED THROUGH DESIGN VARIABLES:

- DESIGN DEFINITION
- INTERFACE TO STRUCTURAL OPTIMIZATION
Fiber orientation issues

BASE PATTERN

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<td>3</td>
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<tr>
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<td>4</td>
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Fiber orientation issues
FIRST - OPTIMIZED
NUMERICAL MODEL

ACTUAL LAYUP

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<th>thickne</th>
<th>thetas</th>
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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
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<table>
<thead>
<tr>
<th>Angle</th>
<th>Target Thickness</th>
<th>Reshuffled Thickness</th>
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<tbody>
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</tr>
<tr>
<td>90°</td>
<td>2.45</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Total 4.83 4.81
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
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GLUE LAYER GENERATION WORKS ON COMPLEX GEOMETRIES

1: surface definition

2: automatic glue generation
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